

ANKARA YILDIRIM BEYAZIT UNIVERSITY
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**THE EFFECT OF FINES CONTENT ON THE FROST
SUSCEPTIBILITY OF SUBBASE AND SUBGRADE
MATERIAL**

M.Sc. Thesis by
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THE EFFECT OF FINES CONTENT ON THE FROST SUSCEPTIBILITY OF SUBBASE AND SUBGRADE MATERIAL

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M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**THE EFFECT OF FINES CONTENT ON THE FROST SUSCEPTIBILITY OF SUBBASE AND SUBGRADE MATERIAL**” completed by **KAWTHER MAKTTOOF** under supervision of **ASSIST. PROF. DR. ZEYNEP H. ÖZKUL BİRGÖREN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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THE EFFECT OF FINES CONTENT ON THE FROST SUSCEPTIBILITY OF SUBBASE AND SUBGRADE MATERIAL

ABSTRACT

The freezing and thawing process has detrimental effects on the structural integrity of roads in regions experiencing seasonal frost conditions. The determination of the frost susceptibility of subbase and subgrade soils is an important part of material selection and can significantly impact construction costs. However, it is effected by many parameters and can be determined on three levels of complexity. Advanced methods, although more accurate, can require specialized equipment, training, and a greater amount of time to process test data. Such advanced testing is currently not included in the KGM design manuals and procedures. In this study, the results of freeze thaw tests conducted using a specially designed frost susceptibility cabin located in the laboratory of Soil Stabilization and Research Development Group of the TC General Directorate of Highways, Research Department (KGM, ARGE) are presented. The device conforms to ASTM D5918 requirements and is capable of conducting a fully-automated 5-day freeze-thaw program which includes two freeze-thaw cycles. Four samples can be tested simultaneously with automatic recording of temperatures, water intake and heave. The new testing device has been used to test a quarry-based gravel with varying percentages of fines content. This study evaluates the influence of fines content and type on the frost susceptibility of mixtures of gravel and sand. The coarse grained material consisted of crushed rock aggregates derived from a limestone quarry with size fractions: 12-19 mm, 5-12 mm, 0-5 mm and fines or “Filler”. Other fine grained material were added to the mixtures included commercially available Kaolinite and Bentonite minerals and a natural clay, denoted “YK”. Fine grained materials were added in percentages varying from 5.24% to 18%. The samples were compacted at maximum dry density and optimum moisture content and CBR values were determined for the as-compacted, soaked and post-freeze thaw states. The frost heave rates and the segregation potential were calculated. The analysis shows that the freeze-thaw testing cabin gives reliable test results. The results also show that the frost susceptibility increases with an increase in the fines content and that mineralogy and grading of the soils impact the frost susceptibility.

Keywords: Frost susceptibility classification, frost heave, segregation potential, new freezing and thawing cabine, and revised soil classification system RSCS.



DONMA VE ÇÖZÜLMENİN ALT TABAN VE TEMEL MALZEMESİNİN İNCE MALZEME İÇERİĞİNE ETKİSİ

ÖZ

Donma ve çözülme sürecinin mevsimsel don koşullarının yaşandığı bölgelerde yolların yapısal bütünlüğü üzerinde olumsuz etkileri bulunmaktadır. Alt temel ve temel zeminlerin dona karşı duyarlılığının belirlenmesi, malzeme seçiminin önemli bir parçası olup inşaat maliyetlerini önemli ölçüde etkileyebilmektedir. Ancak bu duyarlılık birçok parametreden etkilenir ve üç farklı karmaşıklık seviyesinde belirlenebilir. Gelişmiş yöntemler daha doğru sonuçlar sağlamakla birlikte, özel ekipman, eğitim ve test verilerinin işlenmesi için daha fazla zaman gerektirebilir. Bu tür ileri düzey testler şu anda KGM tasarım el kitapları ve prosedürlerinde yer almamaktadır. Bu çalışmada, Karayolları Genel Müdürlüğü Araştırma Dairesi (KGM, ARGE) Zemin Stabilizasyon ve Araştırma Geliştirme Grubu laboratuvarında bulunan özel tasarım dona karşı duyarlılık kabini kullanılarak gerçekleştirilen donma-çözülme testlerinin sonuçları sunulmuştur. Cihaz, ASTM D5918 standartlarına uygun olup tamamen otomatik bir şekilde 5 günlük bir donma-çözülme programını, iki donma-çözülme döngüsü dahil olmak üzere gerçekleştirme kapasitesine sahiptir. Aynı anda dört numune test edilebilmekte ve sıcaklık, su alımı ve şişme otomatik olarak kaydedilebilmektedir. Yeni test cihazı, farklı ince malzeme yüzdeleri içeren taş ocağı temelli bir çakıl malzemesini test etmek için kullanılmıştır. Bu çalışmada, çakıl ve kum karışımlarının dona karşı duyarlılığı üzerinde ince malzeme içeriği ve türünün etkisi değerlendirilmiştir. Kalın malzemeler, bir kireçtaşı ocağından elde edilen 12-19 mm, 5-12 mm, 0-5 mm boyut fraksiyonlarına ve “filler” olarak adlandırılan ince taneli malzemelere sahip kırılmış taş agregalarından oluşmuştur. Karışımlara eklenen diğer ince malzemeler arasında ticari olarak temin edilen Kaolinit ve Bentonit mineralleri ile “YK” olarak adlandırılan doğal bir kil yer almıştır. İnce taneli malzemeler, %5,24 ile %18 arasında değişen oranlarda karışıma dahil edilmiştir. Numuneler, maksimum kuru yoğunlukta ve optimum su içeriğinde sıkıştırılmış, ardından sıkıştırılmış, suya doygun ve donma-çözülme sonrası durumlar için CBR değerleri belirlenmiştir. Donma kabırma oranları ve segregasyon potansiyeli hesaplanmıştır. Analizler, donma-çözülme test kabininin güvenilir test sonuçları sağladığını göstermektedir. Sonuçlar

ayrıca, ince malzeme içeriğinin artışıyla dona karşı duyarlılığın arttığını ve zeminlerin mineralojisi ile gradasyonunun dona karşı duyarlılığı etkilediğini ortaya koymaktadır.

Anahtar Kelimeler: Donma-çözülme, don kabarması, segregasyon potansiyeli ,don penetrasyonu, donma kabini, RSCS.



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NOMENCLATURE

Roman Letter Symbols

C Heat capacity rate, kW/K

v_u Velocity of pore water entering into unfrozen soil

Grad T Temperature gradient

ρ_u Suction at the pore freezing front

ρ_w Suction at the ice lenc

K_f Overall hydraulic conductivity of frozen

d Thickness of frozen fringe

T_s Temperature at the segregation of the freezing front

S_p Segregation potential

V Water intake rate (volume of water entering sample during steady state temperature condition)

$\frac{d_h}{d_t}$ Heave rate

SP_{field} Field segregation potential

LL_{ker} Liquid limit of kerosen

LL_{brine} Liquid limit of brine

LL_{DW} Liquid limit of distilled water

RSCS Revised Soil Classification System

S_E Electrical Sensetivity

Greek Letter Symbols

Δ Difference

μ Dynamic viscosity of fluid, N·s/m²

ν Specific volume of fluid, m³/kg

ρ Bulk density of soil, kg/m³

Subscripts

c Cold fluid

i Inlet

m Mean

max Maximum

min Minimum

Acronyms

BDC Bottom Dead Center

CI Compression-ignition

ICE Internal Combustion Engine

LHC Longitudinal Heat Conduction

LMTD Logarithmic Mean Temperature Difference

SI Spark-ignition

TDC Top Dead Cente



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CHAPTER 1

INTRODUCTION

This chapter describes the introduction of frost-susceptibility, the objectives in this research and the significance of the research while The final section discusses how the chapters are organized in this thesis.

Frost susceptibility refers to the ease with which ice lenses and ice segregation can form in soils when they are frozen. Ice segregation leads to the upward movement of ice lenses and soil particles, significantly affecting the soil's hydraulic conductivity. Methods for reliably testing soil frost sensitivity have existed since Taber's work on the mechanism of ground ice disintegration in 1929 [1].

The criteria for predicting significant ice segregation - it can occur in non-uniform soils with more than 3% of grains smaller than 0.02 mm, and in uniform soils where this size fraction is greater than 10% [2].

Cyclic freezing and thawing can cause significant damage to road structures. The two main processes that contribute to frost damage are: 1) frost heaving during the frost penetration and freezing period and 2) weakening of the soil as thawing occurs. These processes occur due to ice segregation where ice lenses form within the ground mass during freezing. It is noted that frost heaving is not necessary for thaw weakening to occur (Cook 1963; Titov 1965) [3]. Therefore, frost sensitivity criteria need to be made by considering both types of frost damage individually: damage due to heaving (frost heave) and damage from soil weakening when thawing occurs. Thus, frost sensitivity simply reflects the combined effects of frost heave sensitivity, and thaw weakening sensitivity [4].

The study conducted by Slunga et al [5] proposed a level-1 criteria. However, Level-I classifications have serious limitations and cannot clearly distinguish between frost-sensitive and nonfrost-sensitive soils, except in cases where the soil structure is tolerant to frost heave or associated with large soil masses, in which case materials can be simply divided into frost-sensitive and non-frost-sensitive groups based on particle size distribution.

Level-II classifications are based on both grain size distribution and tests addressing soil-water interaction, such as capillary rise, unfrozen capillary rise, hydraulic conductivity, Atterberg limits, specific surface area, and clay content.

Level-III assessments involve direct laboratory or field frost heave tests, such as the TRRL, ASTM, and JGS tests, which measure the amount and rate of soil swelling during freezing, with a frost heave rate less than 0.5 mm/day in the CRREL test indicating sensitivity to frost [6].

1.1 Objectives of this research

The goal of this research is:

1. To develop methods and calculation tools to evaluate the frost sensitivity of soils tested using a newly designed freezing and thawing test cabin in conformance with ASTM D5918 standard test method.
2. To determine the frost-susceptibility of gravel and sand mixtures with different amounts and types of fines content by calculating heave rates and segregation potential from the test results. These values are then compared with accepted threshold fines content values from the literature.
3. To assess the effect of the mineralogy of fine materials on frost heave. Plasticity, grain size ($\% < 0.075$), and electrical sensitivity of the different fine grained soils used were evaluated and compared for their influence on frost-susceptibility.
4. To compare the results (heave rates and segregation potential) with existing frost classification systems which include complexity levels Level I, Level II and Level III and to evaluate their effectiveness in predicting frost susceptibility. To develop regression curves for improved prediction of frost susceptibility.

1.2 Significance of this research

Prediction of frost susceptibility is difficult since it is impacted by many different factors. Both qualitative assessments and quantitative assessments are needed. Qualitative assessments of frost susceptibility is needed to select appropriate material for pavement subgrades. Quantitative assessments are needed in order to assist in improved design using mechanistic empirical pavement design approaches. Such methods require evaluation of the

segregation potential of the subgrade materials. This is the first study of its kind supported by the General Directorate of Highways, Research Department in Türkiye. It will shed light on ways to improve the existing assessment of frost susceptible materials in the design manuals currently in place.

1.3 The organization of this thesis

Following this introduction chapter, the thesis is organized into six additional chapters. Chapter 2 provides a review of relevant literature and a background for this research. Chapter 3 describes the materials and methodologies that were used in this research, and Chapter 4 presents the results of laboratory tests. Chapter 5 Discusses and analysing the laboratory tests performed and compare it to the relevant existing researches from the literature Chapter 6 summarises the outcomes and conclusions as well as providing recommendations for future research. The appendices at the end of the report include Appendix A for phase diagrams, Appendix B for Freeze-Thaw test procedure, Appendix C for Freeze-Thaw test results showing heave and water intake rates, and Appendix D for temperature profiles.

CHAPTER 2

LITERATURE REVIEW

This chapter provides a literature review of the impact that freezing and thawing cycles have on pavement foundation structures. This chapter will clarify the relationship between this research and previous studies, as well as how it builds upon them. The review of the literature covers two main topics: freeze-thaw theory, and freeze-thaw laboratory testing.

2.1 Freeze-Thaw Mechanism and Related Theory

Freezing temperatures in pavement structures can result in detrimental heave and eventual deterioration of pavement support conditions. Ice lenses, also known as ice segregation, develop and cause heave in pavements. For ice lenses to form, three requirements must be met: (i) the soil must be susceptible to frost, (ii) the existing to an sufficient water supply such as a high groundwater table, (iii) The local weather supports sustained freezing conditions (Taber 1929) [1]. The contributions of Stephen Taber and Gunnar Beskow have established the basis for comprehending the mechanics of frost heaving, which persistently impact modern study.

Taber (1929, 1930) [1] was one of the initial proponents of the idea that frost heaving is principally caused by the formation of ice crystals in soil, rather than solely from the volumetric expansion of freezing water. This claim contested the dominant belief that heaving resulted exclusively from the volume expansion caused by water freezing. Taber elucidated the directional formation of ice crystals, providing a refined comprehension of pressure generation in the soil during freezing occurrences.

2.1.1 Water Segregation during Freezing

A fundamental element in Taber's research is the process of water segregation during freezing. As temperatures decrease, water is pulled upward into the freezing zone, resulting in the production of ice lenses. This process, propelled by molecular cohesion, leads to an accumulation of water in the surface soil, which can markedly increase heaving (Taber, 1929) [1].

However, various factors affect the degree of frost heaving. The size and percentage of voids in soil play a critical role; smaller voids increase capillary action, allowing water to rise higher and potentially leading to greater heaving (Beskow, 1935) [7]. The capacity of fine-grained soils, especially clays, to enable the upward transport of water by capillary action is essential for comprehending excessive heaving occurrences. The moisture content in the soil is crucial. Differences in soil texture, encompassing variations in particle size and content, further complicate the heaving response, as seen by several researchers (Harlan, 1973; Miller et al., 1975) [8] [9].

2.1.2 Thermal Dynamics and Freezing Front Penetration

The mechanism of ice lens formation begins with the application of a constant low temperature to the soil surface, initiating unsteady heat flow. As the freezing front advances into the soil, water within the soil pores begins to freeze in situ. The rate of frost front penetration is influenced by the thermal conductivity of the soil and the temperature gradient established between the warm and cold ends (Martin, 1959) [10]. The rapid movement of the freezing front creates a scenario where moisture is drawn towards the freezing zone, leading to localized accumulation and subsequent freezing of water at specific temperatures.

2.1.3 Role of the Frozen Fringe

The frozen fringe, delineated as the area between the freezing front and the ice lens, is crucial throughout the freezing process. This area displays a permeability gradient that decreases with lower temperatures, consequently affecting the water flow into the ice lens (Konrad & Morgenstern, 1980) [11]. The mechanics of moisture transfer across the frozen fringe are essential, as they dictate the degree to which water can move and facilitate ice lens development. Biermans et al. (1978) [12] and others have conducted research demonstrating that the frozen fringe permits continuous water flow under specific conditions, thereby promoting ice lens formation.

2.1.4 Nucleation and Ice Crystal Growth

Ice nucleation preferentially occurs on the surfaces of soil particles, where moisture films exist. As the temperature decreases, the thermodynamic potential of the unfrozen water films increase, causing water to transfer from the unfrozen soil into the freezing zone (Loch & Kay, 1978) [13]. The temperature disparity between the unfrozen and frozen regions creates

a suction gradient that propels this migration. When sufficient water accumulates, a localized pressure on adjacent soil particles creates an ice lens.

2.1.5 Pressure Limitations

The pressure produced after freezing is fundamentally constrained by the tensile strength of the water in the soil. This limitation signifies that not all freezing conditions will lead to substantial heaving, highlighting the intricacy of the frost heaving mechanism (Miller, 1977) [7]. Comprehending these pressure dynamics is essential for formulating predictive models of frost heaving behavior across diverse soil types.

(Hoekstra 1969) [14] reveals in his study that there is a difference in pressure-temperature dependence between granular and clay-type soils. In clay soils, pressure is dependent on the temperature at the ice lens, while in granular soils, pressure is independent of temperature. The temperature dependence is related to the ability of an ice lens to grow at temperatures well below freezing. The difference is related to the conductivity of water in frozen soil, which affects water flow under temperature gradients. In saturated granular soil, only a small number of films appear to be continuous, resulting in minimal water flow. In clay type soils, more unfrozen water per unit volume exists and more films remain continuous. The study suggests that physical models can be used to understand the actual magnitude of pressure-temperature dependence in clay soils.

The research conducted by Taber and Beskow has catalyzed significant investigation into frost heaving mechanisms, resulting in the creation of many models designed to forecast heaving behavior across diverse environmental circumstances. Subsequent research has investigated the influence of thermal gradients and the interplay of heat and moisture transfer in frozen soils (Groenevelt, 1974; Raats, 1975) [15] [16].

Improvements have integrated ideas from irreversible thermodynamics to more accurately characterize the intricate interactions within freezing soils (Miller et al., 1975) [9]. Nonetheless, despite these gains, as observed by Nakano (1990) [17] and others, a substantial gap persists in the experimental validation of numerous theoretical models, underscoring the necessity for ongoing empirical research.

Konrad (1999) [18] states that the segregation potential of silty sand with 20% kaolinite fines is considerably greater than that of the same silty sand with 20% montmorillonite fines. The

mineral surfaces of soil particles significantly affect both capillary water within macropores and water within micropores, which categorize unfrozen water. The size of macropores controls the distance that ice and unfrozen water can touch, while the mineralogy of clay determines the thickness of layers that hold water, which in turn affects the amount of unfrozen water in micropores. The mobility of water in capillary channels exceeds that in adsorbed water films, and frost heave is associated with water movement across the frozen fringe. Rieke et al. (1983) [19] observed a significant link between segregation potential and the specific surface area of the fines fraction in their soils. A larger specific surface area correlates with a reduced quantity of capillary water, where the majority of water movement toward the ice lens transpires. A consistent correlation between SPoSs and $d_{50}(\text{FF})$ is expected to manifest for the majority of soils.

The soils in eastern Turkey experiences to seasonal freezing and thawing, which can significantly impact transportation infrastructure and other civil engineering projects in the region. The mechanical and physical properties of frost-prone soils typically found in those areas, are known to change during the freezing-thawing cycle, leading to issues like frost heave, soil weakening, and reduced bearing capacity. Factors such as soil water content, thermal properties, snow cover, and local climate greatly influence the freezing and thawing processes in this cold region. The detrimental effects of frost action on highways and other infrastructure have been documented, highlighting the need to better understand and account for the frost susceptibility of eastern Turkey's soils in design and maintenance practices for civil engineering projects.

Continued research is crucial to enhance our comprehension of these systems and augment forecasting capacities, hence improving the design and upkeep of infrastructure in frost-prone areas. The contributions of early researchers persist in influencing modern studies, highlighting the necessity for a multidisciplinary strategy to comprehend frost heaving processes.

2.2 Freeze-Thaw Laboratory Testing

Laboratory freezing tests are necessary to accurately characterize the frost susceptibility of soils. This is especially true for borderline granular materials used for the base and sub-base layers in roads and runways. Laboratory testing offers valuable insights into the performance of soils when subjected to frost action.

2.2.1 Open and Closed System

The freeze-thaw testing comprises two distinct systems for evaluation: the open system and the closed system. The open-system means water is supplied from below the soil sample to simulate conditions representative of groundwater presence. This arrangement ensures a continuous availability of moisture throughout the freezing test. Findings indicate that with an open system setup the frost heave increases gradually over time, persisting even beyond 48 hours. This trend underscores the critical role of a sustained water supply in enhancing the frost susceptibility of soils (Wang et al., 2014) [20]. Furthermore, the open system allows for testing under various overburden pressures, offering valuable insights into how external loads influence frost heave behavior. Results from the open system highlight the importance of implementing effective drainage strategies in subgrade construction, especially in regions with high groundwater levels, as moisture presence significantly affects the frost heave response of coarse-grained soils (CGS) [20].

In contrast, with the closed-system configuration where additional water supply is not present, realization of frost heaving relies exclusively on the soil's initial moisture content. These type of tests have been used successfully in research to study the influence of specific soil parameters. It has been observed that with this type of testing the frost heave pattern may be notably different, with an initial rapid increase that plateaus after approximately 10 hours. These observations suggest that frost heave behavior is strongly dependent on the soil's initial moisture content and the limitations imposed by the absence of an external water source (Wang et al., 2014) [20]. The controlled environment of the closed system enables a focused examination of the effects of fines content and other variables on frost susceptibility, thereby advancing the understanding of frost heave mechanisms in coarse-grained soils (CGS) [20].

2.2.2 Devices used for Investigating Freeze-Thaw Cycles

Several types of frost heave testing devices have been developed over the years. Each device has different features depending on the research interest. Devices vary in terms of sample size, insulation, sensor types and placement, water accessibility and other features. Some of the more recent models will be discussed here including:

- a. Rieke's cell (1978, 1983)
- b. ASTM D5918-06 (2010)

- c. Alex Edwin Johnson (2012)
- d. T.L. Wang, Z.R. Yue, C. Ma, and Z. Wu (2014)
- e. Shakhmov and Zhussupbekov (2016)
- f. Qiang Luo, Peng Wu, Tengfei Wang (2019)
- g. B. Loranger, I. Hoff, Ph.D., E. Scibila, Ph.D., and G. Doré, Ph.D. (2019)
- h. Tatsuya Ishikawa, Tianshu Lin, Shinichiro Kawabata, Shuichi Kameyama, and Tetsuya Tokoro (2019)

Ross D. Rieke's research program used a frost heave cell which was an adaptation of Mageau's cell [21] illustrated in . This cell consists of a nylon barrel with an aluminum top cap and bottom plate which constitute the constant temperature boundaries. Foam insulation is placed around the barrel to prevent radial heat flow. The barrel is supported on four pedestals attached to a stainless steel plate. A 1.5 cm diameter solid stainless steel loading rod attaches to the top cap. The rubber membrane is sealed with a single O-ring at the base and a double O-ring seal at the top. Porous sintered stainless steel plates are flush mounted in the top cap and bottom plate for unimpeded drainage.

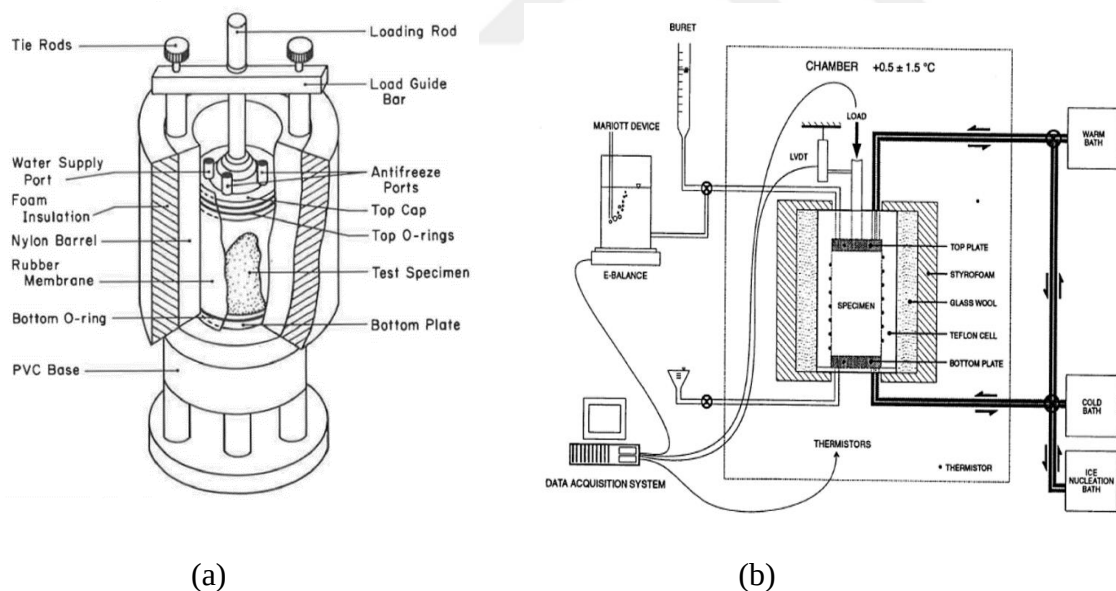


Figure 2.1 (a) Frost heave test cell (After Mageau 1978), (b) Step freezing system [19]

In Rieke's tests, the temperatures of the top cap and bottom plate were maintained at a constant value by circulating a constant temperature fluid through heat exchange mazes. 18 thermistors (YSI Model No. 44004) were used spaced at 0.5 cm intervals along the length of the barrel. These thermistors were embedded in the wall of the nylon cell barrel and were

hence adjacent to the soil. Thermistors were also used in the top cap and bottom plates to monitor boundary temperatures. Two constant temperature baths (Hotpack Refrigerated Bath/Circulator 603340) were used. The entire cell was placed in a refrigerator with a temperature maintained at approximately 2°C (36°F). A load frame with a 1.11 Kn (250 lb) Bellofram pneumatic load actuator was placed inside the refrigerator to allow the specimen to be consolidated. A 50 ml (7.75 in.3) buret was connected to the water intake line, and the change in the height of the specimen during the test was measured by a Linear Variable Differential Transducer (LVDT).

A standardized ASTM test method, ASTM-D5918-13, was first published in 1996 and revised in 2010 [22]. It outlines a standardized test method for assessing the frost susceptibility of soils used in pavement systems. It describes an open system method that involves subjecting compacted soil specimens to two freeze-thaw cycles, during which constant temperatures are applied at the top and bottom of the specimen to simulate environmental conditions. These temperatures are carefully adjusted to compensate for freezing point depression caused by salts present in the soil. Following the second thaw cycle, the California Bearing Ratio of the specimen is measured. The entire procedure can be completed within a five-day time frame and may be conducted either manually or with computer control. The primary objective of this method is to classify soils based on relative frost susceptibility, providing essential data for empirical pavement design in regions subject to seasonal frost.

In the ASTM standard the soil specimen freezing apparatus consists of several key components: temperature-controlled top and bottom plates, a base plate with a porous stone and dual water ports for supply and flushing, six acrylic rings forming a cylindrical mold, and a rubber membrane that contains the soil specimen. Additional components include a surcharge weight (3.5 kPa (0.5 lbf/in.)) a constant-head (Mariotte) water supply, a setup for supporting the displacement measurement system, and a displacement transducer or dial extensometer. The temperature control end plates are fabricated from reinforced phenolic resin, each covered with an aluminum plate to ensure effective heat conduction at the soil specimen's top surface and the base plate's bottom. The base plate itself is a circular aluminum structure with two recessed areas to hold a porous stone or a stainless steel porous disk. Water is supplied from a reservoir consisting of a clear acrylic tube with an internal diameter of at least 57 mm and a height of 508 mm. The water head is maintained at a constant level at the base of the bubble tube, enabling a controlled flow of water from the

reservoir to the soil specimen. Figure 2.2 shows the freezing cabinet in both front and top views.

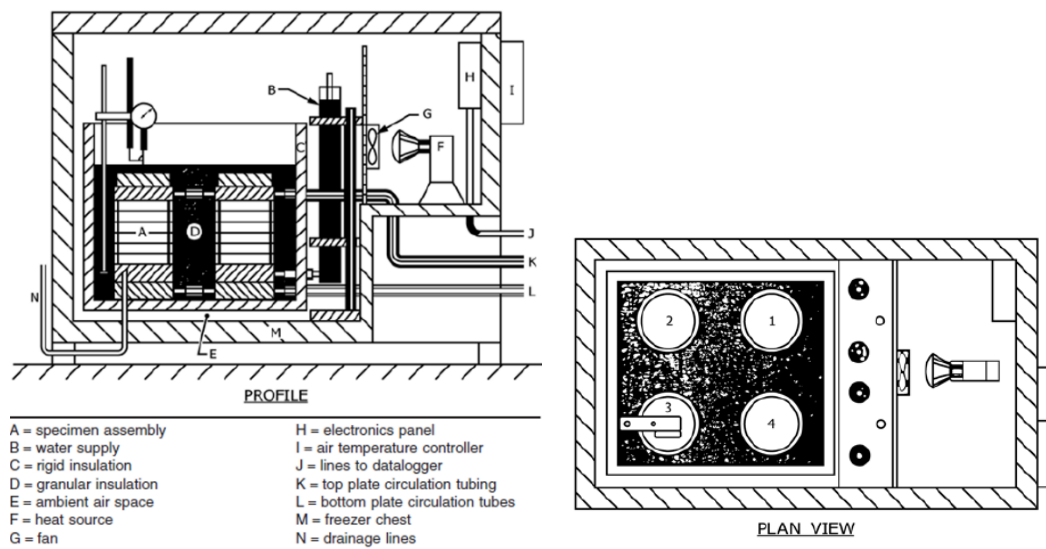


Figure 2.2 ASTM D5918-13 freeze cabinet assembly for freezing test [22]

ASTM D 5918 describes the 5-day freeze-thaw testing method which many researchers and transportation authorities have subsequently referenced and used, albeit, in some cases, with minor modification to testing equipment.

Alex Edwin Johnson (2012) conducted test frost heave and thaw weakening test in accordance with ASTM D5918-06. As per ASTM, the samples were compacted inside six acrylic rings with a rubber membrane between the soil and the rings. A water supply was made available at a level of 13 mm above the bottom of the sample. Laser displacement transducers measured the samples' heave and thermocouple sensors recorded the temperature profile within the samples. A schemete of the test setup and sample assembly is shown in Figure 2.3. The samples were then placed in a temperature-controlled chest freezer. After freeze-thaw testing a CBR test was performed on the thawed samples, and a moisture content profile was determined by trimming the samples and obtaining moisture contents at various depths.

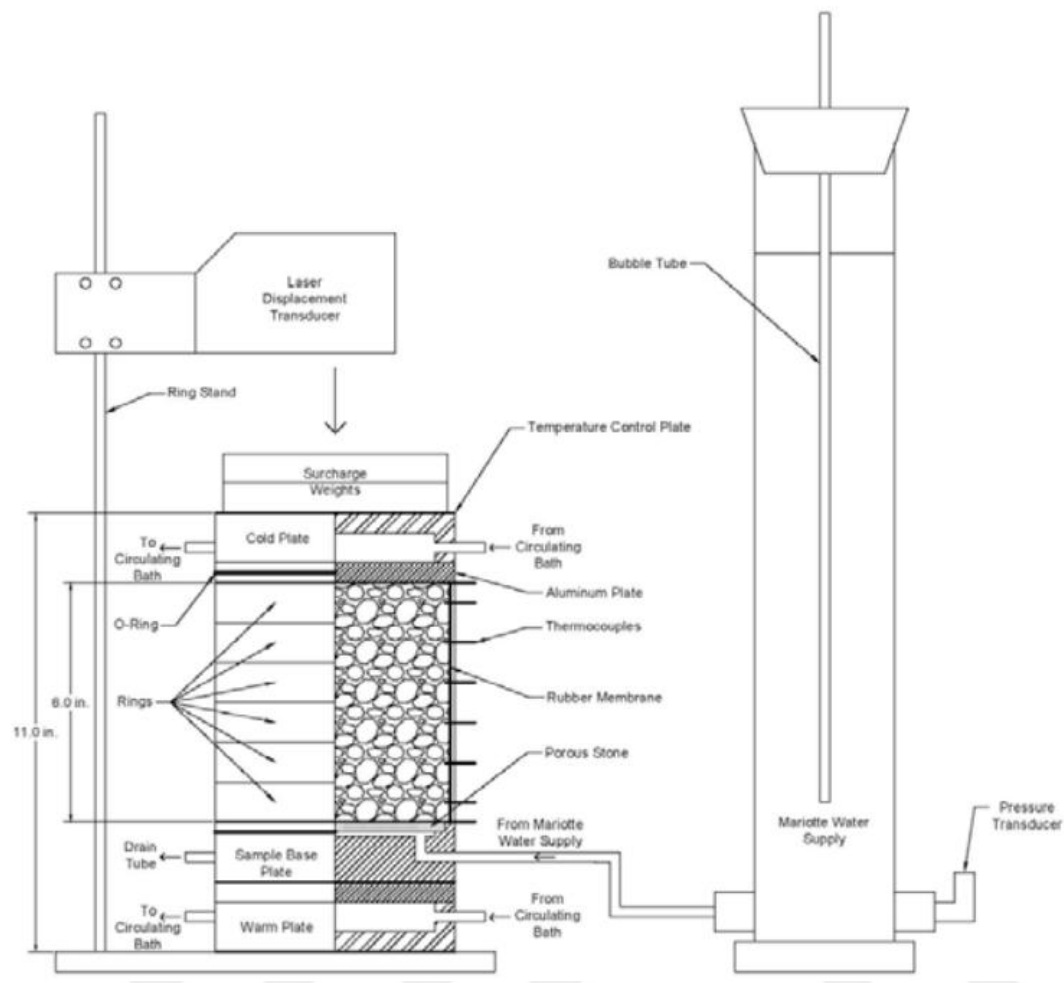


Figure 2.3 Frost-heave and thaw-weakening sample assembly [4]

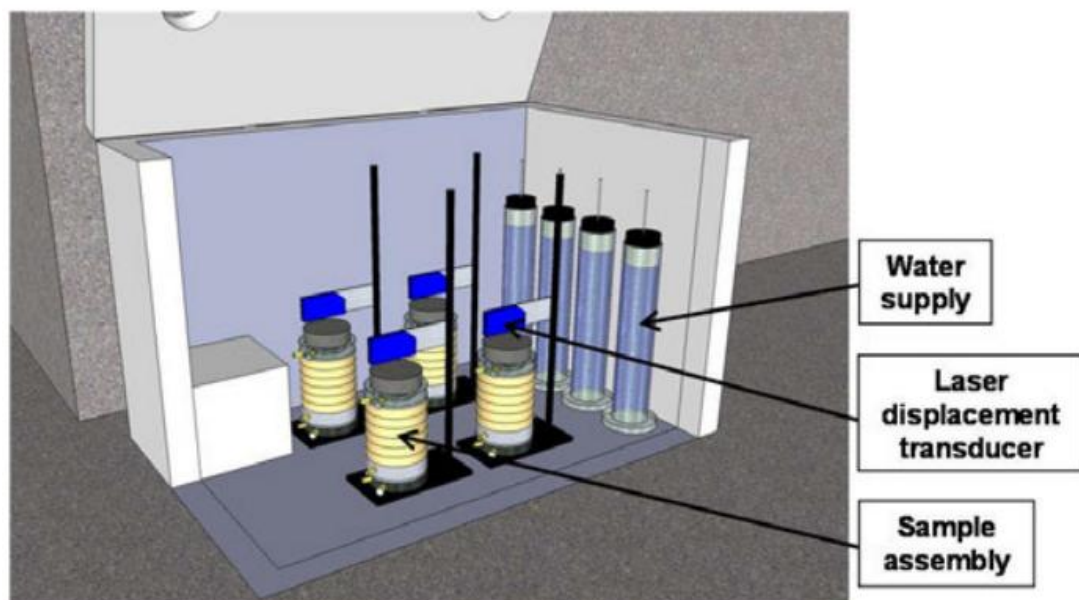


Figure 2.4 Idealized view of the temperature control chamber [4]

The sample freezing apparatus incorporated modifications in the displacement measurement system and the type of sensor employed for detecting displacement. The temperature control end plates shown in Figure 2.5 and Figure 2.6 consisted of an acrylic disk and an aluminum plate, with a serpentine path designed in the aluminum to allow liquid flow in direct contact with the disk. The constant head water supply was constructed from acrylic tubing with a diameter of 76 mm and a height of 508 mm. A pressure transducer was installed at the base of the water supply to monitor the water head applied to the sample [4].

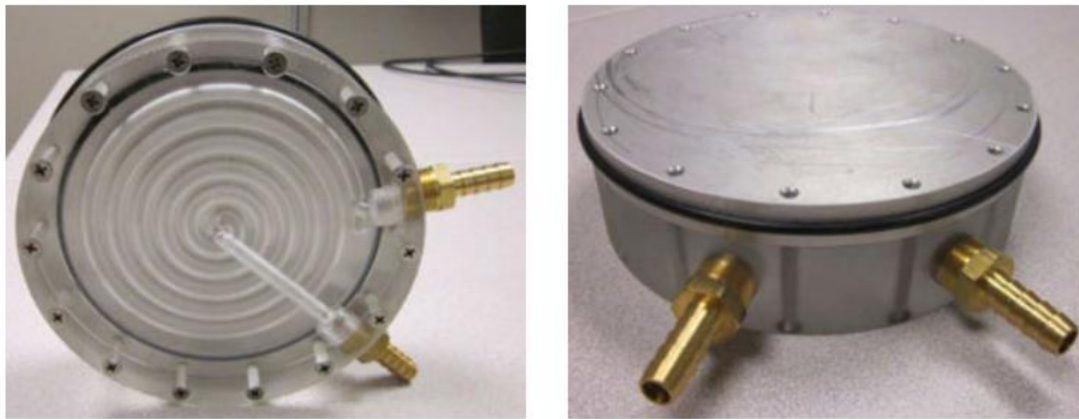


Figure 2.5 Acrylic side (left) and aluminum side (right) of temperature control end plate used to freeze and thaw samples [4]



Figure 2.6 Sample base plate without porous stone (left) and with porous stone (right) [4]

The surcharge weight included two steel disks, each weighing 2268 g (5 lbs), in place of the originally specified single lead disk. Laser displacement transducers were utilized to measure both heave and consolidation. The temperature control baths operated over a range of -30°C to $+200^{\circ}\text{C}$, with a stability of $\pm 0.01^{\circ}\text{C}$. The temperature control chamber was a 0.42 m^3 (14.8 ft^3) chest freezer, equipped with an internal temperature controller and thermocouple [4].

Temperature measurements were conducted using a Type T thermocouple wire system connected to a data acquisition system.

In 2014, T.L. Wang, Z.R. Yue, C. Ma, and Z. Wu developed a frost heaving test apparatus, which included a sample cell, upper and lower cold plates, two constant-temperature cold baths, a Markov bottle, insulation materials, temperature and displacement sensors, and a data acquisition system, as illustrated in Figure 2.7. The sample cell, constructed from organic glass (methyl methacrylate) 2 cm thick, had an internal diameter of 20 cm and a height of 30 cm. The upper and lower cold plates were positioned at the top (cold side) and bottom (warm side) of the soil sample, respectively. To minimize thermal exchange between the sample and the external environment, insulation material was wrapped around the sample cell.

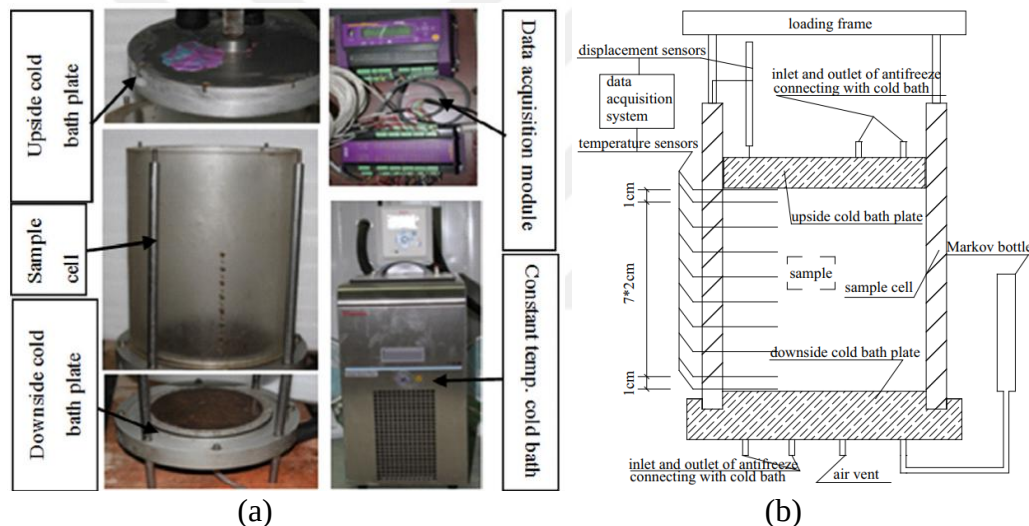


Figure 2.7 Apparatus for the frost heave test (a) photographs of frost heave test components (b) schematic diagram of the frost heave test device [20]

In their study the temperature of the cold baths were regulated to an accuracy of 0.1°C via computer control. Antifreeze solution, maintained at a constant temperature, was circulated through the cold baths to the upper and lower cold plates, enabling precise temperature adjustments to the soil sample. In open-system configurations, water was supplied from the bottom of the sample using a Markov bottle to mimic groundwater supply under natural conditions [20]. During frost heave tests, temperatures within the sample were measured using ten platinum resistance thermometers, each with an accuracy of 0.01°C . These sensors were inserted into the sample cell through round openings in its sidewall, as depicted in Figure 2.7 (b). A displacement sensor, with a reporting range of 2 cm and an accuracy of

0.3%, was positioned at the top of the sample to measure surface heave. All measurement data were recorded using a data acquisition system.

In their 2016 study, researchers Shakhmov and Zhussupbekov conducted experimental tests on soil samples collected from Astana, Kazakhstan, to investigate freezing pressures and the extent of frost heave. .



Figure 2.8 shows the laboratory test setup. The mold used was designed to minimize side friction between the soil and side walls [23].

The samples were prepared by saturating them within the mold before initiating the freezing process. During an initial 24-hour conditioning period, the temperatures of both the top and bottom plates were set to 3°C. Subsequently, the top plate temperature was reduced to -3°C, while the bottom plate was maintained at 3°C for eight hours. Two cycles of freezing were applied and ASTM freezing standards were followed. The tests were continued an additional 4 days beyond the 96-hour ASTM standard so as to be able to compare them with TRRL tests (i.e. to 216 hours) [23].



Figure 2.8 Freezing camera [23]

Qiang Luo, Peng Wu, Tengfei Wang (2019) [24] tested the frost heave susceptibility of well-graded gravel to be used as subgrade material for high speed rail (HSR) systems. The unidirectional freezing apparatus they used was composed of a sample cell ($\varnothing 152\text{mm} \times 170\text{mm}$), top plate, bottom plate, dial gauge, two sets of cold baths (capable of cooling down to $-20\text{ }^{\circ}\text{C}$ with an accuracy of $\pm 0.05\text{ }^{\circ}\text{C}$), three temperature sensors (with an accuracy of $\pm 0.1\text{ }^{\circ}\text{C}$), thermal insulation, and a data acquisition unit. The three thermistors were implanted in the specimen with spacings of 5 cm starting from 3 cm beneath the top face. The hollow top and bottom plates were kept at stable thermal boundary condition using a circulating coolant (industrial alcohol) from two independent cold baths. To guarantee one-dimensional freezing and reduce radial heat flow, mineral wool was adopted as insulation to surround the chamber. The variation of temperature inside the specimen, was measured and recorded using a data acquisition system. Vertical displacement readings were recorded using a dial gauge fixed at the center of the top plate as shown in Figure 2.9.

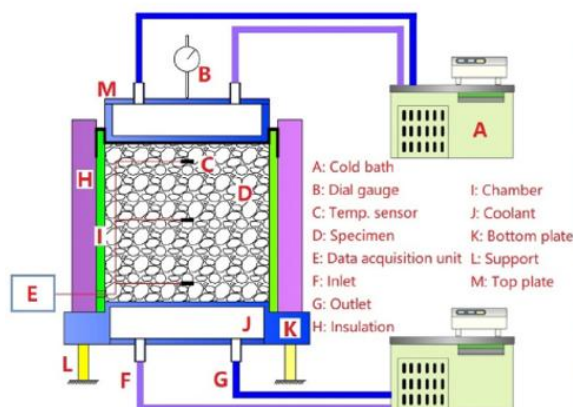


Figure 2.9 Freezing cell scheme [24]

In 2019, B. Loranger, I. Hoff, Ph.D., E. Scibila, Ph.D., and G. Doré, Ph.D., introduced the NTNU frost cell, a high-density polyethylene apparatus designed for testing samples with dimensions of up to 150 mm in diameter and 200 mm in height (extendable to 225 mm with rubber spacers between the rings). The cell incorporates 18 thermistors with a precision of $\pm 0.1\text{ }^{\circ}\text{C}$, strategically positioned in each ring, and is thermally insulated to reduce radial heat transfer. Constructed with a robust 50 mm wall thickness, the cell resists deformation under radial pressure during ice formation.

The sample is positioned between two plates, where the temperature is regulated by dual cryostat units. A rubber membrane is secured around the sample using a split ring to ensure a tight seal. The apparatus is equipped with an air piston to control pressure during testing

and a potentiometer capable of measuring heaving with a precision of 0.01 mm. During the conditioning phase, water flows through the sample for 24 hours, after which the water level at the base is lowered prior to freezing. A glass container with a cork mechanism permits water flow solely via cryosuction.

To maintain stable thermal conditions, the cell is housed in a refrigerator set at 2°C during testing. Samples are subjected to freezing for 96 hours, with data recorded every 5 minutes via a data acquisition system. Additionally, variations in the rings' positions are monitored using graduated markings on the frame, enabling corrections to the thermistor heights over time for SP (specific parameter) calculations. [25].

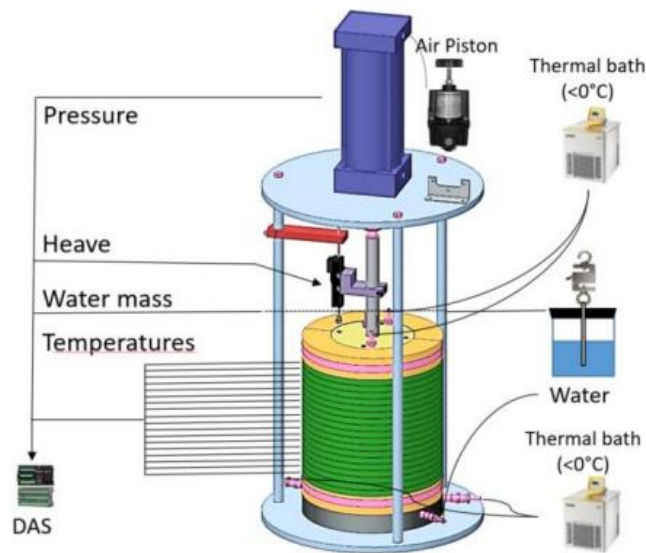


Figure 2.10 NTNU Multi-ring frost heave cell

In 2019, Tatsuya Ishikawa, Tianshu Lin, Shinichiro Kawabata, Shuichi Kameyama, and Tetsuya Tokoro developed a suction-controlled medium-size triaxial apparatus specifically designed for conducting resilient modulus tests on subbase course materials. The apparatus incorporates a structural design utilizing a Versapor membrane filter and a Polyflon filter, employing the pressure membrane method. It accommodates medium-sized cylindrical specimens with dimensions of 150 mm in diameter and 300 mm in height, suitable for testing subbase course materials in accordance with the “Handbook of Pavement Investigation and Examination Methods” and the “Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials” (AASHTO Designation: T307-99).

This apparatus shown in Figure 2.11 is capable of applying matric suction at both ends of the specimen, facilitating drainage of pore water from both the cap and pedestal, thereby

reducing testing duration. It allows for the application of axial loads with high precision through both strain-controlled and stress-controlled methods. Additionally, it supports monotonic loading tests at low loading rates and cyclic loading tests at frequencies up to 10 Hz. Axial strain measurements were obtained using linear variable differential transducers (LVDTs) and displacement transducers, ensuring accurate data collection [26].

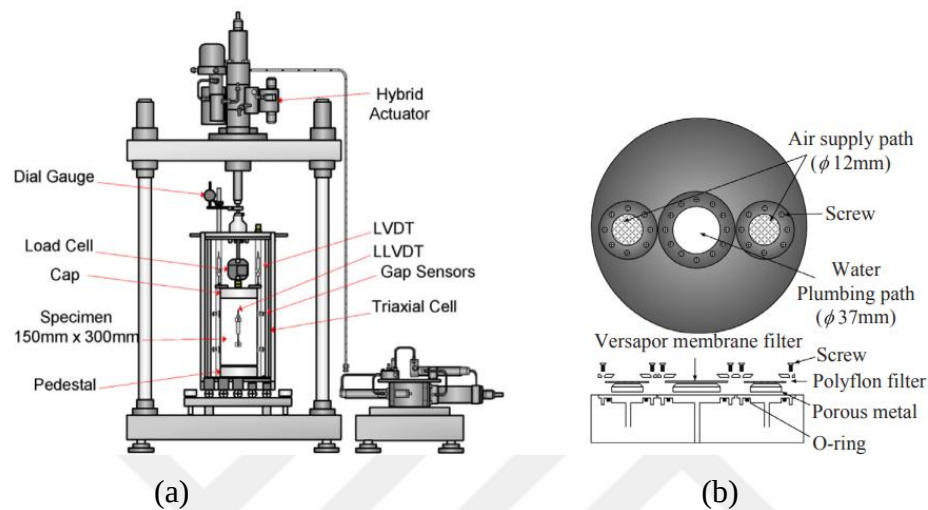


Figure 2.11 Medium-size triaxial apparatus for unsaturated soils: (a) Schematic diagram of test apparatus (b) Structural design of cap and pedestal

2.3 Factors that Affect Frost Heave:

2.3.1 Grain-Size Distribution and Fines Content

Cassagrande (1931) [4] concluded that in soils with more than 3% of particles smaller than 0.02 mm, significant frost heave can be anticipated, and in uniform soils with more than 10% of particles smaller than 0.02 mm, a significant amount of heave might be expected.

However, frost susceptibility in soils with a broad grain-size distribution, such as silty sands or clayey sands, is strongly influenced by the amount of fines (percent < 0.075 mm) (Konrad 1999) [18]. His findings suggest a differentiation between soils where fines occupy the gaps between sand particles and those where fines do not completely fill the voids of coarser-grained soil particles. In the initial scenario, the fines and interlinked unfrozen water films will govern frost susceptibility; however, in the subsequent scenario, the lower continuity of unfrozen water films will significantly diminish water migration within the frozen zone. The porosity of the system depends on the ratio of particle sizes and their relative proportions, suggesting that finer particles occupy the interstices of larger particles while maintaining

their original packing (Furnas 1931; Harr 1977) [18]. The amount of fines at a porosity n_F required to fill the pore space of a coarser sand structure at a porosity n_C can be calculated using the formula $\%Fv = \frac{n_C(1-n_F)}{1-n_F n_C} 100$ [2-1]:

$$\%Fv = \frac{n_C(1-n_F)}{1-n_F n_C} 100 \quad [2-1]$$

For example, a loose sand structure at a porosity $n_C = 0.47$ requires 32% by weight of clayey silt at a porosity $n_F = 0.44$ to fill the voids between the sand grains. A dense assemblage of a sand at a porosity of 0.3 requires only 20% of clayey silt to completely fill the pore space between the coarser particles. The porosity of the fine fraction plays a significant role, as illustrated in Equation $\%Fv = \frac{n_C(1-n_F)}{1-n_F n_C} 100$ [2-1]. In general, when the soil is mostly clay (swelling or nonswelling), the porosity of the fine fraction, denoted as n_F , is likely to exceed 0.6. This depends on the types of clay minerals. The pore network geometry of a soil in which the fines fill the pore space of the coarser fraction is associated with the mean particle size of the fines fraction $d_{50}(\text{FF})$ [18].

Rieke et al. (1983) [19] conducted frost-heave tests on various combinations of sand, silt, and different types of clay. Fully saturated mixtures containing 5, 10, and 20% fines consisting of different mixtures of silt, kaolinite, and montmorillonite were consolidated one-dimensionally under 50 kPa, allowed to rebound without any external force or pressure applied, and subjected to step-freezing tests. At near steady state thermal conditions the segregation potential (SP_o) was determined.

The relationship between SP_o and $d_{50}(\text{FF})$ for soils with kaolinite (K) and montmorillonite (M) was found to increase with decreasing d_{50} of the fines fraction, reflecting the relative effect of increasing unfrozen water content (Rieke et al. 1983) [19]. Different families of $SP_o-d_{50}(\text{FF})$ were obtained for constant fines content values. For example, for a given value of $d_{50}(\text{FF})$, SP_o decreases with decreasing fines content, as it is anticipated that a fines content of less than 15% does not completely fill the pore space between the sand grains [18].

Maximum frost susceptibility may be obtained for soils in which the pore space between the coarser grains is totally filled with fines or in soils where the coarser grains are embedded in the matrix of finer grained soils. The segregation potential of soils can be expressed as a

function of the relative fines content, r_F , defined as the ratio of actual fines content to that required to fill the pore space between the coarse-grained skeleton (eq.[2-1]), (Rieke et al. 1983) [19].

The findings from Jean-Pascal Bilodeau, Guy Dore, and Pascale Pierre demonstrate a significant association between SP values and the condition of tiny particles within the aggregates. The homogeneity coefficient of tiny particles and their specific surface area were recognized as essential determinants of frost susceptibility. A model was created that incorporates these factors to enhance the prediction of frost behavior in various aggregate sources [27].

The authors, Jean-Pascal Bilodeau, Guy Dore, and Pascale Pierre propose that each aggregate source has an optimum fines content that improves the porosity of the fines fraction, hence improving drainage capacity and decreasing susceptibility to frost and thaw. This adjustment is essential for enhancing the overall performance of paving materials in cold climates [27].

Also, a fine content of 9% is identified as the optimal level for achieving satisfactory compaction of coarse-grained soil (CGS) (Tian-liang Wang, Zu-run Yue, Chao Ma, Zhen Wu 2014) [20].

2.3.2 Influence of Mineralogy of Fines

Figure 2.12 shows the macropore and micropore spaces, with macropores controlling the radius of the ice-unfrozen water interface and capillary unfrozen water. Clay mineralogy controls the thickness of adsorbed water layers, affecting the amount of unfrozen water in micropores (Konrad 1999) [18]. Water mobility in capillary channels is greater than in adsorbed water films due to the strongly oriented and structured water molecules. The rate of water movement is related to an effective porosity mainly consisting of capillary unfrozen water channels (Hoeskstra 1969) [14].

Rieke et al. (1983) [19] conclude that there is a strong correlation between segregation potential and specific surface area of the fines fraction for their soils. The thickness of adsorbed water is related to the specific surface area of the fines fraction, S_s . For a given value of $d_{50}(FF)$, the larger the specific surface area, the smaller the amount of capillary water where most of the water movement towards the ice lens occurs. Normalization of water

flow through the same cross section should produce flow rates of similar magnitude. A consistent relationship between (SP_oS_s) and $d_{50}(FF)$ should emerge for most soils.

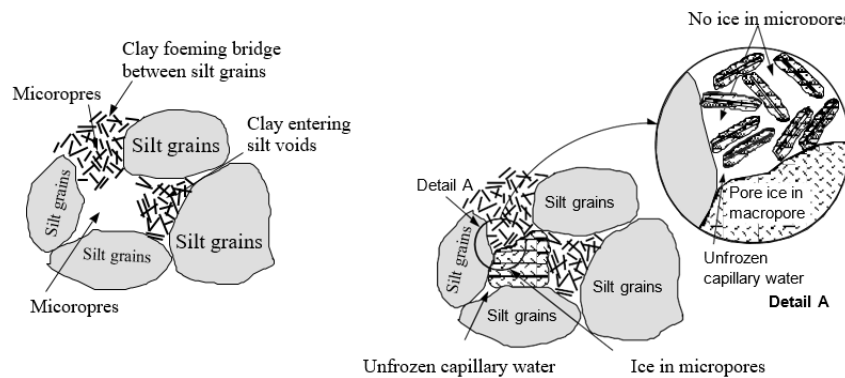


Figure 2.12 Schematic of phase composition of clayey silts during freezing (Konrad 1999)[18].

Additionally, the authors (Benoit Loranger, Guy Doré, Inge Hoff, Elena Scibilia 2022) [28] illustrate that the mineralogy of crushed rock aggregates (CRA) significantly impacts their frost susceptibility.

The mineral composition of aggregates affects their performance under freezing conditions, with different minerals exhibiting distinct responses to freezing temperatures. Softer minerals, like mica and chlorite, can lead to the generation of finer particles during crushing, resulting in a higher specific surface area, which initially increases frost susceptibility due to enhanced water retention and adsorption.

As aggregates undergo multiple crushing phases, their mineralogical characteristics can change, leading to a reduction in damaged particles and influencing frost susceptibility. The enrichment of certain minerals in finer fractions during crushing can affect water retention properties, affecting aggregates' frost susceptibility.

The correlation between specific surface area and frost susceptibility is influenced by the mineral content of aggregates. Aggregates with a high specific surface area due to fine particles may exhibit different frost behavior compared to those with a lower specific surface area, depending on their mineral composition [28].

Understanding the mineralogical properties of crushed rock aggregates is essential for accurately evaluating their frost susceptibility, guiding engineers in making informed

decisions regarding material selection and treatment in cold regions. Further investigation in this area is needed to optimize road construction practices in frost-prone environments [28].

The mineralogical composition of aggregates significantly influences their frost susceptibility, suggesting that both gradation and mineralogy should be considered in pavement design [27].

2.3.3 Influence of Water

The volume of water expands by approximately 9% when it freezes. Hence, soils with higher moisture levels will exhibit higher frost heaving and ice formation within the pore spaces. This process induces internal tensions that may lead to the rearrangement of soil particles, culminating in enhanced density upon thawing (Ponomarev, 1966) [29].

Additionally, migration of water from a water supply source (such as the ground water table in the field or a supply tank open system-freezing test) to the freezing soil can also increase freeze thaw susceptibility. This phenomenon, ice segregation, is the movement of water toward the freezing front, can generate localized increases in pore pressure and intensify frost heave action (Shusherina, 1959) [29].

Research demonstrates that soils with high moisture content levels are more susceptible to frost action. As moisture content increases, the segregation potential of the ice increases, causing water to migrate towards freezing fronts and resulting in the development of ice lenses inside the soil. This phenomenon can result in considerable heaving and structural disruption (Morgenstern & Smith, 1973) [30]. In contrast, soils with diminished water content may lack the moisture to support comparable ice segregation, thereby exhibiting decreased frost susceptibility.

Studies on granular and coarse –grained materials also show that access to a water supply source affects frost susceptibility. The researchers Jean-Pascal Bilodeau, Guy Dore, and Pascale Pierre highlighted that the frost susceptibility of granular materials is markedly affected by the presence of water, which can infiltrate pavement constructions. Freezing, even under unsaturated conditions, can cause volume expansion and heightened water content, negatively impacting pavement performance during thaw periods [27].

Freezing tests on coarse-grained soil (CGS) tested in an open system (i.e. with a water supply) demonstrate an increase in frost heave relative to the same soil tested in a closed

system. This underscores the need of regulating waterproofing and drainage strategies in practical applications [20].

2.3.4 Overburden pressure

Konrad and Morgenstern (1982) [31] conclude that the influence of overburden pressure on segregation potential can be explained by two factors: the reduction in segregation freezing temperature with increasing stress level resulting in reduced hydraulic conductivity of the frozen fringe and the decline in overall hydraulic gradient within the frozen fringe. The freezing test assesses additional elements, such as fabric and suction at the frost front, and immediately incorporates them into the SP value. Jessberger and Jagow (1989) [18] observed a significant tendency for the pressure parameter to decrease as the clay content was increased. These data indicate that supplementary factors must be taken into account to reduce the evident variability in the hypothesized link. Two parameters, clay mineralogy, and fabric may be regarded as an empirical correlation between the pressure factor a and segregation potential.

The application of overburden pressure significantly diminished the extent of frost heave in coarse-grained soil (CGS). Nonetheless, with coarse-grained soil exhibiting reduced compressibility, the mitigation of frost heave plateaued once a substantial rise in pressure was attained [20]. Figure 2.13 shows the relationship between the overburden pressure and the frost heave ratio [20].

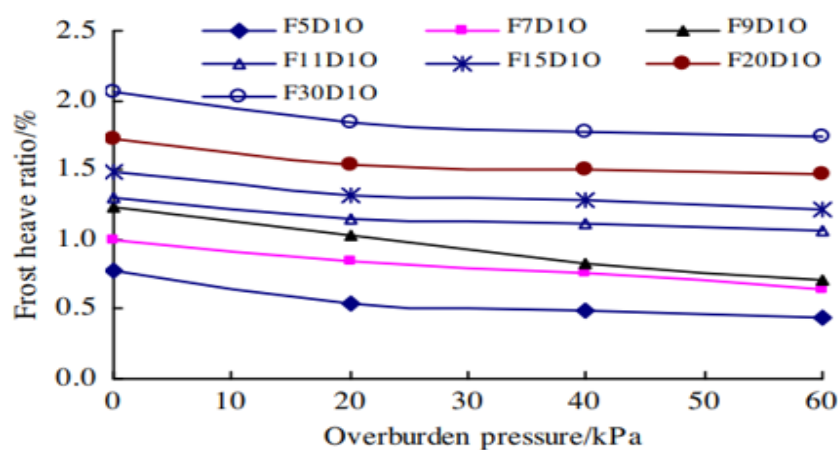


Figure 2.13 curves of overburden pressure vs. frost heave ratio.

2.3.5 The correlation between frost heave ratio and dry density

Dry density also impacts frost heave. This is illustrated in a study conducted by [20] on CGS. For all samples, the frost heave ratio initially increased and subsequently reduced with rising increments of dry density as shown in Figure 2.14. CGS with low or high dry density corresponds to elevated or reduced hydraulic conductivity (Liu et al., 2005)[20], (e.i the lower mobility of water) which results in a decreased frost heave ratio. Consequently, there exists a dry density at which an intermediate maximum value of the frost heave ratio of the CGS is observed.

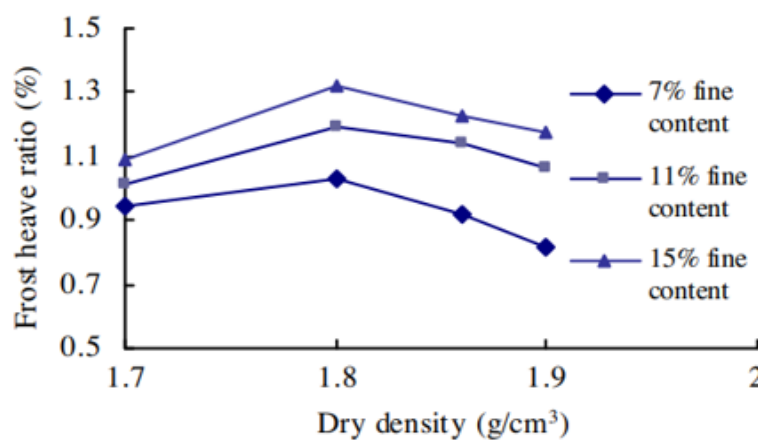


Figure 2.14 Curves of dry density vs. frost heave ratio.

2.4 Direct Frost Heave Testing

2.4.1 Segregation Potential

The segregation potential (SP) is an essential factor in comprehending soil behavior during freezing circumstances, especially with frost heave. Jean-Marie Konrad outlines the key aspects of segregation potential [32].

Konrad and Morgenstern (1980) [11] proposed that the frost heave process is a system of impeded flow to an ice-water interface through unfrozen soil in a thin zone of low permeability called the frozen fringe between the ice-water interface and the zero-degree isotherm. They developed a mechanistic model based on the secondary heave model, which characterizes freezing soil by two parameters: the segregation freezing temperature and the permeability of the frozen fringe. They presented the concept of segregation potential, which can be used to compare the relative frost heave susceptibility of different soils. The

segregation potential was found to be independent of the temperature gradient at steady state conditions, simplifying the interpretation of laboratory frost heave tests.

Konrad and Morgenstern (1980, 1981) [11] showed that at the onset of formation of the final ice lens in step-freezing test the velocity (v_u) of the pore water entering into the unfrozen soil was proportional to the temperature gradient ($\text{Grad } T$) in the frozen fringe provided that the suction at the pore freezing front (P_u) was constant. Their finding is shown in equation [2-2], where P_w is the suction at the ice lens (ie segregation front), K_f is the overall hydraulic conductivity of frozen fringe, d is the thickness of the frozen fringe, T_s is the temperature at the segregation of the freezing front.

$$v_u = \frac{P_w - P_u}{d} \bar{K}_f = \left(\frac{P_w - P_u}{d} \bar{K}_f \right) \text{Grad } T = SP \text{ Grad } T \quad [2-2]$$

Various researchers have investigated the relationship between temperature gradient and flow to an ice-water interface. Vignes and Dykema (1974) [33] connected an ice lens through a capillary tube to a free water reservoir, observing that water flowed from the reservoir to the base of the ice lens. Biermans et al. (1978) [12] measured the suction needed to stop water migration to the lens, confirming the Clausius-Clapeyron relation. Loch (1978) [13] and Williams (1964) [34] also found that the suction created in unfrozen water in frozen soil is dependent on the temperature of the unfrozen water and is independent of the type of soil. Segregation potential denotes the capacity of soil to form ice lenses upon freezing, potentially resulting in frost heave. It is affected by multiple factors, including soil type (gradation, mineralogy of fines fraction, specific surface area, and surface charge density), porosity, over consolidation ratio, pore fluid, overburden pressure, and the number of cycles.

Figure 2.15 shows the schematic of a freezing soil where water is drawn to the bottom of an active ice lense through the frozen fringe. The top of the Frozen Fringe (at the freezing front) is a temperature called the segregation temperature which is lower than the Frost front which is at 0°C). Within this zone there is both frozen and unfrozen water content and the pore pressure are below atmospheric. The frost-heave mechanics creates reduced pressure in the frozen fringe which is the reason for water migrating upwards to the segregation freezing front. Water migration and heaving continue until the pore channels in the frozen fringe became completely frozen impeding any further flow of water.

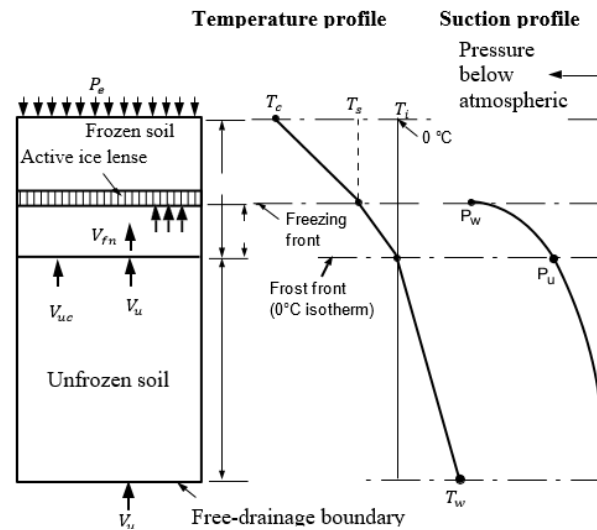


Figure 2.15 Schematic of conditions in a freezing soil (Konrad 1999) [18].

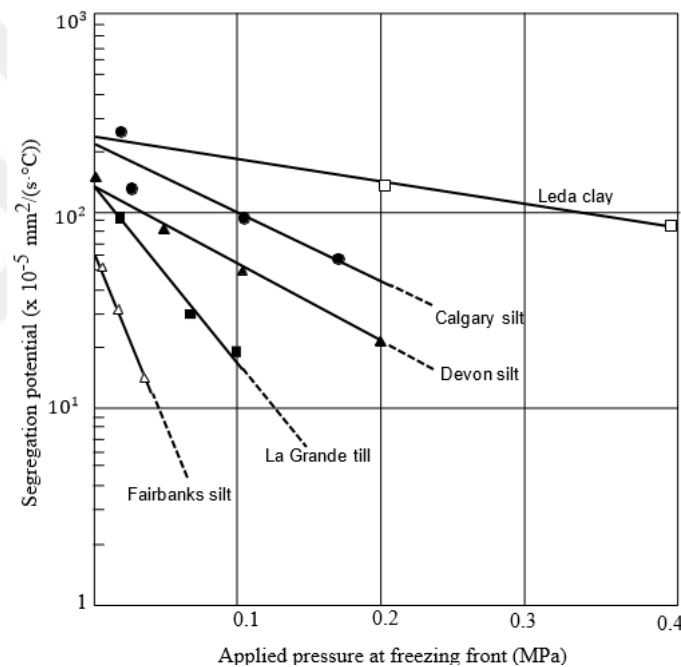


Figure 2.16 Segregation potential-pressure relationships for various soils (Konrad 1999) [18].

2.4.2 Determining Segregation Potential from laboratory freezing test

The segregation potential can be determined from the laboratory freezing test on representative samples from the field or on reconstituted samples.

Step-freezing test may be used. Conditions with small rate of cooling are obtained at the formation of the final ice lens when the rate of frost penetration approaches zero.

In order to evaluate the segregation potential from step-freezing tests two separate approaches may be used. In both approaches the temperature gradient in the frozen fringe needs to have been measured. Segregation potential may be calculated separately using (a) the measured heave rates of the samples at steady-state freezing conditions or (b) the water intake rate at steady-state conditions. By linking the temperature gradient—a crucial element affecting freezing and thawing dynamics—with either the heave rate or the water intake rate, the segregation potential can be determined. Each method provides distinct perspectives on the elements influencing soil segregation during freeze-thaw cycles.

In the heave rate approach the segregation potential is determined by utilizing established heave rate values with the temperature gradient recorded during the freezing process where “dh/dt” is the heave rate.

$$SegPot_h = \frac{\frac{dh}{dt}}{Grad_T} \quad [2-3]$$

In the water intake rate approach segregation potential is calculated by assessing the water intake rate of the soil mixture during thermal steady-state conditions. The water intake rate may be established by measurement of water flow interm of the volume intake to the sample during testing where “V” is the water intake rate.

$$SegPot_w = \frac{V}{Grad_T} \quad [2-4]$$

$$SegPot_{h_convert} = M * SegPot_w \quad [2-5]$$

$$SegPot_{h_convert} = \frac{1.09}{Area\ of\ specimen\ (cm^2)} SegPot_w * 10 \quad [2-6]$$

This metric quantitatively assesses the soil's permeability and its reaction to moisture fluctuations throughout freeze cycles, consequently affecting the overall segregation potential.

2.4.3 Determining Segregation Potential from Field Test

The segregation potential can be determined directly from field observations where surface heave rate and temperature measurement are available. Konrad (1999) [18] gives the following expression for the field segregation potential where (h) is the surface heave, t is time, $Grad_T_field$ is the temperature gradient in the frozen soil near the frozen front.

$$SP_{field} = \frac{\frac{dh}{dt}}{1.09 \text{ Grad } T_{field}} \quad [2-7]$$

This relationship highlights the direct correlation between observable field phenomena and the theoretical framework of frost action.

Konrad emphasizes the utility of this field-based approach in compressible soils, such as lightly overconsolidated clays, where obtaining undisturbed samples is challenging. The method allows for a more straightforward assessment of frost susceptibility without the need for extensive laboratory testing. Field measurements can be less expensive than laboratory tests, especially for large-scale projects.

Field data represent the true conditions experienced by soils, offering a more reliable evaluation of frost susceptibility than laboratory results, which may not entirely capture in-situ conditions. This approach is adaptable across diverse soil types and environmental settings, making it a valuable tool for engineers and geotechnical professionals working in cold-region construction projects.

2.4.4 Use of Segregation Potential to Determine the Frost Heave

Once an assessment for segregation potential in the field is determined acceptance or rejection of the soil should be based on a comparison between predicted and allowable frost heave which is dependent on project type (Konrad 1999) [18]. The method to predict frost heave from an assessment of segregation potential outlined in (Konrad 1999) [18]. This involves the use of a numeric finite elements program FROST-1D (Konrad 1994) [35] to predict heave under specified freezing conditions.

The NCHRP research report on Subgrade Soil Susceptibility to Shrink/Swell and Frost Heave highlights the development of software tools to improve pavement design methodologies. These tools aim to predict pavement performance under various climatic conditions, particularly focusing on soil behavior due to shrink/swell and frost heave (FH). The software integrates newly created models into the existing Pavement Mechanistic-Empirical (ME) Design framework, allowing engineers to evaluate the influence of high-volume change soils on pavement performance.

The NCHRP research report on subgrade soil susceptibility to shrink/swell and frost heave [36] highlights the development of software tools to improve pavement design

methodologies. These tools aim to predict pavement performance under various climatic conditions, particularly focusing on soil behavior due to shrink/swell and frost heave (FH). The software integrates newly created models into the existing Pavement Mechanistic-Empirical (ME) Design framework, allowing engineers to evaluate the influence of high-volume change soils on pavement performance. The key features of this software include:

- 1- **Predictive Modeling:** The software incorporates both deterministic and stochastic models, allowing users to simulate various scenarios related to soil behavior under changing environmental conditions.
- 2- **Sensitivity Analysis:** Users can adjust critical input variables to assess how different factors influence pavement performance, particularly in relation to volume changes due to climatic variations.
- 3- **Integration with Existing Tools:** The new models are designed to be compatible with the current software used in the Pavement ME Design Guide, ensuring that engineers can seamlessly transition to using the enhanced predictive capabilities without needing to overhaul their existing systems.

One of the innovative aspects of the software is its consideration of segregation potential as a parameter for modeling frost heave. 85Within the framework of the software:

- 1- **Incorporation of Segregation Potential:** The software utilizes segregation potential to estimate the maximum depth of frost influence and the associated heave. By analyzing how different soil compositions respond to freezing and thawing cycles, the software can predict the extent of frost penetration and the resultant heave more accurately.
- 2- **Deterministic Estimation:** The models within the software provide deterministic estimates of FH by assessing the soil's behavior in response to seasonal temperature changes and moisture variations.
- 3- **Empirical Correlations:** The software includes empirical models that link segregation potential to observed pavement distress, helping practitioners understand the implications of soil composition on pavement life cycle.

2.4.5 Estimation of Segregation Potential from Index Test

Konrad (2005) [32] demonstrates that assessing segregation potential through an index test involves estimating the likelihood of soil layers separating into distinct strata during freeze-thaw cycles.

Overburden Pressure: The pressure exerted on the soil affects its susceptibility to frost heave, with an analytical relationship showing that segregation potential (SP) decreases as overburden pressure increases.

Influence of Fines and Surface Area: The normalized specific surface area of the fine fraction in the soil can impact the distribution of unfrozen water and influence the temperature at which ice lenses form.

Mathematical Representation: Segregation potential is mathematically defined as $SP_{field} = SP_o \exp(-aP_e)$, where (SP_o) is the segregation potential at zero overburden pressure, and (a) represents a parameter that quantifies soil sensitivity to overburden pressure.

Laboratory Testing: To accurately predict SP in the field, it is essential to conduct laboratory freezing tests on representative soil samples. These tests help establish correlations between soil properties and SP.

Practical Applications: Understanding and evaluating segregation potential is in geotechnical engineering, particularly for predicting frost susceptibility and ensuring effective design for cold-region construction.

In summary, segregation potential is a key concept in geotechnical studies of frozen soils. Influenced by various factors, it is fundamental for anticipating frost heave behavior across different soil types [32].

2.4.6 R-value

The R-value is a new approach for evaluating soil susceptibility to frost heave. The existing methods for assessing frost heave susceptibility are primarily empirical and based on the fine content of soils. The researchers Jidong Teng, Haosong He, Xuemao Feng, Hongye Yan and Sheng Zhang propose a novel criterion in 2023 based on an analytical solution of frost heave, which is directly related to boundary temperatures and soil properties.[37]

The study found that frost heave is proportional to the square root of time, and a new index called the frost heave classification index (R) is introduced, which is directly related to boundary temperatures and soil properties.

The researchers established appropriate threshold values for R by collecting experimental results from 32 groups of tests conducted on different types of soils (coarse-grained, silt, and clay). The growth trends varied among different soils, with silt showing a fast trend, coarse-grained soil showing a slow trend, and clay showing a moderate trend.

Three distinct regions were identified: a dense region with minor values of R and slight frost heave behavior (green region), a dense region with large values of R and severe frost heave behavior (red region), and a sparse region (gray region). Two critical thresholds for R were determined: 0.21 and 1.18. By applying these threshold values, the frost heave susceptibility of the experimental results was classified (see Figure 2.17). A value of R less than 0.21 indicates a non-frost heave susceptible condition, a value greater than 1.18 indicates a high frost heave susceptibility condition, and a value between 0.21 and 1.18 indicates a frost heave susceptibility condition.

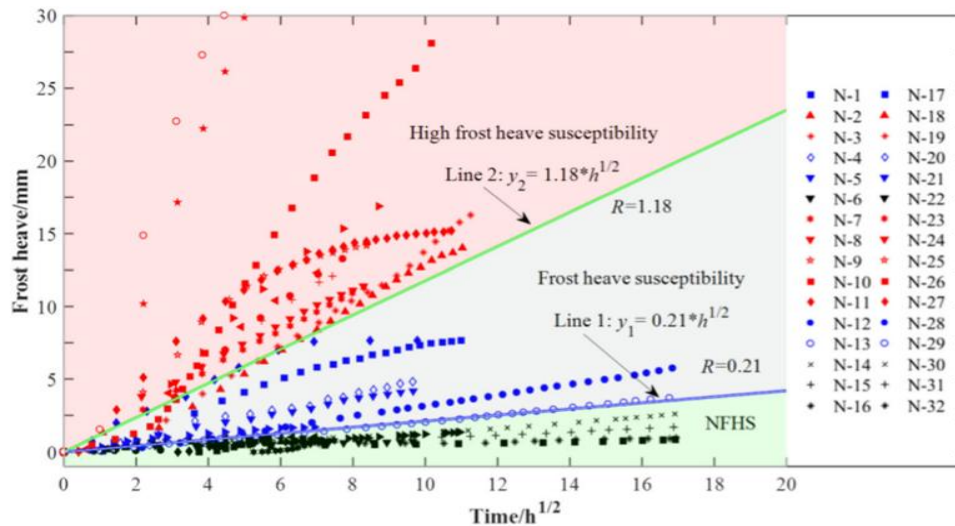


Figure 2.17 New Frost heave susceptibility classification [37]

The R-value criterion is postulated to offer a clear theoretical basis and is easily implemented, suggesting that it can be applied as a rational method for assessing frost heave susceptibility of soils in cold regions.[37]

2.5 Freeze-Thaw Classification Systems

The criteria for determining frost sensitivity can be considered at three different levels of development.

2.5.1 Level I

Cassagrande (1939) [4], the International Society of Soil Mechanics and Foundation Engineering Technical Committee for frost (ISSMFE TC8), are the organizations that have been selected as the Level I classifications that are being examined in this study. The first criteria in the development level I evaluation are made by looking at the percentage of the content finer than a certain grain size in the total weight of the soil. For example, the percentage that passes through No.200 sieves or the percentage that is finer than 0.02 mm. Additionally, it is evaluated whether the grain size distribution is uniform. The ISSMFE TC 8 (Slunga and Saarelainen, 1989) criteria, categorize soil into four regions: 1, 2, 3, 4, and 1L. An explanation of frost susceptibility in the following manner:

- 1) The soil is always frost-susceptible if the GSD falls completely inside region. However, in region 1L the frost susceptibility is low.
- 2) If the GSD falls entirely within one of these regions (2, 3, or 4) the soil is not frost-susceptible.
- 3) If the tip of the curve distribution moves into a thinner region and remains there, it is susceptible to freezing.
- 4) Further testing is required for the soils with GSD close to the boundaries.

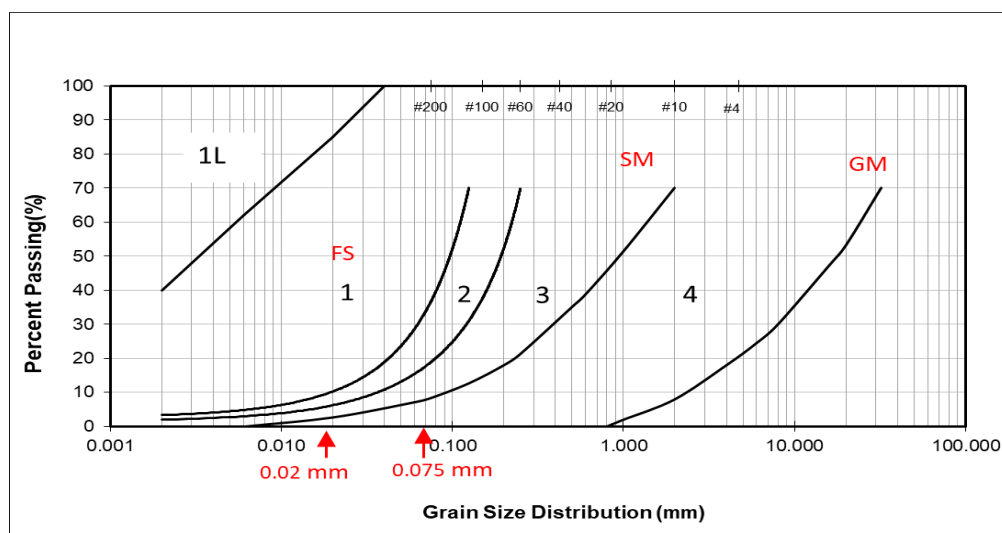


Figure 2.18 Criteria proposed by Slunga and Saarelainen, 1989

2.5.2 Level II

The ISSMFE Technical Committee on Frost (1989) recommended the use of complementary tests to assess susceptibility to frost. These tests include capillary rise, unfrozen capillary rise, hydraulic conductivity of non-frozen ground or Atterberg Limits resulting from the mineralogy of the soil, specific surface area, and amount of clay content. Other criteria include decomposition potential and frost heave rate [5].

$$R = \frac{(\%<0.074mm)(\%<0.0002mm)}{LL_{ff}(\%<f_{fmax})} \quad [2-8]$$

Table 2.1 and Figure 2.19 display the frost classification system that is endorsed by the US Army Corps of Engineers (USACE, 1986). The USACE classifies soils into two categories: non-frost susceptible (NFS) and potentially frost susceptible (PFS) groupings. The technique is derived from Casagrande's method, which measures the proportion of particles smaller than 0.02 mm. It incorporates comprehensive laboratory testing on frost heave and field observations of decreased load-bearing ability following thawing. The soil groups in Table 1 are arranged in an approximate order based on the rate at which they experience a decrease in bearing capacity after undergoing freezing and thawing. The initial two categories are often appropriate for utilization as foundational and secondary foundational content [38].

Within the USACE system, all inorganic materials that have at least 3% of their grains smaller than 0.02 mm in diameter will be considered potentially sensitive to frost (PFS) for the purpose of designing pavements. The PFS soils are classified into the following categories: S1, S2, F1, F2, F3, and F4. Figure 2.19 demonstrates that there is a significant variation in heave rates even within a single category. Therefore, it is necessary to do additional testing on PSF soils in order to assess their response to freezing conditions. If freeze testing is not feasible, the comprehensive database of 377 soils given in Appendix B of the report can be utilized. The relative frost sensitivity of the soil can be calculated without conducting the frost heave test by comparing the index parameter of the soil in question to those provided.

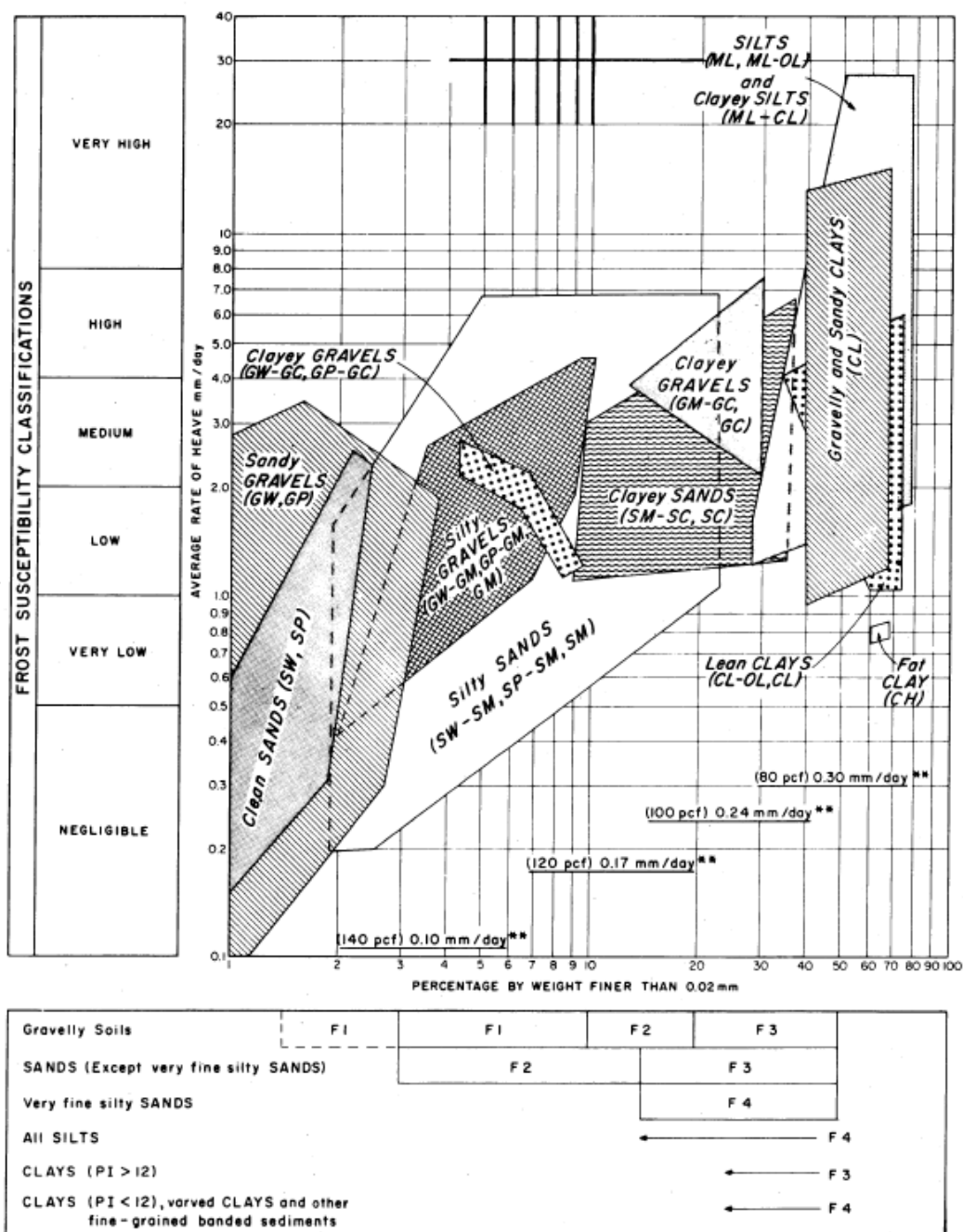
Table 2.2 displays the categorization of soils that are susceptible to frost, as defined by KGM in 2008. The KGM classification utilizes grain size parameters that are determined by the proportion of material that is less than 0.075 mm. Upon comparing these two classifications, it becomes evident that the KGM classification is more stringent for the majority of soil groupings. According to KGM requirements, the base material should possess certain characteristics that are not affected by frost. These include a fine grain content (< 0.075 mm) that should not exceed 12%, a liquid limit that should be less than 25%, and a plastic index that should not exceed 6%.

Table 2.1 Frost susceptibility classification of USACE

<u>Frost group</u>	<u>Kind of soil</u>	<u>Percentage finer than 0.02 mm by weight</u>	<u>Typical soil types under Unified Soil Classification System</u>
NFS**	(a) Gravels Crushed stone Crushed rock	0-1.5	GW, GP
	(b) Sands	0-3	SW, SP
PFS	(a) Gravels Crushed stone Crushed rock	1.5-3	GW, GP
	(b) Sands	3-10	SW, SP
S1	Gravelly soils	3-6	GW, GP, GW-GM, GP-GM
S2	Sandy soils	3-6	SW, SP, SW-SM, SP-SM
F1	Gravelly soils	6 to 10	GM, GW-GM, GP-GM
F2	(a) Gravelly soils (b) Sands	10 to 20 6 to 15	GM, GW-GM, GP-GM, SM, SW-SM, SP-SM
F3	(a) Gravelly soils (b) Sands, except very fine silty sands (c) Clays, PI less than 12	Over 20 Over 15 -	GM, GC SM, SC CL, CH
F4	(a) All silts (b) Very fine silty sands (c) Clays, PI greater than 12 (d) Varved clays and other fine-grained, banded sediments	- Over 15 - -	ML, MH SM CL, CL-ML CL and ML; CL, ML, and SM; CL, CH, ML and SM

** Non-frost-susceptible.

Possibly frost-susceptible, but requires laboratory test to determine frost design soil classification.



NOTES: Standard tests performed by Cold Regions Research and Engineering Laboratory; specimens 6 in. dia. by 6 in. high, frozen at penetration rate of approximately 0.25 in. per day, with free water at 38°F continuously available at base of specimen. Specimens compacted to 95% or better of applicable standard, except undisturbed clays. Saturations before freezing generally 85% or greater.

* Undisturbed specimen

** Indicated heave rate due to expansion in volume, if all original water in 100% saturated specimen were frozen, with rate of frost penetration 0.25 inch per day.

Figure 2.19 Range in the degree of frost susceptibility of soils according to the USACE (1965).

Table 2.2 Frost Classification in KGM manual for design (KGM, 2008).

Frost sensitivity class	Soil type	Percentage finer than 0.075 mm	Typical soil types under Unified Soil Classification System (USCS)	increasing in loss of bearing capacity during freezing-thawing cycle
F1-Very low sensitive to frost	Gravels, sand-gravel mixtures	3-12	GM,GP,GW-GM, GW-GC, GP-GM, GP-GC	
F2-Low sensitive to frost	(a) Gravels, sand-gravel mixtures	12-20	(a) GM, GC, GC-GM	
	(b) Sands	3-15	(b) SW, SP, SM, SC, SW-SM,SW-SC, SP-SM, SP-SC, 3C-3M	
F3-frost Susceptible	(a) Gravels, sand-gravel mixtures	>20	(a) GM, GC,GM-GC	
	(b) Sands (except very fine and silty sands)	>15	(b) SM, SC, SM-SC	
	(c) Clays PI > 12	-	(c) CL, CH	
F4- Very frost Susceptible	(a) Silts	-	(a) ML, MH	
	(b) very fine silty soils	>15	(b) CL, CL-ML	
	(c) Clays PI < 12	-	(c) CL, CL-ML	
	(d) stratified clays and stratified fine-grained soils	-	(d) ML, MH, CL, CH	

2.5.3 Level III

Level-III is based on direct observations of frost heave in the laboratory or field. The classification of frost susceptibility according to ASTM D5918 [22] is shown in Table 2.3. The classification is based on the measured 8-hour heave rate and the loss of soil strength as measured by the post-freezing CBR test.

Table 2.3 Frost susceptibility classification provided in ASTM D5918

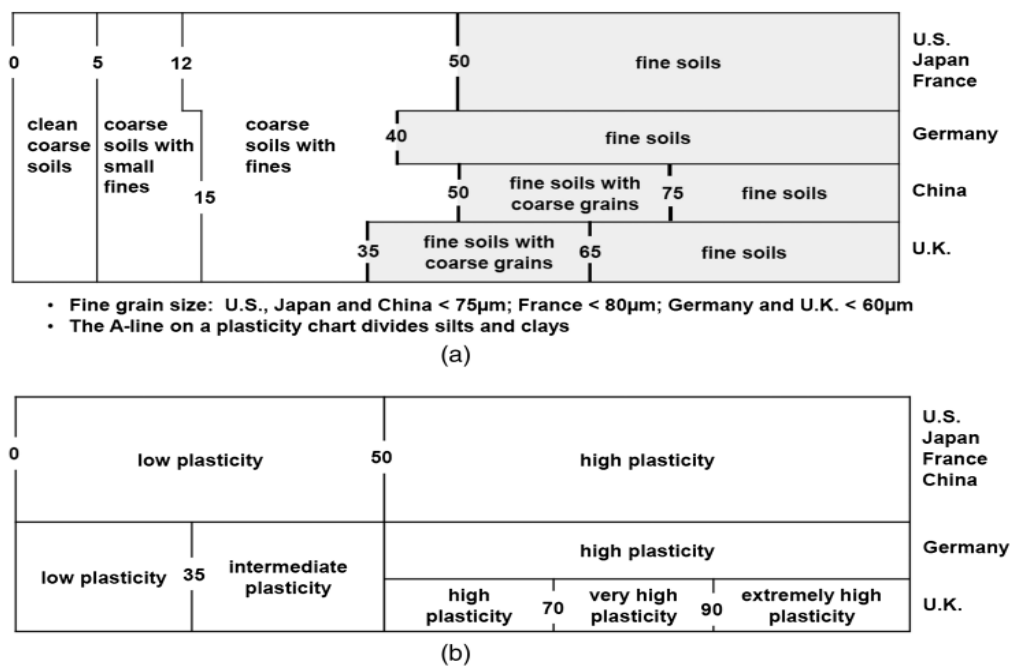
Frost susceptibility classification	Symbol	8-h Heave rate (mm/day)	Bearing ratio after thaw, %
Negligible	NFS	<1	>20
Very low	VL	1 to 2	20 to 15
Low	L	2 to 4	15 to 10
Medium	M	4 to 8	10 to 5
High	H	8 to 16	5 to 2
Very high	VH	>16	<2

2.6 Revised Soil Classification System (RSCS)

The purpose of soil categorization is to help engineers better understand and predict the behavior and physical characteristics of different types of soil. Over the years, geotechnical engineers have developed various classification systems to effectively meet the needs of

modern construction and infrastructure projects. For these classification systems, used around the world, primarily rely on two key factors - the distribution of grain sizes and the Atterberg limits as shown in Figure 2.20. In general, soil grains are considered "fine" if they are smaller than 75 microns (sieve No. 200). The transition from fines-dominant to coarse-dominant soil behavior typically occurs when the fines content falls between 35 to 50 percent. Additionally, a liquid limit (LL) of 50 is often used to differentiate between low-plasticity and high-plasticity fine-grained sediments [39].

The 75-micron size threshold is an important marker, as it helps engineers distinguish differences in the formation history, particle shape, and the way smaller and larger grains interact with each other (Santamarina et al. 2001) [40]. However, the distinctions between fine-grained sediments have become less clear-cut over time, partly due to the ambiguous use of the term "clay" to refer to a wide range of materials [41].



Sources. China: GBT50145 (2007). France: Magnan (1997). Germany: DIN18196 (2011). Japan: JGS0051 (2009). U.K.: BS5930 (1999). U.S.: ASTM D2487.

Figure 2.20 Soil classification systems: (a) mixture qualifiers based on fines content (percent passing sieve No. 200); (b) plasticity qualifiers based on liquid limit (fraction passing sieve No. 40) [39]

2.6.1 Classification of Granular Soils

In 2017, Park and Santamarina [40] introduced a new soil classification method. This classification is a potential improvement to the nearly 100-year-old Unified Soil

Classification System (USCS). Their proposed classification is based on a triangular chart showing the percentages of Gravel, Sand and Fine grain. It is stated that it determines the mechanical and hydraulic behavior of soils more accurately.

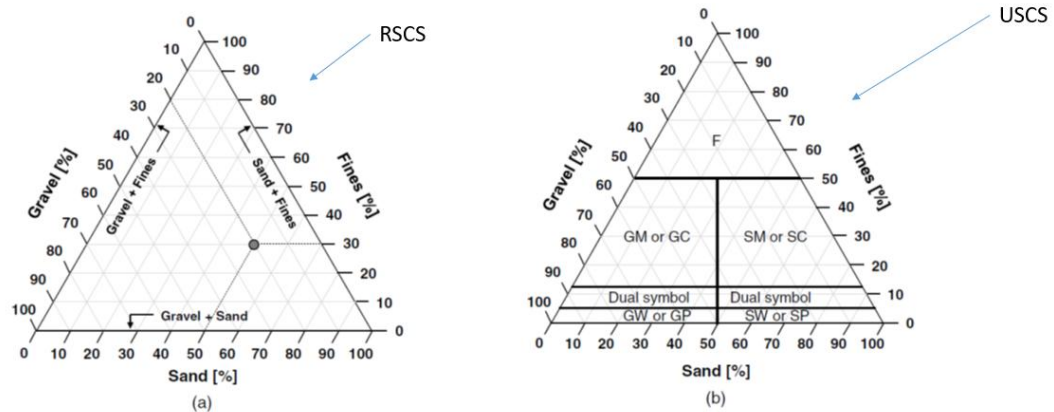


Figure 2.21 Revised Soil Classification System: Granular Soils (Park and Santamarina, 2017) [40]

Figure 2.21 (a) shows a soil composed of 20% gravel, 50% sand and 30% fines plotted in the triangular space. Figure 2.21 (b) shows the boundaries of the USCS classification system plotted on the same triangular space. The difficulty with the USCS system is that the boundaries do not reflect engineering behavior of soil mixtures.

In the new RSCS classification, the boundaries between the different soil classes are based on the mechanical and flow properties of the soils. Instead of the Cassagrande A chart, the RSCS uses a different method to classify fines. The proposed method uses fall cone liquid limit tests conducted on the soil fraction passing the No. 200 sieve. Three test are required using different liquids, Distilled water, Brine and Kerosen to identify the electrical sensetivty of the mineral contents. The values of LL_{dw} , LL_{Brine} and LL_{ker} are used in the classification system.

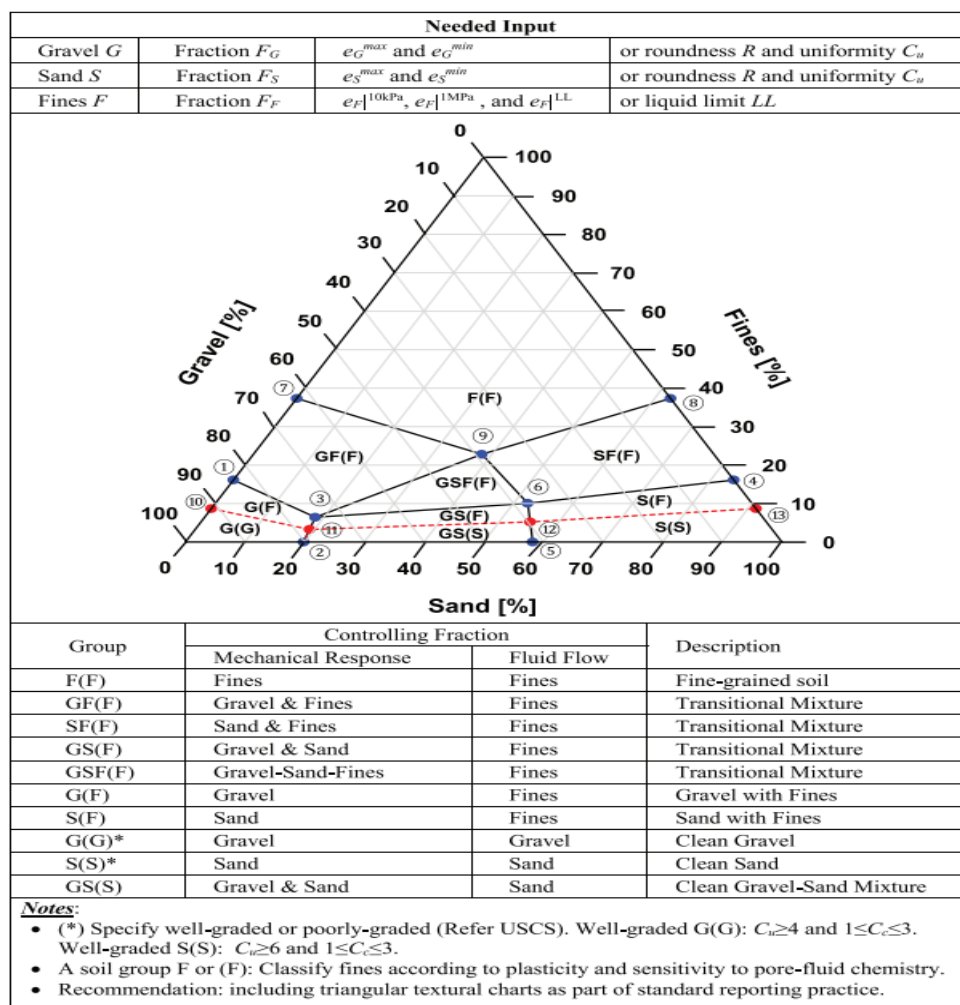


Figure 2.22 RSCS classification for granular materials

The mechanical behavior varies depending on the composition of the substrate mixture: mixtures dominated by coarse grains, mixtures dominated by fine grains, and mixtures described as transition intervals. A 2D analogy of this is shown in Figure 2.23.

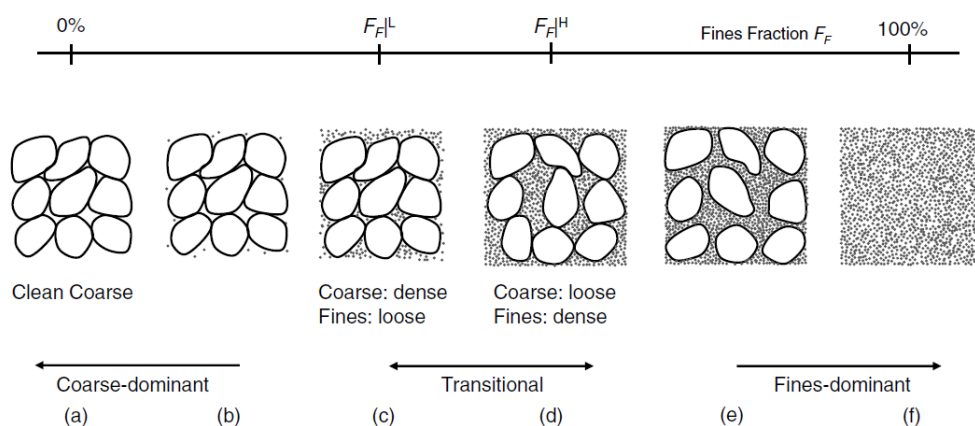


Figure 2.23 RSCS-Coarse-fine grain mixtures: Threshold fractions Coarse grain effect, Transition, and Fine grain effect [40]

The RSCS nomenclature consist of two symbols: The first symbol identifies the sediment size (“S”, “G” or “F”) that controls the mechanical behavior The second symbol identifies the sediment size (“S”, “G” or “F”) that controls the permeability and placed in parentheses (). Figure 2.22 shows the soil group symbols, their description, the soil fraction which controls the mechanical response and fluid flow. The lines that determine the transition boundaries are in a different position for each distribution. The solid lines shows the boundaries for the mechanical response and the dotted line shows the boundary for fluid control.

The required inputs for using RSCS are the Gravel and Sand percentages FG & FS Gravel and Sand maximum and minimum e values (or roundness of grains and C_u) and liquid limit of the fines content. The authors have prepared an Excel sheet and made it publicly available on the KAUST Energy GeoEngineering Laboratory Webpage (<https://egel.kaust.edu.sa/tools-procedures>).

The Revised Soil Classification System (RSCS) is established by conducting a methodical assessment of different soil characteristics, such as particle size, plasticity, and compressibility. The RSCS categorizes soils according to their engineering properties and employs visual and laboratory examinations to evaluate fundamental attributes [40].

2.6.2 Classification of Fine Grained Soil

The classification of fines in the RSCS system is shown in Figure 2.24. This system appears to be successful in differentiating between non-plastic clays and different clay mineralogy.

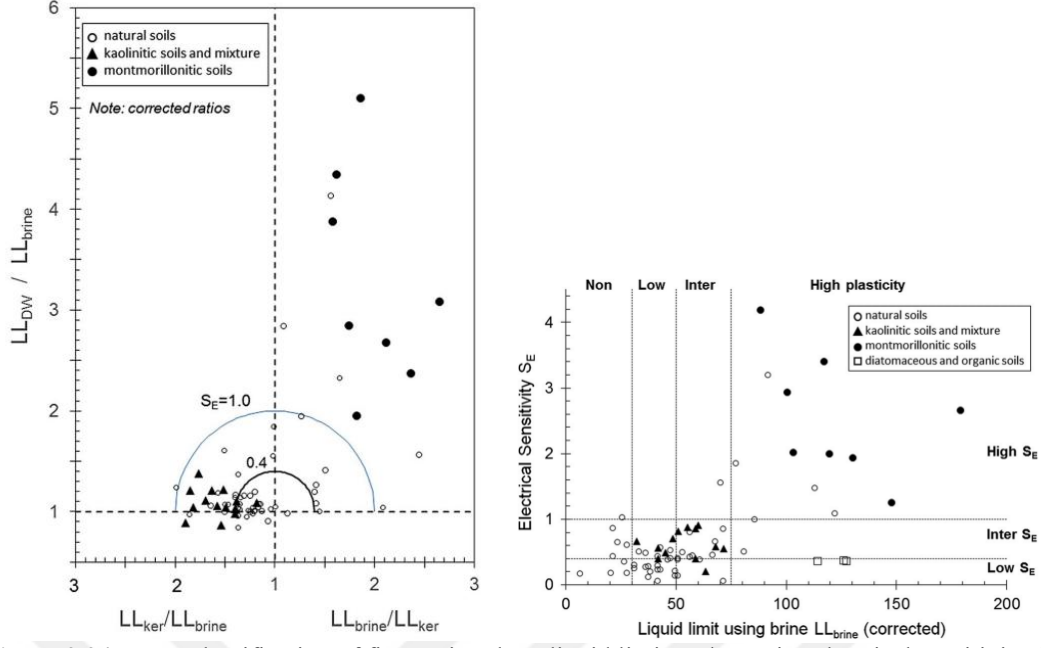


Figure 2.24 RSCS classification of fines using three liquid limit to determines electrical sensitivity (S_E)

The classification uses the results of three liquid limit tests conducted using the fall cone device on the soil fraction finer than 0.075 mm. These 3 LL tests include test conducted using distilled water (LL_{DW}), salty water (2 molar concentration) (LL_{Brine}), and kerosene (LL_{ker}) of the fluid components. The ratios are calculated for salinity specific gravity and percentages. The calculated liquid limits ratios are used to calculate the electrical Sensitivity, S_E . Show in equ.[2-9]

$$S_E = \sqrt{\left(\frac{LL_{DW}}{LL_{brine}} - 1\right)^2 + \left(\frac{LL_{ker}}{LL_{brine}} - 1\right)^2} \quad [2-9]$$

$$LL_{brine_corrected} = \frac{LL_{brine}}{(1 - c_{brine} LL_{brine})} \quad [2-10]$$

$$LL_{ker} = \frac{LL_{ker}}{G_{ker}} \quad [2-11]$$

The S_E and the LL_{Brine} values are used to classify soils into one of 12 categories: Non Plastic/Low/Intermediate/High plasticity with Low/Intermediate/High electrical sensitivity. Figure 2.24 RSCS classification of fines using three liquid limit to determines electrical sensitivity (S_E) Figure 2.24 shows the relevant plots.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 Materials

3.1.1 Materials Used for Mixtures

The materials used for the experiment are mixtures of crushed stone and fine-grained soils. Limestone-based aggregates graded to different sieve size fractions were used: “12-19 mm”, “5-12 mm”, and “0-5 mm. These were mixed with different types of fine-grained soil. The fines that were used are named “Filler”, “Kalonite”, “Bentonite” and “YK”. These materials were added in different proportions such that certain target values of fines content were reached. The target fines contents ranged from 5.24 to 20%.

The grain size distribution for each material used in the mixtures are given in Table 3.1 and Table 3.2 (granular material) and (fine grained material) Figure 3.1 shows the plots of all grain size distribution curves for the material used. A summary of the index properties of the different materials are given in Table 3.3. The 28 tests conducted are listed in Table 3.16.

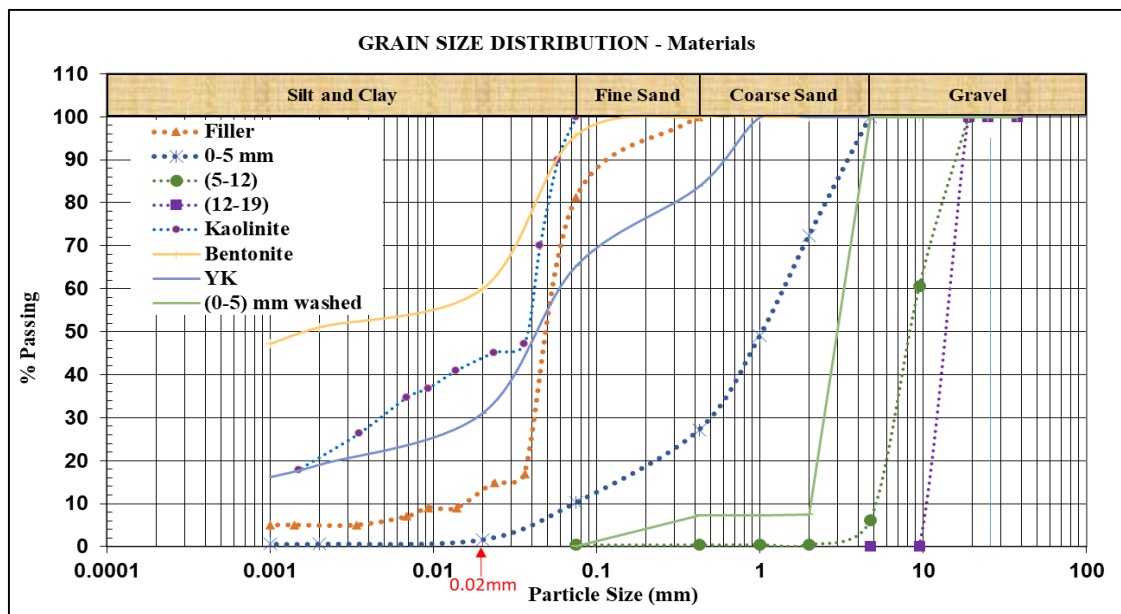
Table 3.1 Index properties of granular material

Sieves		(12-19)mm	(5-12)mm	¹ (5-12)mm	(0-5)mm	(0-5)mm washed	² (12-9)mm+ ¹ (5-12)mm
No.	(mm.)						
3/4 in	19	100	100	100	100	100	100
3/8 in	9.5	0	60.7	64.71	100	100	30
No.4	4.75	0	6.2	0	100	100	0
No.10	2	0	0.5	0	72.3	100	0
No.18	1	0	0.45	0	49	100	0
No.40	0.425	0	0.4	0	27.2	100	0
No.200	0.075	0	0.4	0	10.3	100	0
No.625	0.02	0	0	0	1.65	16.01	0
	0.002	0	0	0	0.65	6.28	0
	0.001	0	0	0	0.65	6.28	0
Roudness		0.0002058	0.0001449				
Specific gravity (G _s)		2.724	2.693		2.689	2.691	

¹ With sand fraction removed
²Gravel mixture used 54% (12-9)mm + 46% ¹(5-12)mm

Table 3.2 Index properties of fine grains materil

Sieves		Filler	Kaolinite	Bentonite	YK
No	(mm.)				
No.4	4.75	100	100	100	100
No.10	2	100	100	100	100
No.18	1	100	100	100	100
No.40	0.425	100	100	100	83,9
No.200	0.075	81.2	100	95.8	65.4
No.625	0.02	13.0	44.5	60	31
	0.002	5.1	20	51	19
	0.001	5.1	14.1	47.1	16.1
LL _C / PL		NP	50/31	462/31	67/23
LL _{DW}		29	54	316	72
LL _{Brine}		31	74	110	63
LL _{Ker}		10	48	41	44
Specific gravity (G _s)		2.751	2.61	2.755	2.691

**Figure 3.1** Grain size distribution for the material

3.1.2 Soil Mixtures Tested

The eight different material are mixed in the proportions shown in Table 3.3 the sum of each row in the table equals 100. The tests carried out are divided into six groups as shown in the

Table 3.3. Each group consists of a coarse grained skeleton and one type of fine grained materials added in different percentages.

The group names identify the type of fines added (“F” for Filler, “K” for Kaolinite, “B” for “Bentonite” and “YK” for the insitu clay) as well as the relative amount of fines such that “0” or “1” refer to the lowest percentage of fines content and higher numbers indicate higher percentages. In general, the fines content corresponding to “1”, “2”, “3” and “4” are 5.24%, 9.5%, 13.75% and 18% respectively. Mixtures without gravel content have been named “Kum”. The fines content used in “Kum” samples are “0”, “1”, “2”, “3” and “4” which correspond to 6.34%, 8.2%, 12.24% 16.28 and 20.32% respectively.

The first set of experiments conducted include a gravel-heavy mixture with fines content composed of Filler material. The second set of experiments conducted included the same gravel and coarse sand “skeleton” but with Kaolinite as the fines content. The third set of experiments also included the same gravel and coarse sand “skeleton” but with Bentonite constituting the fines content.

The first three sets of mixtures involved a well-graded soil skeleton and varying amounts of fines content. In order to determine the influence of soil grading (i.e. well graded/poorly graded) and soil skeleton type (i.e. sand versus gravel), a series of tests were conducted using Filler as the fines and a gap graded skeleton. The fourth group of mixtures named “Kum” included a poorly graded sand mixed with Filler. The fifth group of mixtures named “G F” includes a gap-graded gravel with very little sand and Filler as fines content.

The first 5 sets of tests involve commercially obtained fines (i.e. kaolinite and bentonite) and Filler which is essentially the rock flour produced from the quarrying process. In order to assess the effect of fines that may be found in-situ, a natural clay “YK” was used as the fines content for the sixth set of mixtures.

The soil mixtures for each of the tests in the six groups were obtained using the mix percentages shown in Table 2. The grain size distribution (GSD) curves for each mixture are generated using the mix ratios shown and the grain size distribution curves corresponding to the materials used. The GSD of the resulting mixtures are shown in

Table 3.3 Mixture Percentages.

Mixture Group	No	Mix Name	(12-19) mm	(5-12) mm	(0-5) mm	(0-5) mm-Washed	Filler	Kaolinite	Bentonite	YK
Group 1	1	F-Mix 1	27	23	50		0			
	2	F-Mix 2	27	23	44		6			
	3	F-Mix 3	27	23	38		12			
	4	F-Mix 4	27	23	32		18			
Group-2	5	K-Mix 1	27	23		44.85		5.15		
	6	K-Mix 2	27	23		40.6		9.4		
	7	K-Mix 3	27	23		36.34		13.66		
	8	K-Mix 4	27	23		32.09		17.91		
Group-3	9	B-Mix 1	27	23		44.62			5.38	
	10	B-Mix 2	27	23		40.19			9.81	
	11	B-Mix 3	27	23		35.74			14.26	
Group-4	12	F Kum-Mix 0	0	23.66		70	6.34			
	13	F Kum-Mix 1	0	20		70	10			
	14	F Kum-Mix 2	0	15		70	15			
	15	F Kum-Mix 3	0	10		70	20			
	16	F Kum-Mix 4	0	5		70	25			
Group-5	17	GF-Mix 1	50.52	43.03			6.45			
	18	GF-Mix 2	47.68	40.62			11.7			
	19	GF-Mix 3	44.86	38.21			16.93			
	20	GF-Mix 4	42.03	35.8			22.17			
Group-6	21	YK-Mix 1	27	23		42.13				7.87
	22	YK-Mix 2	27	23		35.62				14.38
	23	YK-Mix 3	27	23		29.11				20.89
	24	YK-Mix 4	27	23		22.61				27.39

Table 3.4 through Table 3.9 The graphical representation of these values are shown in Figures 1, 2, 3, 4 5, and 6. In Group 1, 2, 3 and 6 mixtures, the percentage of gravel is constant and the percentage of sand decreases as fines content increases. In groups 4 and 5, which are gap graded, sand-fines and gravel-fines mixtures respectively, the soil skeleton is composed of one dominant size fraction. In group 4 the sand percentage ranges from 72.6 to 75% and in Group 5 the gravel percentage ranges from 77.8 to 93.6% (Table 2.6). For the sake of comparison, the plots of grain size distribution also include GSD of the sand portion (0-5 mm) and fines content used.

Table 3.4 Grain size distribution of mixtures with Filler (Group-1).

Opening size		F Mix 1	F Mix 2	F Mix 3	F Mix 4
No.	(mm)	27:23:50:0	27:23:44:6	27:23:38:12	27:23:32:18
3/4 in	19	100	100	100	100
3/8 in	9.5	64.0	64.0	64.0	64
No.4	4.75	51.4	51.4	51.4	51.4
No.10	2	36.3	37.9	39.6	41.3
No.18	1	24.6	27.7	30.7	33.8
No.40	0.425	13.7	18.1	22.4	26.8
No.200	0.075	5.24	9.50	13.75	18.00
No.625	0.02	0.82	1.51	2.19	2.87
	0.002	0.32	0.59	0.86	1.13
	0.001	0.32	0.59	0.86	1.13

Table 3.5 Grain size distribution of mixtures with Kaolinite (Group-2).

Sieves		K Mix 1	K Mix 2	K Mix 3	K Mix 4
No.	(mm)	27:23:44.9:5.15	27:23:40.6:9.4	27:23:36.3:13.7	27:23:32.1:17.9
3/4 in	19	100	100	100	100
3/8 in	9.5	64.0	64.0	64.0	64
No.4	4.75	51.4	51.4	51.4	51.4
No.10	2	41.4	42.2	43.1	43.9
No.18	1	29.8	31.7	33.6	35.5
No.40	0.425	18.8	21.8	24.8	27.7
No.200	0.075	5.242	9.49	13.75	18.00
No.625	0.02	2.29	4.18	6.08	7.97
	0.002	1.03	1.88	2.73	3.58
	0.001	0.73	1.33	1.93	2.53

Table 3.6 Grain size distribution of mixtures with Bentonite (Group-3).

Sieves		B Mix 1	B Mix 2	B Mix 3
No.	(mm)	27:23:44.62:5.38	27:23:40.19:9.81	27:23:35.74:14.26
3/4 in	19	100	100	100
3/8 in	9.5	64.0	64.0	64.0
No.4	4.75	51.4	51.4	51.4
No.10	2	41.5	42.3	43.2
No.18	1	29.9	31.9	33.9
No.40	0.425	19.0	22.1	25.2
No.200	0.075	5.242	9.49	13.75
No.625	0.02	3.23	5.89	8.56
	0.002	2.74	5.00	7.27
	0.001	2.53	4.62	6.72

Table 3.7 Grain size distribution of mixtures of sand & Filler (Group-4).

Opening size		Kum F Mix 0	Kum F Mix 1	Kum F Mix 2	Kum F Mix 3	Kum F Mix 4
No.	(mm)	0:20:73.7:6.4	0:20:70:10	0:15:70:10	0:10:70:20	0: 5:70:25
3/4 in	19	100	100	100	100	100
3/8 in	9.5	92.14	92.14	94.1	96.1	98
No.4	4.75	81.2	81.2	85.9	90.6	95.3
No.10	2	7.1	10.7	15.6	20.6	25.6
No.18	1	7.0	10.6	15.6	20.6	25.5
No.40	0.425	6.9	10.5	15.5	20.5	25.5
No.200	0.075	5.236	8.2	12.24	16.28	20.32
No.625	0.02	0.83	1.30	1.95	2.60	3.25
	0.002	0.32	0.51	0.77	1.02	1.28
	0.001	0.32	0.51	0.77	1.02	1.28

Table 3.8 Grain size distribution of mixtures of gravel & Filler (Group-5).

Opening sizes		GF Mix 1	GF Mix 2	GF Mix 3	GF Mix 4
No.	(mm)	50.5:43.0:0:6.4	47.7:40.6:0:11.7	44.9:38.2:0:16.9	44.7:38.2:0:16.9
3/4 in	19	100	100	100	100
3/8 in	9.5	34.3	38.0	41.7	45
No.4	4.75	6.5	11.7	16.9	22.2
No.10	2	6.5	11.7	16.9	22.2
No.18	1	6.5	11.7	16.9	22.2
No.40	0.425	6.5	11.7	16.9	22.2
No.200	0.075	5.24	9.50	13.75	18.00
No.625	0.02	0.84	1.52	2.20	2.88
	0.002	0.33	0.60	0.86	1.13
	0.001	0.33	0.60	0.86	1.13

Table 3.9 Grain size distribution of mixtures with YK fines (Group-6).

Sieves		YK Mix 1	YK Mix 2	YK Mix 3	YK Mix 4
No.	(mm)	27:23:42.13:7.87	27:23:35.62:14.38	27:23:29.11:20.89	27:23:22.61:27.39
3/4 in	19	100	100	100	100
3/8 in	9.5	64.0	64.0	64.0	64
No.4	4.75	51.4	51.4	51.4	51.4
No.10	2	41.9	43.2	44.5	45.7
No.18	1	31.0	33.9	36.9	39.8
No.40	0.425	19.5	23.0	26.4	29.9
No.200	0.075	5.239	9.50	13.75	18.01
No.625	0.02	2.44	4.46	6.48	8.49
	0.002	1.50	2.73	3.97	5.20
	0.001	1.27	2.32	3.36	4.41

All mixtures in Group 1, Group 2 and Group 3 have grain size distribution that are the same in the gravel range (i.e. + No.4 or > 4.75 mm size). The portion of the grain size distribution curves finer than 4.75 mm differ based on the mix percentages used and the GSD of the parent materials. All of the mixtures used have been classified according to USCS, AASHTO, and the Revised Soil Classification system. The relevant information for each mixture is summarized in Table 3.16.

For each category, with corresponding grain size distributions given in the figures (Figure 3.2 through Figure 3.7) and the following tables (Table 3.10 through Table 3.15) detail the materials and ratios for mixing. Apart from the standard requirements for grain size, the percentage of a grain that is smaller than 0.075 mm and 0.02 mm has also been incorporated. Taster and Gaskin (1992) discovered that a material's susceptibility to frost can rise in proportion to the percentage of 0.075mm that passes through. The USACE frost susceptibility classification system also uses the criteria that Cassagrande (1931) [4] first proposed to use as an indicator of frost susceptibility the percentage passing 0.02 mm. The figures also provided display the prescribed maximum and lower limits for the granulometer of the base and sub-base material, as outlined in the KGM standard. Additionally, the figures illustrate the granulometer curves for each fine material within each mixed group, as well as the "0-5" mm material.

Table 3.10 Grain size distribution of "Group-1".

	F-Mixture-1	F-Mixture-2	F-Mixture-3	F-Mixture-4
D ₁₀ (mm)	0.23	0.07	0.04	0.04
D ₃₀ (mm)	1.42	1.18	0.93	0.67
D ₆₀ (mm)	8.45	8.45	8.45	8.45
Cu	36.7	124.3	196.5	211.3
Cc	1.04	2.42	2.38	1.33
% Gravel	48.6	48.6	48.6	48.6
% Sand	46.2	41.9	37.7	33.4
% Fine grain	5.24	9.5	13.75	18
<0.02 mm	0.82	1.51	2.19	2.87
% Silt	4.92	8.91	12.89	16.88
% Clay	0.32	0.59	0.86	1.13
USCS	GW-GM	GW-GM	GM	GM
AASHTO	A-1-a (0)	A-1-a (0)	A-1-a (0)	A-1-a (0)

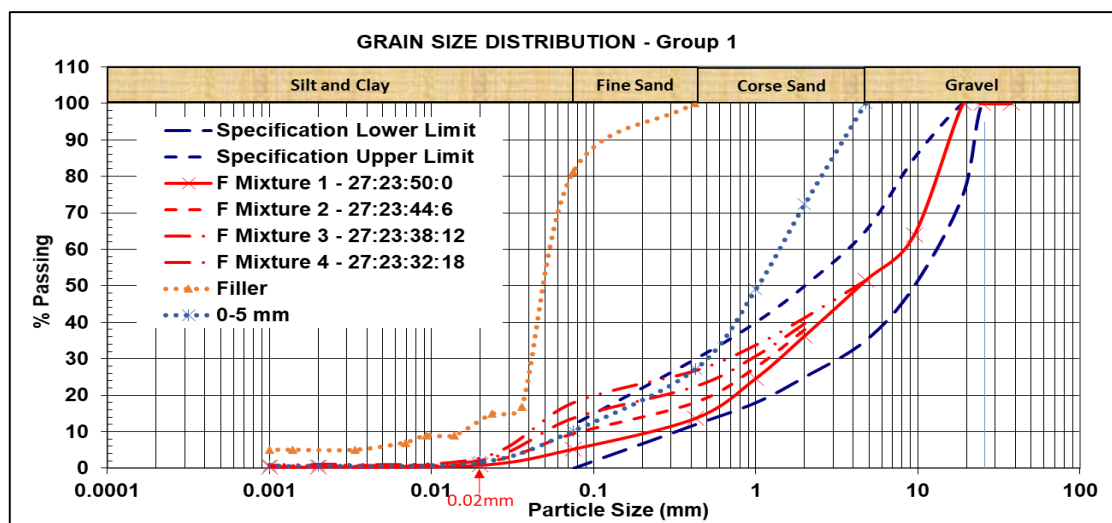
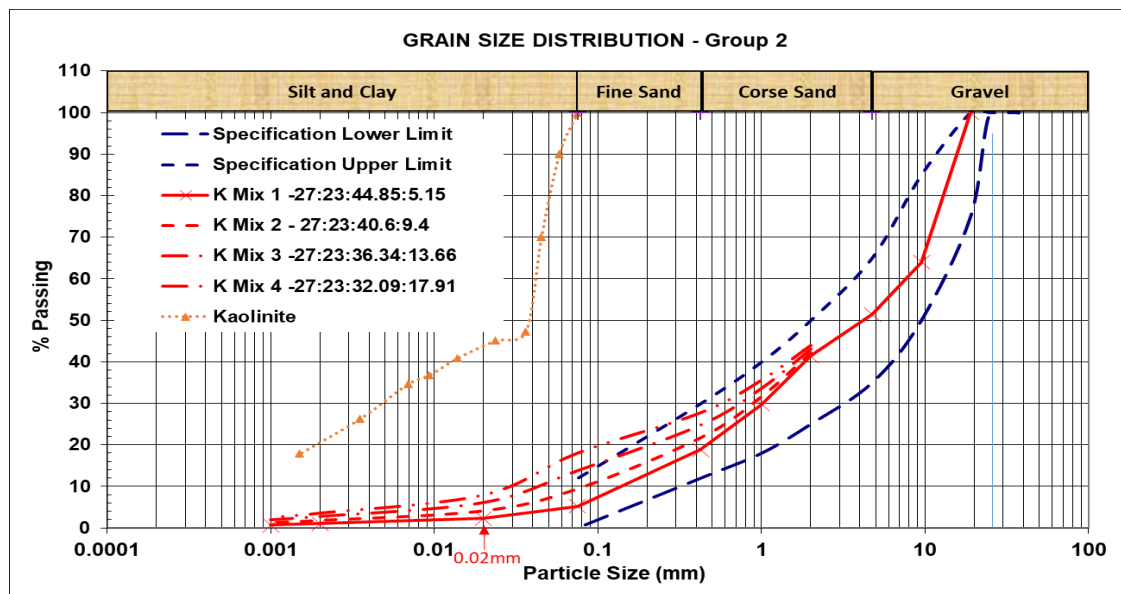


Figure 3.2 Grain size distribution of mixtures with Filler (Group-1)

Table 3.11 Grain size distribution of “Group-2”.

	K-Mixture-1	K-Mixture-2	K-Mixture-3	K-Mixture-4
D ₁₀ (mm)	0.14	0.08	0.04	0.03
D ₃₀ (mm)	1.00	0.88	0.75	0.58
D ₆₀ (mm)	7.50	7.50	7.50	7.50
Cu	53.6	93.8	170.5	250.0
Cc	0.95	1.29	1.70	1.50
% Gravel	48.6	48.6	48.6	48.6
% Sand	46.2	41.9	37.7	33.4
%Fine grain	5.24	9.5	13.75	18.0
<0.02 mm	2.29	4.2	6.08	8.0
% Silt	4.21	7.6	11.02	14.4
% Clay	1.03	1.9	2.73	3.6
USCS	GP-GC	GW-GC	GC	GC
AASHTO	A2-7 (0)	A2-7 (0)	A2-7 (0)	A2-7 (0)

**Figure 3.3** Grain size distribution of mixtures with Kaolinite (Group-2)**Table 3.12** Grain size distribution of “Group-3”.

	B-Mixture-1	B-Mixture-2	B-Mixture-3
D ₁₀ (mm)	0.14	0.08	0.04
D ₃₀ (mm)	1.00	0.88	0.75
D ₆₀ (mm)	7.50	7.50	7.50
Cu	53.6	93.8	170.5
Cc	0.95	1.29	1.70
% Gravel	48.6	48.6	48.6
% Sand	46.2	41.9	37.7
%Fine grain	5.24	9.49	13.75
<0.02 mm	3.23	5.89	8.56
% Silt	2.5	4.488	6.48
% Clay	2.74	5.00	7.27
USCS	GP-GC	GW-GC	GC
AASHTO	A2-7 (0)	A2-7 (0)	A2-7 (0)

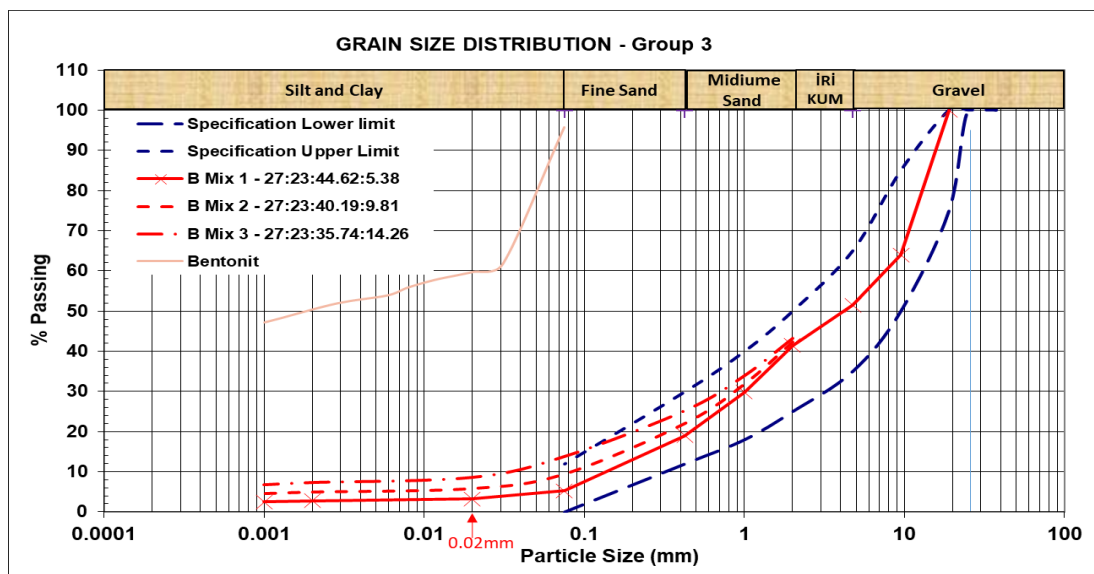


Figure 3.4 Grain size distribution of mixtures with Bentonite (Group-3)

Table 3.13 Grain size distribution of “Group-4”.

	FK-Mixture-0	FK -Mixture-1	FK -Mixture-2	FK -Mixture-3	FK -Mixture-4
D ₁₀ (mm)	2.06	0.25	0.06	0.04	0.03
D ₃₀ (mm)	2.6	2.55	2.40	2.25	2.15
D ₆₀ (mm)	3.75	3.65	3.50	3.24	3.05
Cu	1.8	14.6	62.5	79.0	89.7
Cc	0.88	7.13	29.39	38.11	44.6
% Gravel	22.2	18.8	14.1	9.4	4.7
% Sand	72.6	73.0	73.7	74.3	75.0
%Fine grain	5.24	8.20	12.24	16.28	20.32
<0.02 mm	0.82	1.30	2.0	2.60	3.3
% Silt	4.92	7.69	11.5	15.26	19.0
% Clay	0.32	0.51	0.8	1.02	1.3
USCS	SP-SM	SP-SM	SM	SM	SM
AASHTO	A1-a (0)	A1-a (0)	A1-b (0)	A1-b (0)	A1-b (0)

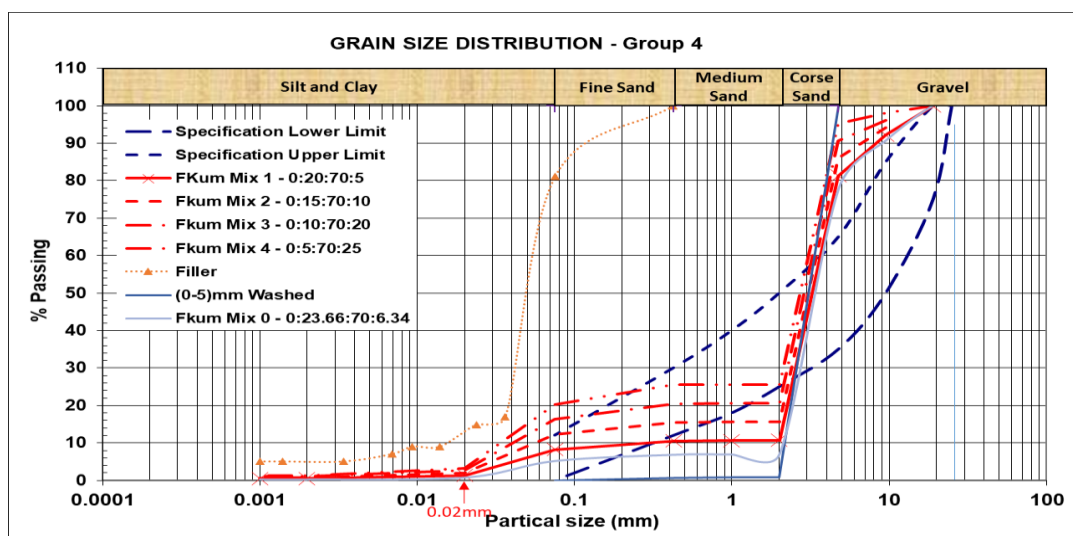
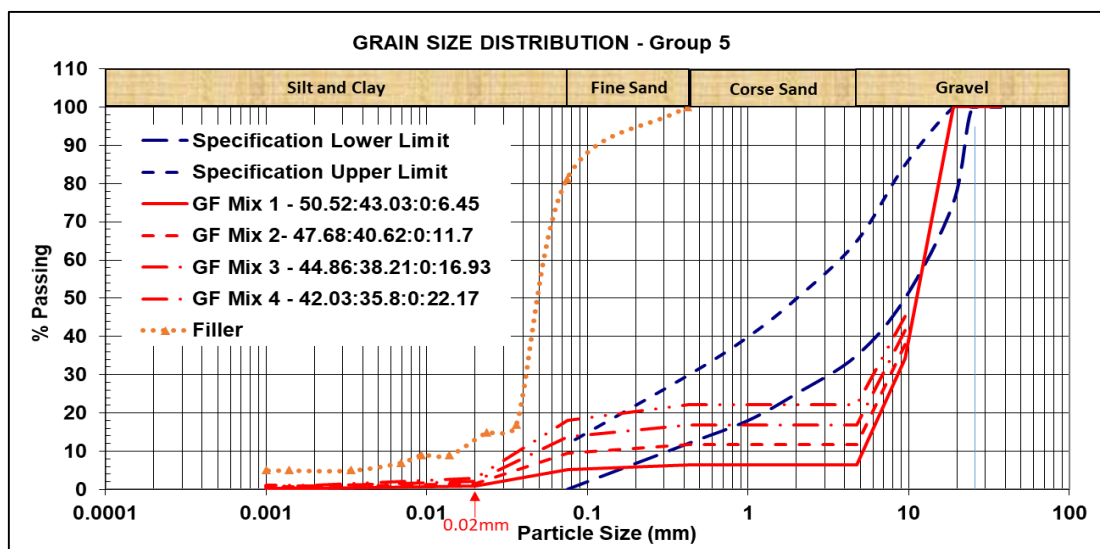


Figure 3.5 Grain size distribution of mixtures of sand & Filler (Group-4)

Table 3.14 Grain size distribution of “Group-5”.

	GF-Mixture-1	GF-Mixture-2	GF-Mixture-3	GF-Mixture-4
D ₁₀ (mm)	5.2	0.077	0.05	0.37
D ₃₀ (mm)	8.6	7.74	6.8	5
D ₆₀ (mm)	12.5	12.5	12.5	12.5
Cu	2.4	162.3	250	337.8
Cc	1.14	62.24	73.98	54.05
% Gravel	93.6	88.3	83.1	77.8
% Sand	1.2	2.2	3.2	4.2
%Fine grain	5.24	9.50	13.75	18.00
<0.02 mm	0.84	1.52	2.20	2.88
% Silt	4.91	8.90	12.88	16.87
% Clay	0.33	0.60	0.86	1.13
USCS	GP-GM	GP-GM	GM	GM
AASHTO	A-1-a (0)	A-1-a (0)	A-1-a (0)	A-1-b (0)

**Figure 3.6** Grain size distribution of mixtures of gravel & Filler (Group-5)**Table 3.15** Grain size distribution of “Group-6”.

	YK-Mixture-1	YK-Mixture-2	YK-Mixture-3	YK-Mixture-4
D ₁₀ (mm)	0.14	0.08	0.04	0.03
D ₃₀ (mm)	0.94	0.75	0.60	0.43
D ₆₀ (mm)	7.50	7.50	7.50	7.50
Cu	55.6	91.5	174.4	267.9
Cc	0.87	0.91	1.12	0.88
% Gravel	48.6	48.6	48.6	48.6
% Sand	46.2	41.9	37.7	33.4
%Fine grain	5.24	9.50	13.75	18.01
<0.02 mm	2.44	4.5	6.48	8.5
% Silt	3.74	6.8	9.78	12.8
% Clay	1.50	2.7	3.97	5.2
USCS	GP-GC	GP-GC	GC	GC
AASHTO	A-2-7(0)	A-2-7(0)	A-2-7(0)	A-2-7(1)

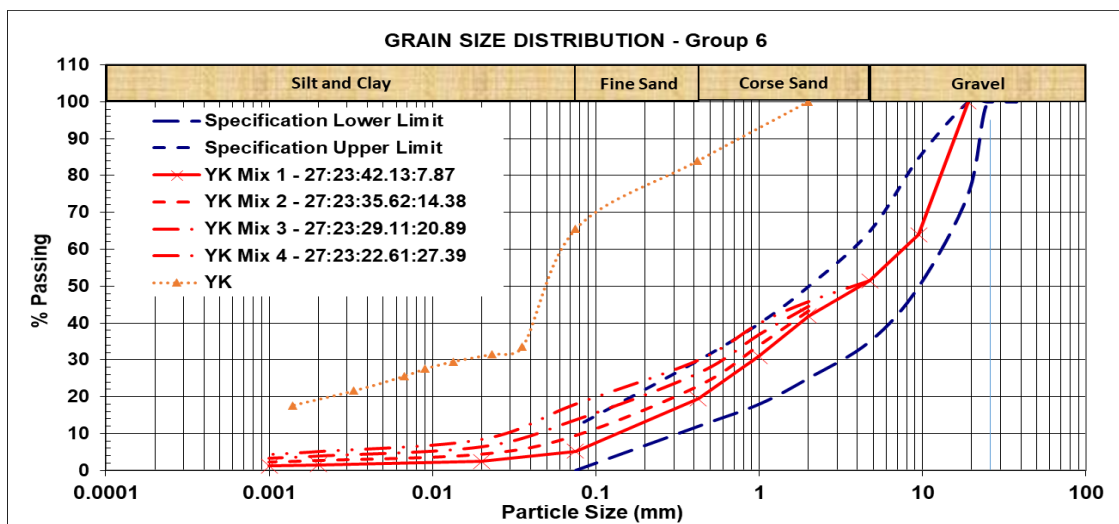


Figure 3.7 Grain size distribution of mixtures with YK fines (Group-6)

3.1.3 Classification of Materials & Mixtures: USCS and RSCS

The USCS and AASHTO classifications for all of the mixtures tested are shown in Table 3.16. The classifications using the RSCS are described in this section.

The revised soil classification was made according to the proposed procedures outlined in the two papers by Park and Snatamarina [40] for coarse-grained and [42] for fined-grained materials. A free downloadable Excel sheet was used from the KAUST Energy GeoEngineering Laboratory Webpage (<https://egel.kaust.edu.sa/tools-procedures>).

Table 3.16 List of tested mixtures with different types of soil classifications.

Mixtures Group	Mixes No	Group Name	USCS	AASHTO	RSCS
Group-1	1	F-Mixture 1	GW-GM	A-1-a (0)	GS(S)
	2	F-Mixture 2	GW-GM	A-1-a (0)	GS(S)
	3	F-Mixture 3	GM	A-1-a (0)	GSF(F) where fines are LH
	4	F-Mixture 4	GM	A-1-b (0)	GF(F) where fines are LH
Group-2	5	K-Mixture 1	GP-GC	A-2-7(0)	GS(F) where fines are HI
	6	K-Mixture 2	GW-GC	A-2-7(0)	GSF(F) where fines are HI
	7	K-Mixture 3	GC	A-2-7(0)	GSF(F) where fines are HI
	8	K-Mixture 4	GC	A-2-7(0)	GF(F) where fines are HI
Group-3	9	B-Mixture 1	GP-GC	A-2-7(0)	GSF(F) where fines are LH
	10	B-Mixture 2	GW-GC	A-2-7(0)	GF(F) where fines are LH
	11	B-Mixture 3	GC	A-2-7(0)	F(F) where fines are LH
Group-4	12	F Kum-Mixture 0	SP-SM	A-1-b (0)	S (S)
	13	F Kum-Mixture 1	SP-SM	A-1-a (0)	S (S)
	14	F Kum-Mixture 2	SP-SM	A-1-a (0)	S (S)
	15	F Kum-Mixture 3	SM	A-1-a (0)	S (F) where fines are LH
	16	F Kum-Mixture 4	SM	A-1-b (0)	S (F) where fines are LH
Group-5	17	GF-Mixture 1	GP-GM	A-1-a (0)	G(G)
	18	GF-Mixture 2	GP-GM	A-1-a (0)	G(G)
	19	GF-Mixture 3	GM	A-1-a (0)	G(G)
	20	GF-Mixture 4	GM	A-1-b (0)	G(G)
Group-6	21	YK-Mixture 1	GP-GC	A-2-7(0)	GS(F) where fines are LI
	22	YK-Mixture 2	GP-GC	A-2-7(0)	GSF(F) where fines are LI
	23	YK-Mixture 3	GC	A-2-7(0)	GSF(F) where fines are LI
	24	YK-Mixture 4	GC	A-2-7(1)	GF(F) where fines are LI

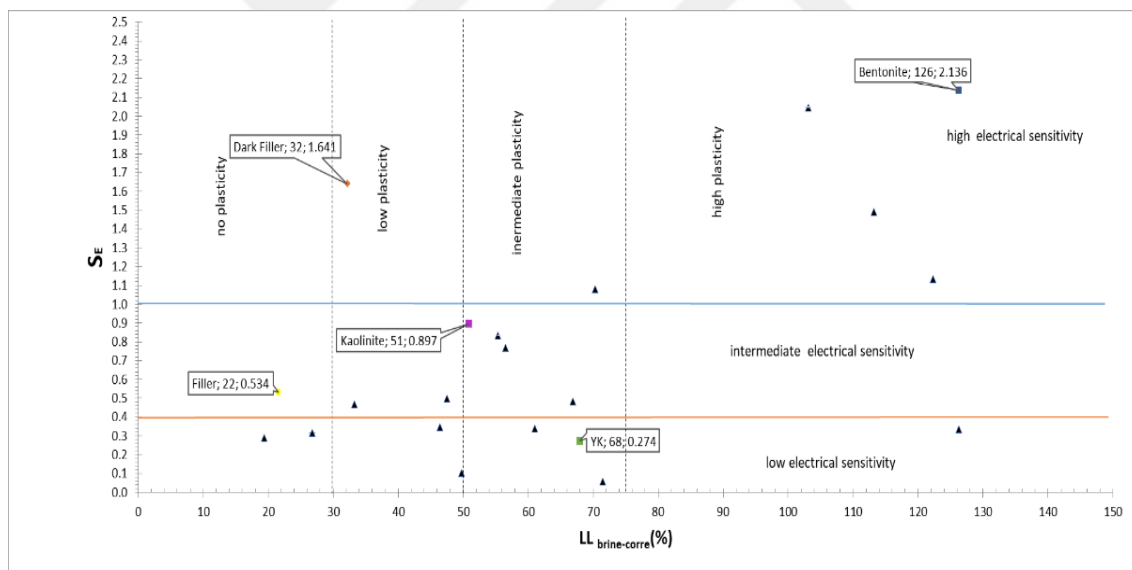
For the RSCS classification, the experimentally obtained e_{max} & e_{min} values have been used instead of C_u , C_c & Roundness data. These values were obtained using the procedures described in section 3.2. The results of the maximum and minimum void ratio determination for the gravel and sand fractions are shown in Table 3.17. Table 3.16 also shows the classifications based on the RSCS. The classification of the fines used in this study are shown in Figure 3.9 through Figure 3.32.

The RSCS plots in Figure 3.9 to Figure 3.32 are based on the three liquid limit values measured using the fall cone test (see Table 3.2). The electrical sensitivity, S_E , is calculated based on these values as shown in equation [2-9]. The two liquid limit ratios LL_{DW}/LL_{Brine} (or LL_{Brine}/LL_{DW}) and LL_{Ker}/LL_{Brine} (or LL_{Brine}/LL_{Ker}) should be corrected for the concentration of salt in the brine (i.e. 2 Molar concentration) and for the lower specific gravity of kerosene (i.e. 0.82) compared to water as shown in equations [2-10] and [2-11].

Table 3.17 Maximum & minimum void ratios for coarse granular material used in mixtures.

Soil	Mix description	e max	e min	Cu & Cc
Gravel	*(5-12) mm = 46% (12-19) mm = 54%	0.960	0.711	2.1 & 1.19
Sand (Washed)	(0-5) mm =100%	0.678	0.414	1.6 & 0.95
Gravel (5-12)	** (5-12) mm =100%	0.976	0.723	
Sand (Unwashed)	(0-5) mm = 100%	0.653	0.378	
*With Sand fraction removed				
**Washed using No.200 sieve				

S_E is essentially the distance between the center of a coordinate system with the origin at (1,1) and the x and y values corresponding to LL_{ker}/LL_{Brine} and LL_{DW}/LL_{Brine} for the fine grained soil. The ratio of liquid limits need to be flipped if the value is less than 1. Hence, the S_E value is calculated using LL_{Brine}/LL_{ker} (or LL_{ker}/LL_{Brine} if the value is less than one) and LL_{DW}/LL_{Brine} (or LL_{Brine}/LL_{DW} if the value is less than one). The S_E value can then be used to classify the fines based on the chart shown in Figure 3.8. Figure 3.8 shows the RSCS classification plot for fines.

**Figure 3.8** Chart for the classification of fine grains on the basis of electrical sensitivity and liquid limit

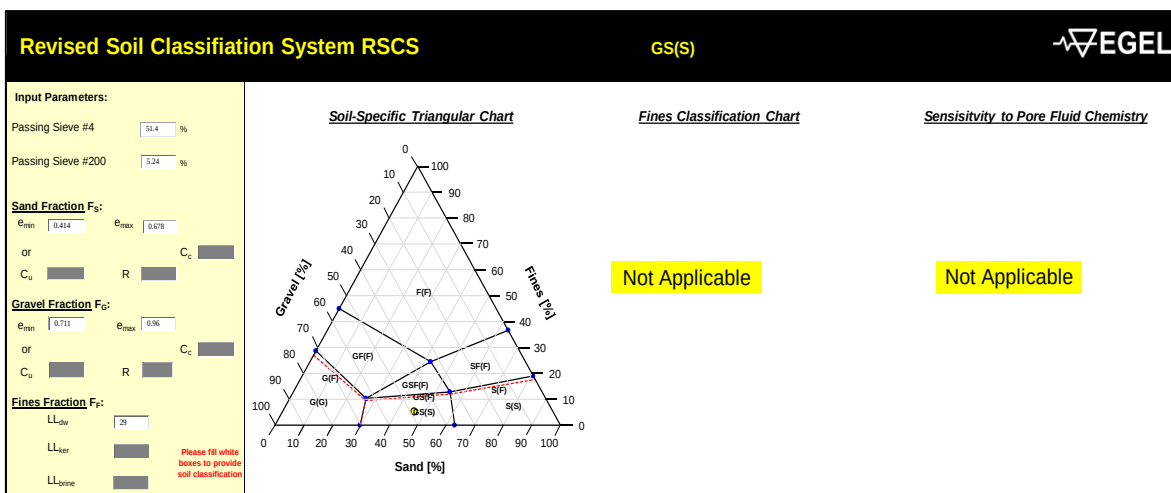


Figure 3.9 Revised soil classification (RSCS) of (1_F Mix 1)

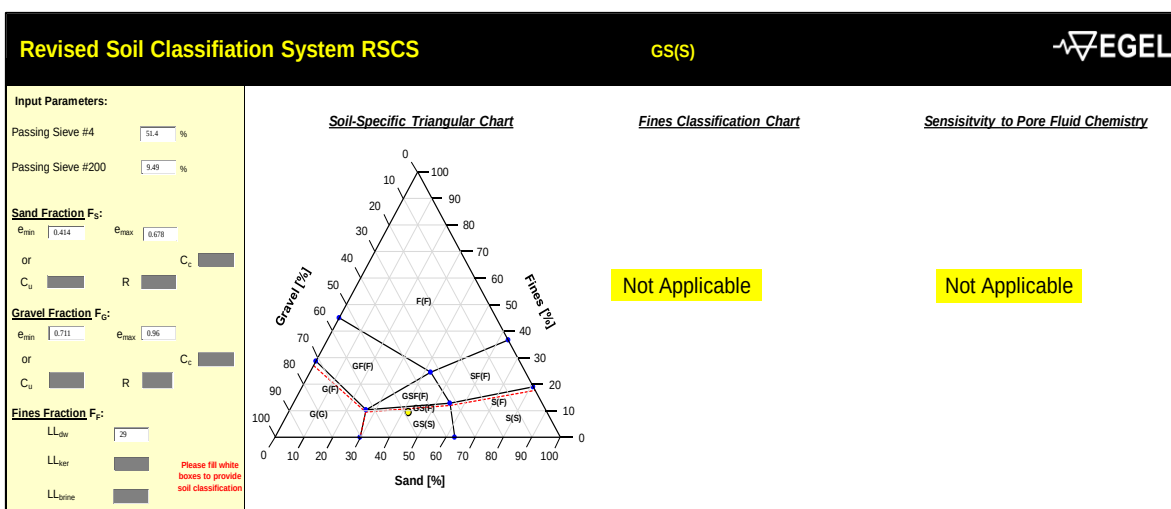


Figure 3.10 Revised soil classification (RSCS) of (2_F Mix 2)

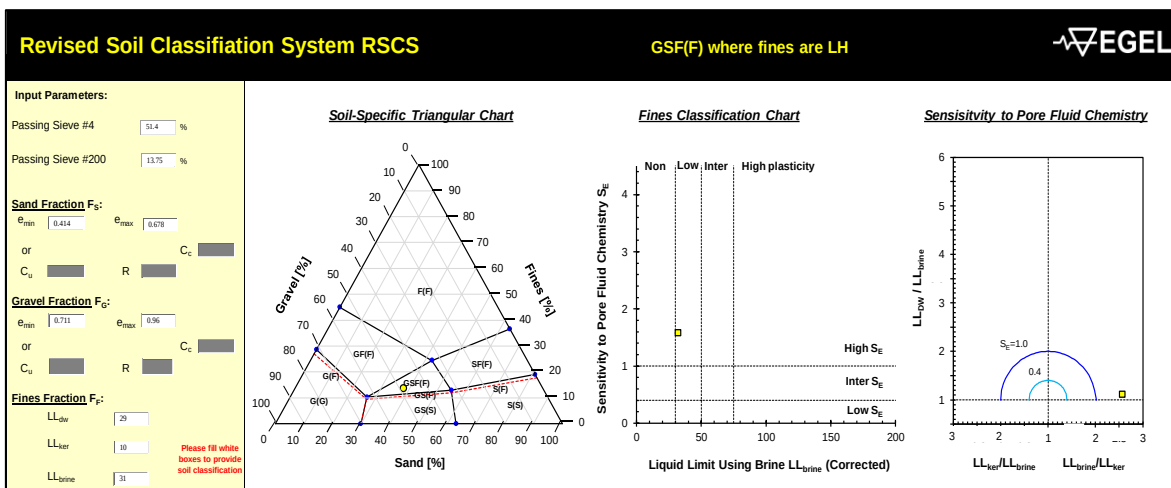


Figure 3.11 Revised soil classification system (RSCS) of (3_F Mix 3)

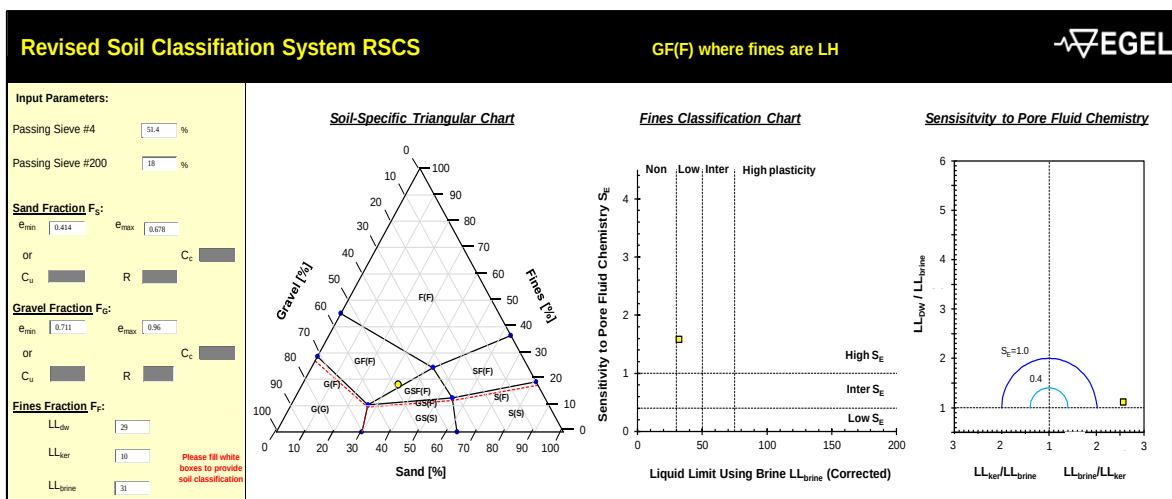


Figure 3.12 Revised soil classification system (RSCS) of (4_F Mix 4)

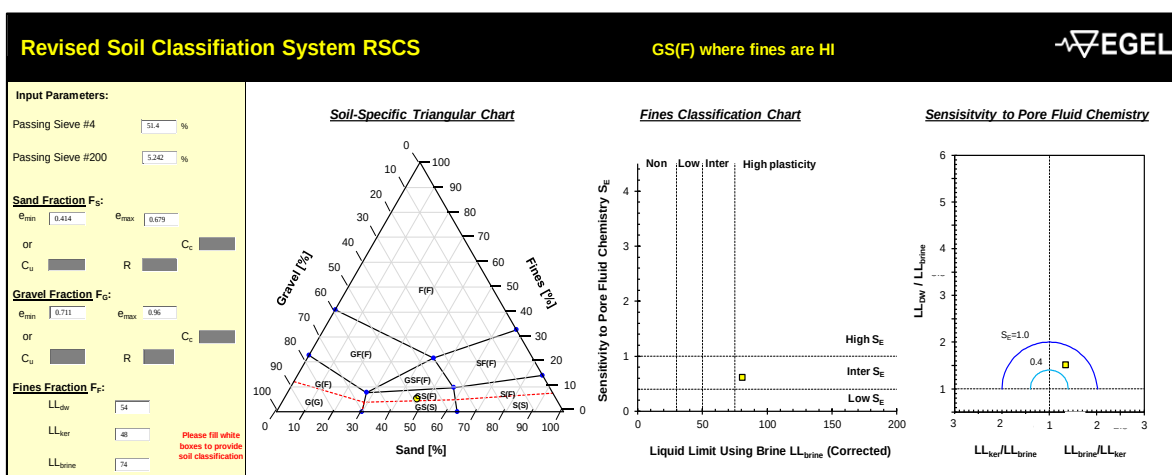


Figure 3.13 Revised soil classification system (RSCS) of (5_K Mix 1)

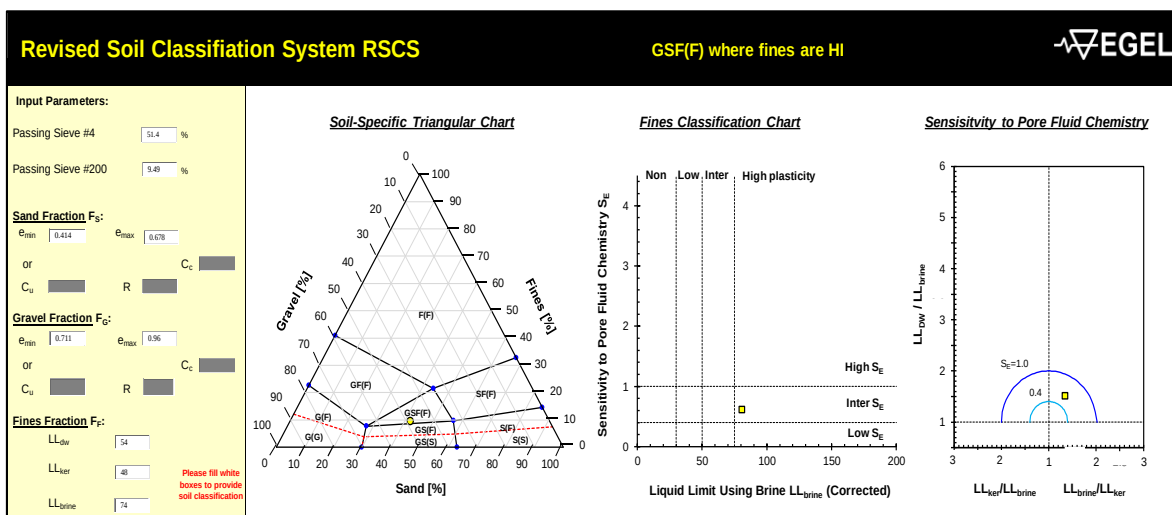


Figure 3.14 Revised soil classification system (RSCS) of (6_K Mix 2)

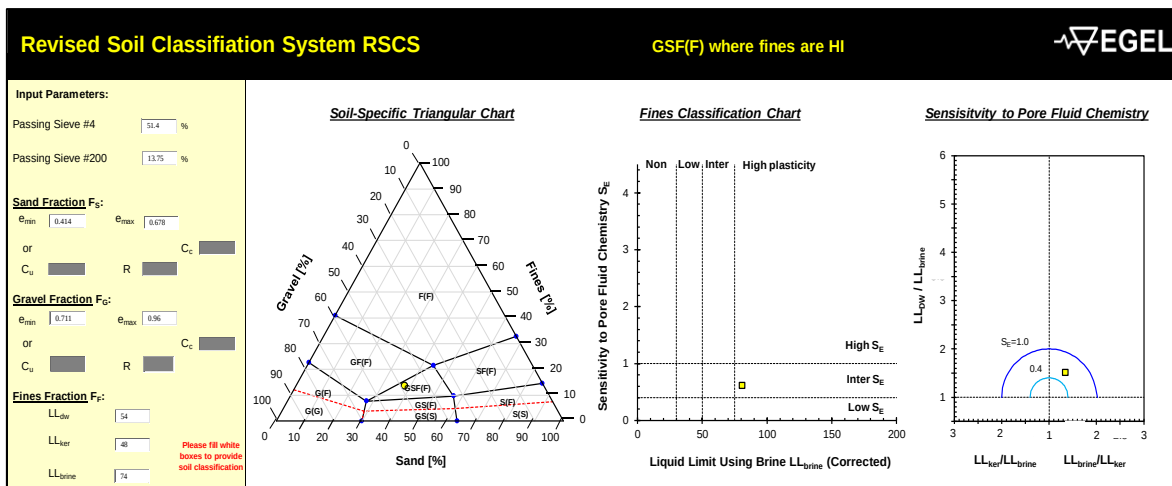


Figure 3.15 Revised soil classification system (RSCS) of (7_K Mix 3)

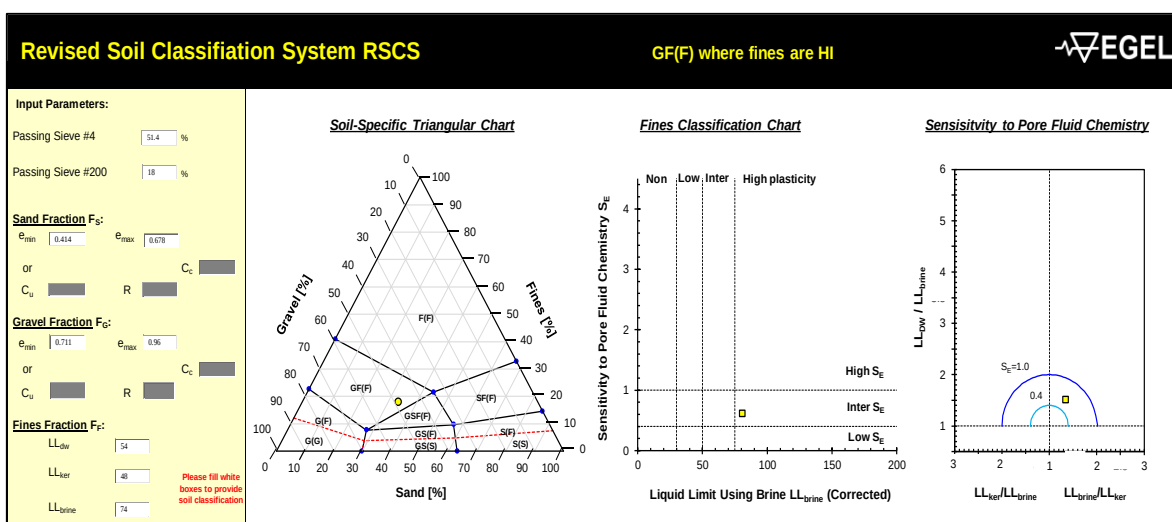


Figure 3.16 Revised soil classification system (RSCS) of (8_K Mix 4)

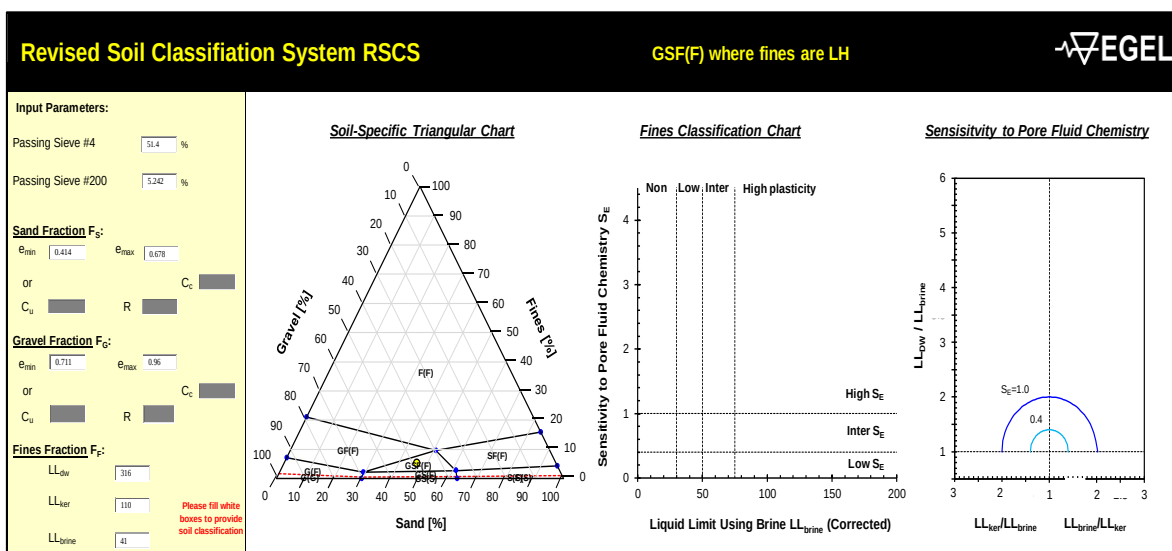


Figure 3.17 Revised soil classification system (RSCS) of (9_B Mix 1)

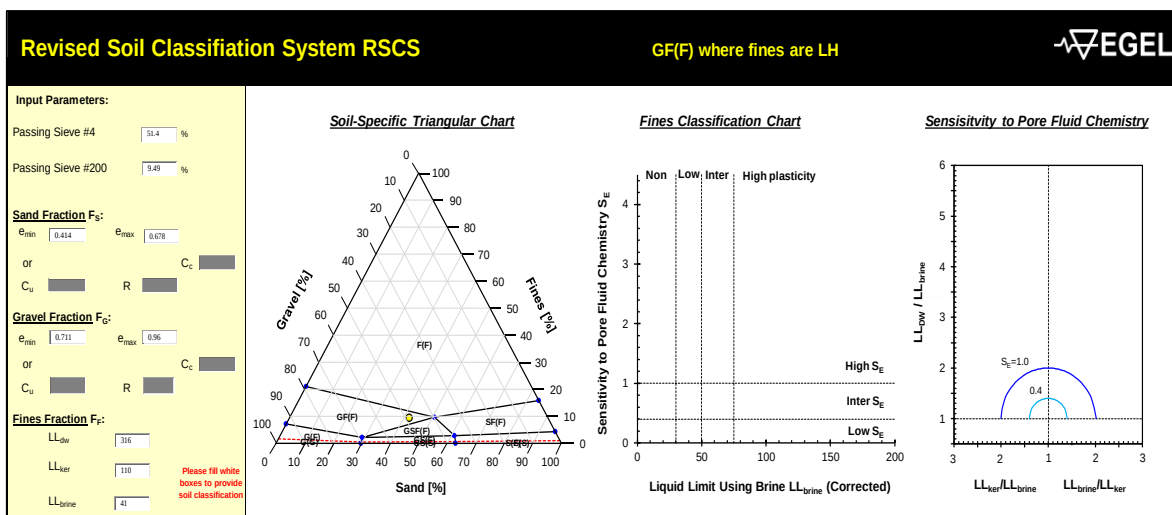


Figure 3.18 Revised soil classification system (RSCS) of (10_B Mix 2)

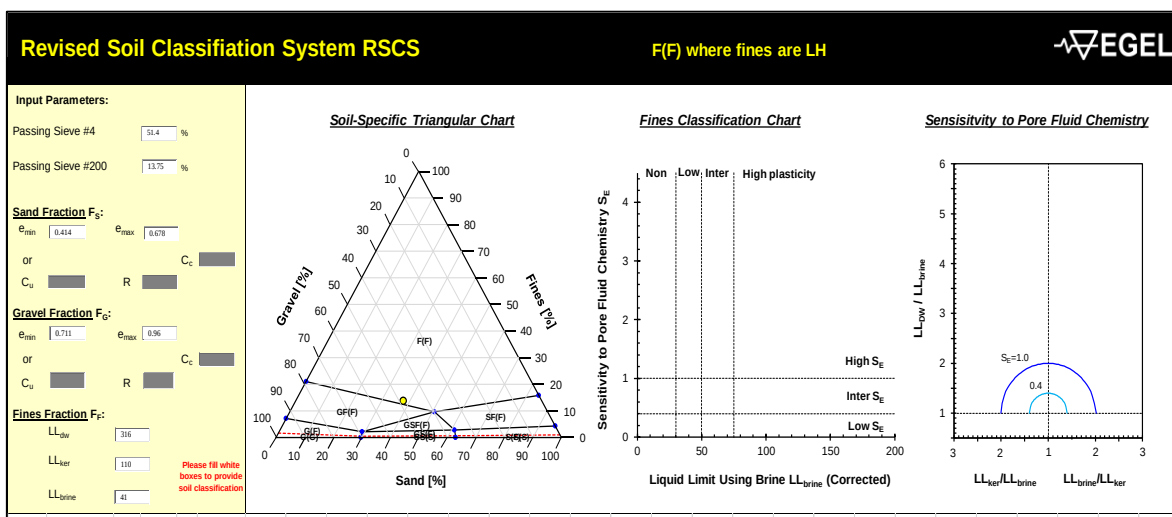


Figure 3.19 Revised soil classification system (RSCS) of (11_B Mix 3)

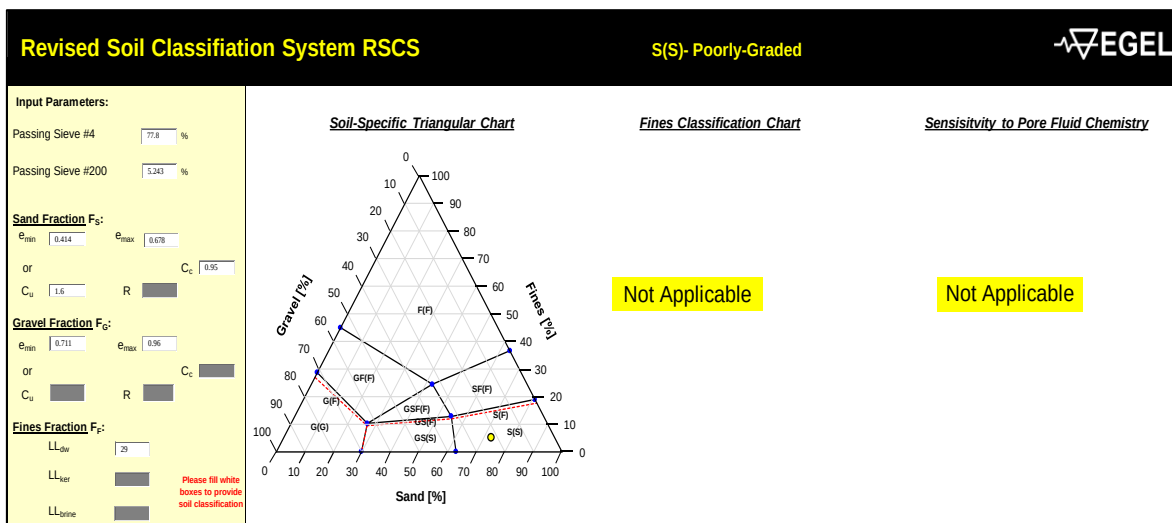


Figure 3.20 Revised soil classification system (RSCS) of (12_F Kum Mix 0)

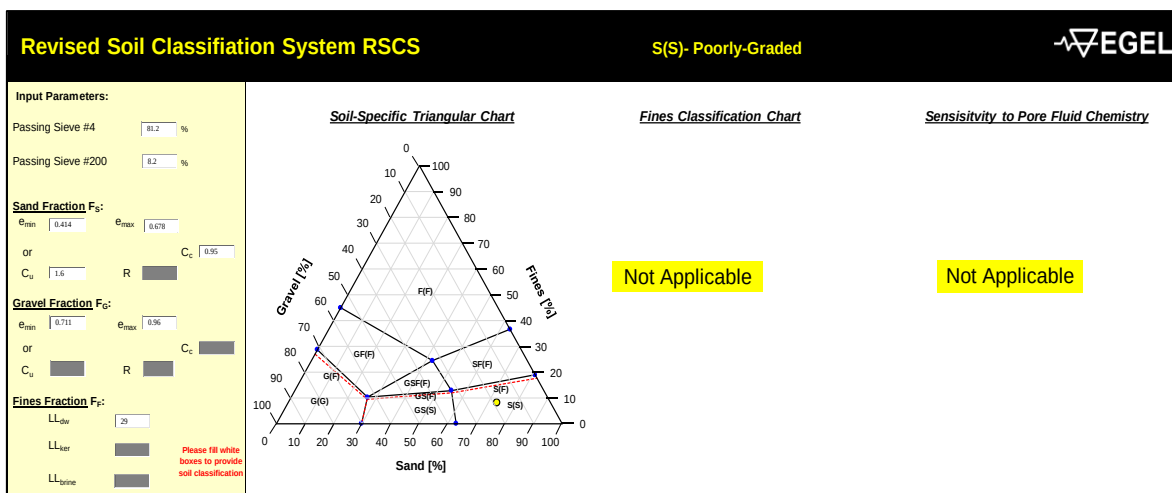


Figure 3.21 Revised soil classification system (RSCS) of (13-F Kum Mix 1).

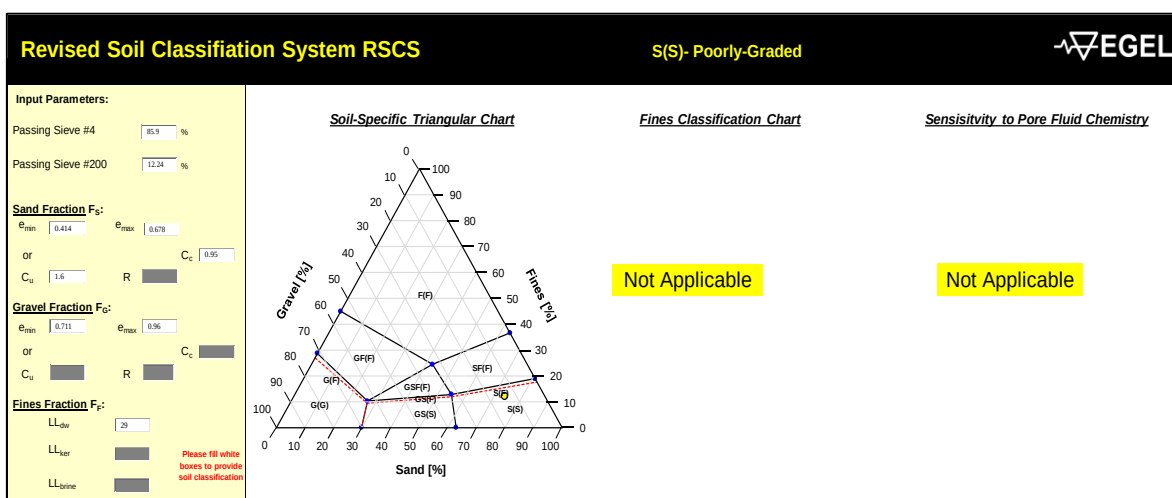


Figure 3.22 Revised soil classification system (RSCS) of (14_F Kum Mix 2)

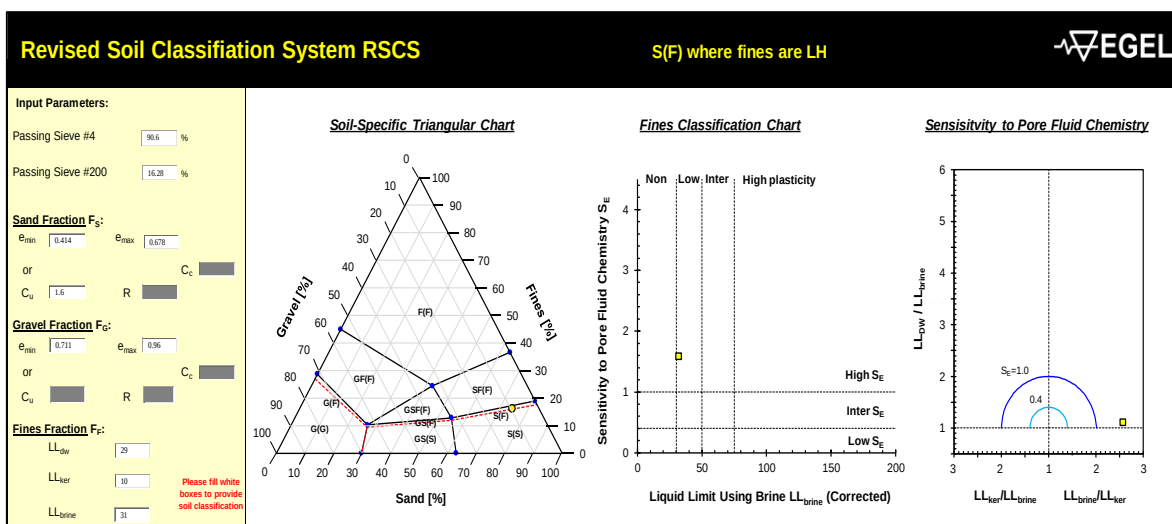


Figure 3.23 Revised soil classification system (RSCS) of (15_F Kum Mix 3)

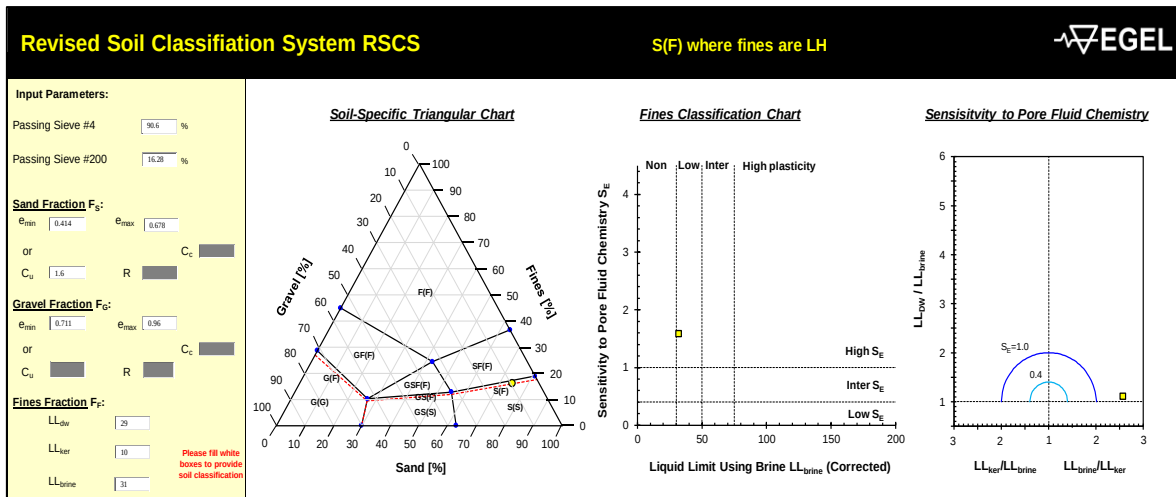


Figure 3.24 Revised soil classification system (RSCS) of (16_F Kum Mix 4)

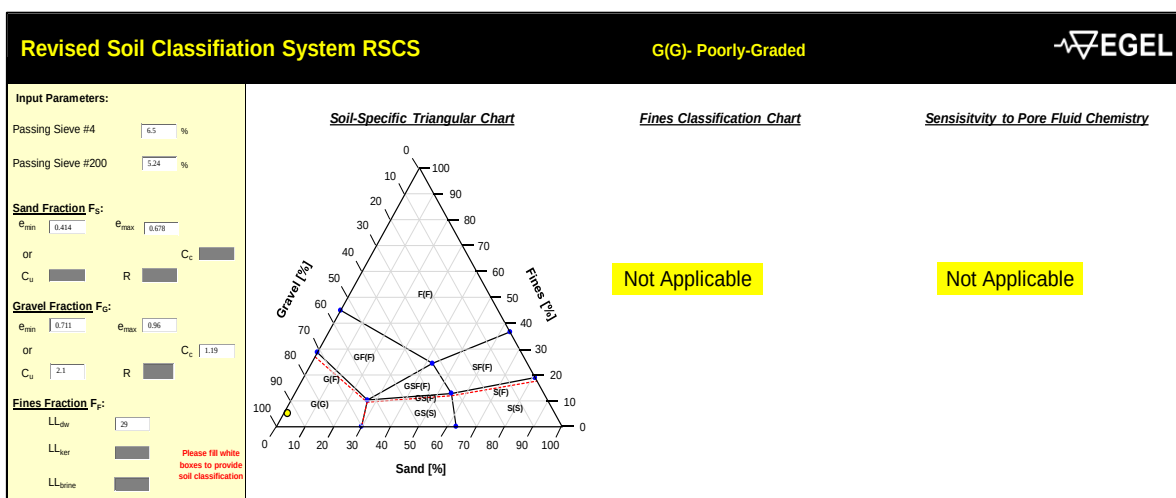


Figure 3.25 Revised soil classification system (RSCS) of (17_GF Mix 1)

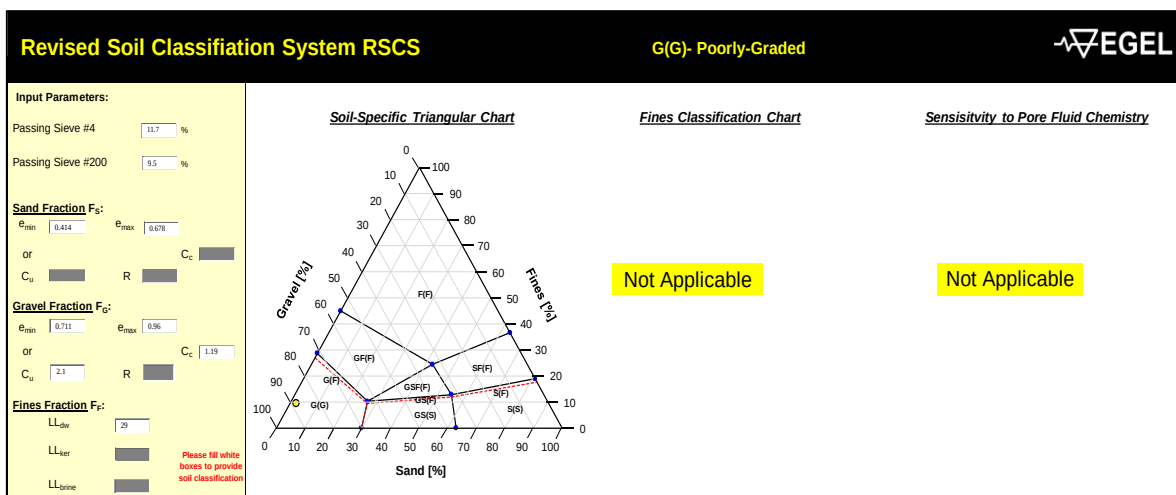


Figure 3.26 Revised soil classification system (RSCS) of (18_GF Mix 2)

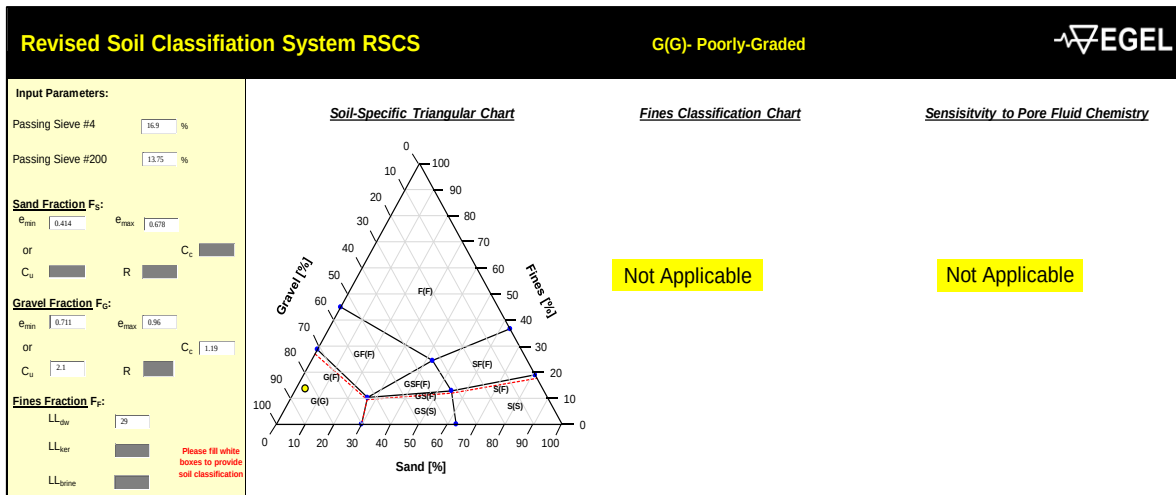


Figure 3.27 Revised soil classification system (RSCS) of (19_GF Mix 3)

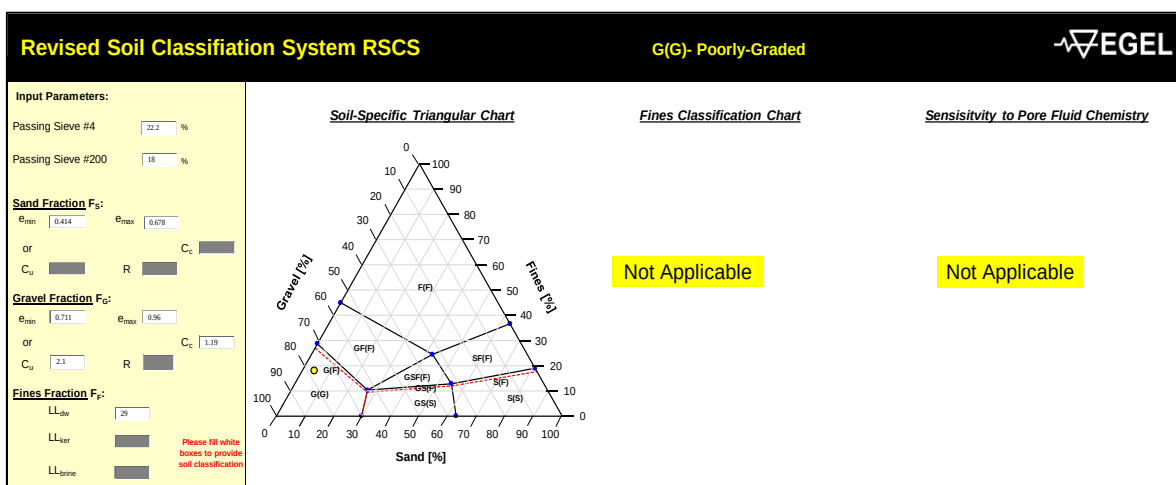


Figure 3.28 Revised soil classification system (RSCS) of (20_GF Mix 4)

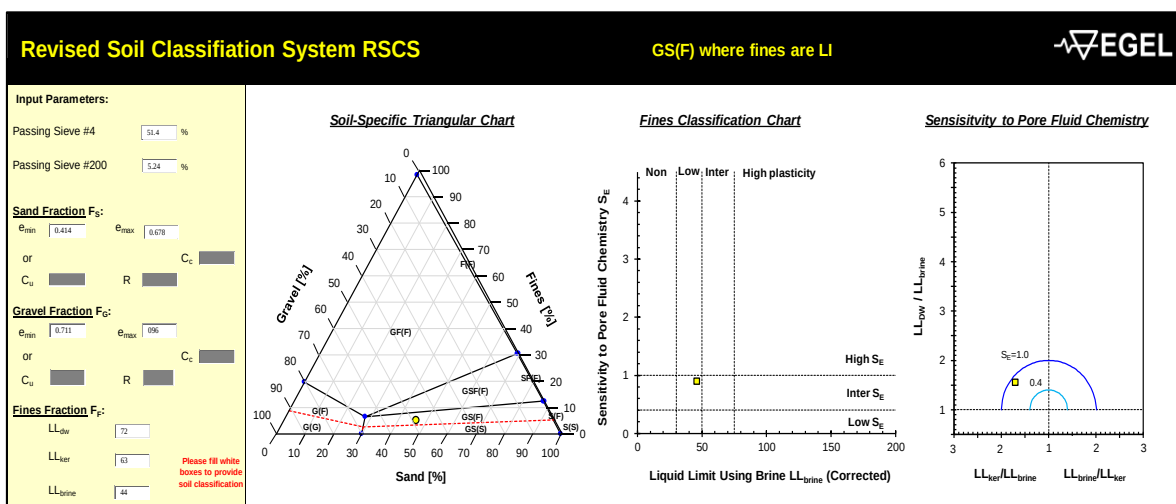


Figure 3.29 Revised soil classification system (RSCS) of (21_YK Mix 1)

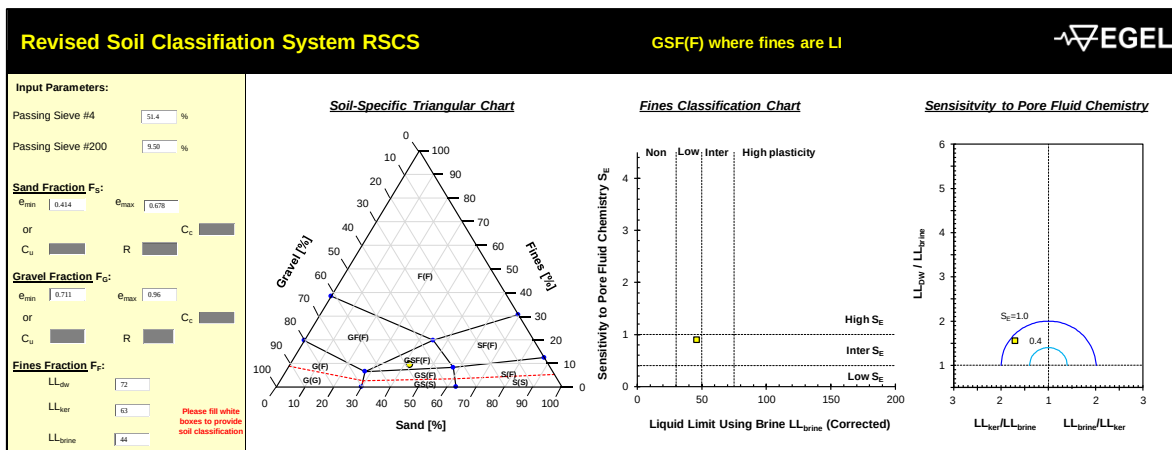


Figure 3.30 Revised soil classification system (RSCS) of (22_YK Mix 2)

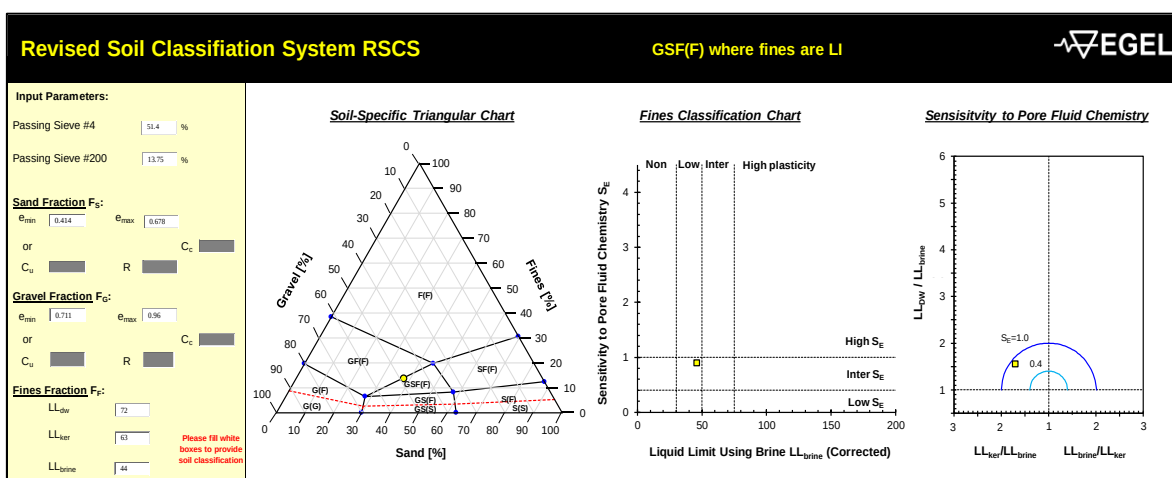


Figure 3.31 Revised soil classification system (RSCS) of (23_YK Mix 3)

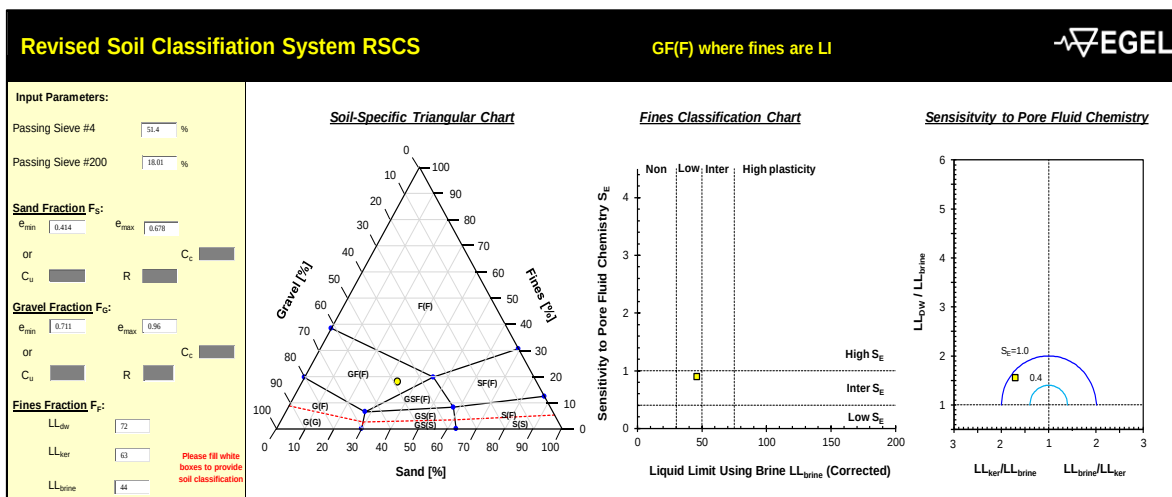


Figure 3.32 Revised soil classification system (RSCS) of (24_YK Mix 4)

In line with the methodology outlined in Chapter 2, the revised classification approach utilizes liquid limit (LL) values derived specifically from the material passing through the No. 200 sieve (0.75 mm opening). This approach allows for a precise assessment of the mixtures' properties and ensures consistent classification across different systems.

The soils were also classified based on the Revised Soil Classification System (RSCS). The new classification of soil employs liquid limits (LLs) assessed on the proportion passing the No. 200 sieve (75- μm opening size) by the fall cone test utilizing three pore fluids: deionized water, 2-M NaCl brine, and kerosene, to characterize soil electrical sensitivity. The fine fraction is categorized as no-plasticity, low-plasticity, intermediate-plasticity, or high-plasticity, with respect to low, intermediate, or high electrical sensitivity, according to these four characteristics. The revised soil classification for fine-grained soils rectifies significant shortcomings of Casagrande's plasticity chart utilized in the Unified Soil Classification System (USCS) for these materials. In this study to the sensitivity to pore-fluid chemistry classification of the five fines samples (Kaolinite, Bentonite, Dark Filler, Filler, and YK) were calculated on the fraction passing the No.200 sieve.

The Fall Cone test was conducted using three different pore fluids, Distilled water, Brine, and kerosene to be able to classify the fines (Figure 3.33).



Figure 3.33 (a) Fall cone test equipment. (b) Tested soil

3.2 Methodology: Routine Tests

3.2.1 Index Tests

A soil's reaction to variables like water and temperature variations can be greatly influenced by the observable physical characteristics, which are known as soil index properties. The consistency, particle size, and density of the soil are all described by the soil index parameters. Index tests conducted include specific gravity, particle size analysis (sieve and hydrometer), and Atterberg limits (Casagrande, and Fall Cone Tests).

Particle size assessments were conducted as follows. ASTM D422-63 standard was followed to analyze fine-grained materials with particle size distribution lower than 0.075 mm. The hydrometer test was conducted to determine the particle size analysis of aggregate materials less than 0.075 mm. The particle size distribution and % passing 0.075 mm for aggregate materials were determined by adhering to the standards ASTM C117-04 and ASTM C136-06. The sample size for each material was about 50 grams, determined according to the specifications outlined in ASTM D422-63. This action was undertaken in order to conserve the sample for subsequent testing.

Laboratory procedures for performing Atterberg limit tests have been done. These limits include liquid limit (LL) and plastic limit (PL) tests used to classify the fine-grained portion of the soil. The practical application of Atterberg limits and geotechnical engineering includes soil description quantitative, soil classification, and correlations to engineering properties such as shear strength. The Atterberg limits are index tests and have been designed to give an idea or indicate how a soil will act under certain conditions.

To ascertain the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the soil, Atterberg limit tests were conducted in compliance with ASTM D4318-05 (see (a)(b)

Figure 3.33). For these tests, both the Casagrande device and Fall Cone test apparatus were used. Soil classifications were determined in accordance with the American Association of State Highway and Transportation Officials (AASHTO) and the Unified Soil 55 categorization system (USCS). The AASHTO classification was determined using ASTM D3282-93, while the USCS classification was determined using ASTM D2487-06.

3.2.2 Specific Gravity Test

The specific gravity of the materials in the range of “12-19” mm and “5-12” mm was measured in KGM using the ASTM D854 Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer [43]. The specific gravity of the sand fractions, “0-5” mm washed, “0-5” mm unwashed, Filler, Kaolinite, and Bentonite were measured in AYBU lab using the ASTM D854 – 10 [43].

The specific gravity test is related to the density of solids. The specific gravity tests were conducted in the AYBU soils lab for the following materials: the “0-5 mm washed”, the “0-

5 mm” (unwashed), Filler and Kaolinite. The specific gravity test for Bentonite was performed in the KGM labs.

In order to obtain reliable results it is important to remove all trapped air bubbles in the soil-liquid mixture. Hence, in determining the specific gravity of Kaolinite clay both a hot plate and vacuum pump were used (see Figure 3.34). The extra measure of heating the soil was not necessary in the case of Filler material. Sample sizes used for the 0-5 size fraction material were in the range of about 75 grams per test whereas for Filler, Kaolinite, and Bentonite this value was about 50 grams based on ASTM D584-10[43].

The ASTM D584-10 Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer [43] general procedure was followed with special attention given to vacuuming the soil-water mixture in order to remove trapped air. Vacuuming was conducted in three different stages with each vacuum period lasting for at least 30 minutes: Stage one, sample and 1/3 of pycnometer filled with water, Stage two, sample and 2/3 of the pycnometer filled with water, Stage three, sample and pycnometer filled to water mark on the neck.



Figure 3.34 Tested material in the pycnometer

Once the three stages of vacuuming are complete, the weight of the pycnometer, water and sample (i.e. “ W_{p+w+s} ”) is recorded. The flask of water only was also vacuumed before weighing (W_{p+w}) by applying the following formula the specific gravity (G_s) result is obtained for the testing temperature (T_1):

$$G_{s(at\ T_1^{\circ}C)} = \frac{W_s}{W_{p+w} + W_s - W_{p+w+s}} \quad [3-1]$$

Correction for the testing temperature (T_1) is made as followed to 20 °C as the following formula [3-2]. The test is repeated three times and the average is calculated. The allowable difference between test values should be less than 1.5 according to ASTM D854 – 10[43].

$$G_{s \text{ at } 20} = G_{s \text{ (at } T_1 \text{ °C)}} * A \quad [3-2]$$

3.2.3 Maximum and Minimum Void Ratio Determination

To determine the Maximum & Minimum void ratios (e_{max} & e_{min}) a Relative Density test has been conducted for the granular material: "12-19" mm, "12-5" mm, and "0-5 mm. The test was carried out using a vibration table by following the guidelines outlined in ASTM D 4254 – 00 Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table [44]. As a main part of the classification that is based on RSCS Maximum & Minimum void ratios are needed to classify the soil.

To determine the maximum void ratio, the test begins with loose soil being poured into a mold with a volume of 3254.21 cm^3 using a funnel. Leveling the sample has been done prior to weighing it as shown in

Figure 3.35. The e-max is calculated by weighing the loose soil following mold filling as shown in the following formula:

$$e_{max} = \frac{W_{mold+loose \text{ soil}} - W_{solid}}{V_{solid}} \quad [3-3]$$

Alternatively, the following formula was also used to determine the e max:

$$e_{max} = \frac{\rho_w - G_{soil}}{\rho_{dmin}} - 1 \quad [3-4]$$

Where ρ_w is density of water, G_{soil} is specific gravity of soil and ρ_{dmin} is



Figure 3.35 Testing granular material at the minimum density

The test for determining minimum void ratio proceeds as follows. The collar, is placed on and additional material ia added. A filter paper is then placed and a 2 lb surcharge weight is placed on top. The vibration table is used to shake the sample for 8 minutes at 60 Hz as shown in

Figure 3.36. Applying the same approach to the e-max equation, first, determine the maximum density, and then determine the value of e-min, as indicated by the following formula:

$$e_{min} = \frac{P_w - G_{soil}}{P_{dmax}} - 1 \quad [3-5]$$



Figure 3.36 Test procedure for testing granular material at the maximum density with the surcharge weight

Table 3.18 shows to the tests that been done to the samples in this study with the locations and what ASTMs followed in each test.

Table 3.18 The location of the tested that done on the samples the ASTMs

Tests	Lab test	ASTMs followed
Sieve Analysis Test	KGM & *AYBU Lab.	ASTM D6913-04 [45]
Hydrometer Test	KGM & AUBU Lab.	ASTM D7928-21 [46]
Fall Cone Test (Atterberg limits)	KGM	ASTM D5778 – 20 [47]
Casagrande Test	KGM	ASTM D4318-17 [48]
Maximum & Minimum void ratio Test	AYBU Lab.	ASTM D4254-00 [44]
Specific gravity Test	KGM & AYBU Lab.	ASTM D854 [43]
Proctor Compaction Test	**KGM	ASTM D698-12
CBR Test	KGM	ASTM D1883-21 [49]
* AYBU: Ankar Yıldırım Beyazıt University Lab.		
**KGM: Karayolları Genel Müdürlüğü ARGE Toprak ve Zemin Stabilizasyon		

3.2.4 Compaction Tests

Standard Proctor compaction test was conducted by following the guidelines outlined in ASTM D698-07. Soil is compacted at varying moisture contents to establish the dry density versus moisture content relationship. The maximum dry unit weight and optimum moisture content are then determined from the plot. The maximum dry unit weight obtained from this test can be used to determine the relative compaction of soils in the field.

The granular materials were analyzed for their index density properties using a vibration table, following the guidelines provided by ASTM D4253-00 and ASTM D4254-00. The samples were subjected to moisture conditioning in order to achieve certain moisture levels and then allowed to mellow for a duration of 24 hours. The soil was compacted using a mechanical Proctor setup, employing a typical Proctor hammer weighing 250 g. Each layer of the soil was subjected to 42 blows to achieve densification. The material was compacted in 5 layers, with each layer intended to have a thickness of approximately 1.2 inches.

When compaction is completed the collar is removed. The soil surface is trimmed with a straight edge without applying any pressure to the sample. Place the acrylic top on the sample such that the sample's weight, including the membrane, disks, and rings.

3.2.5 CBR Test

The California bearing ratio test is a penetration assessment method that evaluates the suitability of a material as a foundation layer for highways. The test was conducted following the ASTM D1883-07 [49]. Using a standard area plunger, the CBR test measures the pressure needed to pierce a sample of soil. Test samples prepared at the same moisture content the frost heave and thaw weakening tests.

For every mixture, two CBR samples were prepared before the frost heave and thaw weakening test. One of these samples tested immediately while the other was soaked for 3 days before testing. The four samples that were tested for frost heave and thaw weakening were also tested in the CBR device after dissabbling as shown in Figure 3.37.

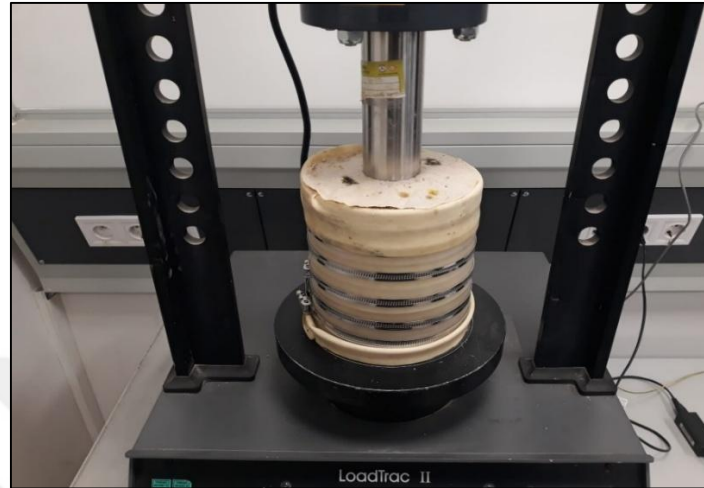


Figure 3.37 California bearing ratio (CBR) test for tested material after sample

3.3 Methodology: Frost Susceptibility Test

Frost Susceptibility tests were conducted using the step-freeze test method described in ASTM D 5918. The test setup is an open-system where sample have access to a water supply during two designed freeze thaw cycles. Details of the samples preparation and testing are described in this section.

3.3.1 Equipment

A specially designed freeze-thaw apparatus has been constructed for this study. Figure 3.38 shows the device and equipment Figure 3.39 shows equipment parts individually.

The new freeze-thaw testing unit consists of the following parts:

- 1- Freeze-thaw cabin and frame(4 Marriotte bottles, two constant temperature baths, 4 hollow heat transfer top cylinder, 4 hollow heat transfer bottom cylinder, 4 bottom caps with water connection and perous Stones, four clamp stands for lazer sensors).
- 2- Data acquisition system and sensors: 32 thermistors, 4 lazer displacement sensors, 4 load cells.
- 3- Sample preparation equipment and molds.
- 4- Four Sample molds (rubber membrane, 8x4 acryllic rings, insulation material).

Insulated pipes for circulating ethyl alcohol

The cabin is essentially a refrigerator which keep the ambient temperature between 3°C and 5°C. The constant temperature baths use ethyl alcohol to circulate cold water (0, -3 or -12) to the top cap of the sample and warm water (i.e. 0°C or 12°C) to the bottom of the sample. The marriotte bottles are a source of water supply (which is at a constant pressure) to each sample.

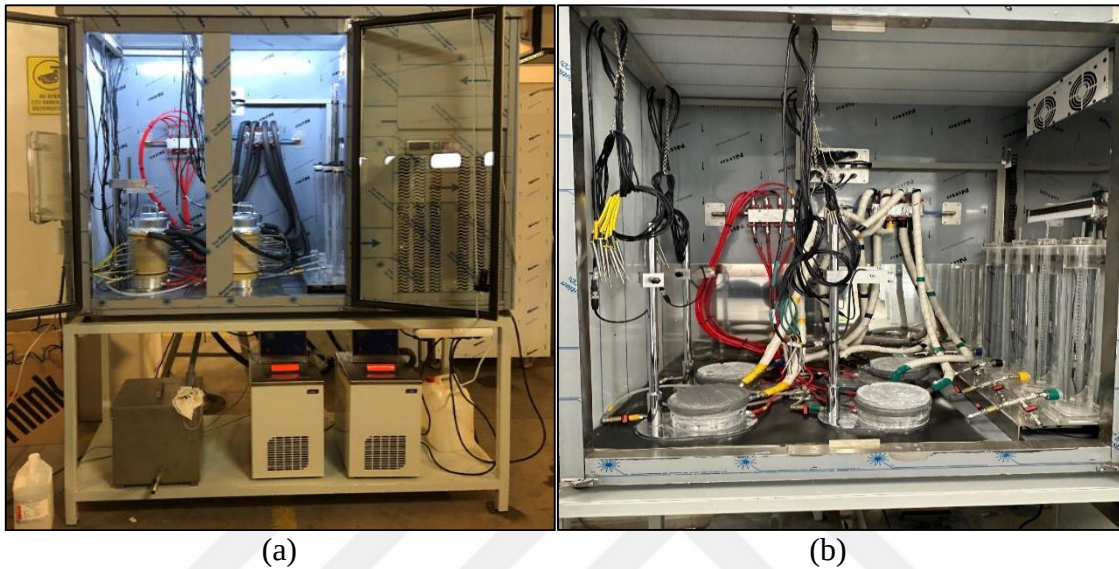


Figure 3.38 Cabine frame (a) Front view of freeze–thaw cabin and frame showing samples and constant temperature water baths (b) Inside view of cabin and equipment lay out

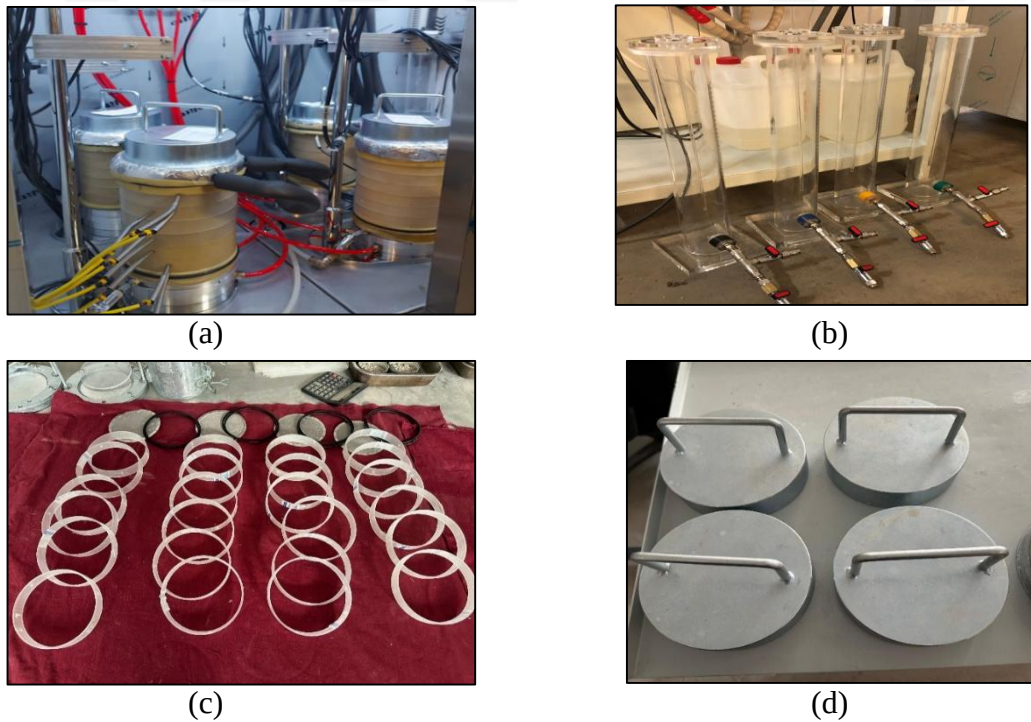
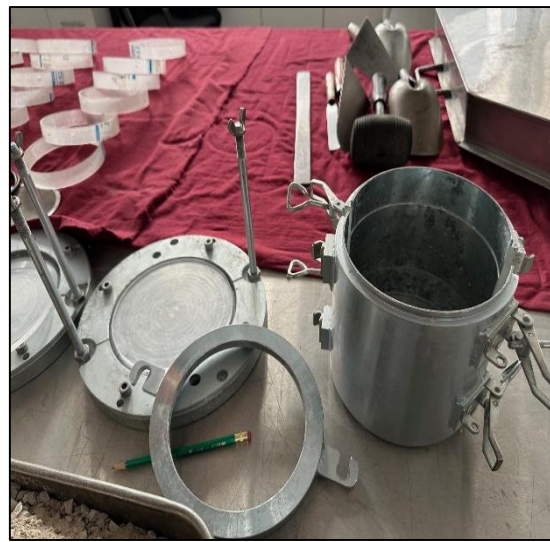


Figure 3.39 (a) Sample setup showing thermistors (b) marriotte cylinders (c) 8x4 acrylic rings (d) surcharge weights



(e)



(f)



(g)



(h)



(i)



(j)

Figure 3 39 (continued) (e) sample bottom caps (f) compaction mold (g) membranes (h) insulation jackets (i) & (j) data acquisition unit

3.3.2 Sample Preparation:

All mixtures are prepared at a moisture content equal to their respective optimum water content. Cohesive materials require approximately 7000 g of soil per sample, whereas noncohesive materials require approximately 6000 g. The moisture-conditioned soils are set aside over night to equilibrate. The moisture content is checked before compaction the next day to confirm accuracy and make any required adjustments.

The samples are prepared using specially designed compaction molds that can accommodate inside it a latex membrane and eight acrylic rings. A motorized compactor compacts the material in 5 layers using 42 strokes per layer. This is equivalent to the Proctor energy standard. The thickness of each layer is around 1.2 inches. When the compaction is completed the collar is removed and the sample surface is trimmed. Trimming the sample was completed by removing excess material from the surface without applying vertical force to the sample. A detailed procedure for sample preparation and saturation is provided in Appendix D. The samples were saturated inside the freezing cabin.

The prepared sample is arranged in the freezing cabin as shown in Figure 3.38 it is placed on the bottom heat exchange plate in the Freeze-Thaw cabinet. The setup of each sample includes eight thermocouples except at the top and bottom of samples where they are spaced 25.29 mm apart (from the 2nd-7th thermocouple, 12.65 mm 1st & 2nd thermocouple and 7th and the 8th thermocouple). Each sample also has a surcharge load of 5510.6 (grams), a laser sensor for monitoring heave, and an insulating jacket to preserve 1-D freezing conditions. The bottom plate of each sample is connected to a Mariotte bottle (to simulate the presence of a local groundwater source) which sits on a load transducer measuring weight changes. This bottom plate overlies a heat exchanger plate connected to a constant temperature bath (i.e. warm plate). The top of each sample has a temperature exchange plate attached to a constant temperature bath (i.e. cold plate) to mimic top-down freezing conditions.

3.3.3 Testing Procedures

Once the samples have been set up in the cabin, they are soaked with water from the Mariotte cylinder. As in ASTM D 5918 [22], the sample is put through two freeze-thaw cycles. The first day is for temperature equilization to 3°C. In the second day and fourth day the cold plate is cooled to -3°C for eight hours and then to -12°C for sixteen hours. On the third day, between the two freezing cycles, the sample is thawed with the cold plate at 12°C

for 16 hours and then at 3 C for 8 hours while the warm plate remains at 3°C for 24 hours. Every five minutes, the data acquisition unit takes measurements of the Mariotte bottle weights, the displacement transducers, and temperature sensors. The freeze-thaw cycle program continues for 5 days. Table 3.19 shows the ASTM D5918 temperature program followed for the upper and lower heat exchanger plates in the circulation baths.

Table 3.19 Boundary Temperature Conditions by ASTM D5918-13

Day	Elapsed Time	Top Plate (cold) Temperature	Bottom Plate (warm) Temperature	Comments
	Hours	C	C	
1	0-24	3	3	24-h conditioning
2	24-32	-3	3	First 8-h freeze
	32-48	-12	0	Freeze to bottom
3	48-64	12	3	First thaw
	64-72	3	3	
4	72-80	-3	3	Second 8-h freeze
	80-96	-12	0	Freeze to bottom
5	96-112	12	3	Second thaw
	112 to 120	3	3	

At the end of the 5-day testing period the samples were disassembled and tested for CBR value. Metal rings were around each acrylic ring to support them during the CBR test. The samples were then removed from the acrylic rings and latex membrane and dried in an oven over night to determine their final water content. The water content of the top section, bottom section and average were determined. The entire sample was dried. The results are shown in the phase diagrams in the appendix A.

At the end of the 5-day test, the recorded sensor data was downloaded from the data acquisition unit using the testing software. The downloaded file was a CSV file. The test data was used to draw plots of temperature vs time, heave vs time, and water intake vs time in Excel.

CHAPTER 4

RESULTS

This chapter present the laboratory test results. The laboratory tests were performed on the mixtures presented in Table 3.16.

4.1 Compaction Test Results

Table 4.1 and Figure 4.1 to Figure 4.8 show the results of the Standard Proctor test for fines material, (0-5) mm. The compaction results data sheet presents the outcomes of the compaction tests conducted on the mixtures, including key parameters such as maximum dry density (MDD) and optimum moisture content (OMC).

Table 4.1 Compaction test results

Group No.	Mixture Name	Maximum Dry Unit Weight (g/cm ³)	Optimum Water Content (%)
Group-1	1_F Mixture 1	2.104	4.5
	2_F Mixture 2	2.102	4.9
	3_F Mixture 3	2.109	5.5
	4_F Mixture 4	2.131	5.7
Group-2	5_K Mixture 1	2.107	5
	6_K Mixture 2	2.111	5.5
	7_K Mixture 3	2.031	6.5
	8_K Mixture 4	1.979	7.8
Group-3	9_B Mixture 1	1.931	5
	10_B Mixture 2	1.941	7.4
	11_B Mixture 3	1.981	10
Group-4	12_F Kum Mixture 0	1.989	2.2
	13_F Kum Mixture 1	2.025	2.1
	14_F Kum Mixture 2	2.034	3.9
	15_F Kum Mixture 3	2.006	6.7
	16_F Kum Mixture 4	1.973	7.3
Group-5	17_GF Mixture 1	1.799	2.8
	18_GF Mixture 2	1.882	3
	19_GF Mixture 3	1.917	5
	20_GF Mixture 4	1.990	6
Group-6	21_YK Mixture 1	2.020	5
	22_YK Mixture 2	2.004	6
	23_YK Mixture 3	1.931	6.9
	24_YK Mixture 4	1.871	7.6

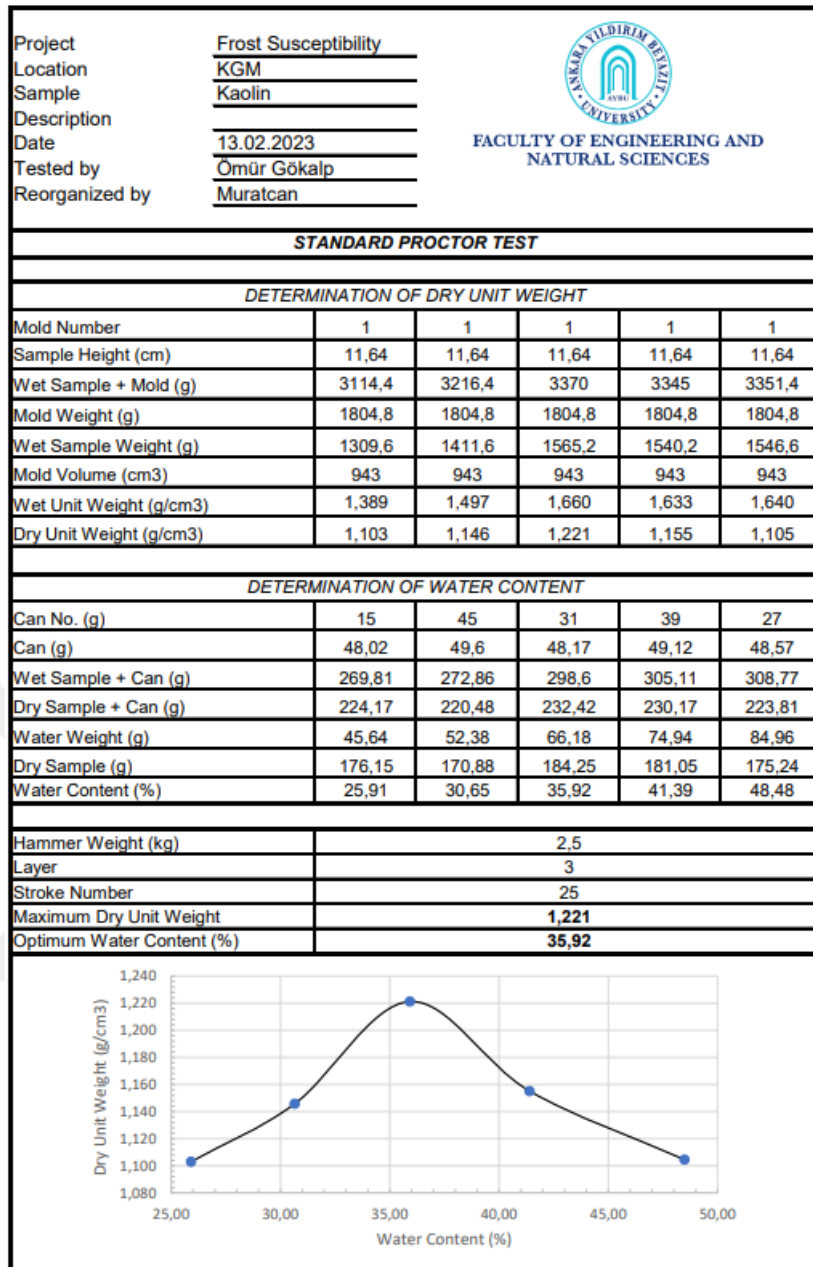


Figure 4.1 Standard proctor test for the “Kaolinite material”

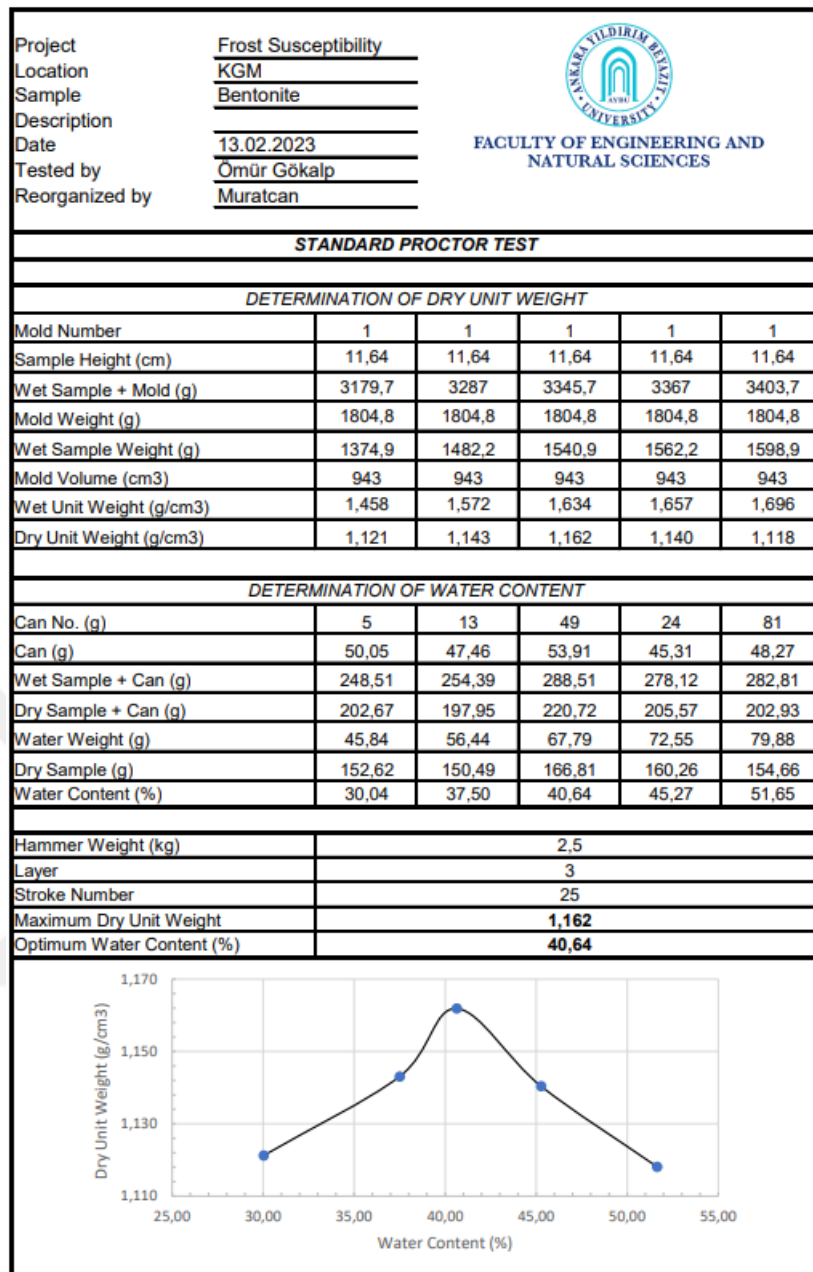


Figure 4.2 Standard proctor test for the “Bentonite material”

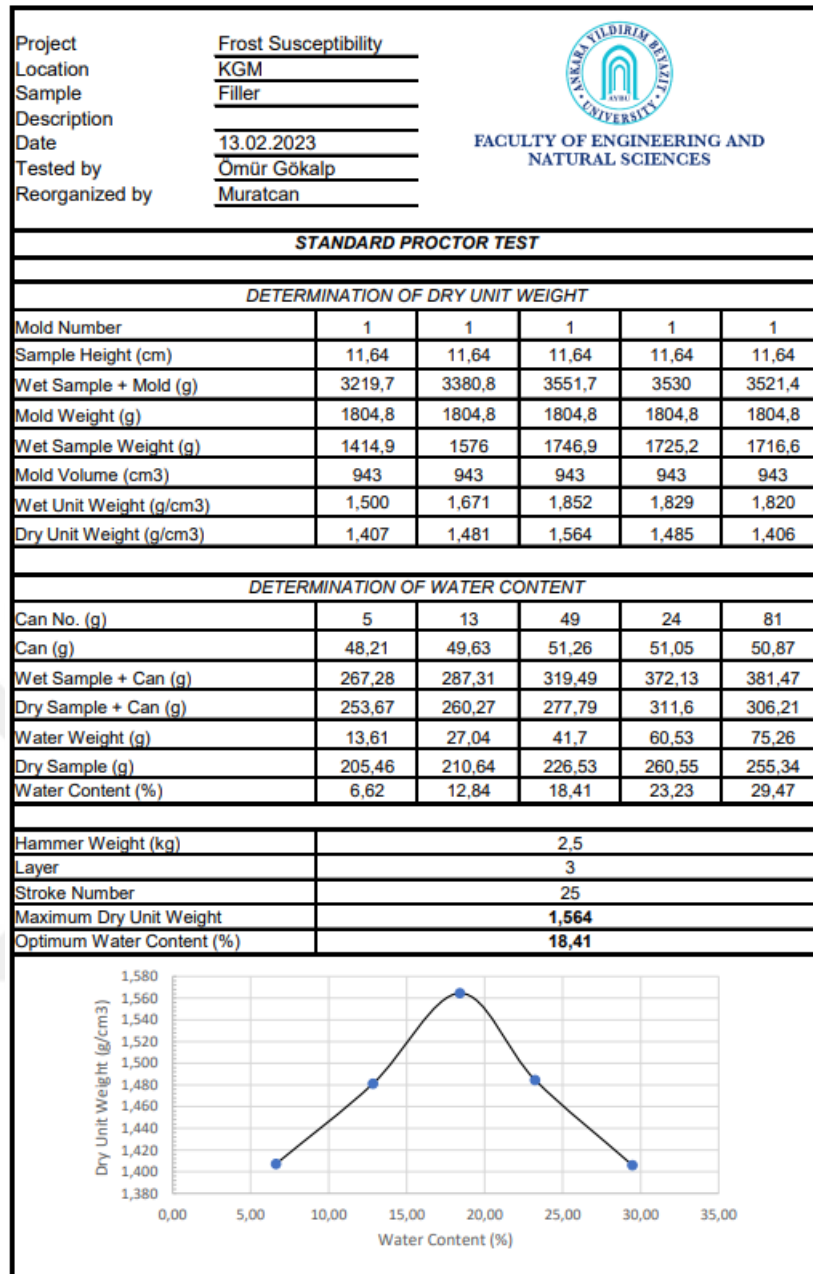


Figure 4.3 Standard proctor test for the “Filler material”

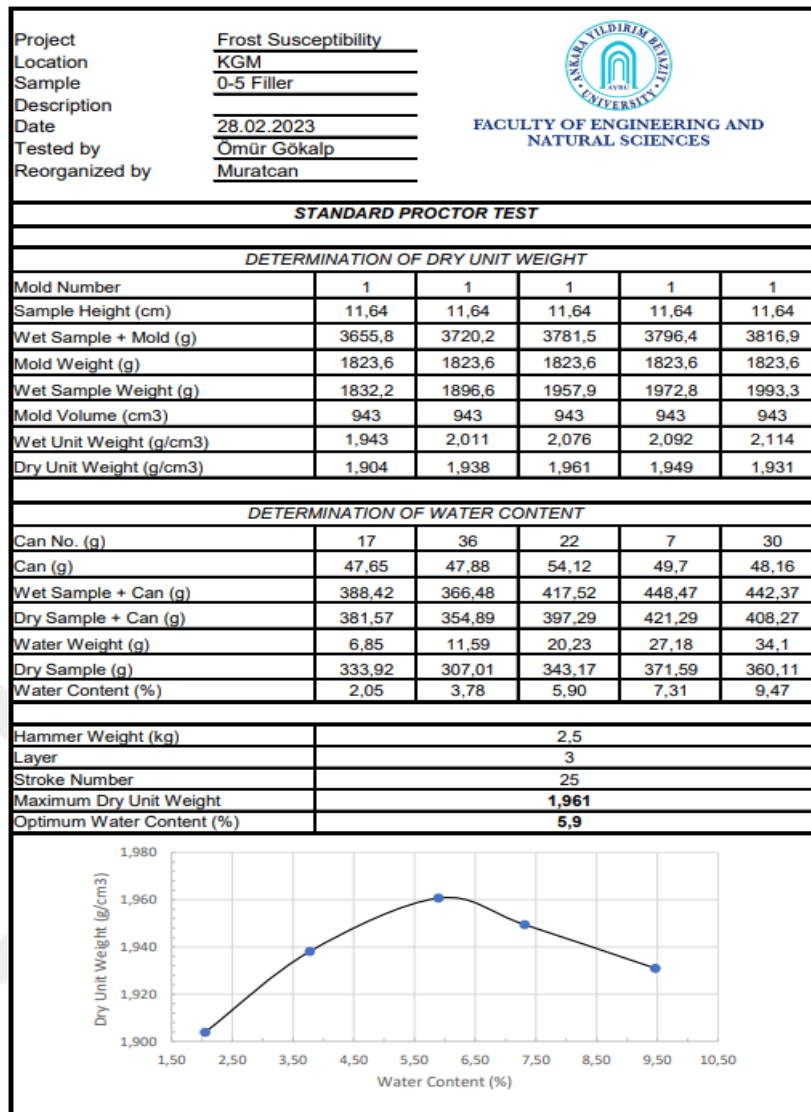


Figure 4.4 Standard proctor test for the “(0-5)mm Filler”

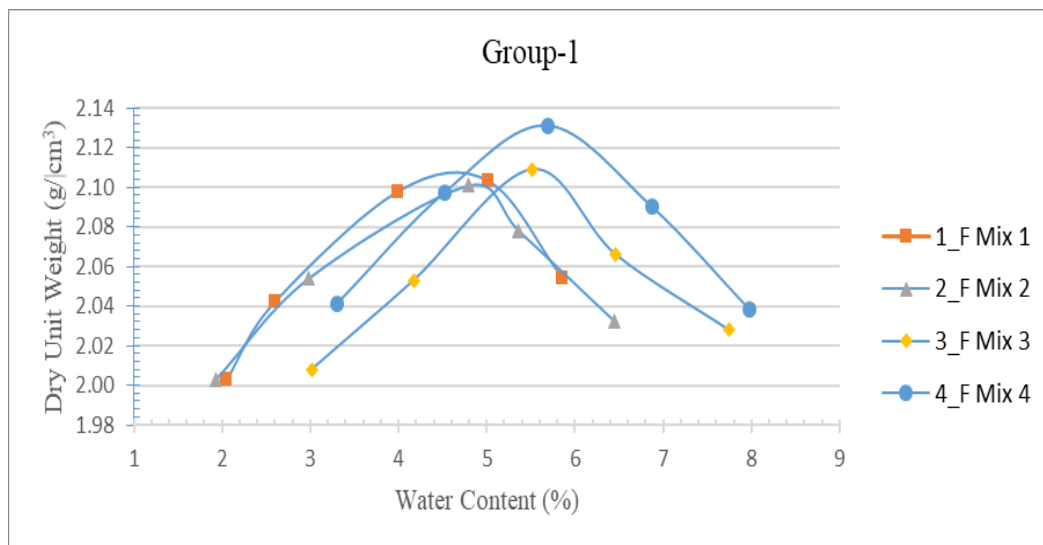


Figure 4.5 Proctor Standard test for Group-1

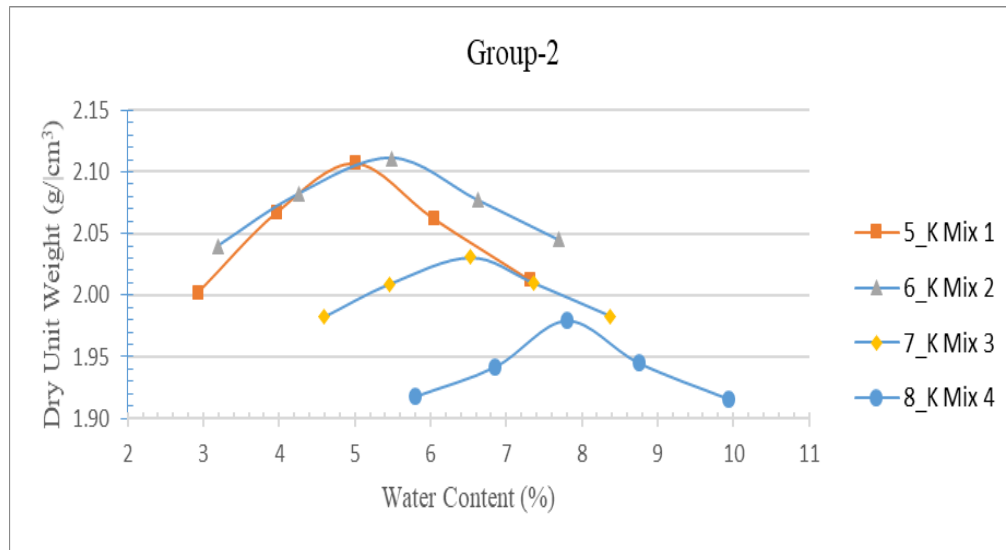


Figure 4.6 Proctor Standard test for Group-2

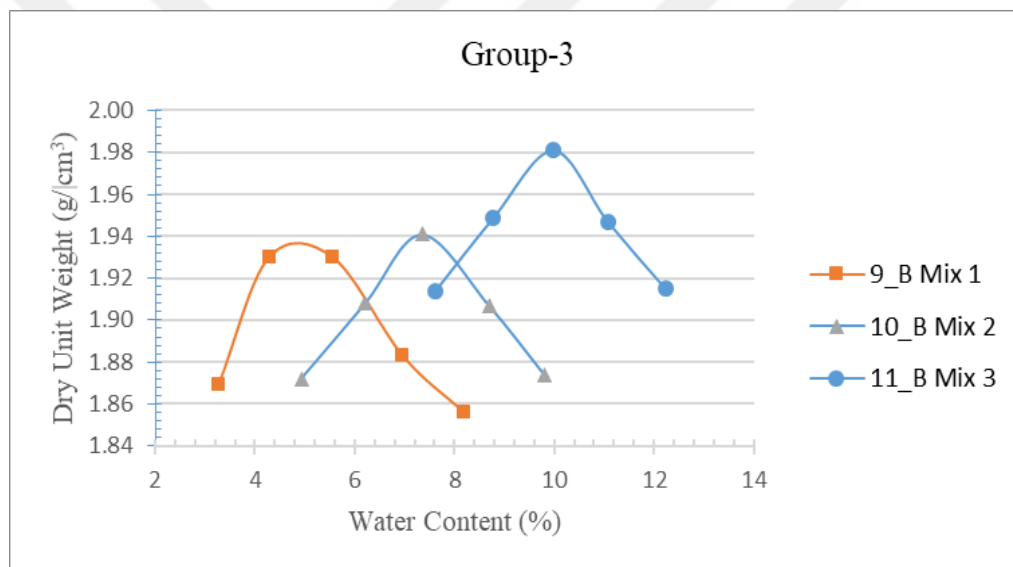


Figure 4.7 Proctor Standard test for Group-3

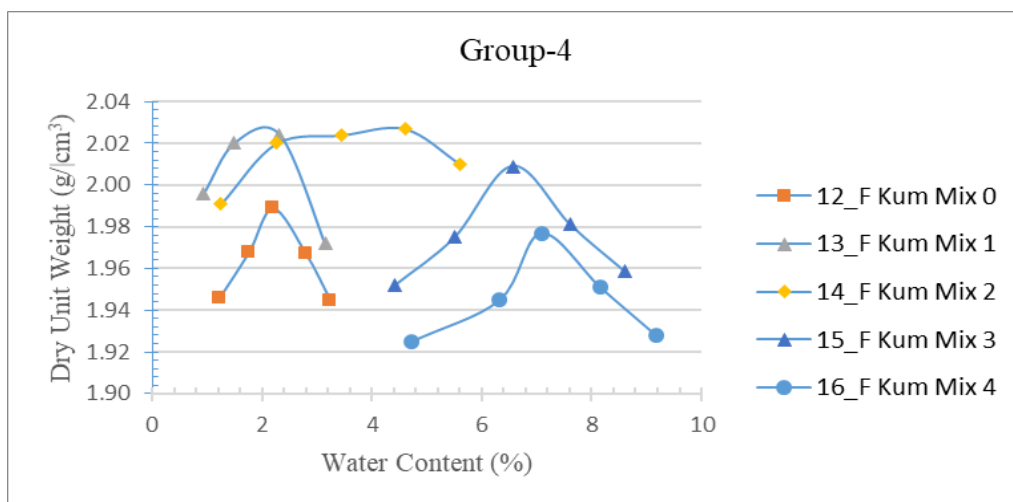


Figure 4.8 Proctor Standard test for Group-4

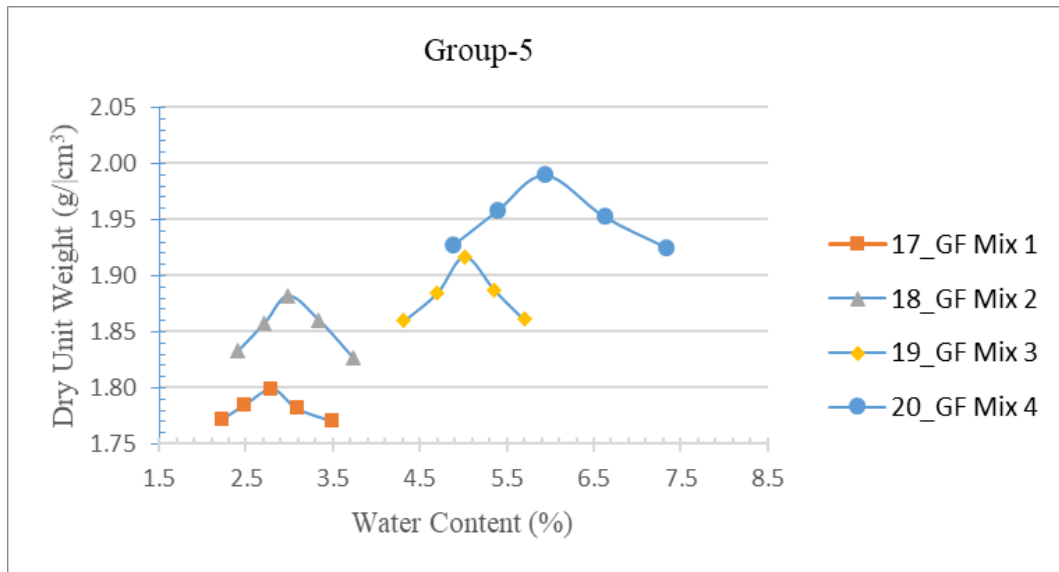


Figure 4.9 Proctor Standard test for Group-5

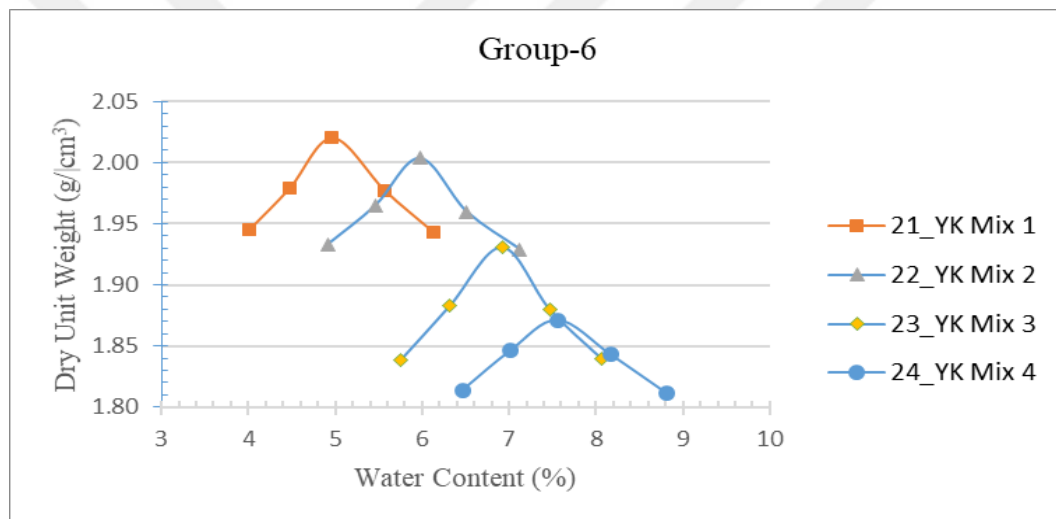


Figure 4.10 Proctor Standard test for Group-6

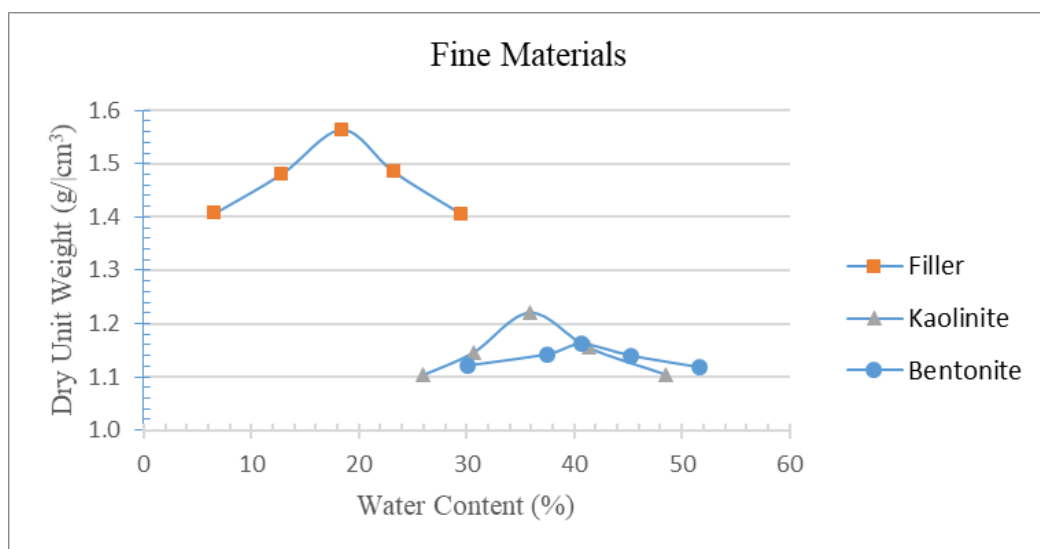


Figure 4.11 Proctor Standard test for Fine materials

4.2 CBR Test Results

For each mixture, two samples were prepared for conducting California Bearing Ratio (CBR) test prior the frost heave and thaw weakening tests. One of these samples was subjected to soaking, while the other remained in a dry condition. Furthermore, four additional samples from each mixture underwent CBR testing following their evaluation in the frost heave and thaw weakening tests (see Table 4.1).

Table 4.2 CBR results for the 26 tested mixtures

Mixtures No.	CBR: Post-freeze-thaw (%)	CBR: Dry (%)	CBR: Soaked (%)
1_F Mix 1	33/ 32/ 41/ 34	84	79
		92	77
2_F Mix 2	17/ 27/ 27/ 41	92	226
		105	149
3_F Mix 3	33/ 28 50/ 59	187	271
		170	285
4_F Mix 4	59/ 82/ 51/ 41	104	302
		105	
5_K Mix 1	39/ 36/ 36/ 39	82	76
6_K Mix 2	25/ 24/ 31/ 36	65	76
7_K Mix 3	6/ 12	61	
8_K Mix 4	19/ 15	**	**
8_K Mix 4	28/ 15/ 27/ 16	**	**
9_B Mix 1	16/ 14/ 13/ 18	31	37
10_B Mix 2	14/ 19/ 16/ 24	22	24
11_B Mix 3	13/ 13/ 11/ 19	14	15
12_F Kum Mix 0	40 34/ 39/ 45	84	111
13_F Kum Mix 1	38/ 41/ 31/ 23	62	60
14_F Kum Mix 2	32/ 47/ 36/ 21	64	89
15_F Kum Mix 3	54/ 58/ 31/21	109	175
16_F Kum Mix 4	12/ 27/ 22/ 30	73	115
17_GF Mix 1	31/ 20/ 29/ 20	59	52
18_GF Mix 2	25/ 28/ 29/ 26	63	66
19_GF Mix 3	34/ 34/ 37/ 28	51	78
20_GF Mix 4	29/ 19/ 44/24	43	178
21_YK Mix 1	26/ 25/ 27/ 26	53	60
22_YK Mix 2	20/ 17/ 20/ 14	34	33
23_YK Mix 3	9/ 6/ 6/ 9	26	22
24_YK Mix 4	4/ 4/ 4/ 3	21	9
*CBR for sample numbers 1/2/3/4			
** Missing data			

4.3 Phase Diagrams

Table 4.3 presents the index properties for each mixture, detailing key parameters such as water content, specific gravity, and other relevant physical properties. These metrics provide foundational information on the composition and behavior of the mixtures under various conditions. Additionally, the table includes the percentage of fine particles necessary to fill

all voids within each mixture, which is critical for understanding compaction and stability characteristics. This data collectively supports a comprehensive evaluation of the mixtures' properties, aiding in predicting performance and suitability for specific applications.

Table 4.3 Mixtures phase diagram

Mixtures No.	Sample No.	Initial water content (%)	Final water content (%)	Dry Density, (g/m ³)	Specific Gravity	Initial Void Ratio	S ₀ (%)	% Fines Req. to Fill Voids PFV
1_F Mix 1	1	3.73	4.74	2.080	2.7	0.298	33.76	28.8
	2	3.90	4.14	2.067		0.306	34.42	28.2
	3	4.06	4.70	2.049		0.318	34.85	27.3
	4	4.30	5.30	2.068		0.305	38	28.3
2_F Mix 2	1	5.24	7.52	2.049	2.703	0.319	44.38	43.8
	2	5.05	7.47	2.076		0.302	45.20	45.7
	3	5.36	7.08	2.096		0.290	50.01	47.1
	4	4.76	7.27	2.113		0.279	46.04	48.4
3_F Mix 3	1	6.29	7.76	2.081	2.707	0.301	56.65	59.7
	2	6.13	7.34	2.096		0.291	56.98	61.0
	3	5.8	7.24	0.156		0.256	61.42	66.6
	4	4.74	7.02	2.179		0.242	52.91	68.9
4_F Mix 4	1	5.41	8.64	2.108	2.711	0.286	51.27	73.5
	2	5.46	8.44	2.133		0.271	54.65	75.9
	3	5.72	8.55	2.131		0.272	56.96	75.7
	4	5.45	8.56	2.141		0.266	55.75	76.8
5_K Mix 1	1	4.26	6.54	2.272	2.696	0.186	61.69	53.6
	2	5.37	6.08	2.084		0.293	49.34	37.0
	3	5.13	6.36	2.125		0.269	51.41	39.8
	4	4.95	6.46	2.128		0.268	49.85	40.0
6_K Mix 2	1	6.33	7.13	2.098	2.693	0.283	60.16	61.1
	2	5.99	6.73	2.080		0.294	54.81	59.4
	3	5.85	7.80	2.067		0.302	52.08	58.1
	4	6.05	7.46	2.083		0.292	55.70	59.6
7_K Mix 3	1	7.47	9.88	2.004	2.689	0.342	58.76	69.6
	2	8.30	10.13	1.977		0.360	61.97	67.0
8_K Mix 4	3	7.88	9.17	2.008	2.686	0.337	62.8	84.2
	4	6.92	10.19	1.953		0.376	49.5	78.4
8_K Mix 4	1	7.21	9.2	2.039	2.686	0.317	61.11	87.59
	2	7.75	9.66	2.012		0.334	62.36	84.75
	3	8.30	9.32	2.016		0.332	67.2	85.07
	4	7.51	9.97	1.996		0.346	58.35	82.83
9_B Mix 1	1	5.58	9.83	1.904	2.704	0.42	35.94	142.4
	2	5.52	11.17	1.929		0.402	37.06	148.0
	3	5.06	13.11	1.909		0.416	32.91	143.6
	4	5.78	11.95	1.908		0.417	37.42	143.2
10_B Mix 2	1	7.54	9.91	1.985	2.707	0.364	56.12	265.4
	2	7.32	8.96	1.998		0.355	55.84	270.7
	3	7.32	10.26	1.942		0.394	50.31	249.3
	4	8.03	9.97	1.998		0.355	61.26	270.7

Mixtures No.	Sample No.	Initial water content (%)	Final water content (%)	Dry Density, (g/m ³)	Specific Gravity	Initial Void Ratio	S ₀ (%)	% Fines Req. to Fill Voids PFV
11_B Mix 3	1	9.59	11.54	1.965	2.709	0.379	68.56	340.3
	2	9.83	11.02	1.98		0.369	72.18	347.2
	3	10.29	11.21	1.952		0.388	71.85	334.5
	4	10.53	10.93	2.007		0.350	81.56	360.9
12_F Kum Mix 0	1	2.15	9.81	1.972	2.695	0.367	15.8	22.8
	2	2.49	10.13	1.950		0.382	17.6	22.1
	3	2.15	9.58	1.987		0.357	16.2	23.4
	4	2.20	10.07	2.002		0.346	17.1	24.0
13_F Kum Mix 1	1	2.67	9.29	1.957	2.697	0.379	19.0	32.2
	2	2.38	9.07	2.015		0.338	19.0	35.2
	3	2.65	9.19	1.976		0.365	19.6	33.2
	4	2.48	9.35	1.999		0.350	19.1	34.3
14_F Kum Mix 2	1	4.49	9.06	2.071	2.7	0.304	39.9	50.9
	2	4.41	9.08	2.050		0.317	37.6	49.4
	3	4.08	9.09	2.012		0.342	32.2	46.9
	4	4.06	9.33	2.015		0.340	32.2	47.1
15_F Kum Mix 3	1	5.97	8.77	2.087	2.703	0.295	54.6	62.1
	2	6.23	8.87	2.133		0.267	63.1	65.9
	3	5.84	9.55	2.104		0.285	55.4	63.4
	4	6.32	9.15	2.115		0.278	61.4	64.3
16_F Kum Mix 4	1	6.82	11.66	2.068	2.706	0.308	58.7	68.9
	2	6.68	11.09	2.069		0.308	60.0	69.0
	3	6.70	10.29	2.117		0.278	65.2	72.9
	4	6.23	10.45	2.105		0.286	59.6	71.8
17_GF Mix 1	1	2.91	4.43	1.799	2.712	0.508	15.5	17.3
	2	2.85	4.47	1.790		0.514	15.0	17.1
	3	2.72	4.35	1.801		0.506	14.6	17.3
	4	2.00	4.28	1.821		0.490	11.1	17.8
18_GF Mix 2	1	2.92	8.68	1.871	2.715	0.451	17.6	31.6
	2	2.35	8.86	1.856		0.461	13.8	31.0
	3	2.95	8.14	1.886		0.440	18.2	32.2
	4	3.54	7.58	1.813		0.498	19.3	29.2
19_GF Mix 3	1	4.23	9.88	1.911	2.717	0.421	27.28	44.07
	2	5.05	8.31	1.921		0.414	33.14	44.63
	3	4.60	9.64	1.916		0.418	29.89	44.31
	4	5.14	9.37	1.911		0.422	33.11	44.04
20_GF Mix 4	1	5.63	9.43	1.993	2.838	0.307	47.70	62.92
	2	5.45	10.13	1.988		0.312	45.57	62.43
	3	6.63	9.44	1.990		0.299	57.37	63.71
	4	6.12	9.93	1.968		0.318	49.87	61.47
21_YK Mix 1	1	5.060	8.22	2.038	2.7	0.325	42.06	24.87
	2	4.970	7.9	2.011		0.343	39.13	23.80
	3	4.930	7.69	2.025		0.333	39.95	24.36
	4	5.390	7.87	1.996		0.353	41.24	23.25
22_YK Mix 2	1	4.51	8.89	2.009	2.7	0.344	35.38	37.27
	2	5.95	9.14	1.954		0.382	42.04	34.58
	3	4.70	8.95	2.041		0.323	39.32	38.98
	4	6.64	9.39	1.962		0.376	47.63	34.96

Mixtures No.	Sample No.	Initial water content (%)	Final water content (%)	Dry Density, (g/m ³)	Specific Gravity	Initial Void Ratio	S _o (%)	% Fines Req. to Fill Voids PFV
23_YK Mix 3	1	7.07	11.54	1.935	2.7	0.396	48.25	43.54
	2	6.91	11.85	1.913		0.411	45.35	42.43
	3	6.65	11.53	1.945		0.388	46.27	44.09
	4	7.76	11.66	1.909		0.415	50.55	42.22
24_YK Mix 4	1	7.38	13.58	1.887	2.7	0.431	46.20	48.85
	2	7.02	14.4	1.854		0.457	41.50	47.16
	3	8.59	14.19	1.854		0.456	50.84	47.19
	4	8.35	13.96	1.875		0.440	51.23	48.25

4.4 Results: Freeze-Thaw Tests

Frost susceptibility tests were performed on all the mixtures presented in Table 3.16. A total of 24 tests on 96 samples were conducted. Details of these calculations and results are presented in sections 4.4.1 to 4.4.3. The results of freeze-thaw tests in different soil types are presented in this section. The main goal is to measure how heave behavior is affected by soil composition, moisture content, and freeze-thaw cycles. The heave rates and the segregation potential were calculated for each mixture. The equations that were used to determine the heave rates and segregation potential are displayed in the following sections and present the outcomes.

4.4.1 Heave Rates

Following the analysis of data obtained from the frost susceptibility program, three graphs have been created: a temperature graph, a heave graph, and a load cell graph (see Figure 4.12).

In order to calculate heave rates, temperature and distance (heave) data plots were compared and the period of time during which the first and second freezing cycles occur were indicated using vertical lines.

A line was fitted to the curve as shown in Figure 4.12 heave plot data for the time range when steady-state temperature conditions were reached. The slope of this line was determined by choosing any two points along the line or the intersection points (see Figure 4.13). The heave rates were evaluated for each freezing cycle (1st and 2nd) using the following formula

(for F Mixture Blue sample). An example of these plots is shown Figure 4.12 in. The plots for other samples are provided in Appendix C.

The heave rates were evaluated using the following formula:

$$\text{Heave Rate } \left(\frac{\text{mm}}{\text{day}} \right) = \frac{H_2 - H_1}{T_2 - T_1} * 24 \quad [4-1]$$

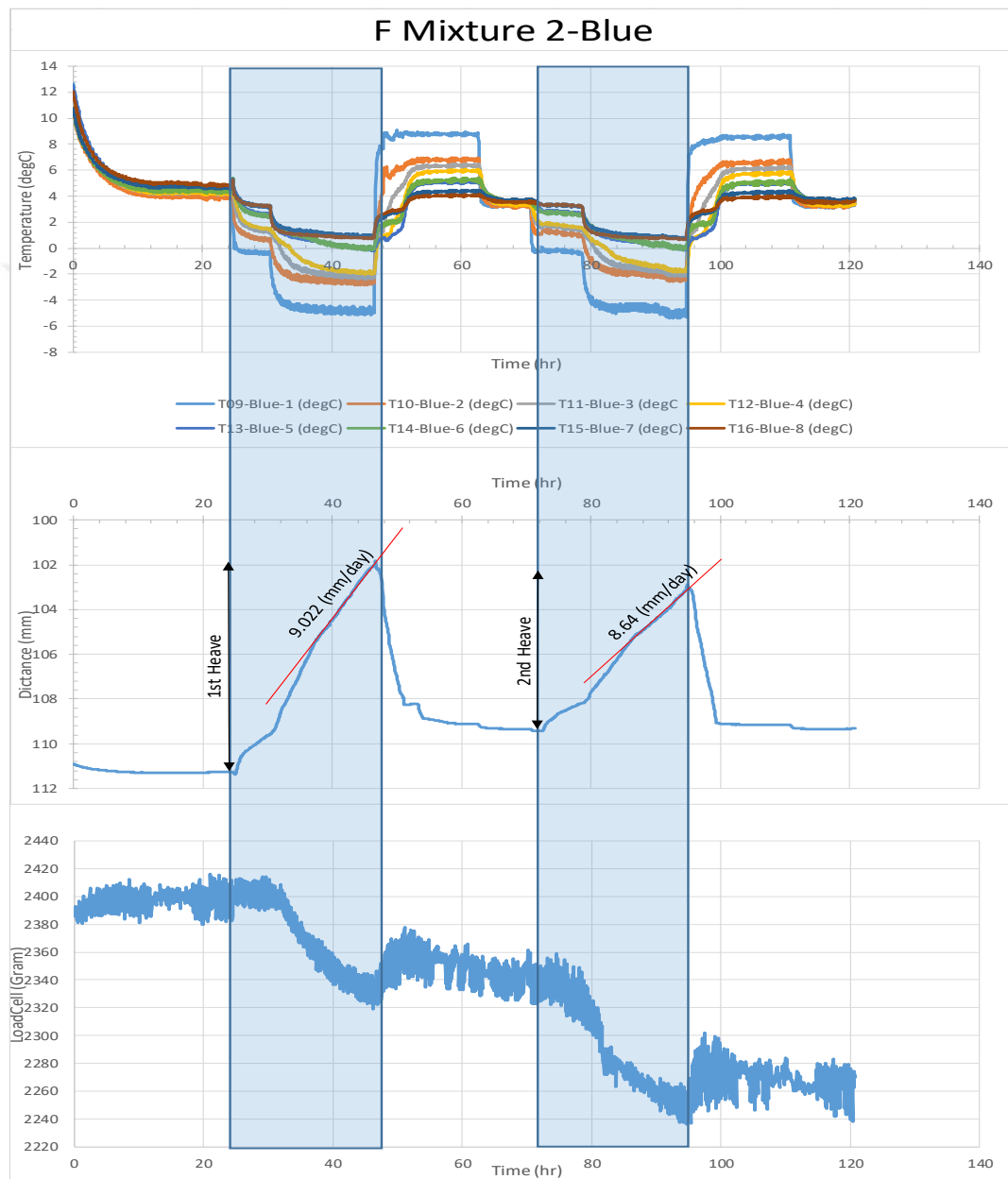


Figure 4.12 Calculated results of heave rate shown on the graphs of the analysis data

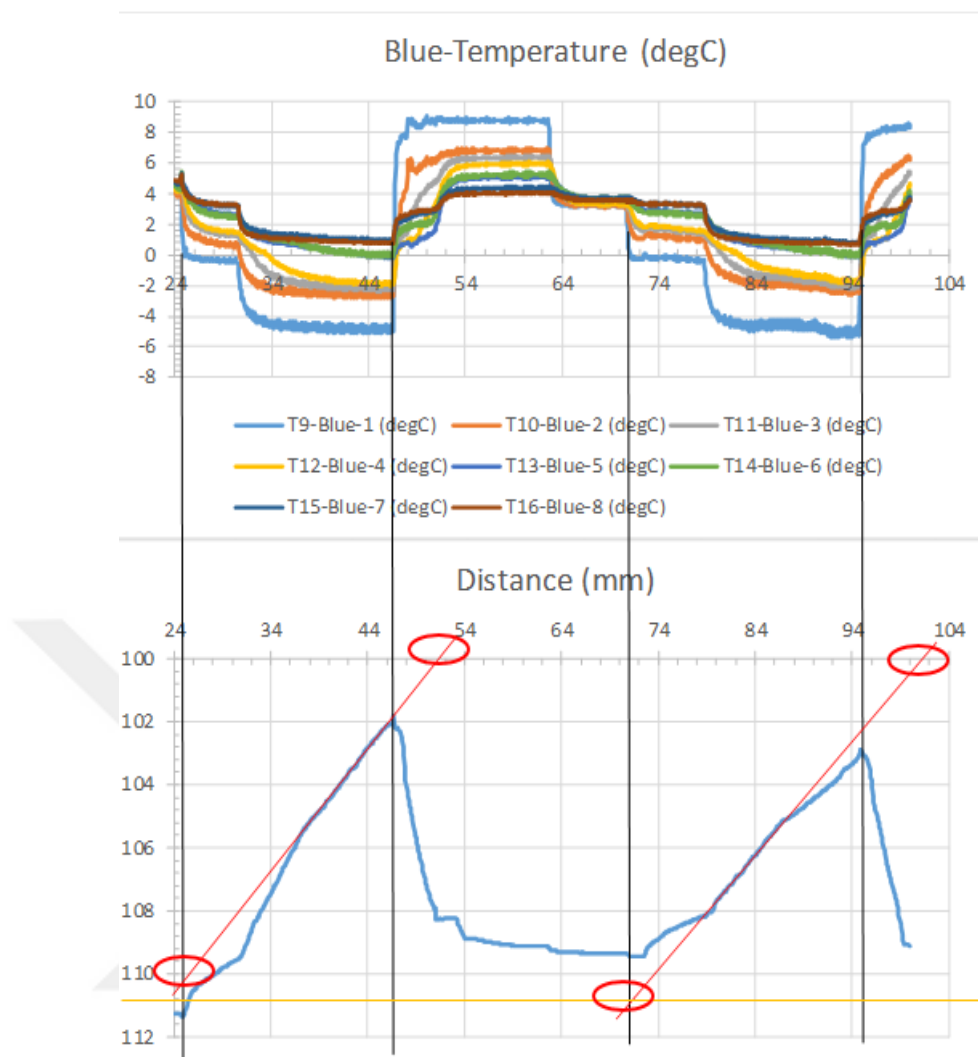


Figure 4.13 An example of “2_F Mix 2-blue sample” to the data analysis: temperature graph (from thermocouple readings) and distance graph (from leaser readings) to calculate the heave rate

An example of the heave rate estimates for "2_F Mixture 2-Blue Sample" can be found in the following Table 4.4.

Table 4.4 An example to the “2_F Mix 2-Blue sample” calculated result to the heave rate

1 st Freezing	Time (hr)	Heave (mm)	2 nd Freezing	Time (hr)	Heave (mm)
Point 1	24.8	110.15	Point 1	71	110.8
Point 2	51.8	100	Point 2	101	100
Heave Rate (mm/day)	9.02		Heave Rate (mm/day)	8.64	

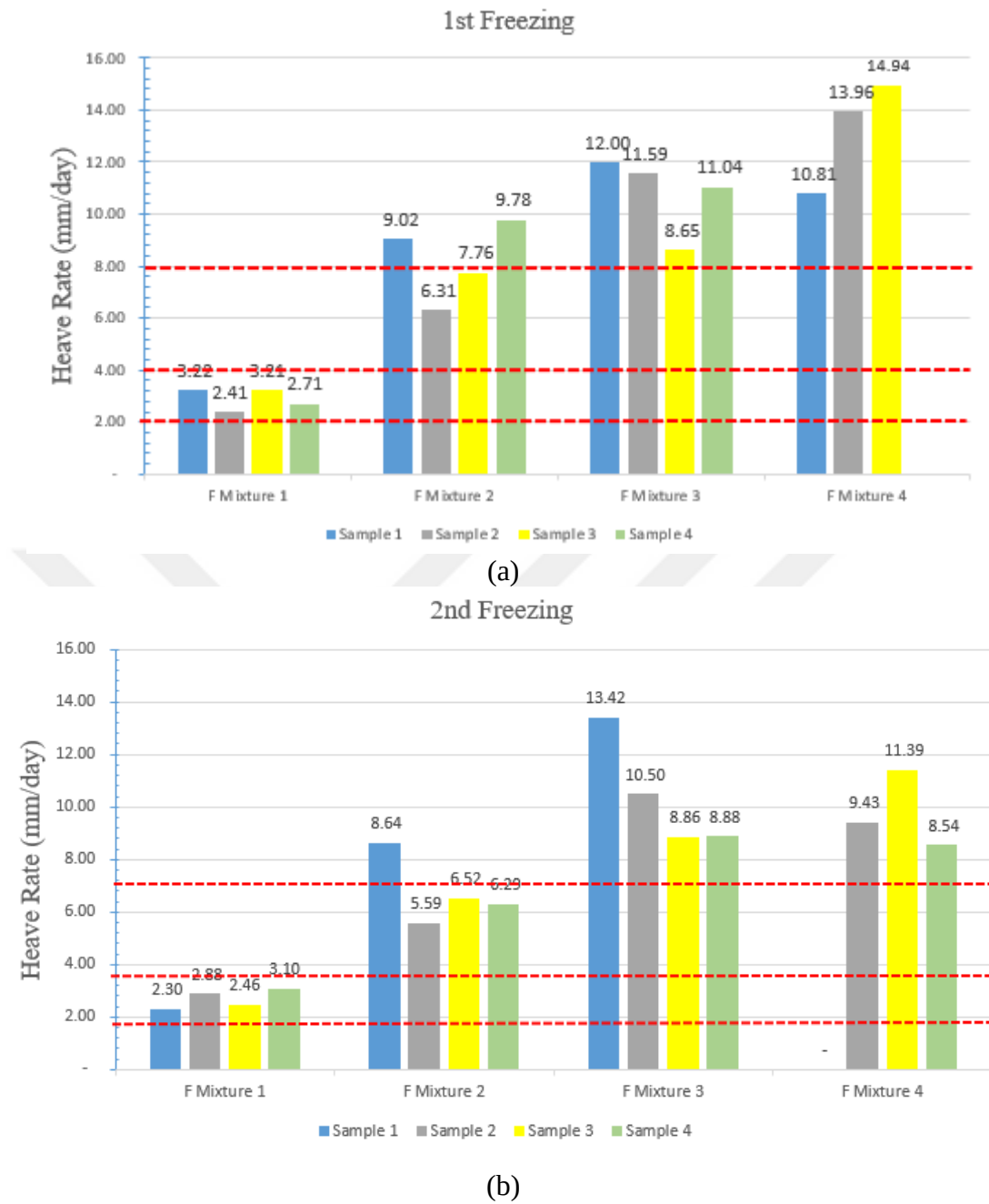
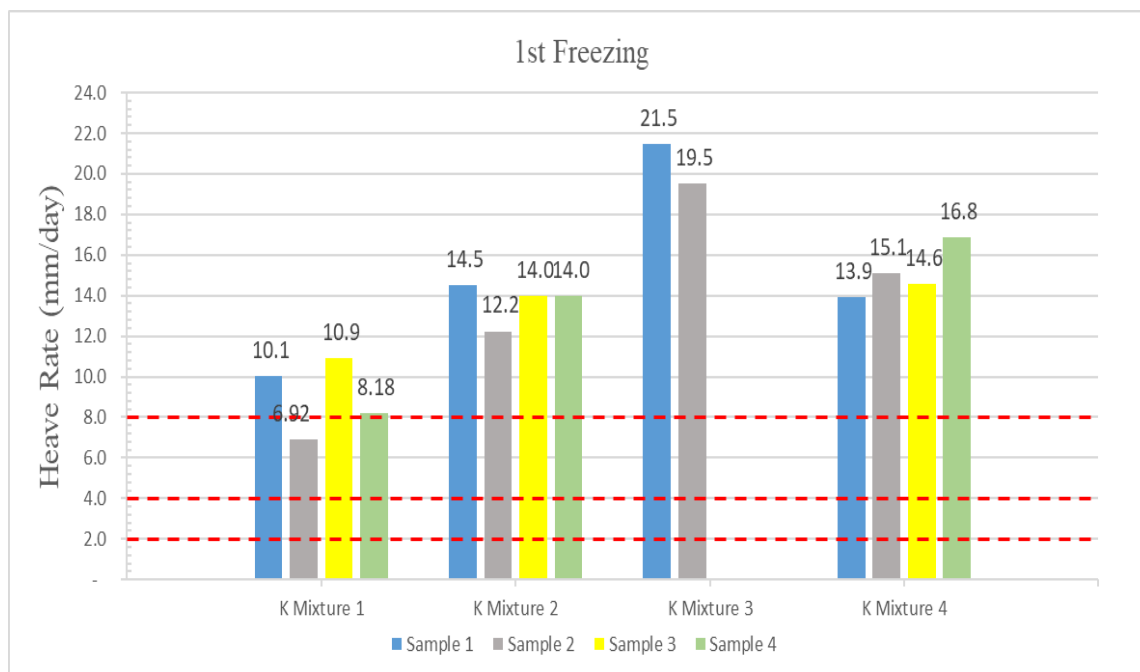
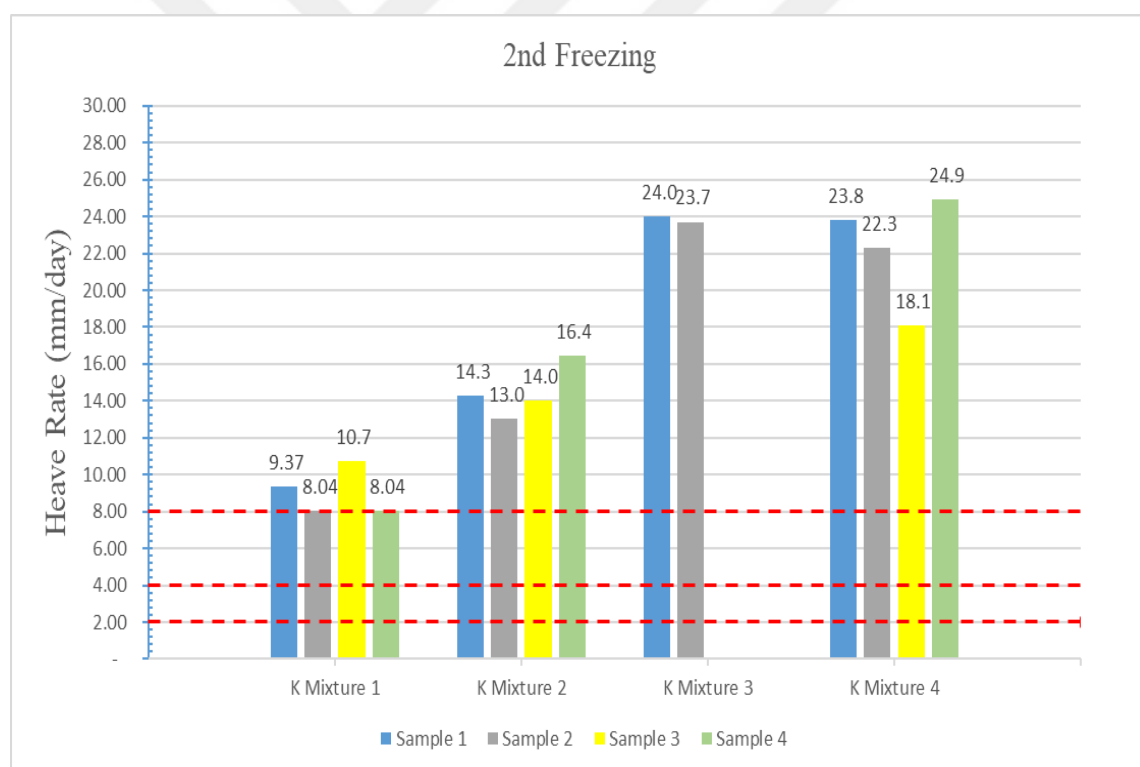


Figure 4.14 The result of heave rate calculations “Group-1”: (a) the heave rate values at the 1st freezing. (b) the have rate values at the 2nd freezing.

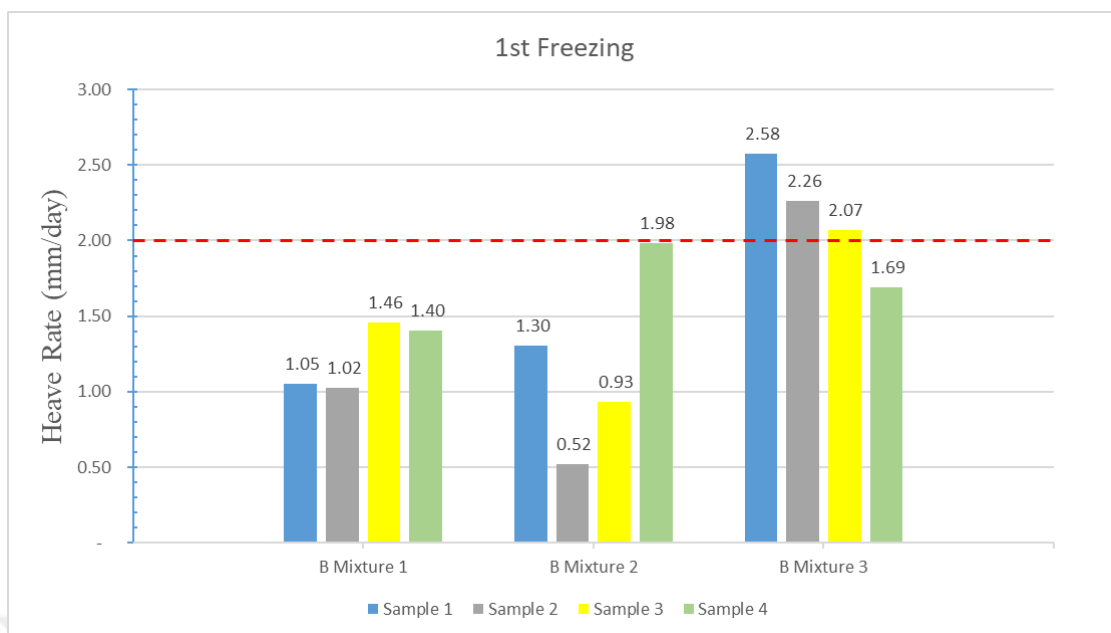


(a)

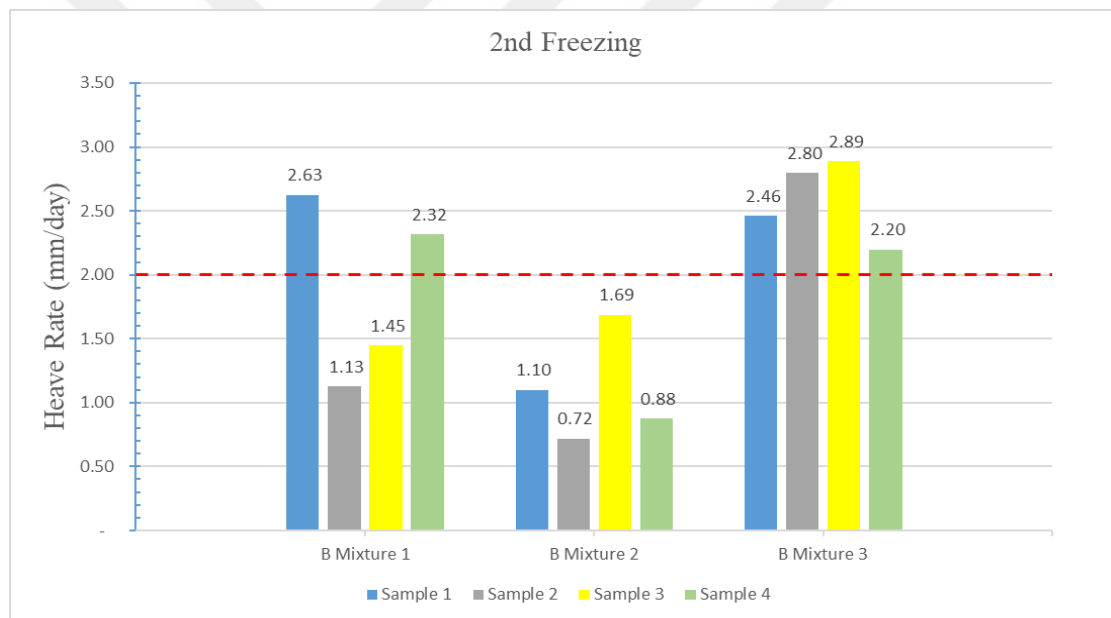


(b)

Figure 4.15 The result of heave rate calculations “Group-2”: (a) the heave rate values at the 1st freezing. (b) the have rate values at the 2nd freezing.

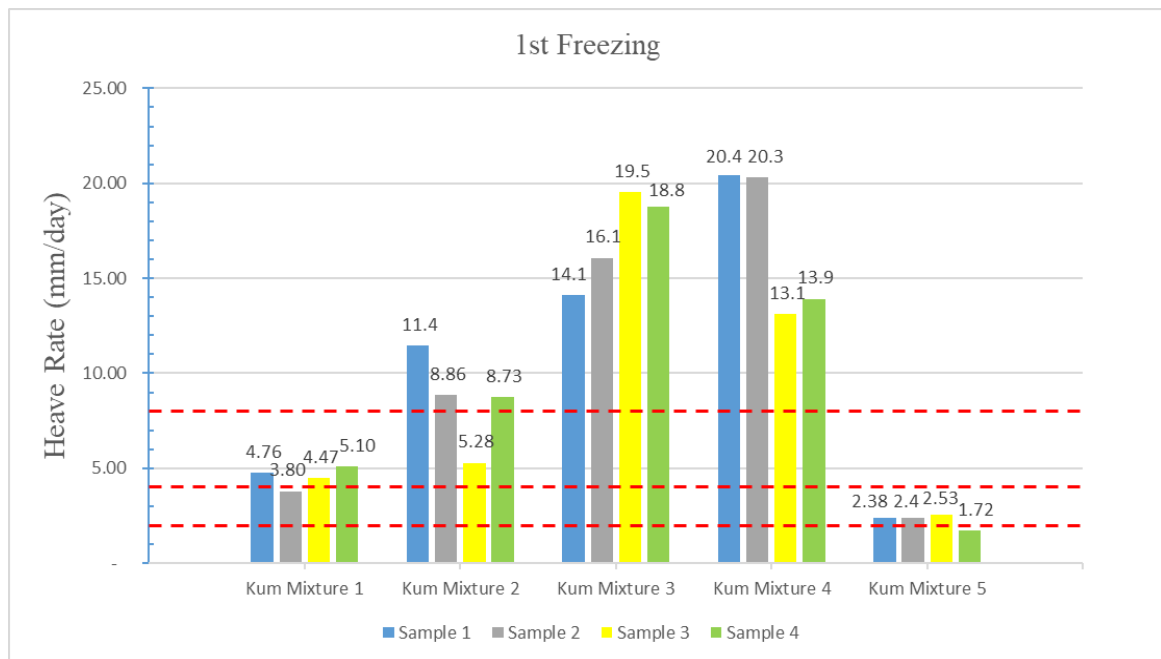


(a)

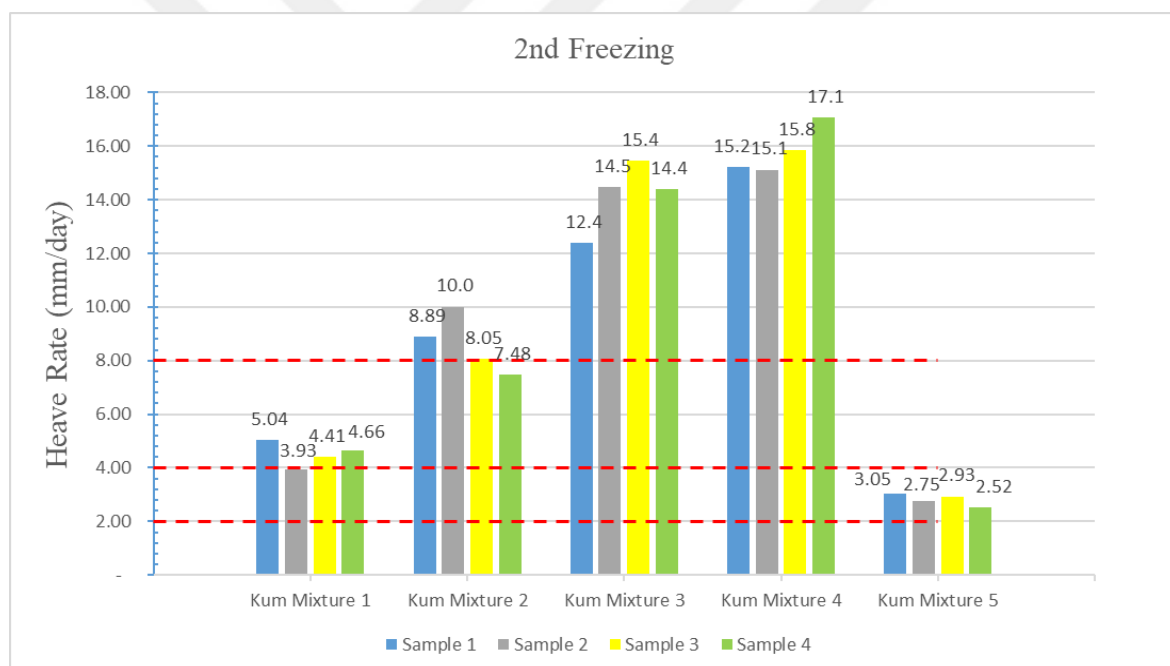


(b)

Figure 4.16 The result of heave rate calculations “Group-3”: (a) the heave rate values at the 1st freezing. (b) the have rate values at the 2nd freezing.

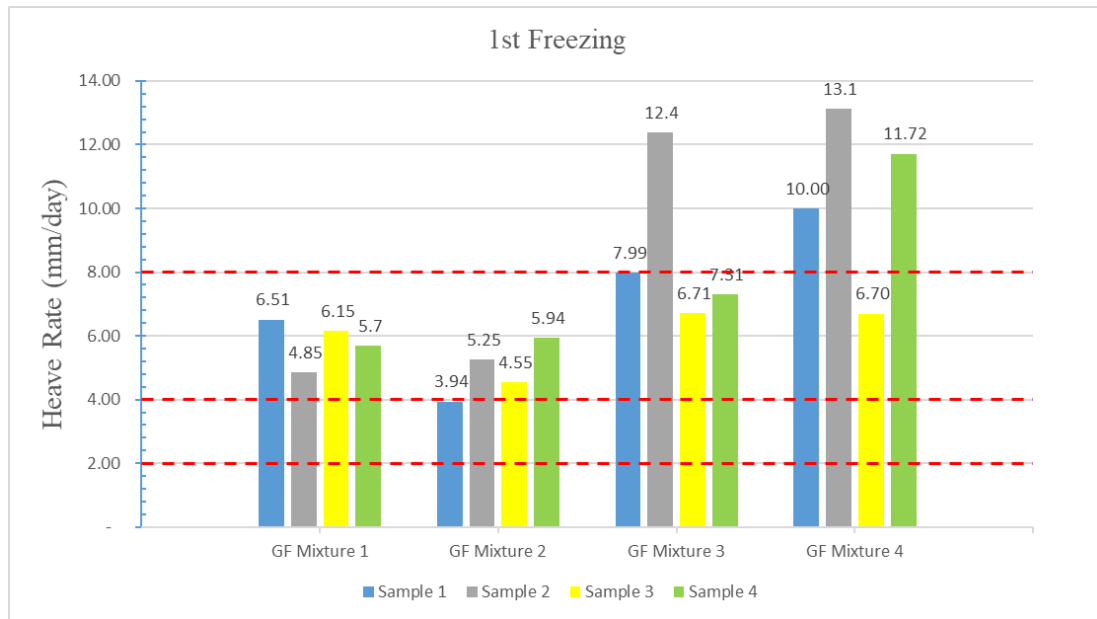


(a)

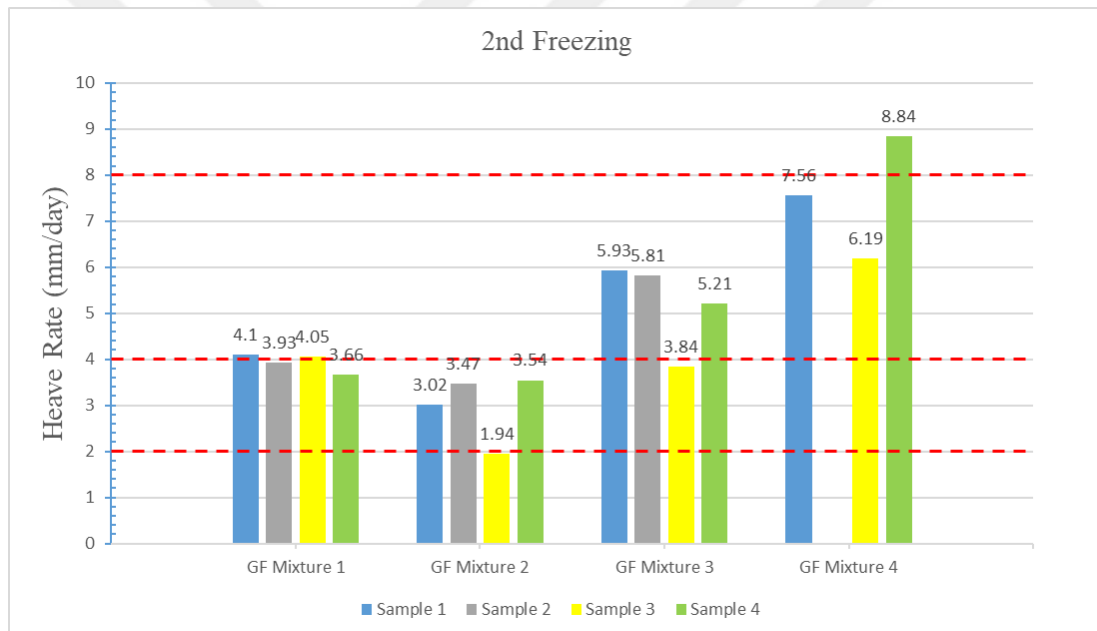


(b)

Figure 4.17 The result of heave rate calculations “Group-4”: (a) the heave rate values at the 1st freezing. (b) the have rate values at the 2nd freezing.

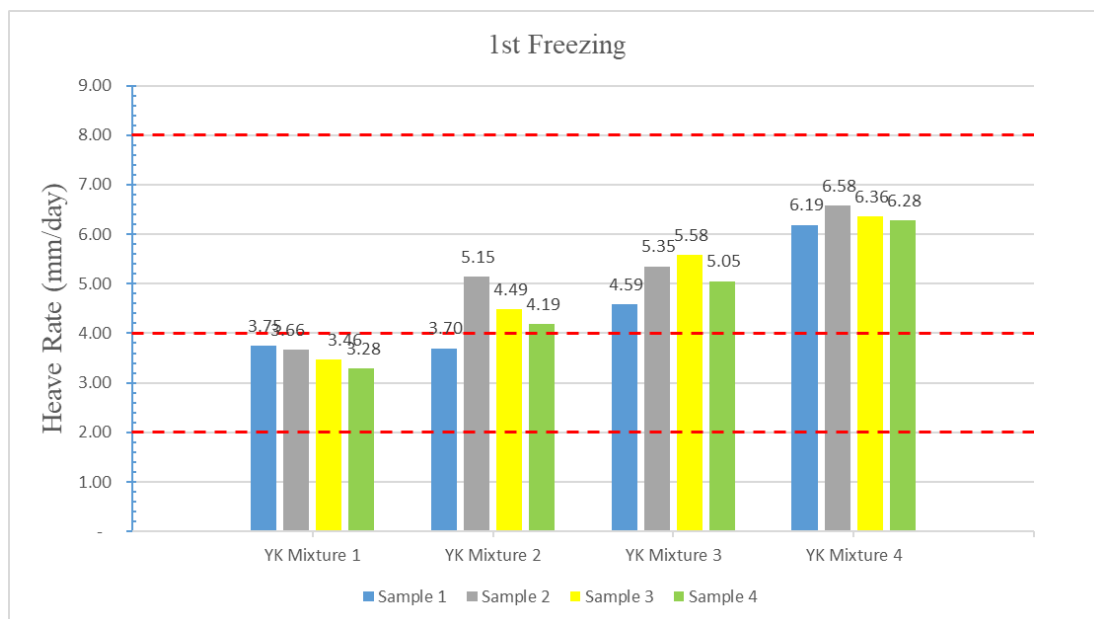


(a)

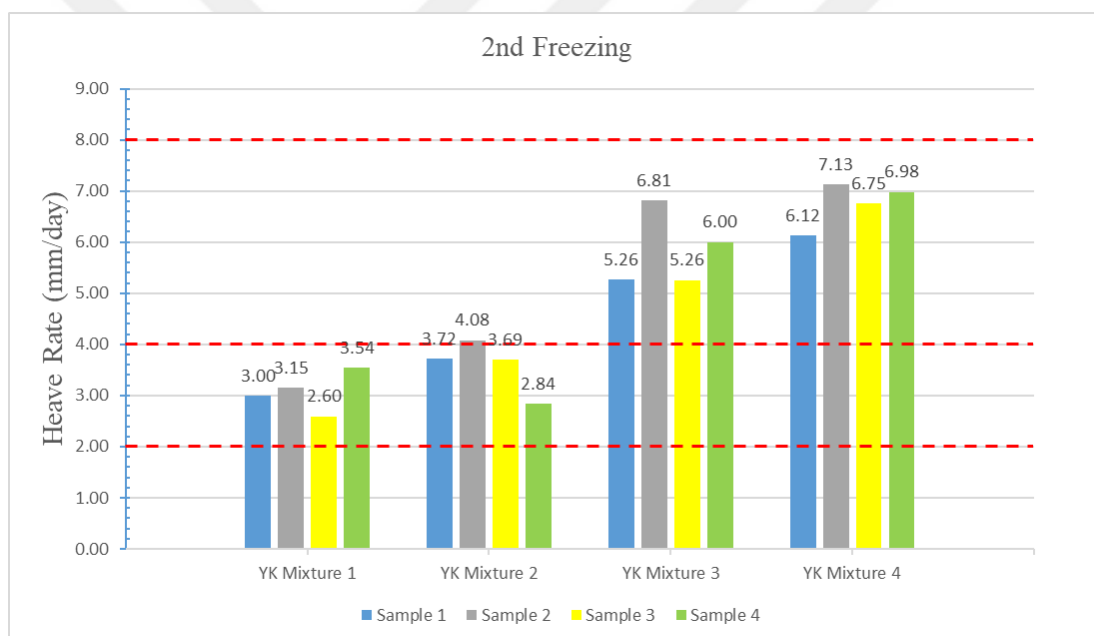


(b)

Figure 4.18 The result of heave rate calculations “Group-5”: (a) the heave rate values at the 1st freezing. (b) the have rate values at the 2nd freezing.



(a)



(b)

Figure 4.19 The result of heave rate calculations “Group-6”: (a) the heave rate values at the 1st freezing. (b) the have rate values at the 2nd freezing.

4.4.2 Residual Heave

The residual heave is the total change in height of the sample at the end of the test. It is calculated as the difference between the intial height of the sample just before freezing (D_i) and the final measured height at the end of the second freeze (D_f).

Table 4.5 presents heave measurement results for 26 distinct mixtures, each containing four samples as outlined in Chapter 3. For each sample, two measurements 1st heave (H1) and 2nd heave (H2)—were calculated to assess the material’s swelling behavior over time. Specifically, H1 corresponds to the first freezing cycle, while H₂ is derived from the second freezing cycle. Table 4.5 also includes the heave difference (ΔH), computed as the difference between H₂ and H₁, to quantify the extent of heave progression throughout the testing period.

Table 4.5 Heave records and heave Difference (ΔH) for 26 Mixtures with Four Samples Each

Mixture No.		Recorded heave (mm)			
		Sample 1	Sample 2	Sample 3	Sample 4
1_F Mix 1	H1	4.3	2.41	3.51	2.72
	H2	3.8	2.7	3.59	2.71
	ΔH	0.52	0.7	0.7	0.75
2_F Mix 2	H1	9.4	6.8	8.21	6.63
	H2	6.2	6.43	6.4	5.82
	ΔH	2.1	1.6	1.79	1.65
3_F Mix 3	H1	7.9	9.8	8.2	9.0
	H2	8.9	8.4	7.95	7.75
	ΔH	2.6	3.1	2.65	2.9
4_F Mix 4	H1	11.3	11.9	10.2	12.4
	H2	9.6	10.4	10.3	10.4
	ΔH	4.7	5.5	4.0	5.55
5_K Mix 1	1st	12.3	8.95	9.5	9.7
	2nd	10.8	7.75	8.8	8.4
	ΔH	2.6	1.2	1.8	1.9
6_K Mix 2	1st	13.0	8.9	14.05	12.3
	2nd	14.55	12.3	14.25	13.45
	ΔH	2.3	2.2	2.8	1.4
7_K Mix 3	1st				
	2nd	17.2	18.3	18.2	14.2
	ΔH				
7-8_K Mix (3-4)	1st	15.9	16.75	14.7	20.1
	2nd	20.5	19.55	17.0	20.7
	ΔH	3.0	2.7	4.9	2.05
8_K Mix 4	1st	11.1	11.42	9.85	13.5
	2nd	15.07	17.7	15.15	20.6

Mixture No.		Recorded heave (mm)			
		Sample 1	Sample 2	Sample 3	Sample 4
	ΔH	2.1	1.97	1.55	3.1
9_B Mix 1	1st	1.18	1.0	1.62	1.46
	2nd	1.2	1.05	1.57	1.58
	ΔH	0.4	0.02	0.23	0.18
10_B Mix 2	H1	0.58	0.76	0.82	1.28
	H2	0.72	0.84	0.78	1.24
	ΔH	0.15	0.15	0.06	0.43
11_B Mix 3	H1	1.03	1.08	0.89	0.68
	H2	1.16	1.3	0.04	0.82
	ΔH	0.32	0.15	0.15	0.32
12_F Kum Mix 0	H1	1.38	1.47	1.45	1.4
	H2	1.9	1.75	1.71	1.87
	ΔH	0.5	0.2	0.3	0.55
13_F Kum Mix 1	H1	2.42	2.54	4.38	4.15
	H2	2.65	2.6	4.33	4.1
	ΔH	0.3	0.6	0.88	0.6
14_F Kum Mix 2	H1	8.4	8.0	5.37	6.7
	H2	7.65	7.1	5.25	6.4
	ΔH	4.1	3.4	2.02	2.0
15_F Kum Mix 3	H1	11.1	11.9	14.8	15.5
	H2	10.7	11.25	12.0	13.4
	ΔH	4.3	6.0	5.7	6.5
16_F Kum Mix 4	H1	16.0	17.5	10.4	10.35
	H2	12.5	13.5	13.5	14.2
	ΔH	8.5	8.0	7.8	9.1
17_GF Mix 1	H1	3.45	3.38	3.33	3.2
	H2	2.81	3.05	2.85	2.77
	ΔH	0.4	0.3	0.54	0.6
18_GF Mix 2	H1	2.09	2.85	2.13	3.3
	H2	1.92	2.55	1.8	2.65
	ΔH	0.23	0.45	0.35	0.3
19_GF Mix 3	H1	4.9	6.05	4.66	4.46
	H2	4.05	4.5	3.38	3.75
	ΔH	0.9	1.37	0.6	0.6

Mixture No.		Recorded heave (mm)			
		Sample 1	Sample 2	Sample 3	Sample 4
20_ GF Mix 4	H1	7.65	11.7	7.29	8.8
	H2	6.1	9.2	6.1	7.95
	ΔH	1.6	3.1	1.69	2.2
21_YK Mix 1	H1	4.0	3.83	3.54	3.56
	H2	2.84	2.73	2.3	2.49
	ΔH	0.83	0.54	0.62	0.51
22_YK Mix 2	H1	4.04	3.25	4.2	3.83
	H2	3.6	3.15	4.0	3.6
	ΔH	0.74	0.4	0.75	0.58
23_YK Mix 3	H1	4.15	5.2	4.96	4.52
	H2	4.53	5.5	4.95	5.2
	ΔH	0.3	1.0	1.5	0.52
24_YK Mix 4	H1	4.89	5.74	5.82	5.07
	H2	5.85	6.4	6.18	5.85
	ΔH	0.69	0.79	0.27	0.22

4.4.3 Segregation Potential

This section describe show the segregation potential associated with frost susceptibility was evaluated. The segregation potential can be calculated using the measured heave rate or it can be calculated using the measured water intake rate during steady-state temperature conditions. Steady state is achieved when the frost front (0°C) is not changing.

The temperature gradient is an essential input factor for calculating segregation potential in by approach, as it directly influences the freezing and thawing processes. The eight test data set includes temperatures determined by numerous sensors placed along the soil sample. The temperature gradient was evaluated by plotting temperature profile along the sample at steady-state temperature conditions (see Figure 2.20) for each sample. The temperature profile needs two factors to be estimated: the temperature measured, and the depth of each sensor along the sample (from top to bottom).

The temperature profile corresponding to steady-state conditions was taken 8 hours after sample freezing. Calculation temperature gradient for sample "2_F-mixture 2-Blue Sample" is shown below in Table 4.6.

Table 4.6 Temperature profile of "2_F-Mixture 2-Blue Sample"

Freezing cycles		T09-Blue-1 (degC)	T10- Blue -2 (degC)	T11- Blue I-3 (degC)	T12- Blue -4 (degC)	T13- Blue -5 (degC)	T14- Blue -6 (degC)	T15- Blue -7 (degC)	T16- Blue -8 (degC)
1 st	Temp. (°C)	-4,8	-2,54	-2,08	-1,68	0,3	0,25	1,06	0,87
	Distance (mm)	0	12,65	37,94	63,23	88,52	113,81	139,1	151,7
2 nd	Temp. (°C)	-4,24	-1,66	-1,37	-1,09	0,47	0,63	1,07	0,86
	Distance (mm)	0	12,65	37,94	63,23	88,52	113,81	139,1	151,7

Each pair of temperature-distance data is plotted to produce the temperature profile through the sample as shown in Figure 4.20. The temperature gradient is taken as the slope of the best fit line through the points representing the frozen fringe (i.e. zone with temperatures in the range of about 0°C to -2°C). The segregation potential based on heave rates is the heave rate divided by the temperature gradient (equ.[2-3]) and is expressed in units of mm²/(°C-day).

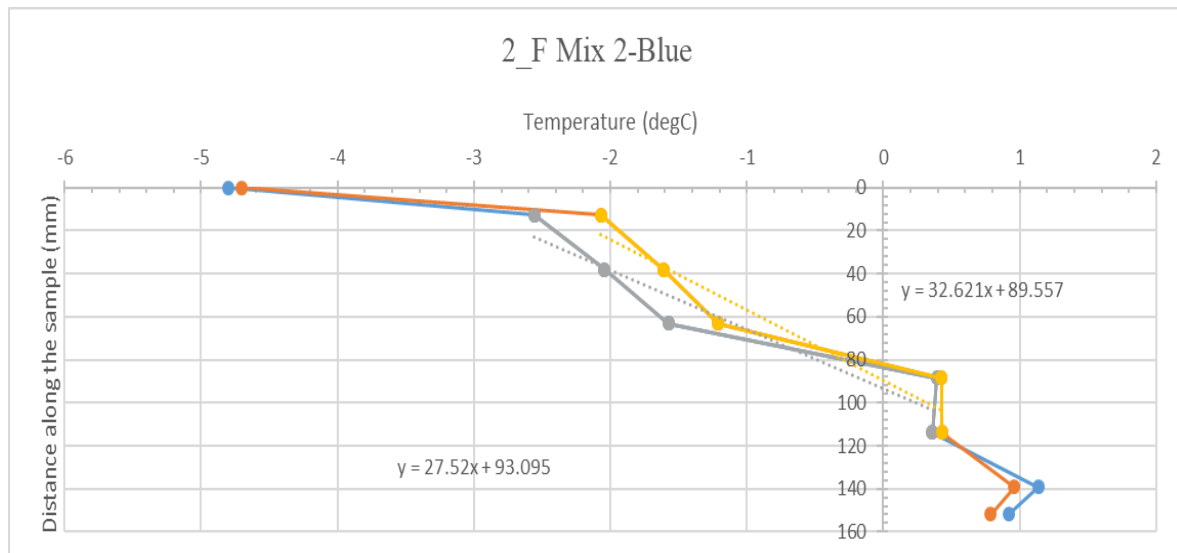


Figure 4.20 Temperature profile of 2_F Mixture 2-Blue sample.

The water intake was determined from the the measured weight of marriotte bottle (L_1 - L_2). The following formula was used to determine the water intake rate in ml/hour, during steady-state conditions:

$$\text{Water Intake Rate (ml)} = \frac{L_1 - L_2}{P_w * T} \quad [4-2]$$

Where

L is the weight of the Marriotte cylinder and water it contains

P_w is the density of water (g/ml)

T is the time period during which reading L_1 & L_2 were taken

The segregation potential based on water flow is calculated by dividing the water volume intake rate by the temperature gradient (see Figure 4.21), and it has units of ml-mm/°C-day. Referred to th formula in the litreture review (see equ. [2-4]).

The segregation potential calculated from water intake has units of ml-mm/°C-day. For the sake of comparison, the volume of water intake most be converted to an equivelant height as described by Reike (1983)

$$SegPot_h = \frac{(SegPot_w)(1.09)}{Area\ of\ Specimen} \quad [4-3]$$

2_F Mixture 2-Blue

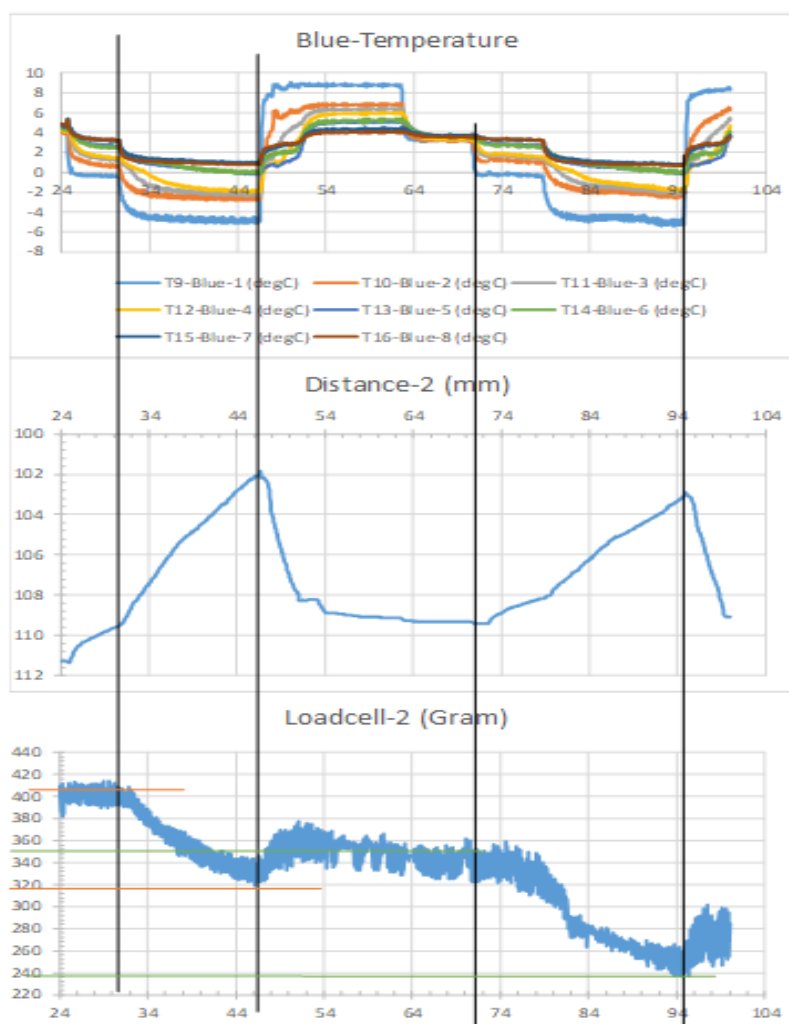


Figure 4.21 An example to the evaluated of water intake rate process

Table 4.7 An example for “2_F Mix 2” (a) water intake values (b) Time measurements during water intake

	LoadCell 1	LoadCell 2		Time 1 (hr)	Time 2 (hr)
Point 1	2392	2352	Point 1	30.5	71
Point 2	2316	2236	Point 2	46.1	94.5
Water Intake (ml)	76	116	Time (hr)	15.6	23.5

(a)

(b)

Table 4.8 to Table 4.38 show the derived segregation potential values based on measured heave rates, temperature gradient and measured water intake values.

Table 4.8 The result of Segregation Potential calculations “1_F Mix 1

1_F-Mixture 1							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (ml-mm/°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	15.315	mm/°C	49.26	307.6	19.83
		Temp. gradient	0.0653	°C/mm			
		Heave Rate	3.2162	mm/day			
		Water Intake Rate	20.08	ml/day			
	2nd	Slope	14.229	mm/°C	32.73	314.35	20.27
		Temp. gradient	0.0703	°C/mm			
		Heave Rate	2.3004	mm/day			
		Water Intake Rate	22.1	ml/day			
Black-2	1st	Slope	21.043	mm/°C	50.7	629.3	40.58
		Temp. gradient	0.0475	°C/mm			
		Heave Rate	2.4093	mm/day			
		Water Intake Rate	29.91	ml/day			
	2nd	Slope	22.517	mm/°C	74.94	1351.02	87.12
		Temp. gradient	0.0444	°C/mm			
		Heave Rate	3.328	mm/day			
		Water Intake Rate	60	ml/day			
Yellow-3	1st	Slope	15.059	mm/°C	48.4	609.9	39.33
		Temp. Gradient	0.0664	°C/mm			
		Heave Rate	3.2143	mm/day			
		Water Intake Rate	40.5	ml/day			
	2nd	Slope	17.086	mm/°C	42.03	1102.05	71.07
		Temp. Gradient	0.0585	°C/mm			
		Heave Rate	2.46	mm/day			
		Water Intake Rate	65	ml/day			
Green-4	1st	Slope	57.057	mm/°C	154.5	2054.05	132.46
		Temp. gradient	0.0175	°C/mm			
		Heave Rate	2.7082	mm/day			
		Water Intake Rate	36	ml/day			
	2nd	Slope	71.063	mm/°C	220.1	4405.9	284.12
		Temp. gradient	0.0141	°C/mm			
		Heave Rate	3.0971	mm/day			
		Water Intake Rate	62.00	ml/day			

Table 4.9 The segregation potential calculations for “2_F Mix 2”

2_F Mixture 2							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	27.52	mm/°C	250.1	3217.7	207.50
		Temp.gradient	0.0363	°C/mm			
		Heave Rate	9.0896	mm/day			
		Water Intake Rate	116.92	ml/day			
	2nd	Slope	32.621	mm/°C	282.4	3864.5	249.21
		Temp. gradient	0.0307	°C/mm			
		Heave Rate	8.6560	mm/day			
		Water Intake Rate	118.5	ml/day			
Black-2	1st	Slope	22.635	mm/°C	143.3	3312.4	213.60
		Temp. gradient	0.0442	°C/mm			
		Heave Rate	6.3319	mm/day			
		Water Intake Rate	146.34	ml/day			
	2nd	Slope	21.83	mm/°C	123.0	2054.6	132.49
		Temp. gradient	0.0458	°C/mm			
		Heave Rate	5.635	mm/day			
		Water Intake Rate	94.1176	ml/day			
Yellow-3	1st	Slope	16.511	mm/°C	139.6	2864.6	184.72
		Temp. gradient	0.0606	°C/mm			
		Heave Rate	8.4560	mm/day			
		Water Intake Rate	173.4940	ml/day			
	2nd	Slope	15.937	mm/°C	102.30	2027.6	130.8
		Temp. gradient	0.0627	°C/mm			
		Heave Rate	6.419	mm/day			
		Water Intake Rate	127.229	ml/day			
Green-4	1st	Slope	22.39	mm/°C	218.0	3813.52	245.92
		Temp. gradient	0.0447	°C/mm			
		Heave Rate	9.7376	mm/day			
		Water Intake Rate	170.32	ml/day			
	2nd	Slope	24.401	mm/°C	153.1	2928.1	188.8
		Temp. gradient	0.0410	°C/mm			
		Heave Rate	6.2743	mm/day			
		Water Intake Rate	120.00	ml/day			

Table 4.10 The segregation potential calculations for “24_YK Mix 4”

3_F Mixture 3							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_{conv}er_t} (mm ² /°C-day)
Blue-1	1st	Slope	25.371	mm/°C	304.5	3615.4	233.14
		Temp. gradient	0.0394	°C/mm			
		Heave Rate	12	mm/day			
		Water Intake Rate	142.5	ml/day			
	2nd	Slope	22.442	mm/°C	301.1	2019.8	130.25
		Temp. gradient	0.0446	°C/mm			
		Heave Rate	13.416	mm/day			
		Water Intake Rate	90	ml/day			
Black-2	1st	Slope	21.602	mm/°C	250.3	3953.2	254.92
		Temp. gradient	0.0463	°C/mm			
		Heave Rate	11.5862069	mm/day			
		Water Intake Rate	183	ml/day			
	2nd	Slope	22.296	mm/°C	234.1	3946.4	254.49
		Temp. gradient	0.0449	°C/mm			
		Heave Rate	10.5	mm/day			
		Water Intake Rate	177	ml/day			
Yellow-3	1st	Slope	17.53	mm/°C	151.7	4811.99	310.30
		Temp. gradient	0.0570	°C/mm			
		Heave Rate	8.652360515	mm/day			
		Water Intake Rate	274.5	ml/day			
	2nd	Slope	14.472	mm/°C	128.24	3907.4	252.0
		Temp. gradient	0.0691	°C/mm			
		Heave Rate	8.861538462	mm/day			
		Water Intake Rate	270	ml/day			
Green-4	1st	Slope	26.015	mm/°C	287.2	4292.48	276.80
		Temp. gradient	0.0384	°C/mm			
		Heave Rate	11.04	mm/day			
		Water Intake Rate	165	ml/day			
	2nd	Slope	27.502	mm/°C	260.1	6149.5	396.6
		Temp. gradient	0.0364	°C/mm			
		Heave Rate	9.456	mm/day			
		Water Intake Rate	223.602	ml/day			

Table 4.11 The segregation potential calculations for “4_F Mix 4”

4_F-Mixture 4							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
1 Blue	1st	Slope	23.424	mm/°C	253.2	4764.2	307.22
		Temp. gradient	0.0427	°C/mm			
		Heave Rate	10.8108108	mm/day			
		Water Intake Rate	203.39	ml/day			
	2nd	Slope	23.821	mm/°C	0.0	2372.2	152.97
		Temp. gradient	0.0420	°C/mm			
		Heave Rate	0	mm/day			
		Water Intake Rate	99.58506224	ml/day			
Black-2	1st	Slope	28.289	mm/°C	395.02	5584.3	360.11
		Temp. gradient	0.0353	°C/mm			
		Heave Rate	13.964	mm/day			
		Water Intake Rate	197.403	ml/day			
	2nd	Slope	29.772	mm/°C	280.7	2629.2	169.55
		Temp. gradient	0.0336	°C/mm			
		Heave Rate	9.429	mm/day			
		Water Intake Rate	88.312	ml/day			
Yellow-3	1st	Slope	12.798	mm/°C	191.2	2616.99	168.76
		Temp. gradient	0.0781	°C/mm			
		Heave Rate	14.943	mm/day			
		Water Intake Rate	204.484	ml/day			
	2nd	Slope	13.561	mm/°C	154.51	2724.8	175.7
		Temp. gradient	0.0737	°C/mm			
		Heave Rate	11.394	mm/day			
		Water Intake Rate	200.930	ml/day			
Green-4	1st	Slope	25.925	mm/°C	0.0	7805.78	503.36
		Temp. gradient	0.0386	°C/mm			
		Heave Rate	0	mm/day			
		Water Intake Rate	301.091	ml/day			
	2nd	Slope	25.719	mm/°C	219.7	4523.99	291.7
		Temp. gradient	0.0389	°C/mm			
		Heave Rate	8.542	mm/day			
		Water Intake Rate	175.901	ml/day			

Table 4.12 The segregation potential calculations for “5_K Mix 1”

5_K-Mixture 1							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	25.968	mm/°C	261.2	2072.7	133.66
		Temp. gradient	0.0385	°C/mm			
		Heave Rate	10.05714	mm/day			
		Water Intake Rate	79.81777	ml/day			
	2nd	Slope	26.92	mm/°C	252.3	2153.6	138.88
		Temp. gradient	0.0371	°C/mm			
		Heave Rate	9.371429	mm/day			
		Water Intake Rate	80	ml/day			
Black-2	1st	Slope	33.515	mm/°C	232.0	7360.2	474.62
		Temp. gradient	0.0298	°C/mm			
		Heave Rate	6.923077	mm/day			
		Water Intake Rate	219.6078	ml/day			
	2nd	Slope	32.71	mm/°C	262.97	5699.96	367.57
		Temp. gradient	0.0306	°C/mm			
		Heave Rate	8.039409	mm/day			
		Water Intake Rate	174.2574	ml/day			
Yellow-3	1st	Slope	16.524	mm/°C	180.1	3571.6	230.32
		Temp. gradient	0.0605	°C/mm			
		Heave Rate	10.89908	mm/day			
		Water Intake Rate	216.1491	ml/day			
	2nd	Slope	17.888	mm/°C	191.77	4431.6	285.8
		Temp. gradient	0.0559	°C/mm			
		Heave Rate	10.72081	mm/day			
		Water Intake Rate	247.7419	ml/day			
Green-4	1st	Slope	22.351	mm/°C	182.9	1940.26	125.12
		Temp. gradient	0.0447	°C/mm			
		Heave Rate	8.184332	mm/day			
		Water Intake Rate	86.80851	ml/day			
	2nd	Slope	21.481	mm/°C	172.6	997.8	64.35
		Temp. gradient	0.0466	°C/mm			
		Heave Rate	8.036697	mm/day			
		Water Intake Rate	46.45161	ml/day			

Table 4.13 The segregation potential calculations for “6_K Mix 2”

6_K-Mixture 2							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	26.384	mm/°C	382.2	2736.8	176.48
		Temp. gradient	0.0379	°C/mm			
		Heave Rate	14.48458	mm/day			
		Water Intake Rate	103.7288	ml/day			
	2nd	Slope	28.839	mm/°C	411.5	4599.9	296.63
		Temp. gradient	0.0347	°C/mm			
		Heave Rate	14.27027	mm/day			
		Water Intake Rate	159.5031	ml/day			
Black-2	1st	Slope	30.972	mm/°C	379.1	6325.2	407.89
		Temp. gradient	0.0323	°C/mm			
		Heave Rate	12.24161	mm/day			
		Water Intake Rate	204.2236	ml/day			
	2nd	Slope	28.983	mm/°C	378.2	11111.97	716.56
		Temp. gradient	0.0345	°C/mm			
		Heave Rate	13.04854	mm/day			
		Water Intake Rate	383.3962	ml/day			
Yellow-3	1st	Slope	11.626	mm/°C	162.3	2665.04	171.86
		Temp. gradient	0.0860	°C/mm			
		Heave Rate	13.95595	mm/day			
		Water Intake Rate	229.2308	ml/day			
	2nd	Slope	11.708	mm/°C	163.91	3179.6	205.04
		Temp. gradient	0.0854	°C/mm			
		Heave Rate	14	mm/day			
		Water Intake Rate	271.5789	ml/day			
Green-4	1st	Slope	29.125	mm/°C	407.18	6374.53	411.07
		Temp. gradient	0.0343	°C/mm			
		Heave Rate	13.98058	mm/day			
		Water Intake Rate	218.8679	ml/day			
	2nd	Slope	29.641	mm/°C	486.99	7706.66	496.97
		Temp. gradient	0.0337	°C/mm			
		Heave Rate	16.42953	mm/day			
		Water Intake Rate	260	ml/day			

Table 4.14 The segregation potential calculations for “(7-8)_K Mix (3-4)”

7_K-Mixture 3							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	24.17	mm/°C	519.2	3335.5	215.09
		Temp. gradient	0.0414	°C/mm			
		Heave Rate	21.48148	mm/day			
		Water Intake Rate	138	ml/day			
	2nd	Slope	23.039	mm/°C	552.9	1570.8	101.30
		Temp. gradient	0.0434	°C/mm			
		Heave Rate	24	mm/day			
		Water Intake Rate	68.18182	ml/day			
Black-2	1st	Slope	32.849	mm/°C	640.6	3941.88	254.19
		Temp. gradient	0.0304	°C/mm			
		Heave Rate	19.5	mm/day			
		Water Intake Rate	120	ml/day			
	2nd	Slope	28.123	mm/°C	666.5	2300.97	148.38
		Temp. gradient	0.0356	°C/mm			
		Heave Rate	23.7	mm/day			
		Water Intake Rate	81.81818	ml/day			
8_K-Mixture 4							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Yellow-3	1st	Slope	23.695	mm/°C	426.5	5331.4	343.80
		Temp. gradient	0.0422	°C/mm			
		Heave Rate	18	mm/day			
		Water Intake Rate	225	ml/day			
	2nd	Slope	20.055	mm/°C	421.16	6918.98	446.17
		Temp. gradient	0.0499	°C/mm			
		Heave Rate	21	mm/day			
		Water Intake Rate	345	ml/day			
Green-4	1st	Slope	21.942	mm/°C	507.46	3949.56	254.69
		Temp. gradient	0.0456	°C/mm			
		Heave Rate	23.12727	mm/day			
		Water Intake Rate	180	ml/day			
	2nd	Slope	16.509	mm/°C	481.12	2386.3	153.88
		Temp. gradient	0.0606	°C/mm			
		Heave Rate	29.14286	mm/day			
		Water Intake Rate	144.5455	ml/day			

Table 4.15 The segregation potential calculations for “8_K Mix 4 (Repeat)”

8_K-Mixture 4 (Repeat)							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_{convert}} (mm ² /°C-day)
Blue-1	1st	Slope	28.906	mm/°C	393.47	0.0	0.0
		Temp. Gradient	0.0346	°C/mm			
		Heave Rate	13.61194	mm/day			
		Water Intake Rate	0	ml/day			
	2nd	Slope	25.036	mm/°C	383.5	0.0	0.0
		Temp. Gradient	0.0399	°C/mm			
		Heave Rate	15.31915	mm/day			
		Water Intake Rate	0	ml/day			
Black-2	1st	Slope	27.583	mm/°C	417.1	5715.3	368.56
		Temp. gradient	0.0363	°C/mm			
		Heave Rate	15.12	mm/day			
		Water Intake Rate	207.205	ml/day			
	2nd	Slope	27.032	mm/°C	602.7	8089.3	521.64
		Temp. gradient	0.0370	°C/mm			
		Heave Rate	22.29586	mm/day			
		Water Intake Rate	299.25	ml/day			
Yellow-3	1st	Slope	18.262	mm/°C	266.1	2068.9	133.42
		Temp. gradient	0.0548	°C/mm			
		Heave Rate	14.57143	mm/day			
		Water Intake Rate	113.2919	ml/day			
	2nd	Slope	17.474	mm/°C	315.71	3907.2	252.0
		Temp. gradient	0.0572	°C/mm			
		Heave Rate	18.06742	mm/day			
		Water Intake Rate	223.6025	ml/day			
Green-4	1st	Slope	34.705	mm/°C	584.5	9156.95	590.49
		Temp. gradient	0.0288	°C/mm			
		Heave Rate	16.84211	mm/day			
		Water Intake Rate	263.8509	ml/day			
	2nd	Slope	34.337	mm/°C	856.2	11516.76	742.66
		Temp. gradient	0.0291	°C/mm			
		Heave Rate	24.93506	mm/day			
		Water Intake Rate	335.4037	ml/day			

Table 4.16 The segregation potential calculations for “8_K Mix 4 (Unused)”

8_K-Mixture 4 (Unused)							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	111.43	mm/°C	1991.51	24686.03	1591.89
		Temp. gradient	0.0090	°C/mm			
		Heave Rate	17.87234	mm/day			
		Water Intake Rate	221.5385	ml/day			
	2nd	Slope	70.633	mm/°C	1386.98	13561.5	874.52
		Temp. gradient	0.0142	°C/mm			
		Heave Rate	19.63636	mm/day			
		Water Intake Rate	192	ml/day			
Black-2	1st	Slope	36.08	mm/°C	858.7	10824	697.99
		Temp. gradient	0.0277	°C/mm			
		Heave Rate	23.8	mm/day			
		Water Intake Rate	300	ml/day			
	2nd	Slope	38.652	mm/°C	252.99	6679.1	430.70
		Temp. gradient	0.0259	°C/mm			
		Heave Rate	6.545455	mm/day			
		Water Intake Rate	172.8	ml/day			
Yellow-3	1st	Slope	24.898	mm/°C	343.9	7469.4	481.67
		Temp. gradient	0.0402	°C/mm			
		Heave Rate	13.81295	mm/day			
		Water Intake Rate	300	ml/day			
	2nd	Slope	17.609	mm/°C	311.40	4124.73	265.99
		Temp. gradient	0.0568	°C/mm			
		Heave Rate	17.68421	mm/day			
		Water Intake Rate	234.24	ml/day			
Sample 4 Green	1st	Slope	86.798	mm/°C	1225.4	25560.15	1648.26
		Temp. gradient	0.0115	°C/mm			
		Heave Rate	14.11765	mm/day			
		Water Intake Rate	294.4785	ml/day			
	2nd	Slope	66.225	mm/°C	961.03	10172.16	655.96
		Temp. gradient	0.0151	°C/mm			
		Heave Rate	14.51163	mm/day			
		Water Intake Rate	153.6	ml/day			

Table 4.17 The segregation potential calculations for “9_B Mix 1”

9_B-Mixture 1							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	11.082	mm/°C	11.62	13.38	0.86
		Temp. gradient	0.0902	°C/mm			
		Heave Rate	1.048889	mm/day			
		Water Intake Rate	1.208	ml/day			
	2nd	Slope	18.537	mm/°C	48.66	69.95	4.51
		Temp. gradient	0.0539	°C/mm			
		Heave Rate	2.625	mm/day			
		Water Intake Rate	3.774	ml/day			
Black-2	1st	Slope	40.654	mm/°C	41.57	91.47	5.90
		Temp. gradient	0.0246	°C/mm			
		Heave Rate	1.022609	mm/day			
		Water Intake Rate	2.25	ml/day			
	2nd	Slope	33.089	mm/°C	37.27	74.45	12584.33
		Temp. gradient	0.0302	°C/mm			
		Heave Rate	1.126408	mm/day			
		Water Intake Rate	2.25	ml/day			
Yellow-3	1st	Slope	20.512	mm/°C	29.91	93.84	6.05
		Temp. gradient	0.0488	°C/mm			
		Heave Rate	1.458228	mm/day			
		Water Intake Rate	4.575	ml/day			
	2nd	Slope	17.308	mm/°C	25.10	-38.94	-2.51
		Temp. gradient	0.0578	°C/mm			
		Heave Rate	1.45	mm/day			
		Water Intake Rate	-2.25	ml/day			
Green-4	1st	Slope	33.564	mm/°C	47.06	92.26	5.95
		Temp. gradient	0.0298	°C/mm			
		Heave Rate	1.402105	mm/day			
		Water Intake Rate	2.75	ml/day			
	2nd	Slope	28.166	mm/°C	65.23	4.54	0.29
		Temp. gradient	0.0355	°C/mm			
		Heave Rate	2.315789	mm/day			
		Water Intake Rate	0.1611	ml/day			

Table 4.18 The segregation potential calculations for “10_B Mix 4”

10_B-Mixture 2							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	25.859	mm/°C	33.7	3297.0	212.61
		Temp. gradient	0.0387	°C/mm			
		Heave Rate	1.304698	mm/day			
		Water Intake Rate	127.5	ml/day			
	2nd	Slope	26.06	mm/°C	28.7	0.0	0.00
		Temp. gradient	0.0384	°C/mm			
		Heave Rate	1.100637	mm/day			
		Water Intake Rate	0	ml/day			
Black-2	1st	Slope	29.363	mm/°C	15.2	528.5	34.08
		Temp. gradient	0.0341	°C/mm			
		Heave Rate	0.516923	mm/day			
		Water Intake Rate	18	ml/day			
	2nd	Slope	28.89	mm/°C	20.8	470.8	30.36
		Temp. gradient	0.0346	°C/mm			
		Heave Rate	0.72	mm/day			
		Water Intake Rate	16.2963	ml/day			
Yellow-3	1st	Slope	14.817	mm/°C	13.8	187.7	12.11
		Temp. gradient	0.0675	°C/mm			
		Heave Rate	0.930909	mm/day			
		Water Intake Rate	12.67081	ml/day			
	2nd	Slope	15.236	mm/°C	25.70	102.2	6.6
		Temp. gradient	0.0656	°C/mm			
		Heave Rate	1.686957	mm/day			
		Water Intake Rate	6.708	ml/day			
Green-4	1st	Slope	28.825	mm/°C	57.1	648.56	41.82
		Temp. gradient	0.0347	°C/mm			
		Heave Rate	1.982609	mm/day			
		Water Intake Rate	22.5	ml/day			
	2nd	Slope	24.34	mm/°C	21.3	141.5	9.1
		Temp. gradient	0.0411	°C/mm			
		Heave Rate	0.876349	mm/day			
		Water Intake Rate	5.8137	ml/day			

Table 4.19 The segregation potential calculations for “11_B Mix 3”

11_B-Mixture 3							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	25.785	mm/°C	66.4	119.2	7.68
		Temp. gradient	0.0388	°C/mm			
		Heave Rate	2.57561	mm/day			
		Water Intake Rate	4.6211	ml/day			
	2nd	Slope	25.607	mm/°C	63.0	153.6	9.91
		Temp. gradient	0.0391	°C/mm			
		Heave Rate	2.461538	mm/day			
		Water Intake Rate	6	ml/day			
Black-2	1st	Slope	27.065	mm/°C	61.2	61.1	3.94
		Temp. gradient	0.0369	°C/mm			
		Heave Rate	2.262857	mm/day			
		Water Intake Rate	2.257	ml/day			
	2nd	Slope	26.685	mm/°C	74.7	200.1	12.91
		Temp. gradient	0.0375	°C/mm			
		Heave Rate	2.8	mm/day			
		Water Intake Rate	7.5	ml/day			
Yellow-3	1st	Slope	21.124	mm/°C	43.7	48.28	3.11
		Temp. gradient	0.0473	°C/mm			
		Heave Rate	2.067153	mm/day			
		Water Intake Rate	2.286	ml/day			
	2nd	Slope	20.925	mm/°C	60.46	216.6	14.0
		Temp. gradient	0.0478	°C/mm			
		Heave Rate	2.88932	mm/day			
		Water Intake Rate	10.35	ml/day			
Green-4	1st	Slope	51.217	mm/°C	86.4	298.47	19.25
		Temp. gradient	0.0195	°C/mm			
		Heave Rate	1.6875	mm/day			
		Water Intake Rate	5.827	ml/day			
	2nd	Slope	47.442	mm/°C	104.3	238.97	15.4
		Temp. gradient	0.0211	°C/mm			
		Heave Rate	2.199203	mm/day			
		Water Intake Rate	5.037	ml/day			

Table 4.20 The segregation potential calculations for “12_F Kum Mix 0”

12_F Kum-Mixture 0							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	30.041	mm/°C	71.5	330.5	21.31
		Temp. gradient	0.0333	°C/mm			
		Heave Rate	2.38	mm/day			
		Water Intake Rate	11.0	ml/day			
	2nd	Slope	31.236	mm/°C	95.4	7809.0	503.57
		Temp. gradient	0.0320	°C/mm			
		Heave Rate	3.0533	mm/day			
		Water Intake Rate	250.0	ml/day			
Black-2	1st	Slope	31.032	mm/°C	74.48	323.8	20.88
		Temp. gradient	0.0322	°C/mm			
		Heave Rate	2.4	mm/day			
		Water Intake Rate	10.43	ml/day			
	2nd	Slope	34.128	mm/°C	93.74	497.5	32.08
		Temp. gradient	0.0293	°C/mm			
		Heave Rate	2.75	mm/day			
		Water Intake Rate	14.5767	ml/day			
Yellow-3	1st	Slope	13.085	mm/°C	33.1	4803.0	309.72
		Temp. gradient	0.0764	°C/mm			
		Heave Rate	2.533	mm/day			
		Water Intake Rate	367.0588	ml/day			
	2nd	Slope	18.787	mm/°C	55.08	0.0	0.00
		Temp. gradient	0.0532	°C/mm			
		Heave Rate	2.932	mm/day			
		Water Intake Rate	0	ml/day			
Green-4	1st	Slope	26.187	mm/°C	45.1	46.94	3.04
		Temp. gradient	0.0382	°C/mm			
		Heave Rate	1.72	mm/day			
		Water Intake Rate	1.79	ml/day			
	2nd	Slope	24.716	mm/°C	62.17	1076.2	63.45
		Temp. gradient	0.0405	°C/mm			
		Heave Rate	2.5155	mm/day			
		Water Intake Rate	43.54	ml/day			

Table 4.21 The segregation potential calculations for “13_F Kum Mix 1”

13_F Kum-Mixture 1							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_{convert}} (mm ² /°C-day)
Blue-1	1st	Slope	28.682	mm/°C	136.6	924.99	59.65
		Temp. gradient	0.0349	°C/mm			
		Heave Rate	4.7622	mm/day			
		Water Intake Rate	32.3	ml/day			
	2nd	Slope	26.534	mm/°C	133.84	589.05	37.99
		Temp. gradient	0.0377	°C/mm			
		Heave Rate	5.0441	mm/day			
		Water Intake Rate	22.20	ml/day			
Black-2	1st	Slope	29.413	mm/°C	111.7	922.1	59.46
		Temp. gradient	0.0340	°C/mm			
		Heave Rate	3.7962	mm/day			
		Water Intake Rate	31.35	ml/day			
	2nd	Slope	30.817	mm/°C	121.2	970.7	62.60
		Temp. gradient	0.0324	°C/mm			
		Heave Rate	3.93	mm/day			
		Water Intake Rate	31.5	ml/day			
Yellow-3	1st	Slope	15.503	mm/°C	69.3	1300.4	83.86
		Temp. gradient	0.0645	°C/mm			
		Heave Rate	4.4727	mm/day			
		Water Intake Rate	83.8835	ml/day			
	2nd	Slope	16.506	mm/°C	72.79	1683.6	108.6
		Temp. gradient	0.0606	°C/mm			
		Heave Rate	4.410	mm/day			
		Water Intake Rate	102	ml/day			
Green-4	1st	Slope	20.851	mm/°C	106.39	795.7	51.31
		Temp. gradient	0.0480	°C/mm			
		Heave Rate	5.1025	mm/day			
		Water Intake Rate	38.159	ml/day			
	2nd	Slope	20.006	mm/°C	93.21	1129.75	72.85
		Temp. gradient	0.0500	°C/mm			
		Heave Rate	4.6593	mm/day			
		Water Intake Rate	56.47	ml/day			

Table 4.22 The segregation potential calculations for “14_F Kum Mix 2”

14_F Kum-Mixture 2							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	30.13	mm/°C	344.6	4709.3	303.68
		Temp. gradient	0.0332	°C/mm			
		Heave Rate	11.4383	mm/day			
		Water Intake Rate	156.3	ml/day			
	2nd	Slope	30.701	mm/°C	273.03	4485.02	289.22
		Temp. gradient	0.0326	°C/mm			
		Heave Rate	8.8931	mm/day			
		Water Intake Rate	146.09	ml/day			
Black-2	1st	Slope	27.02	mm/°C	239.44	0.0	0.00
		Temp. gradient	0.0370	°C/mm			
		Heave Rate	8.8615	mm/day			
		Water Intake Rate	0	ml/day			
	2nd	Slope	27.827	mm/°C	278.61	0.0	0.00
		Temp. gradient	0.0359	°C/mm			
		Heave Rate	10.01	mm/day			
		Water Intake Rate	0	ml/day			
Yellow-3	1st	Slope	10.998	mm/°C	49.19	1731.1	111.63
		Temp. gradient	0.0909	°C/mm			
		Heave Rate	4.4727	mm/day			
		Water Intake Rate	157.4026	ml/day			
	2nd	Slope	11.269	mm/°C	49.7	1445.83	93.2
		Temp. gradient	0.0887	°C/mm			
		Heave Rate	4.410	mm/day			
		Water Intake Rate	128.302	ml/day			
Green-4	1st	Slope	33.214	mm/°C	169.48	4490.2	289.55
		Temp. gradient	0.0301	°C/mm			
		Heave Rate	5.1025	mm/day			
		Water Intake Rate	135	ml/day			
	2nd	Slope	30.823	mm/°C	143.61	3020.29	194.77
		Temp. gradient	0.0324	°C/mm			
		Heave Rate	4.6593	mm/day			
		Water Intake Rate	97.99	ml/day			

Table 4.23 The segregation potential calculations for “15_F Kum Mix 3”

15_F Kum-Mixture 3							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_{convert}} (mm ² /°C-day)
Blue-1	1st	Slope	29.068	mm/°C	410.01	7194.3	463.93
		Temp. gradient	0.0344	°C/mm			
		Heave Rate	14.1053	mm/day			
		Water Intake Rate	247.5	ml/day			
	2nd	Slope	27.746	mm/°C	343.8	6017.95	388.07
		Temp. gradient	0.0360	°C/mm			
		Heave Rate	12.390	mm/day			
		Water Intake Rate	216.89	ml/day			
Black-2	1st	Slope	13.365	mm/°C	214.8	3327.9	214.60
		Temp. gradient	0.0748	°C/mm			
		Heave Rate	16.0724	mm/day			
		Water Intake Rate	249	ml/day			
	2nd	Slope	27.249	mm/°C	394.58	6131.03	395.36
		Temp. gradient	0.0367	°C/mm			
		Heave Rate	14.48	mm/day			
		Water Intake Rate	225	ml/day			
Yellow-3	1st	Slope	12.623	mm/°C	246.55	4087.03	263.55
		Temp. gradient	0.0792	°C/mm			
		Heave Rate	19.5320	mm/day			
		Water Intake Rate	323.7764	ml/day			
	2nd	Slope	13.063	mm/°C	201.76	3407.7	219.75
		Temp. gradient	0.0766	°C/mm			
		Heave Rate	15.445	mm/day			
		Water Intake Rate	261	ml/day			
Green-4	1st	Slope	24.097	mm/°C	452.1	8602.63	554.75
		Temp. gradient	0.0415	°C/mm			
		Heave Rate	18.7636	mm/day			
		Water Intake Rate	357	ml/day			
	2nd	Slope	17.971	mm/°C	258.78	4527.5	291.96
		Temp. gradient	0.0556	°C/mm			
		Heave Rate	14.4	mm/day			
		Water Intake Rate	251.93	ml/day			

Table 4.24 The segregation potential calculations for “16_F Kum Mix 4”

16_F Kum-Mixture 4							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	28.497	mm/°C	581.5	6497.3	418.98
		Temp. gradient	0.0351	°C/mm			
		Heave Rate	20.4064	mm/day			
		Water Intake Rate	228	ml/day			
	2nd	Slope	25.891	mm/°C	394.0	6177.3	398.35
		Temp. gradient	0.0386	°C/mm			
		Heave Rate	15.2177	mm/day			
		Water Intake Rate	238.59	ml/day			
Black-2	1st	Slope	26.259	mm/°C	533.7	0.0	0.00
		Temp. gradient	0.0381	°C/mm			
		Heave Rate	20.3259	mm/day			
		Water Intake Rate	0	ml/day			
	2nd	Slope	23.511	mm/°C	355.5	6330.3	408.22
		Temp. gradient	0.0425	°C/mm			
		Heave Rate	15.12	mm/day			
		Water Intake Rate	269.25	ml/day			
Yellow-3	1st	Slope	17.565	mm/°C	230.35	4030.0	259.88
		Temp. gradient	0.0569	°C/mm			
		Heave Rate	13.1141	mm/day			
		Water Intake Rate	229.434	ml/day			
	2nd	Slope	16.083	mm/°C	257.33	4077.04	262.9
		Temp. gradient	0.0622	°C/mm			
		Heave Rate	16	mm/day			
		Water Intake Rate	253.5	ml/day			
Green-4	1st	Slope	23.58	mm/°C	328.3	5501.02	354.74
		Temp. gradient	0.0424	°C/mm			
		Heave Rate	13.9227	mm/day			
		Water Intake Rate	233.29	ml/day			
	2nd	Slope	18.221	mm/°C	310.77	5239.4	337.9
		Temp. gradient	0.0549	°C/mm			
		Heave Rate	17.0558	mm/day			
		Water Intake Rate	287.55	ml/day			

Table 4.25 The segregation potential calculations for “17_GF Mix 1”

17_GF-Mixture 1							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot_Heave (mm ² /°C-day)	Seg Pot_water intake rate (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	77.193	mm/°C	502.4	183.99	11.86
		Temp. gradient	0.0130	°C/mm			
		Heave Rate	6.5090	mm/day			
		Water Intake Rate	2.4	ml/day			
	2nd	Slope	44.233	mm/°C	181.4	1559.0	100.53
		Temp. gradient	0.0226	°C/mm			
		Heave Rate	4.1	mm/day			
		Water Intake Rate	35.25	ml/day			
Black-2	1st	Slope	33.966	mm/°C	164.8	352.0	22.70
		Temp. gradient	0.0294	°C/mm			
		Heave Rate	4.8525	mm/day			
		Water Intake Rate	10.362	ml/day			
	2nd	Slope	37.084	mm/°C	145.6	548.2	35.35
		Temp. gradient	0.0270	°C/mm			
		Heave Rate	3.93	mm/day			
		Water Intake Rate	14.7815	ml/day			
Yellow-3	1st	Slope	14.853	mm/°C	91.4	481.6	31.05
		Temp. gradient	0.0673	°C/mm			
		Heave Rate	6.1523	mm/day			
		Water Intake Rate	32.4224	ml/day			
	2nd	Slope	16.249	mm/°C	65.80	954.5	61.6
		Temp. gradient	0.0615	°C/mm			
		Heave Rate	4.050	mm/day			
		Water Intake Rate	59	ml/day			
Green-4	1st	Slope	50.827	mm/°C	289.7	1871.56	120.69
		Temp. gradient	0.0197	°C/mm			
		Heave Rate	5.7	mm/day			
		Water Intake Rate	37	ml/day			
	2nd	Slope	71.675	mm/°C	262.1	2914.8	187.96
		Temp. gradient	0.0140	°C/mm			
		Heave Rate	3.6566	mm/day			
		Water Intake Rate	40.67	ml/day			

Table 4.26 The segregation potential calculations for “18_GF Mix 2”

18_GF-Mixture 2							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h₂o convert} (mm ² /°C-day)
Blue-1	1st	Slope	33.497	mm/°C	131.9	-245.7	-15.84
		Temp. gradient	0.0299	°C/mm			
		Heave Rate	3.9366	mm/day			
		Water Intake Rate	-7.3	ml/day			
	2nd	Slope	37.827	mm/°C	114.1	0.0	0.0
		Temp. gradient	0.0264	°C/mm			
		Heave Rate	3.0168	mm/day			
		Water Intake Rate	0.0	ml/day			
Black-2	1st	Slope	46.72	mm/°C	245.2	2.8	0.18
		Temp. gradient	0.0214	°C/mm			
		Heave Rate	5.2490	mm/day			
		Water Intake Rate	0.06	ml/day			
	2nd	Slope	45.211	mm/°C	156.9	145.3	9.37
		Temp. gradient	0.0221	°C/mm			
		Heave Rate	3.47	mm/day			
		Water Intake Rate	3.2145	ml/day			
Yellow-3	1st	Slope	17.562	mm/°C	79.86	658.05	42.43
		Temp. gradient	0.0569	°C/mm			
		Heave Rate	4.5474	mm/day			
		Water Intake Rate	37.4700	ml/day			
	2nd	Slope	18.474	mm/°C	35.85	1005.17	64.82
		Temp. gradient	0.0541	°C/mm			
		Heave Rate	1.941	mm/day			
		Water Intake Rate	54.4	ml/day			
Green-4	1st	Slope	28.109	mm/°C	166.9	311.59	20.09
		Temp. gradient	0.0356	°C/mm			
		Heave Rate	5.9377	mm/day			
		Water Intake Rate	11.08	ml/day			
	2nd	Slope	29.707	mm/°C	105.3	162.96	10.5
		Temp. gradient	0.0337	°C/mm			
		Heave Rate	3.5433	mm/day			
		Water Intake Rate	5.49	ml/day			

Table 4.27 The segregation potential calculations for “19_GF Mix 3”

19_GF-Mixture 3							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h₂O convert} (mm ² /°C-day)
Blue-1	1st	Slope	28.383	mm/°C	226.7	2256.4	145.51
		Temp. gradient	0.0352	°C/mm			
		Heave Rate	7.9871	mm/day			
		Water Intake Rate	79.5	ml/day			
	2nd	Slope	22.119	mm/°C	131.1	-115.4	-7.44
		Temp. gradient	0.0452	°C/mm			
		Heave Rate	5.9287	mm/day			
		Water Intake Rate	-5.22	ml/day			
Black-2	1st	Slope	32.307	mm/°C	400.3	1235.7	79.69
		Temp. gradient	0.0310	°C/mm			
		Heave Rate	12.39	mm/day			
		Water Intake Rate	38.25	ml/day			
	2nd	Slope	33.782	mm/°C	196.4	1133.1	73.07
		Temp. gradient	0.0296	°C/mm			
		Heave Rate	5.81	mm/day			
		Water Intake Rate	33.54	ml/day			
Yellow-3	1st	Slope	14.764	mm/°C	99.0	276.8	17.85
		Temp. gradient	0.0677	°C/mm			
		Heave Rate	6.7079	mm/day			
		Water Intake Rate	18.75	ml/day			
	2nd	Slope	12.016	mm/°C	46.18	378.5	24.4
		Temp. gradient	0.0832	°C/mm			
		Heave Rate	3.843	mm/day			
		Water Intake Rate	31.5	ml/day			
Green-4	1st	Slope	26.442	mm/°C	193.3	1348.54	86.96
		Temp. gradient	0.0378	°C/mm			
		Heave Rate	7.3091	mm/day			
		Water Intake Rate	51	ml/day			
	2nd	Slope	31.098	mm/°C	162.1	1668.9	107.6
		Temp. gradient	0.0322	°C/mm			
		Heave Rate	5.2127	mm/day			
		Water Intake Rate	53.66	ml/day			

Table 4.28 The segregation potential calculations for “20_GF Mix 4”

20_GF-Mixture 4							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_{th} convert} (mm ² /°C-day)
Blue-1	1st	Slope	7.2291	mm/°C	72.27	997.6	64.33
		Temp. gradient	0.1383	°C/mm			
		Heave Rate	9.9967	mm/day			
		Water Intake Rate	138.0	ml/day			
	2nd	Slope	1.4042	mm/°C	10.6	166.4	10.73
		Temp. gradient	0.7121	°C/mm			
		Heave Rate	7.5608	mm/day			
		Water Intake Rate	118.5	ml/day			
Black-2	1st	Slope	27.815	mm/°C	365.05	4986.1	321.53
		Temp. gradient	0.0360	°C/mm			
		Heave Rate	13.1244	mm/day			
		Water Intake Rate	179	ml/day			
	2nd	Slope	26.832	mm/°C	0.0	3461.3	223.21
		Temp. gradient	0.0373	°C/mm			
		Heave Rate	0.00	mm/day			
		Water Intake Rate	129.0000	ml/day			
Yellow-3	1st	Slope	12.83	mm/°C	85.9	1289.4	83.15
		Temp. gradient	0.0779	°C/mm			
		Heave Rate	6.6980	mm/day			
		Water Intake Rate	100.5	ml/day			
	2nd	Slope	12.745	mm/°C	78.89	1147.1	73.97
		Temp. gradient	0.0785	°C/mm			
		Heave Rate	6.190	mm/day			
		Water Intake Rate	90	ml/day			
Green-4	1st	Slope	27.193	mm/°C	318.7	3364.50	216.96
		Temp. gradient	0.0368	°C/mm			
		Heave Rate	11.7183	mm/day			
		Water Intake Rate	124	ml/day			
	2nd	Slope	39.055	mm/°C	345.2	3186.9	205.5
		Temp. gradient	0.0256	°C/mm			
		Heave Rate	8.8375	mm/day			
		Water Intake Rate	81.6	ml/day			

Table 4.29 The segregation potential calculations for “22_YK Mix 1”

21_YK Mixture 1							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_{convert}} (mm ² /°C-day)
Blue-1	1st	Slope	22.691	mm/°C	85.06	724.98	46.75
		Temp. gradient	0.0441	°C/mm			
		Heave Rate	3.7486	mm/day			
		Water Intake Rate	31.9500	ml/day			
	2nd	Slope	24.22	mm/°C	72.57	296.09	19.09
		Temp. gradient	0.0413	°C/mm			
		Heave Rate	2.9963	mm/day			
		Water Intake Rate	12.225	ml/day			
Black-2	1st	Slope	27.989	mm/°C	102.5	505.9	32.62
		Temp. gradient	0.0357	°C/mm			
		Heave Rate	3.6612	mm/day			
		Water Intake Rate	18.075	ml/day			
	2nd	Slope	27.922	mm/°C	87.95	699.1	45.08
		Temp. gradient	0.0358	°C/mm			
		Heave Rate	3.15	mm/day			
		Water Intake Rate	25.04	ml/day			
Yellow-3	1st	Slope	13.286	mm/°C	45.99	308.9	19.92
		Temp. gradient	0.0753	°C/mm			
		Heave Rate	3.4615	mm/day			
		Water Intake Rate	23.25	ml/day			
	2nd	Slope	12.943	mm/°C	33.59	417.4	26.92
		Temp. gradient	0.0773	°C/mm			
		Heave Rate	2.595	mm/day			
		Water Intake Rate	32.25	ml/day			
Green-4	1st	Slope	16.902	mm/°C	55.49	329.6	21.25
		Temp. gradient	0.0592	°C/mm			
		Heave Rate	3.283	mm/day			
		Water Intake Rate	19.5	ml/day			
	2nd	Slope	18.016	mm/°C	63.78	284.7	18.36
		Temp. gradient	0.0555	°C/mm			
		Heave Rate	3.5404	mm/day			
		Water Intake Rate	15.8012	ml/day			

Table 4.30 The segregation potential calculations for “22_YK Mix 2”

22_YK Mixture 2							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_{convert}} (mm ² /°C-day)
Blue-1	1st	Slope	29.21	mm/°C	109.5	1007.7	64.99
		Temp. gradient	0.0342	°C/mm			
		Heave Rate	3.7486	mm/day			
		Water Intake Rate	34.5	ml/day			
	2nd	Slope	27.117	mm/°C	81.2	935.5	60.33
		Temp. gradient	0.0369	°C/mm			
		Heave Rate	2.9963	mm/day			
		Water Intake Rate	34.5	ml/day			
Black-2	1st	Slope	29.118	mm/°C	106.6	1834.4	118.29
		Temp. gradient	0.0343	°C/mm			
		Heave Rate	3.6612	mm/day			
		Water Intake Rate	63	ml/day			
	2nd	Slope	28.865	mm/°C	90.9	2108.4	135.96
		Temp. gradient	0.0346	°C/mm			
		Heave Rate	3.15	mm/day			
		Water Intake Rate	73.0435	ml/day			
Yellow-3	1st	Slope	15.265	mm/°C	52.8	728.2	46.96
		Temp. gradient	0.0655	°C/mm			
		Heave Rate	3.4615	mm/day			
		Water Intake Rate	47.7019	ml/day			
	2nd	Slope	15.515	mm/°C	40.26	1861.8	120.1
		Temp. gradient	0.0645	°C/mm			
		Heave Rate	2.595	mm/day			
		Water Intake Rate	120	ml/day			
Green-4	1st	Slope	26.417	mm/°C	86.7	1188.77	76.66
		Temp. gradient	0.0379	°C/mm			
		Heave Rate	3.2830	mm/day			
		Water Intake Rate	45	ml/day			
	2nd	Slope	25.784	mm/°C	91.3	1527.7	98.5
		Temp. gradient	0.0388	°C/mm			
		Heave Rate	3.5404	mm/day			
		Water Intake Rate	59.25	ml/day			

Table 4.31 The segregation potential calculations for “23_YK Mix 3”

23_YK Mixture 3							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_{convert}} (mm ² /°C-day)
Blue-1	1st	Slope	22.132	mm/°C	101.6	1958.7	126.31
		Temp. gradient	0.0452	°C/mm			
		Heave Rate	4.5885	mm/day			
		Water Intake Rate	88.5	ml/day			
	2nd	Slope	22.884	mm/°C	120.4	1956.6	126.17
		Temp. gradient	0.0437	°C/mm			
		Heave Rate	5.2606	mm/day			
		Water Intake Rate	85.5	ml/day			
Black-2	1st	Slope	28.366	mm/°C	151.8	2106.2	135.82
		Temp. gradient	0.0353	°C/mm			
		Heave Rate	5.3509	mm/day			
		Water Intake Rate	74.25	ml/day			
	2nd	Slope	29.486	mm/°C	200.9	2698.0	173.98
		Temp. gradient	0.0339	°C/mm			
		Heave Rate	6.81	mm/day			
		Water Intake Rate	91.5	ml/day			
Yellow-3	1st	Slope	16.583	mm/°C	92.5	1201.5	77.48
		Temp. gradient	0.0603	°C/mm			
		Heave Rate	5.5770	mm/day			
		Water Intake Rate	72.4528	ml/day			
	2nd	Slope	12.672	mm/°C	66.60	1090.3	70.3
		Temp. gradient	0.0789	°C/mm			
		Heave Rate	5.256	mm/day			
		Water Intake Rate	86.0377	ml/day			
Green-4	1st	Slope	21.348	mm/°C	107.8	1855.67	119.66
		Temp. gradient	0.0468	°C/mm			
		Heave Rate	5.0512	mm/day			
		Water Intake Rate	86.925	ml/day			
	2nd	Slope	20.331	mm/°C	122.0	1951.8	125.9
		Temp. gradient	0.0492	°C/mm			
		Heave Rate	6	mm/day			
		Water Intake Rate	96	ml/day			

Table 4.32 The segregation potential calculations for “24_YK Mix 4”

24_YK Mixture 4							
Sample No.	Freeze No.	Measured Values		Units	Seg Pot _{Heave} (mm ² /°C-day)	Seg Pot _{water intake rate} (mm ² /°C-day)	Seg Pot _{h_convert} (mm ² /°C-day)
Blue-1	1st	Slope	21.857	mm/°C	135.2	1889.7	121.86
		Temp. gradient	0.0458	°C/mm			
		Heave Rate	6.1870	mm/day			
		Water Intake Rate	86.46	ml/day			
	2nd	Slope	25.516	mm/°C	156.2	2277.3	146.85
		Temp. gradient	0.0392	°C/mm			
		Heave Rate	6.12197	mm/day			
		Water Intake Rate	89.25	ml/day			
Black-2	1st	Slope	27.254	mm/°C	179.4	2616.4	168.72
		Temp. gradient	0.0367	°C/mm			
		Heave Rate	6.58156	mm/day			
		Water Intake Rate	96	ml/day			
	2nd	Slope	26.803	mm/°C	191.1	2437.2	157.17
		Temp. gradient	0.0373	°C/mm			
		Heave Rate	7.13	mm/day			
		Water Intake Rate	90.93	ml/day			
Yellow-3	1st	Slope	9.7713	mm/°C	62.1	1978.7	127.60
		Temp. gradient	0.1023	°C/mm			
		Heave Rate	6.3594	mm/day			
		Water Intake Rate	202.5	ml/day			
	2nd	Slope	11.731	mm/°C	79.23	3800.8	245.1
		Temp. gradient	0.0852	°C/mm			
		Heave Rate	6.754	mm/day			
		Water Intake Rate	324	ml/day			
Green-4	1st	Slope	14.282	mm/°C	89.6	1542.46	99.47
		Temp. gradient	0.0700	°C/mm			
		Heave Rate	6.2752	mm/day			
		Water Intake Rate	108	ml/day			
	2nd	Slope	14.055	mm/°C	98.1	1349.28	87.0
		Temp. gradient	0.0711	°C/mm			
		Heave Rate	6.9795	mm/day			
		Water Intake Rate	96.00	ml/day			

And the Table 4.33 and Table 4.34 show the freeze-thaw results in a summary for both 1st and 2nd freezing cycles.

Table 4.33 Summary table to the heave rate and the Segregation potential calculations of the 1st freezing cycle

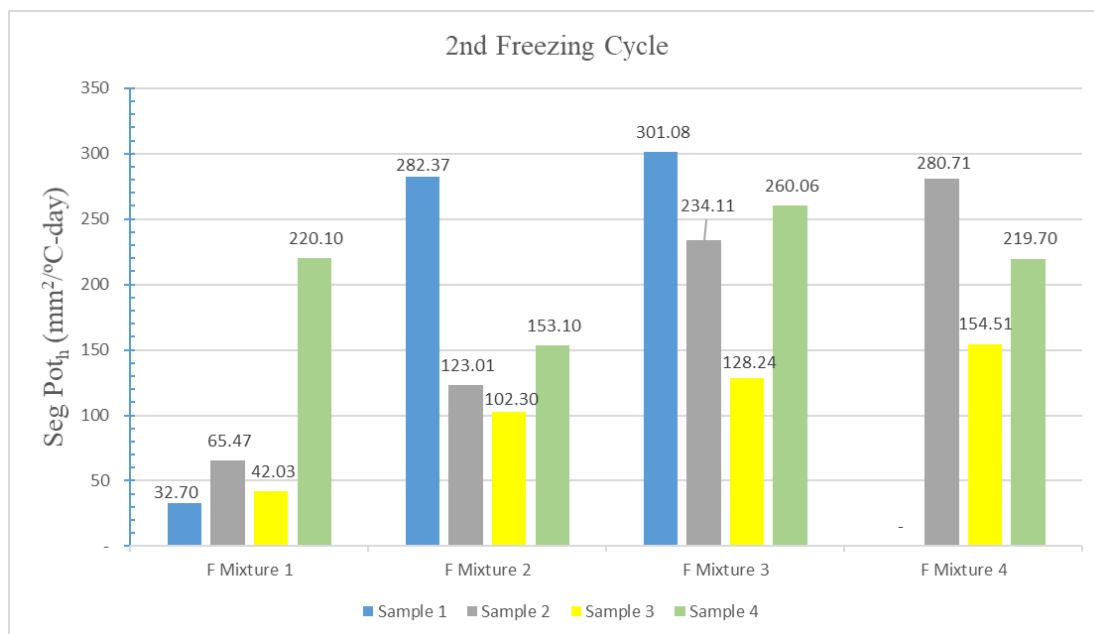
Mixtures group	Mixtures name	Fines content, ρ_F (%)	Average 1 st frostheave rate	Maximum & minimum 1 st frost heave	Average 1 st Freezing Segregation Potential, SegPot (from Heave or Water Intake)			Maximum & minimum of the 1 st Freezing Segregation Potential		
			(mm/day)		Seg Pot _{th} (mm ² /°C-day)	Seg Pot _w (ml-mm/°C-day)	Seg Pot _{th convert} (mm ² /°C-day)	Seg Pot _{th} (mm ² /°C-day)	Seg Pot _w (ml-mm/°C-day)	Seg Pot _{th convert} (mm ² /°C-day)
Group-1	1_F-Mix1	5.24	2.89	3.21-2.41	75.7	900.2	58.1	154.52-48.40	2054.05-307.58	132.45-19.83
	2_F-Mix 2	9.5	8.42	9.78-6.33	187.8	3302.1	212.9	250.14-139.61	3813.52-2864.55	245.91-184.72
	3_F-Mix 3	13.75	10.8	12-8.65	248.4	4168.2	268.8	304.45-151.67	4811.98-3615.36	310.3-233.13
	4_F-Mix 4	18	13.2	14.94-10.81	279.8	5192.8	334.9	395.01-191.24	7805.78-2616.99	503.36-168.75
Group -2	5_K-Mix 1	5.24	9.02	10.89-6.92	214.1	3736.2	240.9	261.16-180.09	7360.15-1940.25	474.62-125.11
	6_K-Mix 2	9.5	13.7	14.48-12.24	332.7	4525.4	291.8	407.18-162.25	6374.52-2665.03	411.06-171.85
	(7-8)_K-Mix (3-4)	13.75	20.5	21.48-19.5	579.9	3638.7	234.6	640.55-519.20	3941.88-3335.46	254.19-215.08
		18	20.6	23.12-18	467.0	4640.5	299.2	507.45-426.51	5331.37-3949.56	343.79-254.68
	8_K-Mix 4	18	15.1	16.84-13.92	415.3	5647.1	364.2	584.5,266.1	9156.94-2068.93	590.49-133.41
Group-3	9_B-Mix 1	5.24	1.23	1.45-1.02	32.5	72.7	4.7	47.06-11.62	93.84-13.38	6.05-0.86
	10_B-Mix 2	9.5	1.18	1.98-0.51	30.0	1165.5	75.2	57.14-13.79	3297.02-187.74	212.61-12.10
	11_B Mix 3	13.75	2.15	2.57-1.68	64.4	131.7	8.5	86.42-43.66	298.46-48.28	19.24-3.11
Group - 4	12_F Kum Mix 0	5.2	2.26	2.53-1.72	56.0	1376.1	88.7	74.48-33.1	4803-46.94	309.72-3.04
	13_F Kum Mix 1	8.2	4.53	5.10-3.79	106.0	985.8	63.6	136.58-69.34	1300.44-795.65	83.86-51.30
	13_F Kum Mix 1	12.2	8.58	11.43-5.28	200.7	3643.5	235.0	344.63-49.19	4709.31-1731.11	303.68-111.63
	15_F Kum Mix 3	16.3	17.1	19.53-14.10	330.9	5803.0	374.2	452.14-214.8	8602.62-3327.88	554.74-214.6
	16_F Kum Mix 3	20.3	16.9	20.40-13.13	418.5	5342.8	344.5	581.52-230.34	6497.31-4030	418.98-259.87
Group - 5	17_GF Mix 1	5.24	5.80	6.5-4.85	262.1	722.3	46.6	502.44-91.38	1871.56,-183.99	120.68-11.86
	18_GF Mix 2	9.5	4.92	5.93-3.93	156.0	324.1	20.9	245.23-79.86	658.04-2.8	42.43-0.18
	19_GF Mix 3	13.75	8.60	12.39-6.7	229.8	1279.4	82.5	400.33-99.03	2256.44-276.82	145.50-17.85
	20_GF Mix 4	18	10.38	13.12-6.69	210.5	2659.4	171.5	365.05-72.26	4986.09-997.61	321.53-64.33

Mixtures group	Mixtures name	Fines content, ρ_F (%)	Average 1 st frostheave rate	Maximum & minimum 1 st frost heave	Average 1 st Freezing Segregation Potential, SegPot (from Heave or Water Intake)			Maximum & minimum of the 1 st Freezing Segregation Potential		
			(mm/day)	(mm/day)	Seg Pot _h (mm ² /°C-day)	Seg Pot _w (ml-mm/°C-day)	Seg Pot _{h convert} (mm ² /°C-day)	Seg Pot _h (mm ² /°C-day)	Seg Pot _w (ml-mm/°C-day)	Seg Pot _{h convert} (mm ² /°C-day)
Group -6	21_YK Mix 1	5.24	3.54	3.74-3.28	72.3	467.3	30.1	102.47-45.99	724.97-308.89	46.75-19.91
	22_YK Mix 2	9.5	4.38	5.14-3.69	88.9	1189.8	76.7	109.49-52.84	1834.43-728.16	118.29-46.95
	23_YK-Mix 3	13.75	5.14	5.57-4.58	113.4	1780.5	114.8	151.78-92.48	2106.17-1201.48	135.81-77.47
	24_YK Mix 4	18	6.35	6.58-6.18	116.6	2006.8	129.4	179.37-62.14	2616.38-1542.45	168.71-99.46

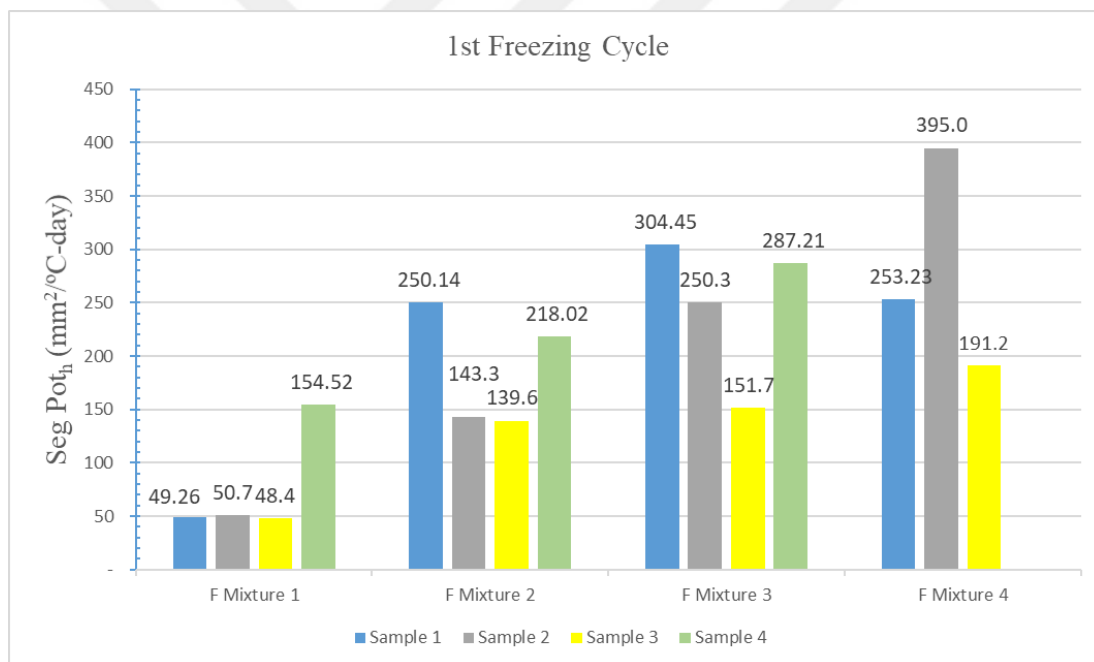
Table 4.34 Summary table to the heave rate and the Segregation potential calculations of the 2nd freezing cycle

Mixtures group	Mixtures name	Fines content, ρ_F (%)	Average 2 nd frostheave rate	Maximum & minimum 2 nd frost heave rate	Average 2 nd Freezing segregation potential, SegPot (from Heave or Water Intake)			Maximum & minimum of the 2 nd Freezing Segregation Potential		
			(mm/day)	(mm/day)	Seg Pot _h (mm ² /°C-day)	Seg Pot _w (ml-mm/°C-day)	Seg Pot _{h convert} (mm ² /°C-day)	Seg Pot _h (mm ² /°C-day)	Seg Pot _w (ml-mm/°C-day)	Seg Pot _{h convert} (mm ² /°C-day)
Group- 1	1_F Mix1	5.2	2.69	3.09-2.3	90.1	1793.3	115.6	220.1-32.7	4405.9-314.3	284.11-20.27
	2_F-Mix 2	9.5	6.75	8.65-5.63	165.2	2718.7	175.3	282.36-102.29	3864.54-2027.64	249.2-130.75
	3_F Mix 3	13.8	10.4	13.41-8.86	230.9	4005.8	258.3	301.08-128.24	6149.51-2019.78	396.55-130.24
	4_F Mix 4	18	9.79	11.39-8.5	218.3	3062.6	197.5	280.7-154.51	4523.98-2372.21	291.73-152.97
Group - 2	5_K-Mix 1	5.24	9.04	10.72-8	219.9	3320.7	214.1	262.96-172.63	5699.96-997.82	367.56-64.34
	6_K-Mix 2	9.5	14.4	16.4-13	360.2	6649.5	428.8	486.98-163.91	11111.97-3179.64	716.56-205.04
	(7-8)_K-Mix (3-4)	13.75	23.9	23.9	609.7	1935.9	124.8	666.51-552.93	2300.97-1570.84	148.37-101.29
	8_K Mix 4	18	25.1	25.1	451.1	4652.6	300.0	481.12-421.15	6918.97-2386.3	446.17-153.88

Mixtures group	Mixtures name	Fines content, ρ_F (%)	Average 2 nd frostheave rate	Maximum & minimum 2 nd frost heave rate	Average 2 nd Freezing segregation potential, SegPot (from Heave or Water Intake)			Maximum & minimum of the 2 nd Freezing Segregation Potential		
			(mm/day)	(mm/day)	Seg Pot _{th} (mm ² /°C-day)	Seg Pot _w (ml-mm ² /°C-day)	Seg Pot _{th convert} (mm ² /°C-day)	Seg Pot _{th} (mm ² /°C-day)	Seg Pot _w (ml-mm ² /°C-day)	Seg Pot _{th convert} (mm ² /°C-day)
Group - 3	8_K Mix 4	18	22.3	24.93-18.06	539.5	7837.8	505.4	856.19-315.71	11516.75-3907.22	742.66-251.96
	9_B Mix 1	5.2	1.88	2.62-1.12	44.1	49.6	3.2	65.22-25.09	74.45-4.53	4.8-0.29
	10_B Mix 2	9.5	1.10	1.68-0.7	24.1	238.2	15.4	28.68-20.8	470.8-102.2	30.35-6.59
Group - 4	11_B Mix 3	13.8	2.59	2.88-2.19	75.6	202.3	13.0	104.33-60.45	238.96-153.64	15.4-9.9
	13_F Kum Mix 1	8.2	4.51	5.04-3.93	105.3	1093.3	70.5	133.83-72.79	1683.61-589.05	108.56-37.98
	13_F Kum Mix 1	12.24	8.61	10.01-7.48	186.2	2983.7	192.4	278.61-49.69	4485.01-1445.83	289.21-93.23
	15_F Kum Mix 3	16.28	14.2	15.44-12.38	299.7	5021.1	323.8	394.57-201.76	6131.02-3407.73	395.36-219.75
	16_F Kum Mix 3	20.32	15.8	17.05-15.11	329.4	5456.0	351.8	394-257.32	6330.33-4077.04	408.21-262.91
	12_Kum Mix 0	5.24	2.81	3.05-2.51	76.6	3127.6	199.7	95.4-55.08	7809-497.5	503.57-32.08
Group - 5	17_GF Mix 1	5.24	3.93	4.09-3.65	163.7	1494.1	96.3	262.08-65.8	2914.78-548.15	187.96-35.34
	18_GF Mix 2	9.5	2.99	3.54-1.94	103.0	437.8	28.2	156.88-35.85	1005.16-145.33	64.81-9.37
	19_GF Mix 3	13.75	5.20	5.92-3.84	134.0	1060.1	68.4	196.44-46.18	1668.86-378.504	107.61-24.41
	20_GF Mix 4	18	7.53	8.83-6.19	108.7	1990.4	128.4	345.15-0	3461.32-166.41	223.2-10.73
Group - 6	21_YK Mix 1	5.24	3.07	3.54-2.59	64.5	424.3	27.4	87.95-33.58	699.08-284.67	45.08-18.35
	22_YK Mix 2	9.5	3.59	4.08-2.84	75.9	1608.4	103.7	91.28-40.26	2108.4-935.53	135.96-60.32
	23_YK Mix 3	13.75	5.83	6.81-5.25	127.5	1924.1	124.1	200.88-66.6	2697.96-1090.27	173.98-70.30
	24_YK Mix 4	18	6.75	7.12-6.12	131.2	2466.2	159.0	191.08-79.22	3800.84-1349.28	245.09-87.009

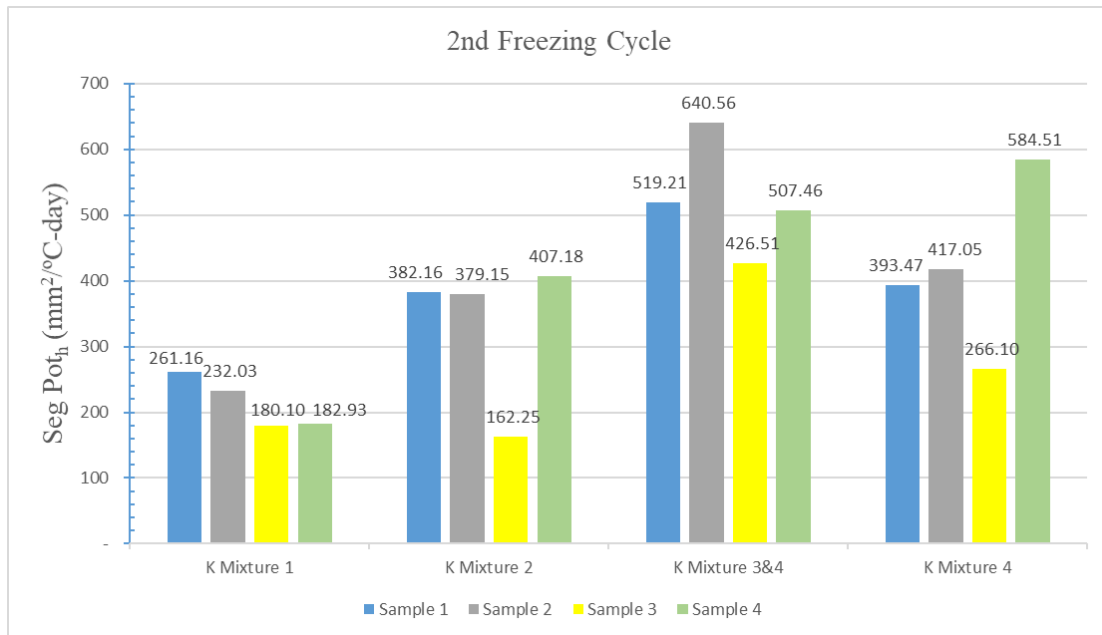


(a)

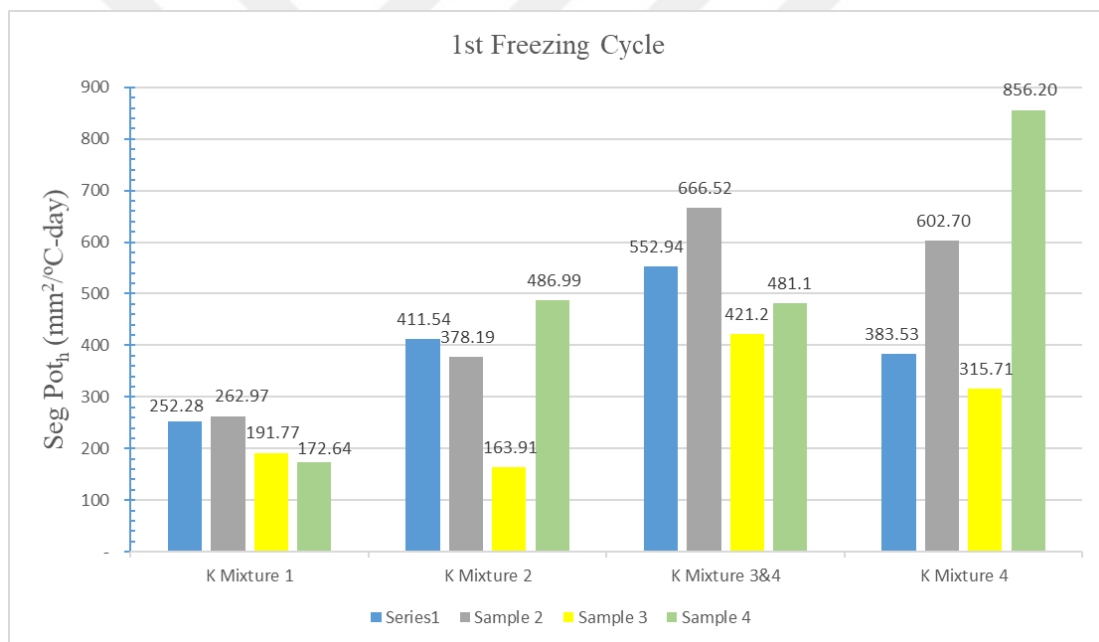


(b)

Figure 4.22 The result of Seg Pot_h (mm²/°C-day) calculations “Group-1”: (a) the Seg Pot_h values at the 1st freezing. (b) the Seg Pot_h values at the 2nd freezing

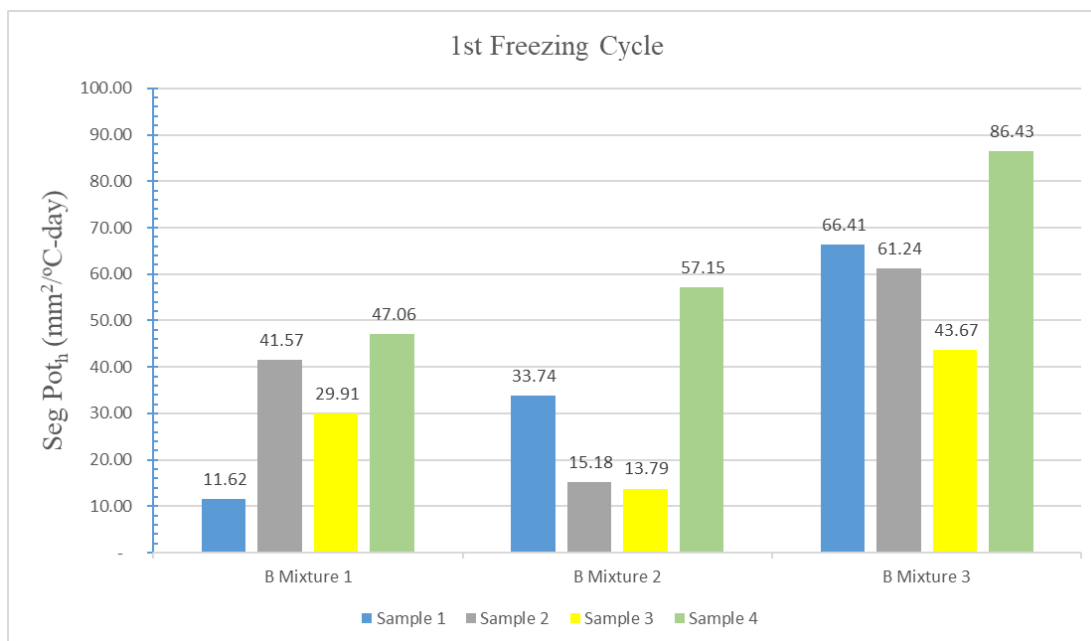


(a)

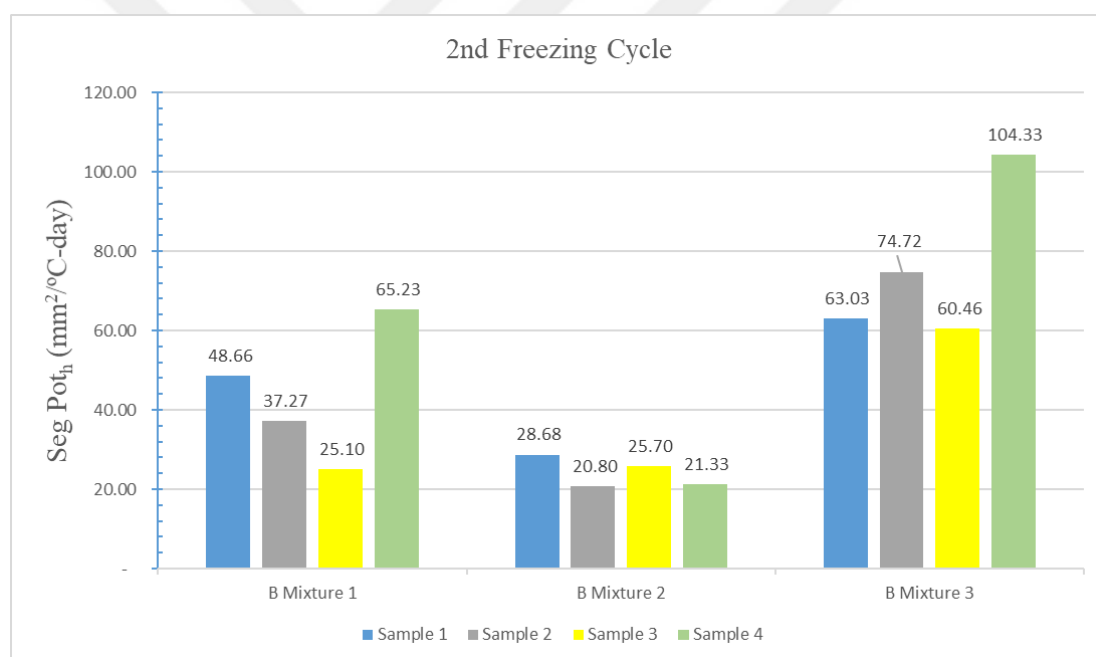


(b)

Figure 4.23 The result of Seg Pot_h (mm²/°C-day) calculations “Group-2”: (a) the Seg Pot_h values at the 1st freezing. (b) the Seg Pot_h values at the 2nd freezing

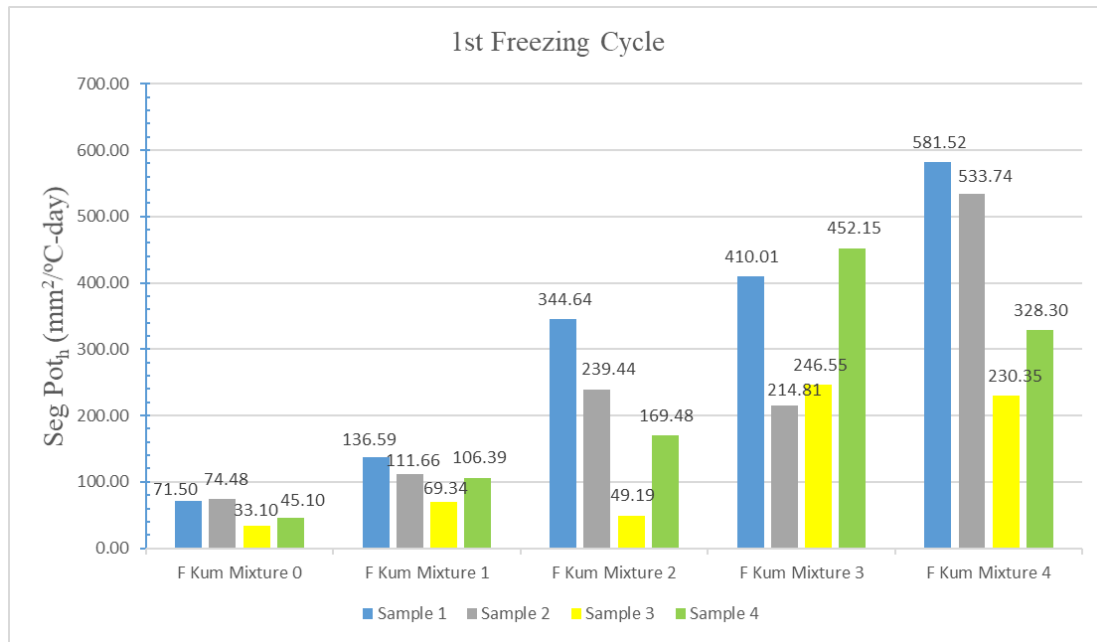


(a)

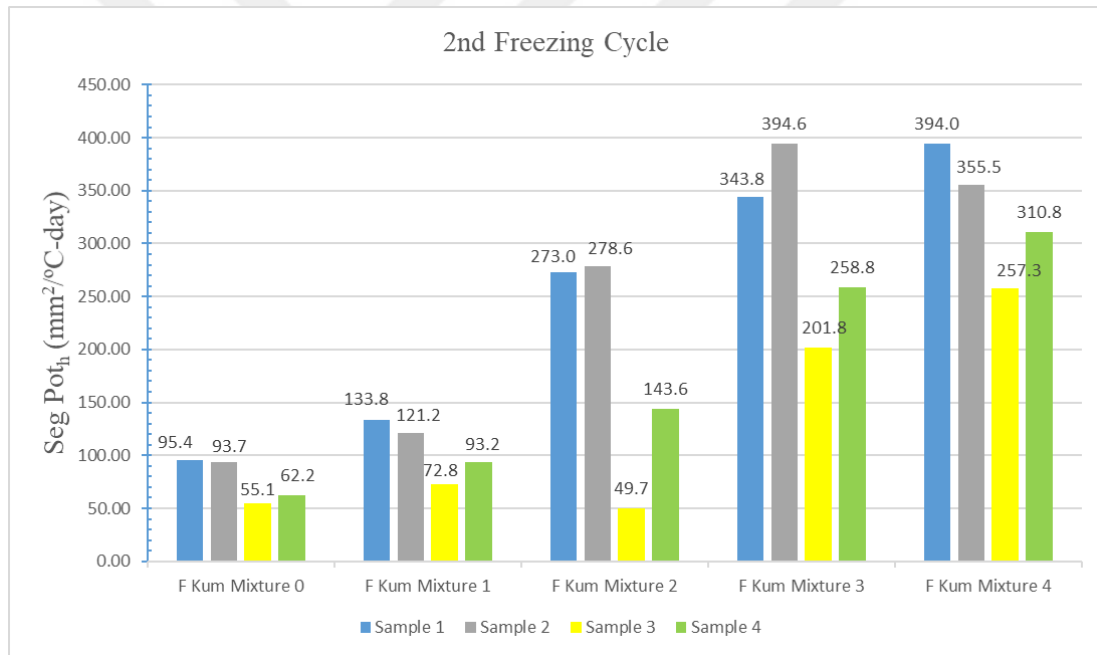


(b)

Figure 4.14 The result of Seg Pot_h (mm²/°C-day) calculations “Group-3”: (a) the Seg Pot_h values at the 1st freezing, (b) the Seg Pot_h values at the 2nd freezing

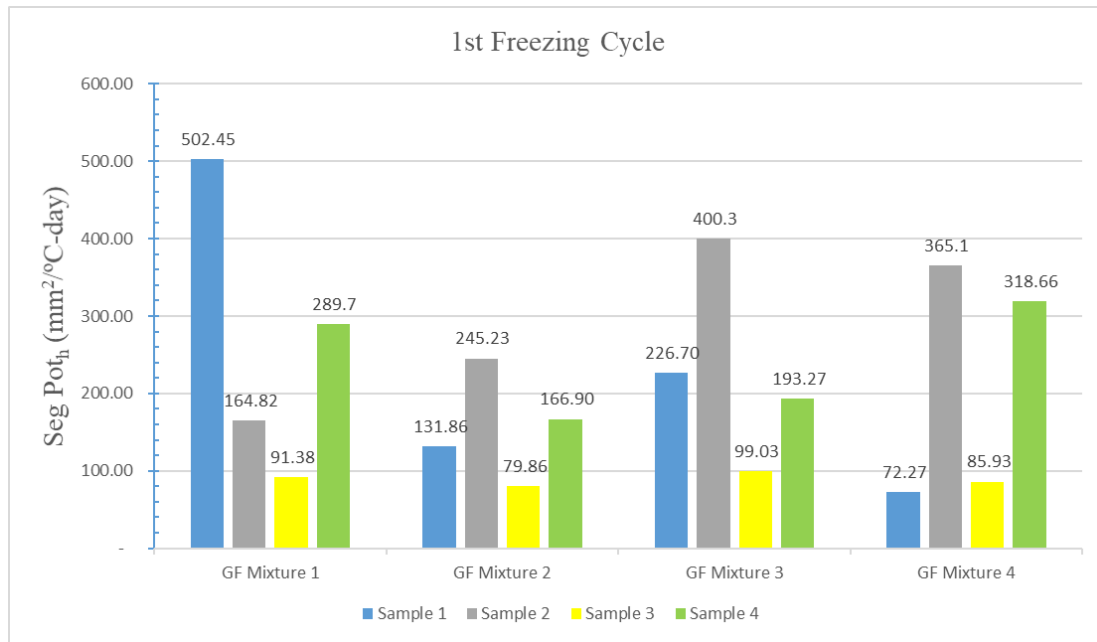


(a)

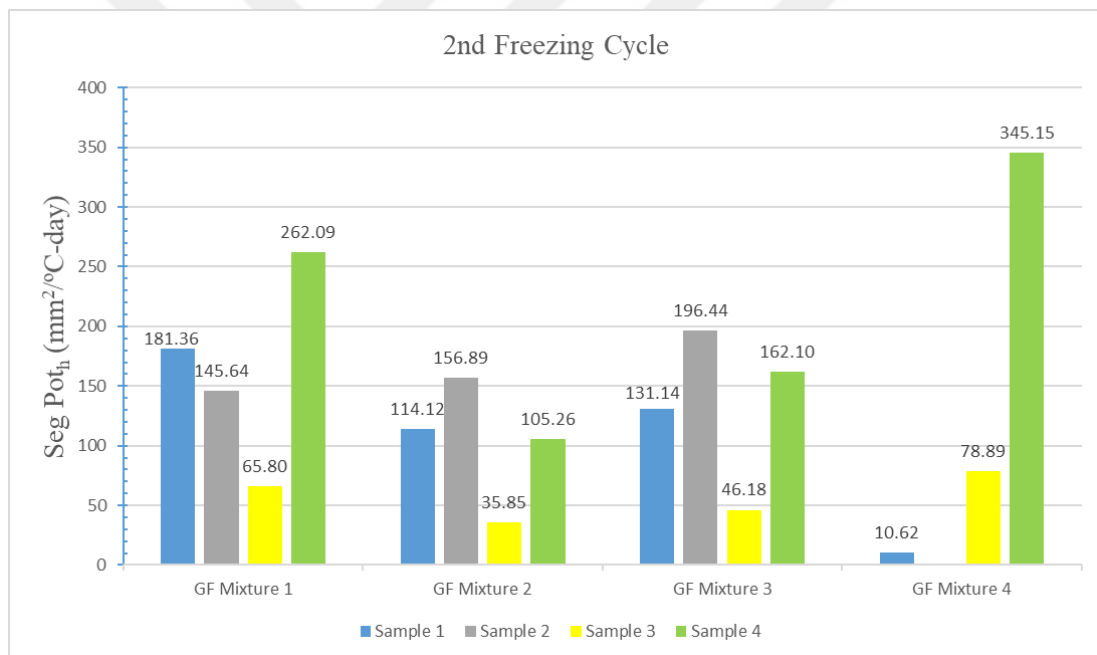


(b)

Figure 4.24 The result of Seg Pot_h (mm²/°C-day) calculations “Group-4”: (a) the Seg Pot_h values at the 1st freezing. (b) the Seg Pot_h values at the 2nd freezing

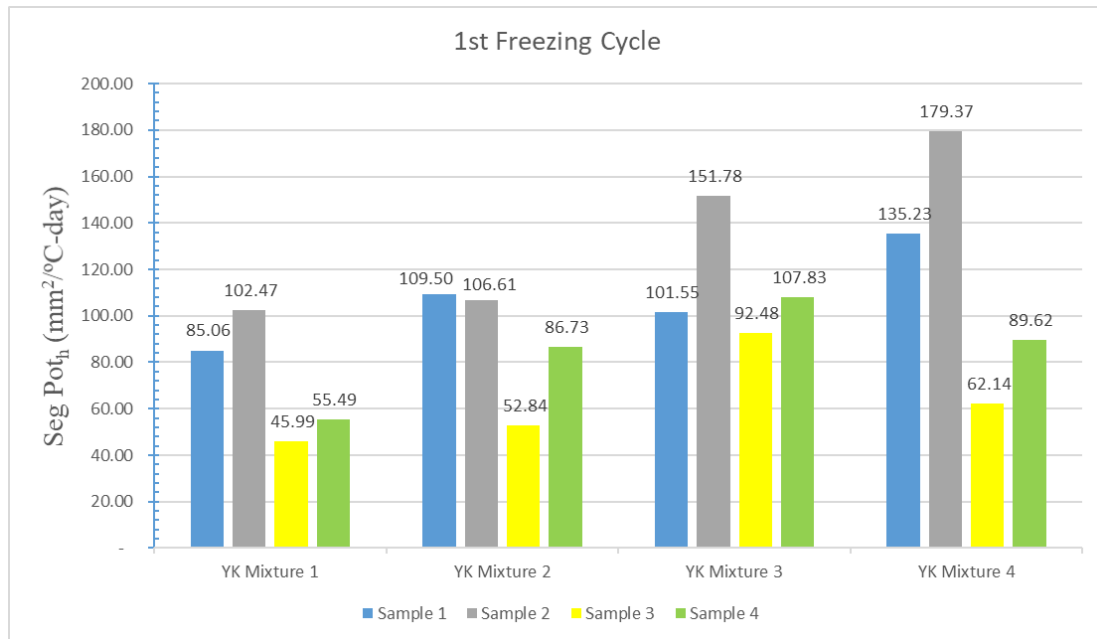


(a)

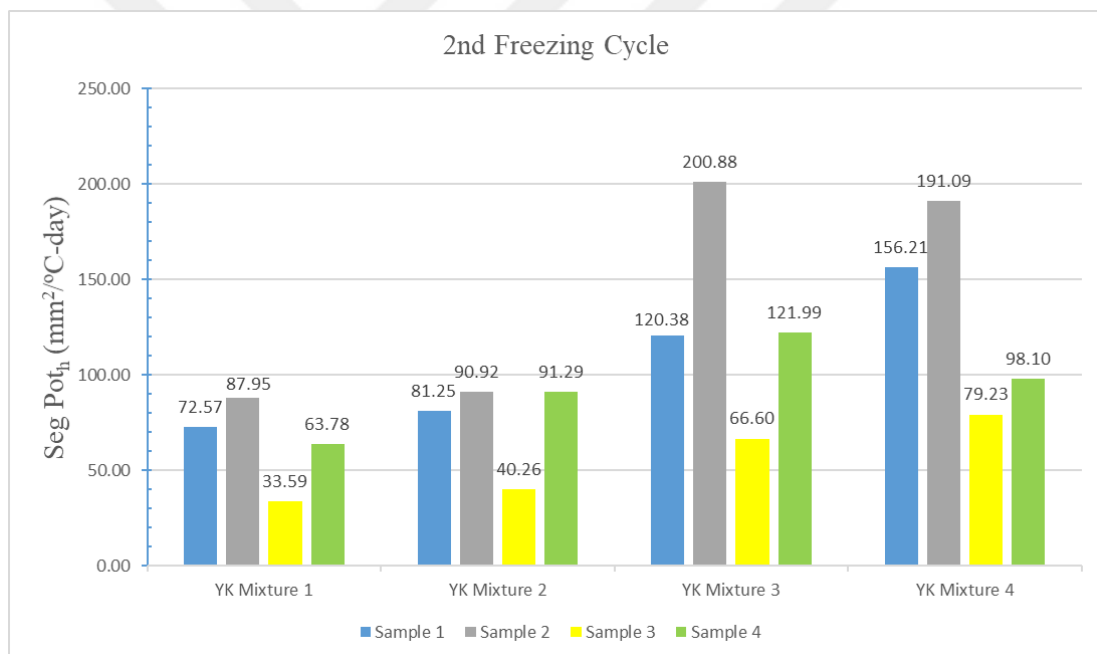


(b)

Figure 4.25 The result of Seg Pot_i (mm²/°C-day) calculations “Group-5”: (a) the Seg Pot_i values at the 1st freezing, (b) the Seg Pot_i values at the 2nd freezing

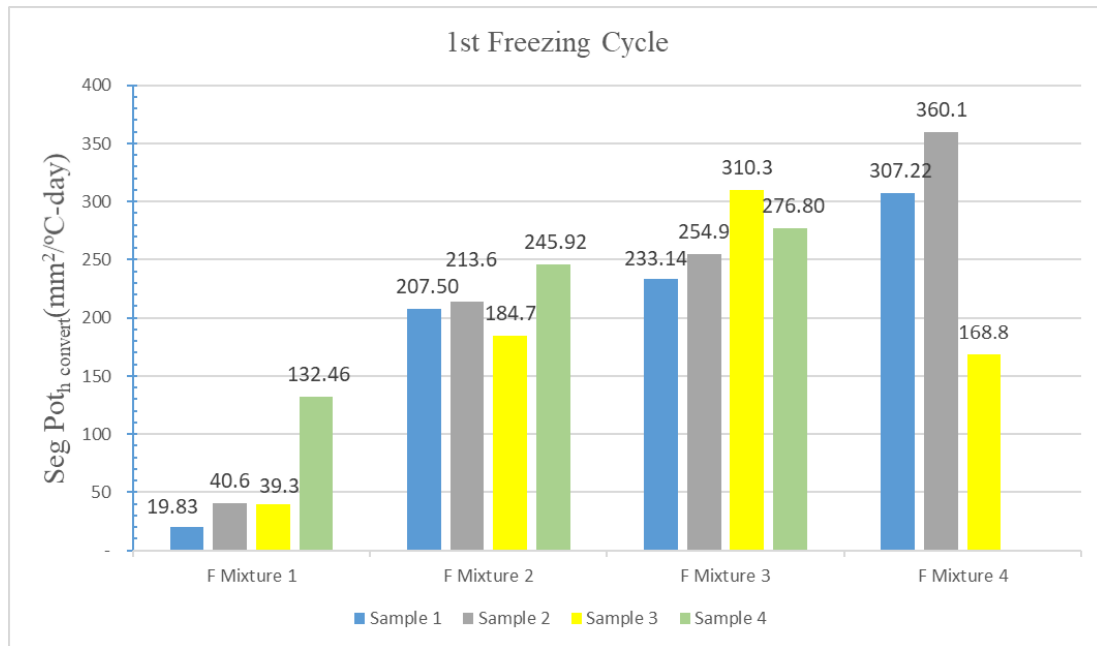


(a)

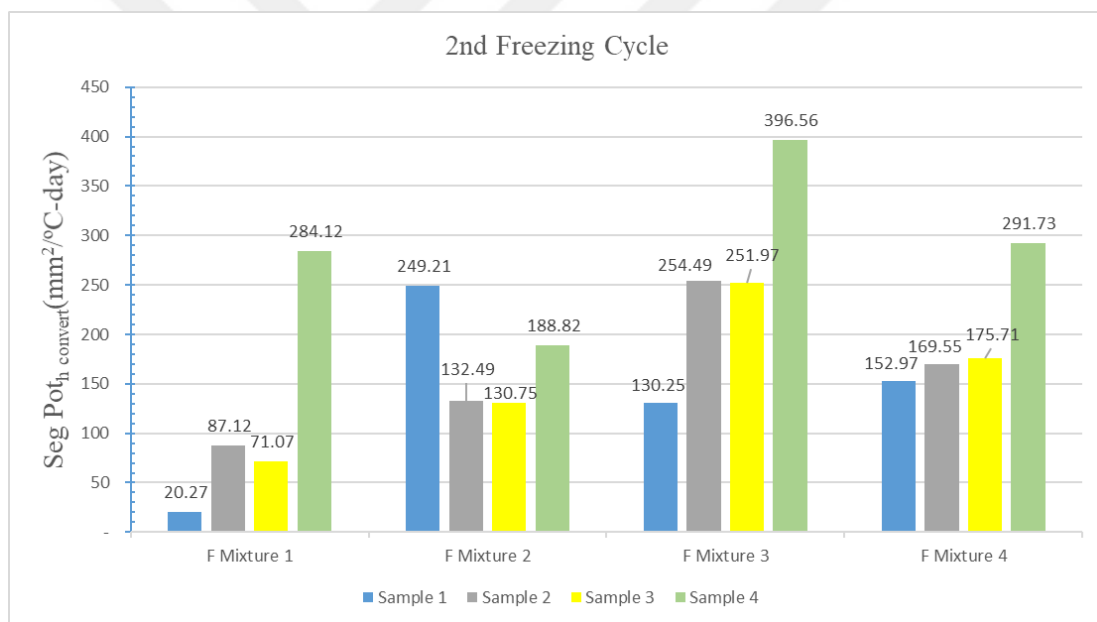


(b)

Figure 4.26 The result of Seg Pot_h (mm²/°C-day) calculations “Group-6”: (a) the Seg Pot_h values at the 1st freezing. (b) the Seg Pot_h values at the 2nd freezing

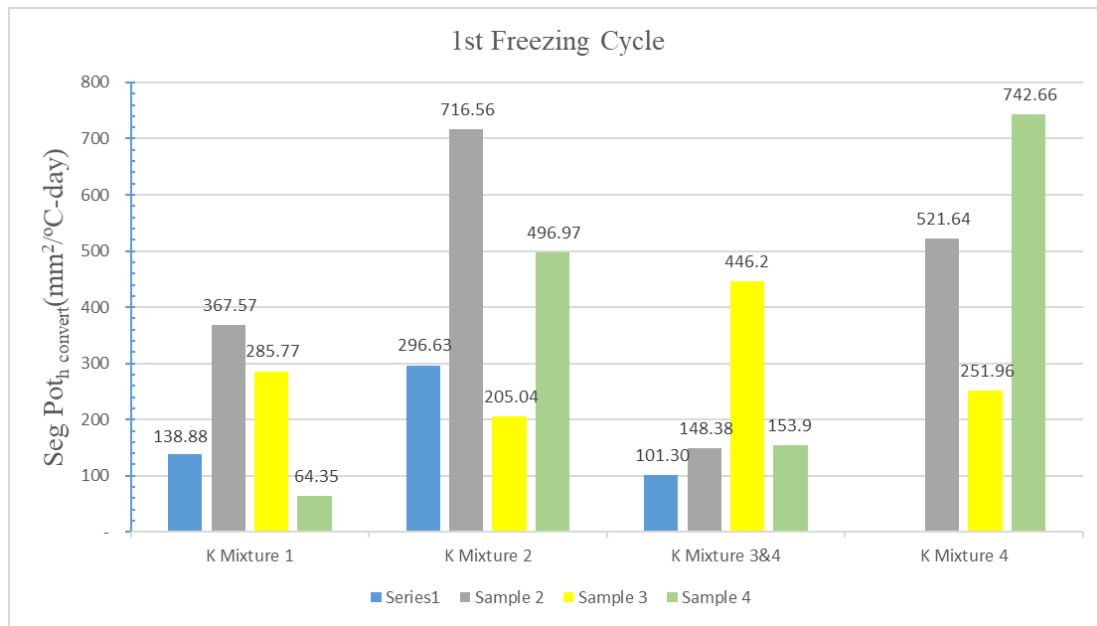


(a)

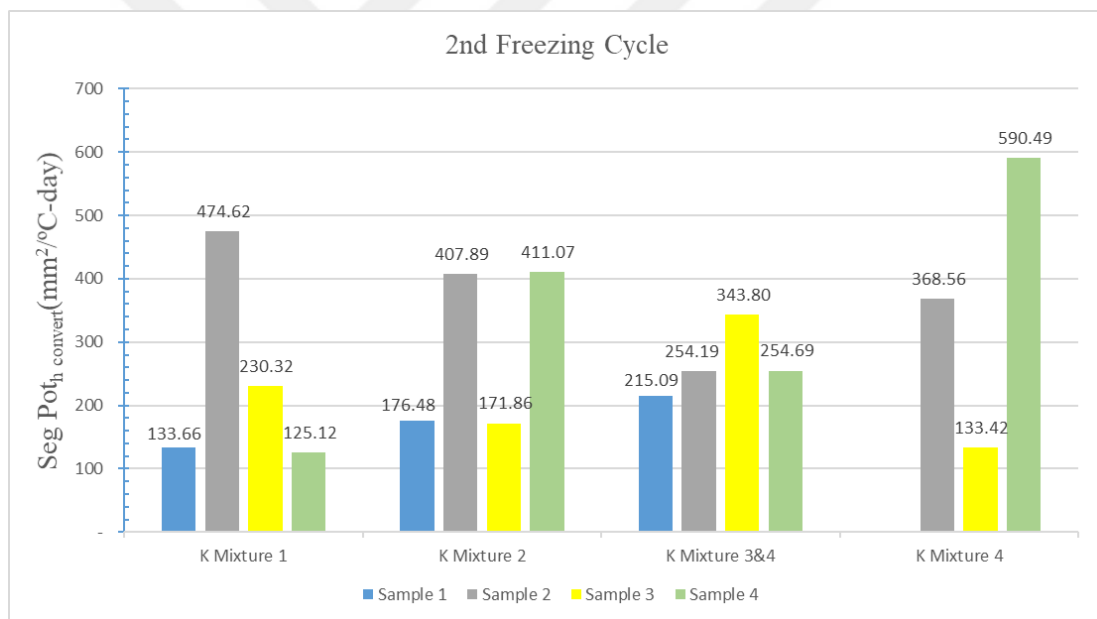


(b)

Figure 4.27 The result of Seg Poth_convert (mm²/°C-day) calculations “Group-1”: (a) the Seg Poth_convert values at the 1st freezing. (b) the Seg Poth_convert values at the 2nd freezing

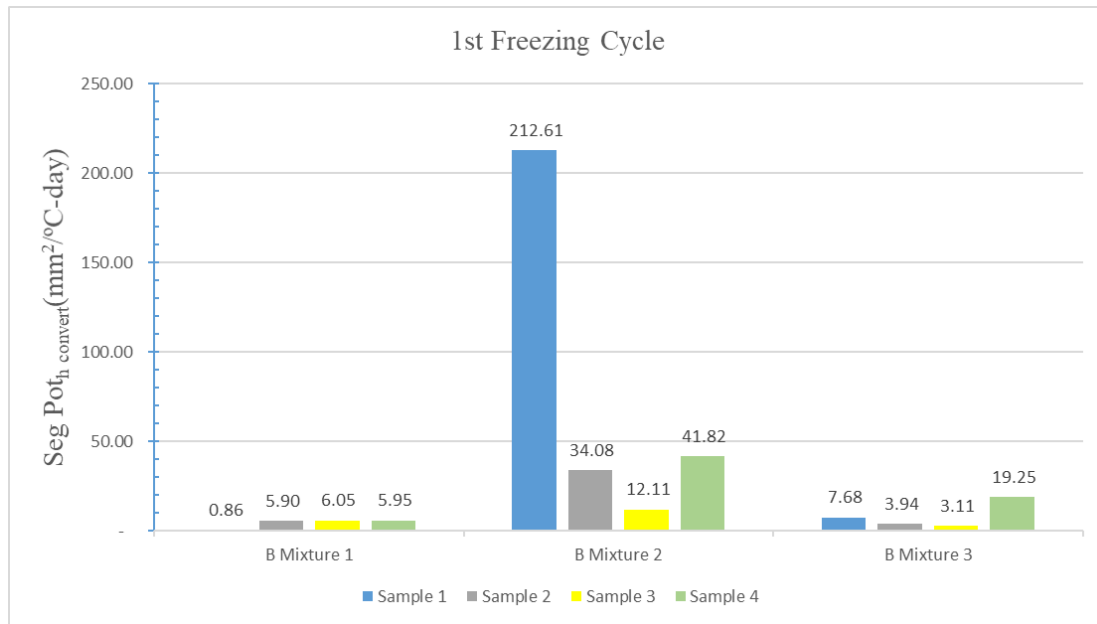


(a)

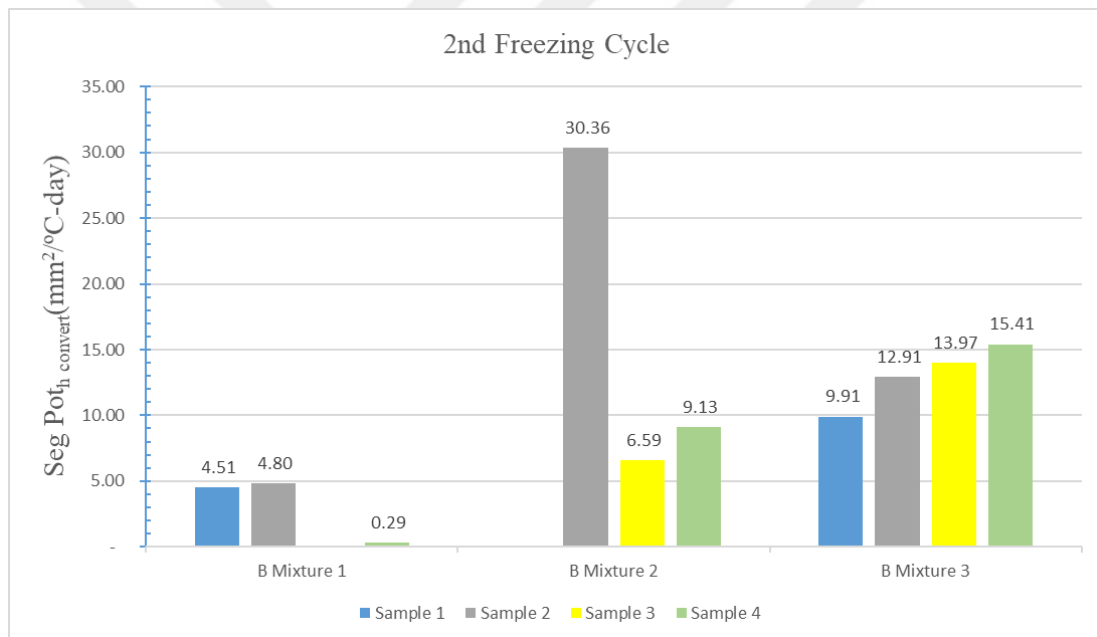


(b)

Figure 4.28 The result of Seg Pot_h_convert (mm²/°C-day) calculations “Group-2”: (a) the Seg Pot_h_convert values at the 1st freezing. (b) the Seg Pot_h_convert values at the 2nd freezing

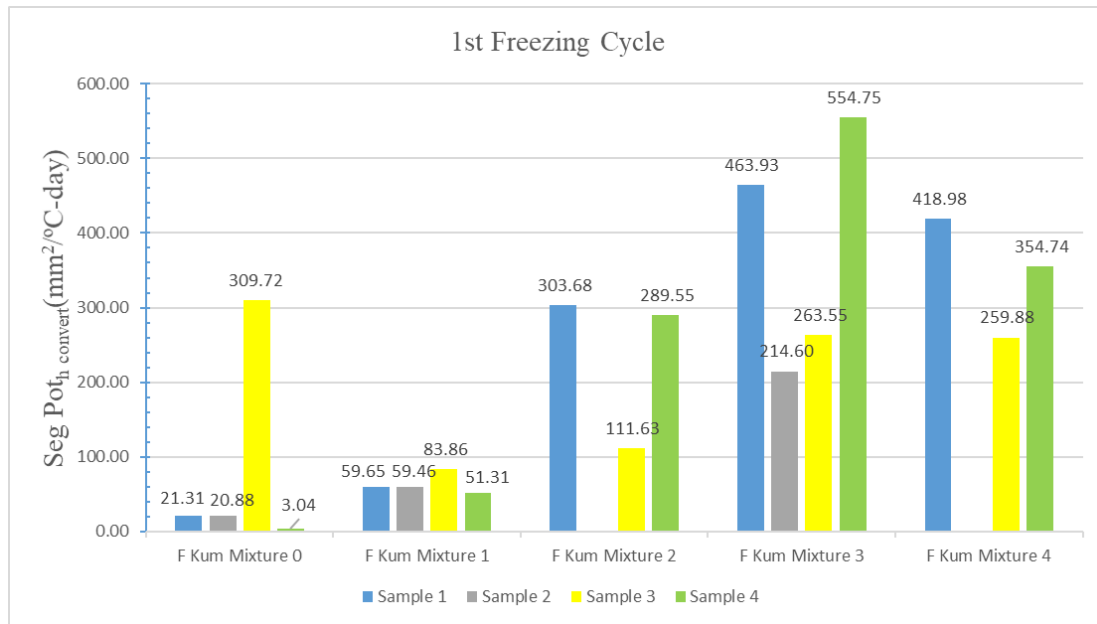


(a)

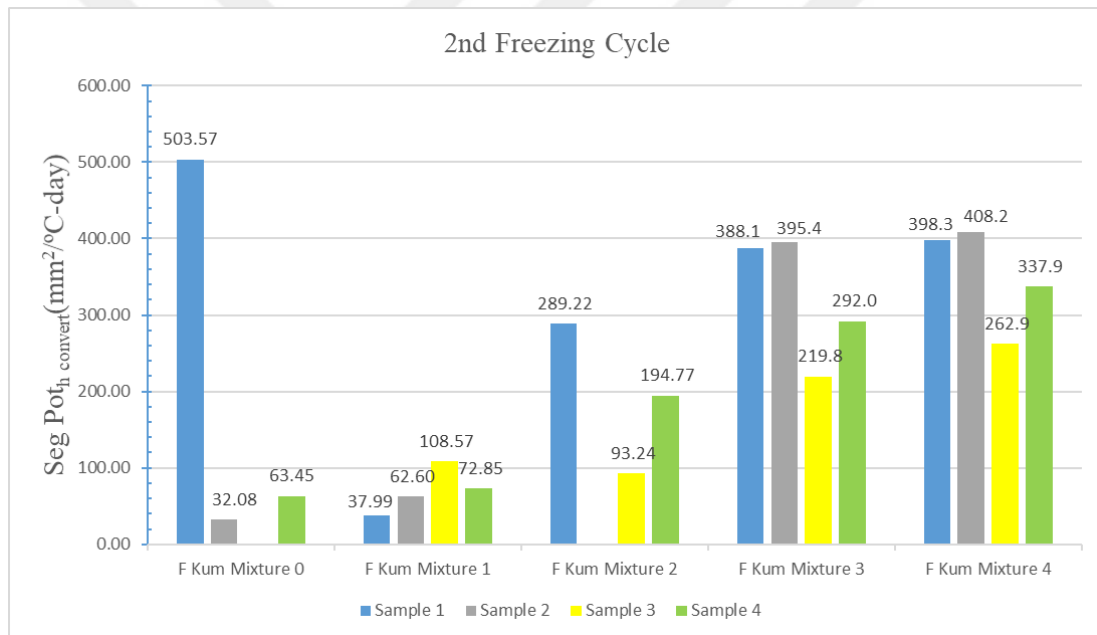


(b)

Figure 4.29 The result of Seg Pot_h_convert (mm²/°C-day) calculations “Group-3”: (a) the Seg Pot_h_convert values at the 1st freezing. (b) the Seg Pot_h_convert values at the 2nd freezing

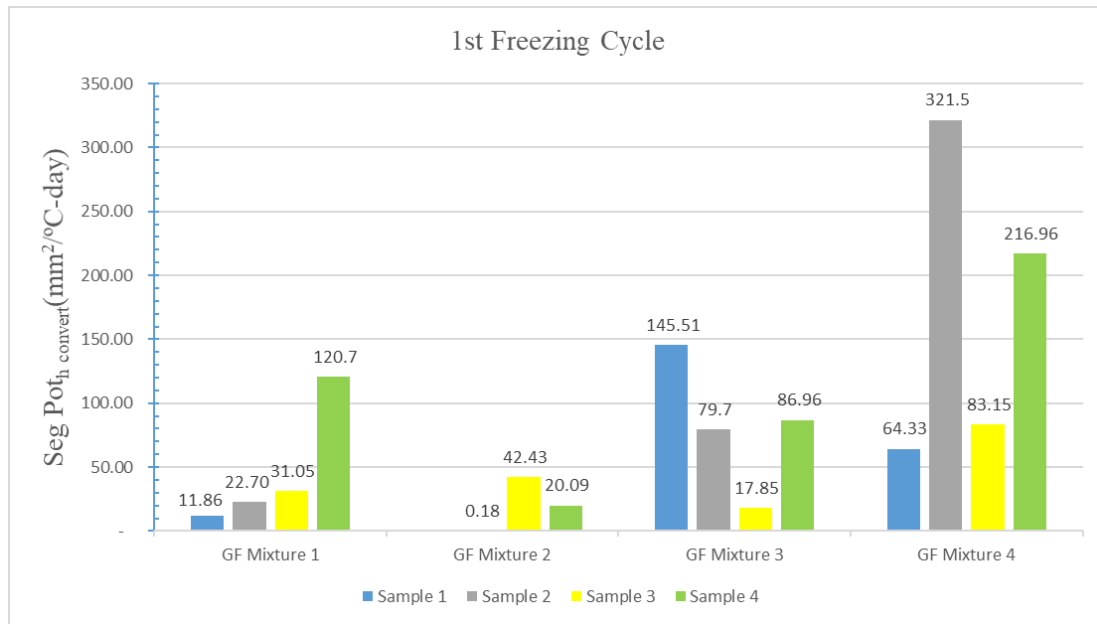


(a)

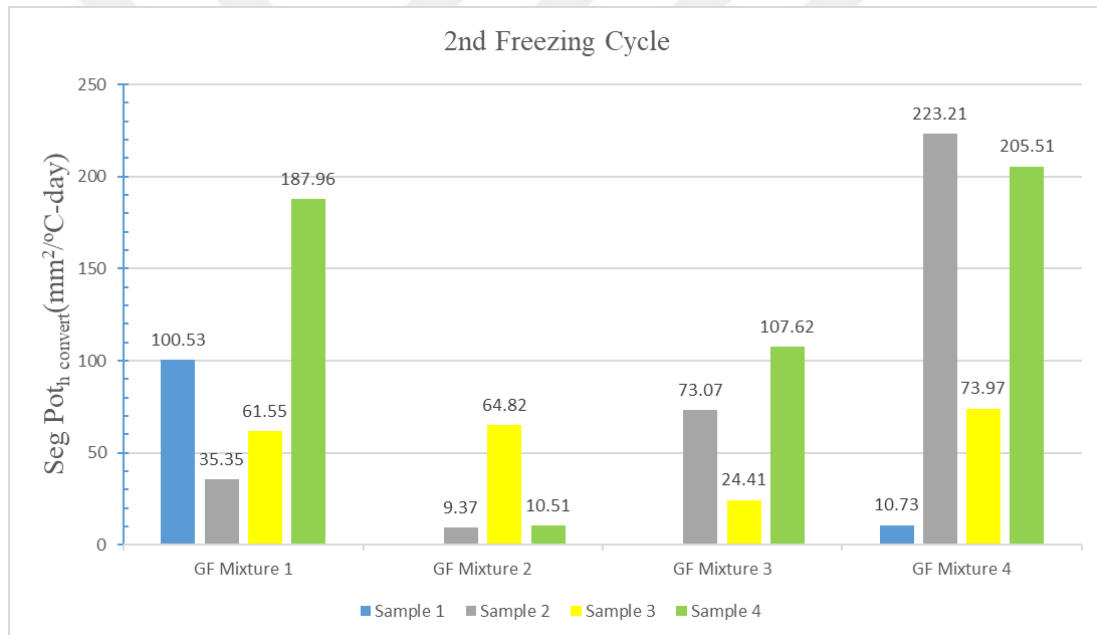


(b)

Figure 4.30 The result of Seg Poth_convert (mm²/°C-day) calculations “Group-4”: (a) the Seg Poth_convert values at the 1st freezing. (b) the Seg Poth_convert values at the 2nd freezing

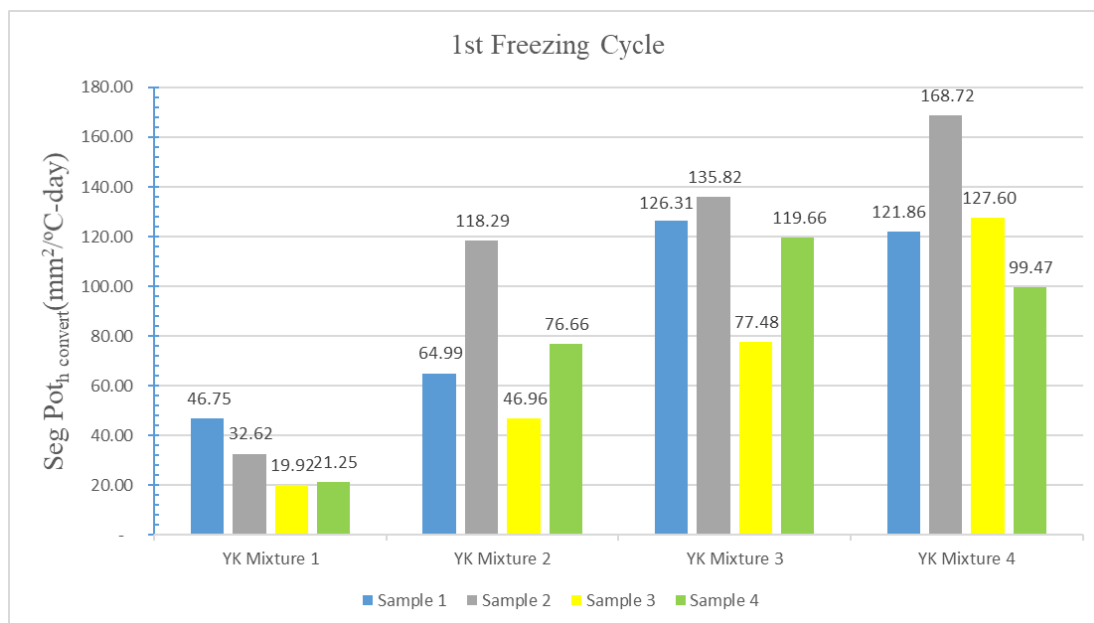


(a)

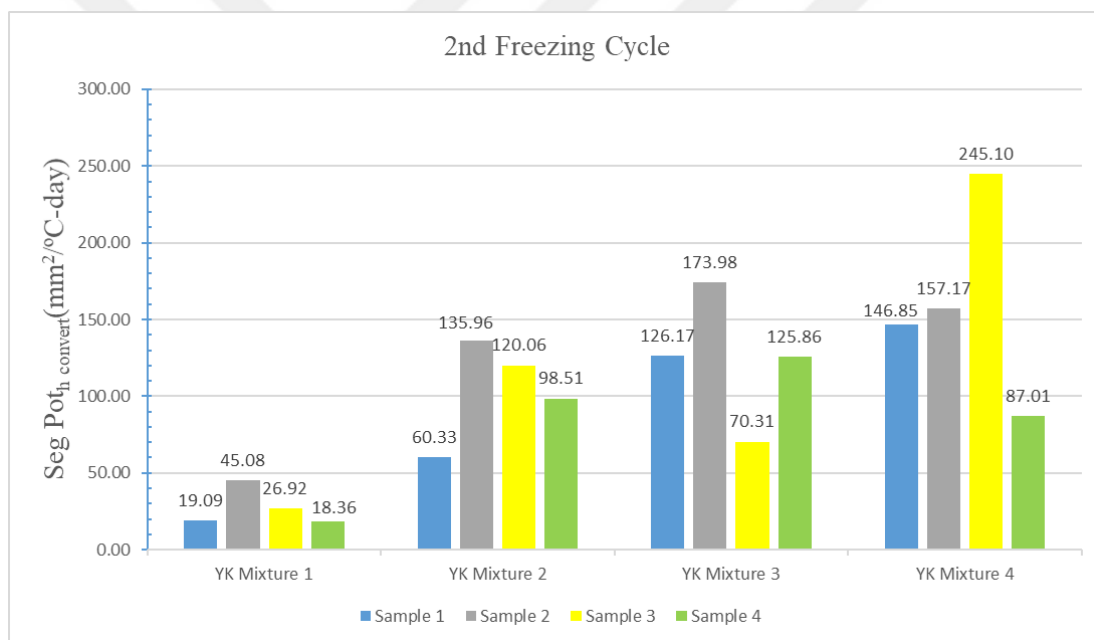


(b)

Figure 4.31 The result of Seg Poth_convert (mm²/°C-day) calculations “Group-5”: (a) the Seg Poth_convert values at the 1st freezing. (b) the Seg Poth_convert values at the 2nd freezing



(a)



(b)

Figure 4.32 The result of Seg Poth_convert (mm²/°C-day) calculations “Group-6”: (a) the Seg Poth_convert values at the 1st freezing. (b) the Seg Poth_convert values at the 2nd freezing

4.4.4 RSCS and Heave Rates

The result of the freeze thaw test were evaluated using the RSCS classification triangle. The maximum and minimum void ratios of the sand and gravel soil skeleton were used together with the liquid limit of the fines to determine the mechanical and flow threshold values. The classification triangle is shown in Figure 4.33 to Figure 4.38 Plot it on these diagrams are the calculated heave rates shown as data labels together with the fines contents. Two triangles are shown for each fines type: one shows the result of the first freeze and the other shows the results of the second freeze. The heave rate shown are the average of four samples. The red dash line shows the flow control boundry as described in the RSCS classification system.

It apeares based on this initial analysis that a boundry similar to the flow boundry may be deviced for limiting frost heave conditions. The yellow line is currently an arbitrary line selected to show the boundry for four mm per day heave rate. A regression analysis to determin the exact location of this boundry constitutes future work.

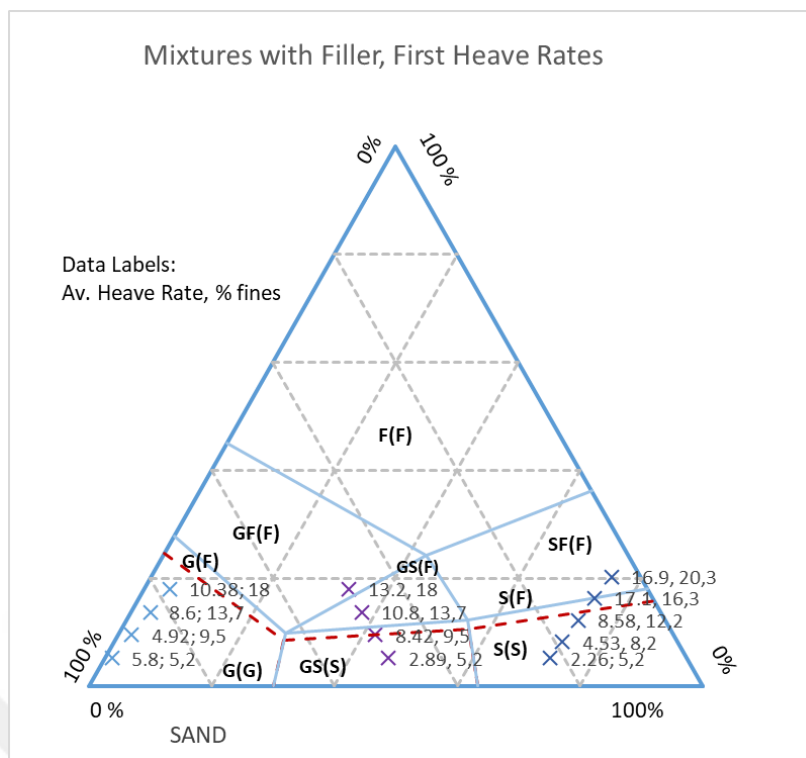


Figure 4.33 Mixtures with Filler: input data for RSCS are as follows: Gravel ($e_{\max}=0.96$, $e_{\min}=0.711$), Sand ($e_{\max}=0.678$, $e_{\min}=0.414$) and liquid limit of fines ($LL_{dw}=31$)

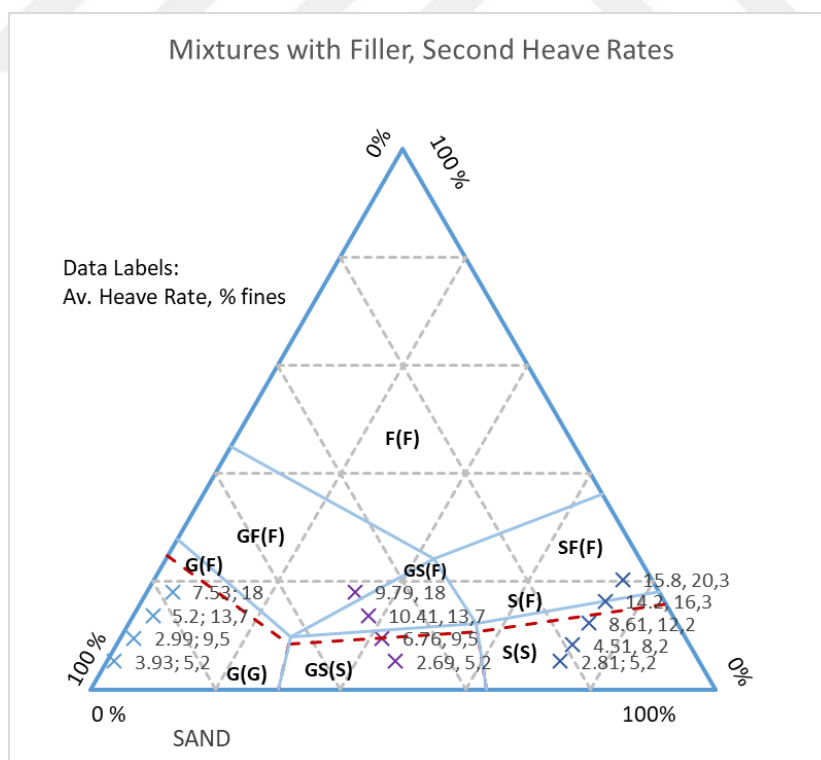


Figure 4.34 Mixtures with Filler: input data for RSCS are as follows: Gravel ($e_{\max}=0.96$, $e_{\min}=0.711$), Sand ($e_{\max}=0.678$, $e_{\min}=0.414$) and liquid limit of fines ($LL_{dw}=31$)

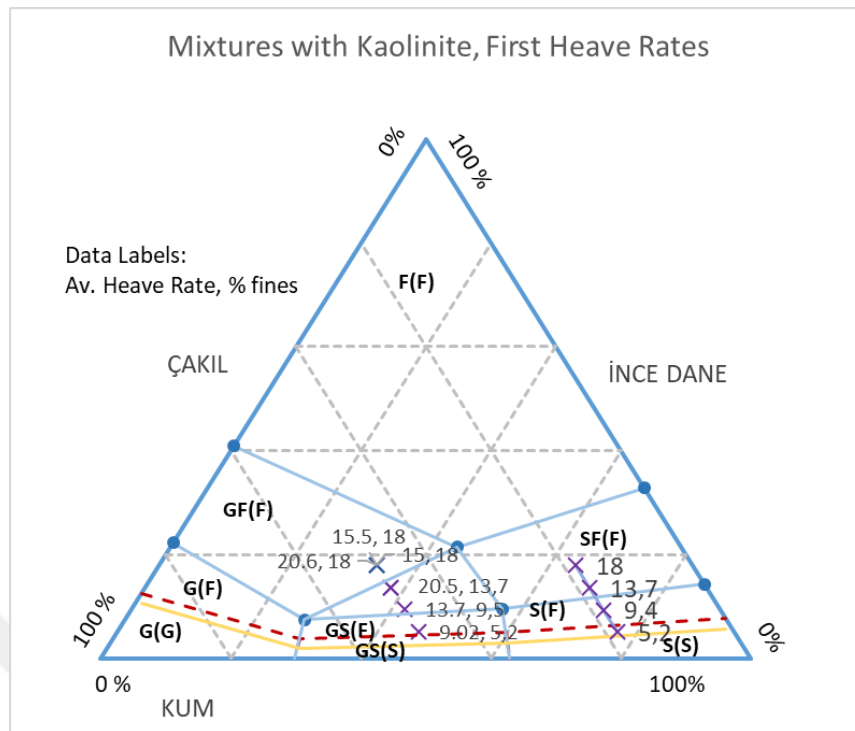


Figure 4.35 Mixtures with Filler: input data for RSCS are as follows: Gravel ($e_{max}=0.96$, $e_{min}=0.711$), Sand ($e_{max}=0.678$, $e_{min}=0.414$) and liquid limit of fines ($LL_{dw}=54$)

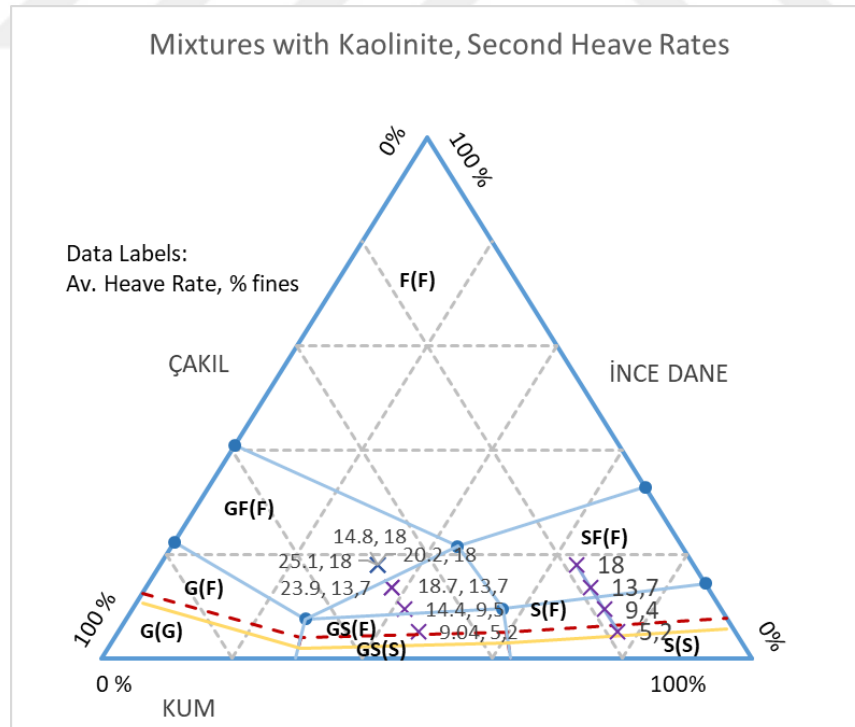


Figure 4.36 Mixtures with Filler: input data for RSCS are as follows: Gravel ($e_{max}=0.96$, $e_{min}=0.711$), Sand ($e_{max}=0.678$, $e_{min}=0.414$) and liquid limit of fines ($LL_{dw}=54$)

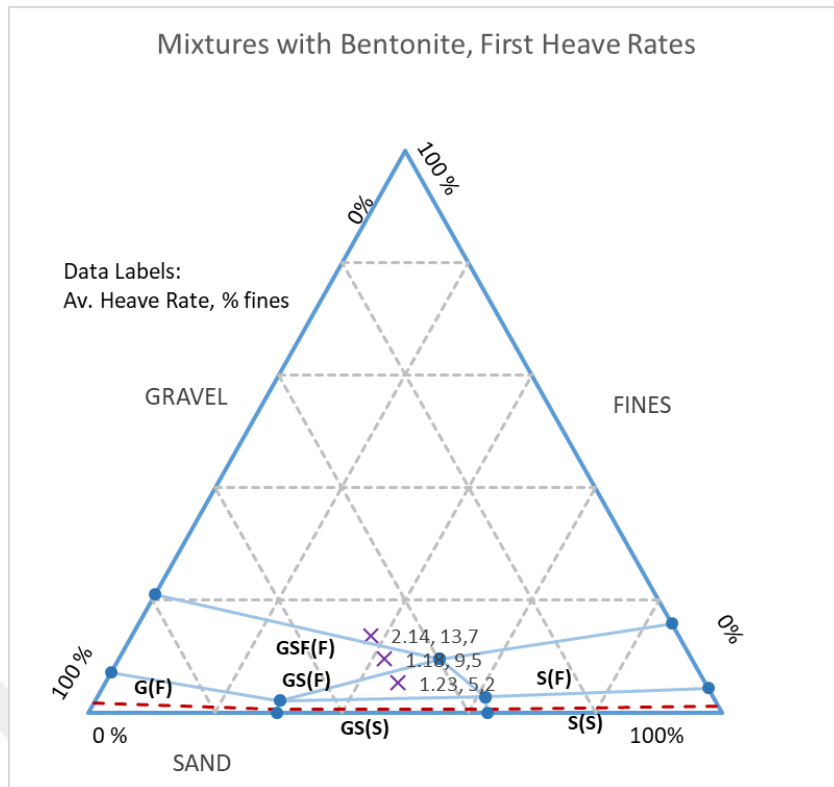


Figure 4.37 Mixtures with Filler: input data for RSCS are as follows: Gravel ($e_{\max}=0.96$, $e_{\min}=0.711$), Sand ($e_{\max}=0.678$, $e_{\min}=0.414$) and liquid limit of fines ($LL_{dw}=316$)

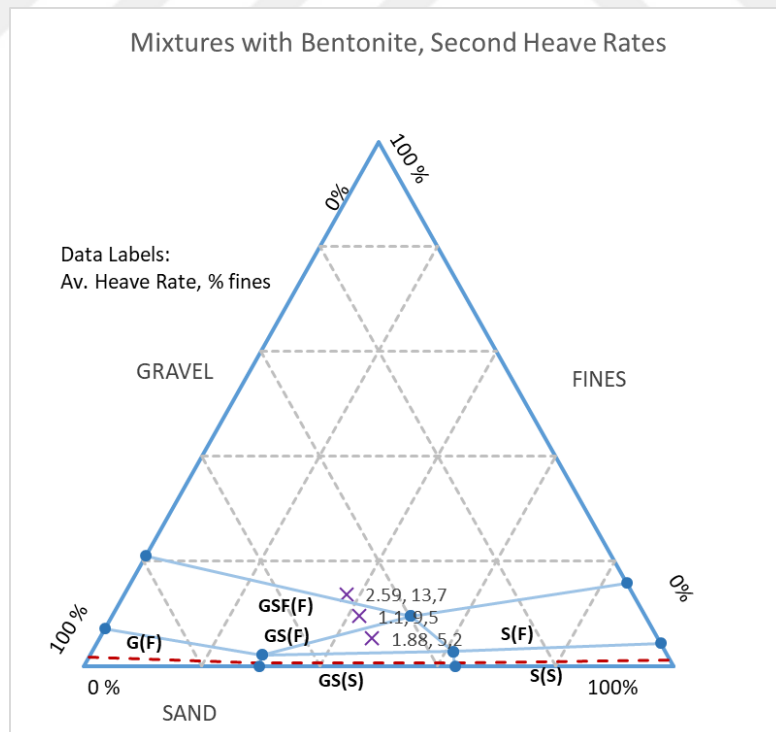


Figure 4.38 Mixtures with Filler: input data for RSCS are as follows: Gravel ($e_{\max}=0.96$, $e_{\min}=0.711$), Sand ($e_{\max}=0.678$, $e_{\min}=0.414$) and liquid limit of fines ($LL_{dw}=316$)

4.4.5 Freeze-Thaw Classification Analysis (Regression lines)

The graphs presented in Figure 4.39 to Figure 4.44 illustrate the relationship between the percentage fines required to fill all voids in the mixture (ρ_f) and the normalized segregation potential ($SP_h/SP_{o(FF)}$). The $SP_h/SP_{o(FF)}$ values calculated as the segregation potential of the tested samples (SP_h) divided by the segregation potential of the fines content in the respective mixtures ($SP_{o(FF)}$). Where SP_h is the calculated segregation potential from heave rate results. The same relationship was presented in Figure 4.45 to Figure 4.50 but by using the ($SP_{h\text{ convert}}$) That has been calculated from the water intake rate. Hence, the calculated segregation potential is evaluated for the soil mixtures in two ways, both of them used to the regression.

These results replicate the trends observed by Konrad (1999, 2005) [18] [32] in his studies on freeze-thaw durability. The data points represent the results from the first freezing cycle (triangles) and the second freezing cycle (circles), providing insights into the performance of different mixtures under repeated freeze-thaw conditions.

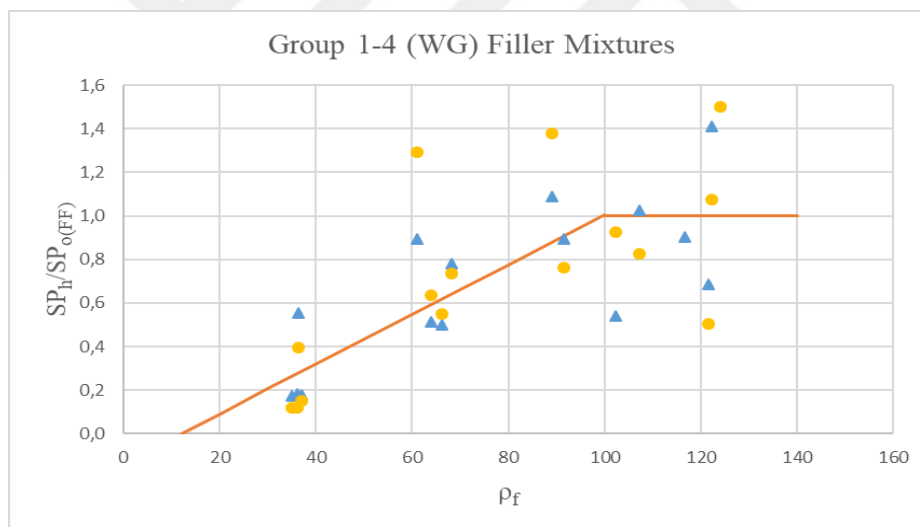


Figure 4.39 Influence of relative fines content of well-graded Filler Mixes

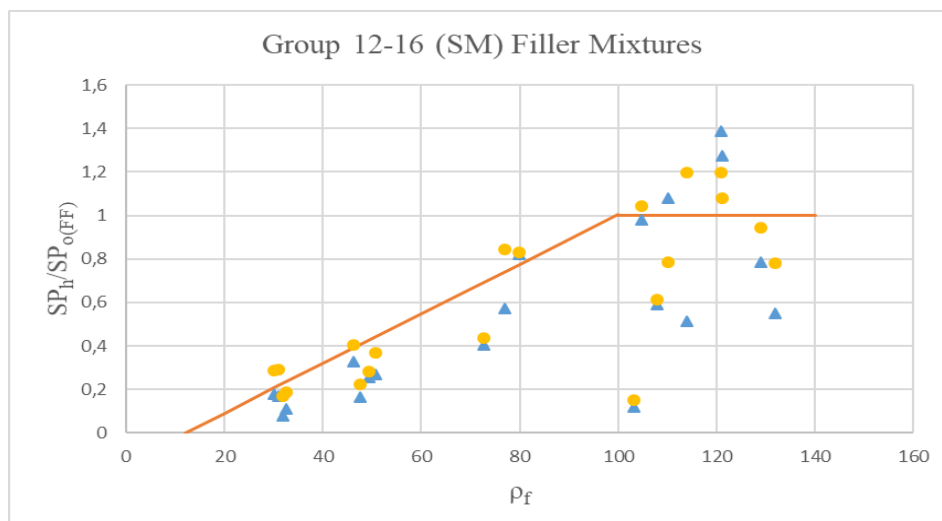


Figure 4.40 Influence of relative fines content of gap-graded Filler Mixes

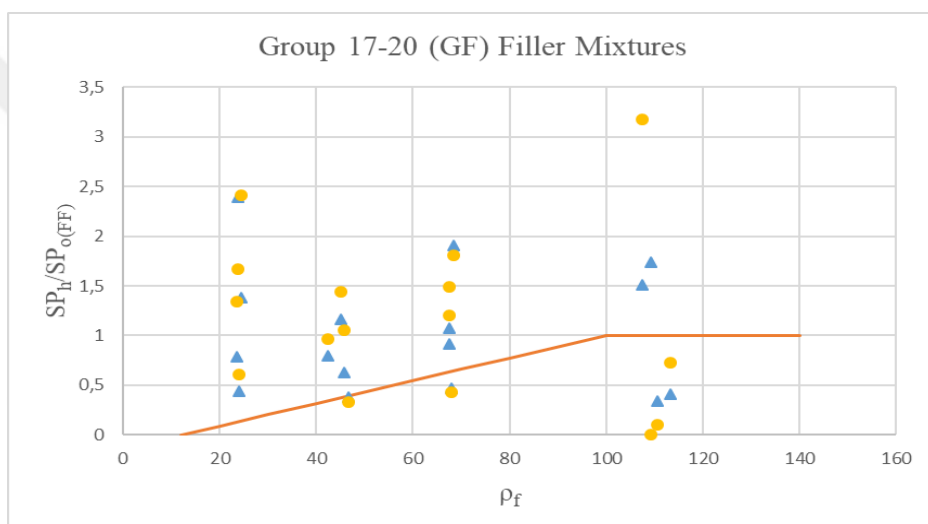


Figure 4.41 Influence of relative fines content of gap-graded Filler Mixes

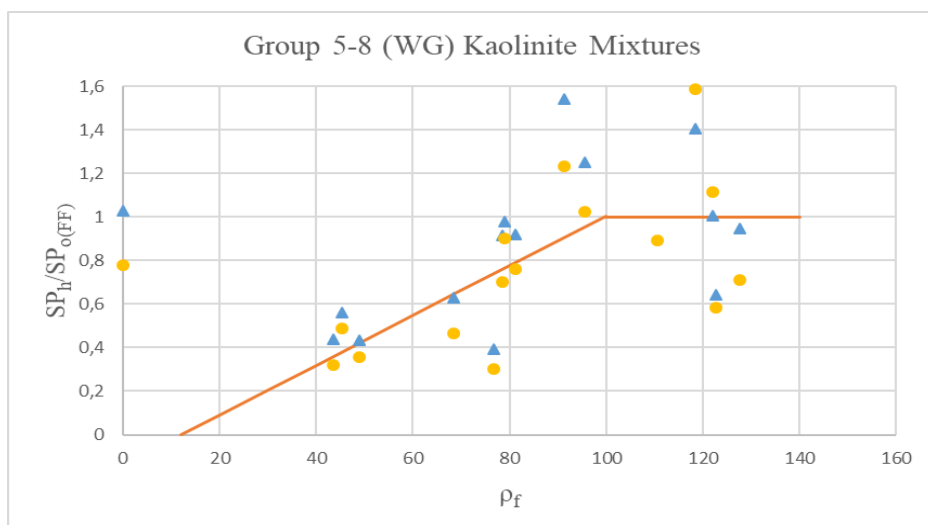


Figure 4.42 Influence of relative fines content of well-graded Kaolinite Mixes

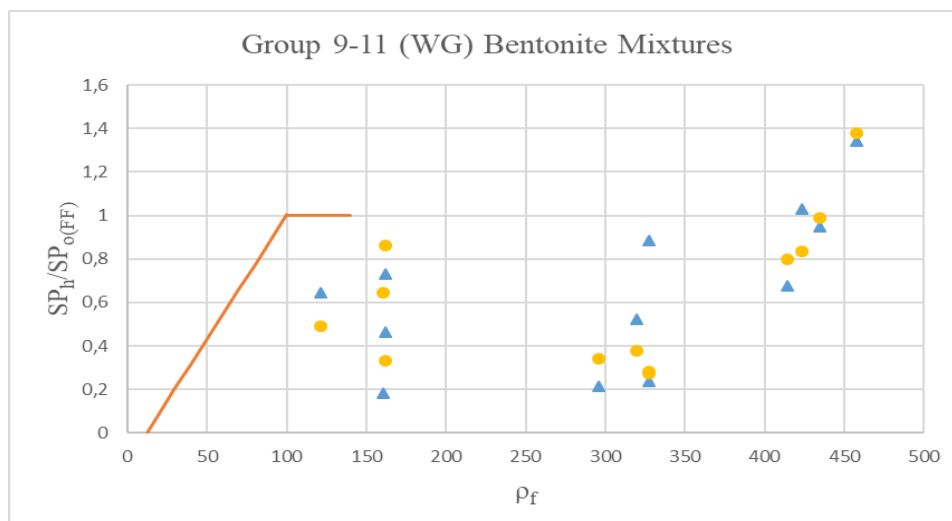


Figure 4.43 Influence of relative fines content of well-graded Bentonite Mixes

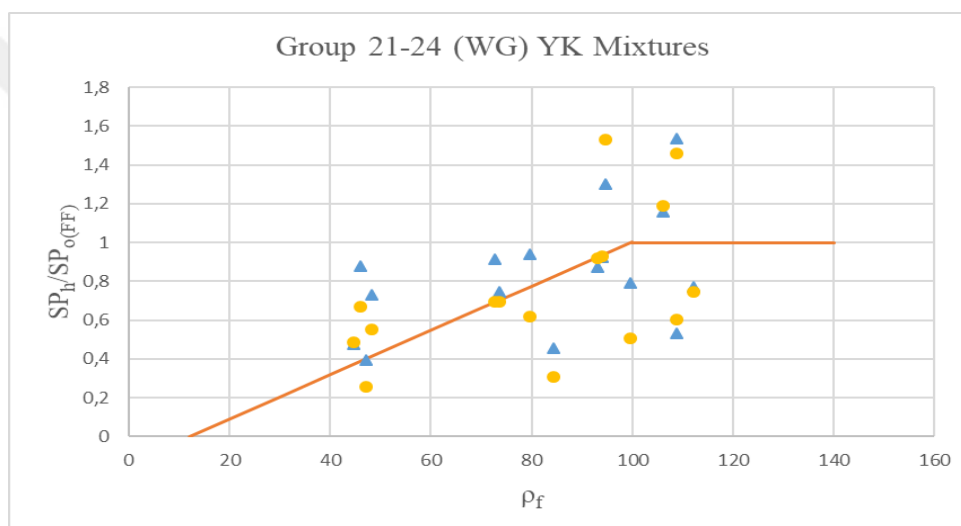


Figure 4.44 Influence of relative fines content of well-graded YK Mixes

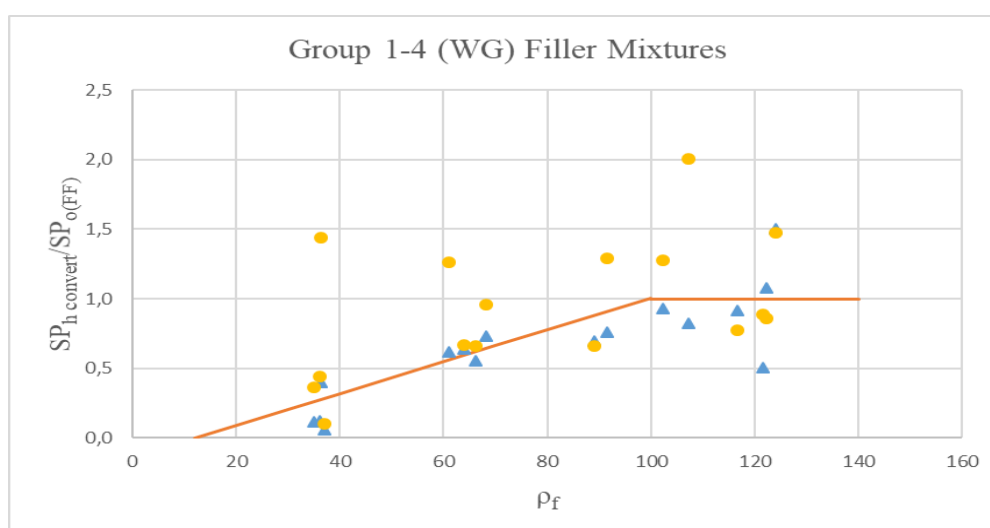


Figure 4.45 Influence of relative fines content of well-graded Filler Mixes

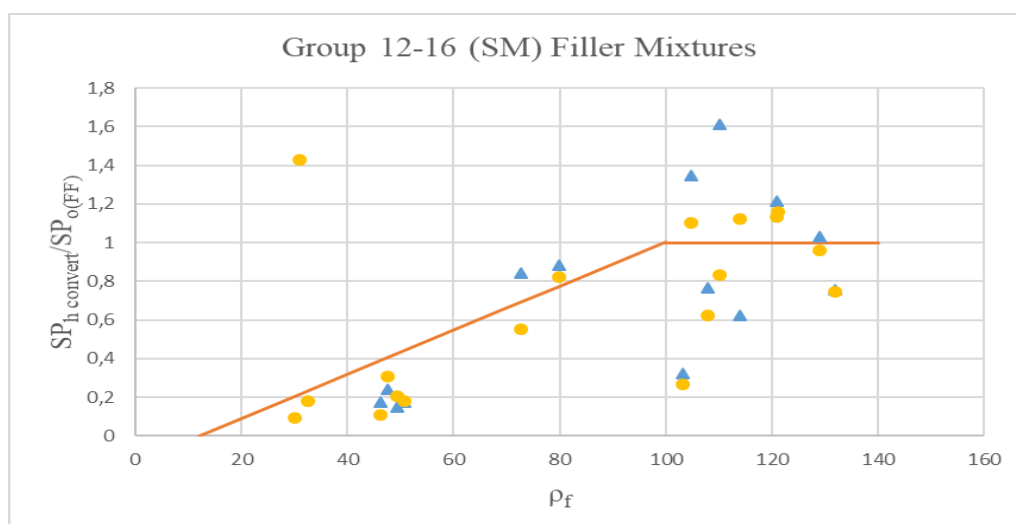


Figure 4.46 Influence of relative fines content of gap-graded Filler Mixes

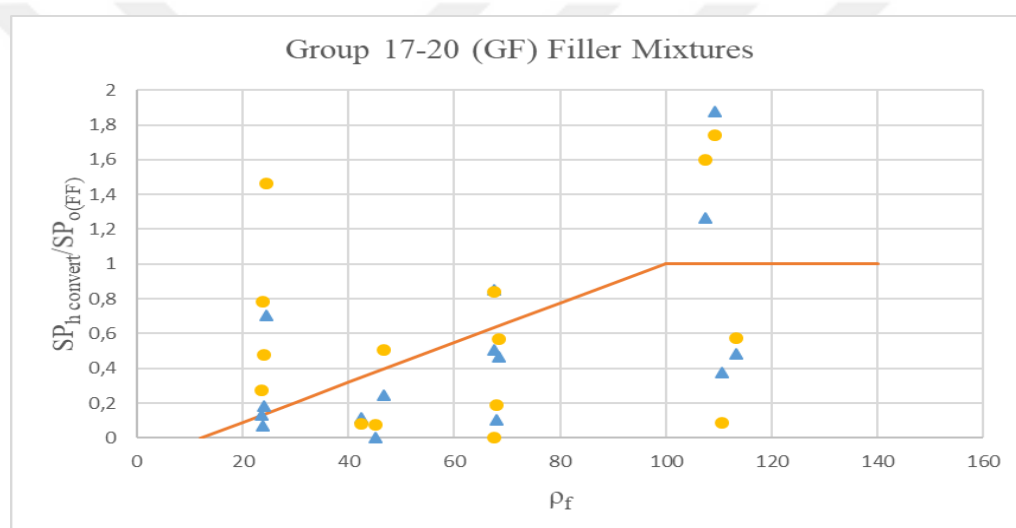


Figure 4.47 Influence of relative fines content of gap-graded Filler Mixes

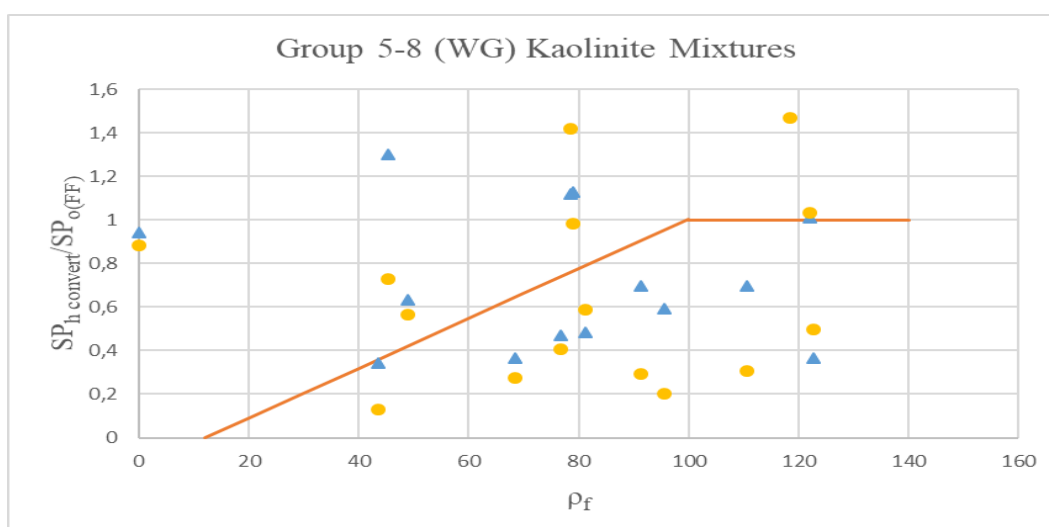


Figure 4.48 Influence of relative fines content of well-graded Kaolinite Mixes

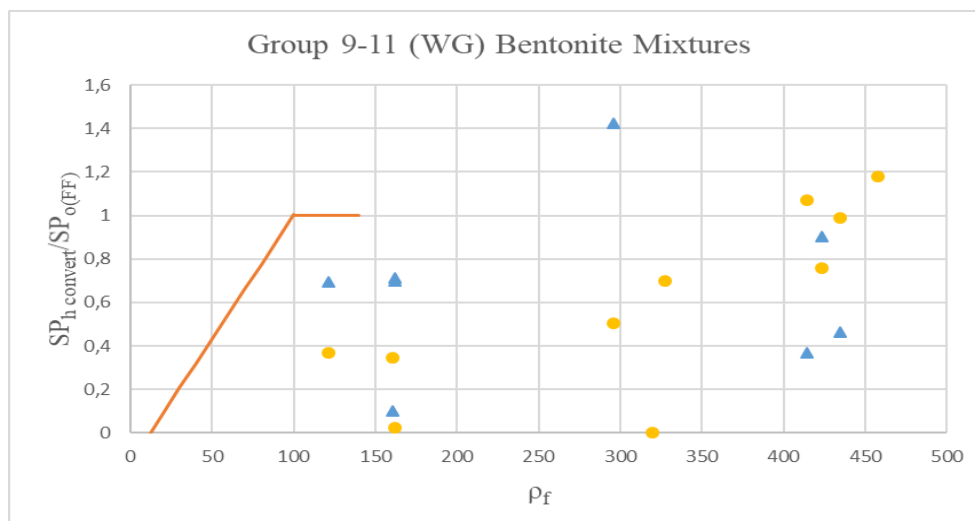


Figure 4.49 Influence of relative fines content of well-graded Bentonite Mixes

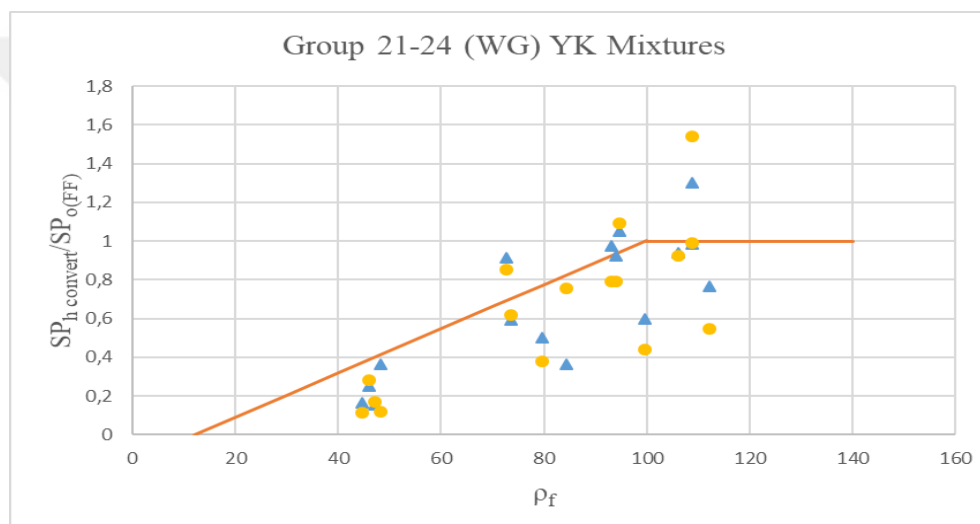


Figure 4.50 Influence of relative fines content of well-graded YK Mixes

CHAPTER 5

DISCUSSION

Standard Proctor compaction test results for each group of mixtures are shown in Table 4.1. As expected, as the percentage of fines content increases the optimum water content and maximum dry density also increases. This is true for the six mixture groups (Groups 1 to Group 6) that were tested. The freeze-thaw test samples were prepared at the respective optimum water content for that mixture. The measured initial water contents are shown in the phase diagrams for each sample. With the exception of three samples (KMix3 No2, KumMix4 No4, YKMix2 No1, YKMix2 No3), the achieved moisture contents are within ± 1 percentage points around the target optimum moisture content. The four exceptions fall within ± 2 percentage points around wopt. The relative compaction ranges between 96% and 108% with an average of 100%. Based on these observations it can be stated that the sample preparation was adequate for all mixture groups.

The freeze thaw testing caused an increase in the water contents of all samples tested. The recorded increases ranged in value between 3.8% and 358% with an average value of 77%. The recorded average increase in water content for Group 1 mixtures (gravel-sand with filler) are 18%, 44%, 29% and 55% for fines contents of 5.24%, 9.5%, 13.75% and 18% respectively. Those for Group 2 mixtures (gravel-sand with kaolinite) are 30%, 20%, 37% and 30% for fines contents of 5.24%, 9.5%, 13.75% and 18% respectively. Those for Group 3 mixtures (gravel-sand with bentonite) are 111%, 29% and 11% for fines contents of 5.24%, 9.5% and 13.75% respectively. Those for Group 4 mixtures (sand with filler) are 341%, 263%, 115%, 49% and 64% for fines contents of 5.24%, 8.2%, 12.24%, 16.28% and 20.32% respectively. Those for Group 5 mixtures (gravel with filler) are 71%, 191%, 98% and 65% for fines contents of 5.24%, 9.5%, 13.75% and 18%. Those for Group 6 mixtures (gravel-sand with YK clay) are 56%, 71%, 65% and 80% for fines contents of 5.24%, 9.5%, 13.75% and 18%. The very large increases in final water content (i.e. close to or above 100%) occurred in mixtures with gravel-sand and bentonite with low fines content (B-Mix 1), in mixtures with sand and filler where the fines content is less than 13% (Kum Mix 0, Kum Mix 1 and Kum Mix 2) and in gravel with filler with fines contents of 9.5% and 13.75% (GF Mix 2 and GF Mix 3). The increase in final water content is affected by the plasticity of the

fines such that higher plasticity fines will absorb more moisture and retain it during the thawing phase.

Due to time limitations about 4 hours maximum was available for the saturation phase. It was possible to visually confirm (i.e. by observing moistening of filter paper on top of sample) that mixtures with filler and kaolinite became saturated during this period. This was not the case with bentonite mixtures. The Bentonite mixtures had initial saturation values that ranged from 32%-37% for B Mix 1, 50%-60% for B Mix 2 and 69%-82% for B Mix 3. It seems as though upon initial saturation, the highly expansive bentonite near the sample bottom would quickly swell in the pores and effectively clog them reducing further upward movement of water and preventing full saturation from being reached. Because these samples are not near saturation, the results of the freeze thaw tests with bentonite are not deemed reliable. The absorbed water reflects the total potential due to both plasticity related frost related heave. For this reason, the results of the Bentonite tests are viewed with caution.

The CBR test results are shown in Table 4.2. In all soil mixtures, the CBR tests performed after freeze-thaw testing show values that are lower than the dry and soaked CBR values. This is as expected and confirms that freeze-thaw cycles tend to deteriorate the deformation response of soils to loading. Even mixtures with low fines contents showed a deterioration. This can be partially explained by the increase in the final water contents that are observed in all samples.

Frost susceptibility of subbase and subgrade materials is a crucial factor influencing pavement performance in regions experiencing freeze-thaw cycles. This study evaluates the effects of various fines, including Kaolinite, Bentonite, Filler with different grain size distribution (GSD) (which is, F Group, F Kum Group, GF Group) as discussed in chapter three, and YK (Yeşil Köseb), on frost susceptibility by analyzing segregation potential (SP) and heave rate results. Segregation potential was calculated from heave rate (SP_h) and water intake rate (SP_w), with both metrics providing complementary insights into frost behavior.

5.1 Segregation Potential and Heave Analysis

The segregation potential is calculated from both heave rate measurements and water intake rate measurements. These values are shown in Figures 4.21 through 4.31. It can be seen that the segregation potential steadily increases as fines contents increase from 5.24% to 13.75% for all mixture groups. The increase in fines content from 13.75% to 18% does not seem to cause as great a change in segregation potential as the previous increases. This seems to indicate that there is a plateau value of segregation potential that is reached when the voids are mostly filled with fines. Figures 4.38 through Figure 4.49 illustrates this trend however, further analysis of this phenomenon is needed. An initial analysis is provided in section 5.1.2.

The heave results for different mixtures provide direct evidence of frost susceptibility, as frost heave is the primary driver behind pavement distress in cold climates. Mixtures containing Kaolinite exhibited higher heave rates compared to other materials. This can be attributed to the mineral's ability to retain water in its pore spaces and the influence of its higher silt content, which enhances capillary water movement. Silt particles facilitate the migration of water toward the freezing front, increasing frost heave. The Kaolinite-well graded mixtures also showed higher SP values, reinforcing the correlation between heave rate and segregation potential.

Bentonite-well graded mixtures, on the other hand, presented an anomaly in the results due to insufficient saturation during testing. Bentonite is highly plastic and capable of significant water absorption, which would typically result in higher frost heave if fully saturated. However, the incomplete saturation during testing likely suppressed both heave rates and SP values, leading to an underestimation of bentonite's frost susceptibility. While the measured results for bentonite mixtures appear moderate, they may not accurately reflect the true potential for frost-induced heave and segregation.

For the F Group, which represents well-graded mixtures containing Filler, the heave results were lower compared to Kaolinite mixtures. This can be explained by the difference in the mineralogy of fines content materials, which has larger $d_{50}(FF)$ for Filler than Kaolinite. Kaolinite is a clay material and it typically absorbed more water. This causes a worse effect in the 2nd cycle. As a result, F mixtures exhibit lower segregation potential and better resistance to frost action than the K mixes.

In contrast, the F Kum Group, which includes gap-graded mixtures with filler, demonstrated slightly higher heave rates and SP values compared to the F gravel-sand mixtures. The larger void spaces observed in the 12_F Kum mixture 0, which contains 5.242% fines, likely facilitate greater water movement. In contrast, the 1_F mixture with the same fines content, classified as a well-graded material, exhibits reduced void spaces. This difference in void structure increases the frost susceptibility of the 12_F Kum mixture compared to the well-graded 1_F mixture, as the larger voids enhance water migration and accumulation during freezing conditions.

The GF Group, associated with SP mixtures, exhibited variable results depending on grading and filler content. The presence of finer particles in these mixtures increased water retention and capillary action, resulting in moderate frost heave and SP values. The variability in the results highlights the importance of grading in determining frost susceptibility, as finer gradations are more prone to frost heave due to enhanced water migration.

YK (Yeşil Köseb) fines exhibited the lowest heave rates and SP values among the tested materials. This can be attributed to their coarser particle size and lower plasticity, which reduce water retention and capillary action. The low heave and SP results for YK fines suggest that they are well-suited for use in subbase and subgrade materials in frost-prone regions, as they exhibit minimal frost susceptibility.

5.2 Correlation Between SP and Heave Results

It is observed that the shapes of the hydrometer grain size distribution curves are similar for all four of the fine grained soil used in the study. It seems odd that such different materials should give similar shapes. The d50 of fines calculated from these curves give the following values: 0.038mm for kaolinite and 0.00187 mm for Bentonite. For the YK clay the d50 of fines was find to be 0.03 mm. These values are much larger than those reported by some researchers. In the test conducted by Rieki on Kaolinite clay the d50 value used was 0.002 mm. In the Test conducted by Konrad (1999) the d50 value used for montmorillonite clay was 0.003 mm. In the case of Kaolinite our value is about 40 times larger and in the case of bentonite, which is a form of montmorillonite mineral, our value is 40% smaller.

The segregation potential assessment is very sensitive to the d50 value used. The calculations for SSA_calculated, SSA_ref and SPo_ref use the d50 value. In our study we calculated the specific surface area for the filler and Kaolinite using the d50 value from the hydrometer

test. For the Bentonite the specific surface area was calculated using the expression for sheet structure clays minerals ($\text{thickness} \ll \text{length}$ and $\text{thickness} \ll \text{width}$) (Santamarina, 2002) . For the YK, we calculated the specific surface using a correlation based on liquid limit (value for liquid limit between 28_121) by Farrar& Coleman (1967). The SSA_ref and the SPo_ref were calculated using the d50 for all the four of fines. The activity of YK clay is 2.3 ($44\% \div 19\%$). It is likely that the clay minerals present in the soil is some type of montmorillonite (activity greater than 1) hence a smaller d50 than the measured value of 0.03 mm might be relevant.

The calculations of SSA_calculated, SSA_ref and SPo_ref for the Kaolinite mixtures and the YK mixtures may need to be recalculated based on revised d50 values in future studies.

5.3 Practical Implications

The results of this study provide important insights for the selection and design of subbase and subgrade materials in cold climates. Fines with high frost susceptibility, such as Kaolinite and Filler-rich mixtures, require additional measures to mitigate frost damage. These measures may include stabilization through lime or cement to reduce water retention or modifications to grading to minimize capillary water movement. Bentonite-rich mixtures, due to their high water absorption potential, require full saturation during testing to accurately assess their frost behavior. If used in subbase or subgrade materials, Bentonite should be carefully stabilized to reduce its plasticity and swelling potential.

Well-graded mixtures, such as those in the F Group, offer better resistance to frost heave due to their optimized particle size distribution. These materials are preferable for use in frost-prone regions as they exhibit lower heave rates and SP values. Similarly, YK fines, with their coarse texture and low frost susceptibility, provide a reliable option for minimizing frost-related pavement damage.

They were classified using level I classification methods and the KGM method The accuracy of level I classifications to predict frost susceptibility were evaluated by comparing with level III freeze-thaw test results because the development of ice lenses and the weathering phenomenon of soil are affected by many factors that cannot be easily explained by the index test results. However, the frost heave rate criterion appears to have a higher potential for accurate classification between different soils.

In summary, the relationship between the plasticity of soil and frost susceptibility is complex and depends on factors such as soil composition, water content, and temperature fluctuations. Soils with high plasticity may be more prone to certain frost-related issues, especially if they experience significant changes in moisture content and freeze-thaw cycles. Understanding these relationships is crucial for engineering and construction practices, especially in regions where freezing temperatures are common.

The classification results demonstrate a clear relationship between fines content, heave rate, and frost susceptibility. Mixes with higher fine content and heave rates, such as Mix 3 and Mix 4, exhibit a significant tendency toward frost heave, indicating a higher risk of ice segregation. This suggests that these mixes may be less suitable for applications in freezing conditions due to their increased potential for frost-related damage. In contrast, Mix 0 and Mix 1, characterized by lower fines content and heave rates, show minimal frost susceptibility, making them more appropriate for use in cold climates where durability is essential. Mix 2 presents a moderate level of frost susceptibility, placing it between the low- and high-risk categories; this intermediate classification suggests that additional caution may be necessary when considering its use in frost-prone environments.

The Cassagrande criteria indicate that significant ice segregation is not expected in F Kum mixes 0, 1, 2 and 3, as the percentage of particles passing the 0.02 mm sieve is below 3%. However, in 16_F Kum Mix 4, where the percentage passing the 0.02 mm sieve exceeds 3%, there is an indication of potential ice segregation. Despite these predictions, the Cassagrande criteria have proven inadequate in accurately assessing frost susceptibility, as the results show frost heave classifications ranging from medium to very high across Mixes 1 to 4.

Table 55.1 Criteria of classifications for Filler mixtures

Criteria	1_F Mix 1	2_F Mix 2	3_F Mix 3	4_F Mix 4
	GW-GM	GW-GM	GM	GM
	Fine content : %5.2	Fine content : %9.5	Fine content : %13.8	Fine content : %18
	<0.02 mm: %0.8	<0.02 mm: %1.5	<0.02 mm: %2.2	<0.02 mm: %2.87
Cassagrande	Significant ice segregation is not expected			
ISSMFE	NFS	Uncertain	uncertain	uncertain
USACE	PFS/S1, sensitive to frost	PFS/S1, sensitive to frost	PFS/F1, sensitive to frost	PFS/F2, sensitive to frost
KGM specification	F1, very low sensitivity	F1,very low sensitivity	F2, low sensitivity	F2, low sensitivity
Heave rate (mm/day) 1 st Freezing / 2 nd Freezing	2.89 / 2.8	8.22 / 6.76	10.8 / 10.4	13.2 / 9.79
Frost heave class (ASTM)	Low	Medium	High	High

The heave rate results reveal that the maximum recorded heave rate is 17.1 mm/day, observed during the first freeze cycle in 15_F Kum mix 3, which the ASTM classifies as having a "very high" frost heave susceptibility. Conversely, the minimum heave rate of 2.26 mm/day occurs in the first freeze cycle of 17_F Kum Mix 5, classified by ASTM as "low" in frost heave susceptibility. These findings underscore the variability in frost susceptibility across the mixes, with Mix 3 exhibiting substantial frost heave potential, indicating higher risk in freeze-thaw environments, while Mix 0 demonstrates stability with minimal heave, making it more suitable for applications in frost-prone areas. This range of heave rates highlights the need for careful selection of materials based on ASTM frost susceptibility classifications to ensure structural stability in cold regions

5.4 RSCS and Heave Rates

The mixtures to be tested in this study will also be evaluated according to this new classification system. It will be investigated whether this new classification will be useful in determining frost sensitivity.

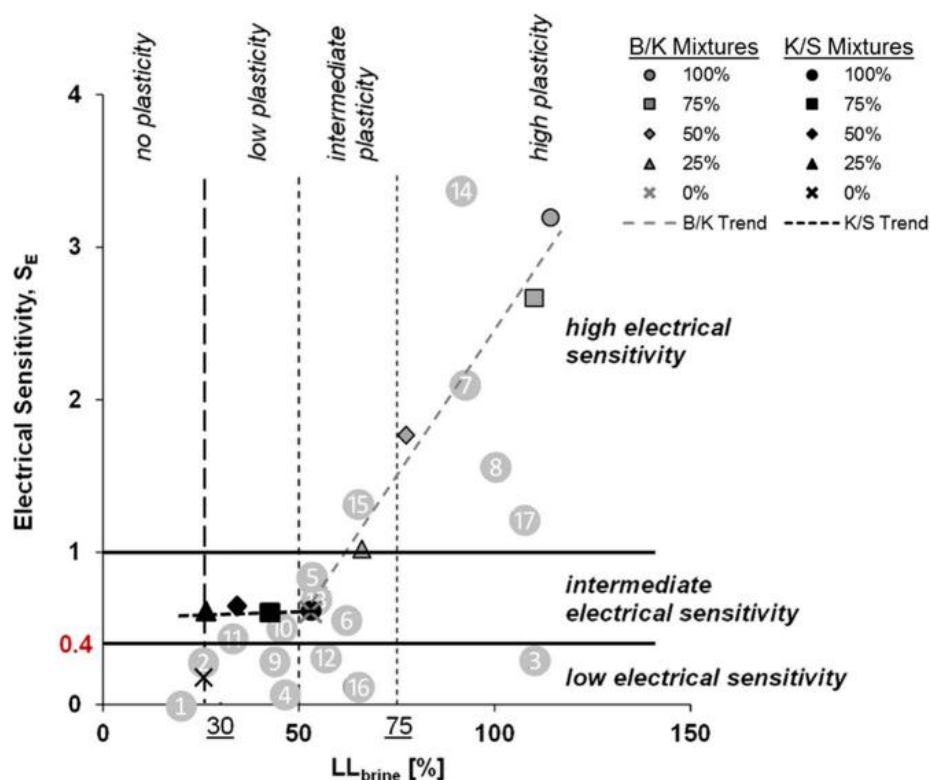


Figure 5.1 Fines Classification figure for RSCS

In recent years, the Revised Soil Classification System (RSCS) has emerged as a significant framework that categorizes soil types based on their physical, chemical, and biological characteristics. This innovative approach is a major breakthrough in the field of soil science, with implications for various applications, including agriculture, land use planning, environmental management, and engineering. It aims to provide a more comprehensive and up-to-date classification system that can accurately describe soils based on our current understanding of their properties and behaviors. This new method improves upon earlier classification systems by integrating the latest advancements in soil science research and overcoming the constraints of previous frameworks. [50]

The liquid limit and electrical sensitivity of soil are also crucial considerations when assessing its vulnerability to frost damage. Soils with higher liquid limits and greater electrical sensitivity are more prone to the detrimental effects of freezing temperatures, as they have a greater capacity to hold water and are more responsive to changes in moisture levels. Understanding these soil characteristics is essential for predicting how different soil types will perform under various climatic conditions.

In summary, the purpose of soil categorization is to help engineers better understand and anticipate the behavior and physical properties of different soil types. By considering factors like grain size distribution, plasticity, and frost sensitivity, the RSCS enables engineers to make more informed decisions and better mitigate the challenges posed by diverse soil conditions. The RSCS seems to have potential for aiding frost susceptibility classification of soils.



CHAPTER 6

CONCLUSION

Frost susceptibility of subbase and subgrade materials is a crucial factor influencing pavement performance in regions experiencing freeze-thaw cycles. It is affected by many factors including the amount of fine grained material that is present (i.e. the percent finer than 0.075 mm). This study evaluates the influence of fines content and type on the frost susceptibility of mixtures of gravel and sand. The coarse grained material consisted of crushed rock aggregates derived from a limestone quarry. They were sieved into four separate size fractions: 12-19 mm, 5-12 mm, 0-5 mm and fines. The finer particle fraction, or the so-called rock flour, were provided in bags and denoted “Filler”.

The fine grained material added to the gravel-sand mixtures included commercially available Kaolinite and Bentonite minerals, the non-plastic “Filler” (rock flour) and a natural soil, Yeşil Kesob clay, denoted “YK”. These fine grained materials were added to the coarse soil mixtures in percentages varying from 5.24% to 18%. The maximum dry density and optimum moisture content of each mixture was determined using Standard Proctor compaction tests. The California Bearing Ratio for the as-compacted and soaked condition were determined for each mixture. The CBR was also determined after freeze thaw testing.

Four samples, with diameters of 14.67 cm and height 15.42 cm, were compacted at optimum water content and density for each of the mixtures and tested in a specially designed freeze-thaw testing cabin. The freeze-thaw tests conducted were step-freeze tests with two cycles of freezing and thawing conducted over a period of 5 days. Each of the four samples were equipped with 8 thermistors to measure temperature, a laser displacement transducer to measure heave, and a load cell to measure water intake. The freeze-thaw test setup conformed to ASTM D5918 with an open water supply system where samples had constant access to a water source. Freezing occurred from the top of the sample and progressed downward. Samples were wrapped with insulation material to facilitate 1-D freezing conditions.

This study is part of a joint research project between Ankara Yıldırım Bayazıt Üniversitesi Civil Engineering Department and the Republic of Turkey General Directorate of Highways (KGM) Soil Stabilization and Research Development Group. The project “Karayolları

Üstyapısı Açısından Zeminlerin ve Yol Malzemelerinin Don Hassasiyetinin Değerlendirilmesi ve İyileştirme Metotları” or “Evaluation of Frost Sensitivity of Soils and Road Materials in Terms of Highway Superstructure and Improvement Methods” is directed by Dr. Zeynep H.Özkul Birgören and advisor to this thesis.

A specially designed freeze thaw cabin was used for the first time in Türkiye to determine the frost susceptibility of soils. This study establishes the means and methods to conduct the freeze thaw test and to evaluate the recorded data. The CVs data file for each 5-day freeze thaw test includes 1440 rows and 43 columns for each test run. Information in this file includes data from 24 thermistors, 4 laser displacement units, and 4 load cell units. A spreadsheet solution tool was developed as part of this study to be able to view and analyse the test recorded data. A spreadsheet tool was also developed to calculate the segregation potentials. Future work needed is the development of a software package instead of using spreadsheet solutions to facilitate viewing analysis and reporting the freeze thaw test data. Such a tool could possibly be written in the R or python language.

The sample preparation and much of the laboratory testing have been conducted in the KGM soils lab by their own staff of engineers and technicians. Some testing has been conducted in the AYBU soil mechanics lab (maximum and minimum void ratio determination, and specific gravity). The evaluation of all test results were conducted by the author under the direction of the project manager/MSc advisor.

Six groups of soil mixtures, each with four different percentages of fines content, were tested. A total of 25 different soil mixes were tested as part of this study. Each of the mixes were classified using USCS, AASHTO and the Revised Soil Classification System. The heave rates of each soil mixture were determined from the results of the freeze-thaw tests and based on these values, the frost heave susceptibility was determined for each mixture according to the classification system from ASTM D5918. The segregation potential was also determined for each mixture. This value may be used to determine the frost classification class or it may be used in a frost simulation software to predict frost heave for different climate and road conditions. This is an important step in the transition of pavement design from empirical methods to mechanistic-empirical based methods.

Regression analysis was performed on the test results to try and find a relationship between fines content and heave rates. The findings show that the heave rates increase with

increasing percentages of fines. Results also show that the type of fines affect the amount of heave rate recorded. Non-plastic fines (Filler) and low plasticity clay (Kaolinite) produce the largest heave rates. These are consistent with findings from the literature. It was found that slightly larger heave rates were possible in the 2nd cycle of freezing for samples with fines consisting of Kaolinite.

Within the scope of this study different frost classification systems were evaluated. There are many different methods but for this study the following were selected: Cassagrande criteria, ISSMGE criteria, USACE method, ASTM heave rate method and KGM method. These methods include level I, level II and level III classifications. All tested mixtures were classified using these methods and compared. The findings from this study show:

- Level I criteria are not able to consistently identify FS soils that are in the marginal range. Other times they may be over conservative.
- Level II criteria take into consideration the plasticity of fines but are still not able to consistently identify FS soils.
- Level III criteria are best suited for this purpose, but are time consuming and expensive to perform.

These findings are consistent with the literature on FS classification systems. The frost susceptibility test conducted in this study were also used to determine segregation potential. This parameter may be used as a means of soil FS classification. It may also be used as a soil input parameter for calculating pavement heave due to frost in a given project site as part of a mechanistic empirical design strategy. Konrad (1999, 2005) has developed a pavement frost design procedure using segregation potential. This method was also reviewed and applied to the segregation potential measured in this study. A comparison was made between his findings and those of this study. It was found that this new procedure is promising. Future research should concentrate on finding ways to effectively use the segregation potential parameter in the design of pavements that are resistant to frost action.

This study highlights the varying impacts of the type of fines and grain size distribution (GSD), (including Kaolinite, Bentonite, Filler, and YK), on frost susceptibility. The heave results and SP values underscore the critical roles of mineralogy, particle size distribution, and saturation in determining frost behavior. Well-graded F Group mixtures, influenced by high silt content, exhibited high frost susceptibility. Kaolinite mixtures, which also have

high silt content, showed the highest values of segregation potential and heave rates, possibly due to the clay content and their capacity to adsorb water and increase overall water content. For well-graded mixtures, YK mixtures showed lower heave rates and segregation potential compared to Filler and Kaolinite mixtures. This is likely due to the higher ratio of clay to silt fraction for same fines content.

The soils tested included well-graded and gap-graded soil mixtures. The sand mixtures consisted of a uniform sand with grain sizes mostly in the 4.75 mm to 2 mm range. This uniform grading for the soil skeleton is markedly different than the well-graded mixtures where more than 48% consisted of gravel. Larger frost heave was observed in the sand and fines mixtures compared to the well-graded gravel mixture. This finding indicates that the nature of the soil skeleton impacts the void channels where water can migrate and consequently impacts the degree of frost susceptibility.

All samples were classified using the Revised soil classification system (RSCS) in order to test whether this classification scheme can be useful in frost susceptibility classification. Our findings show that there is promise but more research is needed. Future work should pursue to find a relationship or regression curve that can relate heave rate or segregation potential to electrical sensitivity, the three liquid limits and the soil composition.

The findings emphasize the importance of controlled testing and material selection to optimize frost performance in subbase and subgrade materials. Future work should address the limitations of incomplete saturation in Bentonite mixtures to provide a more accurate assessment of their frost susceptibility.

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APPENDICES

Appendix A: Phase Diagrams

Appendix B: Freeze Thaw Testing Manual

Appendix C: Freeze-Thaw Test Results

Appendix D: Temperature Profile of Samples & Temperature Gradient at Steady State Condition



Appendix A: Phase Diagrams

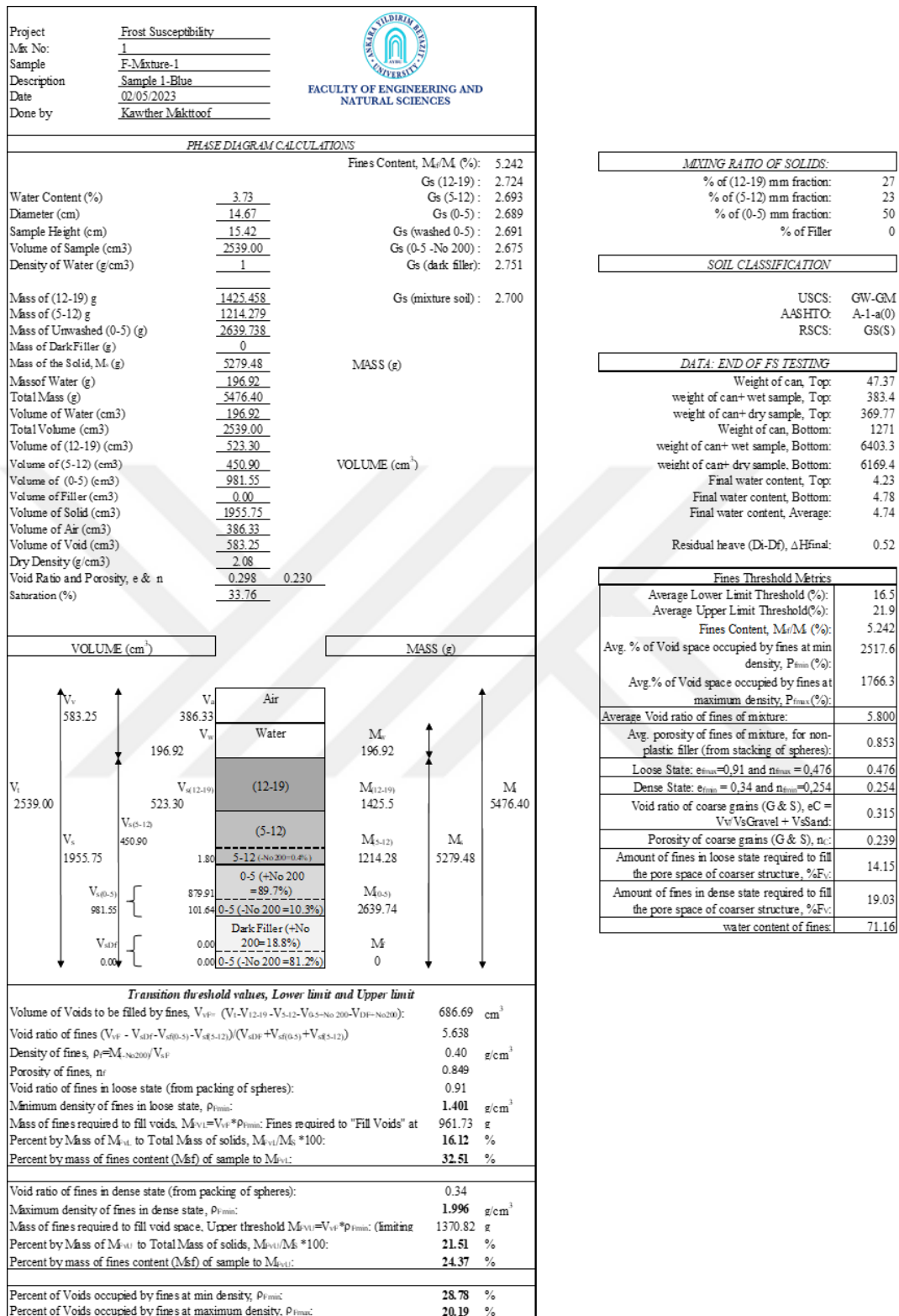
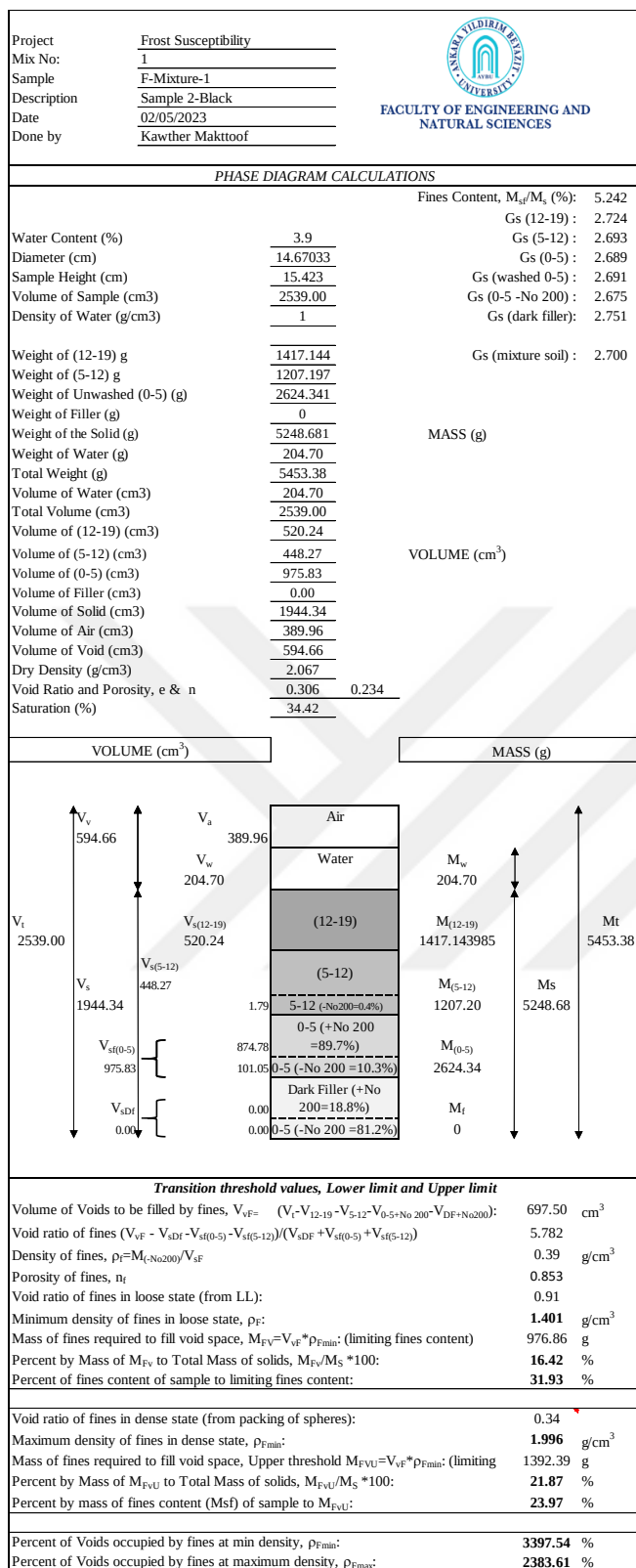


Figure A. 1 Phase Diagram for "1_F Mix 1-Blue"



MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of (0-5) mm fraction:	50
% of Filler	0

SOIL CLASSIFICATION	
USCS:	GW-GM
AASHTO:	A-1-a(0)
RSCS:	GS(S)

DATA: END OF FS TESTING	
Weight of can, Top:	49.69
weight of can+ wet sample, Top:	380.7
weight of can+ dry sample, Top:	368.25
Weight of can, Bottom:	1273.5
weight of can+ wet sample, Bottom:	6390.1
weight of can+ dry sample, Bottom:	6186
Final water content, Top:	3.91
Final water content, Bottom:	4.15
Final water content, Average:	4.14
Residual heave (Di-Df), ΔH_{final} :	0.7

Fines Threshold Metrics	
Loose State: $e_{max}=0.91$ and $n_{max}=0.476$	0.476
Dense State: $e_{min}=0.34$ and $n_{min}=0.254$	0.254
Void ratio of coarse grains (G & S), $e_c = V_v/V_{sGravel} + V_{sSand}$:	0.323
Porosity of coarse grains (G & S), n_c :	0.244
Amount of fines in loose state required to fill the pore space of coarser structure, % F_v :	14.46
Amount of fines in dense state required to fill the pore space of coarser structure, % F_v :	19.42
Water content of fines:	74.40

Figure A. 2 Phase Diagram for "1_F Mix 1-Black"

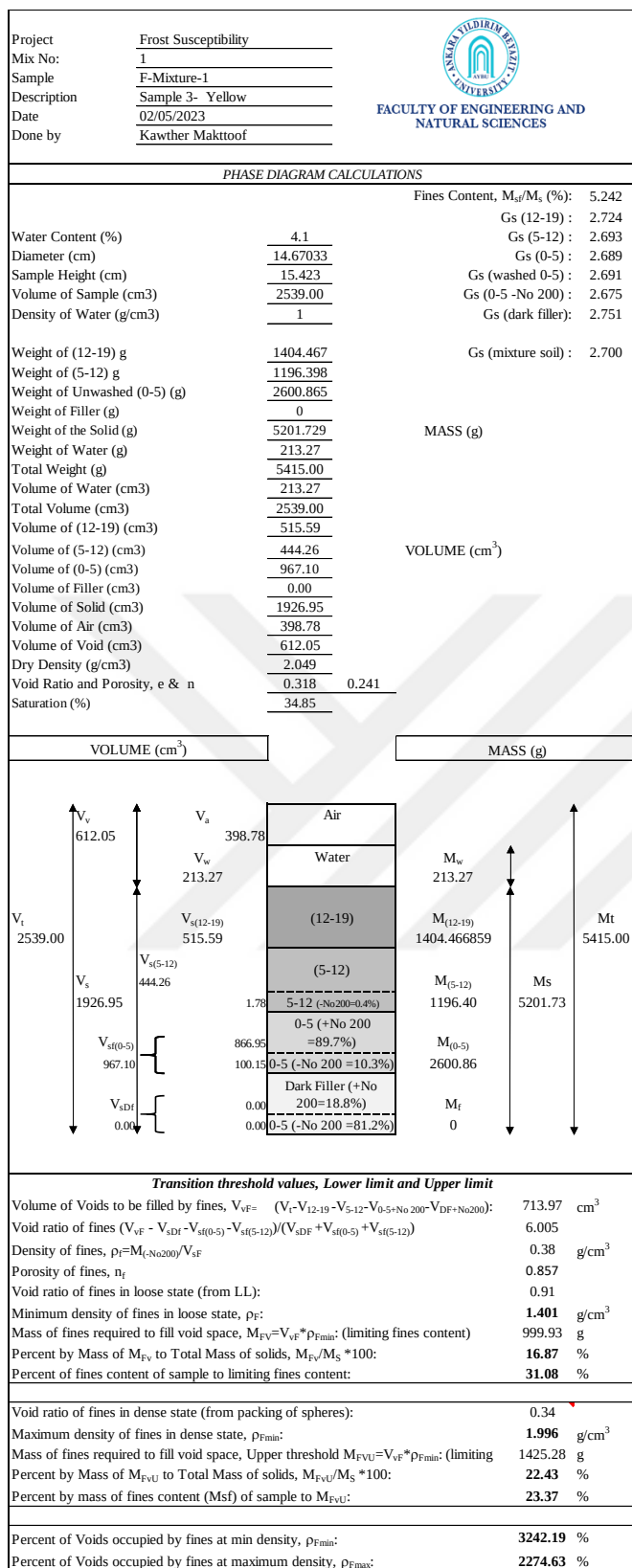
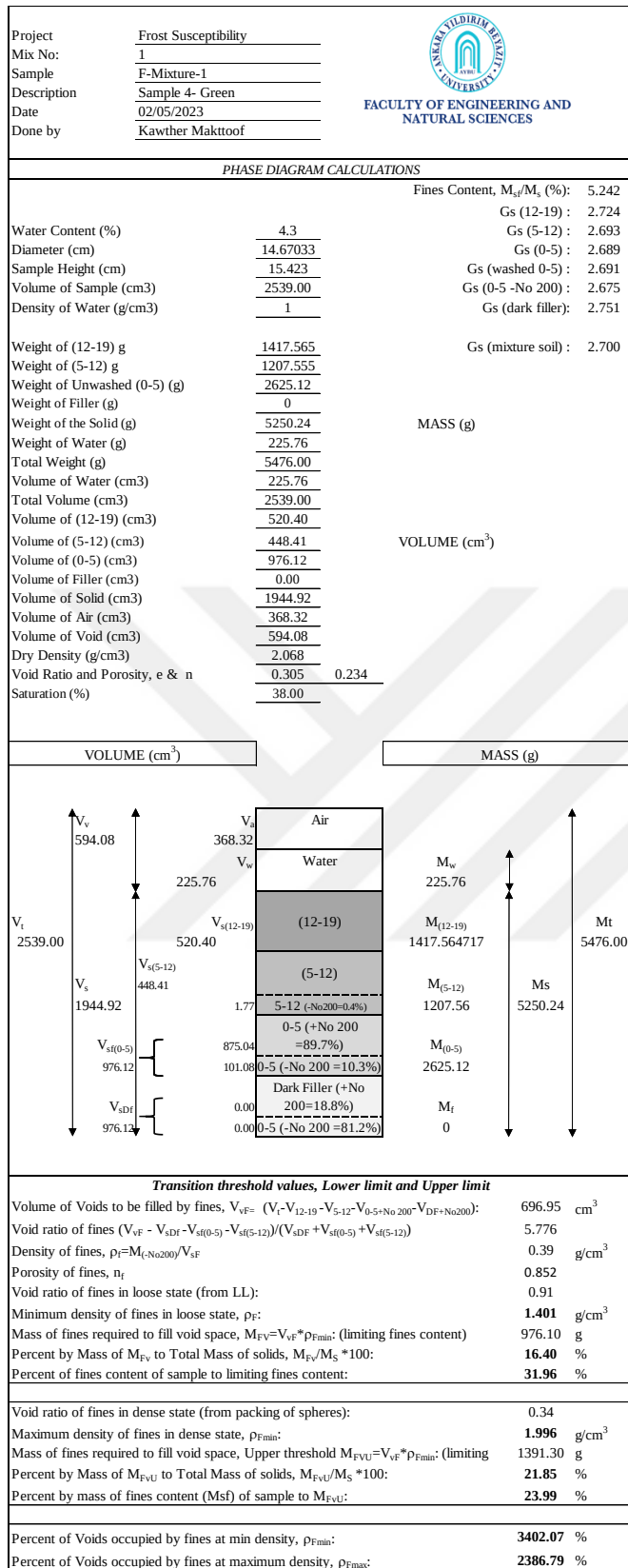


Figure A. 3 Phase Diagram for “1_F Mix 1-Yellow”



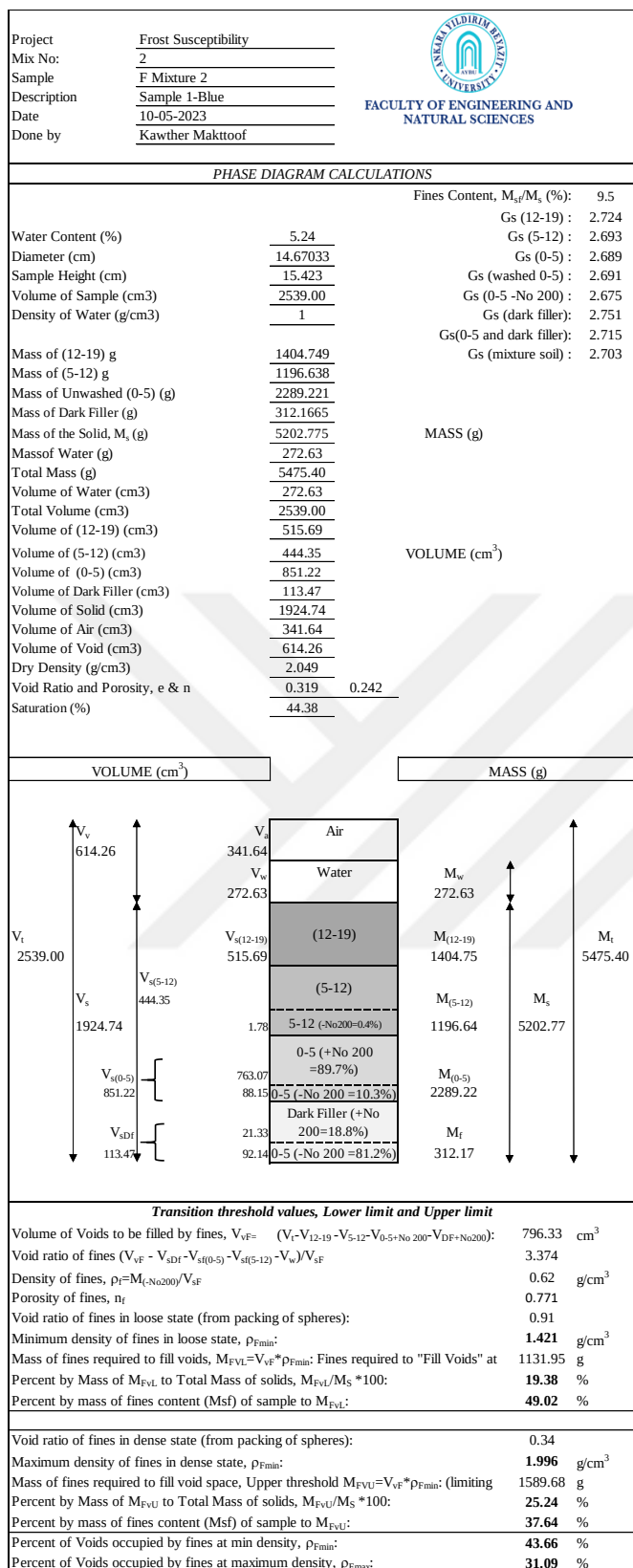
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of (0-5) mm fraction:	50
% of Filler	0

SOIL CLASSIFICATION	
USCS:	GW-GM
AASHTO:	A-1-a(0)
RSCS:	GS(S)

DATA: END OF FS TESTING	
Weight of can, Top:	47.93
weight of can+ wet sample, Top:	404.81
weight of can+ dry sample, Top:	386.61
Weight of can, Bottom:	1262.3
weight of can+ wet sample, Bottom:	6404.9
weight of can+ dry sample, Bottom:	6146.3
Final water content, Top:	5.37
Final water content, Bottom:	5.29
Final water content, Average:	5.30
Residual heave (Di-Df), ΔH_{final} :	0.75

Fines Threshold Metrics	
Loose State: $e_{fmax}=0.91$ and $n_{fmax}=0.476$	0.476
Dense State: $e_{fmin}=0.34$ and $n_{fmin}=0.254$	0.254
Void ratio of coarse grains (G & S), $e_c = V_v/V_{sGravel} + V_{sSand}$:	0.323
Porosity of coarse grains (G & S), n_c :	0.244
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	14.45
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	19.40
Water content of fines:	82.03

Figure A. 4 Phase Diagram for "1_F Mix 1-Green"



MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of (0-5) mm fraction:	44
% of Filler	6

SOIL CLASSIFICATION	
USCS:	GW-GM
AASHTO:	A-1-a(0)
RSCS:	GS(S)

DATA: END OF FS TESTING	
Weight of can, Top:	44.64
weight of can+ wet sample, Top:	369.17
weight of can+ dry sample, Top:	337.05
Weight of can, Bottom:	1099.1
weight of can+ wet sample, Bottom:	6358.4
weight of can+ dry sample, Bottom:	5999.9
Final water content, Top:	10.98
Final water content, Bottom:	7.32
Final water content, Average:	7.52
Residual heave ($D_i - D_f$), ΔH_{final} :	2.1

Fines Threshold Values	
Average Lower Limit Threshold (%):	18.6
Average Upper Limit Threshold (%):	24.2
Fines Content, M_{sf}/M_s (%):	9.50
Avg. % of Void space occupied by fines at min density, P_{min} (%):	46.1
Avg. % of Void space occupied by fines at maximum density, P_{max} (%):	32.8
Average Void ratio of fines of mixture:	3.146
Avg. porosity of fines of mixture, for non-plastic filler (from stacking of spheres):	0.758
Loose State: $e_{fmax} = 0.91$ and $n_{fmax} = 0.476$	0.476
Dense State: $e_{fmin} = 0.34$ and $n_{fmin} = 0.254$	0.254
Void ratio of coarse grains (G & S), $e_c = V_v/V_{sGravel} + V_{sSand}$:	0.352
Porosity of coarse grains (G & S), n_c :	0.261
Amount of fines in loose state required to fill the pore space of coarser structure, % F_v :	15.58
Amount of fines in dense state required to fill the pore space of coarser structure, % F_v :	20.83
Water content of fines:	55.18

Figure A. 5 Phase Diagram for "2_F Mix 2-Blue"

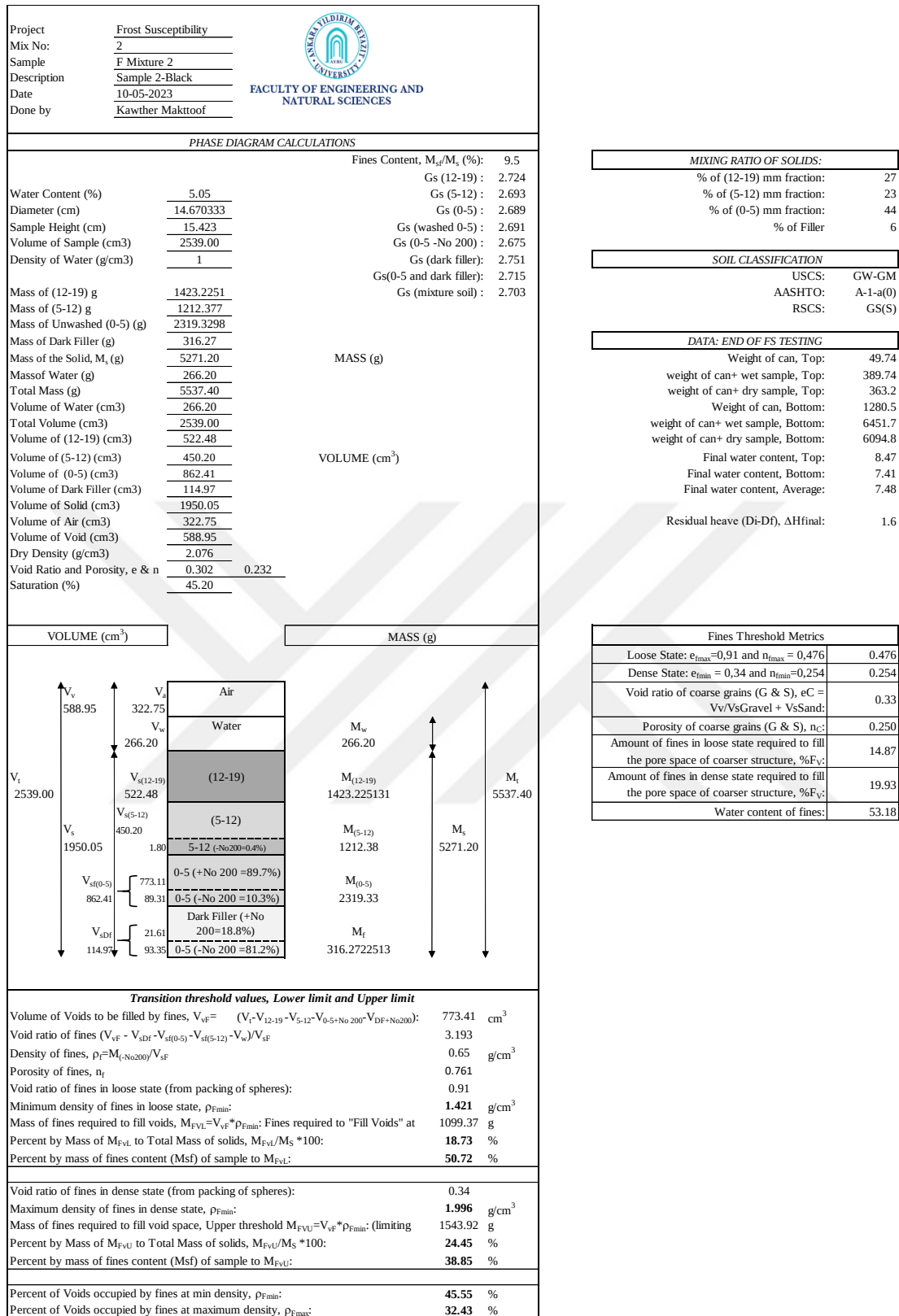


Figure A. 6 Phase Diagram for “2_F Mix 2-Black”

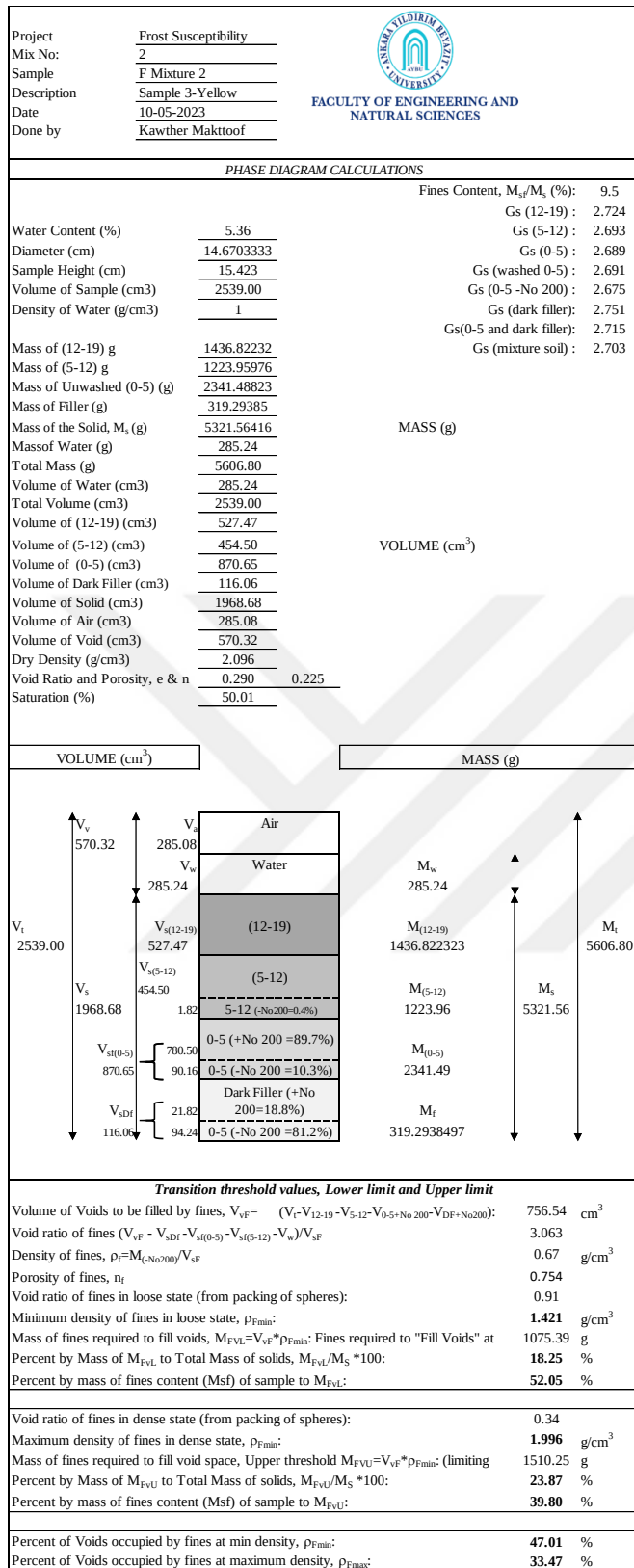
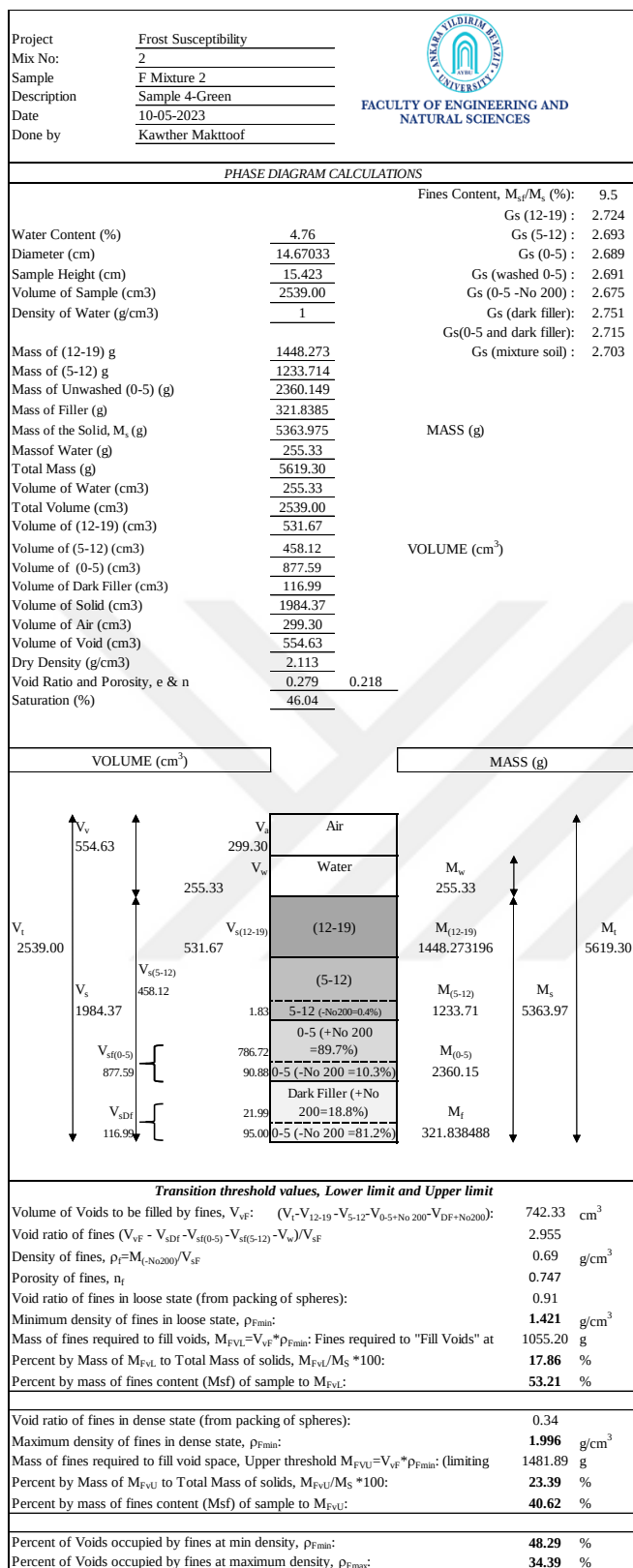


Figure A. 7 Phase Diagram for "2_F Mix 2-Yellow"



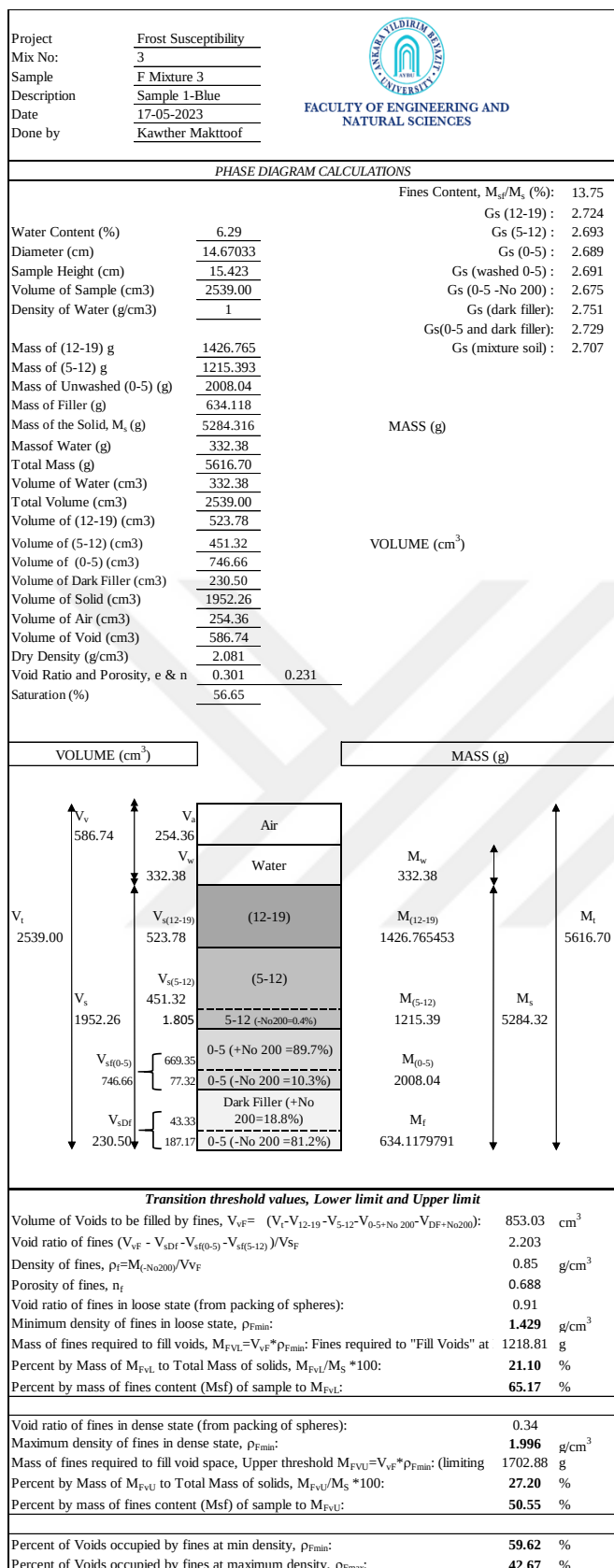
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of (0-5) mm fraction:	44
% of Filler	6

SOIL CLASSIFICATION	
USCS:	GW-GM
AASHTO:	A-1-a(0)
RSOS:	GS(S)

DATA: END OF FS TESTING	
Weight of can, Top:	47.97
weight of can+ wet sample, Top:	399.35
weight of can+ dry sample, Top:	372.7
Weight of can, Bottom:	1301.9
weight of can+ wet sample, Bottom:	6637.8
weight of can+ dry sample, Bottom:	6278.9
Final water content, Top:	8.21
Final water content, Bottom:	7.21
Final water content, Average:	7.27
Residual heave (Di-Df), ΔH_{final} :	1.65

Fines Threshold Metrics	
Loose State: $e_{max}=0.91$ and $n_{max}=0.476$	0.476
Dense State: $e_{min}=0.34$ and $n_{min}=0.254$	0.254
Void ratio of coarse grains (G & S), $e_c = V_v/V_{sGravel} + V_{sSand}$:	0.309
Porosity of coarse grains (G & S), n_c :	0.236
Amount of fines in loose state required to fill the pore space of coarser structure, % F_{Vf} :	13.91
Amount of fines in dense state required to fill the pore space of coarser structure, % F_{Vf} :	18.72
Water content of fines:	50.13

Figure A. 8 Phase Diagram for "2_F Mix 2-Green"



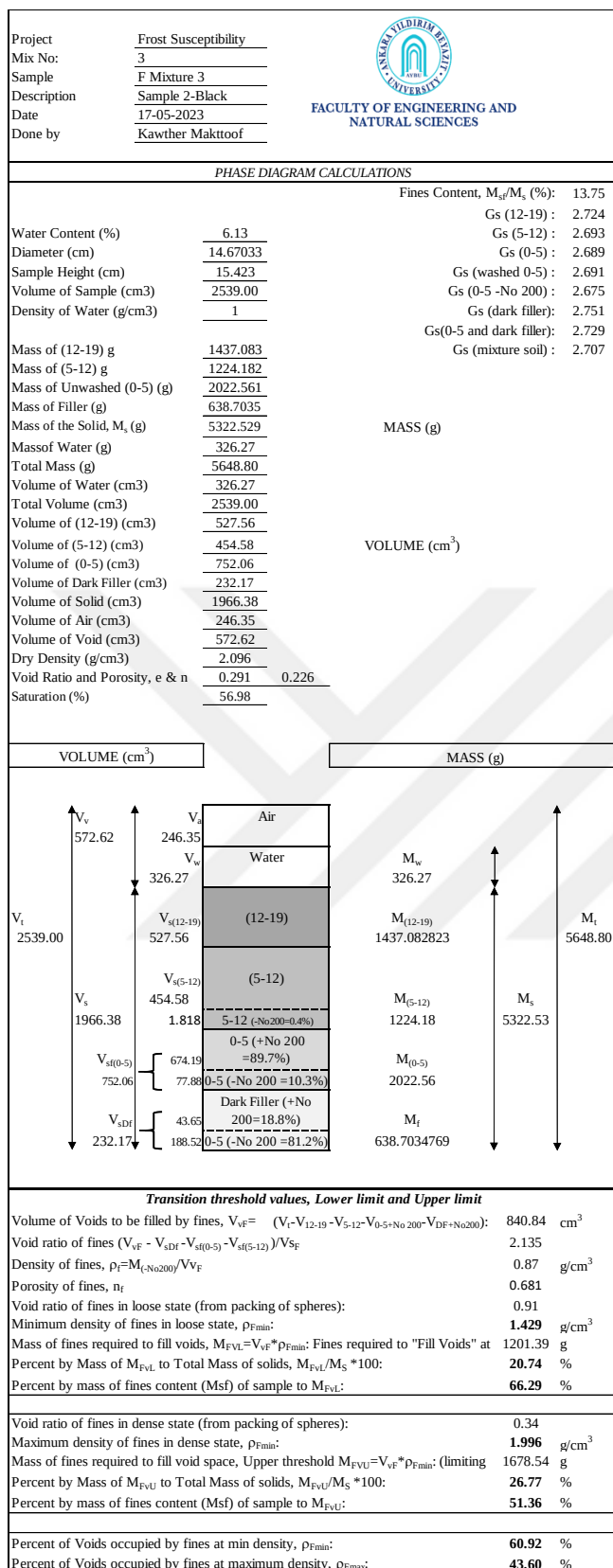
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of (0-5) mm fraction:	38
% of Filler	12

SOIL CLASSIFICATION	
USCS:	GM
AASHTO:	A-1-a(0)
RSCS:	GSF(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	51.95
weight of can+ wet sample, Top:	395.24
weight of can+ dry sample, Top:	365.27
Weight of can, Bottom:	1274
weight of can+ wet sample, Bottom:	6581.8
weight of can+ dry sample, Bottom:	6205.00
Final water content, Top:	9.57
Final water content, Bottom:	7.64
Final water content, Average:	7.76
Residual heave (Di-Df), ΔH_{final} :	2.6

Fines Threshold Values	
Average Lower Limit Threshold (%):	20.0
Average Upper Limit Threshold(%):	25.9
Fines Content, M_{sf}/M_s (%):	13.750
Avg. % of Void space occupied by fines at min density, P_{fmin} (%):	63.9
Avg.% of Void space occupied by fines at maximum density, P_{fmax} (%):	45.8
Average Void ratio of fines of mixture:	1.997
Avg. porosity of fines of mixture, for non-plastic filler (from stacking of spheres):	0.532
Loose State: $e_{fmax}=0.91$ and $n_{fmax} = 0.476$	0.476
Dense State: $e_{fmin} = 0.34$ and $n_{fmin}=0.254$	0.254
Void ratio of coarse grains (G & S), $eC = V_v/V_{sGravel} + V_{sSand}$:	0.348
Porosity of coarse grains (G & S), n_c :	0.258
Amount of fines in loose state required to fill the pore space of coarser structure, % F_v :	15.41
Amount of fines in dense state required to fill the pore space of coarser structure, % F_v :	20.62
water content of fines:	45.75

Figure A. 9 Phase Diagram for "3_F Mix 3-Blue"



MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of (0-5) mm fraction:	38
% of Filler	12

SOIL CLASSIFICATION	
USCS:	GM
AASHTO:	A-1-a(0)
RSCS:	GSF(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	49.11
weight of can+ wet sample, Top:	397.13
weight of can+ dry sample, Top:	369.54
Weight of can, Bottom:	1274.3
weight of can+ wet sample, Bottom:	6622.1
weight of can+ dry sample, Bottom:	6260
Final water content, Top:	8.61
Final water content, Bottom:	7.26
Final water content, Average:	7.34
Residual heave (Di-Df), ΔH_{final} :	3.1

Fines Threshold Metrics		
Loose State: $e_{fmax}=0.91$ and $n_{fmax}=0.476$		0.476
Dense State: $e_{fmin}=0.34$ and $n_{fmin}=0.254$		0.254
Void ratio of coarse grains (G & S), $e_c = V_v/V_{sGravel} + V_{sSand}$:		0.337
Porosity of coarse grains (G & S), n_c :		0.252
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :		15.01
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :		20.11
water content of fines:		44.58

Figure A. 10 Phase Diagram for "3_F Mix 3-Black"

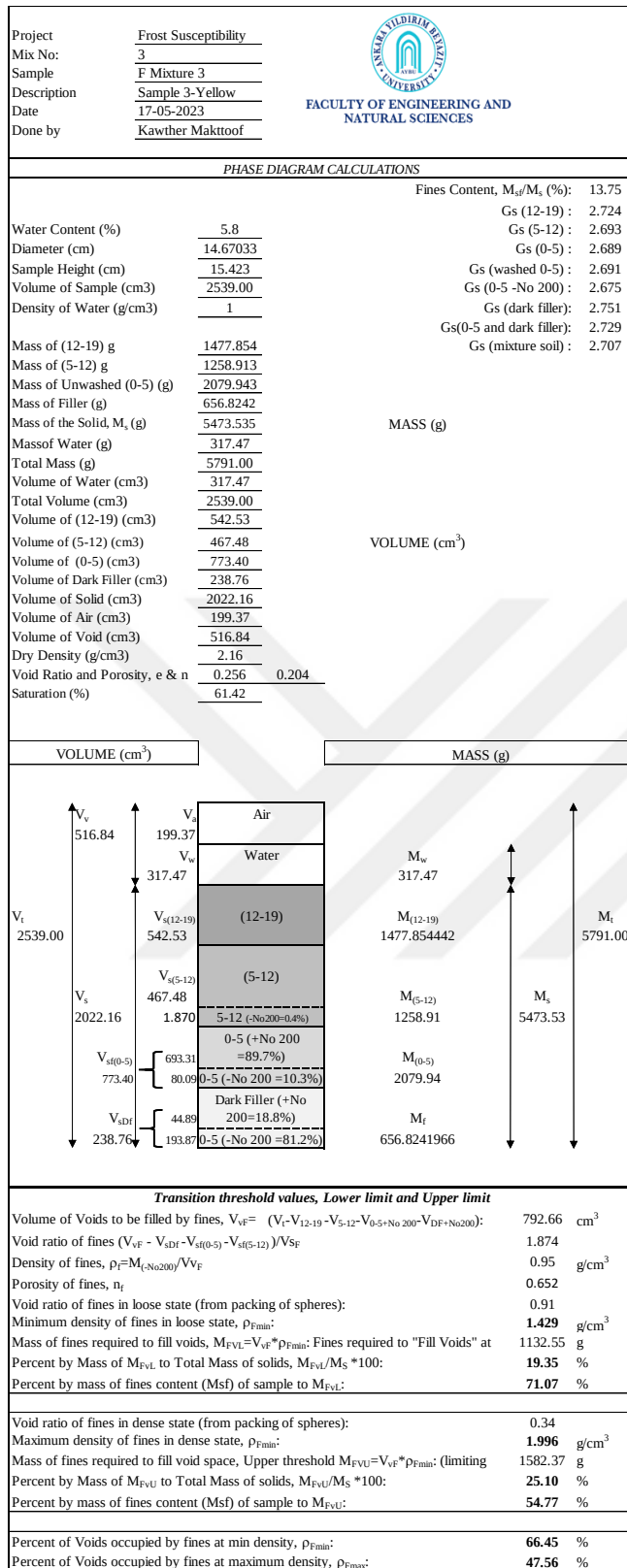


Figure A. 11 Phase Diagram for "3_F Mix 3-Yellow"

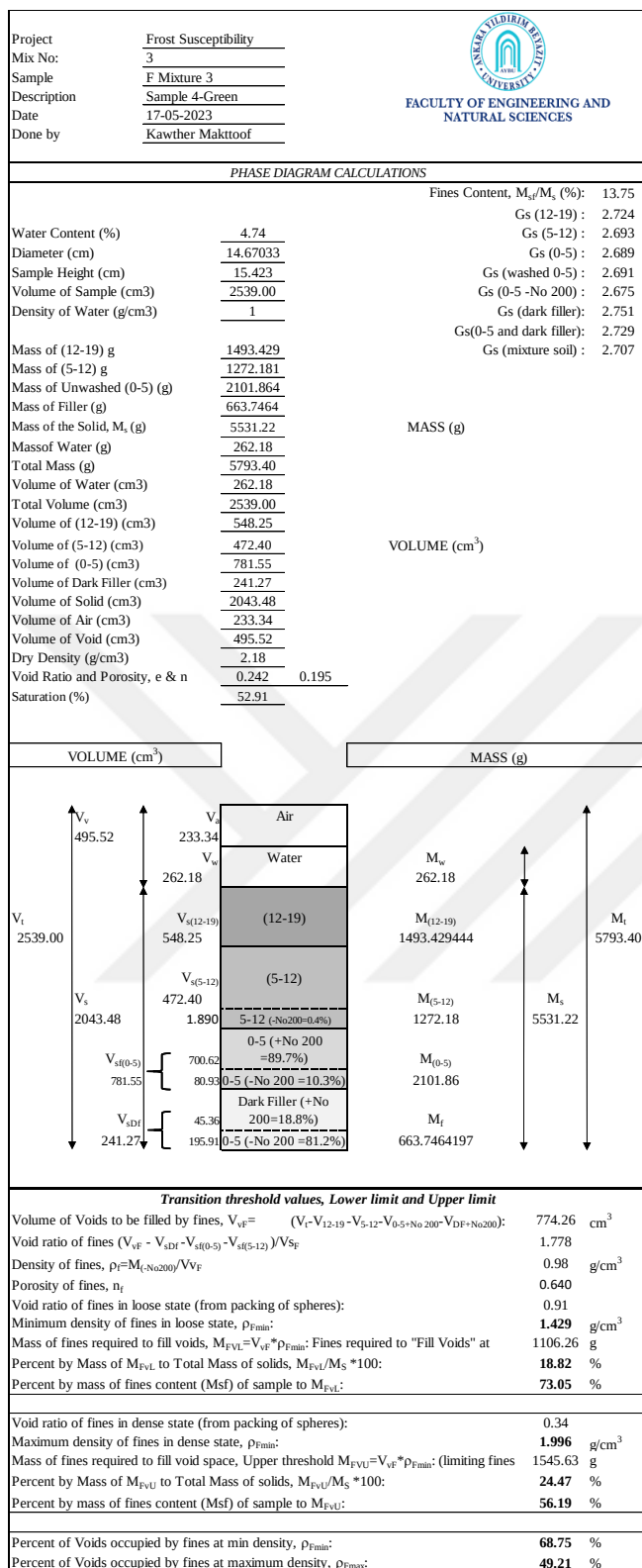
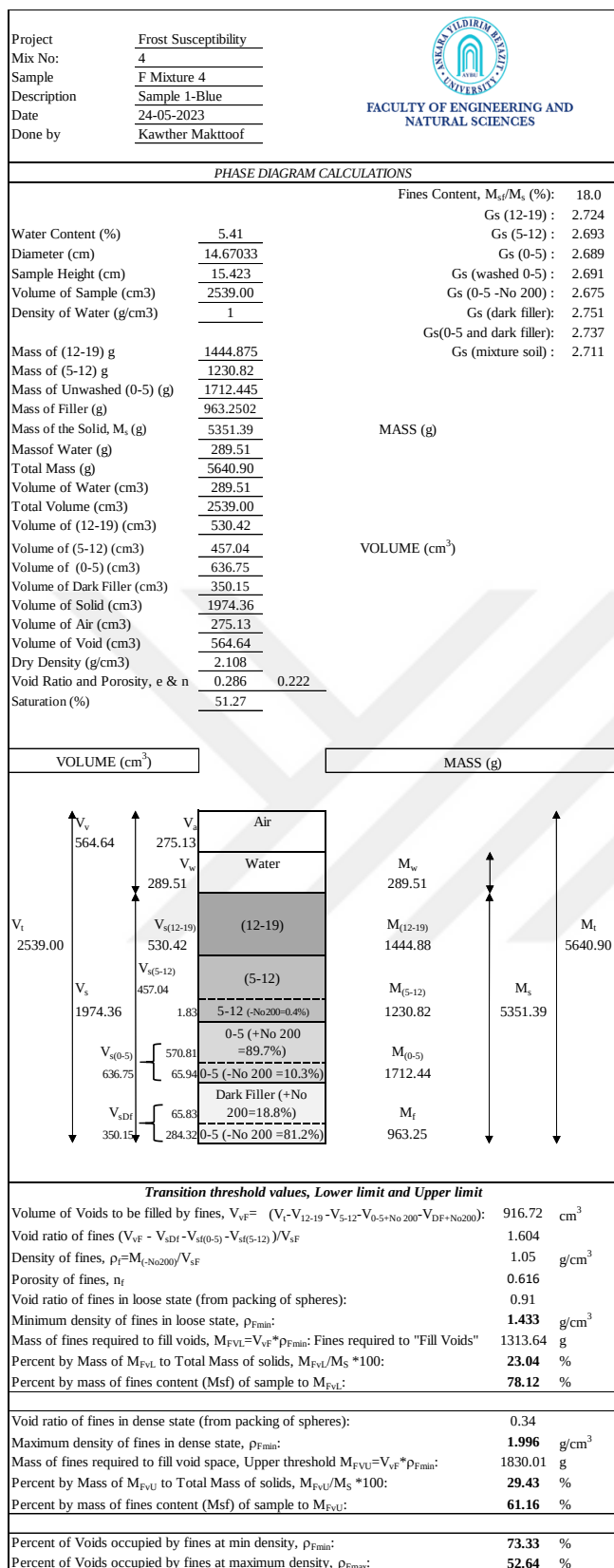
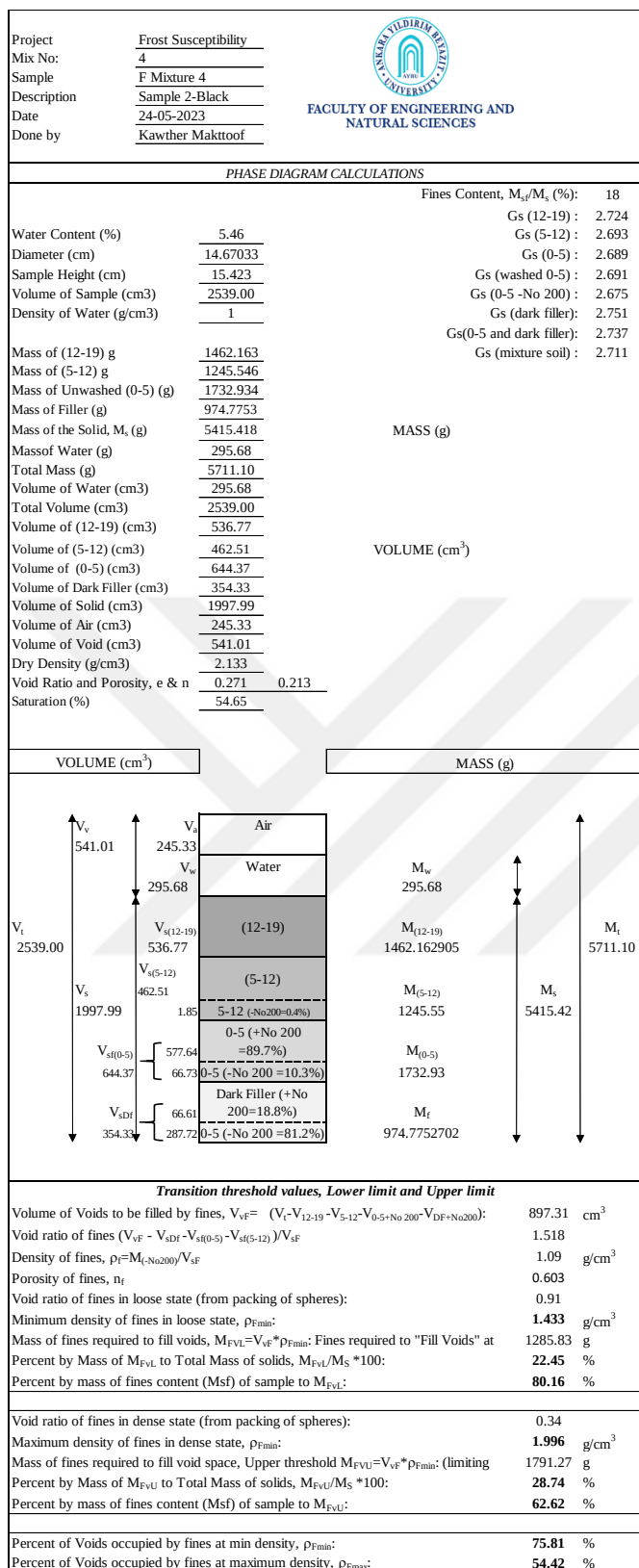


Figure A. 12 Phase Diagram for "3_F Mix 3-Green"





MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of (0-5) mm fraction:	32
% of Filler	18

SOIL CLASSIFICATION	
USCS:	GM
AASHTO:	A-1-b(0)
RSCS:	GSF(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	49.41
weight of can+ wet sample, Top:	377.98
weight of can+ dry sample, Top:	346.45
Weight of can, Bottom:	1274
weight of can+ wet sample, Bottom:	6754.8
weight of can+ dry sample, Bottom:	6334.1
Final water content, Top:	10.61
Final water content, Bottom:	8.31
Final water content, Average:	8.44
Residual heave ($D_i - D_f$), ΔH_{final} :	5.5

Fines Threshold Metrics	
Loose State: $e_{tmax}=0.91$ and $n_{tmax} = 0.476$	0.476
Dense State: $e_{tmin} = 0.34$ and $n_{tmin}=0.254$	0.254
Void ratio of coarse grains (G & S), $e_C = V_w/V_{sGravel} + V_{sSand}$:	0.330
Porosity of coarse grains (G & S), n_C :	0.248
Amount of fines in loose state required to fill the pore space of coarser structure, $\%F_{V_L}$:	14.71
Amount of fines in dense state required to fill the pore space of coarser structure, $\%F_{V_D}$:	19.74
water content of fines:	30.33

Figure A. 14 Phase Diagram for "4_F Mix 4-Black"

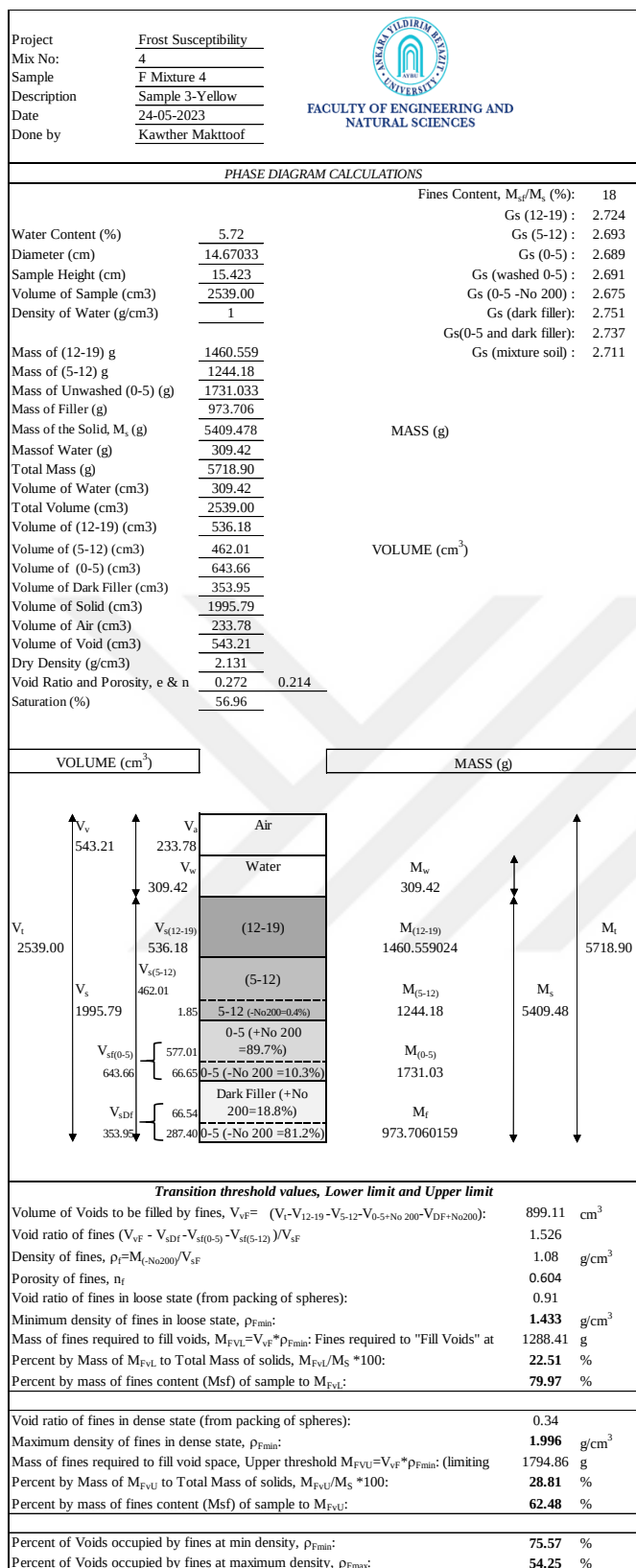


Figure A. 15 Phase Diagram for "4_F Mix 4-Yellow"

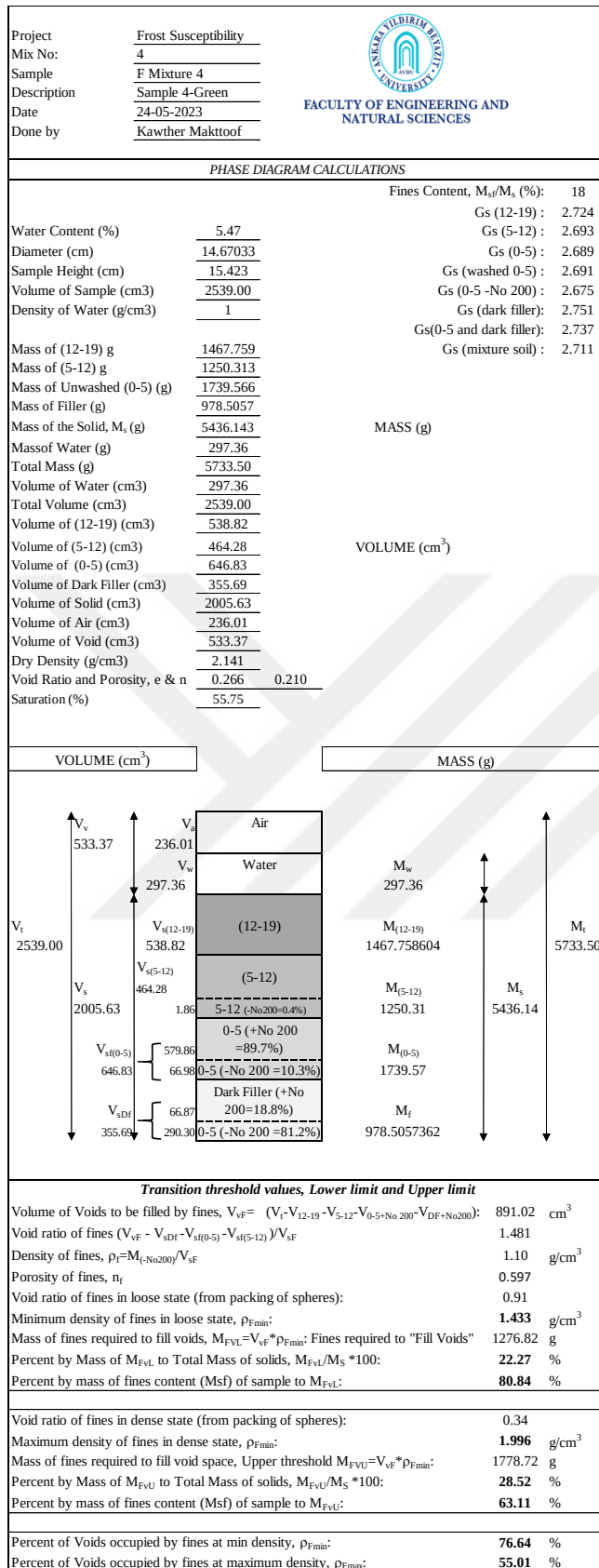
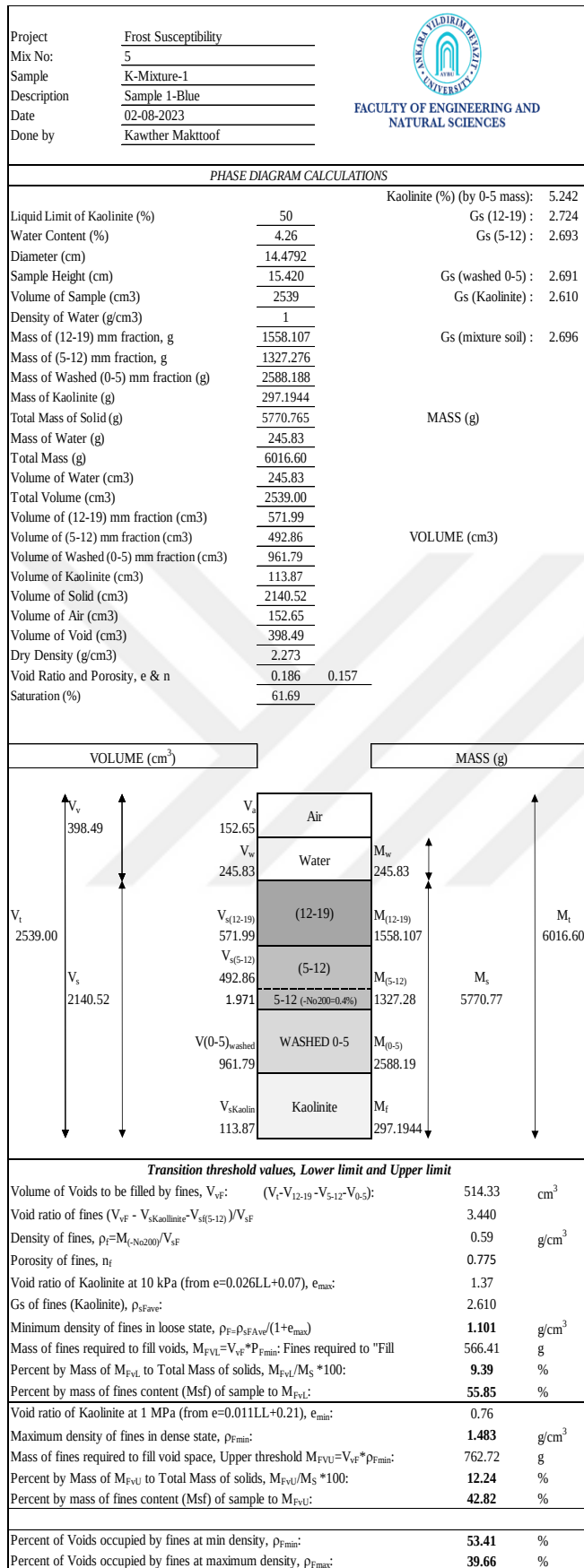


Figure A. 16 Phase Diagram for "4_F Mix 4-Green"



MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	44.85
% of Kaolinite:	5.15

SOIL CLASSIFICATION	
USCS:	GP-GC
AASHTO:	A2-7 (0)
RSCS:	GS(F) where fines are HI

DATA: END OF FS TESTING	
Weight of can, Top:	48.24
weight of can+ wet sample, Top:	444.2
weight of can+ dry sample, Top:	424.47
Weight of can, Bottom:	1238
weight of can+ wet sample, Bottom:	6513.7
weight of can+ dry sample, Bottom:	6185.4
Final water content, Top:	5.24
Final water content, Bottom:	6.64
Final water content, Average:	6.54
Residual heave (Di-Df), ΔHfinal:	2.6

Fines Threshold Values	
Average Lower Limit Threshold (%):	12.4
Average Upper Limit Threshold(%):	16.0
Fines Content, M _{sf} /M _s (%):	5.242
Avg. % of Void space occupied by fines at min density, P _{fmin} (%):	40.7
Avg.% of Void space occupied by fines at maximum density, P _{fmax} (%):	30.2
Average Void ratio of fines of mixture:	4.206
Average porosity of fines of mixture:	0.800
Loose State:	0.578
Dense State:	0.432
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.197
Porosity of coarse grains (G & S), n _C :	0.164
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	7.67
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	10.06
water content of fines:	81.27

Figure A. 17 Phase Diagram for "5_K Mix 1-Blue"

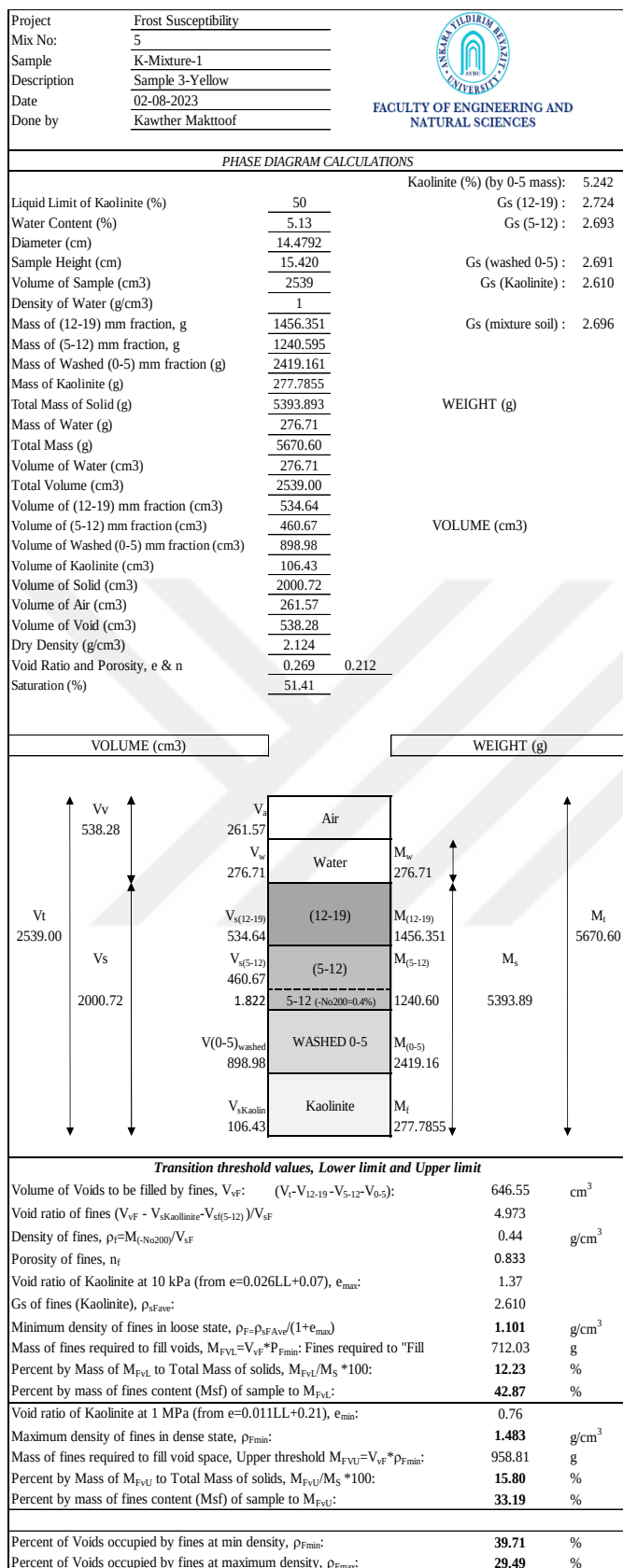


Figure A. 19 Phase Diagram for “5_K Mix 1-Yellow”

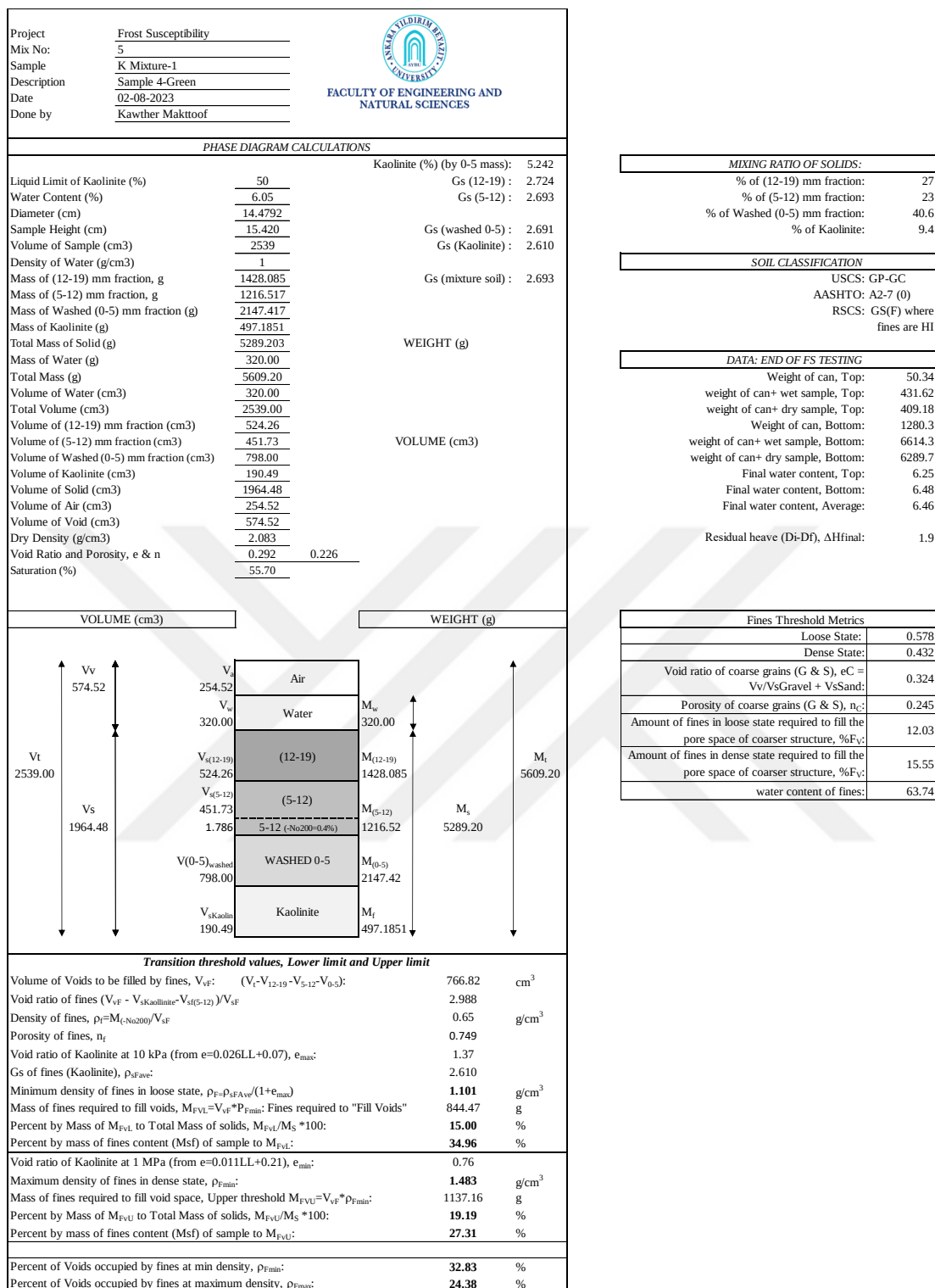
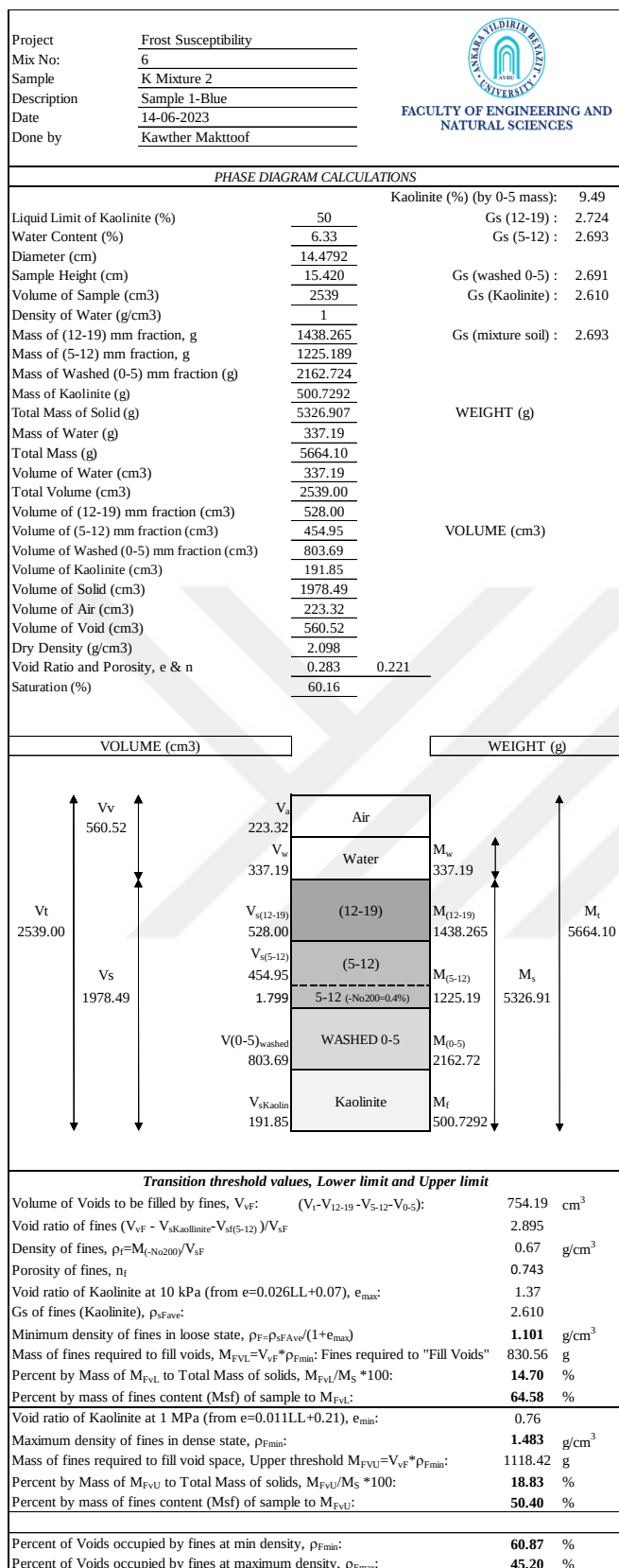


Figure A. 20 Phase Diagram for "5_K Mix 1-Green"



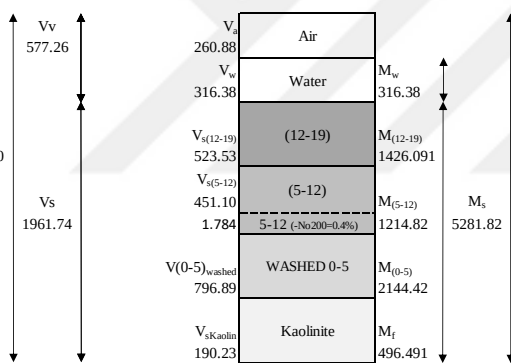
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	40.6
% of Kaolinite:	9.4

SOIL CLASSIFICATION	
USCS:	GW-GC
AASHTO:	A2-7 (0)
RSCS:	GS(F) where fines are HI

DATA: END OF FS TESTING	
Weight of can, Top:	48.35
weight of can+ wet sample, Top:	421.36
weight of can+ dry sample, Top:	395.68
Weight of can, Bottom:	1273.9
weight of can+ wet sample, Bottom:	6553.7
weight of can+ dry sample, Bottom:	6203.4
Final water content, Top:	7.39
Final water content, Bottom:	7.11
Final water content, Average:	7.13
Residual heave (D _i -D _f), ΔH _{final} :	2.3

Fines Threshold Values	
Average Lower Limit Threshold (%):	15.0
Average Upper Limit Threshold(%):	19.2
Fines Content, M _s /M _t (%):	9.490
Avg. % of Void space occupied by fines at min density, P _{min} (%):	59.4
Avg.% of Void space occupied by fines at maximum density, P _{max} (%):	44.1
Average Void ratio of fines of mixture:	2.995
Average porosity of fines of mixture:	0.750
Loose State:	0.578
Dense State:	0.432
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.31404
Porosity of coarse grains (G & S), n _c :	0.239
Amount of fines in loose state required to fill the pore space of coarser	11.70
Amount of fines in dense state required to fill the pore space of coarser	15.14
water content of fines:	66.69

Figure A. 21 Phase Diagram for "6_K Mix 2-Blue"

Project	Frost Susceptibility	 FACULTY OF ENGINEERING AND NATURAL SCIENCES
Mix No:	6	
Sample	K Mixture 2	
Description	Sample 2-Black	
Date	14-06-2023	
Done by	Kawther Makttoof	
PHASE DIAGRAM CALCULATIONS		
Liquid Limit of Kaolinite (%)	50	Kaolinite (%) (by 0-5 mass): 9.49
Water Content (%)	5.99	Gs (12-19) : 2.724
Diameter (cm)	14.4792	Gs (5-12) : 2.693
Sample Height (cm)	15.420	Gs (washed 0-5) : 2.691
Volume of Sample (cm3)	2539	Gs (Kaolinite) : 2.610
Density of Water (g/cm3)	1	Gs (mixture soil) : 2.693
Mass of (12-19) mm fraction, g	1426.091	
Mass of (5-12) mm fraction, g	1214.818	
Mass of Washed (0-5) mm fraction (g)	2144.419	
Mass of Kaolinite (g)	496.491	
Total Mass of Solid (g)	5281.819	WEIGHT (g)
Mass of Water (g)	316.38	
Total Mass (g)	5598.20	
Volume of Water (cm3)	316.38	
Total Volume (cm3)	2539.00	
Volume of (12-19) mm fraction (cm3)	523.53	
Volume of (5-12) mm fraction (cm3)	451.10	VOLUME (cm3)
Volume of Washed (0-5) mm fraction (cm3)	796.89	
Volume of Kaolinite (cm3)	190.23	
Volume of Solid (cm3)	1961.74	
Volume of Air (cm3)	260.88	
Volume of Void (cm3)	577.26	
Dry Density (g/cm3)	2.080	
Void Ratio and Porosity, e & n	0.294 0.227	
Saturation (%)	54.81	
VOLUME (cm3)		WEIGHT (g)
		
Transition threshold values, Lower limit and Upper limit		
Volume of Voids to be filled by fines, V_{vf} :	$(V_t - V_{12-19} - V_{5-12} - V_{0-5})$:	769.29 cm ³
Void ratio of fines $(V_{vf} - V_{sKaolinite} - V_{st(5-12)}) / V_{sF}$		3.007
Density of fines, $\rho_f = M_{(No200)} / V_{sF}$		0.65 g/cm ³
Porosity of fines, n_f		0.750
Void ratio of Kaolinite at 10 kPa (from $e = 0.026LL + 0.07$), e_{max} :		1.37
Gs of fines (Kaolinite), ρ_{sFave} :		2.610
Minimum density of fines in loose state, $\rho_F = \rho_{sFAve} / (1 + e_{max})$		1.101 g/cm ³
Mass of fines required to fill voids, $M_{FVL} = V_{vf} * \rho_{Fmin}$: Fines required to "Fill		847.20 g
Percent by Mass of M_{FVL} to Total Mass of solids, $M_{FVL} / M_s * 100$:		15.05 %
Percent by mass of fines content (Msf) of sample to M_{FVL} :		63.04 %
Void ratio of Kaolinite at 1 MPa (from $e = 0.011LL + 0.21$), e_{min} :		0.76
Maximum density of fines in dense state, ρ_{Fmin} :		1.483 g/cm ³
Mass of fines required to fill void space, Upper threshold $M_{FVU} = V_{vf} * \rho_{Fmin}$:		1140.83 g
Percent by Mass of M_{FVU} to Total Mass of solids, $M_{FVU} / M_s * 100$:		19.27 %
Percent by mass of fines content (Msf) of sample to M_{FVU} :		49.26 %
Percent of Voids occupied by fines at min density, ρ_{Fmin} :		59.17 %
Percent of Voids occupied by fines at maximum density, ρ_{Fmax} :		43.94 %

MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	40.6
% of Kaolinite:	9.4

SOIL CLASSIFICATION	
USCS:	GW-GC
AASHTO:	A2-7 (0)
RSCS:	GS(F) where fines are HI

DATA: END OF FS TESTING	
Weight of can, Top:	48.08
weight of can+ wet sample, Top:	437.48
weight of can+ dry sample, Top:	415.1
Weight of can, Bottom:	1307.9
weight of can+ wet sample, Bottom:	6578.6
weight of can+ dry sample, Bottom:	6243.5
Final water content, Top:	6.10
Final water content, Bottom:	6.79
Final water content, Average:	6.74
Residual heave (Di-Df), ΔH_{final} :	2.2

Fines Threshold Metrics	
Loose State:	0.578
Dense State:	0.432
Void ratio of coarse grains (G & S), $e_c = V_v / V_{sGravel} + V_{sSand}$:	0.326
Porosity of coarse grains (G & S), n_c :	0.246
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	12.10
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	15.64
water content of fines:	63.11

Figure A. 22 Phase Diagram for "6_K Mix 2-Black"

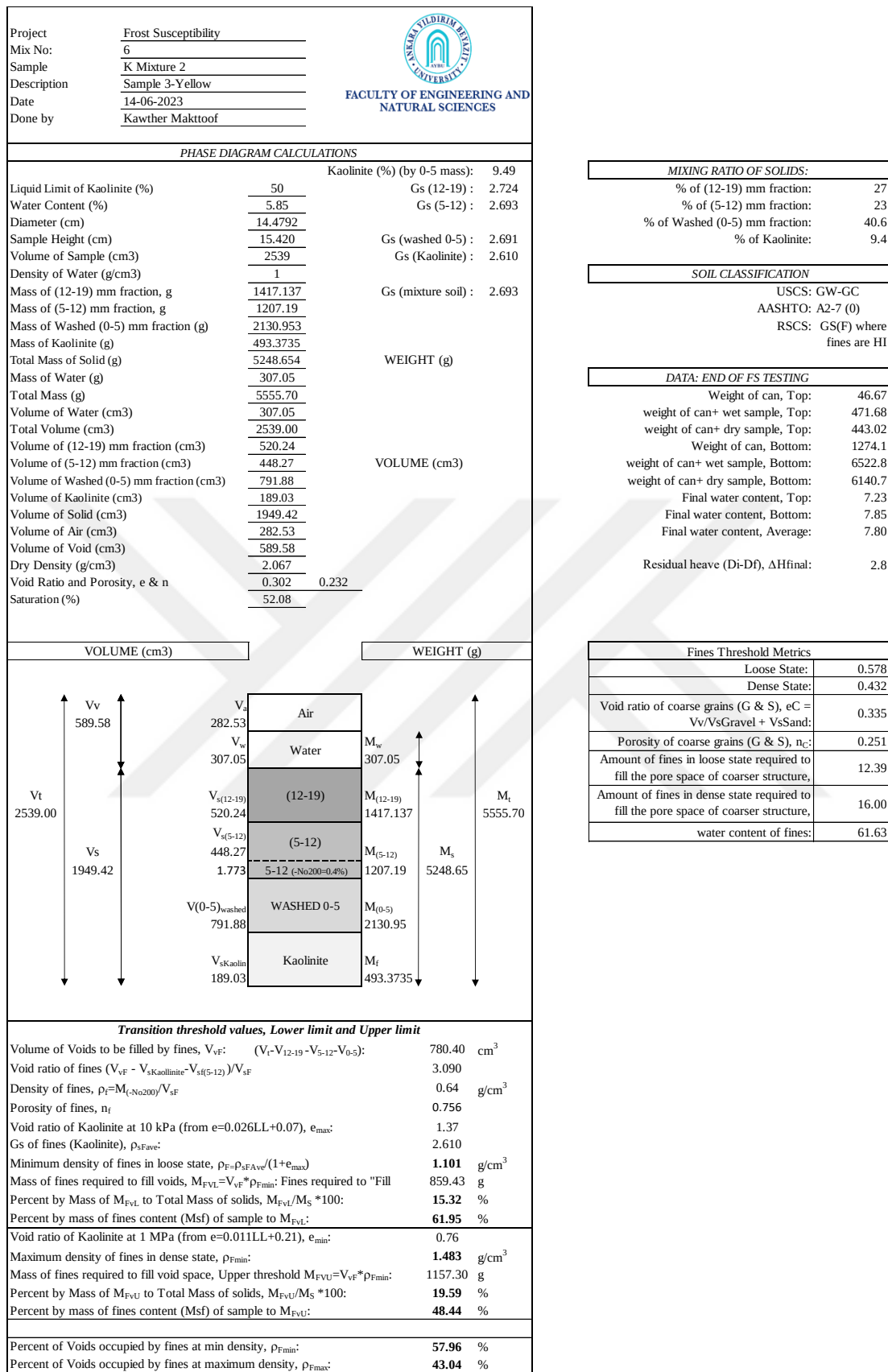
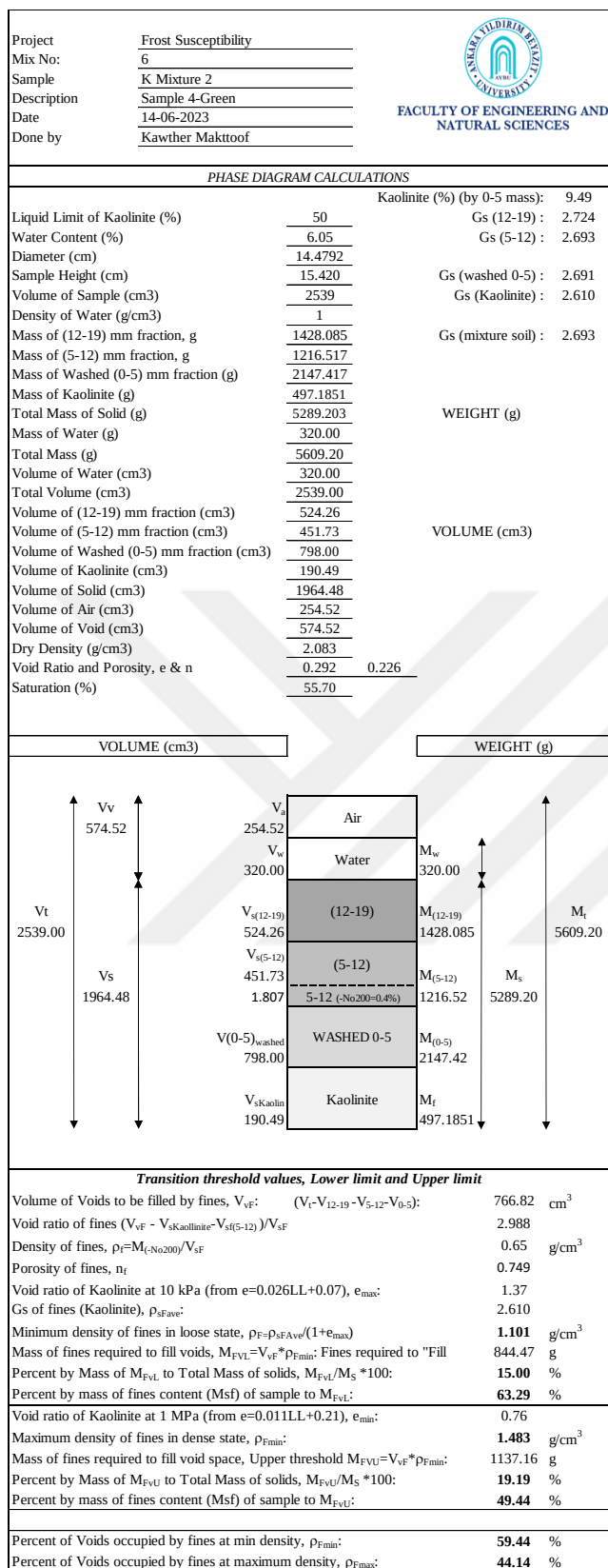


Figure A. 23 Phase Diagram for “6_K Mix 2-Yellow”



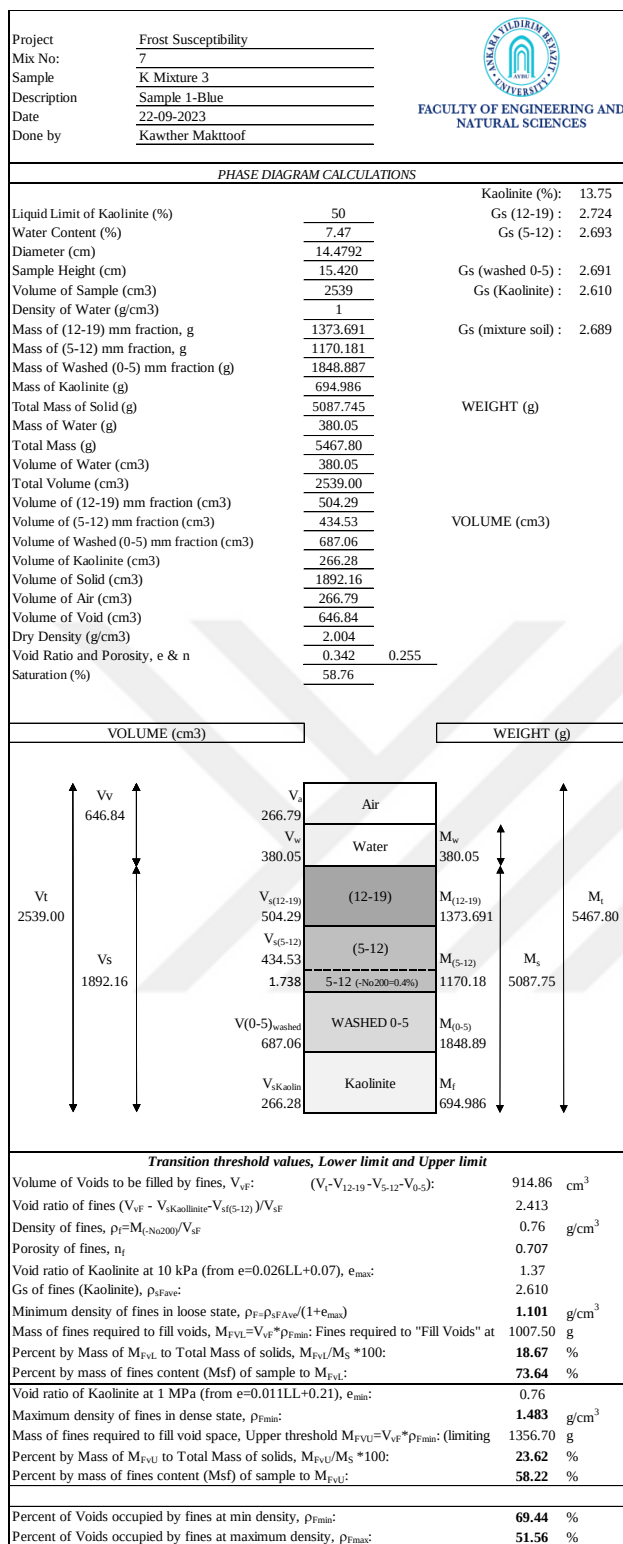
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	40.6
% of Kaolinite:	9.4

SOIL CLASSIFICATION	
USCS:	GW-GC
AASHTO:	A2-7 (0)
RSCS:	GS(F) where fines are HI

DATA: END OF FS TESTING	
Weight of can, Top:	46.62
weight of can+ wet sample, Top:	418.67
weight of can+ dry sample, Top:	397.03
Weight of can, Bottom:	1068.1
weight of can+ wet sample, Bottom:	6360.1
weight of can+ dry sample, Bottom:	5988.4
Final water content, Top:	6.18
Final water content, Bottom:	7.55
Final water content, Average:	7.46
Residual heave (D _i -D _f), ΔH _{final} :	1.4

Fines Threshold Metrics	
Loose State:	0.578
Dense State:	0.432
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.324
Porosity of coarse grains (G & S), n _C :	0.245
Amount of fines in loose state required to fill the pore space of coarser structure, %F _Y :	12.03
Amount of fines in dense state required to fill the pore space of coarser structure, %F _Y :	15.55
water content of fines:	63.74

Figure A. 24 Phase Diagram for "6_K Mix 2-Green"



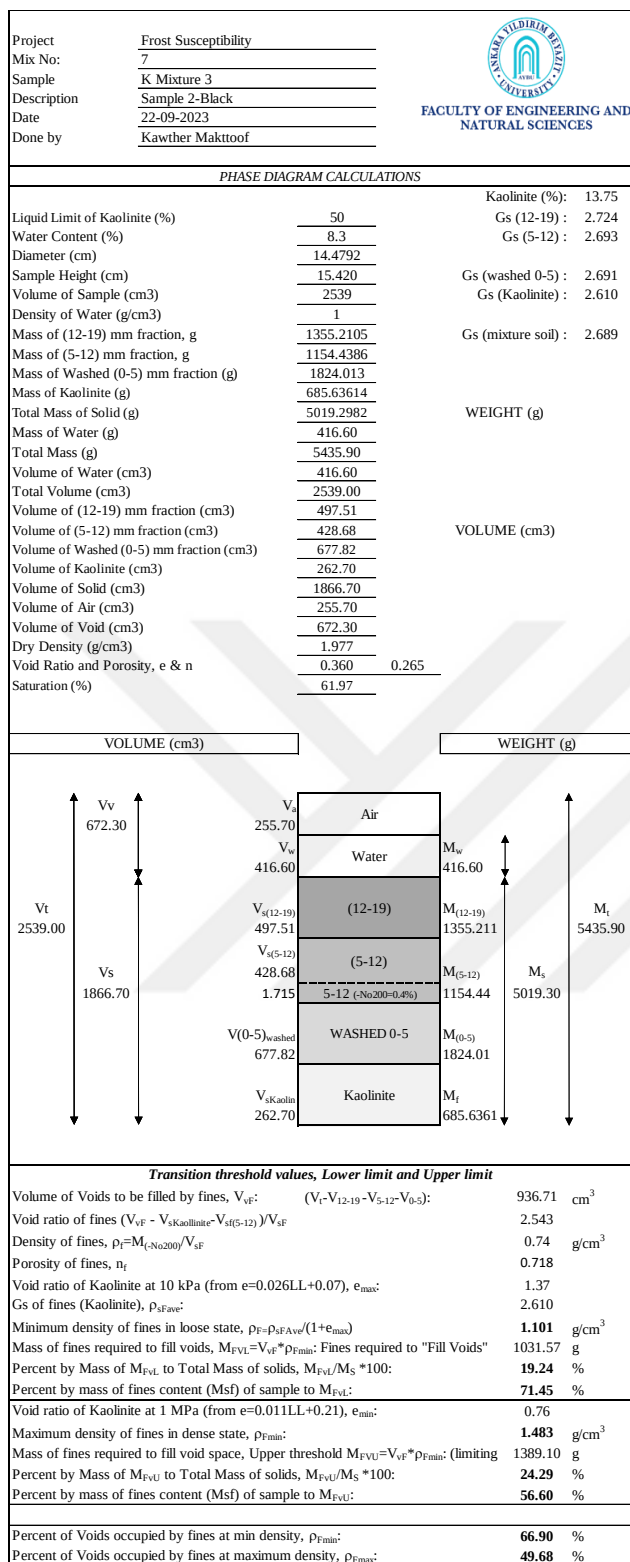
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	36.34
% of Kaolinite:	13.66

SOIL CLASSIFICATION	
USCS:	GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are HI

DATA: END OF FS TESTING	
Weight of can, Top:	50.39
weight of can+ wet sample, Top:	331.71
weight of can+ dry sample, Top:	303.78
Weight of can, Bottom:	1275.5
weight of can+ wet sample, Bottom:	6492.6
weight of can+ dry sample, Bottom:	6026
Final water content, Top:	11.02
Final water content, Bottom:	9.82
Final water content, Average:	9.88
Residual heave (Di-Df), ΔHfinal:	3

Fines Threshold Values	
Average Lower Limit Threshold (%):	20.1
Average Upper Limit Threshold(%):	25.3
Fines Content, M _{ef} /M _s (%):	13.75
Avg. % of Void space occupied by fines at min density, P _{min} (%):	74.7
Avg.% of Void space occupied by fines at maximum density, P _{max} (%):	55.4
Average Void ratio of fines of mixture:	2.201
Average porosity of fines of mixture:	0.685
Loose State:	0.578
Dense State:	0.432
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.398
Porosity of coarse grains (G & S), n _c :	0.285
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	14.39
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	18.45
water content of fines:	54.32

Figure A. 25 Phase Diagram for "7_K Mix 3-Blue"



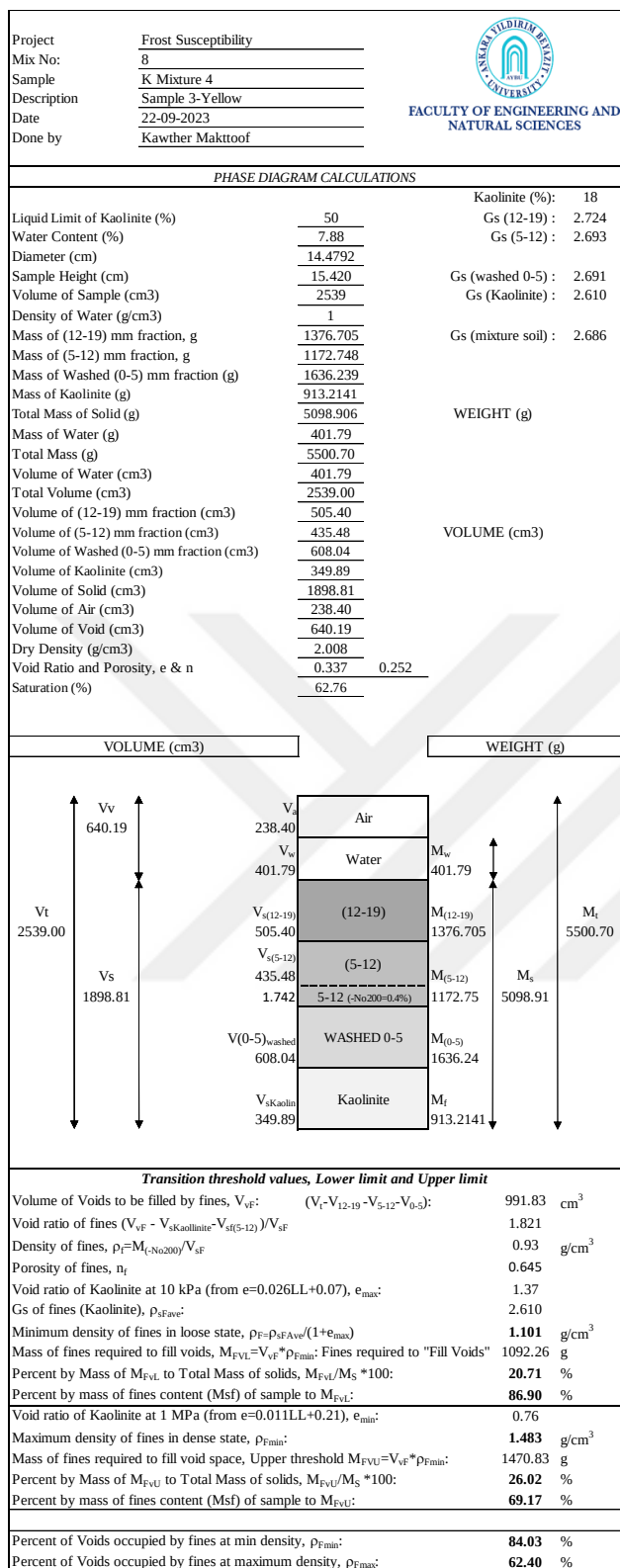
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	36.34
% of Kaolinite:	13.66

SOIL CLASSIFICATION	
USCS:	GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are HI

DATA: END OF FS TESTING	
Weight of can, Top:	47.67
weight of can+ wet sample, Top:	379.32
weight of can+ dry sample, Top:	350.29
Weight of can, Bottom:	1320.7
weight of can+ wet sample, Bottom:	6468.7
weight of can+ dry sample, Bottom:	5993.5
Final water content, Top:	9.59
Final water content, Bottom:	10.17
Final water content, Average:	10.13
Residual heave (Di-Df), ΔH_{final} :	2.7

Fines Threshold Metrics	
Loose State:	0.578
Dense State:	0.432
Void ratio of coarse grains (G & S), $e_C = V_v/V_{sGravel} + V_{sSand}$:	0.420
Porosity of coarse grains (G & S), n_C :	0.296
Amount of fines in loose state required to fill the pore space of coarser structure, $\%F_V$:	15.04
Amount of fines in dense state required to fill the pore space of coarser structure, $\%F_V$:	19.25
water content of fines:	60.35

Figure A. 26 Phase Diagram for "7_K Mix 3-Black"



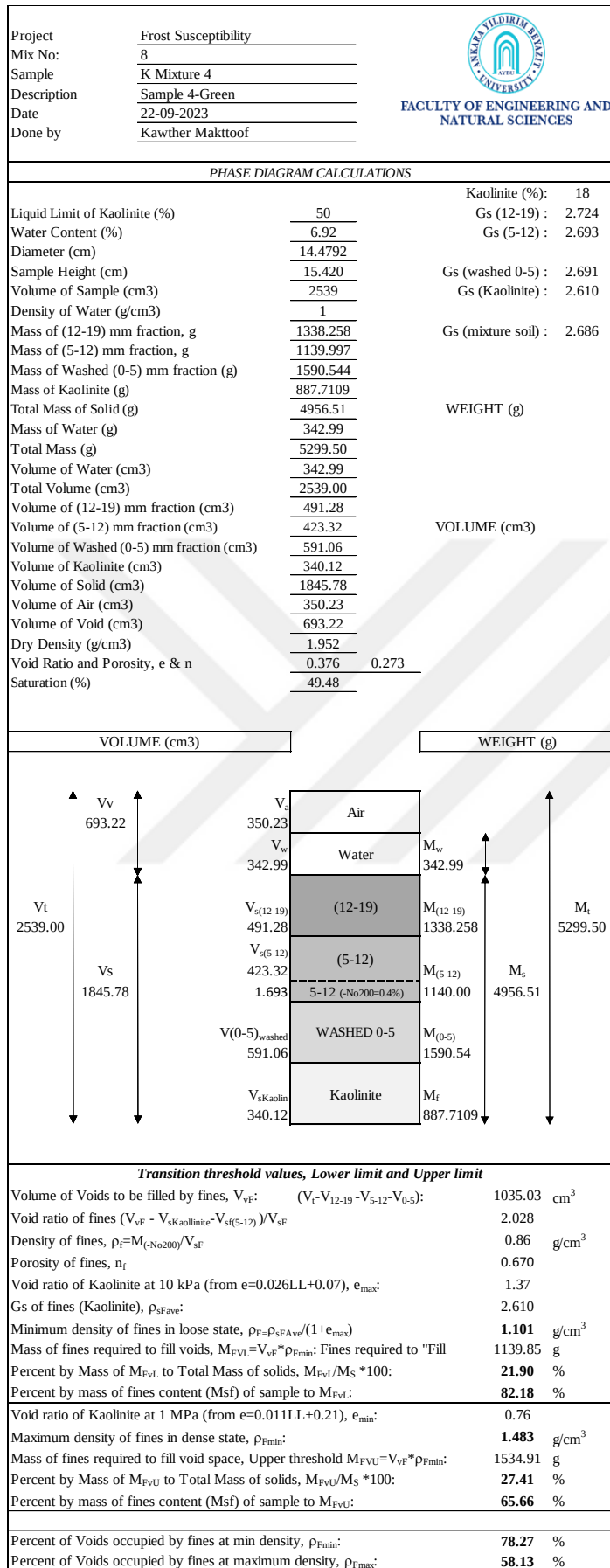
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	32.09
% of Kaolinite:	17.91

SOIL CLASSIFICATION	
USCS:	GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are HI

DATA: END OF FS TESTING	
Weight of can, Top:	48.35
weight of can+ wet sample, Top:	371.71
weight of can+ dry sample, Top:	342.47
Weight of can, Bottom:	1360.4
weight of can+ wet sample, Bottom:	6561.5
weight of can+ dry sample, Bottom:	6126.9
Final water content, Top:	9.94
Final water content, Bottom:	9.12
Final water content, Average:	9.17
Residual heave (Di-Df), ΔHfinal:	4.9

Fines Threshold Metrics	
Loose State:	0.578
Dense State:	0.432
Void ratio of coarse grains (G & S), eC = Vv/VsGravel + VsSand:	0.414
Porosity of coarse grains (G & S), n _c :	0.293
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	14.86
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	19.04
water content of fines:	43.77

Figure A. 27 Phase Diagram for "8_K Mix 4-Yellow"



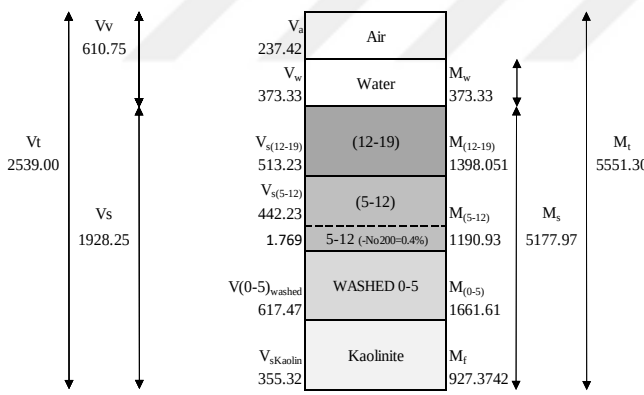
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	32.09
% of Kaolinite:	17.91

SOIL CLASSIFICATION	
USCS:	GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are HI

DATA: END OF FS TESTING	
Weight of can, Top:	47.89
weight of can+ wet sample, Top:	357.79
weight of can+ dry sample, Top:	330.3
Weight of can, Bottom:	1094.9
weight of can+ wet sample, Bottom:	6141.8
weight of can+ dry sample, Bottom:	5673.9
Final water content, Top:	9.73
Final water content, Bottom:	10.22
Final water content, Average:	10.19
Residual heave (D _i -D _f), ΔH _{final} :	2.05

Fines Threshold Metrics	
Loose State:	0.578
Dense State:	0.432
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.461
Porosity of coarse grains (G & S), n _C :	0.316
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	16.28
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	20.75
water content of fines:	38.44

Figure A. 28 Phase Diagram for “8_K Mix 4-Green”

Project	Frost Susceptibility		
Mix No:	8		
Sample	K Mixture 4 Used		
Description	Sample 1-Blue		
Date	06-10-2023		
Done by	Kawther Makttoof		
 FACULTY OF ENGINEERING AND NATURAL SCIENCES			
PHASE DIAGRAM CALCULATIONS			
Liquid Limit of Kaolinite (%)	50	Kaolinite (%)	18
Water Content (%)	7.21	Gs (12-19) :	2.724
Diameter (cm)	14.4792	Gs (5-12) :	2.693
Sample Height (cm)	15.420	Gs (washed 0-5) :	2.691
Volume of Sample (cm3)	2539	Gs (Kaolinite) :	2.610
Density of Water (g/cm3)	1	Gs (mixture soil) :	2.686
Mass of (12-19) mm fraction, g	1398.051		
Mass of (5-12) mm fraction, g	1190.933		
Mass of Washed (0-5) mm fraction (g)	1661.61		
Mass of Kaolinite (g)	927.3742		
Total Mass of Solid (g)	5177.968	WEIGHT (g)	
Mass of Water (g)	373.33		
Total Mass (g)	5551.30		
Volume of Water (cm3)	373.33		
Total Volume (cm3)	2539.00		
Volume of (12-19) mm fraction (cm3)	513.23		
Volume of (5-12) mm fraction (cm3)	442.23	VOLUME (cm3)	
Volume of Washed (0-5) mm fraction (cm3)	617.47		
Volume of Kaolinite (cm3)	355.32		
Volume of Solid (cm3)	1928.25		
Volume of Air (cm3)	237.42		
Volume of Void (cm3)	610.75		
Dry Density (g/cm3)	2.039		
Void Ratio and Porosity, e & n	0.317 0.241		
Saturation (%)	61.13		
VOLUME (cm3)		WEIGHT (g)	
			
Transition threshold values, Lower limit and Upper limit			
Volume of Voids to be filled by fines, V_{vf} :	$(V_t - V_{12-19} - V_{5-12} - V_{0-5})$:	967.84	cm ³
Void ratio of fines ($V_{vf} - V_{sKaolinite} - V_{sf(5-12)})/V_{sf}$		1.710	
Density of fines, $\rho_f = M_{f(-No200)}/V_{sf}$		0.96	g/cm ³
Porosity of fines, n_f		0.631	
Void ratio of Kaolinite at 10 kPa (from $e = 0.026LL + 0.07$), e_{min} :		1.37	
Gs of fines (Kaolinite), ρ_{sfave} :		2.610	
Minimum density of fines in loose state, $\rho_F = \rho_{sfave}/(1 + e_{min})$		1.101	g/cm ³
Mass of fines required to fill voids, $M_{FVL} = V_{vf} * \rho_{Fmin}$; Fines required to "Fill		1065.84	g
Percent by Mass of M_{FVL} to Total Mass of solids, $M_{FVL}/M_s * 100$:		20.07	%
Percent by mass of fines content (Msf) of sample to M_{FVL} :		89.70	%
Void ratio of Kaolinite at 1 MPa (from $e = 0.011LL + 0.21$), e_{min} :		0.76	
Maximum density of fines in dense state, ρ_{Fmin} :		1.483	g/cm ³
Mass of fines required to fill void space, Upper threshold $M_{FVU} = V_{vf} * \rho_{Fmin}$:		1435.26	g
Percent by Mass of M_{FVU} to Total Mass of solids, $M_{FVU}/M_s * 100$:		25.26	%
Percent by mass of fines content (Msf) of sample to M_{FVU} :		71.25	%
Percent of Voids occupied by fines at min density, ρ_{Fmin} :		87.45	%
Percent of Voids occupied by fines at maximum density, ρ_{Fmax} :		64.94	%

MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	32.09
% of Kaolinite:	17.91

SOIL CLASSIFICATION

USCS:	GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are HI

DATA: END OF FS TESTING

Weight of can, Top:	48.34
weight of can+ wet sample, Top:	398.23
weight of can+ dry sample, Top:	368.91
Weight of can, Bottom:	1295.5
weight of can+ wet sample, Bottom:	6518.2
weight of can+ dry sample, Bottom:	6077.9
Final water content, Top:	9.15
Final water content, Bottom:	9.21
Final water content, Average:	9.20

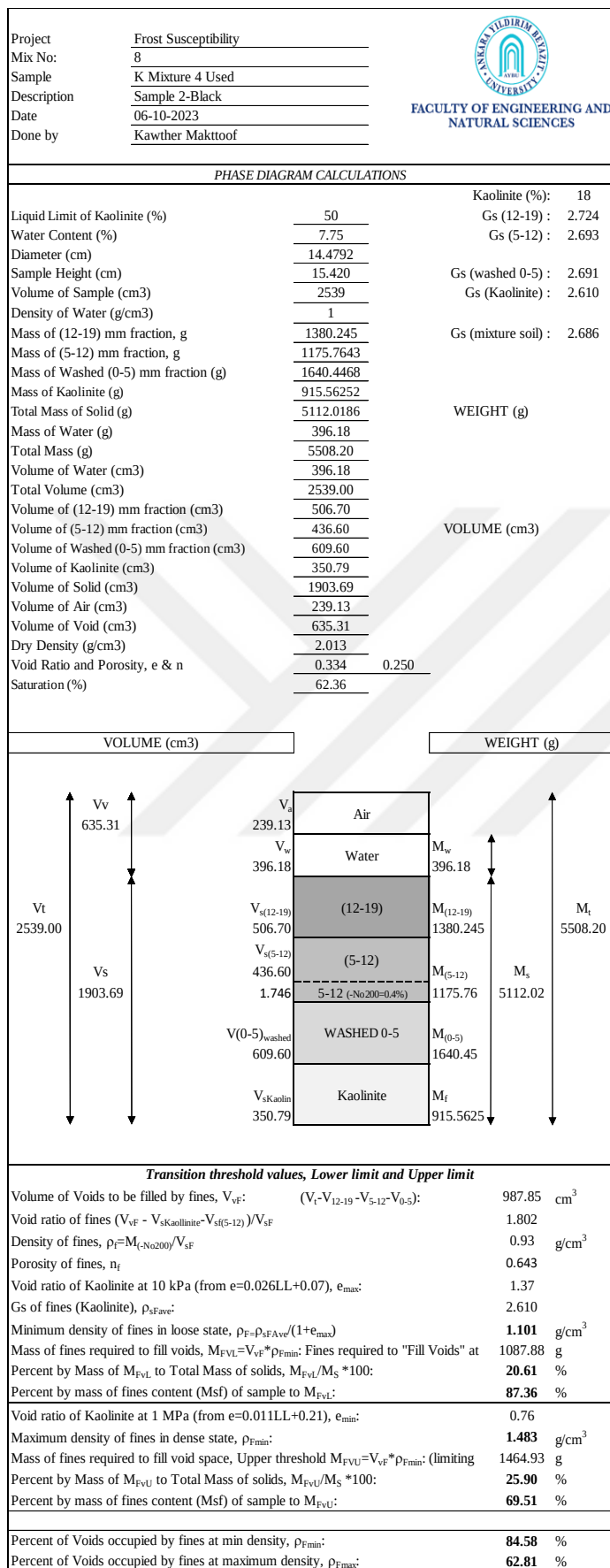
Residual heave (Di-Df), ΔH_{final} :

2.1

Fines Threshold Values

Average Lower Limit Threshold (%):	20.5
Average Upper Limit Threshold(%):	25.8
Fines Content, M_{sf}/M_s (%):	18
Avg. % of Void space occupied by fines at min density, P_{fmin} (%):	84.9
Avg.% of Void space occupied by fines at maximum density, P_{fmax} (%):	50.4
Average Void ratio of fines of mixture:	1.792
Average porosity of fines of mixture:	0.642
Loose State:	0.578
Dense State:	0.432
void ratio of coarse grains (G & S), $e_C = V_v/V_{sGravel} + V_{sSand}$:	0.389
Porosity of coarse grains (G & S), n_C :	0.280
Amount of fines in loose state required to fill the pore space of coarser structure, % F_v :	14.09
Amount of fines in dense state required to fill the pore space of coarser structure, % F_v :	18.09
water content of fines:	40.05

Figure A. 29 Phase Diagram for “8_K Mix 4 used-Blue”



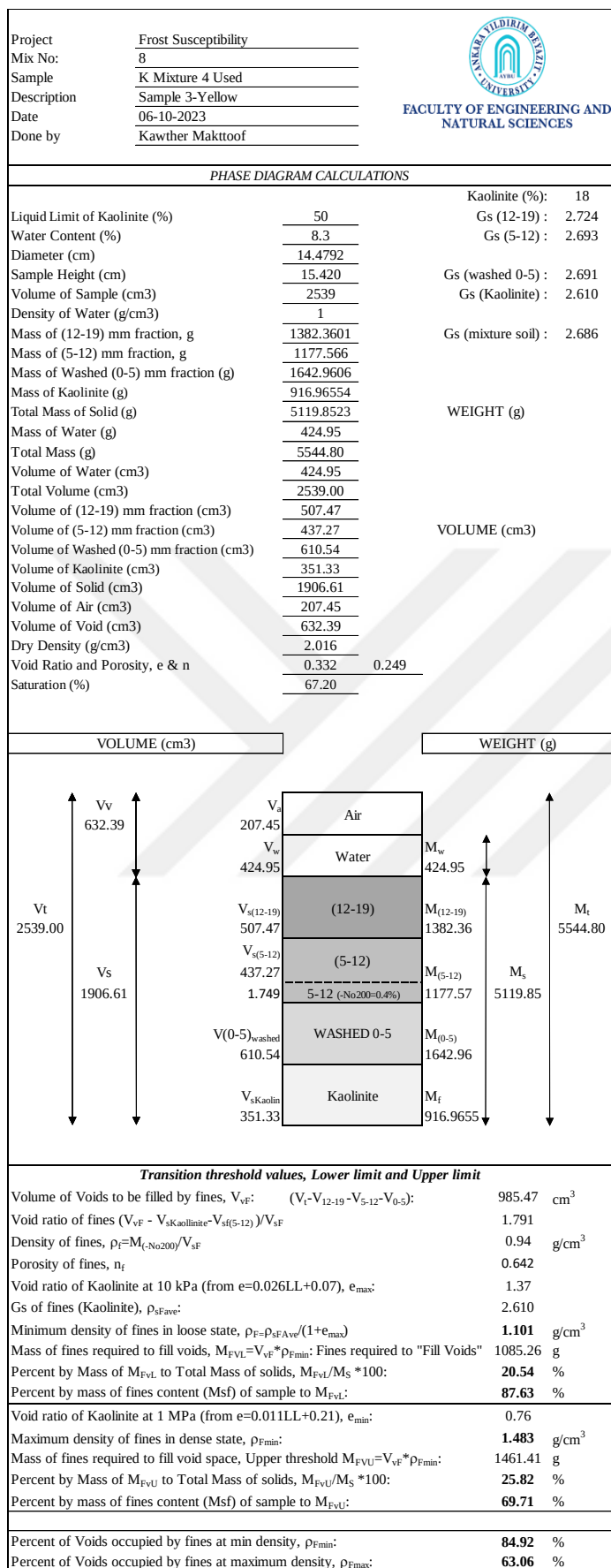
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	32.09
% of Kaolinite:	17.91

SOIL CLASSIFICATION	
USCS:	GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are HI

DATA: END OF FS TESTING	
Weight of can, Top:	49.32
weight of can+ wet sample, Top:	319.51
weight of can+ dry sample, Top:	295.82
Weight of can, Bottom:	1274.1
weight of can+ wet sample, Bottom:	6531.1
weight of can+ dry sample, Bottom:	6067.8
Final water content, Top:	9.61
Final water content, Bottom:	9.66
Final water content, Average:	9.66
Residual heave (Di-Df), ΔHfinal:	1.97

Fines Threshold Metrics	
Loose State:	0.578
Dense State:	0.432
void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.410
Porosity of coarse grains (G & S), n _C :	0.291
Amount of fines in loose state required to fill the pore space of coarser structure, %F _y :	14.74
Amount of fines in dense state required to fill the pore space of coarser structure, %F _y :	18.88
water content of fines:	43.05

Figure A. 30 Phase Diagram for "8_K Mix 4 used-Black"



MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	32.09
% of Kaolinite:	17.91

SOIL CLASSIFICATION	
USCS:	GC
AASHTO:	A2-7 (0) Gr(F)
RSCS:	where fines are 0.075

DATA: END OF FS TESTING	
Weight of can, Top:	54.2
weight of can+ wet sample, Top:	341.52
weight of can+ dry sample, Top:	317.59
Weight of can, Bottom:	1340.5
weight of can+ wet sample, Bottom:	6620.4
weight of can+ dry sample, Bottom:	6169.6
Final water content, Top:	9.09
Final water content, Bottom:	9.34
Final water content, Average:	9.32
Residual heave (Di-Df), ΔHfinal:	1.55

Fines Threshold Metrics	
Loose State:	0.578
Dense State:	0.432
void ratio of coarse grains (G & S), eC = Vv/VsGravel + VsSand:	0.407
Porosity of coarse grains (G & S), n _C :	0.289
Amount of fines in loose state required to fill the pore space of coarser structure, %F _V :	14.66
Amount of fines in dense state required to fill the pore space of coarser structure, %F _V :	18.78
water content of fines:	46.11

Figure A. 31 Phase Diagram for "8_K Mix 4 used-Yellow"

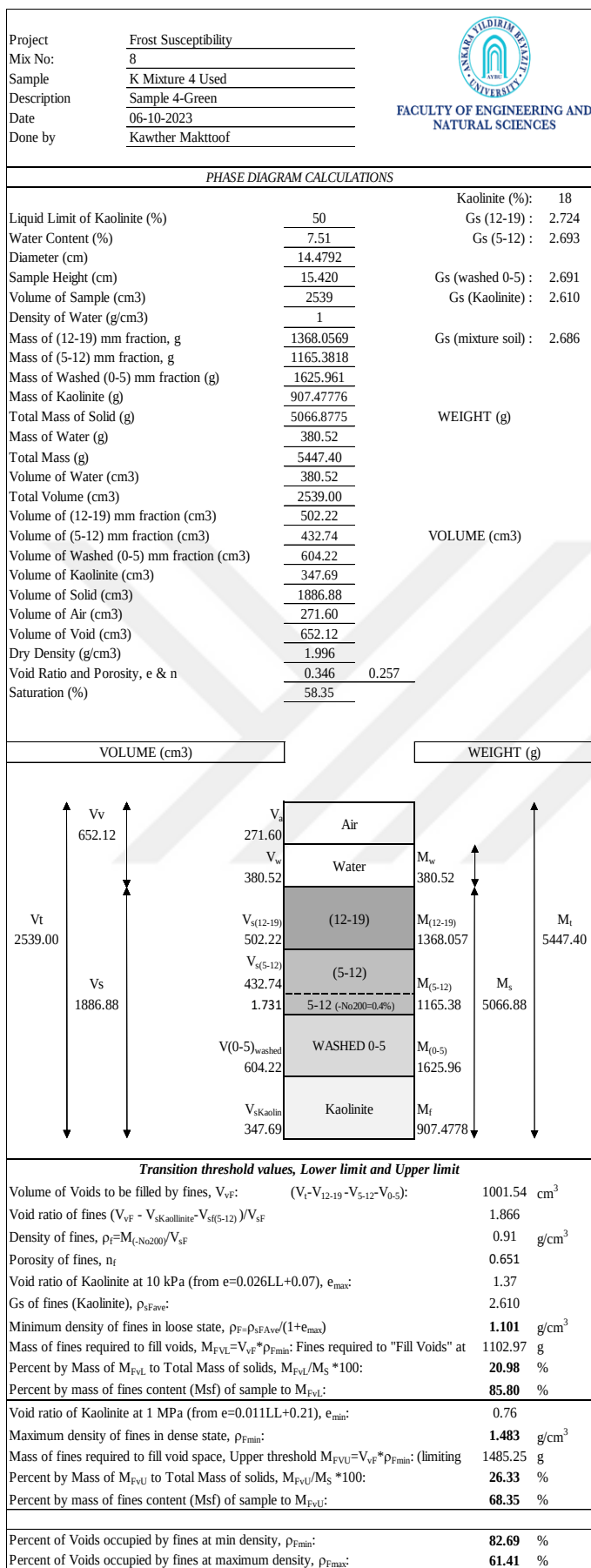
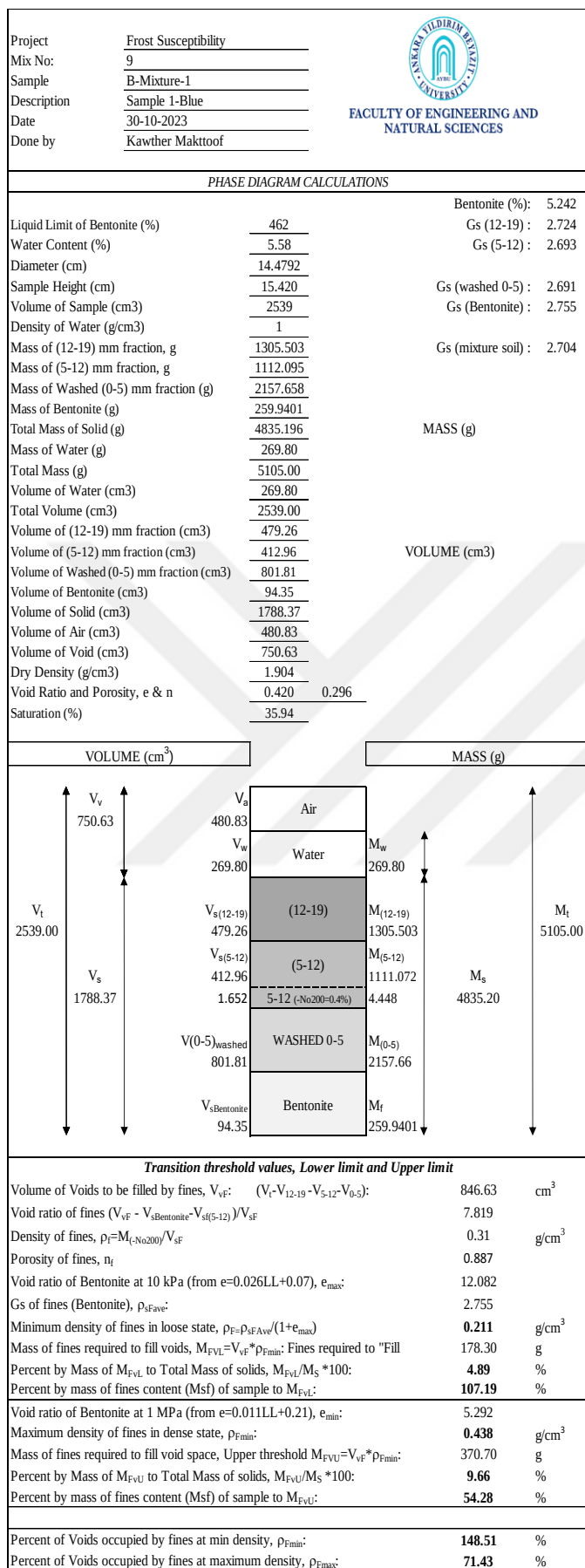


Figure A. 32 Phase Diagram for "8_K Mix 4 used-Green"



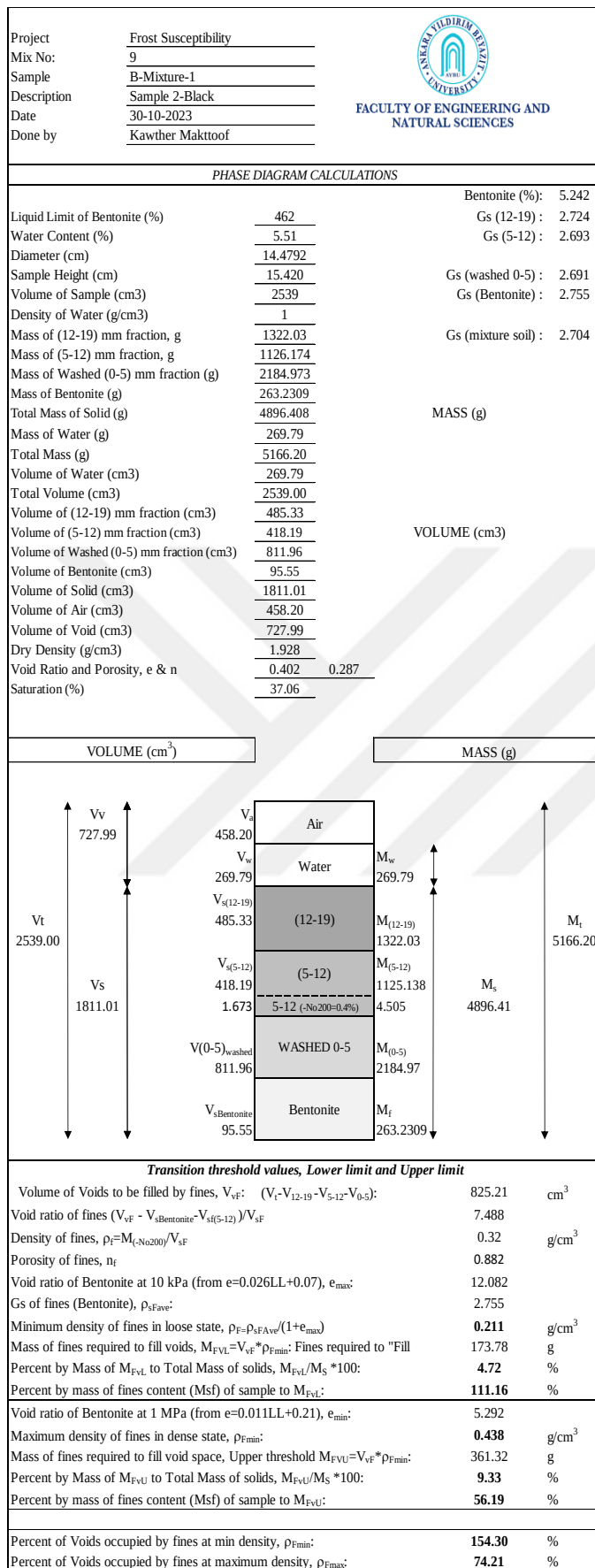
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	44.624
% of Bentonite:	5.376

SOIL CLASSIFICATION	
USCS:	GP-GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	45.31
weight of can+ wet sample, Top:	334.69
weight of can+ dry sample, Top:	307.82
Weight of can, Bottom:	1360.6
weight of can+ wet sample, Bottom:	6432
weight of can+ dry sample, Bottom:	5978.9
Final water content, Top:	10.24
Final water content, Bottom:	9.81
Final water content, Average:	9.83
Residual heave (Di-Df), ΔHfinal:	0.4

Fines Threshold Values	
Average Lower Limit Threshold (%):	4.8
Average Upper Limit Threshold(%):	9.54
Fines Content, M _{sf} /M _s (%):	5.24
Avg. % of Void space occupied by fines at min density, P _{fmin} (%):	150.50
Avg. % of Void space occupied by fines at maximum density, P _{fmax} (%):	72.38
Average Void ratio of fines of mixture:	7.704
Average porosity of fines of mixture:	0.885
Loose State:	0.924
Dense State:	0.841
void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.444
Porosity of coarse grains (G & S), n _C :	0.307
Amount of fines in loose state required to fill the pore space of coarser structure, %F _Y :	3.28
Amount of fines in dense state required to fill the pore space of coarser structure, %F _Y :	6.59
water content of fines:	102.05

Figure A. 33 Phase Diagram for "9_B Mix 1-Blue"



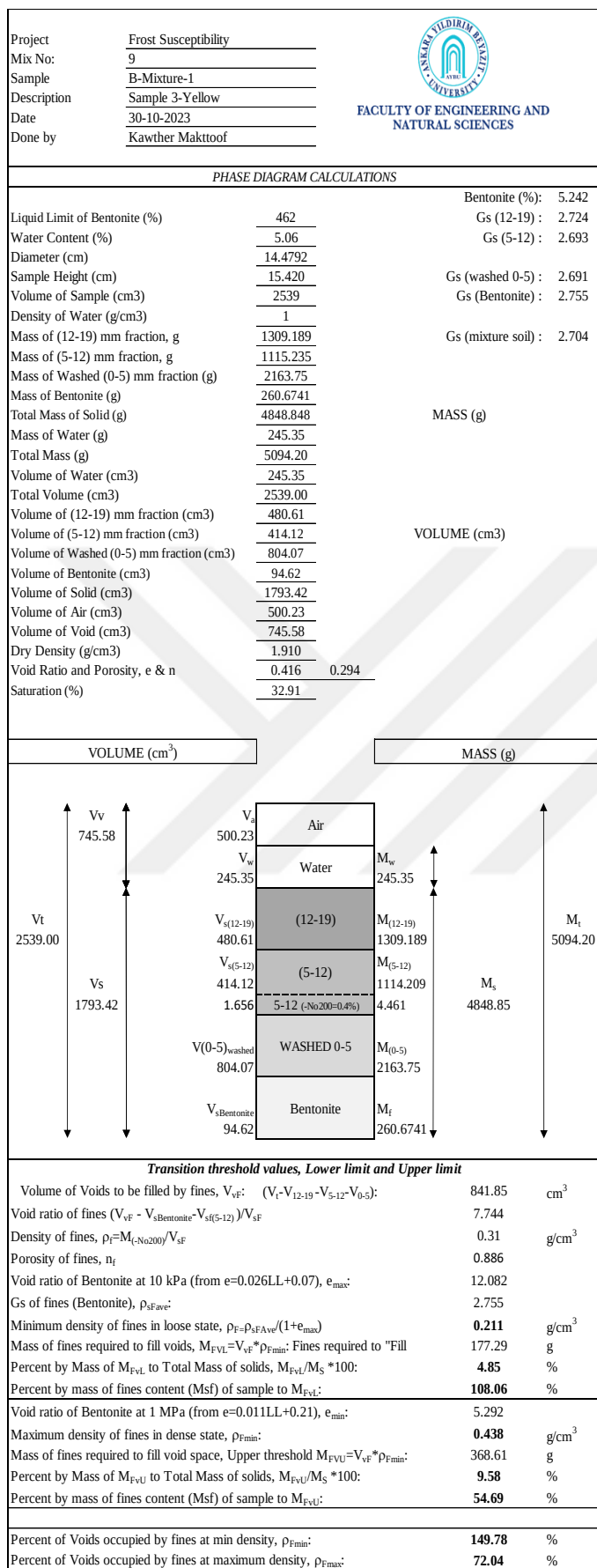
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	44.624
% of Bentonite:	5.376

SOIL CLASSIFICATION	
USCS:	GP-GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	47.38
weight of can+ wet sample, Top:	298.36
weight of can+ dry sample, Top:	281.61
Weight of can, Bottom:	1270
weight of can+ wet sample, Bottom:	6390.3
weight of can+ dry sample, Bottom:	5867.3
Final water content, Top:	7.15
Final water content, Bottom:	11.38
Final water content, Average:	11.17
Residual heave (Di-Df), ΔHfinal:	0.02

Fines Threshold Metrics	
Loose State:	0.924
Dense State:	0.841
void ratio of coarse grains (G & S), eC = Vv/VsGravel + VsSand:	0.593
Porosity of coarse grains (G & S), nC:	0.372
Amount of fines in loose state required to fill the pore space of coarser structure,	4.33
Amount of fines in dense state required to fill the pore space of coarser structure,	8.61
water content of fines:	100.77

Figure A. 34 Phase Diagram for "9_B Mix 1-Black"



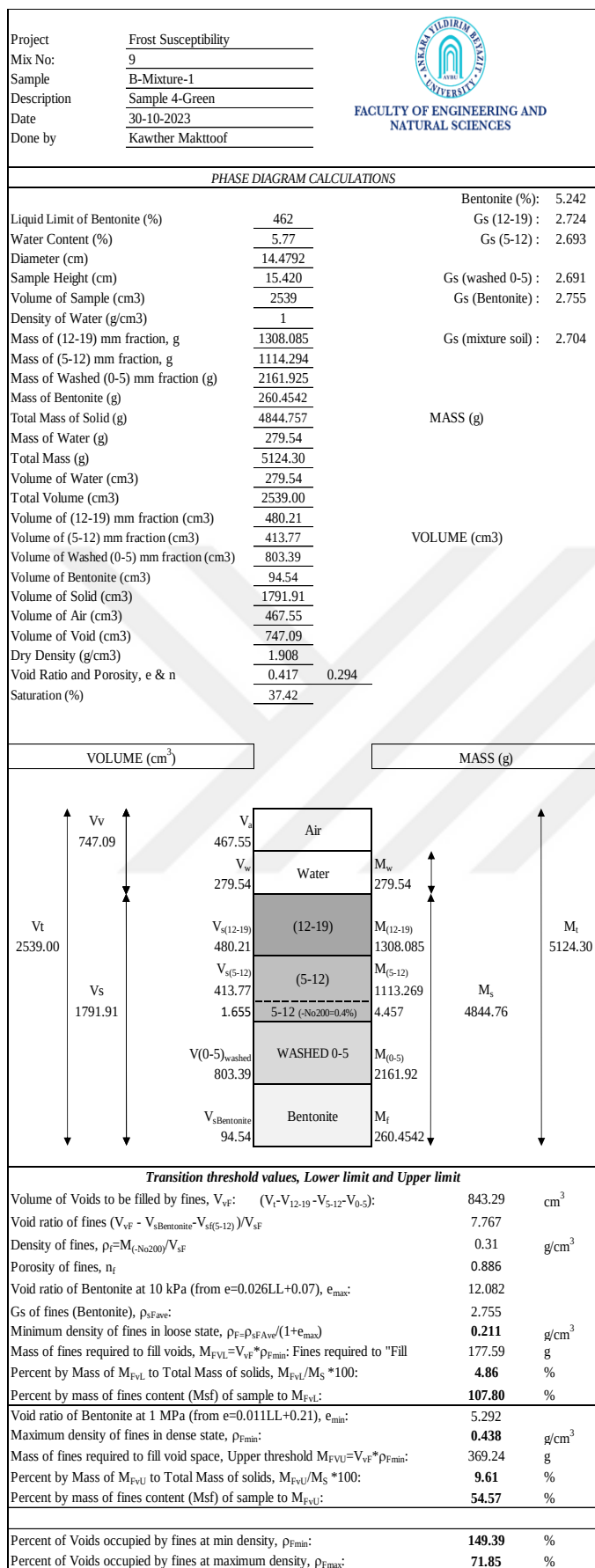
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	44.624
% of Bentonite:	5.376

SOIL CLASSIFICATION	
USCS:	GP-GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	48.18
weight of can+ wet sample, Top:	357.24
weight of can+ dry sample, Top:	326.84
Weight of can, Bottom:	1238.3
weight of can+ wet sample, Bottom:	6341.3
weight of can+ dry sample, Bottom:	5744.5
Final water content, Top:	10.91
Final water content, Bottom:	13.24
Final water content, Average:	13.11
Residual heave (Di-Df), ΔHfinal:	0.23

Fines Threshold Metrics	
Loose State:	0.924
Dense State:	0.841
void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.439
Porosity of coarse grains (G & S), n _C :	0.305
Amount of fines in loose state required to fill the pore space of coarser structure, %F _V :	3.25
Amount of fines in dense state required to fill the pore space of coarser structure, %F _V :	6.53
water content of fines:	92.54

Figure A. 35 Phase Diagram for "9_B Mix 1-Yellow"



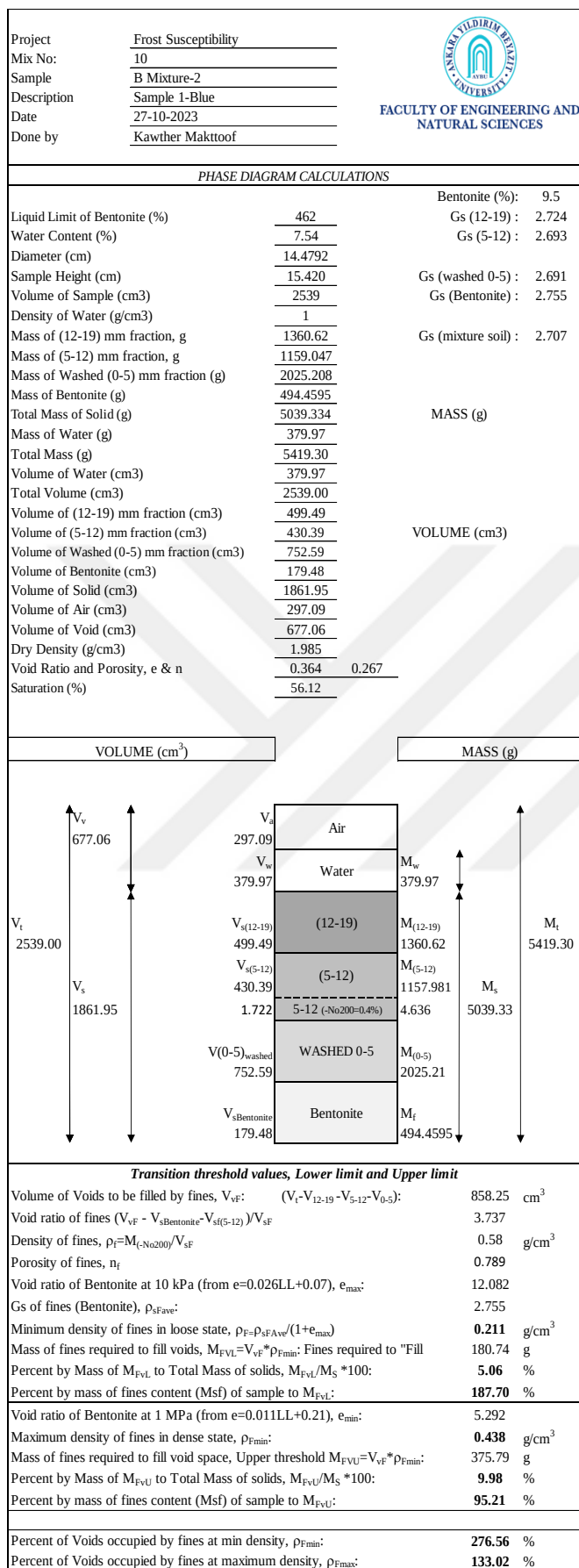
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	44.624
% of Bentonite:	5.376

SOIL CLASSIFICATION	
USCS:	GP-GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	50.41
weight of can+ wet sample, Top:	301.7
weight of can+ dry sample, Top:	284.78
Weight of can, Bottom:	1306.4
weight of can+ wet sample, Bottom:	6492.9
weight of can+ dry sample, Bottom:	5929.4
Final water content, Top:	7.22
Final water content, Bottom:	12.19
Final water content, Average:	11.95
Residual heave (Di-Df), ΔHfinal:	0.18

Fines Threshold Metrics	
Loose State:	0.924
Dense State:	0.841
void ratio of coarse grains (G & S), eC = Vv/VsGravel + VsSand:	0.441
Porosity of coarse grains (G & S), n _c :	0.306
Amount of fines in loose state required to fill the pore space of coarser structure, %F _V :	3.26
Amount of fines in dense state required to fill the pore space of coarser structure, %F _V :	6.54
water content of fines:	105.52

Figure A. 36 Phase Diagram for "9_B Mix 1-Green"



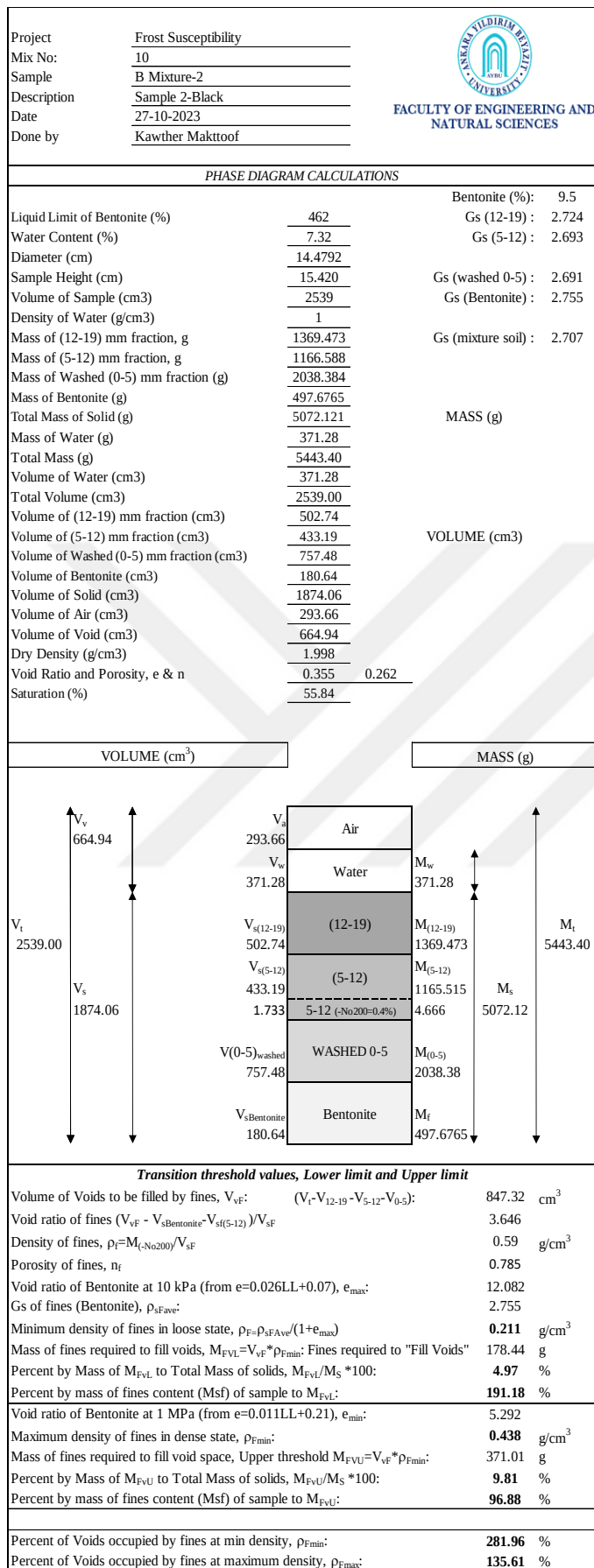
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	40.188
% of Bentonite:	9.812

SOIL CLASSIFICATION	
USCS:	GW-GC
AASHTO:	A2-7 (0)
RSCS: GSF(F) where fines are LH	

DATA: END OF FS TESTING	
Weight of can, Top:	50.36
weight of can+ wet sample, Top:	387.19
weight of can+ dry sample, Top:	345.35
Weight of can, Bottom:	1319.5
weight of can+ wet sample, Bottom:	6495.3
weight of can+ dry sample, Bottom:	6040
Final water content, Top:	14.18
Final water content, Bottom:	9.65
Final water content, Average:	9.91
Residual heave (Di-Df), ΔHfinal:	0.15

Fines Threshold Values	
Average Lower Limit Threshold (%):	5.1
Average Upper Limit Threshold(%):	10.0
Fines Content, M _{sf} /M _s (%):	9.50
Avg. % of Void space occupied by fines at min density, P _{fmin} (%):	275.0
Avg.% of Void space occupied by fines at maximum density, P _{fmax} (%):	132.3
Average Void ratio of fines of mixture:	3.769
Average porosity of fines of mixture:	0.790
Loose State:	0.924
Dense State:	0.841
void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.403
Porosity of coarse grains (G & S), n _C :	0.287
Amount of fines in loose state required to fill the pore space of coarser structure, %F _V :	2.99
Amount of fines in dense state required to fill the pore space of coarser structure, %F _V :	6.02
water content of fines:	76.13

Figure A. 37 Phase Diagram for "10_B Mix 2-Blue"



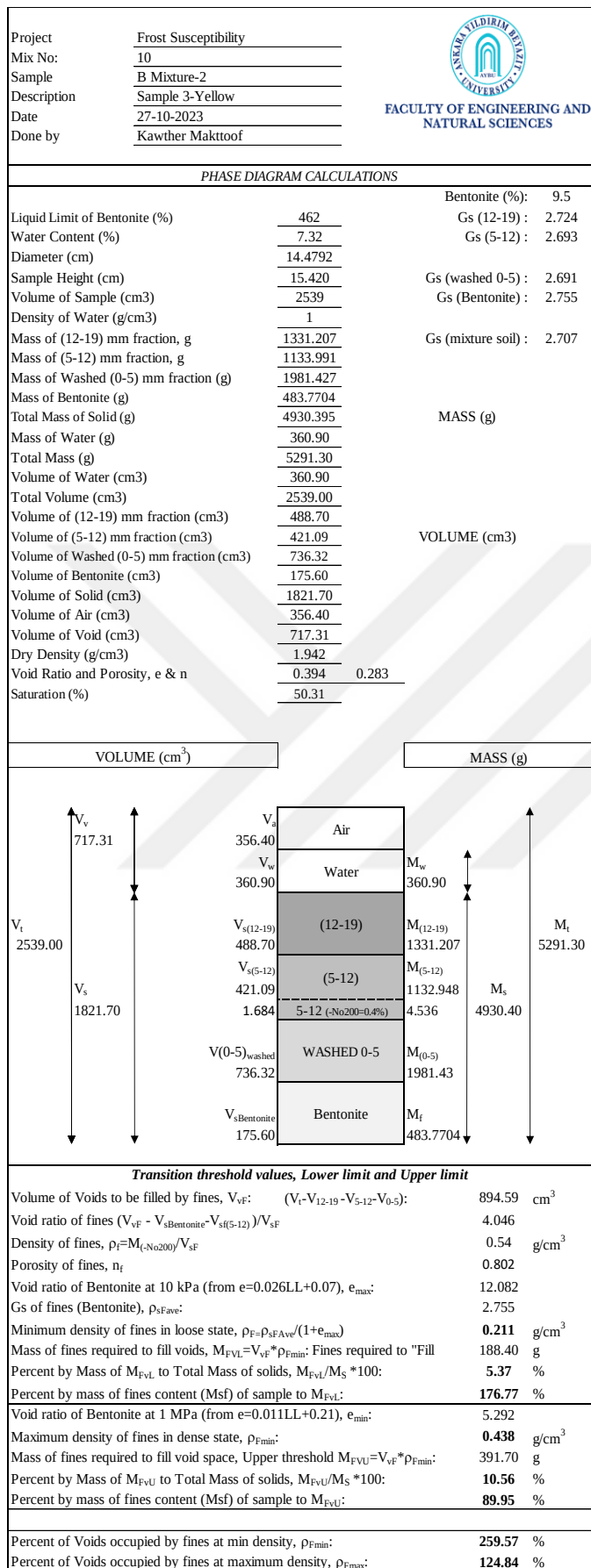
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	40.188
% of Bentonite:	9.812

SOIL CLASSIFICATION	
USCS:	GW-GC
AASHTO:	A2-7 (0)
RSCS:	where fines

DATA: END OF FS TESTING	
Weight of can, Top:	49.09
weight of can+ wet sample, Top:	288.08
weight of can+ dry sample, Top:	262.04
Weight of can, Bottom:	1238
weight of can+ wet sample, Bottom:	6501
weight of can+ dry sample, Bottom:	6074.2
Final water content, Top:	12.23
Final water content, Bottom:	8.83
Final water content, Average:	8.97
Residual heave (Di-Df), ΔHfinal:	0.15

Fines Threshold Metrics	
Loose State:	0.924
Dense State:	0.841
void ratio of coarse grains (G & S), eC = Vv/VsGravel + VsSand:	0.393
Porosity of coarse grains (G & S), n _c :	0.282
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	2.92
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	5.88
water content of fines:	73.91

Figure A. 38 Phase Diagram for "10_B Mix 2-Black"



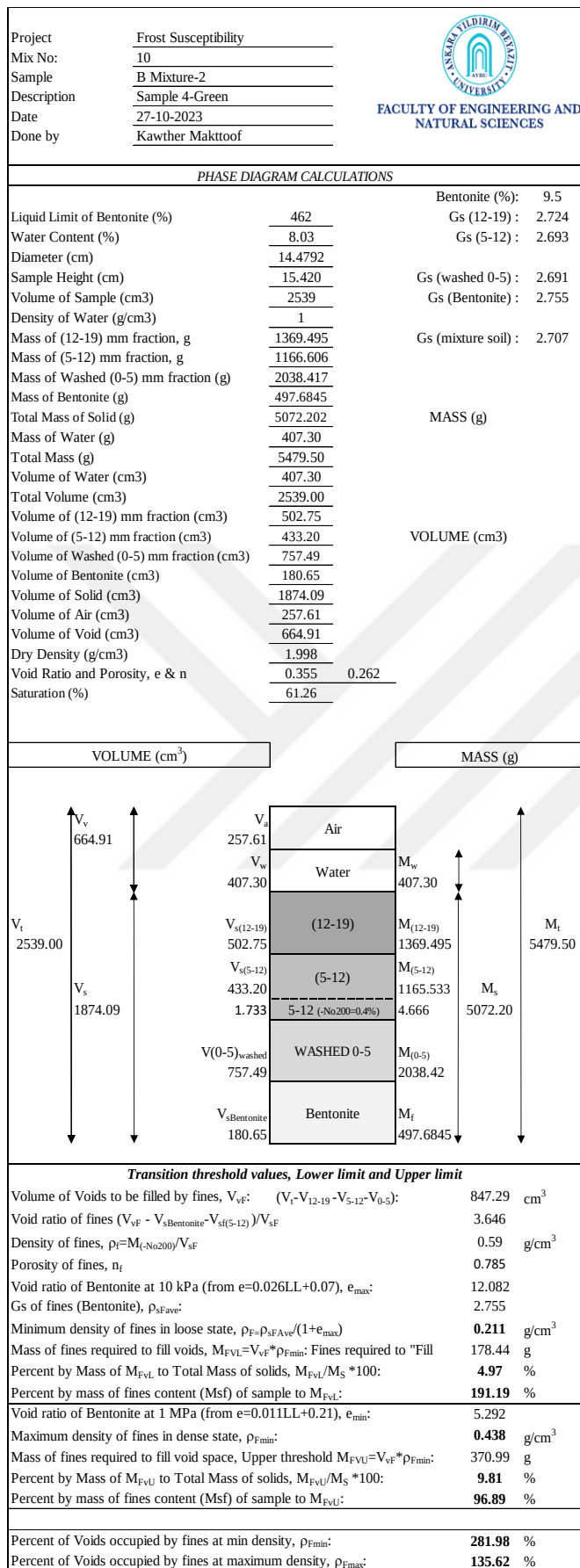
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	40.188
% of Bentonite:	9.812

SOIL CLASSIFICATION	
USCS:	GW-GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	49.7
weight of can+ wet sample, Top:	308.25
weight of can+ dry sample, Top:	270.42
Weight of can, Bottom:	1305.8
weight of can+ wet sample, Bottom:	6459.8
weight of can+ dry sample, Bottom:	5994.1
Final water content, Top:	17.14
Final water content, Bottom:	9.93
Final water content, Average:	10.26
Residual heave (Di-Df), ΔH_{final} :	0.06

Fines Threshold Metrics	
Loose State:	0.924
Dense State:	0.841
void ratio of coarse grains (G & S), $e_c = V_v / (V_s(Gravel) + V_s(Sand))$:	0.436
Porosity of coarse grains (G & S), n_c :	0.304
Amount of fines in loose state required to fill the pore space of coarser structure,	3.23
Amount of fines in dense state required to fill the pore space of coarser structure,	6.48
water content of fines:	73.91

Figure A. 39 Phase Diagram for "10_B Mix 2-Yellow"



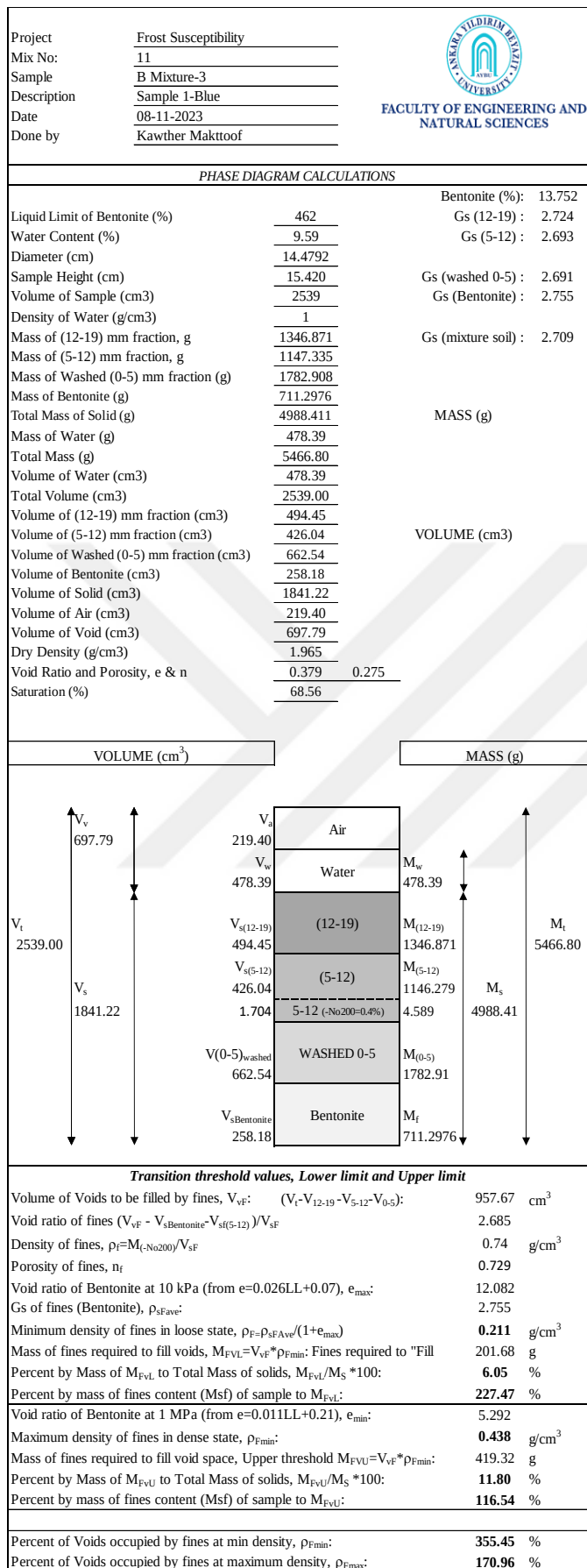
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	40.188
% of Bentonite:	9.812

SOIL CLASSIFICATION	
USCS:	GW-GC
AASHTO:	A2-7 (0)
RSCS:	GSF(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	47.38
weight of can+ wet sample, Top:	312.64
weight of can+ dry sample, Top:	284.45
Weight of can, Bottom:	1269.8
weight of can+ wet sample, Bottom:	6582.7
weight of can+ dry sample, Bottom:	6105.2
Final water content, Top:	11.89
Final water content, Bottom:	9.88
Final water content, Average:	9.97
Residual heave (Di-Df), ΔH_{final} :	0.43

Fines Threshold Metrics	
Loose State:	0.924
Dense State:	0.841
void ratio of coarse grains (G & S), $e_c = V_v / (V_sGravel + V_sSand)$:	0.393
Porosity of coarse grains (G & S), n_c :	0.282
Amount of fines in loose state required to fill the pore space of coarser structure, % F_v :	2.92
Amount of fines in dense state required to fill the pore space of coarser structure, % F_v :	5.88
water content of fines:	81.08

Figure A. 40 Phase Diagram for "10_B Mix 2-Green"



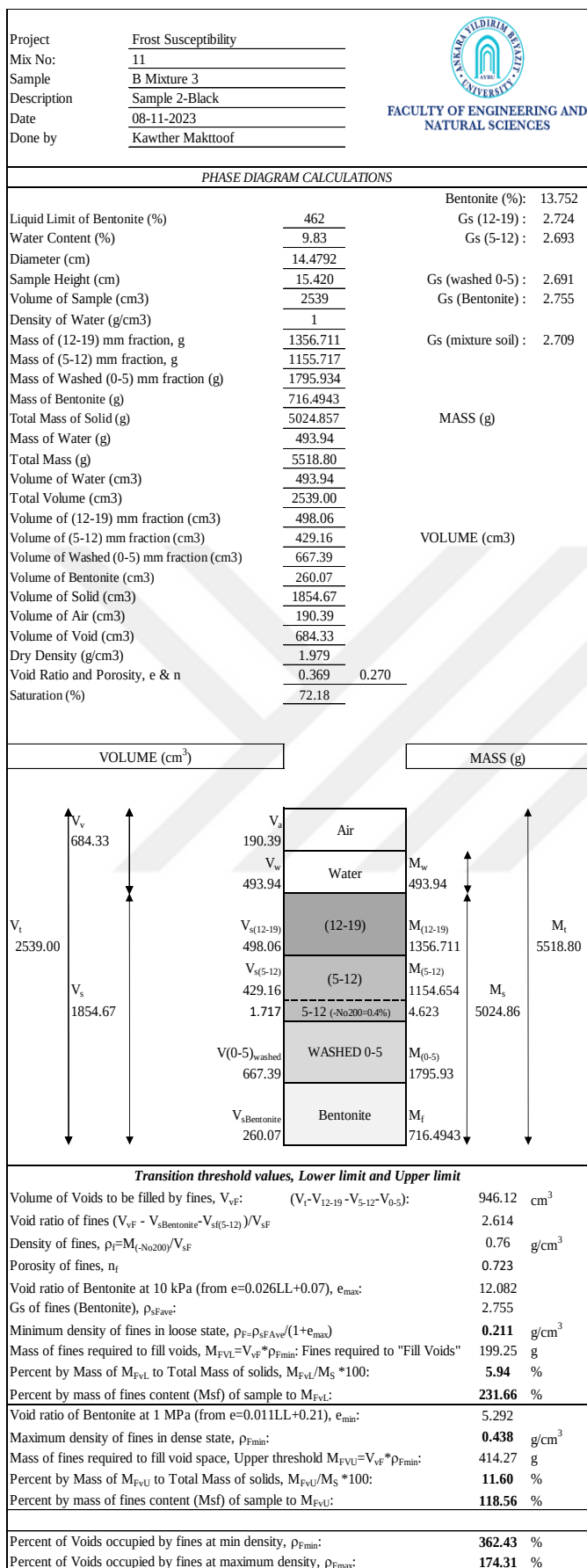
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	35.741
% of Bentonite:	14.259

SOIL CLASSIFICATION	
USCS:	GC
AASHTO:	A2-7 (0)
RSCS:	F(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	49.72
weight of can+ wet sample, Top:	299.94
weight of can+ dry sample, Top:	272.56
Weight of can, Bottom:	1381.7
weight of can+ wet sample, Bottom:	6641.2
weight of can+ dry sample, Bottom:	6099
Final water content, Top:	12.29
Final water content, Bottom:	11.49
Final water content, Average:	11.53
Residual heave (Di-Df), ΔH_{final} :	0.32

Fines Threshold Values	
Average Lower Limit Threshold (%):	6.0
Average Upper Limit Threshold(%):	11.7
Fines Content, M_{sf}/M_s (%):	13.75
Avg. % of Void space occupied by fines at min density, P_{fmin} (%):	361.2
Avg.% of Void space occupied by fines at maximum density, P_{fmax} (%):	173.7
Average Void ratio of fines of mixture:	2.630
Average porosity of fines of mixture:	0.724
Loose State:	0.924
Dense State:	0.841
Void ratio of coarse grains (G & S), $e_C = V_v/V_{sGravel} + V_{sSand}$:	0.441
Porosity of coarse grains (G & S), n_C :	0.306
Amount of fines in loose state required to fill the pore space of coarser structure, $\%F_V$:	3.26
Amount of fines in dense state required to fill the pore space of coarser structure, $\%F_V$:	6.55
Water content of fines:	66.82

Figure A. 41 Phase Diagram for "11_B Mix 3-Blue"



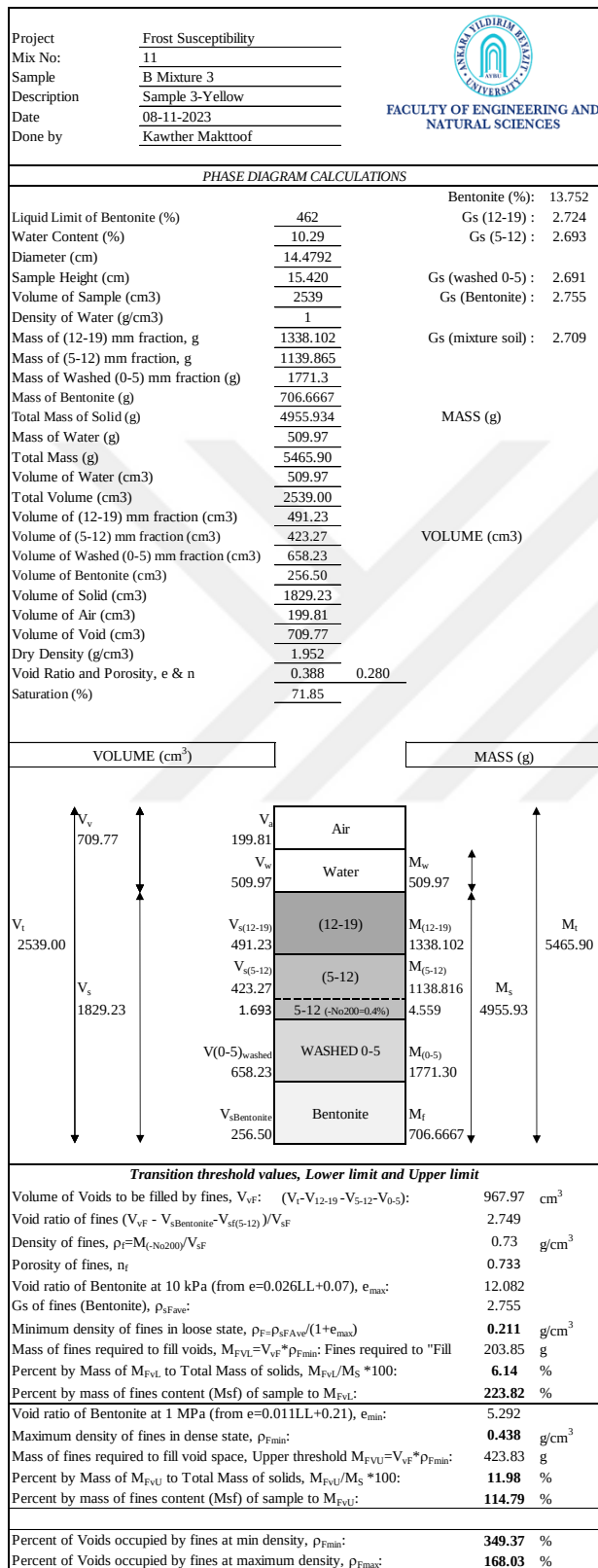
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	35.741
% of Bentonite:	14.259
	100

SOIL CLASSIFICATION	
USCS:	GC
AASHTO:	A2-7 (0)
RSCS:	F(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	50.02
weight of can+ wet sample, Top:	362.39
weight of can+ dry sample, Top:	331.76
Weight of can, Bottom:	1295.4
weight of can+ wet sample, Bottom:	6531.3
weight of can+ dry sample, Bottom:	6011
Final water content, Top:	10.87
Final water content, Bottom:	11.03
Final water content, Average:	11.02
Residual heave (D _i -D _f), ΔH _{final} :	0.15

Fines Threshold Metrics	
Loose State:	0.924
Dense State:	0.841
void ratio of coarse grains (G & S), e _c = V _v /V _{sGravel} + V _{sSand} :	0.430
Porosity of coarse grains (G & S), n _c :	0.301
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	3.18
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	6.39
water content of fines:	68.50

Figure A. 42 Phase Diagram for "11_B Mix 3-Black"



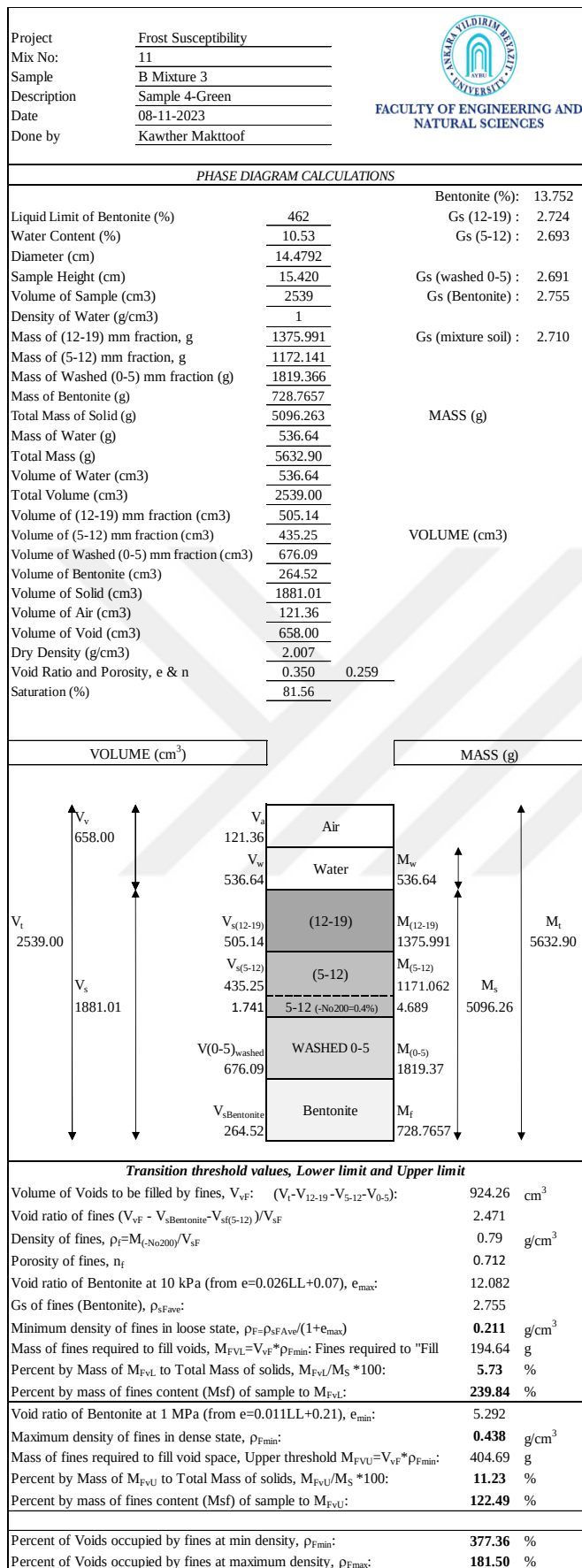
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	35.741
% of Bentonite:	14.259

SOIL CLASSIFICATION	
USCS:	GC
AASHTO:	A2-7 (0)
RSCS:	F(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	47.67
weight of can+ wet sample, Top:	333.48
weight of can+ dry sample, Top:	297.33
Weight of can, Bottom:	1319.4
weight of can+ wet sample, Bottom:	6530
weight of can+ dry sample, Bottom:	6011.9
Final water content, Top:	14.48
Final water content, Bottom:	11.04
Final water content, Average:	11.21
Residual heave (D _i -D _f), ΔH _{final} :	0.15

Fines Threshold Metrics	
Loose State:	0.924
Dense State:	0.841
void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.452
Porosity of coarse grains (G & S), n _c :	0.311
Amount of fines in loose state required to fill the pore space of coarser structure, %F _y :	3.34
Amount of fines in dense state required to fill the pore space of coarser structure, %F _y :	6.70
water content of fines:	71.70

Figure A. 43 Phase Diagram for "11_B Mix 3-Yellow"



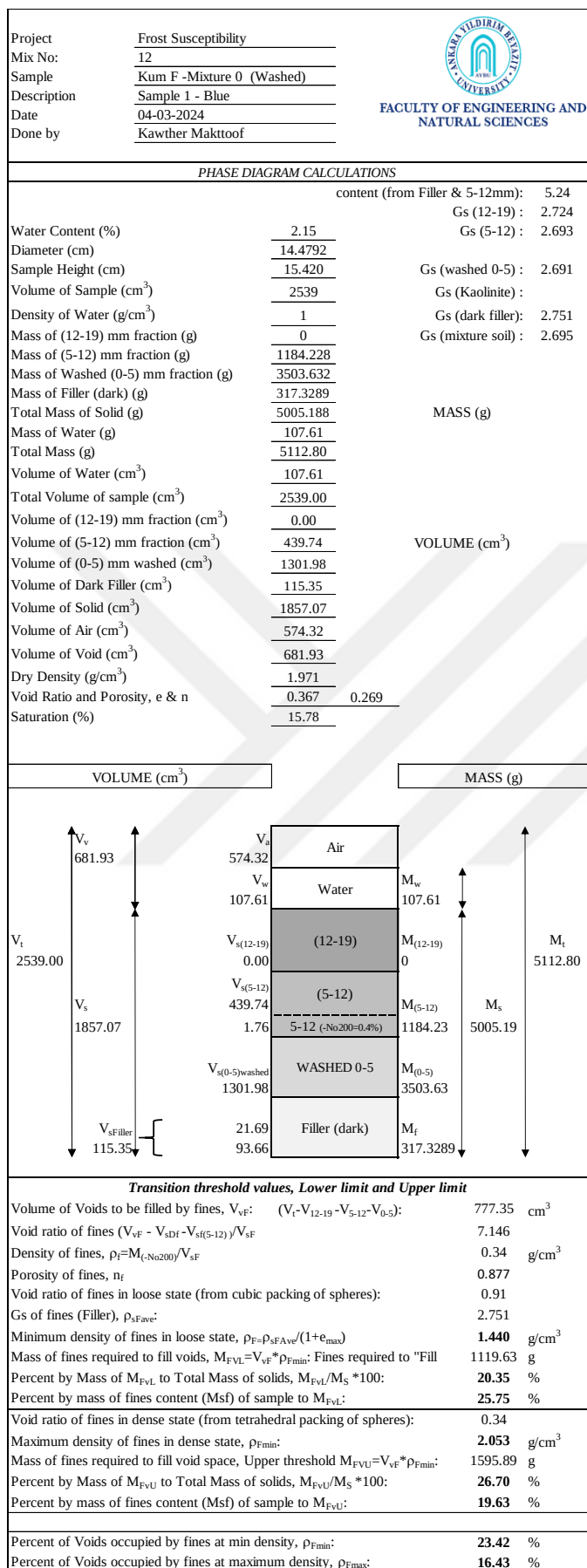
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	35.7
% of Bentonite:	14.3

SOIL CLASSIFICATION	
USCS:	GC
AASHTO:	A2-7 (0)
RSCS:	F(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can, Top:	49.11
weight of can+ wet sample, Top:	285.5
weight of can+ dry sample, Top:	259.52
Weight of can, Bottom:	1265.8
weight of can+ wet sample, Bottom:	6698.2
weight of can+ dry sample, Bottom:	6165.4
Final water content, Top:	12.35
Final water content, Bottom:	10.87
Final water content, Average:	10.94
Residual heave (Di-Df), ΔHfinal:	0.32

Fines Threshold Metrics	
Loose State:	0.924
Dense State:	0.841
void ratio of coarse grains (G & S), eC = Vv/VsGravel + VsSand:	0.407
Porosity of coarse grains (G & S), n _c :	0.290
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	3.02
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	6.08
water content of fines:	73.17

Figure A. 44 Phase Diagram for "11_B Mix 3-Green"



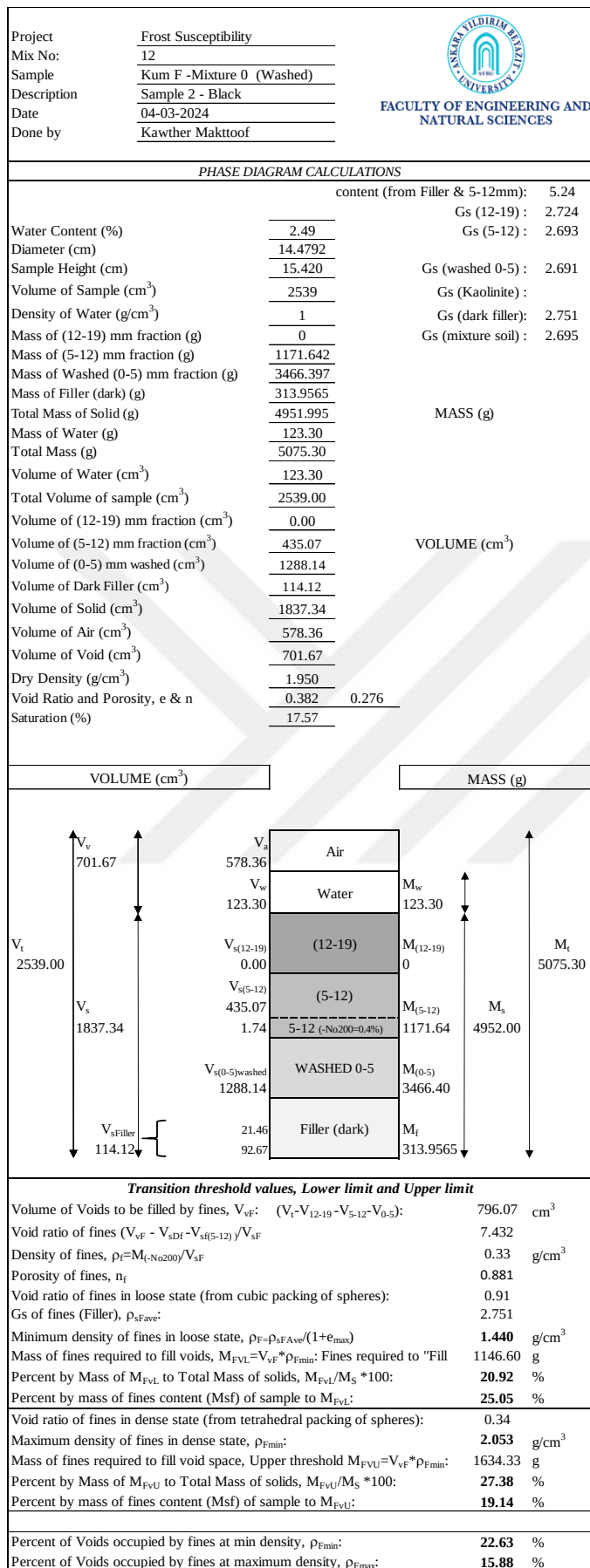
MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 0
% of (5-12) mm fraction: 23.66
%Washed (0-5) mm fraction: 70
% of dark Filler: 6.34

SOIL CLASSIFICATION
USCS: SP-SM
AASHTO: A-1-b(0)
RSCS: S(S)

DATA: END OF FS TESTING
Weight of can, Top: 48.07
weight of can+ wet sample, Top: 410.99
weight of can+ dry sample, Top: 380.62
Weight of can, Bottom: 1305.8
weight of can+ wet sample, Bottom: 6402.7
weight of can+ dry sample, Bottom: 5945.3
Final water content, Top: 9.13
Final water content, Bottom: 9.86
Final water content, Average: 9.81
Residual heave (Di-Df), ΔHfinal: 0.5

Fines Threshold Values
Average Lower Limit Threshold (%): 20.2
Average Upper Limit Threshold(%): 26.5
Fines Content, M _{sf} /M _s (%): 5.24
Avg. % of Void space occupied by fines at min density, P _{fmin} (%): 23.7
Avg.% of Void space occupied by fines at maximum density, P _{fmax} (%): 16.6
Average Void ratio of fines of mixture: 7.068
Avg. porosity of fines of mixture, for non-plastic filler (from stacking of spheres): 0.876
Loose State: e _{fmax} =0.91 and n _{fmax} = 0.476
Dense State: e _{fmin} = 0.34 and n _{fmin} =0.254
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} : 0.387
Porosity of coarse grains (G & S), n _C : 0.279
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v : 16.85
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v : 22.41
water content of fines: 41.01

Figure A. 45 Phase Diagram for "12_F Kum Mix 0-Blue"



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction: 0
 % of (5-12) mm fraction: 23.66
 %Washed (0-5) mm fraction: 70
 % of dark Filler: 6.34

SOIL CLASSIFICATION

USCS: SP-SM
 AASHTO: A-1-b(0)
 RSCS: S(S)

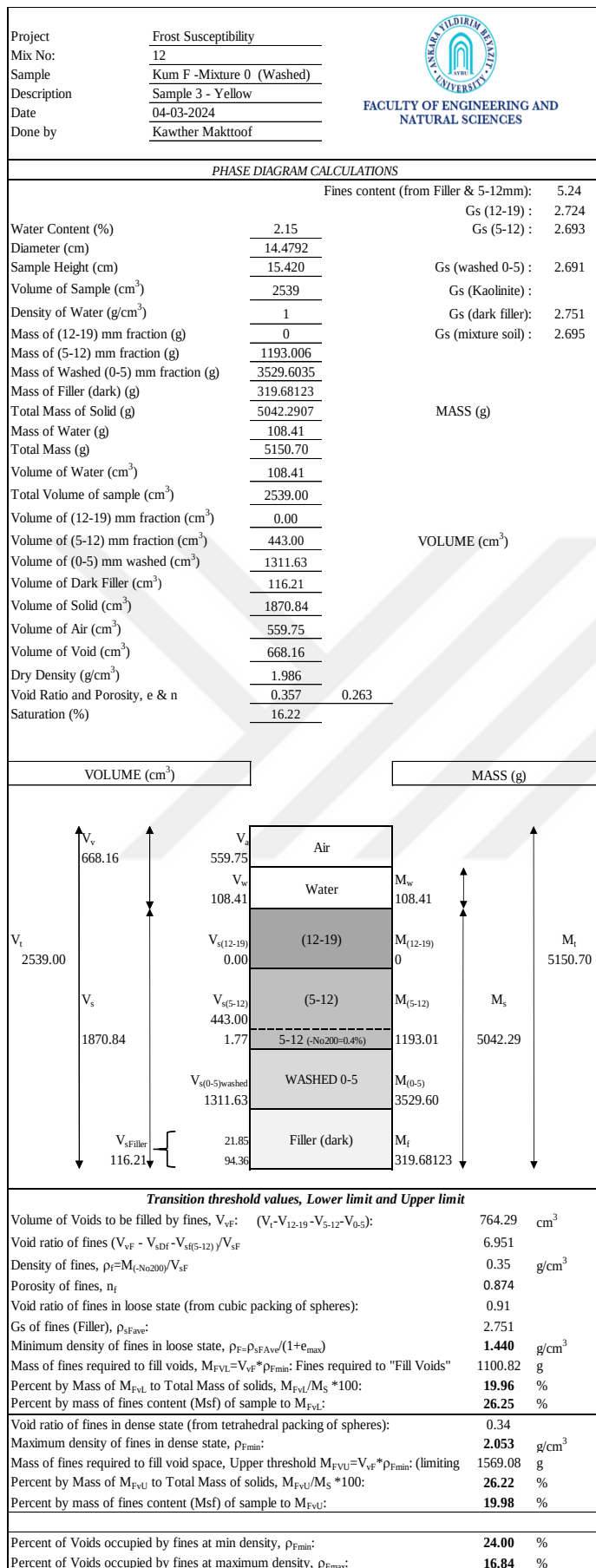
DATA: END OF FS TESTING

Weight of can, Top: 51.98
 weight of can+ wet sample, Top: 346.19
 weight of can+ dry sample, Top: 320.34
 Weight of can, Bottom: 1317
 weight of can+ wet sample, Bottom: 6454.9
 weight of can+ dry sample, Bottom: 5981.6
 Final water content, Top: 9.63
 Final water content, Bottom: 10.15
 Final water content, Average: 10.12
 Residual heave (Di-Df), ΔHfinal: 0.2

Fines Threshold Metrics

Loose State: e _{fmax} =0,91 and n _{fmax} = 0,476	0.476
Dense State: e _{fmin} = 0,34 and n _{fmin} =0,254	0.254
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.403
Porosity of coarse grains (G & S), n _C :	0.287
Amount of fines in loose state required to fill the pore space of coarser structure, %F _V :	17.41
Amount of fines in dense state required to fill the pore space of coarser structure, %F _V :	23.10
water content of fines:	47.49

Figure A. 46 Phase Diagram for "12_F Kum Mix 0-Black"



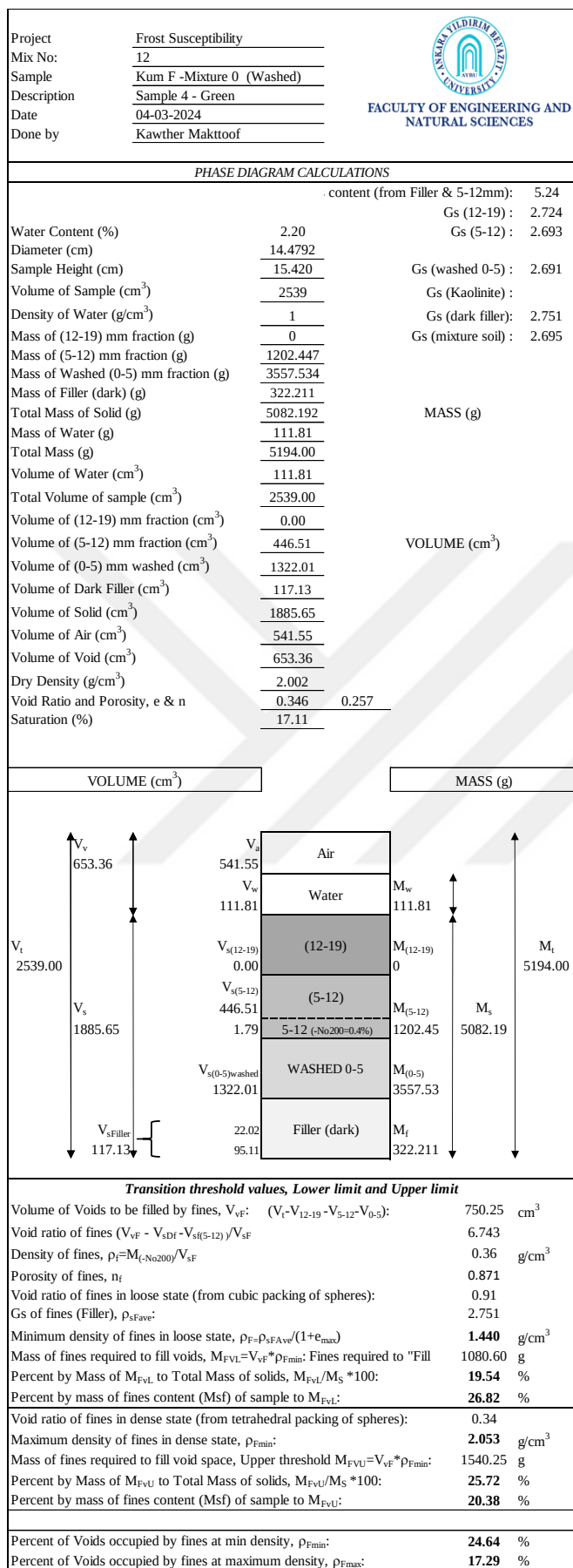
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	0
% of (5-12) mm fraction:	23.66
%Washed (0-5) mm fraction:	70
% of dark Filler:	6.34

SOIL CLASSIFICATION	
USCS:	SP-SM
AASHTO:	A-1-b(0)
RSCS:	S(S)

DATA: END OF FS TESTING	
Weight of can, Top:	48.18
weight of can+ wet sample, Top:	373.01
weight of can+ dry sample, Top:	348.14
Weight of can, Bottom:	1102.1
weight of can+ wet sample, Bottom:	6239.9
weight of can+ dry sample, Bottom:	5787
Final water content, Top:	8.29
Final water content, Bottom:	9.67
Final water content, Average:	9.58
Residual heave (Di-Df), ΔHfinal:	0.3

Fines Threshold Metrics		
Loose State: e _{max} =0,91 and n _{max} = 0,476		0.476
Dense State: e _{min} = 0,34 and n _{min} =0,254		0.254
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :		0.376
Porosity of coarse grains (G & S), n _C :		0.274
Amount of fines in loose state required to fill the pore space of coarser structure, %F _V :		16.47
Amount of fines in dense state required to fill the pore space of coarser structure, %F _V :		21.93
water content of fines:		41.01

Figure A. 47 Phase Diagram for "12_F Kum Mix 0-Yellow"



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction: 0

% of (5-12) mm fraction: 23.66

%Washed (0-5) mm fraction: 70

% of dark Filler: 6.34

SOIL CLASSIFICATION

USCS: SP-SM

AASHTO: A-1-b(0)

RSCS: S(S)

DATA: END OF FS TESTING

Weight of can, Top: 50.4

weight of can+ wet sample, Top: 380.41

weight of can+ dry sample, Top: 351.57

Weight of can, Bottom: 1308.1

weight of can+ wet sample, Bottom: 6536.3

weight of can+ dry sample, Bottom: 6056.8

Final water content, Top: 9.58

Final water content, Bottom: 10.10

Final water content, Average: 10.07

Residual heave (Di-Df), ΔHfinal: 0.55

Fines Threshold Metrics

Loose State: e _{fmax} =0.91 and n _{fmax} = 0.476	0.476
Dense State: e _{fmin} = 0.34 and n _{fmin} =0.254	0.254
Void ratio of coarse grains (G & S), eC = V _v /V _{sGravel} + V _{sSand} :	0.365
Porosity of coarse grains (G & S), n _c :	0.268
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	16.05
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	21.42
water content of fines:	41.96

Figure A. 48 Phase Diagram for "12_F Kum Mix 0-Green"

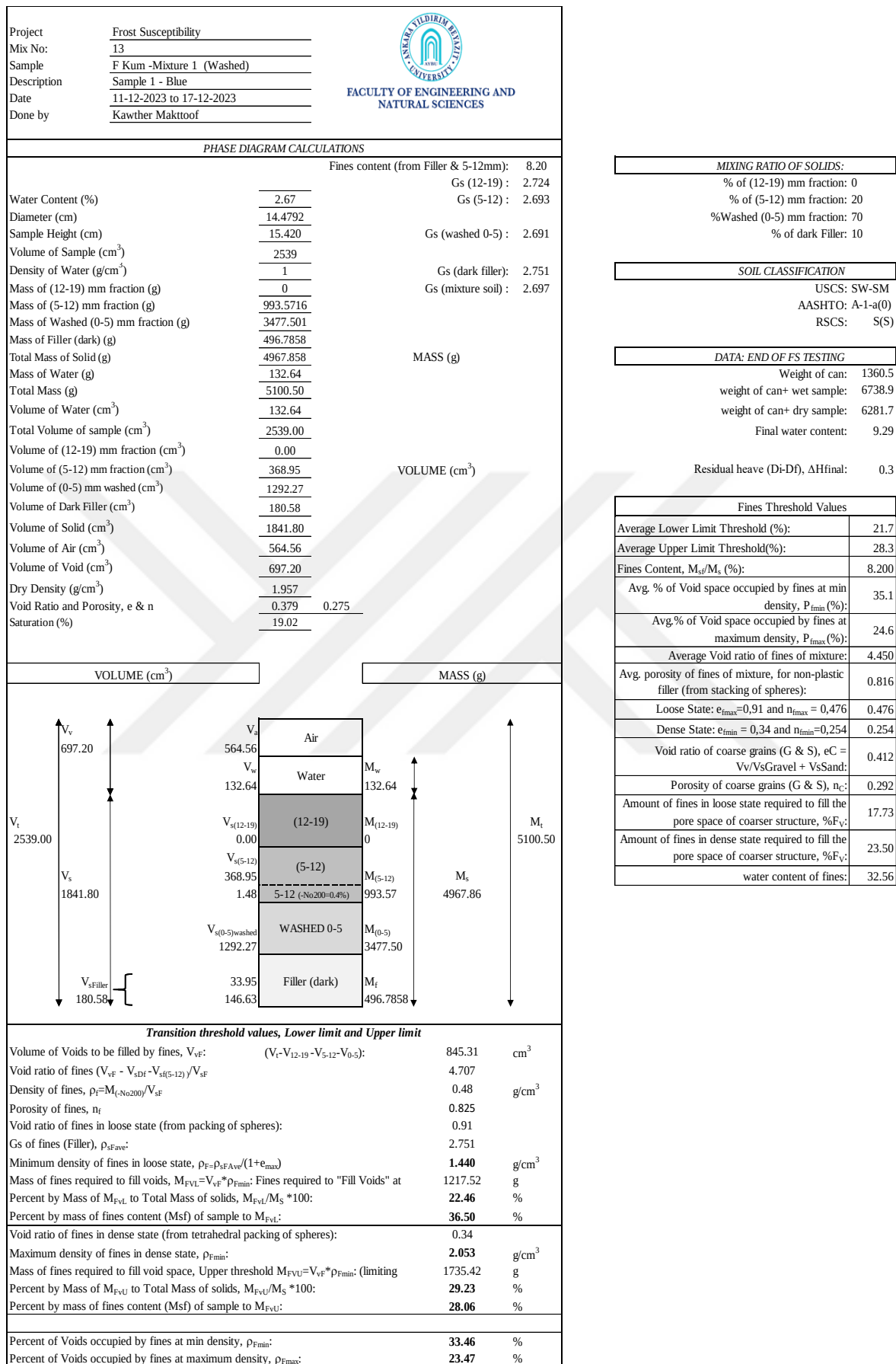


Figure A. 49 Phase Diagram for "13_F Kum Mix 1-Blue"

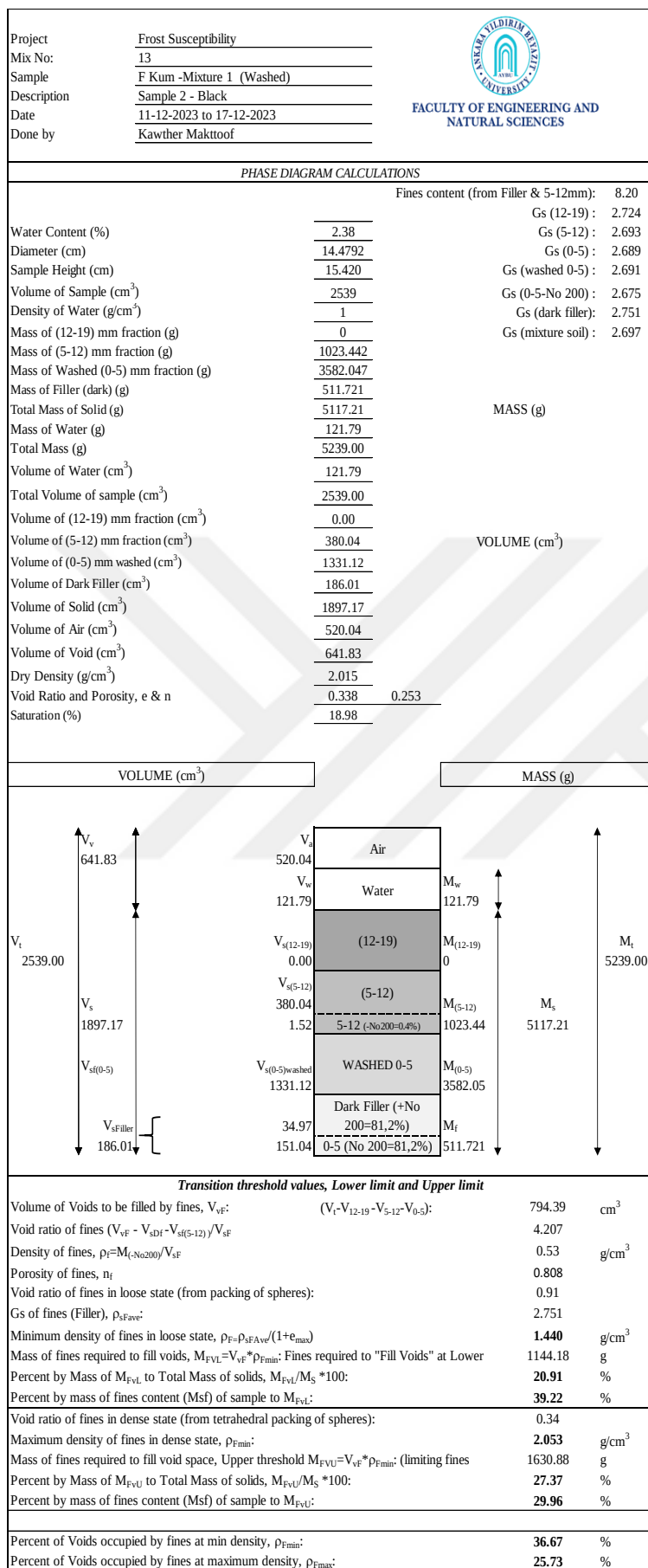


Figure A. 50 Phase Diagram for "13_F Kum Mix 1-Black"

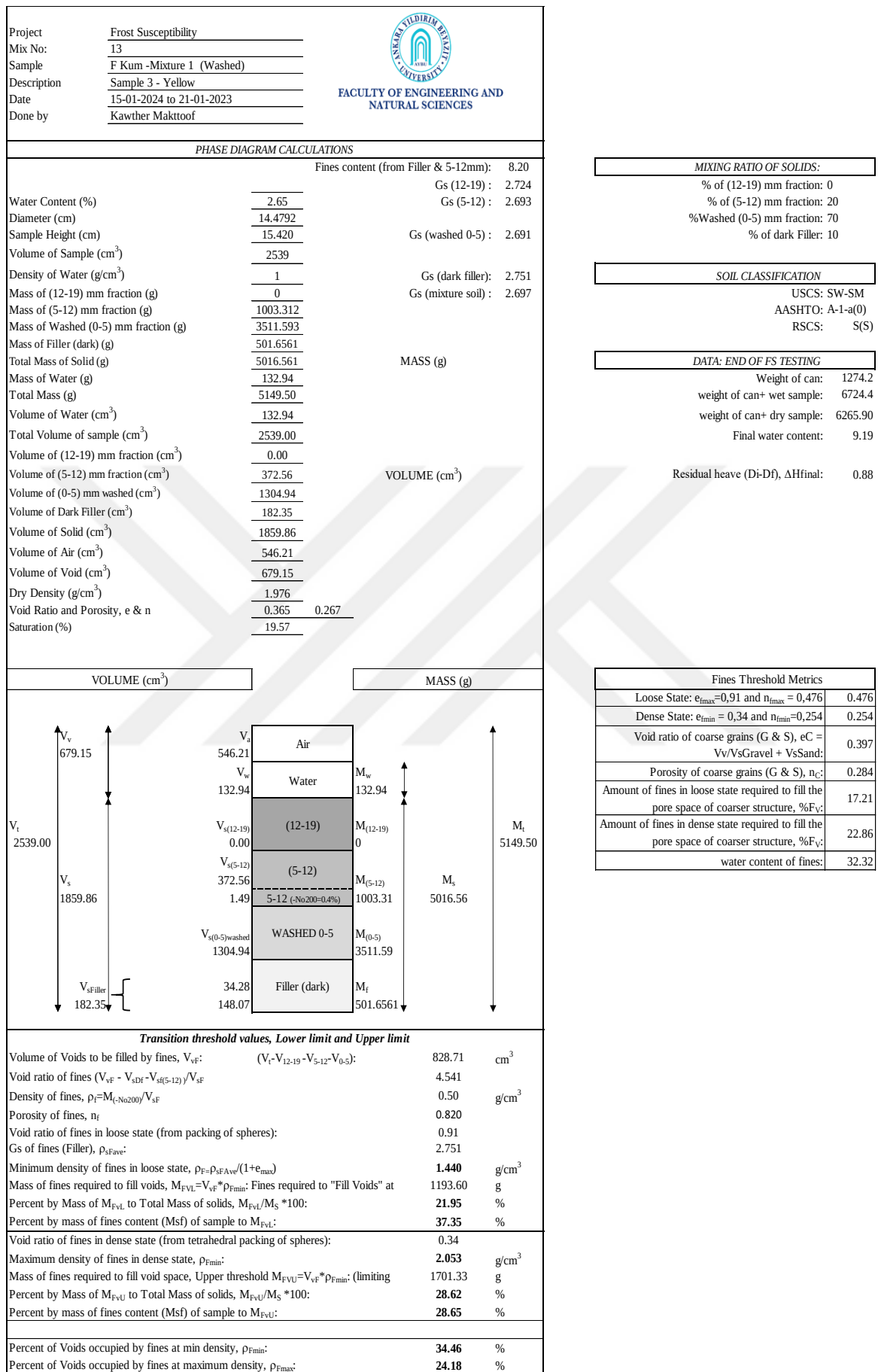
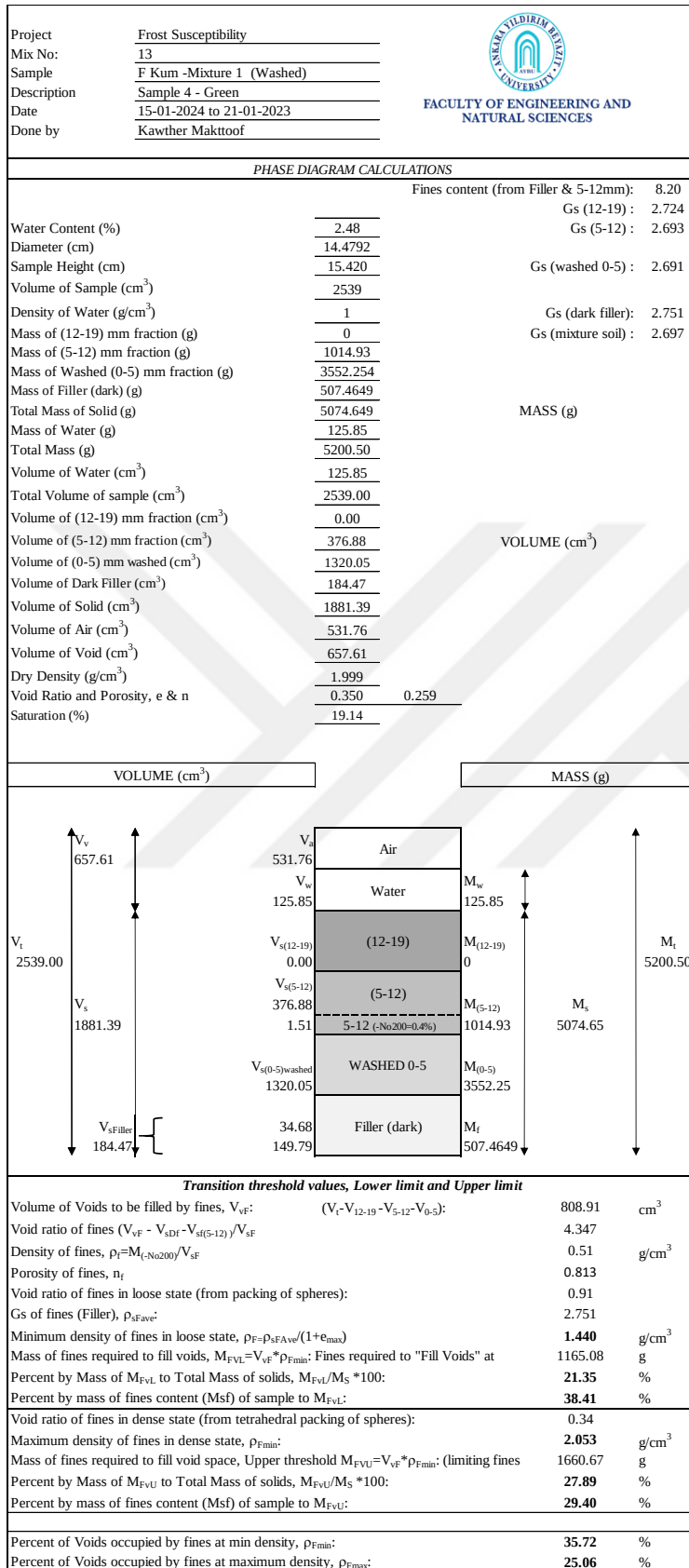


Figure A. 51 Phase Diagram for "13_F Kum Mix 1-Yellow"



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction: 0
 % of (5-12) mm fraction: 20
 %Washed (0-5) mm fraction: 70
 % of dark Filler: 10

SOIL CLASSIFICATION

USCS: SW-SM
 AASHTO: A-1-a(0)
 RSCS: S(S)

DATA: END OF FS TESTING

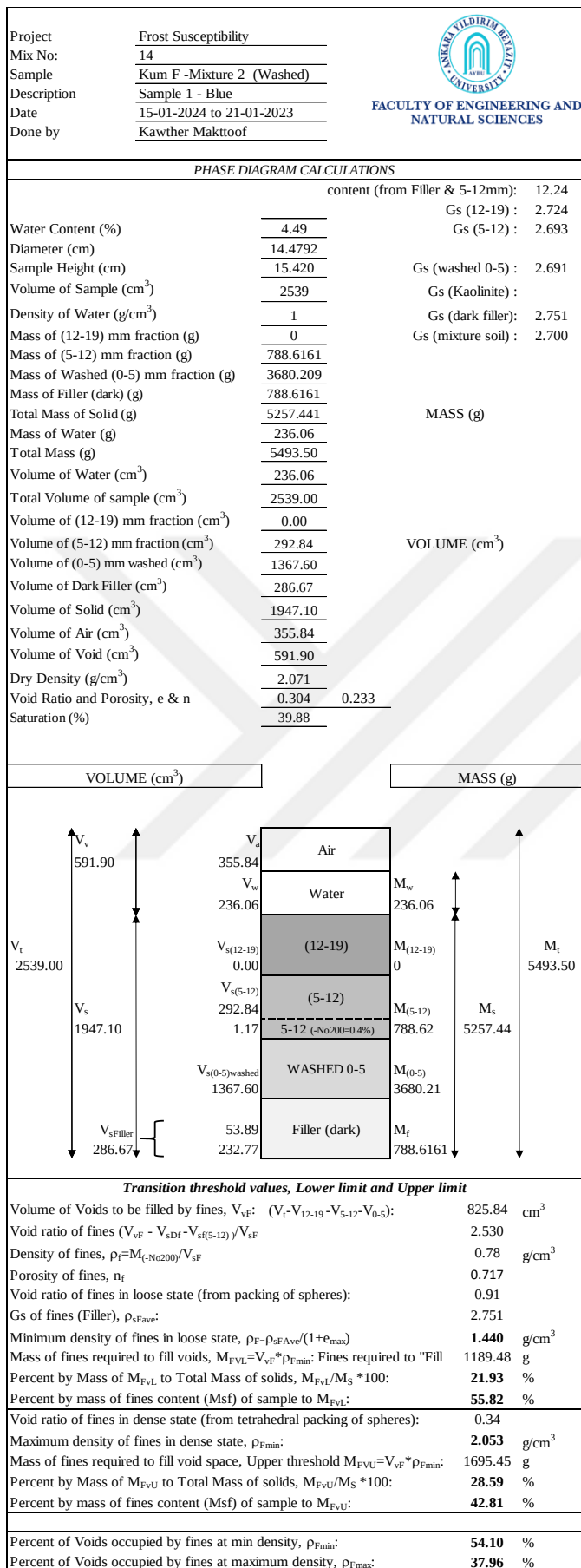
Weight of can: 1360.4
 weight of can+ wet sample: 6870.9
 weight of can+ dry sample: 6399.60
 Final water content: 9.35

Residual heave $(D_i - D_f)$, ΔH_{final} : 0.6

Fines Threshold Metrics

Loose State: $e_{fmax}=0.91$ and $n_{fmax} = 0.476$	0.476
Dense State: $e_{fmin} = 0.34$ and $n_{fmin}=0.254$	0.254
Void ratio of coarse grains (G & S), $e_c = V_v / V_{sGravel} + V_{sSand}$:	0.380
Porosity of coarse grains (G & S), n_c :	0.275
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	16.60
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	22.10
water content of fines:	30.24

Figure A. 52 Phase Diagram for "13_F Kum Mix 1-Green"



MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 0
% of (5-12) mm fraction: 15
%Washed (0-5) mm fraction: 70
% of dark Filler: 15

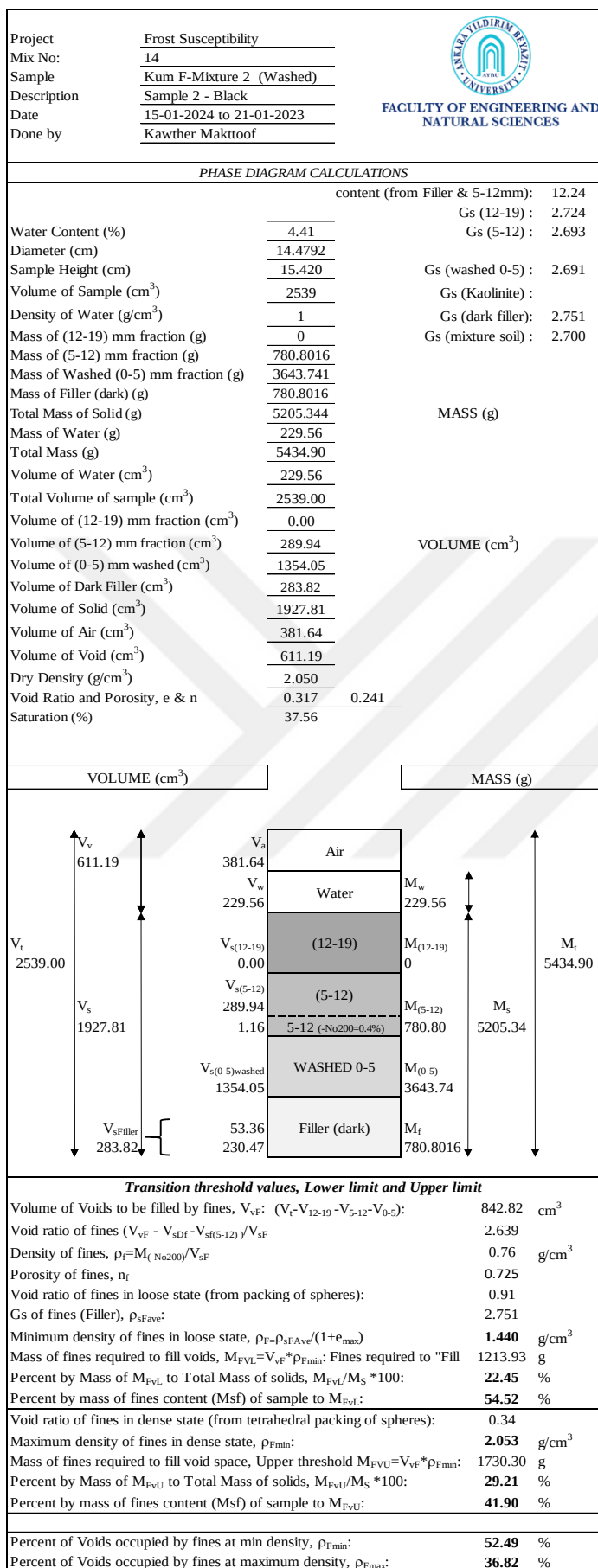
SOIL CLASSIFICATION
USCS: SW-SM
AASHTO: A-1-a(0)
RSCS: S(S)

DATA: END OF FS TESTING
Weight of can: 1300.5
weight of can+ wet sample: 7003
weight of can+ dry sample: 6529.20
Final water content: 9.06

Residual heave (Di-Df), ΔHfinal:	4.1
----------------------------------	-----

Fines Threshold Values	
Average Lower Limit Threshold (%):	22.8
Average Upper Limit Threshold(%):	29.6
Fines Content, M _{sf} /M _s (%):	12.240
Avg. % of Void space occupied by fines at min density, P _{fmin} (%):	51.5
Avg.% of Void space occupied by fines at maximum density, P _{fmax} (%):	36.1
Average Void ratio of fines of mixture:	2.712
Avg. porosity of fines of mixture, for non-plastic filler (from stacking of spheres):	0.730
Loose State: e _{fmax} =0.91 and n _{fmax} = 0.476	0.476
Dense State: e _{fmin} = 0.34 and n _{fmin} =0.254	0.254
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.346
Porosity of coarse grains (G & S), n _C :	0.257
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	15.32
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	20.50
water content of fines:	36.68

Figure A. 53 Phase Diagram for "14_F Kum Mix 2-Blue"



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction: 0
 % of (5-12) mm fraction: 15
 %Washed (0-5) mm fraction: 70
 % of dark Filler: 15

SOIL CLASSIFICATION

USCS: SW-SM
 AASHTO: A-1-a(0)
 RSCS: S(S)

DATA: END OF FS TESTING

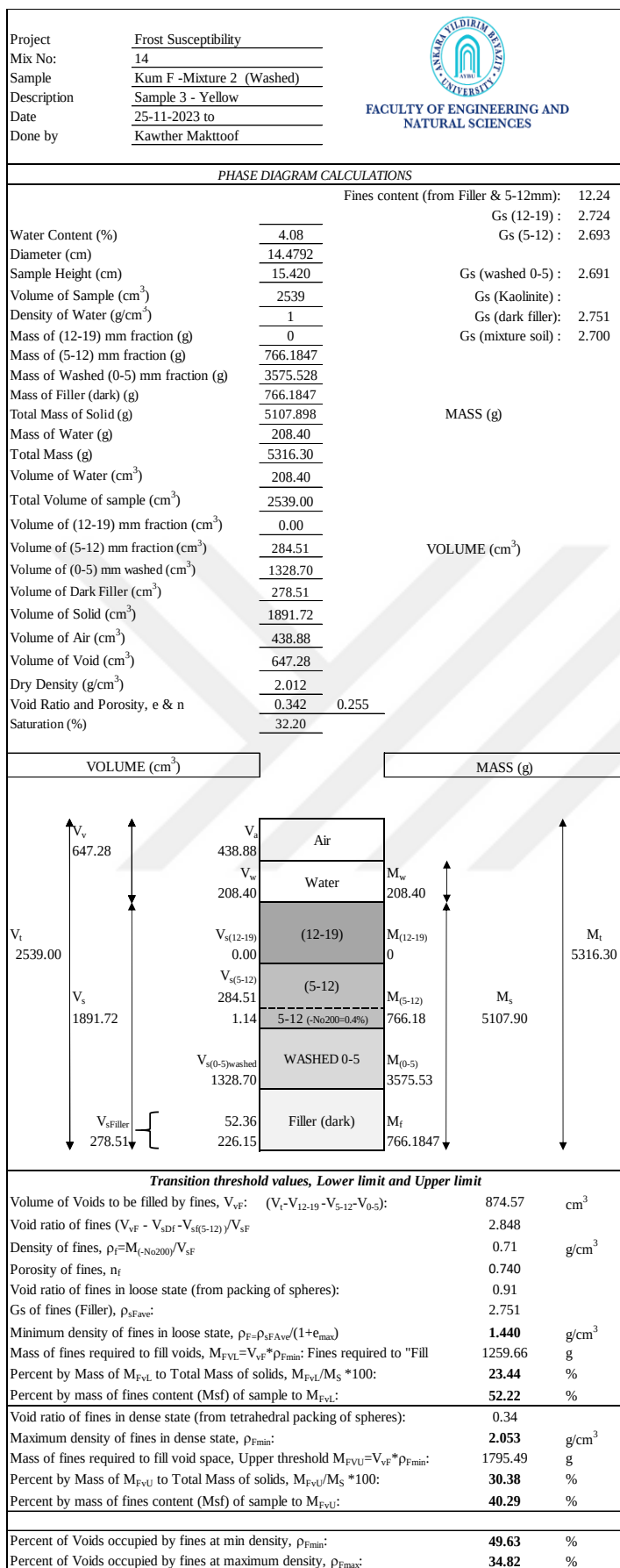
Weight of can: 1265.9
 weight of can+ wet sample: 6909.9
 weight of can+ dry sample: 6440.30
 Final water content: 9.08

Residual heave (Di-Df), ΔH_{final}: 3.4

Fines Threshold Metrics

Loose State: e _{fmax} =0,91 and n _{fmax} = 0,476	0.476
Dense State: e _{fmin} = 0,34 and n _{fmin} =0,254	0.254
Void ratio of coarse grains (G & S), eC = Vv/VsGravel + VsSand:	0.360
Porosity of coarse grains (G & S), n _c :	0.265
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	15.87
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	21.19
water content of fines:	36.03

Figure A. 54 Phase Diagram for "14_F Kum Mix 2-Black"



MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 0
% of (5-12) mm fraction: 15
%Washed (0-5) mm fraction: 70
% of dark Filler: 15

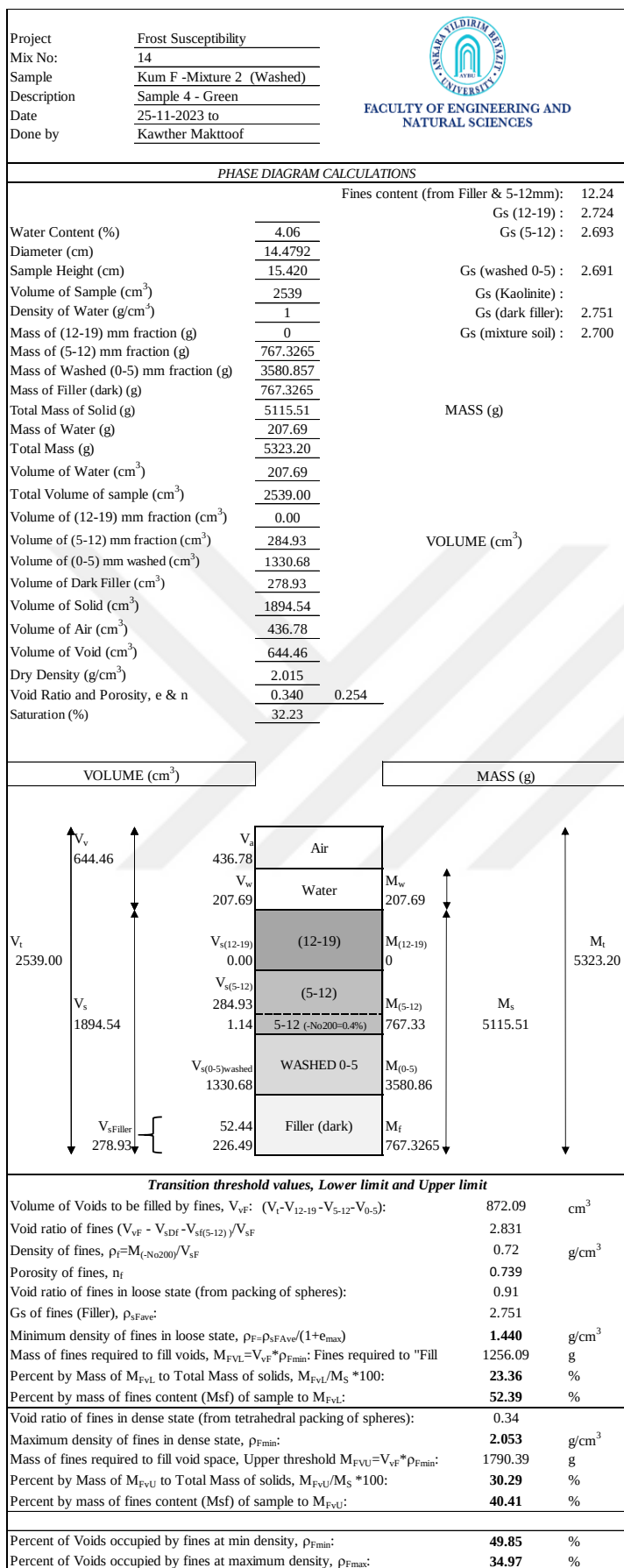
SOIL CLASSIFICATION
USCS: SW-SM
AASHTO: A-1-a(0)
RSCS: S(S)

DATA: END OF FS TESTING
Weight of can: 1307.9
weight of can+ wet sample: 6870.4
weight of can+ dry sample: 6407.00
Final water content: 9.09

Residual heave (Di-Df), ΔHfinal: 2.02

Fines Threshold Metrics	
Loose State: e _{max} =0.91 and n _{max} = 0.476	0.476
Dense State: e _{min} = 0.34 and n _{min} =0.254	0.254
Void ratio of coarse grains (G & S), e _c = V _v /V _{sGravel} + V _{sSand} :	0.389
Porosity of coarse grains (G & S), n _c :	0.280
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	16.92
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	22.49
water content of fines:	33.33

Figure A. 55 Phase Diagram for "14_F Kum Mix 2-Yellow"



MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 0
% of (5-12) mm fraction: 15
%Washed (0-5) mm fraction: 70
% of dark Filler: 15

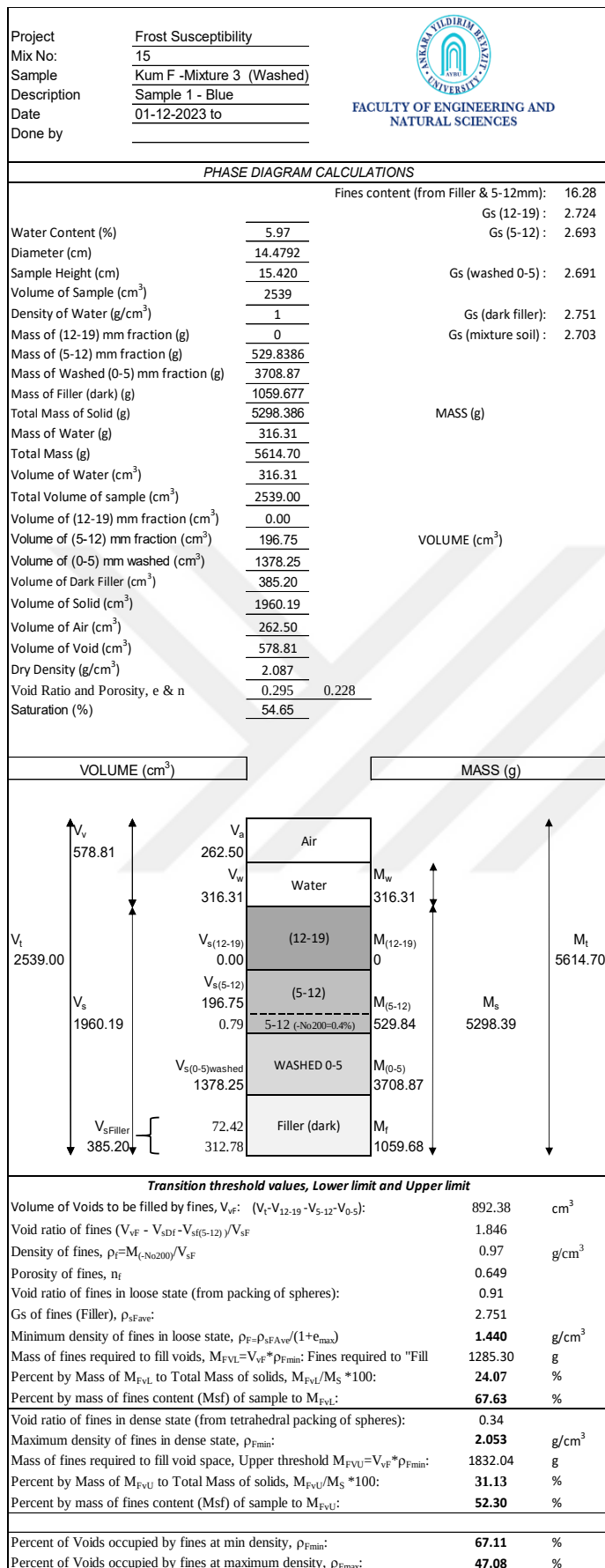
SOIL CLASSIFICATION
USCS: SW-SM
AASHTO: A-1-a(0)
RSCS: S(S)

DATA: END OF FS TESTING
Weight of can: 1285.3
weight of can+ wet sample: 6835.5
weight of can+ dry sample: 6361.70
Final water content: 9.33

Residual heave (Di-Df), ΔHfinal: 2

Fines Threshold Metrics	
Loose State: e _{fmax} =0.91 and n _{fmax} = 0.476	0.476
Dense State: e _{fmin} = 0.34 and n _{fmin} =0.254	0.254
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.387
Porosity of coarse grains (G & S), n _c :	0.279
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	16.83
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	22.39
water content of fines:	33.17

Figure A. 56 Phase Diagram for "14_F Kum Mix 2-Green"



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction: 0
 % of (5-12) mm fraction: 10
 %Washed (0-5) mm fraction: 70
 % of dark Filler: 20

SOIL CLASSIFICATION

USCS: SM
 AASHTO: A-1-a(0)
 RSCS: S(F) where
 fines are LH

DATA: END OF FS TESTING

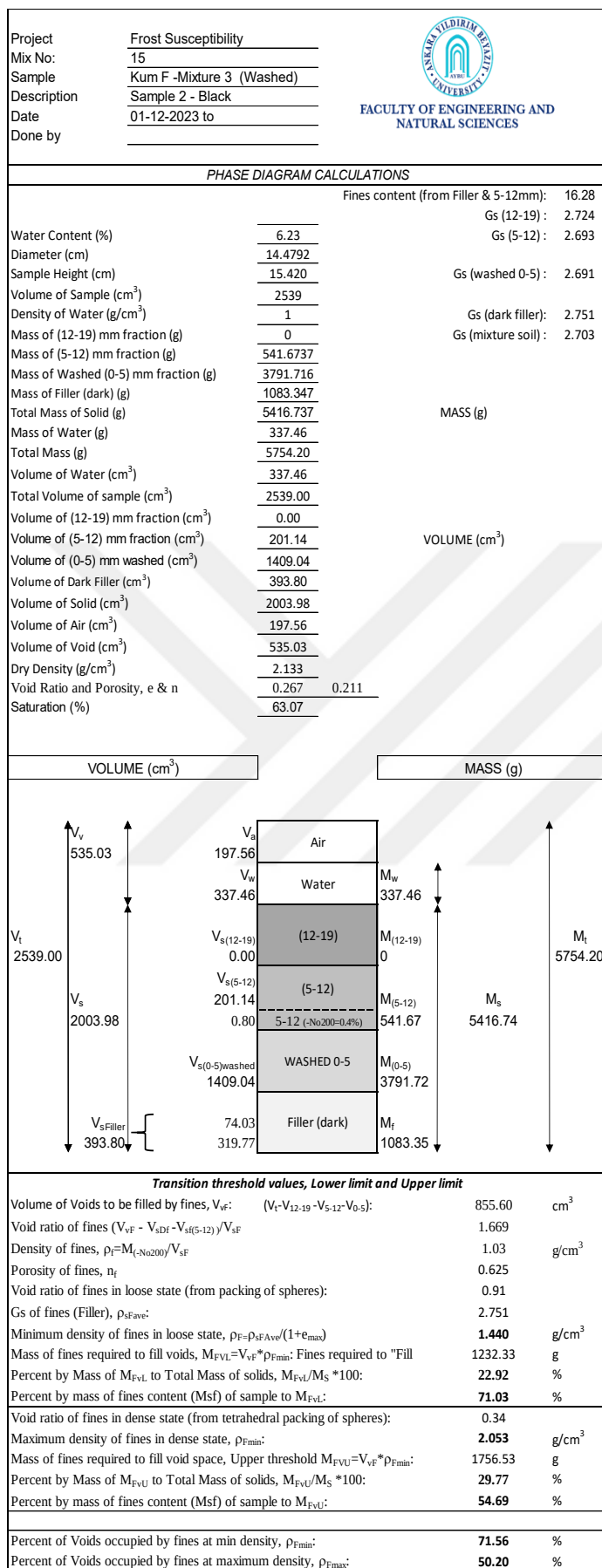
Weight of can: 1095.5
 weight of can+ wet sample: 6834.3
 weight of can+ dry sample: 6371.8
 Final water content: 8.77

Residual heave (Di-Df), ΔH_{final} : 4.3

Fines Threshold Values

Average Lower Limit Threshold (%):	23.5
Average Upper Limit Threshold(%):	30.5
Fines Content, M_{sf}/M_s (%):	16.28
Avg. % of Void space occupied by fines at min density, P_{fmin} (%):	69.3
Avg.% of Void space occupied by fines at maximum density, P_{fmax} (%):	48.6
Average Void ratio of fines of mixture:	1.8
Avg. porosity of fines of mixture, for non-plastic filler (from stacking of spheres):	0.637
Loose State: $e_{fmax}=0.91$ and $n_{fmax}=0.476$	0.476
Dense State: $e_{fmin}=0.34$ and $n_{fmin}=0.254$	0.254
Void ratio of coarse grains (G & S), $e_c = V_v/V_{sGravel} + V_{sSand}$:	0.352
Porosity of coarse grains (G & S), n_c :	0.260
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	15.54
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	20.78
water content of fines:	36.67

Figure A. 57 Phase Diagram for "15_F Kum Mix 3-Blue"



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction: 0
 % of (5-12) mm fraction: 10
 %Washed (0-5) mm fraction: 70
 % of dark Filler: 20

SOIL CLASSIFICATION

USCS: SM
 AASHTO: A-1-a(0)
 RSCS: S(F) where
 fines are LH

DATA: END OF FS TESTING

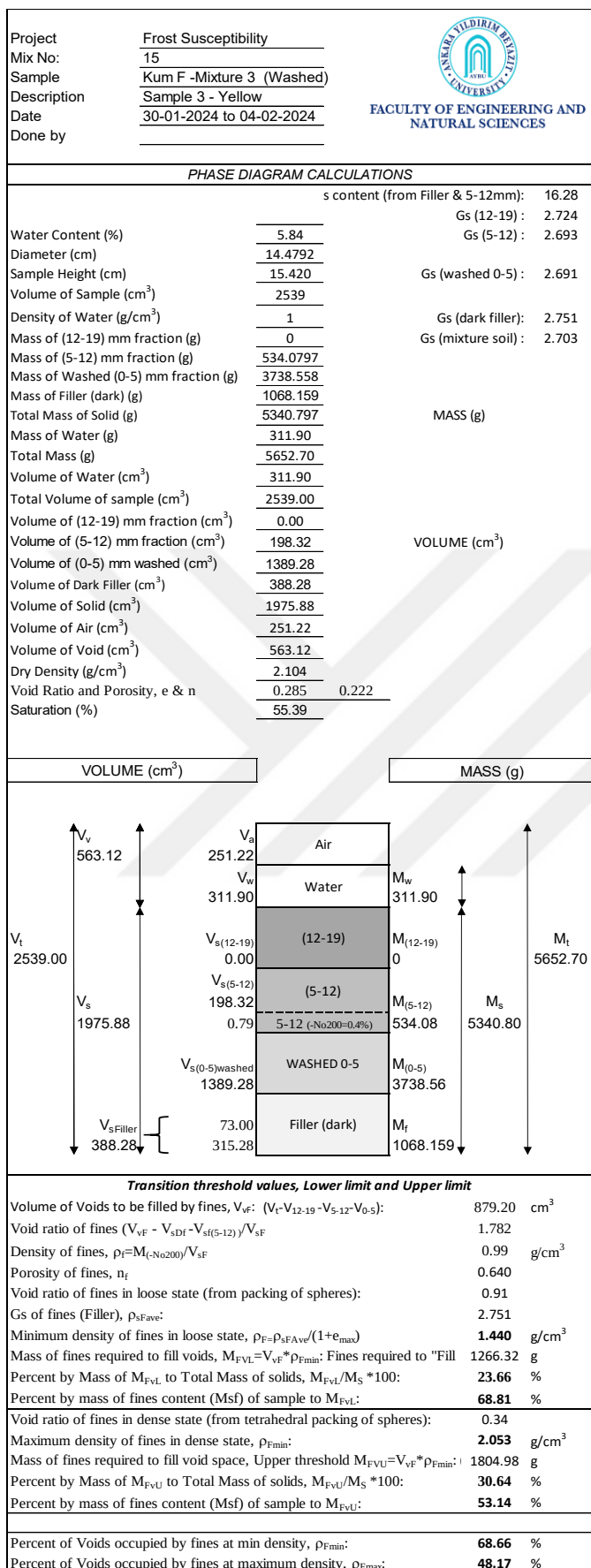
Weight of can: 1274.6
 weight of can+ wet sample: 7150.7
 weight of can+ dry sample: 6672.6
 Final water content: 8.86

Residual heave (Di-Df), ΔHfinal: 6

Fines Threshold Metrics

Loose State: e _{fmax} =0.91 and n _{fmax} = 0.476	0.476
Dense State: e _{fmin} = 0.34 and n _{fmin} =0.254	0.254
Void ratio of coarse grains (G & S), e _c = V _v /V _{sGravel} + V _{sSand} :	0.318
Porosity of coarse grains (G & S), n _c :	0.241
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	14.27
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	19.17
water content of fines:	38.27

Figure A. 58 Phase Diagram for “15_F Kum Mix 3-Black”



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction: 0
 % of (5-12) mm fraction: 10
 %Washed (0-5) mm fraction: 70
 % of dark Filler: 20

SOIL CLASSIFICATION

USCS: SM
 AASHTO: A-1-a(0)
 RSCS: S(F) where
 fines are LH

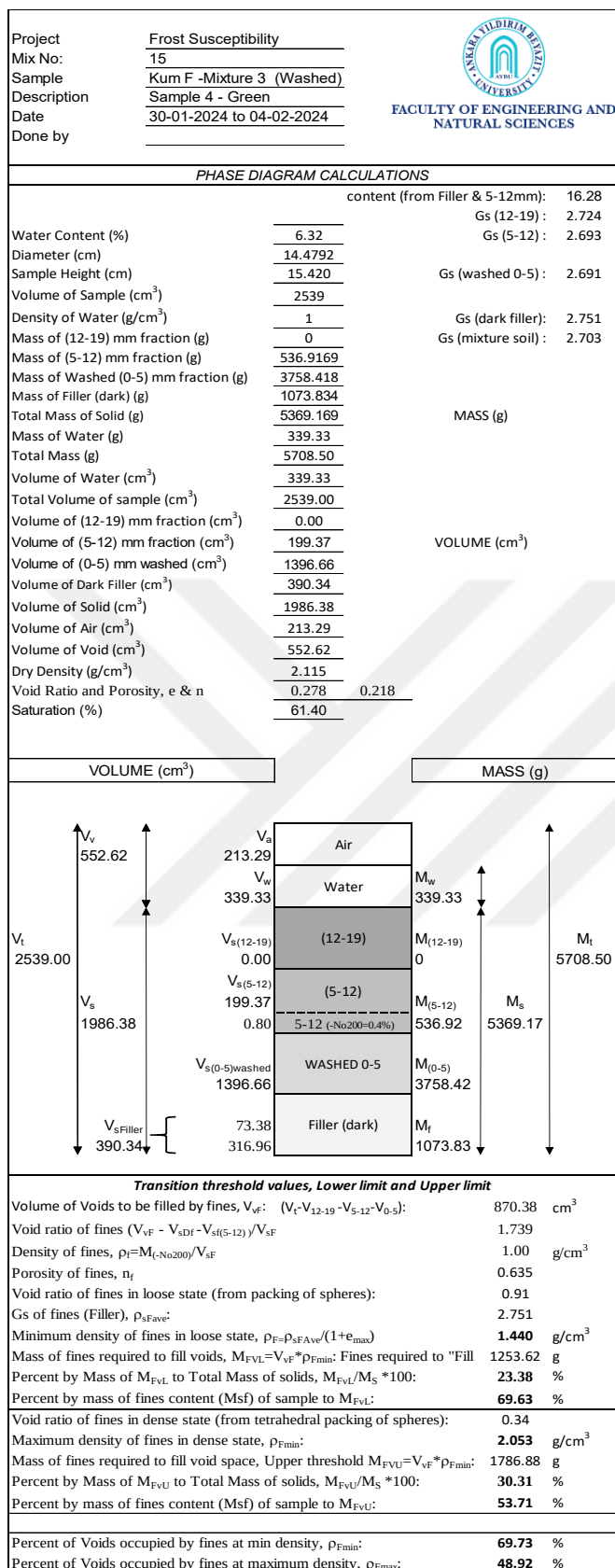
DATA: END OF FS TESTING

Weight of can: 1274.9
 weight of can+ wet sample: 7072.3
 weight of can+ dry sample: 6567
 Final water content: 9.55
 Residual heave (Di-Df), ΔHfinal: 5.7

Fines Threshold Metrics

Loose State: e _{fmax} =0,91 and n _{fmax} = 0,476	0.476
Dense State: e _{fmin} = 0,34 and n _{fmin} =0,254	0.254
Void ratio of coarse grains (G & S), e _c = V _v /V _{sGravel} + V _{sSand} :	0.339
Porosity of coarse grains (G & S), n _c :	0.253
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	15.08
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	20.20
water content of fines:	35.87

Figure A. 59 Phase Diagram for "15_F Kum Mix 3-Yellow"



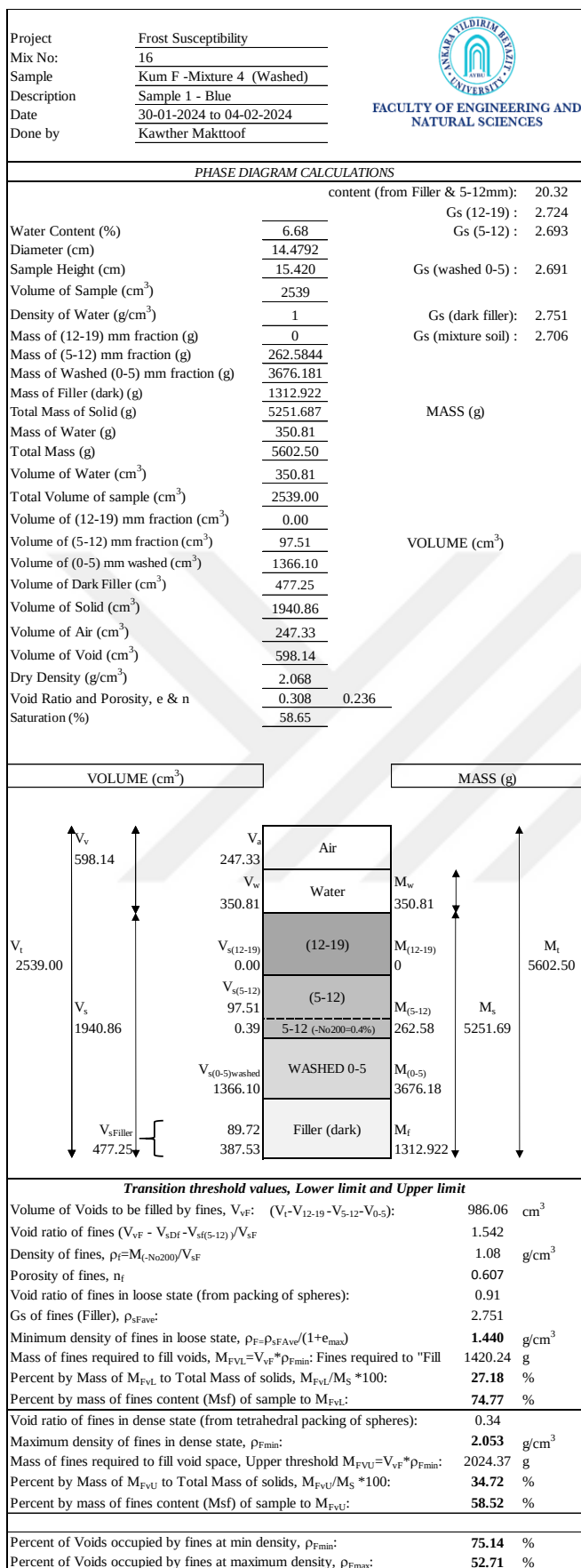
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	0
% of (5-12) mm fraction:	10
%Washed (0-5) mm fraction:	70
% of dark Filler:	20

SOIL CLASSIFICATION	
USCS:	SM
AASHTO:	A-1-a(0)
RSCS:	S(F) where fines are LH

DATA: END OF FS TESTING	
Weight of can:	1102.1
weight of can+ wet sample:	6923.1
weight of can+ dry sample:	6435.3
Final water content:	9.15
Residual heave (Di-Df), ΔHfinal:	6.5

Fines Threshold Metrics	
Loose State: e _{fmax} =0,91 and n _{fmax} = 0,476	0.476
Dense State: e _{fmin} = 0,34 and n _{fmin} =0,254	0.254
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.331
Porosity of coarse grains (G & S), n _C :	0.249
Amount of fines in loose state required to fill the pore space of coarser structure, %F _V :	14.78
Amount of fines in dense state required to fill the pore space of coarser structure, %F _V :	19.82
water content of fines:	38.82

Figure A. 60 Phase Diagram for "15_F Kum Mix 3-Green"



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction: 0
 % of (5-12) mm fraction: 5
 %Washed (0-5) mm fraction: 70
 % of dark Filler: 25

SOIL CLASSIFICATION

USCS: SM
 AASHTO: A-1-b(0)
 RSCS: S(F) where
 fines are LH

DATA: END OF FS TESTING

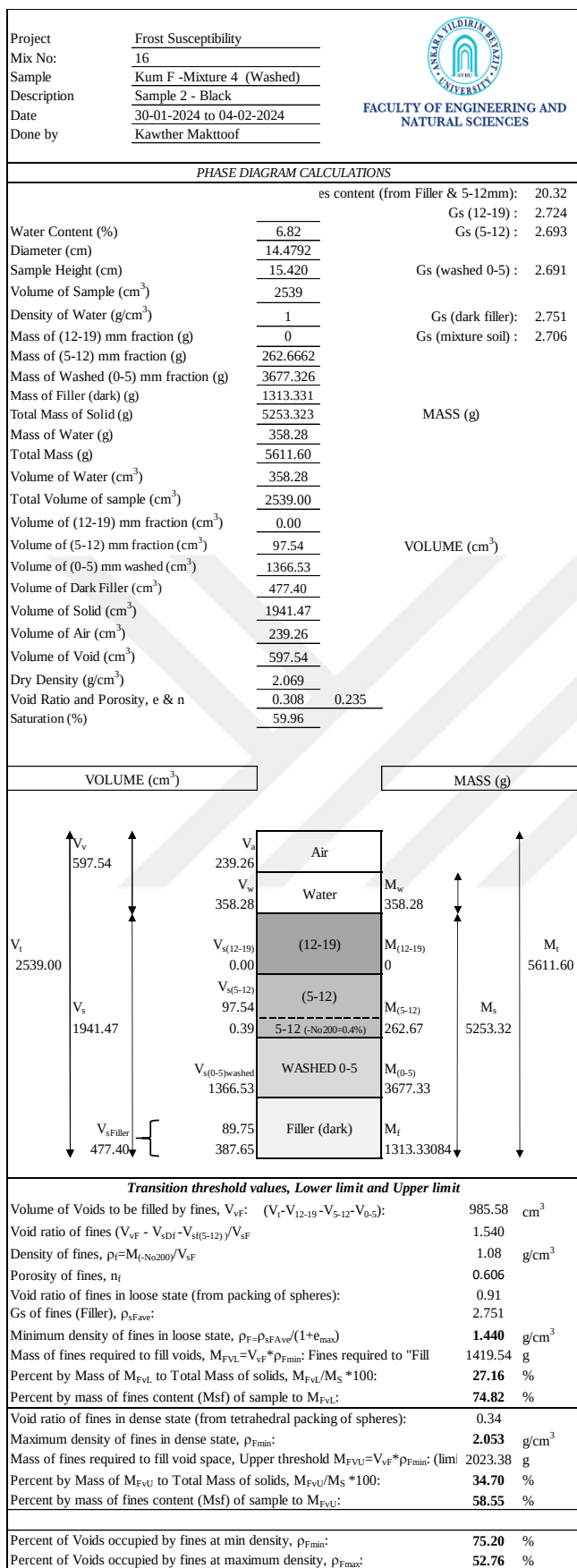
Weight of can: 1069.3
 weight of can+ wet sample: 6891.3
 weight of can+ dry sample: 6283.5
 Final water content: 11.66

Residual heave (Di-Df), ΔHfinal: 8.5

Fines Threshold Metrics

Average Lower Limit Threshold (%):	26.6
Average Upper Limit Threshold(%):	34.1
Fines Content, M _{sf} /M _s (%):	20.32
Avg. % of Void space occupied by fines at min density, P _{fmin} (%):	77.2
Avg.% of Void space occupied by fines at maximum density, P _{fmax} (%):	54.2
Average Void ratio of fines of mixture:	1.5
Avg. porosity of fines of mixture, for non-plastic filler (from stacking of spheres):	0.596
Loose State: e _{imax} =0,91 and n _{imax} = 0,476	0.476
Dense State: e _{fmin} = 0,34 and n _{fmin} =0,254	0.254
void ratio of coarse grains (G & S), eC = V _v /(V _{sGravel} + V _{sSand}):	0.385
Porosity of coarse grains (G & S), n _C :	0.278
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	16.78
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	22.33
water content of fines:	32.87

Figure A. 61 Phase Diagram for "16_F Kum Mix 4-Blue"



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction: 0
 % of (5-12) mm fraction: 5
 %Washed (0-5) mm fraction: 70
 % of dark Filler: 25

SOIL CLASSIFICATION

USCS: SM
 AASHTO: A-1-b(0)
 RSCS: S(F) where
 fines are LH

DATA: END OF FS TESTING

Weight of can: 1319.5
 weight of can+ wet sample: 7120.2
 weight of can+ dry sample: 6544
 Final water content: 11.03

Residual heave (Di-Df), ΔHfinal: 8

Fines Threshold Metrics

Loose State: e _{fmax} =0.91 and n _{fmax} = 0.476	0.476
Dense State: e _{fmin} = 0.34 and n _{fmin} =0.254	0.254
void ratio of coarse grains (G & S), e _C = V _v /(V _{sGravel} + V _{sSand}):	0.385
Porosity of coarse grains (G & S), n _C :	0.278
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	16.76
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	22.30
water content of fines:	33.56

Figure A. 62 Phase Diagram for “16_F Kum Mix 4-Black”

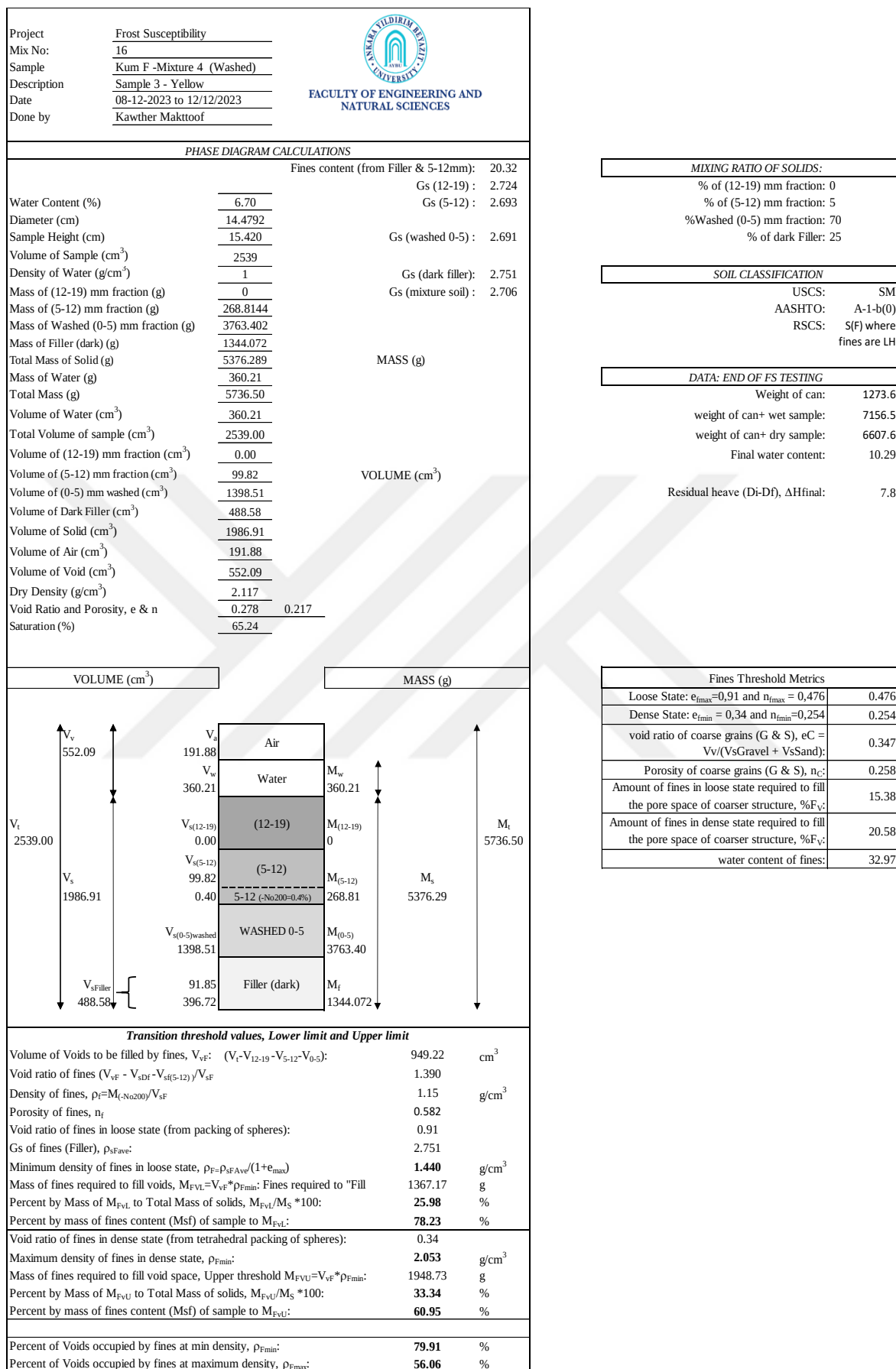


Figure A. 63 Phase Diagram for "16_F Kum Mix 4-Yellow"

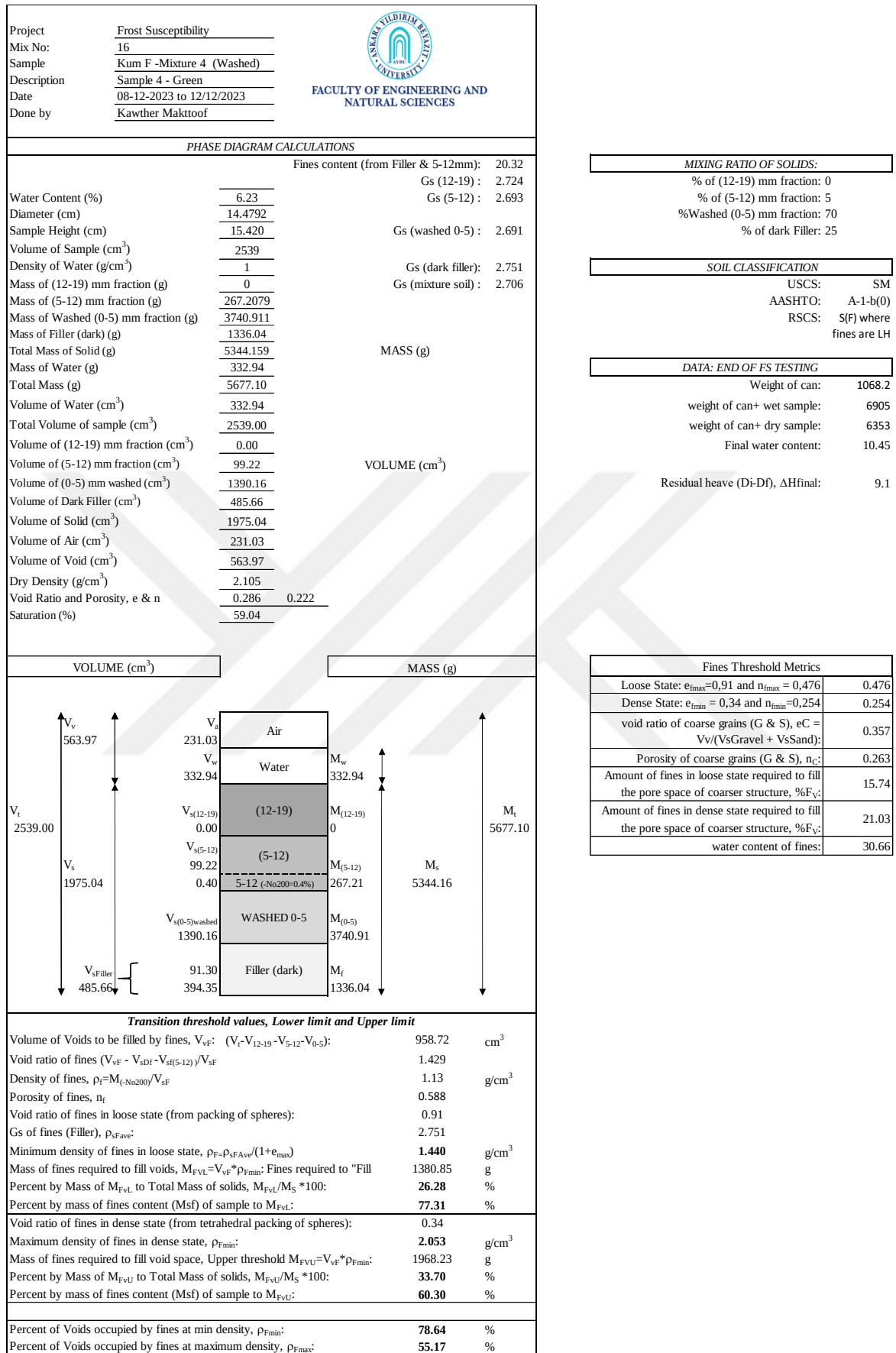
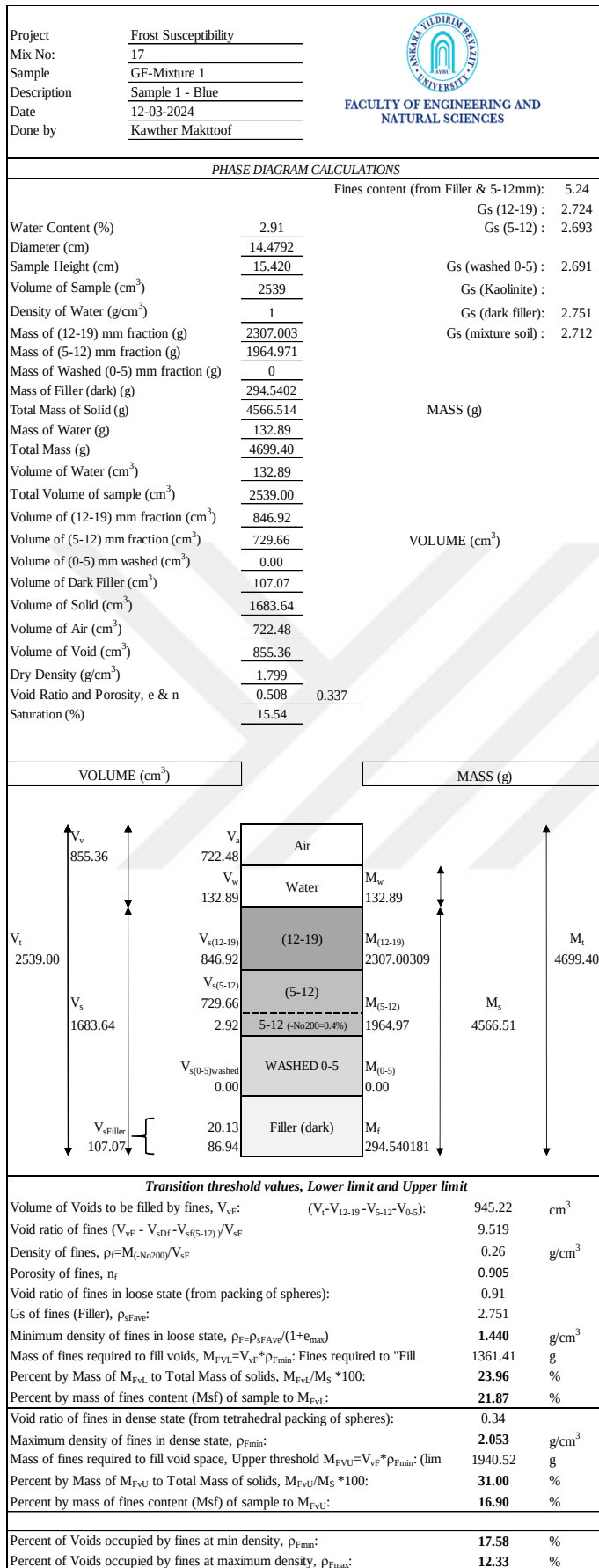


Figure A. 64 Phase Diagram for "16_F Kum Mix 4-Green"



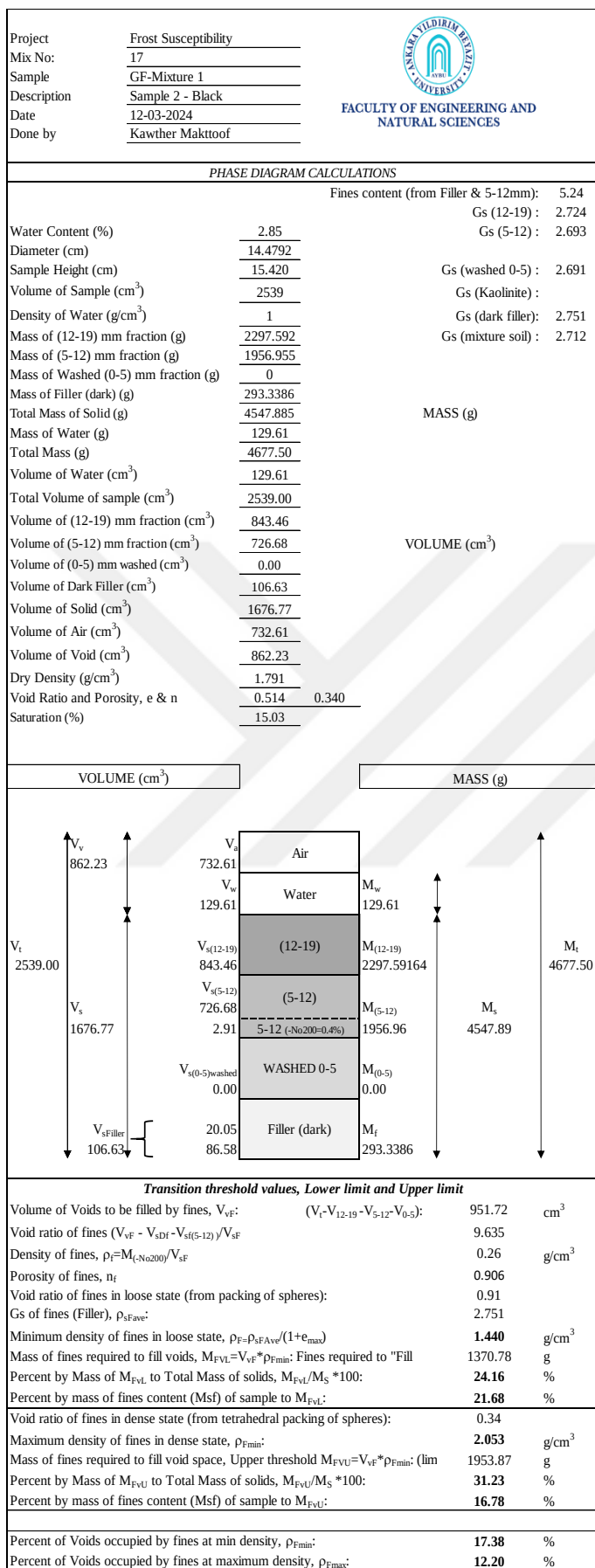
MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 50.52
% of (5-12) mm fraction: 43.03
% of Washed (0-5) mm fraction: 0
% of dark Filler 6.45

SOIL CLASSIFICATION
USCS: GP-GM
AASHTO: A-1-a(0)
RSCS: G(G)

DATA: END OF FS TESTING
Weight of can, Top: 44.64
weight of can+ wet sample, Top: 398.5
weight of can+ dry sample, Top: 386.25
Weight of can, Bottom: 1086.3
weight of can+ wet sample, Bottom: 5507.6
weight of can+ dry sample, Bottom: 5317.2
Final water content, Top: 3.59
Final water content, Bottom: 4.50
Final water content, Average: 4.43
Residual heave (Di-Df), ΔHfinal: 0.4

Fines Threshold Values
Average Lower Limit Threshold (%): 23.8
Average Upper Limit Threshold(%): 30.9
Fines Content, M _{sf} /M _s (%): 5.24
Avg. % of Void space occupied by fines at min density, P _{fmin} (%): 17.7
Avg.% of Void space occupied by fines at maximum density, P _{fmax} (%): 12.4
Average Void ratio of fines of mixture: 9.453
Avg. porosity of fines of mixture, for non-plastic filler (from stacking of spheres): 0.904
Loose State: e _{imax} =0.91 and n _{imax} = 0.476
Dense State: e _{fmin} = 0.34 and n _{fmin} =0.254
Void ratio of coarse grains (G & S), eC = V _v /V _{sGravel} + V _{sSand} : 0.537
Porosity of coarse grains (G & S), n _c : 0.349
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v : 21.94
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v : 28.60
water content of fines: 53.79

Figure A. 65 Phase Diagram for "17_GF Mix 1-Blue"



MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 50.52
% of (5-12) mm fraction: 43.03
% of Washed (0-5) mm fraction: 0
% of dark Filler 6.45

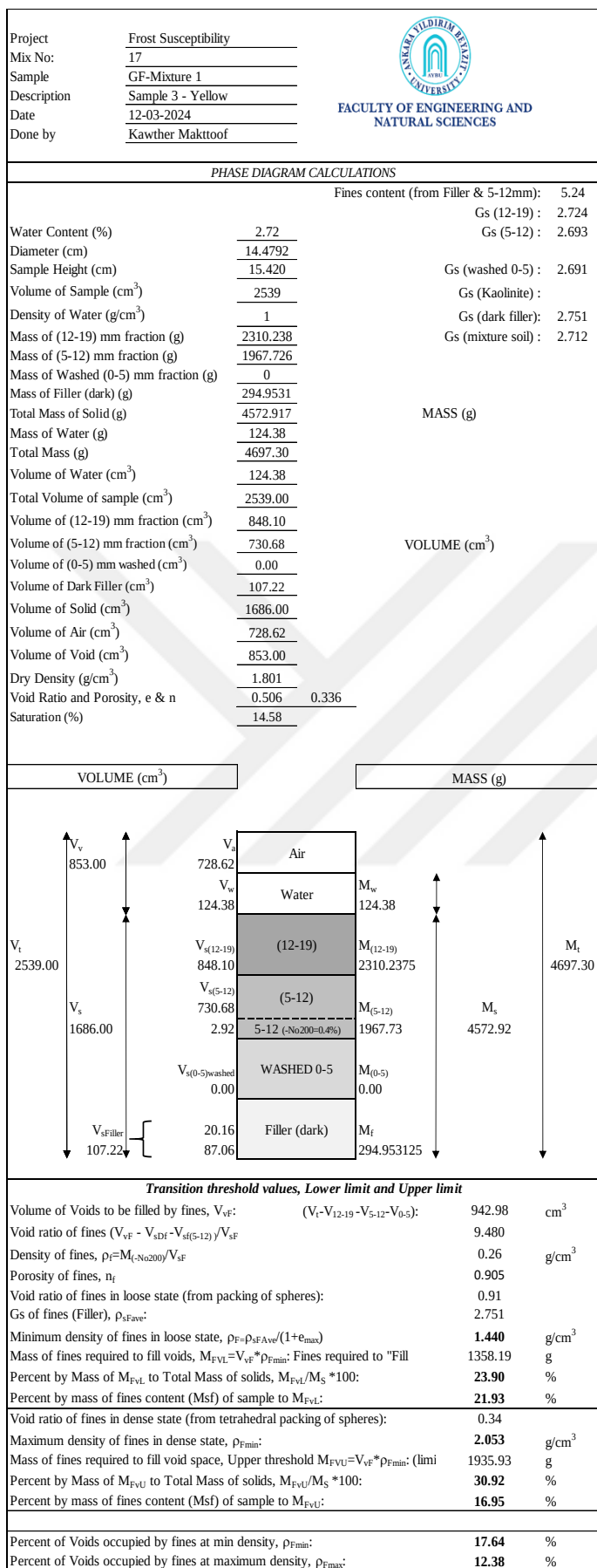
SOIL CLASSIFICATION
USCS: GP-GM
AASHTO: A-1-a(0)
RSCS: G(G)

DATA: END OF FS TESTING
Weight of can, Top: 47.69
weight of can+ wet sample, Top: 388.75
weight of can+ dry sample, Top: 377.65
Weight of can, Bottom: 1099.1
weight of can+ wet sample, Bottom: 5469.8
weight of can+ dry sample, Bottom: 5279.4
Final water content, Top: 3.36
Final water content, Bottom: 4.55
Final water content, Average: 4.47

Residual heave (Di-Df), ΔHfinal: 0.3

Fines Threshold Metrics		
Loose State: e _{fmax} =0.91 and n _{fmax} = 0.476		0.476
Dense State: e _{fmin} = 0.34 and n _{fmin} =0.254		0.254
void ratio of coarse grains (G & S), eC = Vv/(VsGravel + VsSand):		0.543
Porosity of coarse grains (G & S), n _C :		0.352
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :		22.14
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :		28.84
water content of fines:		52.68

Figure A. 66 Phase Diagram for "17_GF Mix 1-Black"



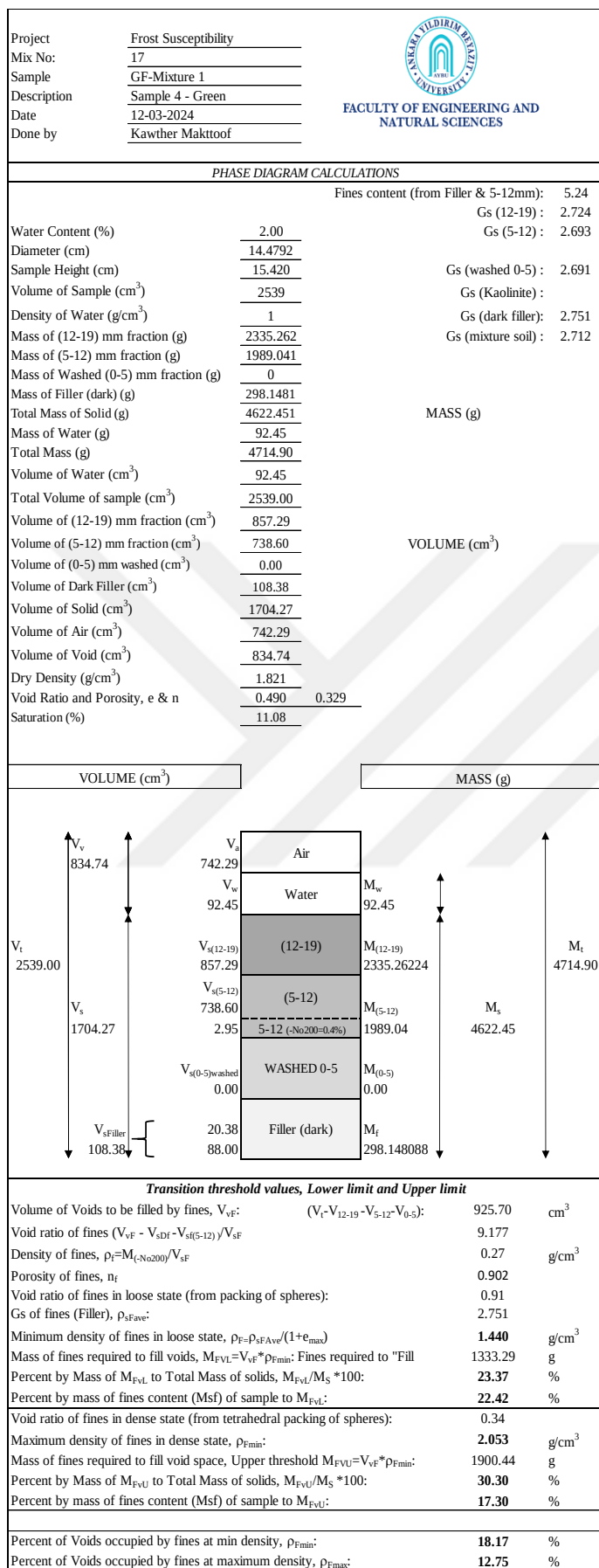
MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 50.52
% of (5-12) mm fraction: 43.03
% of Washed (0-5) mm fraction: 0
% of dark Filler 6.45

SOIL CLASSIFICATION
USCS: GP-GM
AASHTO: A-1-a(0)
RSCS: G(G)

DATA: END OF FS TESTING
Weight of can, Top: 48.33
weight of can+ wet sample, Top: 363.6
weight of can+ dry sample, Top: 353.66
Weight of can, Bottom: 1309.7
weight of can+ wet sample, Bottom: 5762.4
weight of can+ dry sample, Bottom: 5573.5
Final water content, Top: 3.26
Final water content, Bottom: 4.43
Final water content, Average: 4.35
Residual heave (Di-Df), ΔHfinal: 0.54

Fines Threshold Metrics	
Loose State: e _{fmax} =0.91 and n _{fmax} = 0.476	0.476
Dense State: e _{fmin} = 0.34 and n _{fmin} =0.254	0.254
void ratio of coarse grains (G & S), eC = Vv/(VsGravel + VsSand):	0.534
Porosity of coarse grains (G & S), nC:	0.348
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	21.86
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	28.51
water content of fines:	50.28

Figure A. 67 Phase Diagram for "17_GF Mix 1-Yellow"



MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 50.52
% of (5-12) mm fraction: 43.03
% of Washed (0-5) mm fraction: 0
% of dark Filler 6.45

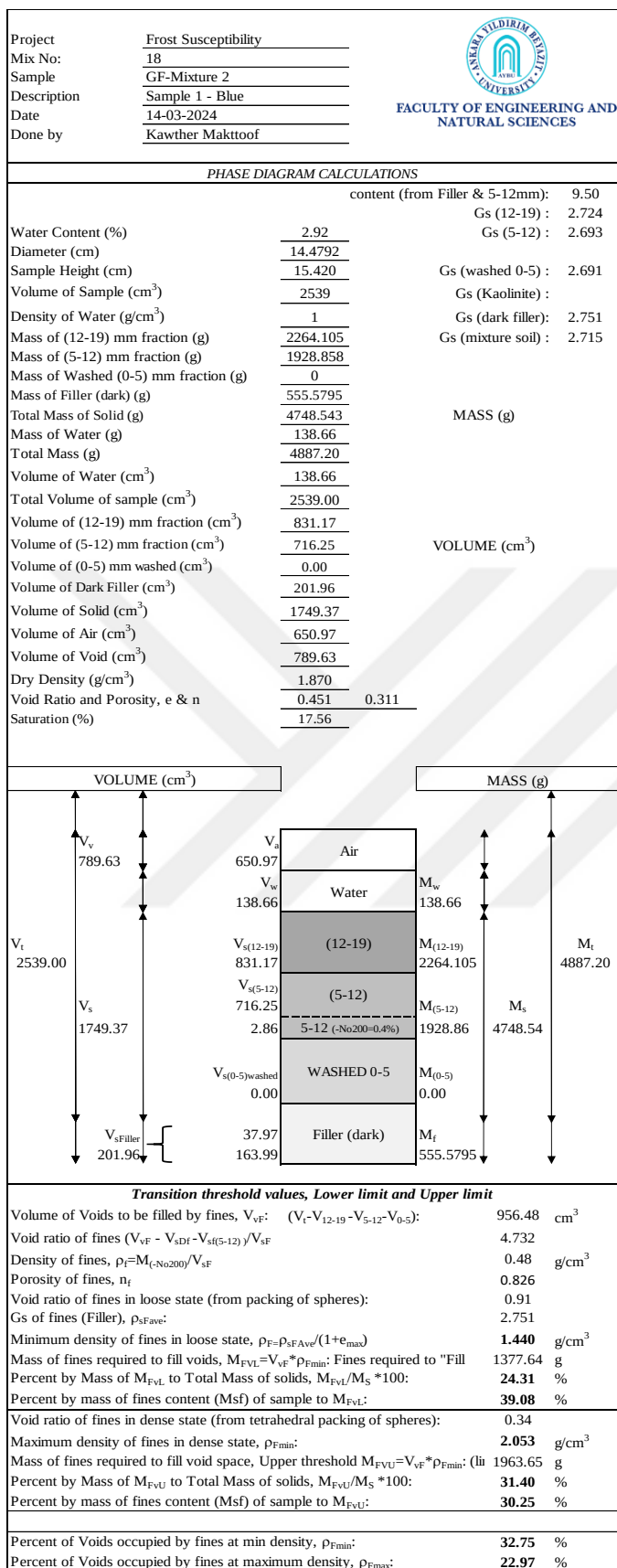
SOIL CLASSIFICATION
USCS: GP-GM
AASHTO: A-1-a(0)
RSOS: G(G)

DATA: END OF FS TESTING
Weight of can, Top: 49.49
weight of can+ wet sample, Top: 396.15
weight of can+ dry sample, Top: 383.17
Weight of can, Bottom: 1273.6
weight of can+ wet sample, Bottom: 5720.8
weight of can+ dry sample, Bottom: 5537.2
Final water content, Top: 3.89
Final water content, Bottom: 4.31
Final water content, Average: 4.28

Residual heave (Di-Df), ΔHfinal: 0.6

Fines Threshold Metrics		
Loose State: e _{max} =0.91 and n _{max} = 0.476		0.476
Dense State: e _{min} = 0.34 and n _{min} =0.254		0.254
void ratio of coarse grains (G & S), e _c = V _v /(V _{sGravel} + V _{sSand}):		0.517
Porosity of coarse grains (G & S), n _c :		0.341
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :		21.32
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :		27.86
water content of fines:		36.97

Figure A. 68 Phase Diagram for "17_GF Mix 1-Green"



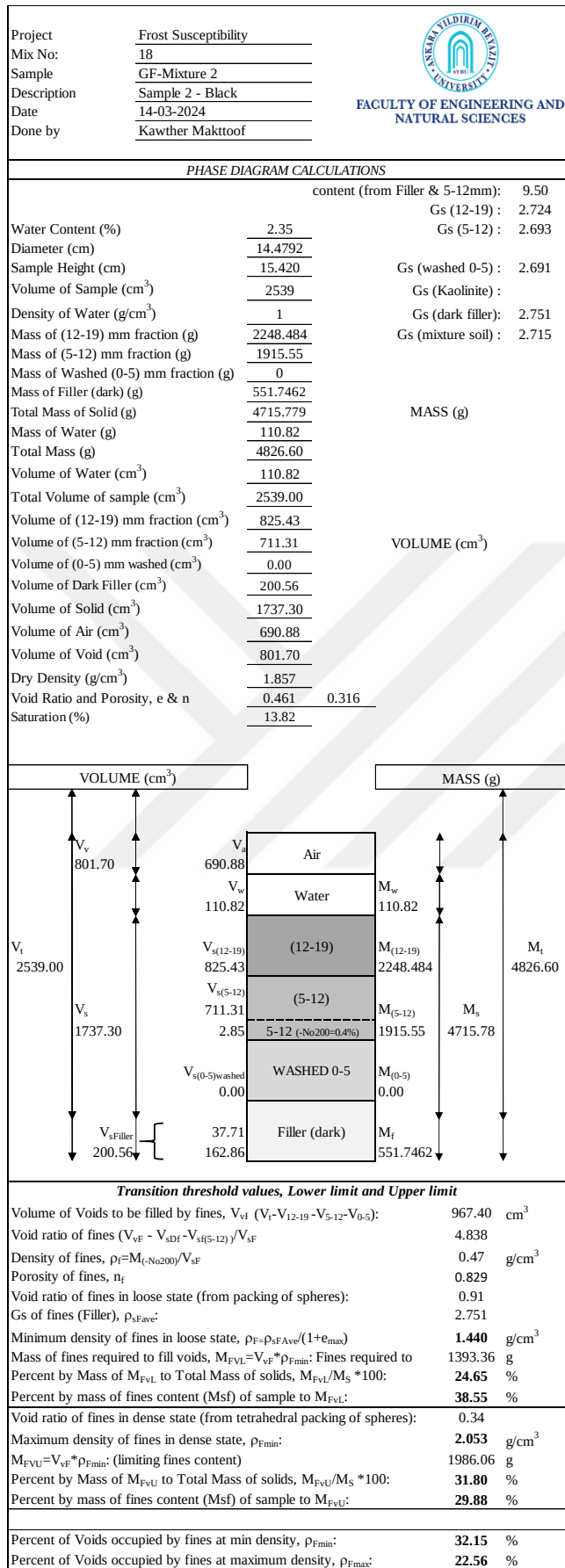
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	47.68
% of (5-12) mm fraction:	40.62
% of Washed (0-5) mm fraction:	0
% of dark Filler	11.7

SOIL CLASSIFICATION	
USCS:	GP-GM
AASHTO:	A-1-a(0)
RSCS:	G(G)

DATA: END OF FS TESTING	
Weight of can, Top:	47.39
weight of can+ wet sample, Top:	417.05
weight of can+ dry sample, Top:	404.09
Weight of can, Bottom:	1102.1
weight of can+ wet sample, Bottom:	5876.4
weight of can+ dry sample, Bottom:	5478.6
Final water content, Top:	3.63
Final water content, Bottom:	9.09
Final water content, Average:	8.68
Residual heave (Di-Df), ΔH_{final} :	0.23

Fines Threshold Values	
Average Lower Limit Threshold (%):	24.7
Average Upper Limit Threshold(%):	31.8
Fines Content, M_{sf}/M_s (%):	9.50
Avg. % of Void space occupied by fines at min density, P_{fmin} (%):	32.1
Avg.% of Void space occupied by fines at maximum density, P_{fmax} (%):	22.5
Average Void ratio of fines of mixture:	4.851
Avg. porosity of fines of mixture, for non-plastic filler (from stacking of spheres):	0.829
Loose State: $e_{fmax}=0.91$ and $n_{fmax} = 0.476$	0.476
Dense State: $e_{fmin} = 0.34$ and $n_{fmin}=0.254$	0.254
Void ratio of coarse grains (G & S), $e_C = V_v/V_{sGravel} + V_{sSand}$:	0.499
Porosity of coarse grains (G & S), n_C :	0.333
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	20.71
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	27.13
water content of fines:	30.22

Figure A. 69 Phase Diagram for "18_GF Mix 2-Blue"



MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 47.68
% of (5-12) mm fraction: 40.62
% of Washed (0-5) mm fraction: 0
% of dark Filler 11.7

SOIL CLASSIFICATION
USCS: GP-GM
AASHTO: A-1-a(0)
RSCS: G(G)

DATA: END OF FS TESTING
Weight of can, Top: 49.66
weight of can+ wet sample, Top: 413.2
weight of can+ dry sample, Top: 388.93
Weight of can, Bottom: 1095.3
weight of can+ wet sample, Bottom: 5824.1
weight of can+ dry sample, Bottom: 5434
Final water content, Top: 7.15
Final water content, Bottom: 8.99
Final water content, Average: 8.86
Residual heave (Di-Df), ΔH_{final} : 0.45

Fines Threshold Metrics
Loose State: $e_{fmax} = 0.91$ and $n_{fmax} = 0.476$
Dense State: $e_{fmin} = 0.34$ and $n_{fmin} = 0.254$
void ratio of coarse grains (G & S), $e_c = V_v / (V_{sGravel} + V_{sSand})$: 0.510
Porosity of coarse grains (G & S), n_c : 0.338
Amount of fines in loose state required to fill the pore space of coarser structure, 21.08
Amount of fines in dense state required to fill the pore space of coarser structure, 27.57
water content of fines: 24.32

Figure A. 70 Phase Diagram for "18_GF Mix 2-Black"

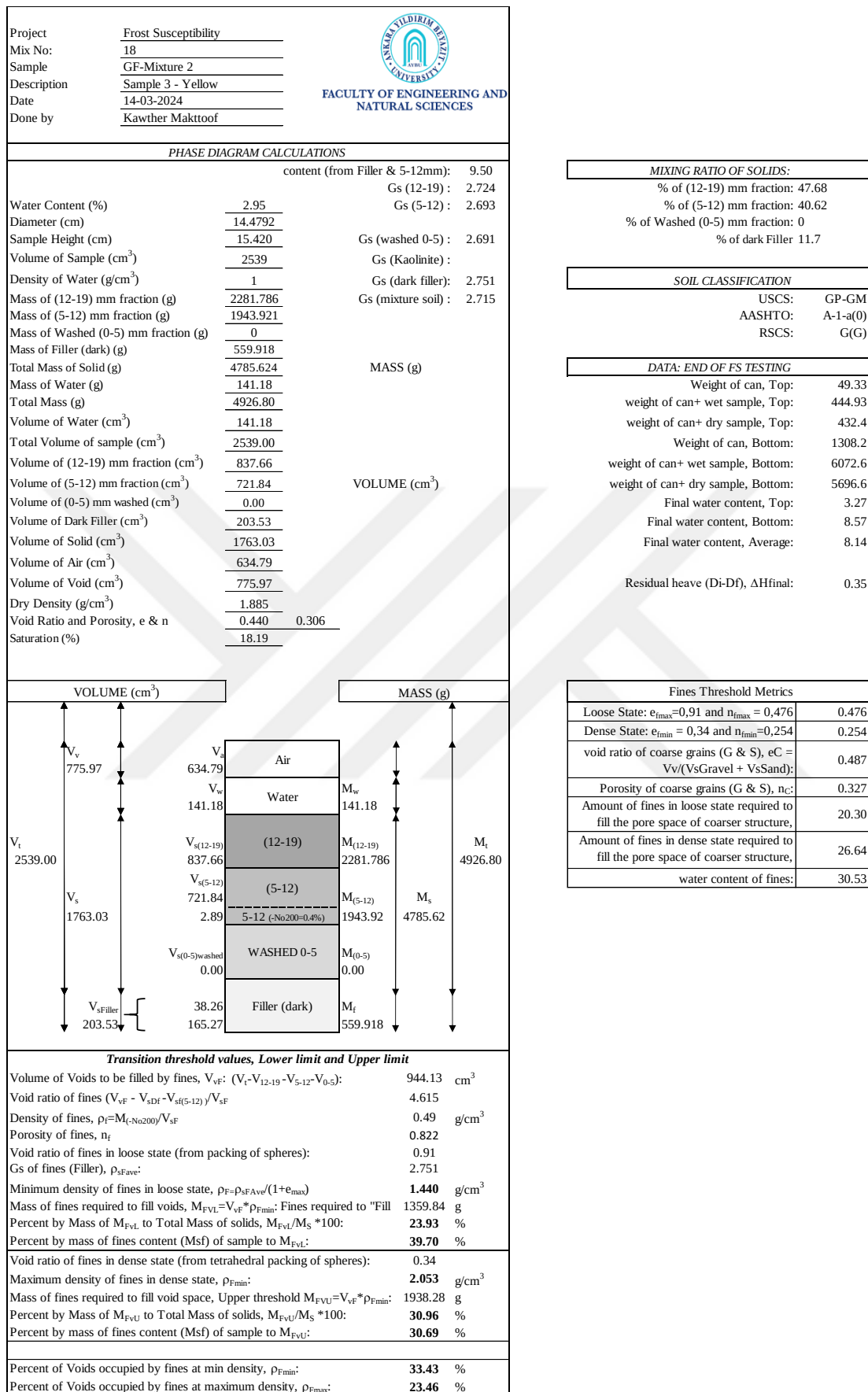


Figure A. 71 Phase Diagram for "18_GF Mix 2-Yellow"

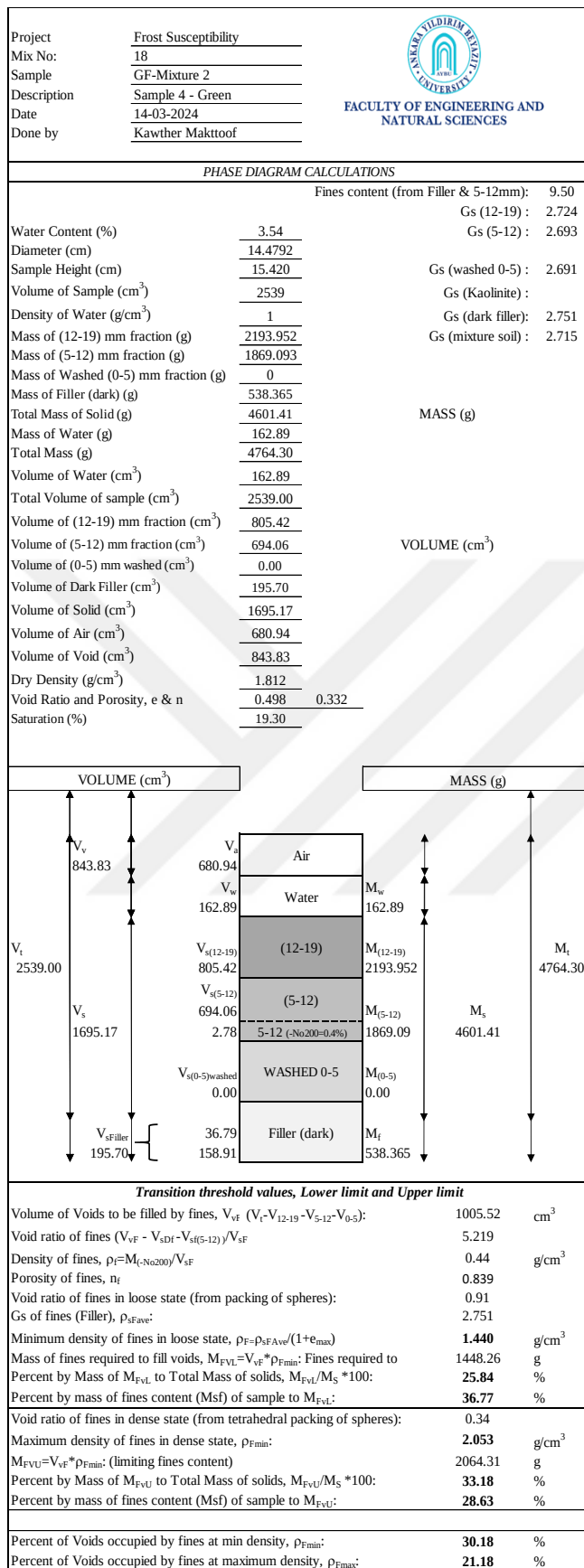
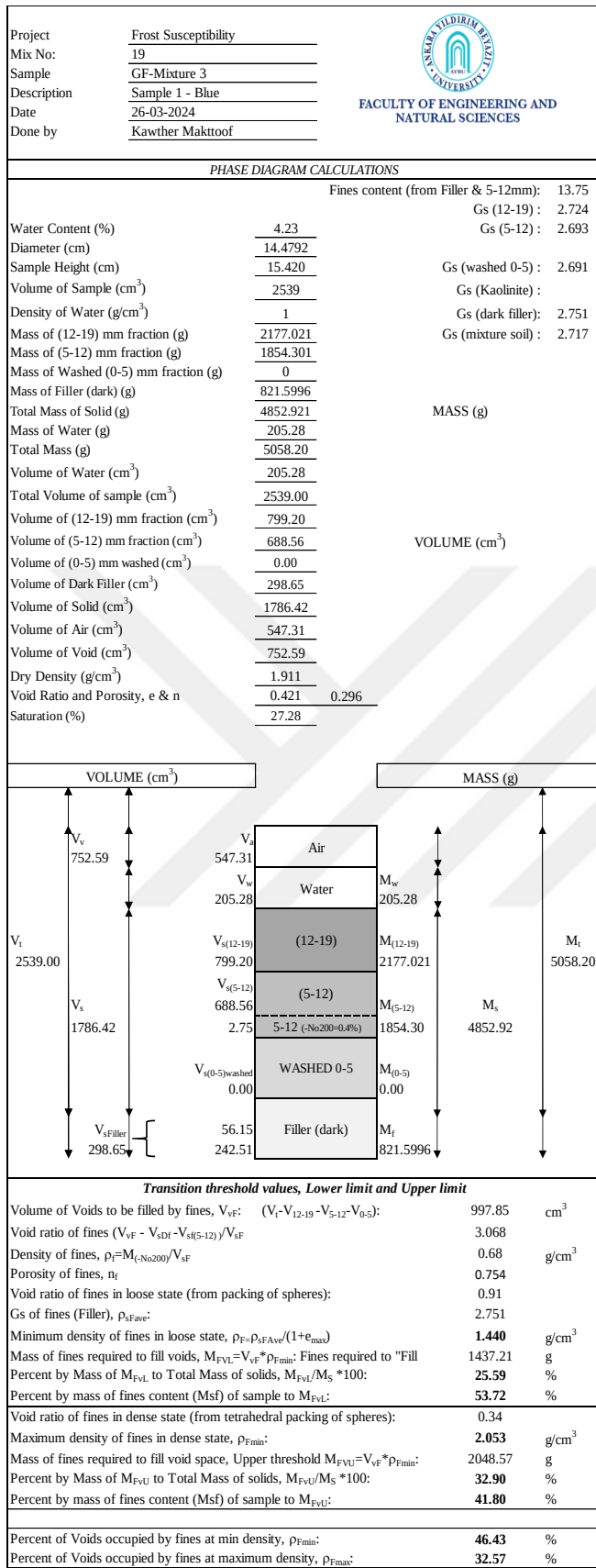


Figure A. 72 Phase Diagram for "18_GF Mix 2-Green"



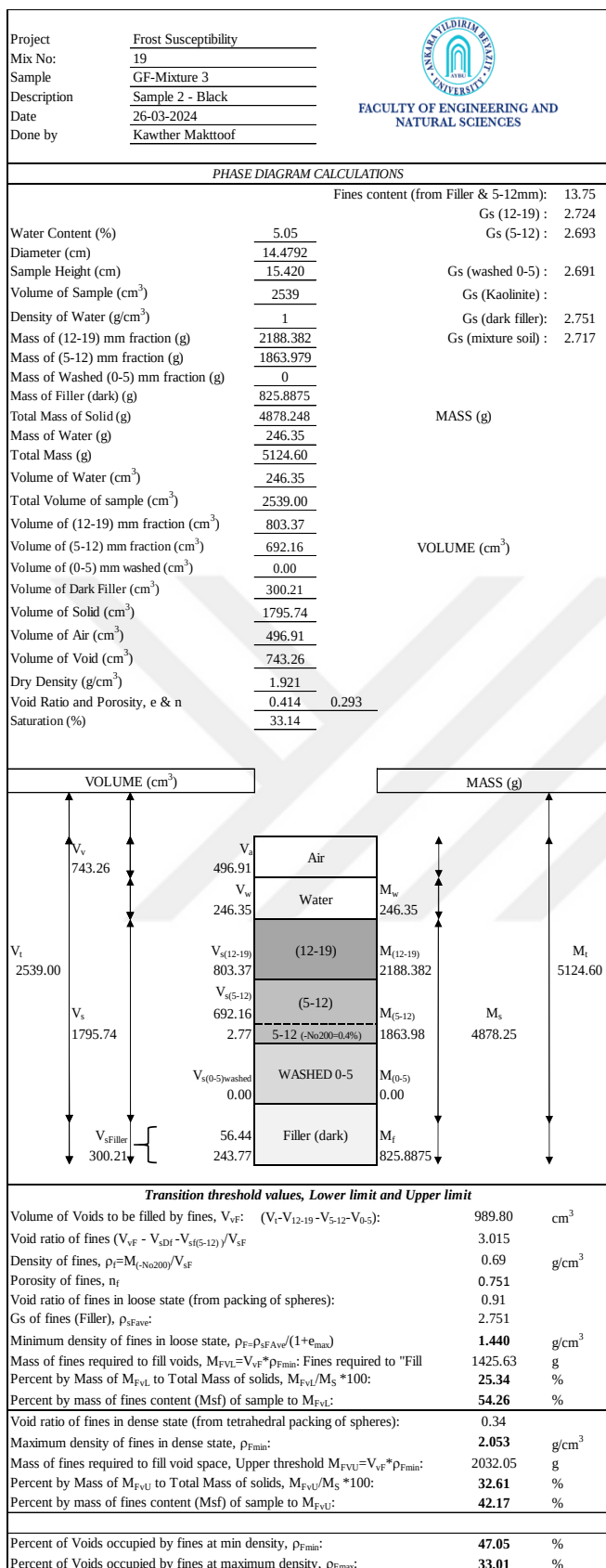
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	44.86
% of (5-12) mm fraction:	38.21
% of Washed (0-5) mm fraction:	0
% of dark Filler	16.93

SOIL CLASSIFICATION	
USCS:	GM
AASHTO:	A-1-a(0)
RSCS:	G(G)

DATA: END OF FS TESTING	
Weight of can, Top:	47.37
weight of can+ wet sample, Top:	428.76
weight of can+ dry sample, Top:	397.05
Weight of can, Bottom:	1099.1
weight of can+ wet sample, Bottom:	6000.6
weight of can+ dry sample, Bottom:	5557.5
Final water content, Top:	9.07
Final water content, Bottom:	9.94
Final water content, Average:	9.88
Residual heave (Di-Df), ΔHfinal:	0.9

Fines Threshold Values	
Average Lower Limit Threshold (%):	25.5
Average Upper Limit Threshold(%):	32.8
Fines Content, M _{sf} /M _s (%):	13.75
Avg. % of Void space occupied by fines at min density, P _{fmin} (%):	46.6
Avg.% of Void space occupied by fines at maximum density, P _{fmax} (%):	32.7
Average Void ratio of fines of mixture:	3.050
Avg. porosity of fines of mixture, for non-plastic filler (from stacking of spheres):	0.753
Loose State: e _{fmax} =0.91 and n _{fmax} =0.476	0.476
Dense State: e _{fmin} =0.34 and n _{fmin} =0.254	0.254
void ratio of coarse grains (G & S), e _c = V _v /(V _{sGravel} + V _{sSand}):	0.488
Porosity of coarse grains (G & S), n _c :	0.328
Amount of fines in loose state required to fill the pore space of coarser structure,	20.36
Amount of fines in dense state required to fill the pore space of coarser structure,	26.71
water content of fines:	30.43

Figure A. 73 Phase Diagram for "19_GF Mix 3-Blue"



MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	44.86
% of (5-12) mm fraction:	38.21
% of Washed (0-5) mm fraction:	0
% of dark Filler	16.93

SOIL CLASSIFICATION	
USCS:	GM
AASHTO:	A-1-a(0)
RSCS:	G(G)

DATA: END OF FS TESTING	
Weight of can, Top:	54.16
weight of can+ wet sample, Top:	478.68
weight of can+ dry sample, Top:	446.87
Weight of can, Bottom:	1317
weight of can+ wet sample, Bottom:	6420.5
weight of can+ dry sample, Bottom:	5862
Final water content, Top:	8.10
Final water content, Bottom:	12.29
Final water content, Average:	11.96
Residual heave (Di-Df), ΔH_{final} :	1.37

Fines Threshold Metrics	
Loose State: $e_{fmax}=0.91$ and $n_{fmax}=0.476$	0.476
Dense State: $e_{fmin}=0.34$ and $n_{fmin}=0.254$	0.254
void ratio of coarse grains (G & S), $e_c = V_v/(V_{sGravel} + V_{sSand})$:	0.480
Porosity of coarse grains (G & S), n_c :	0.324
Amount of fines in loose state required to fill the pore space of coarser structure, % F_v :	20.08
Amount of fines in dense state required to fill the pore space of coarser structure, % F_v :	26.36
water content of fines:	36.33

Figure A. 74 Phase Diagram for "19_GF Mix 3-Black"

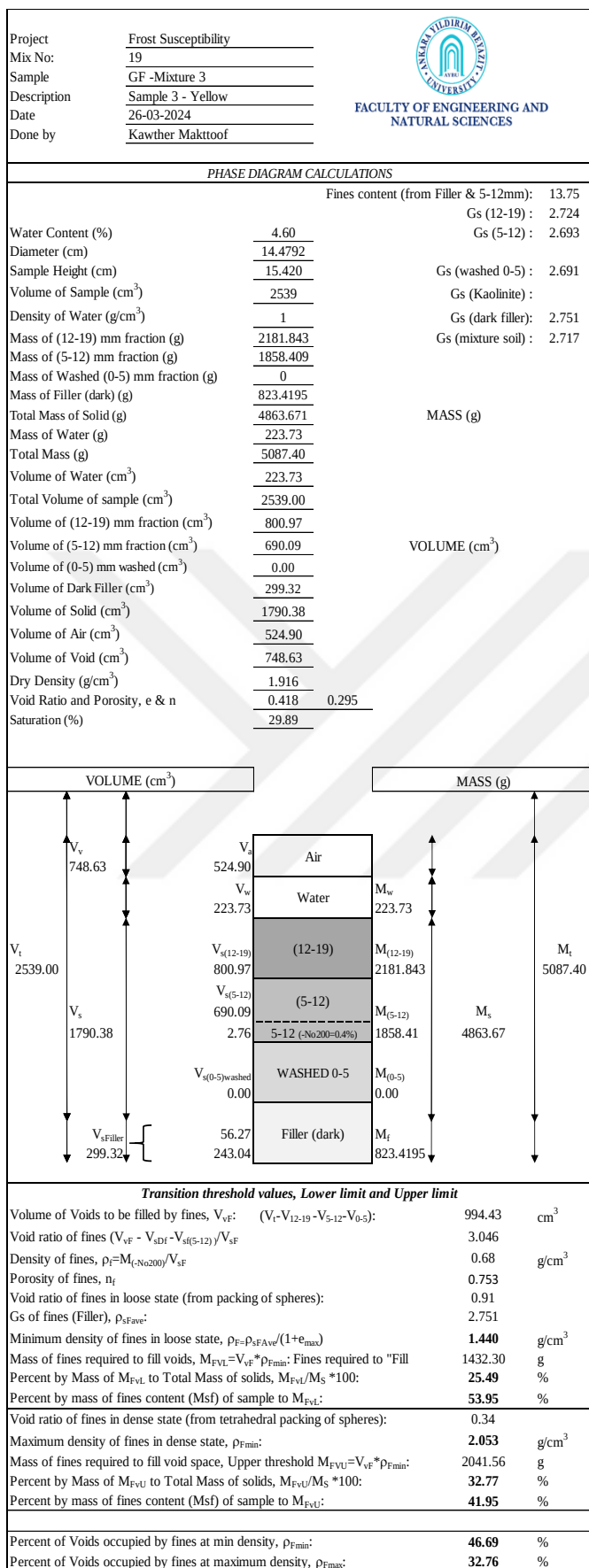
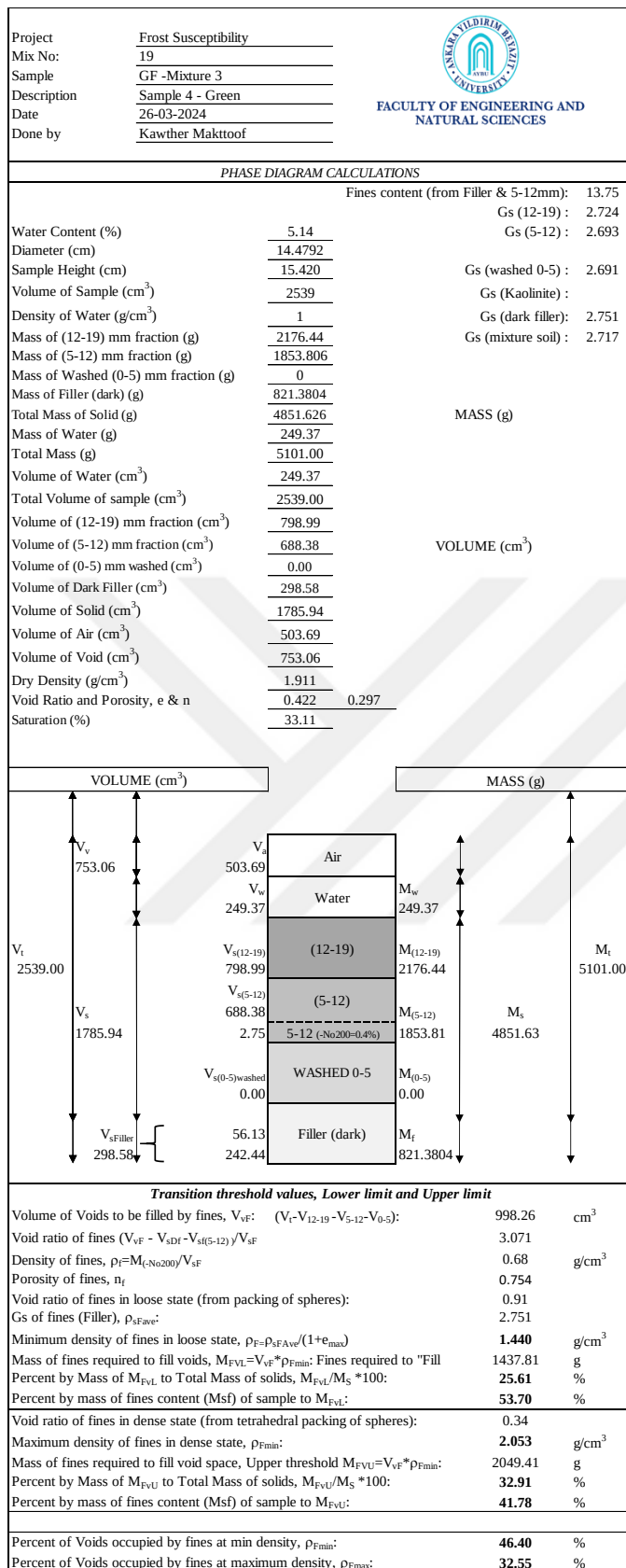


Figure A. 75 Phase Diagram for "19_GF Mix 3-Yellow"



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction:	44.86
% of (5-12) mm fraction:	38.21
% of Washed (0-5) mm fraction:	0
% of dark Filler	16.93

SOIL CLASSIFICATION

USCS:	GM
AASHTO:	A-1-a(0)
RSCS:	G(G)

DATA: END OF FS TESTING

Weight of can, Top:	47.68
weight of can+ wet sample, Top:	424.3
weight of can+ dry sample, Top:	397.25
Weight of can, Bottom:	1274.6
weight of can+ wet sample, Bottom:	6219.5
weight of can+ dry sample, Bottom:	5790.5
Final water content, Top:	7.74
Final water content, Bottom:	9.50
Final water content, Average:	9.37
Residual heave (Di-Df), ΔHfinal:	0.6

Fines Threshold Metrics

Loose State: e _{tmax} =0.91 and n _{tmax} = 0.476	0.476
Dense State: e _{tmin} = 0.34 and n _{tmin} =0.254	0.254
void ratio of coarse grains (G & S), e _c = V _v /(V _{sGravel} + V _{sSand}):	0.489
Porosity of coarse grains (G & S), n _c :	0.328
Amount of fines in loose state required to fill the pore space of coarser structure,	20.38
Amount of fines in dense state required to fill the pore space of coarser structure,	26.73
water content of fines:	36.98

Figure A. 76 Phase Diagram for "19_GF Mix 3-Green"

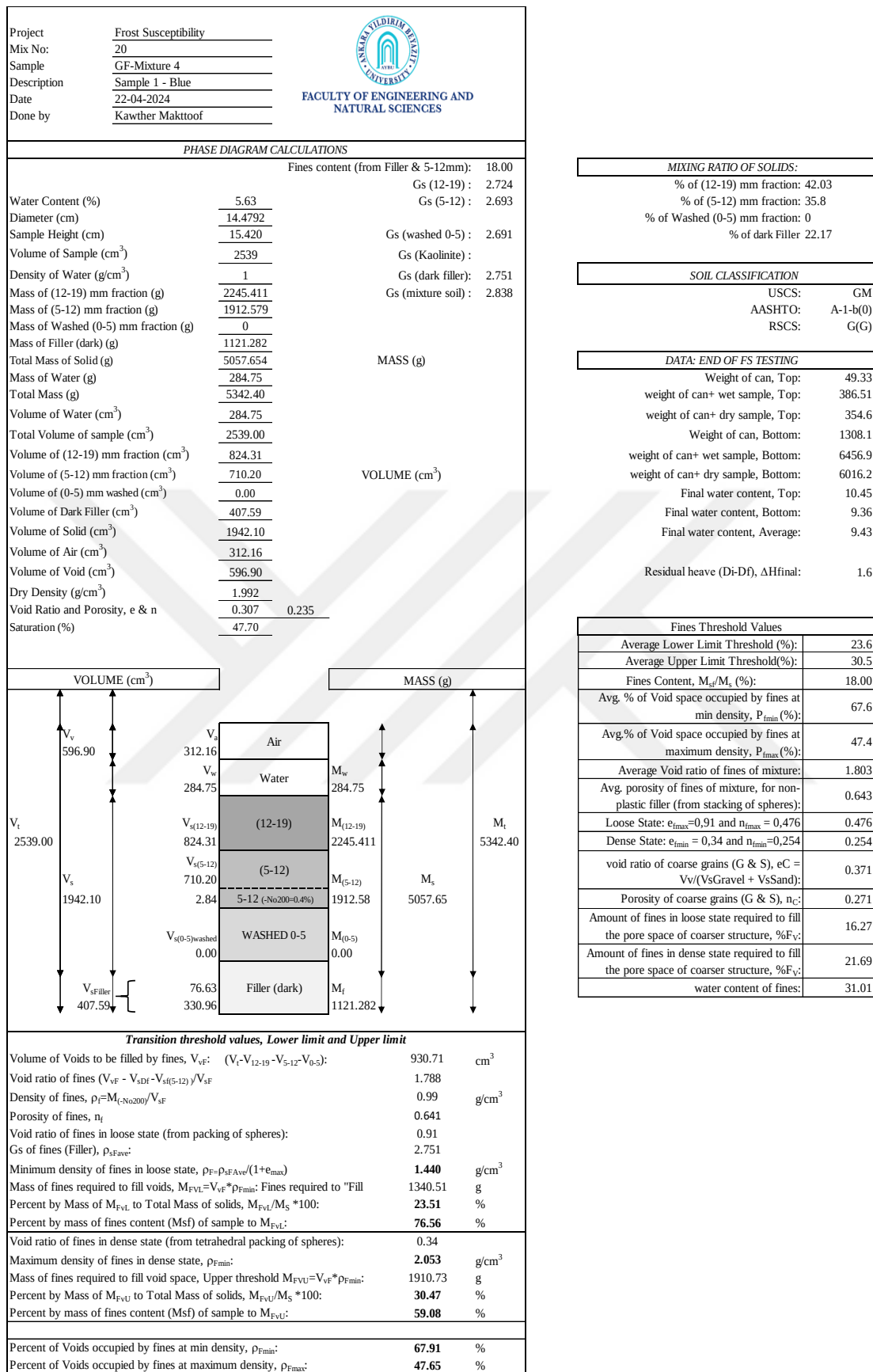


Figure A. 77 Phase Diagram for “20_GF Mix 4-Blue”

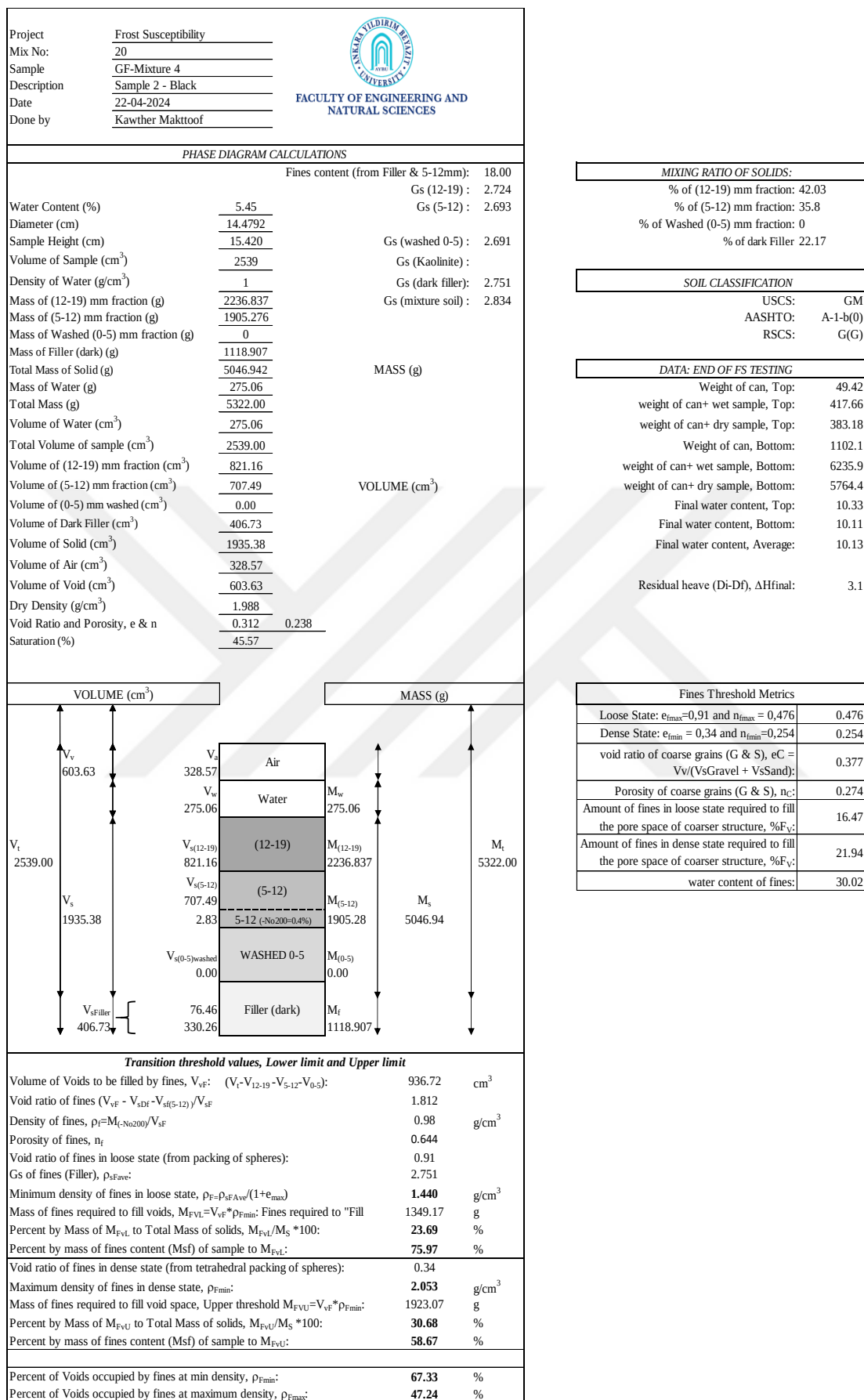
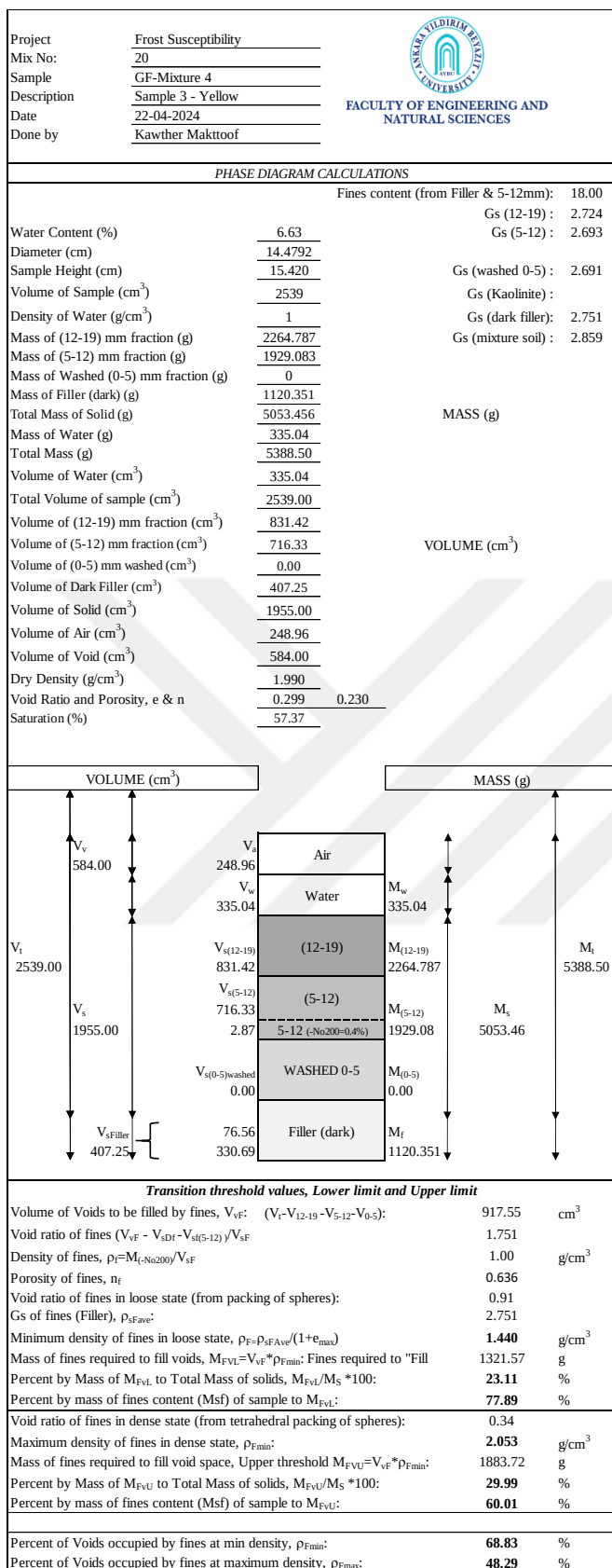


Figure A. 78 Phase Diagram for "20_GF Mix 4-Black"



MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	42.03
% of (5-12) mm fraction:	35.8
% of Washed (0-5) mm fraction:	0
% of dark Filler	22.17

SOIL CLASSIFICATION	
USCS:	GM
AASHTO:	A-1-b(0)
RSCS:	G(G)

DATA: END OF FS TESTING	
Weight of can, Top:	46.63
weight of can+ wet sample, Top:	347.09
weight of can+ dry sample, Top:	317.98
Weight of can, Bottom:	1068.3
weight of can+ wet sample, Bottom:	6281.1
weight of can+ dry sample, Bottom:	5835.2
Final water content, Top:	10.73
Final water content, Bottom:	9.35
Final water content, Average:	9.43
Residual heave (Di-Df), ΔHfinal:	1.69

Fines Threshold Metrics	
Loose State: e _{fmax} =0.91 and n _{fmax} = 0.476	0.476
Dense State: e _{fmin} = 0.34 and n _{fmin} =0.254	0.254
void ratio of coarse grains (G & S), e _C = V _v /(V _{sGravel} + V _{sSand}):	0.360
Porosity of coarse grains (G & S), n _C :	0.265
Amount of fines in loose state required to fill the pore space of coarser structure, %F _V :	15.87
Amount of fines in dense state required to fill the pore space of coarser structure, %F _V :	21.18
water content of fines:	36.52

Figure A. 79 Phase Diagram for “20_GF Mix 4-Yellow”

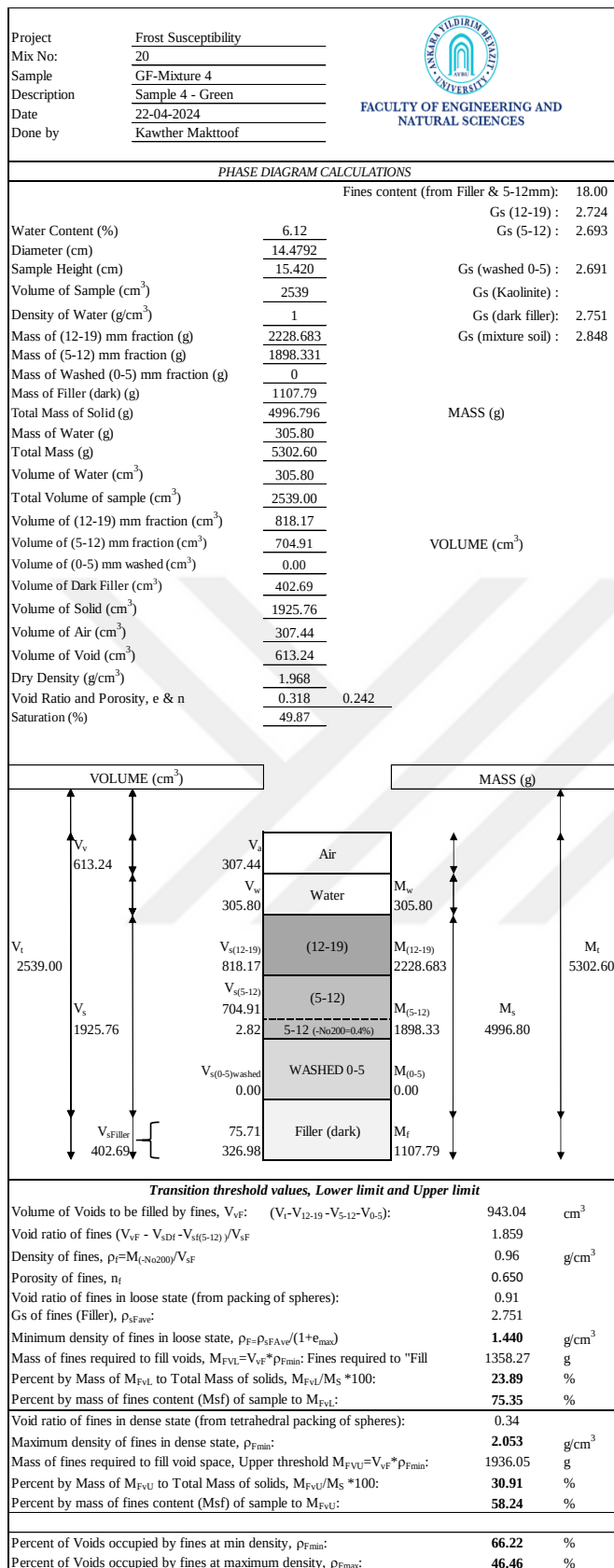
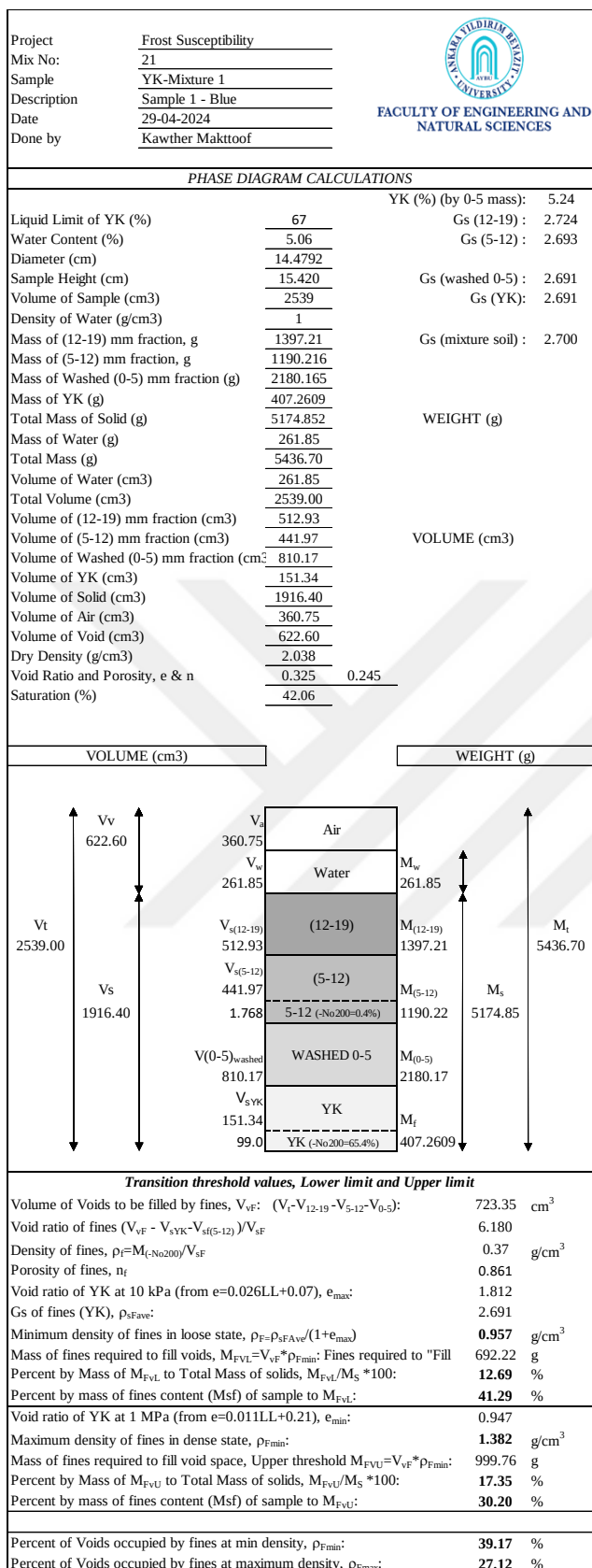


Figure A. 80 Phase Diagram for "20_GF Mix 4-Green"



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction: 27
% of (5-12) mm fraction: 23
% of Washed (0-5) mm fraction: 42.13
% of YK 7.87

SOIL CLASSIFICATION

USCS:	GP-GC
AASHTO:	A-2-7(0)
RSCS:	GS(F) where fines are LI

DATA: END OF FS TESTING

Weight of can, Top:	51.99
weight of can+ wet sample, Top:	357.21
weight of can+ dry sample, Top:	334.95
Weight of can, Bottom:	1099.3
weight of can+ wet sample, Bottom:	6348.3
weight of can+ dry sample, Bottom:	5948.7
Final water content, Top:	7.87
Final water content, Bottom:	8.24
Final water content, Average:	8.22
Residual heave (Di-Df), ΔHfinal:	0.83

Fines Threshold Values

Average Lower Limit Threshold (%):	13.1
Average Upper Limit Threshold(%):	17.9
Fines Content, M _{sf} /M _s (%):	5.24
Avg. % of Void space occupied by fines at min density, P _{fmin} (%):	37.8
Avg.% of Void space occupied by fines at maximum density, P _{fmax} (%):	26.2
Average Void ratio of fines of mixture:	6.439
Average porosity of fines of mixture:	0.865
Loose State:	0.644
Dense State:	0.486
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.343
Porosity of coarse grains (G & S), n _C :	0.255
Amount of fines in loose state required to fill the pore space of coarser structure, %F _V :	10.87
Amount of fines in dense state required to fill the pore space of coarser structure, %F _V :	14.97
Water content of fines:	96.58

Figure A. 81 Phase Diagram for "21_YK Mix 1-Blue"

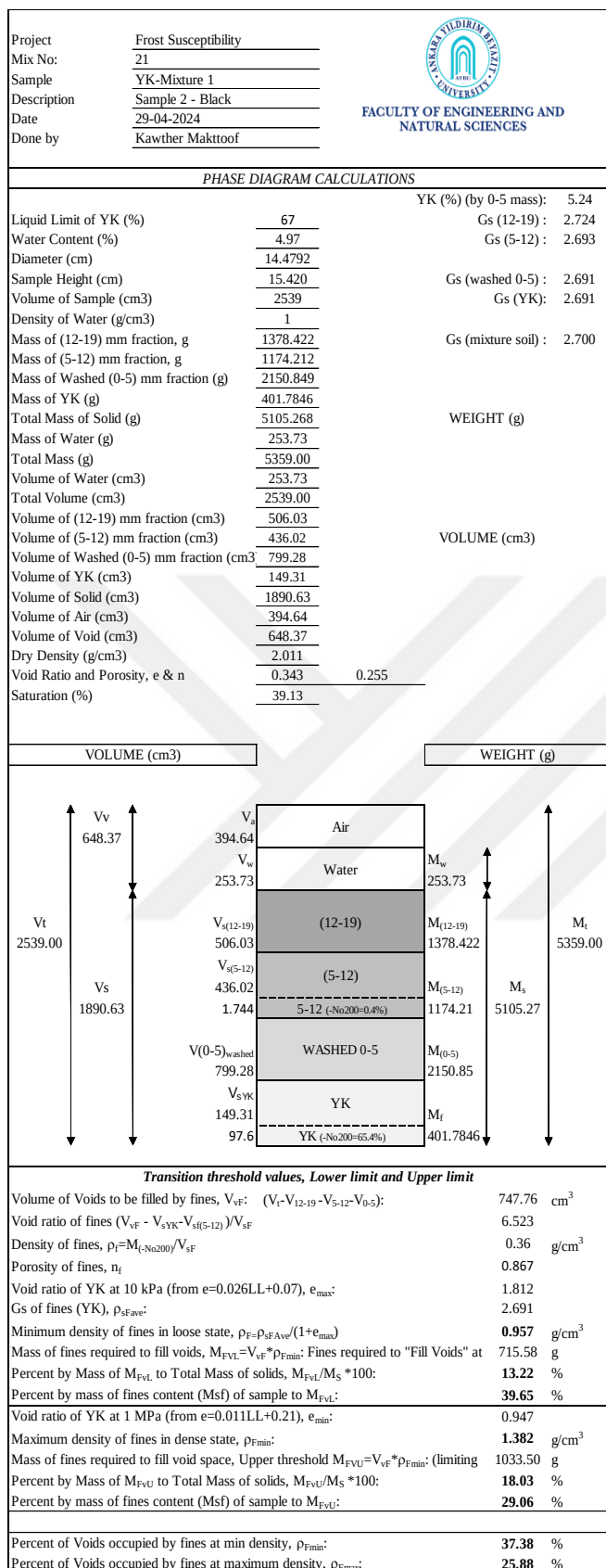


Figure A. 82 Phase Diagram for "21_YK Mix 1-Black"

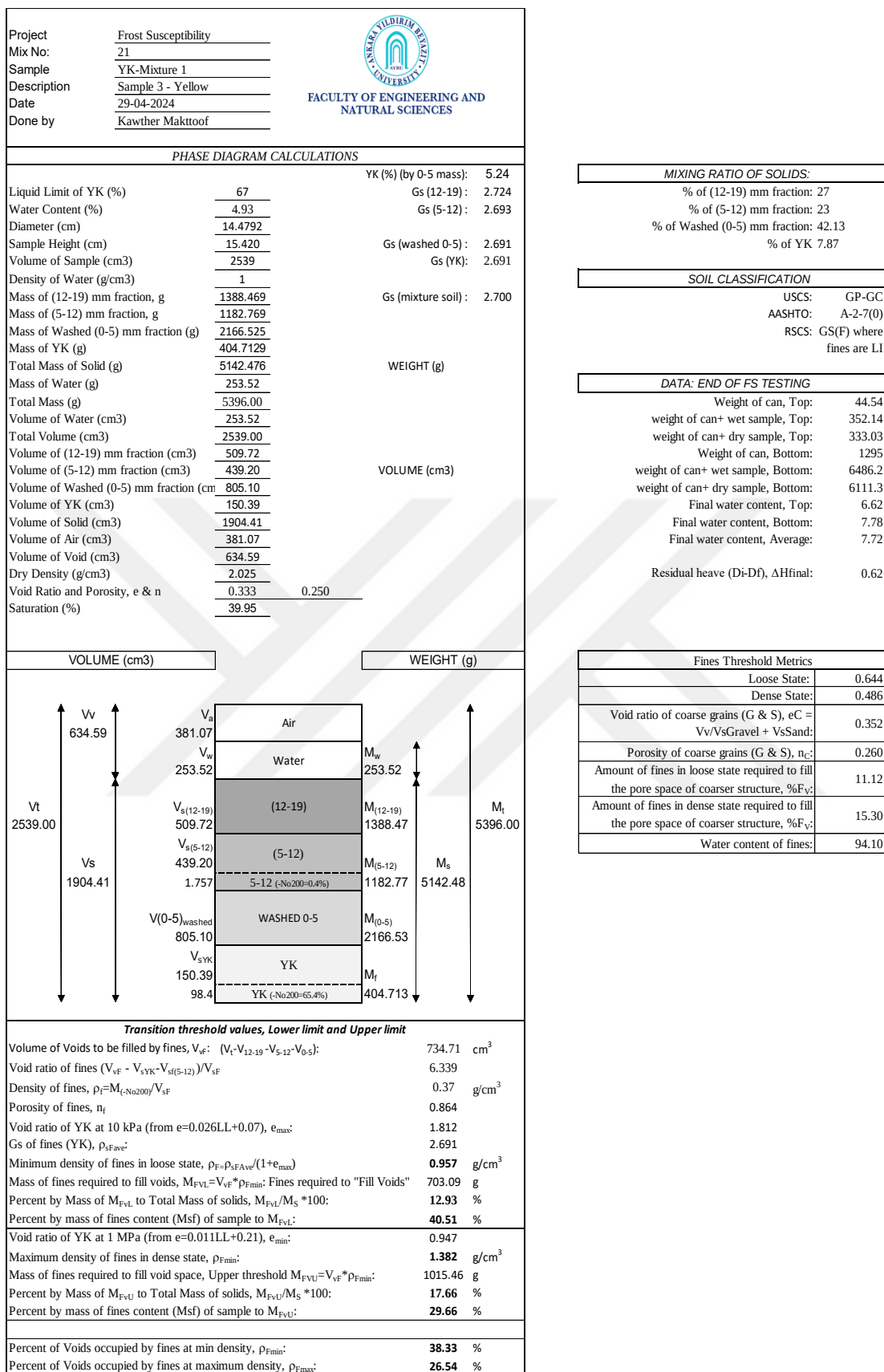


Figure A. 83 Phase Diagram for “21_YK Mix 1-Yellow”

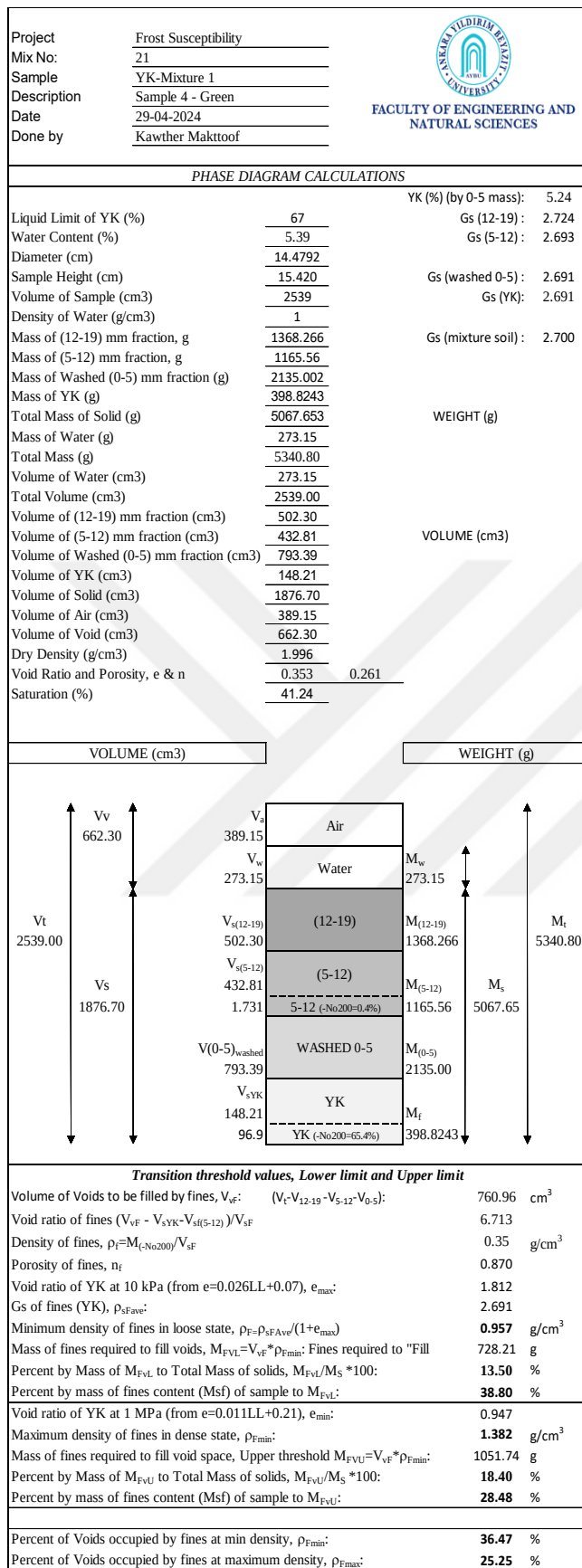
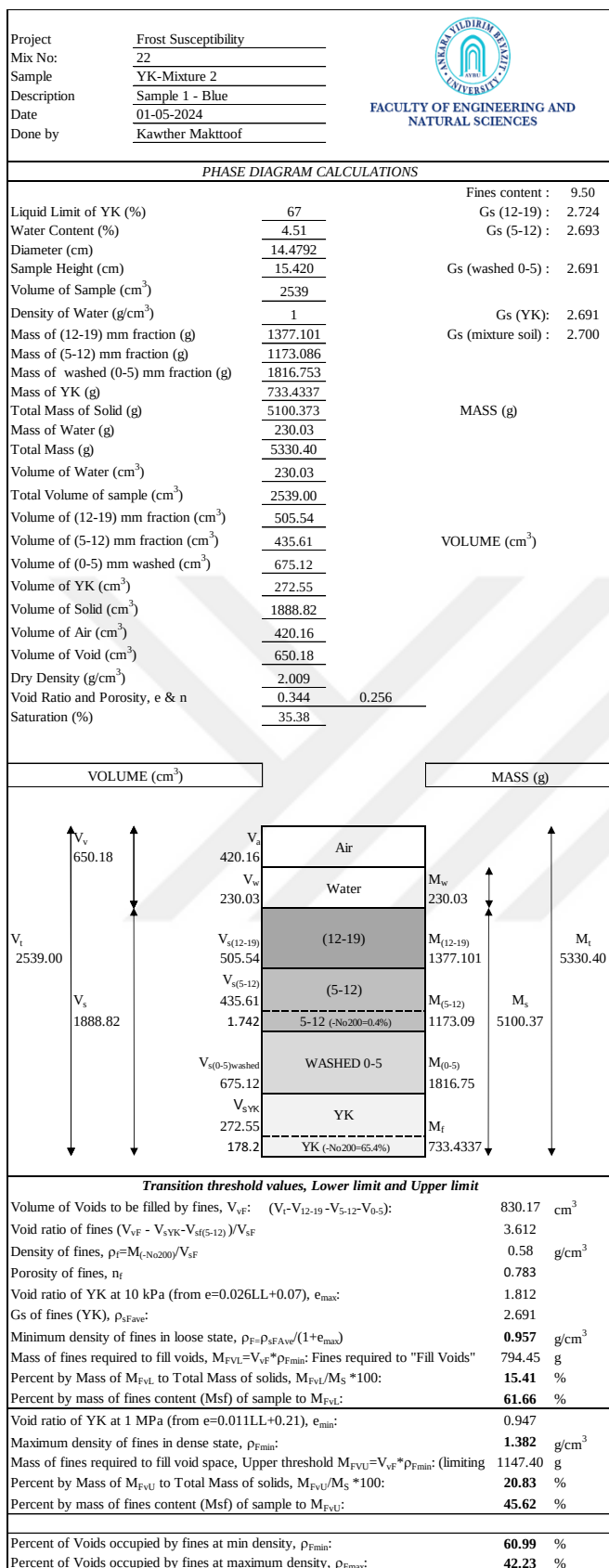


Figure A. 84 Phase Diagram for "21_YK Mix 1-Green"



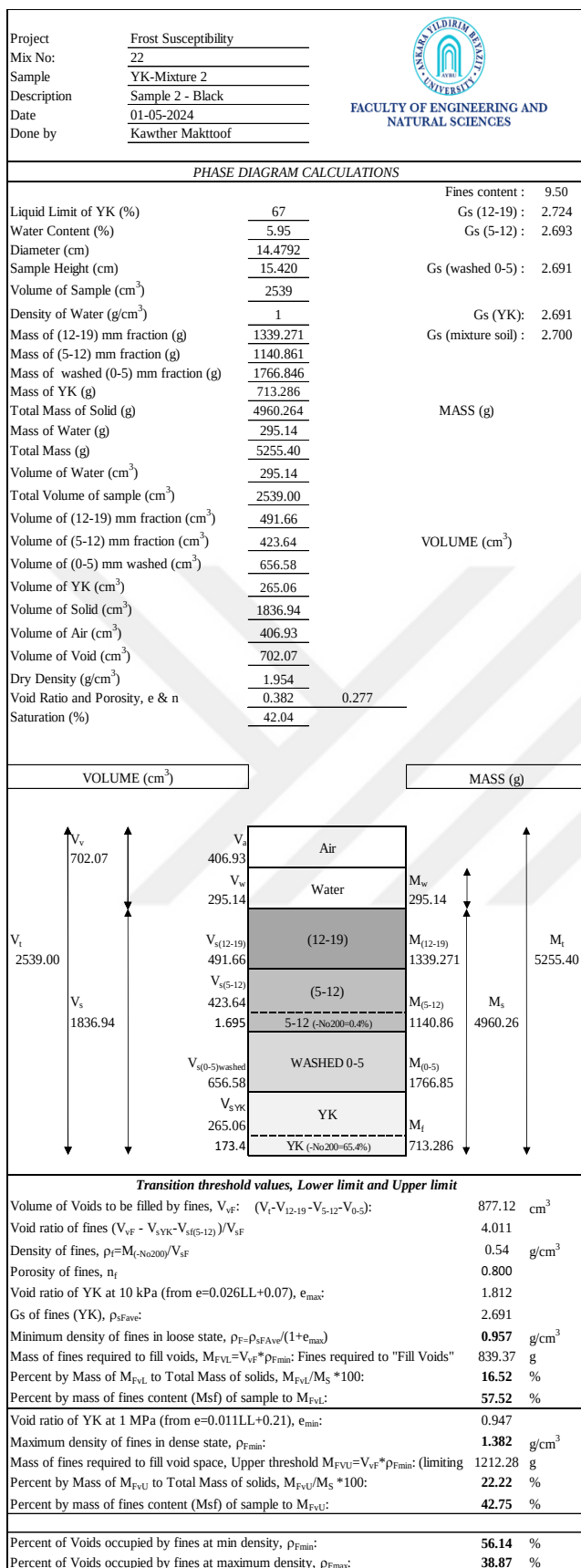
MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 27
% of (5-12) mm fraction: 23
% of Washed (0-5) mm fraction: 35.62
% of YK 14.38

SOIL CLASSIFICATION
USCS: GP-GC
AASHTO: A-2-7(0)
USCS: GSF(F) where fines are LI

DATA: END OF FS TESTING
Weight of can, Top: 44.62
weight of can+ wet sample, Top: 416.5
weight of can+ dry sample, Top: 384.16
Weight of can, Bottom: 1305.4
weight of can+ wet sample, Bottom: 6407.8
weight of can+ dry sample, Bottom: 5993.3
Final water content, Top: 9.52
Final water content, Bottom: 8.84
Final water content, Average: 8.89
Residual heave (Di-Df), ΔHfinal: 0.74

Fines Threshold Values
Average Lower Limit Threshold (%): 15.8
Average Upper Limit Threshold(%): 21.3
Fines Content, M _{sf} /M _s (%): 9.50
Avg. % of Void space occupied by fines at min density, P _{fmin} (%): 59.5
Avg.% of Void space occupied by fines at maximum density, P _{fmax} (%): 41.2
Average Void ratio of fines of mixture: 3.740
Average porosity of fines of mixture: 0.788
Loose State: 0.644
Dense State: 0.486
Void ratio of coarse grains (G & S), eC = V _v /V _{sGravel} + V _{sSand} : 0.380
Porosity of coarse grains (G & S), n _c : 0.276
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v : 11.92
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v : 16.35
Water content of fines: 47.49

Figure A. 85 Phase Diagram for "22_YK Mix 2-Blue"



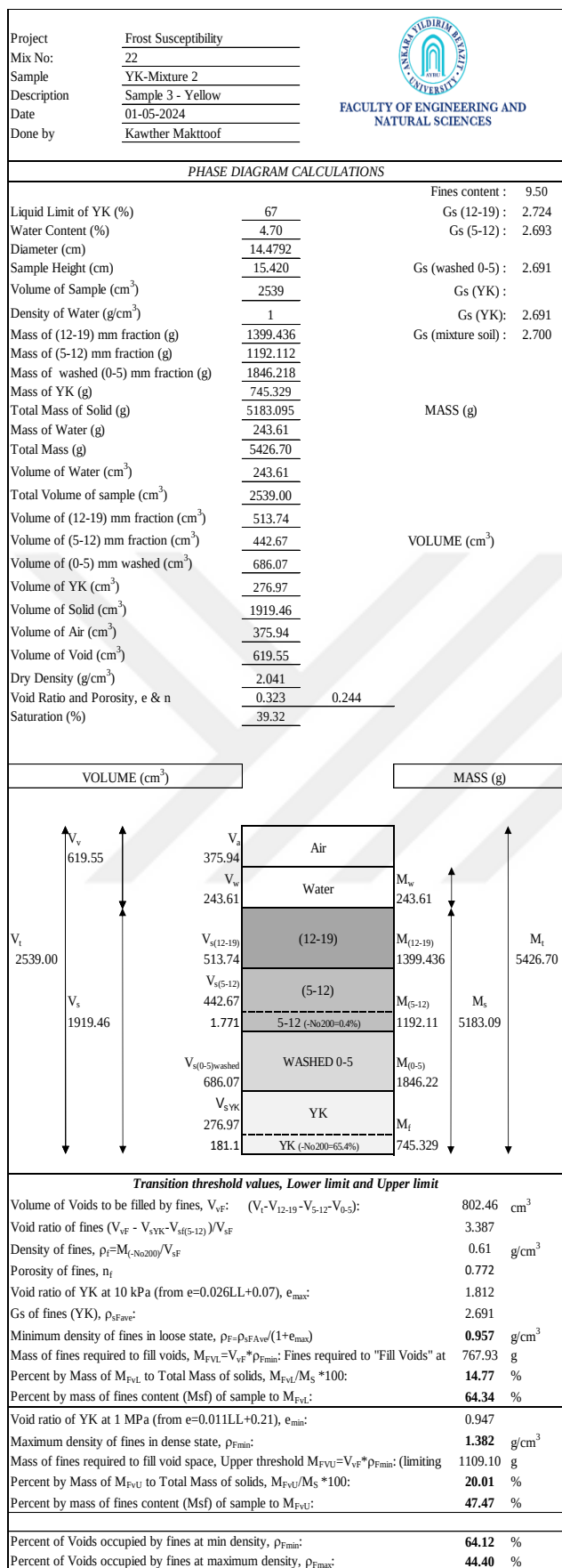
MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	35.62
% of YK	14.38

SOIL CLASSIFICATION	
USCS:	GP-GC
AASHTO:	A-2-7(0)
RSCS:	GSF(F) where fines are LI

DATA: END OF FS TESTING	
Weight of can, Top:	50.36
weight of can+ wet sample, Top:	376.07
weight of can+ dry sample, Top:	365.05
Weight of can, Bottom:	1296.9
weight of can+ wet sample, Bottom:	6344
weight of can+ dry sample, Bottom:	5923.5
Final water content, Top:	3.50
Final water content, Bottom:	9.09
Final water content, Average:	8.73
Residual heave (Di-Df), ΔHfinal:	0.4

Fines Threshold Metrics	
Loose State:	0.644
Dense State:	0.486
Void ratio of coarse grains (G & S), e _C = V _v /V _{sGravel} + V _{sSand} :	0.422
Porosity of coarse grains (G & S), n _C :	0.297
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	13.06
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	17.83
Water content of fines:	62.65

Figure A. 86 Phase Diagram for "22_YK Mix 2-Black"



MIXING RATIO OF SOLIDS:

% of (12-19) mm fraction: 27
 % of (5-12) mm fraction: 23
 % of Washed (0-5) mm fraction: 35.62
 % of YK 14.38

SOIL CLASSIFICATION

USCS: GP-GC
 AASHTO: A-2-7(0)
 RSCS: GSF(F) where
 fines are LI

DATA: END OF FS TESTING

Weight of can, Top: 47.4
 weight of can+ wet sample, Top: 452.68
 weight of can+ dry sample, Top: 414.46
 Weight of can, Bottom: 1068.2
 weight of can+ wet sample, Bottom: 6250.6
 weight of can+ dry sample, Bottom: 5829.9
 Final water content, Top: 10.41
 Final water content, Bottom: 8.84
 Final water content, Average: 8.95
 Residual heave (Di-Df), ΔH_{final}: 0.75

Fines Threshold Metrics

Loose State:	0.644
Dense State:	0.486
Void ratio of coarse grains (G & S), eC = V _v /V _{sGravel} + V _{sSand} :	0.357
Porosity of coarse grains (G & S), n _c :	0.263
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	11.26
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	15.49
Water content of fines:	49.49

Figure A. 87 Phase Diagram for "22_YK Mix 2-Yellow"

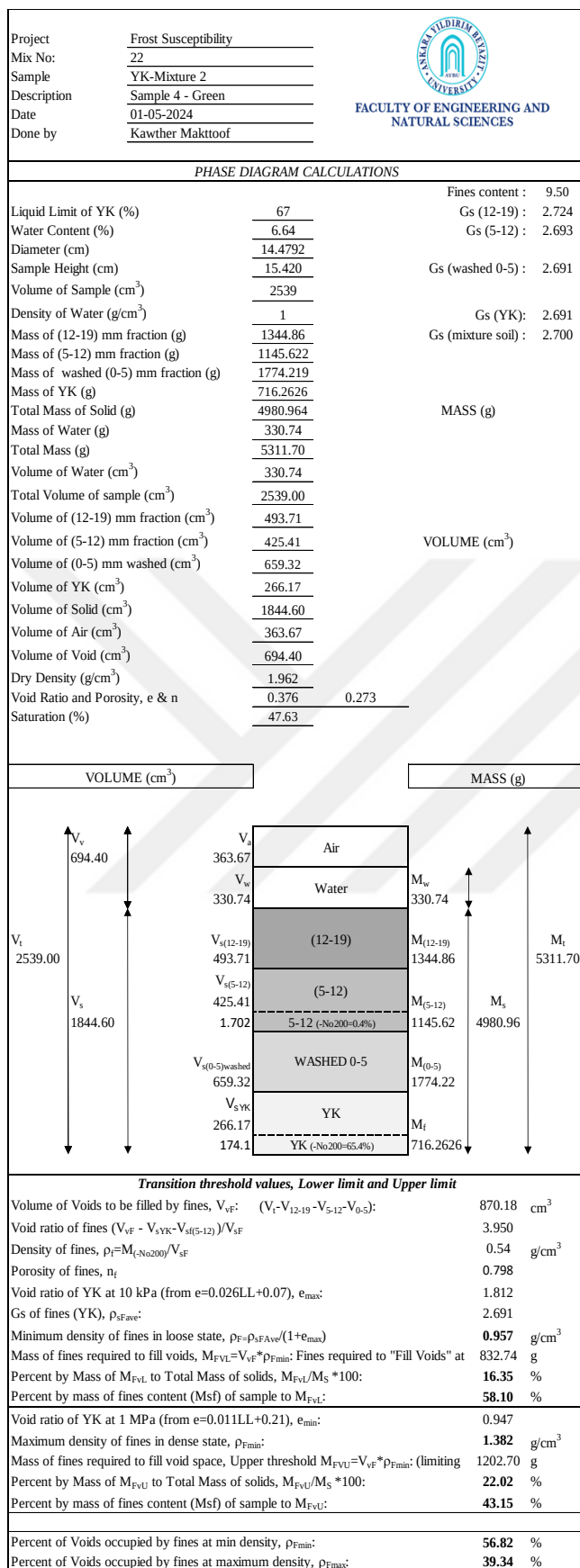


Figure A. 88 Phase Diagram for "22_YK Mix 2-Green"

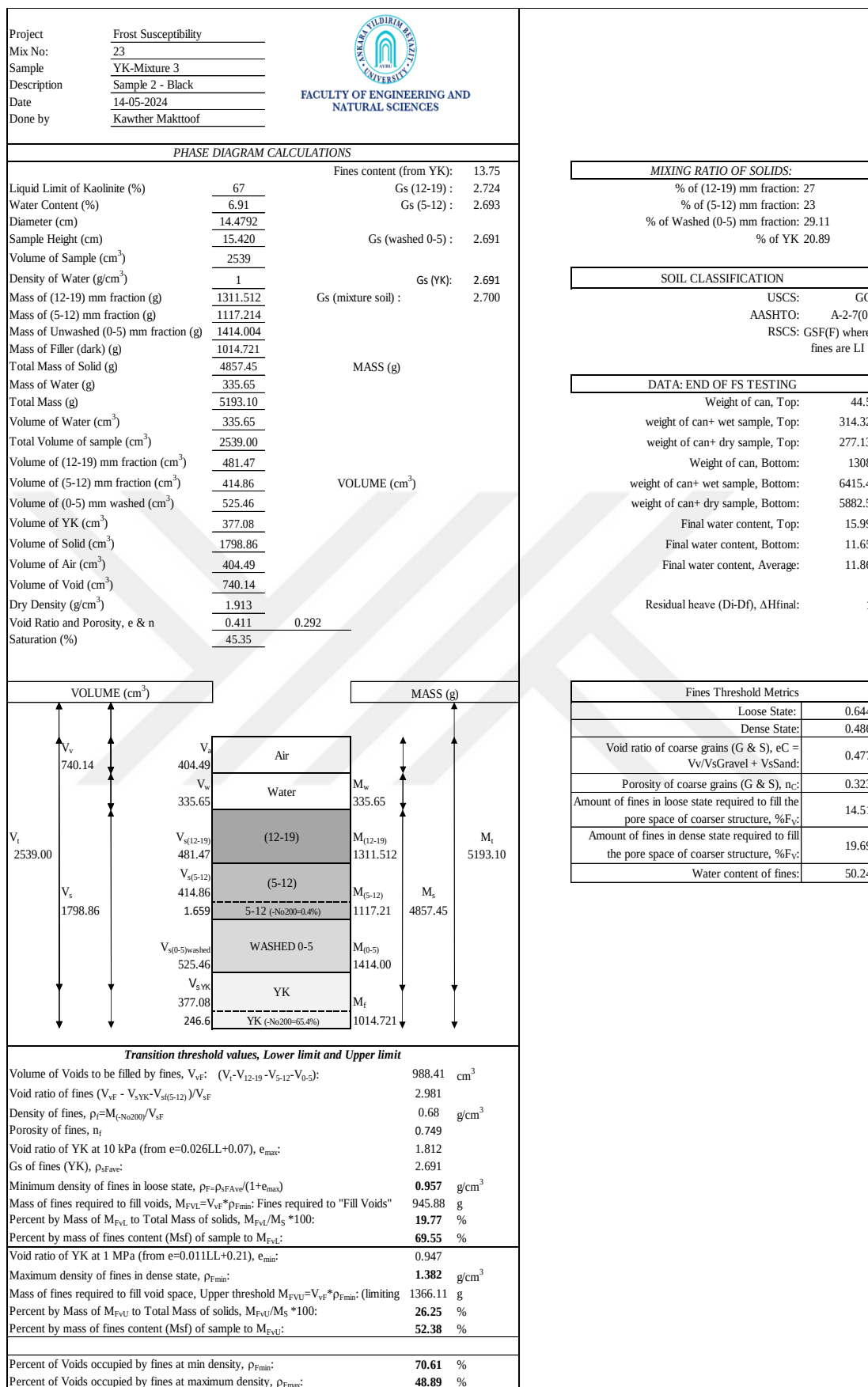
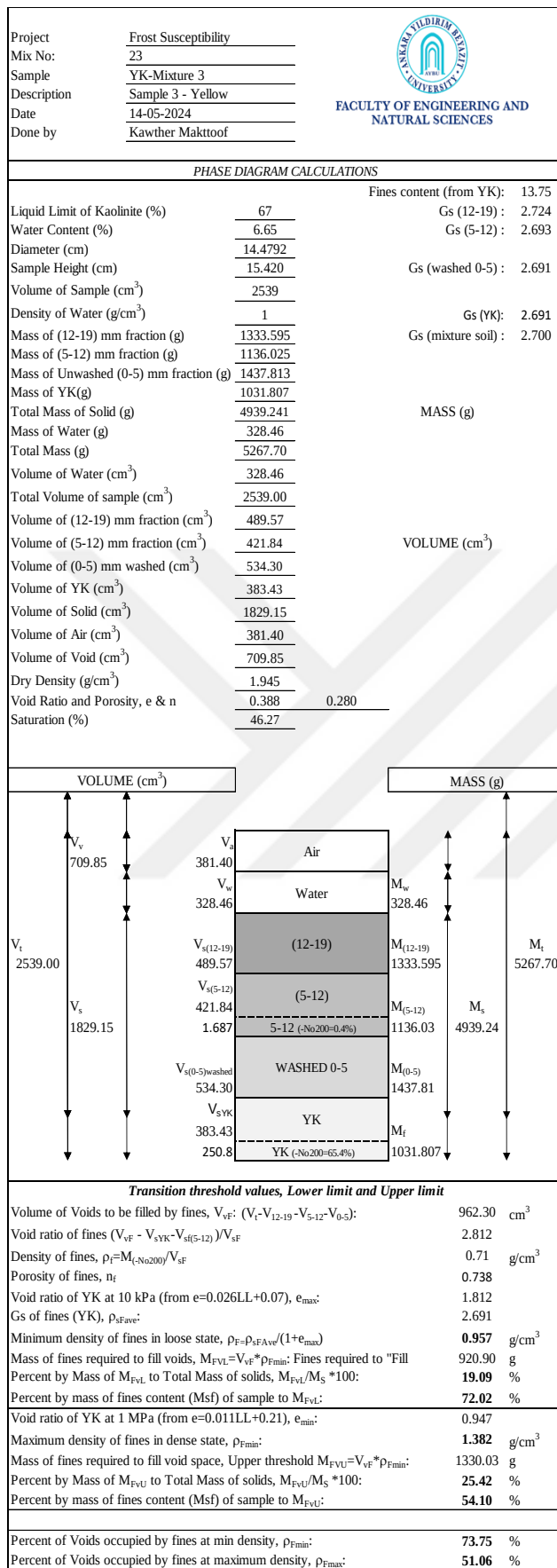
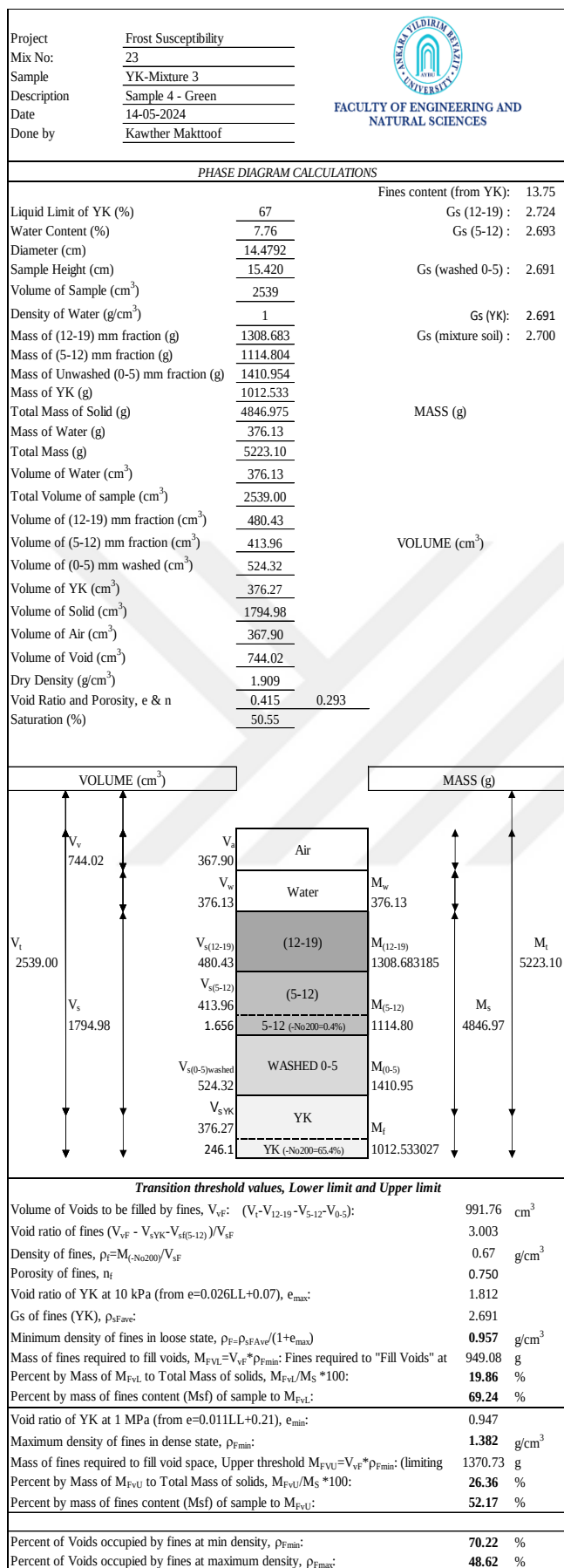


Figure A. 90 Phase Diagram for "23_YK Mix 3-Black"





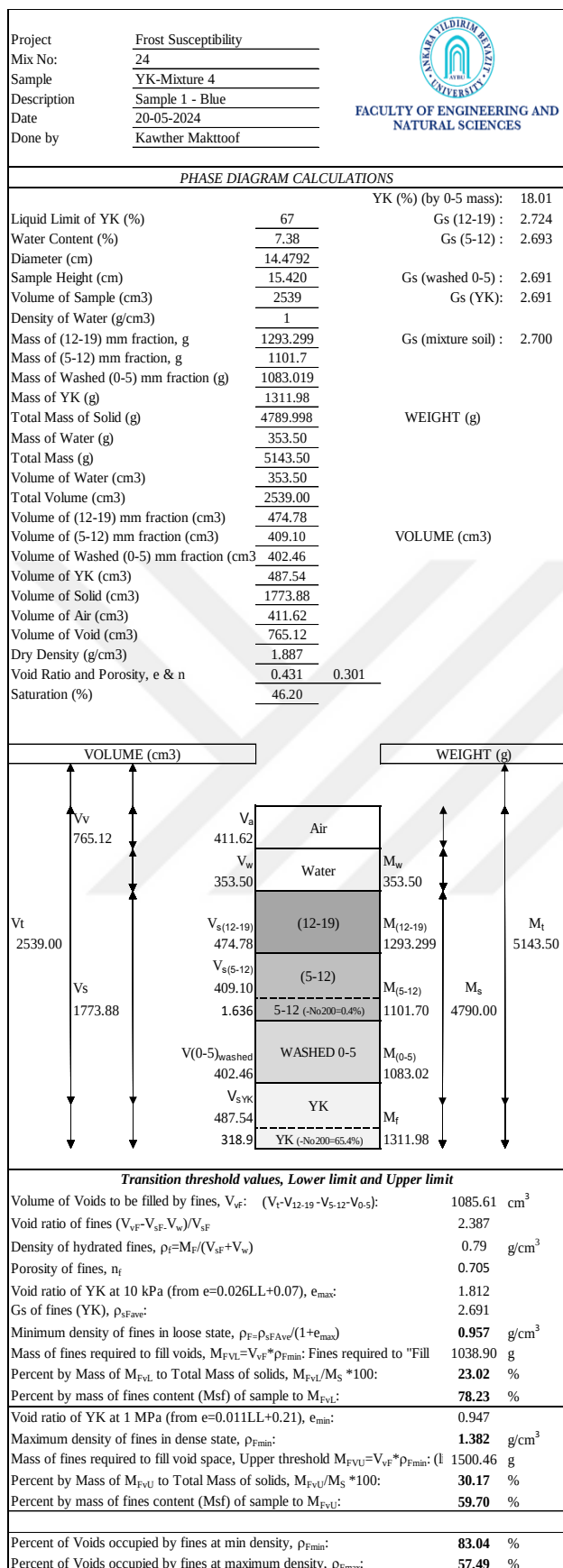
MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 27
% of (5-12) mm fraction: 23
% of Washed (0-5) mm fraction: 29.11
% of YK 20.89

SOIL CLASSIFICATION
USCS: GC
AASHTO: A-2-7(0)
RSCS: GSF(F) where fines are LI

DATA: END OF FS TESTING
Weight of can, Top: 49.6
weight of can+ wet sample, Top: 378.4
weight of can+ dry sample, Top: 342.29
Weight of can, Bottom: 1095.4
weight of can+ wet sample, Bottom: 6171.8
weight of can+ dry sample, Bottom: 5643.3
Final water content, Top: 12.34
Final water content, Bottom: 11.62
Final water content, Average: 11.66
Residual heave (Di-Df), ΔHfinal: 0.52

Fines Threshold Metrics	
Loose State:	0.644
Dense State:	0.486
Void ratio of coarse grains (G & S), eC = V _v /V _{sGravel} + V _{sSand} :	0.481
Porosity of coarse grains (G & S), n _c :	0.325
Amount of fines in loose state required to fill the pore space of coarser structure, %F _v :	14.60
Amount of fines in dense state required to fill the pore space of coarser structure, %F _v :	19.81
Water content of fines:	56.42

Figure A. 92 Phase Diagram for "23_YK Mix 3-Green"



MIXING RATIO OF SOLIDS:
% of (12-19) mm fraction: 27
% of (5-12) mm fraction: 23
% of Washed (0-5) mm fraction: 22.61
% of YK 27.39

SOIL CLASSIFICATION
USCS: GC
AASHTO: A-2-7(1)
RSCS: GSF(F) where fines are LI

DATA: END OF FS TESTING
Weight of can, Top: 45.28
weight of can+ wet sample, Top: 420.52
weight of can+ dry sample, Top: 368.89
Weight of can, Bottom: 1274.2
weight of can+ wet sample, Bottom: 6062.9
weight of can+ dry sample, Bottom: 5497
Final water content, Top: 15.95
Final water content, Bottom: 13.40
Final water content, Average: 13.58
Residual heave (Di-Df), ΔHfinal: 0.69

Fines Threshold Values
Average Lower Limit Threshold (%): 23.4
Average Upper Limit Threshold(%): 30.7
Fines Content, M _{sf} /M _s (%): 18.01
Avg. % of Void space occupied by fines at min density, P _{fmin} (%): 81.1
Avg.% of Void space occupied by fines at maximum density, P _{fmax} (%): 56.2
Average Void ratio of fines of mixture: 2.469
Average porosity of fines of mixture: 2.049
Loose State: 0.644
Dense State: 0.486
Void ratio of coarse grains (G & S), eC = V _v /V _{sGravel} + V _{sSand} : 0.574
Porosity of coarse grains (G & S), n _C : 0.365
Amount of fines in loose state required to fill the pore space of coarser structure, %F _V : 16.96
Amount of fines in dense state required to fill the pore space of coarser structure, %F _V : 22.78
Water content of fines: 40.99

Figure A. 93 Phase Diagram for "24_YK Mix 4-Blue"

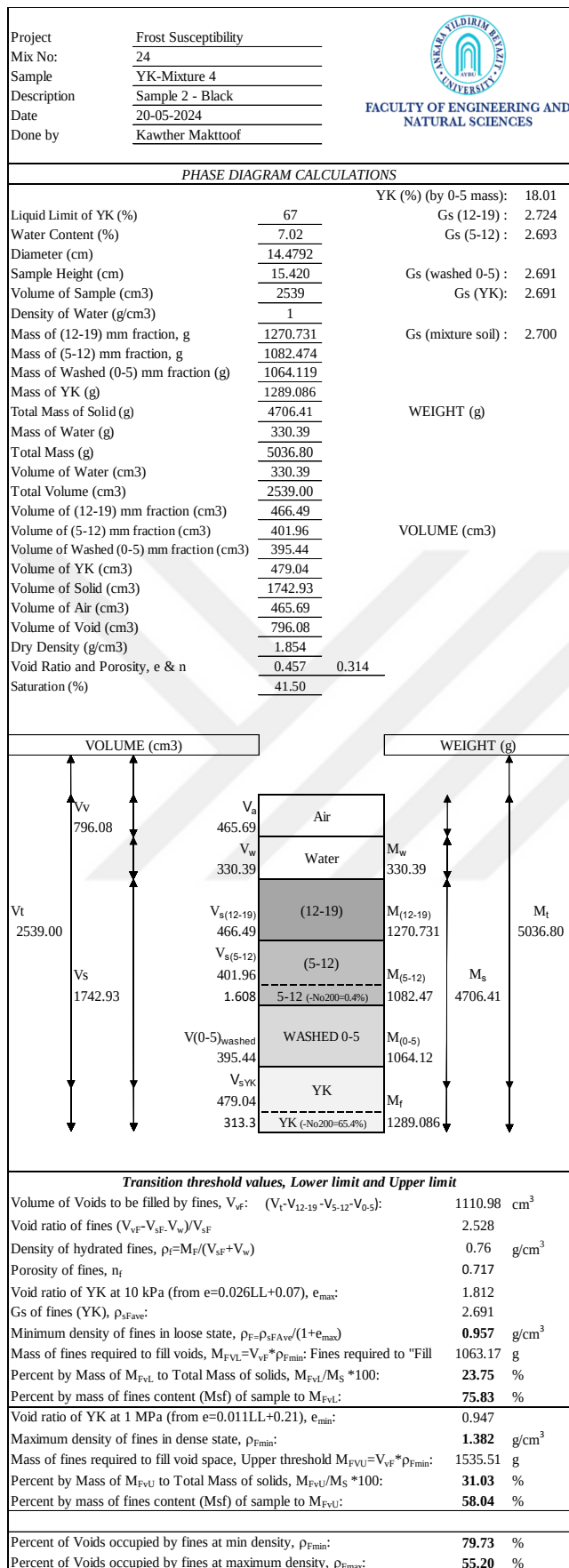


Figure A. 94 Phase Diagram for "24_YK Mix 4-Black"

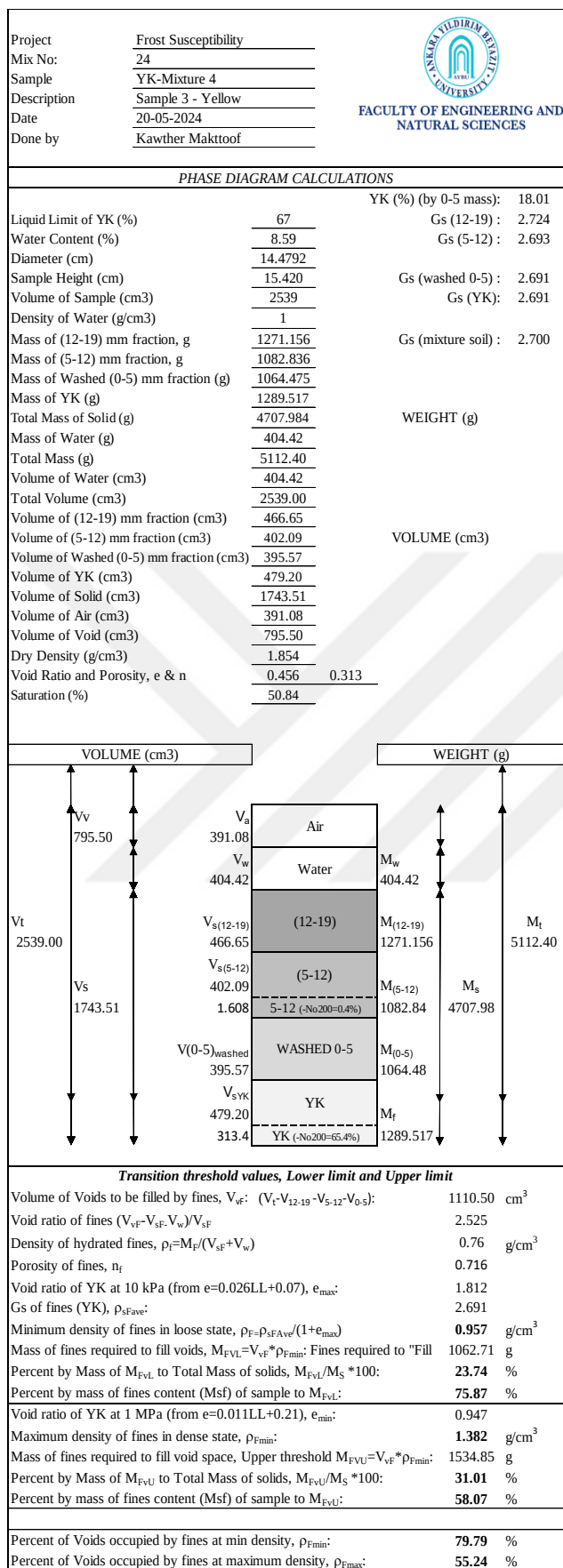
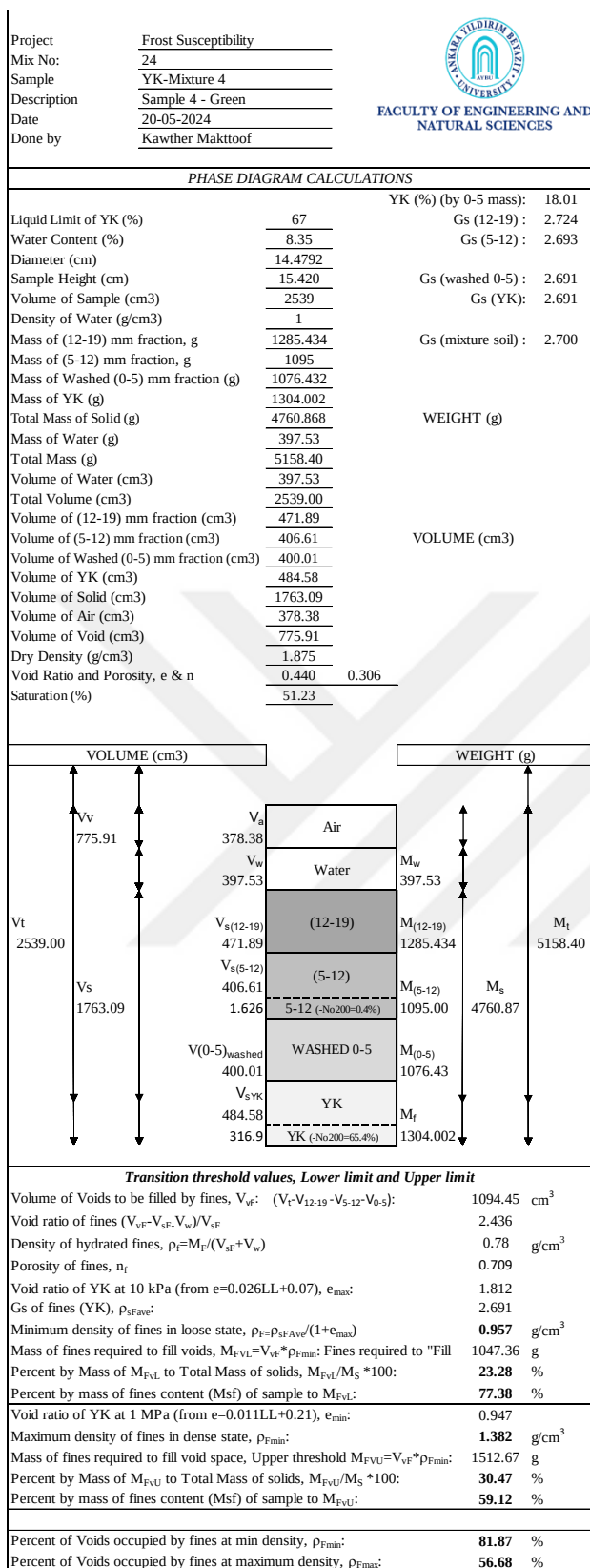


Figure A. 95 Phase Diagram for "24_YK Mix 4-Yellow"



MIXING RATIO OF SOLIDS:	
% of (12-19) mm fraction:	27
% of (5-12) mm fraction:	23
% of Washed (0-5) mm fraction:	22.61
% of YK	27.39

SOIL CLASSIFICATION	
USCS:	GC
AASHTO:	A-2-7(1)
RSCS:	GSF(F) where fines are LI

DATA: END OF FS TESTING	
Weight of can, Top:	48.2
weight of can+ wet sample, Top:	382.14
weight of can+ dry sample, Top:	330.53
Weight of can, Bottom:	1309.6
weight of can+ wet sample, Bottom:	6320.3
weight of can+ dry sample, Bottom:	5717.3
Final water content, Top:	18.28
Final water content, Bottom:	13.68
Final water content, Average:	13.96
Residual heave (Di-Df), ΔHfinal:	0.22

Fines Threshold Metrics	
Loose State:	0.644
Dense State:	0.486
Void ratio of coarse grains (G & S), eC = Vv/VsGravel + VsSand:	0.537
Porosity of coarse grains (G & S), nC:	0.349
Amount of fines in loose state required to fill the pore space of coarser structure, %Fv:	16.04
Amount of fines in dense state required to fill the pore space of coarser structure, %Fv:	21.62
Water content of fines:	46.38

Figure A. 96 Phase Diagram for "24_YK Mix 4-Green"

Appendix B: Freeze Thaw Testing Manual

The frost sensitivity test procedure consists of the following stages:

- I. Sample preparation
- II. Sample setup and saturation
- III. Thermocouple placement and cyclic freeze-thaw testing
- IV. Removal of the sample from the test chamber
- V. Application of the California Bearing Ratio (CBR) test

I. Sample Preparation

- 1) Prepare soil samples at the optimal water content determined for the specific mixture. Ensure sufficient material is available to fill four molds. Each mold requires at least 6 kg of wet sample.
- 2) Measure the mass of the upper and lower acrylic disks. A single set of disks can be reused for the preparation of four samples.
- 3) Record the mass of the rings, membrane, and acrylic disks required for each of the four samples.
- 4) Stack six rings such that the thermocouple holes are aligned. Ensure the top and bottom rings are notched, with the top ring's notch facing upwards and the bottom ring's notch facing downwards.
- 5) Place the membrane along the inner surface of the stacked acrylic rings and fold it over the outer walls of the rings at both the top and bottom. Avoid pinching the membrane between the rings and smooth out any wrinkles as much as possible (see Figure B.1, a)
- 6) Place the ring structure with the membrane into a custom two-piece mold designed for the frost sensitivity test, ensuring the thermocouple holes remain aligned, and the membrane stays undisturbed. Place filter paper at the bottom to prevent soil spillage. Attach the mold collar, tighten the butterfly nuts, and position the mold for compaction in a proctor device. (see Figure B.1, b & c)

- 7) Divide the prepared soil into five equal portions. For each layer, compact the soil in the mold using a standard Proctor hammer with 42 blows per layer.
- 8) Once compaction is complete, remove the mold collar and nuts, and detach the two-part compaction mold, leaving the sample wrapped with the membrane and acrylic rings intact. (see Figure B.1, d & e)
- 9) Trim any excess material from the top of the sample using a metal ruler to achieve a level surface. Take a representative sample of the remaining material to determine the water content.
- 10) Place the upper acrylic disk on the prepared sample and measure the total mass of the sample (including rings, membrane, and both acrylic disks) to calculate the dry unit weight.
- 11) Repeat the steps above to prepare the remaining three samples.

II. Sample Setup and Saturation

- 12) Place thin porous stones on the bottom base plate where the sample will sit and place a filter paper on top of it. Connect the water source, allowing water to saturate the pipes and porous stones. Remove any air bubbles from the pipes. Once saturated, remove the upper and lower acrylic disks from the sample and place it on the saturated bottom porous stone. Place another saturated porous stone. (see Figure B.1, f & g)
- 13) Align the notch on the lowest ring of the sample with the notch on the bottom base, ensuring proper centering. For convenience, align the thermocouple holes with the direction of the nozzle connection to the water source.
- 14) Connect the sample base to the water source, ensuring proper connections between the samples and the Mariotte bottles as follows:
 - Area 1 (back left, blue): 1st Mariotte bottle from the back.
 - Area 2 (back right, black): 2nd Mariotte bottle from the back.
 - Area 3 (front left, yellow): 2nd Mariotte bottle from the front.
 - Area 4 (front right, green): 1st Mariotte bottle from the front.

- 15) Fill the Mariotte bottles with water. Position the lower end of the capillary tube inside each bottle to be 2.5 cm above the sample's water inlet level to establish a water pressure corresponding to a 2.5 cm height difference.
- 16) Open the valve controlling water flow between the Mariotte bottle and the sample, releasing any air from the tube. As water flows into the bottom plate, the water level in the capillary tube will move all the way down and air bubbles will enter the Mariotte bottle. The system ensures that the water pressure in the supply line remains constant even as the water level in the Mariotte jar changes.
- 17) Before opening the valve, mark the initial water level in the Mariotte bottle.
- 18) The saturation phase may be completed inside the freeze thaw cabin. It may be completed outside of the cabin if a saturation tank and connections are available. For low-permeability samples, the saturation process requires 24 hours, with the following procedure:
 - Gradually raise the bubble tube by 2.5 cm (1 inch) every hour for the first 6 to 8 hours.
- 19) - Maintain the bubble tube at a height of 15 cm (6 inches) for the remaining 16 to 18 hours. Once the saturation is complete close valves to the water supply. Measure the change in water level in the Mariotte bottle and refill as needed.

For high-permeability samples, this process can be completed in a significantly shorter amount of time. It is possible to see the water level in the sample through the translucent rubber membrane. Based on these observations the water pressure may be increased at time intervals shorter than one hour.

- 20) At the end of saturation, place the upper porous stone and cooling plate onto the sample. Wrap the upper section of the membrane around the upper cooling plate and secure it with an O-ring. Add the surcharge weight to the top of the sample. (see Figure B.1, h)

III. Thermocouple Placement and Cyclic Freeze-Thaw Testing

- 21) Organize the thermocouple color series according to the sample locations and the color coding outlined in the diagram. Insert the thermocouples into the holes in the

- acrylic rings of the sample body, following a sequence from top to bottom (1 through 8). For loose or highly porous samples, applying silicone adhesive to the thermocouple tips before insertion may improve contact and ensure proper sealing.
- 22) Wrap each of the samples with the insulation jackets to reduce radial heat loss.
 - 23) Check that the tip of the pipette in the Mariotte jar is 2.5 cm above the sample water inlet. Adjust if necessary. Reopen the valves of the water sources that were disconnected earlier allowing water to flow into the samples. If the samples were saturated outside the cabin, flush the water supply tube system to remove any air by letting water flow out, before connecting it to the water inlet in the sample base plate.
 - 24) Mark the initial water level in the Mariotte bottles to be able to compare it with the final water level observed at the end of the test. This measurement provides a visual indication of water level changes but is not critical for recording purposes, as load cells at the base of the Mariotte bottles automatically capture the change in water mass in grams. These recorded data can later be transferred to an Excel file for detailed analysis.
 - 25) Position the laser displacement sensors on the samples ensuring they are set at a height sufficient to measure the full range of heaving.
 - 26) Close the freezing cabin doors and turn on the water baths and the freezer. Set the target temperature of the cabin to 3°C. Input the 5-day temperature fluctuation program for the upper and lower plates into the interface of the computer system used for data recording. This ensures that the temperature-controlled water baths connected to the inlets of the upper and lower plates are properly calibrated. (see Figure B.1 , i & j)
 - 27) Verify the following key points before commencing the experiment:
 - The readings from pressure transducers, thermocouples, and swell measurement sensors are within acceptable ranges.
 - The water levels in the Mariotte bottles are sufficient, and water pressure is correctly set.
 - There are no leaks at the pipe connection points.
 - The water supply valves are open.

- The valves connected to the cooling tanks are open, and the relevant pipes are not bent or blocked.
- Thermocouples are correctly installed.
- The cabin floor is clear of water accumulations to detect potential leaks. -

28) Restart the data acquisition system and water bath control system.

29) The lid of the experiment cabin is left closed for the next 5 days. During this period, observe physical changes in the samples through the glass lid of the chamber. Monitor thermocouple temperature readings, laser swell measurements, and weight changes in the Mariotte bottles via the data recording system.

IV. Removal from the Freezer Cabinet and Application of the CBR Test

Following the five-day test duration, the experimental termination procedure is initiated, and the samples are removed from the freezer cabinet.

- 30) Data related to temperature, swelling, and Mariotte bottle weight are retrieved through the software used for data recording.
- 31) The cooling pool switches are turned off.
- 32) The test cabin switch is turned off.
- 33) The data logger switch is also turned off.
- 34) The cabinet cover is opened, and the inlet and outlet valves on the water lines connecting the Mariotte bottles to the samples are closed.
- 35) The pipes linking the Mariotte bottles to the samples are carefully detached from the self-locking mechanism, allowing the samples to rotate freely during removal, thereby facilitating the transportation process.
- 36) The top cooling plate is connected by insulated tubes to a valve box located near the top of the cabin back wall. The valves here should be closed.
- 37) The bottom cooling plates are connected to a different valve box with red (insulated?) pipes. These valves should also be closed.
- 38) Laser measuring instruments are removed.

- 39) Thermocouples submerged in the samples are carefully extracted, with the thermocouples specific to each sample left suspended on the respective laser measuring instrument.
- 40) Surcharge weights applied to the samples are removed.
- 41) The O-ring of the upper plate is slid upward and removed, ensuring it is positioned on the cooling pipes. A pen may be used to facilitate this process by inserting it between the O-ring and the membrane, rotating it around the sample, and sliding the O-ring upward. The membrane is subsequently lowered and folded.
- 42) Similarly, the O-ring of the lower plate is slid downward along the membrane, which is then folded upward with the aid of a pen.
- 43) An acrylic disk is placed on the top portion of the sample.
- 44) A transport shovel is positioned beneath the sample, and the sample is gently slid onto the shovel for transfer to a transport table.
- 45) A label is prepared for the sample, detailing its identification and the color of its associated thermocouple.
- 46) The final weight of the sample (including six rings and the membrane) is measured and recorded. If the CBR test cannot be conducted immediately, the sample is wrapped in stretch film or enclosed in a nylon bag and stored in a curing room.

V. CBR Test Application

- 47) Four pipe clamps are secured around the top four acrylic rings. The CBR surcharge loads are applied, and the CBR test is conducted in accordance with standard procedures.



(a)



(b)



(c)



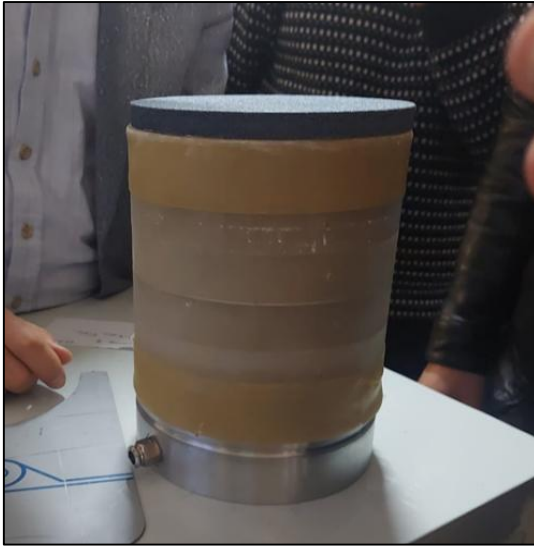
(d)



(e)



(f)



(g)



(h)



(i)



(j)

Figure B. 1 (a) to (e) Sample compaction and preparation (f) to (g) sample saturation (I) and (j) Sample setup in freezing cabin

Appendix C: Freeze-Thaw Test Results

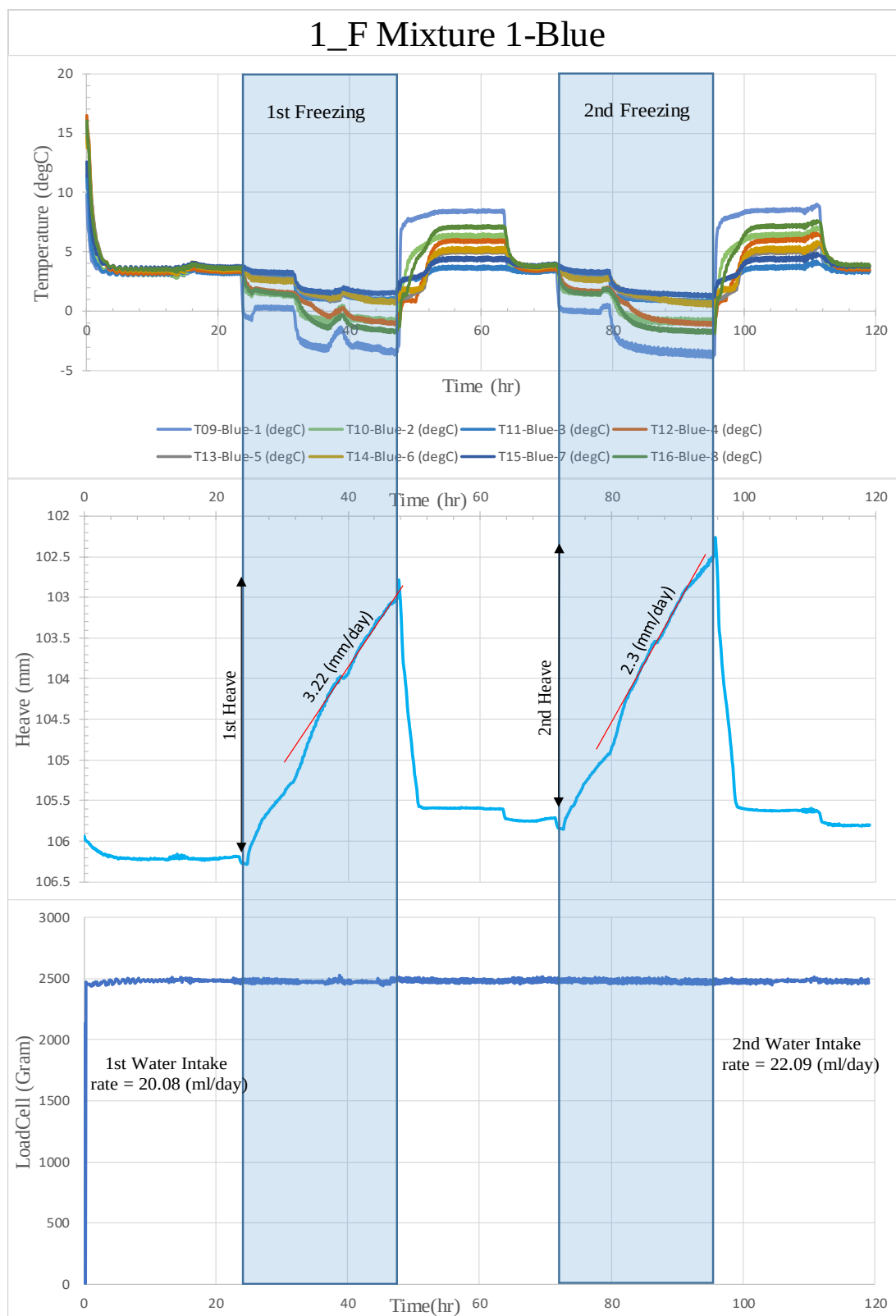


Figure C. 1 Freez-Thaw Test Results for “1_F Mix 1-Blue”

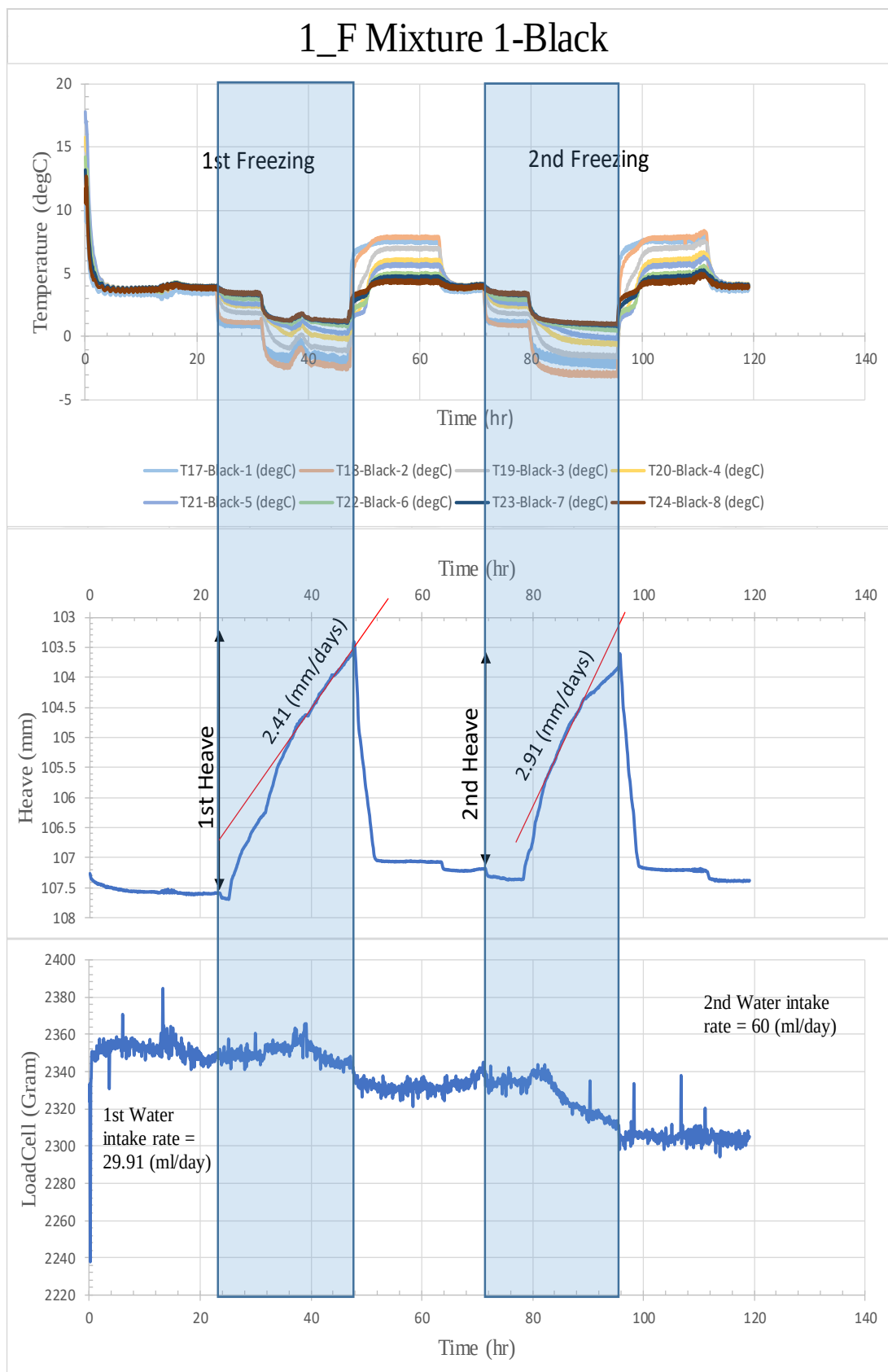


Figure C. 2 Freez-Thaw Test Results for “1_F Mix 1-Black”

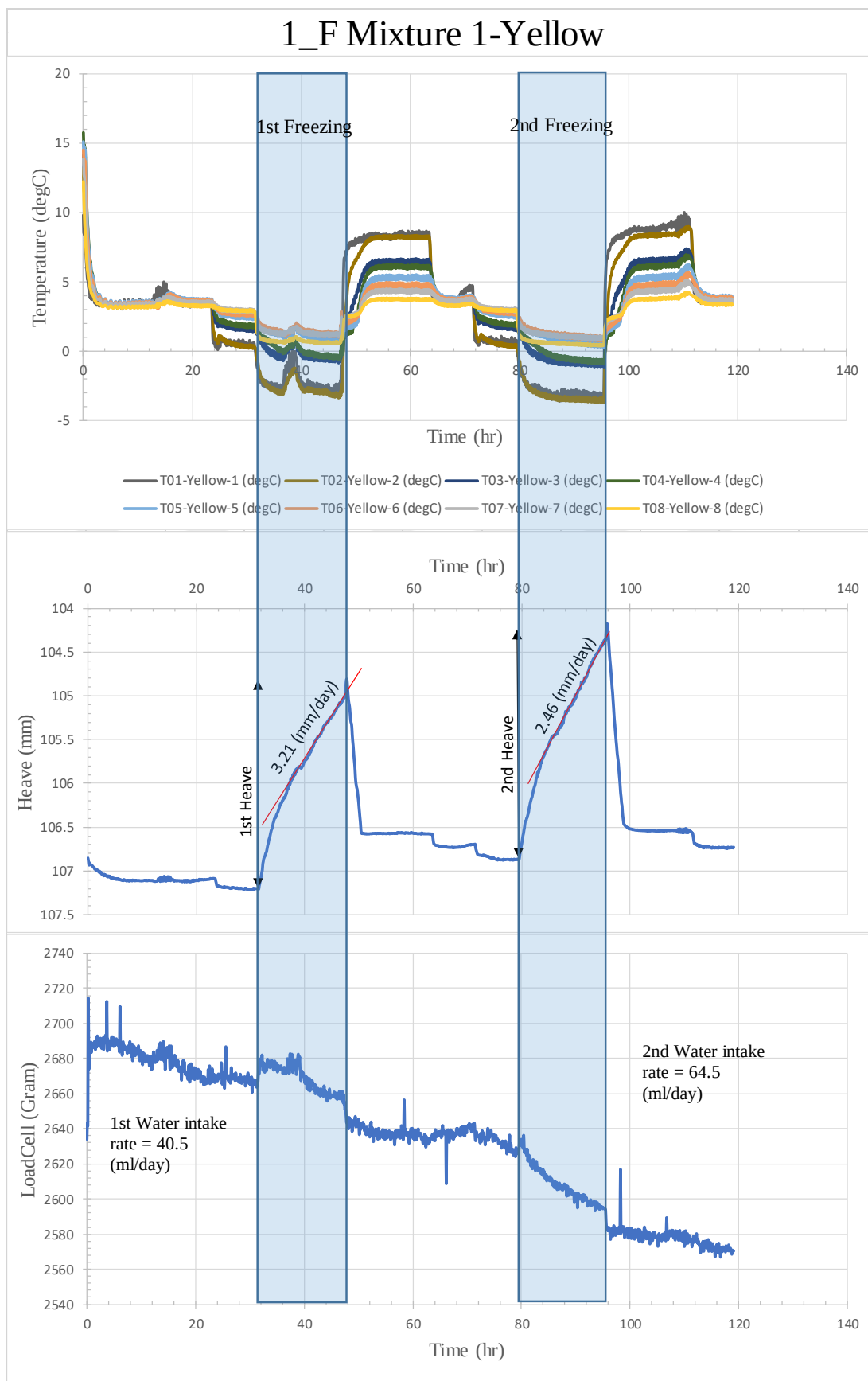


Figure C. 3 Freez-Thaw Test Results for “1_F Mix 1-Yellow”

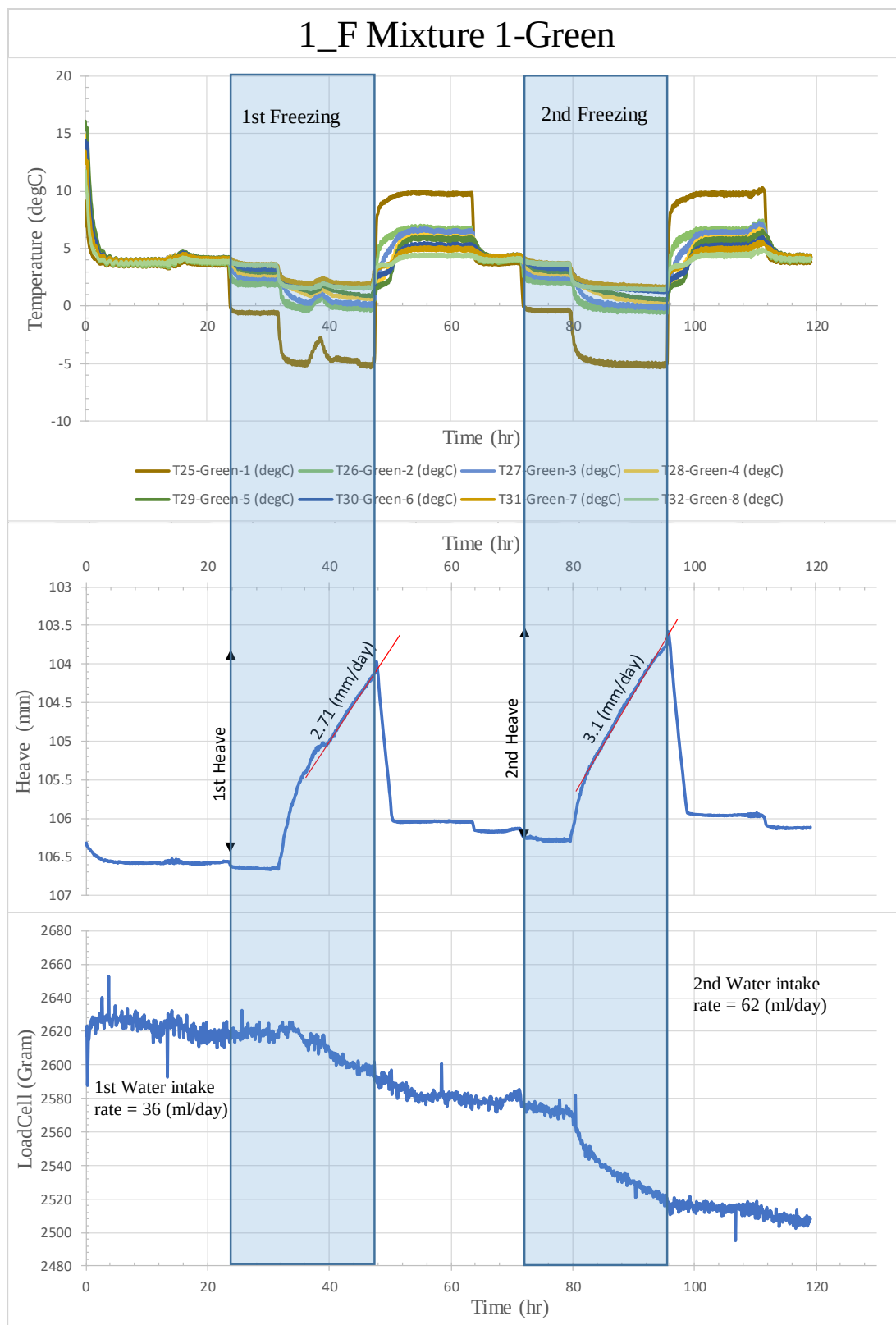


Figure C. 4 Freez-Thaw Test Results for “1_F Mix 1-Green”

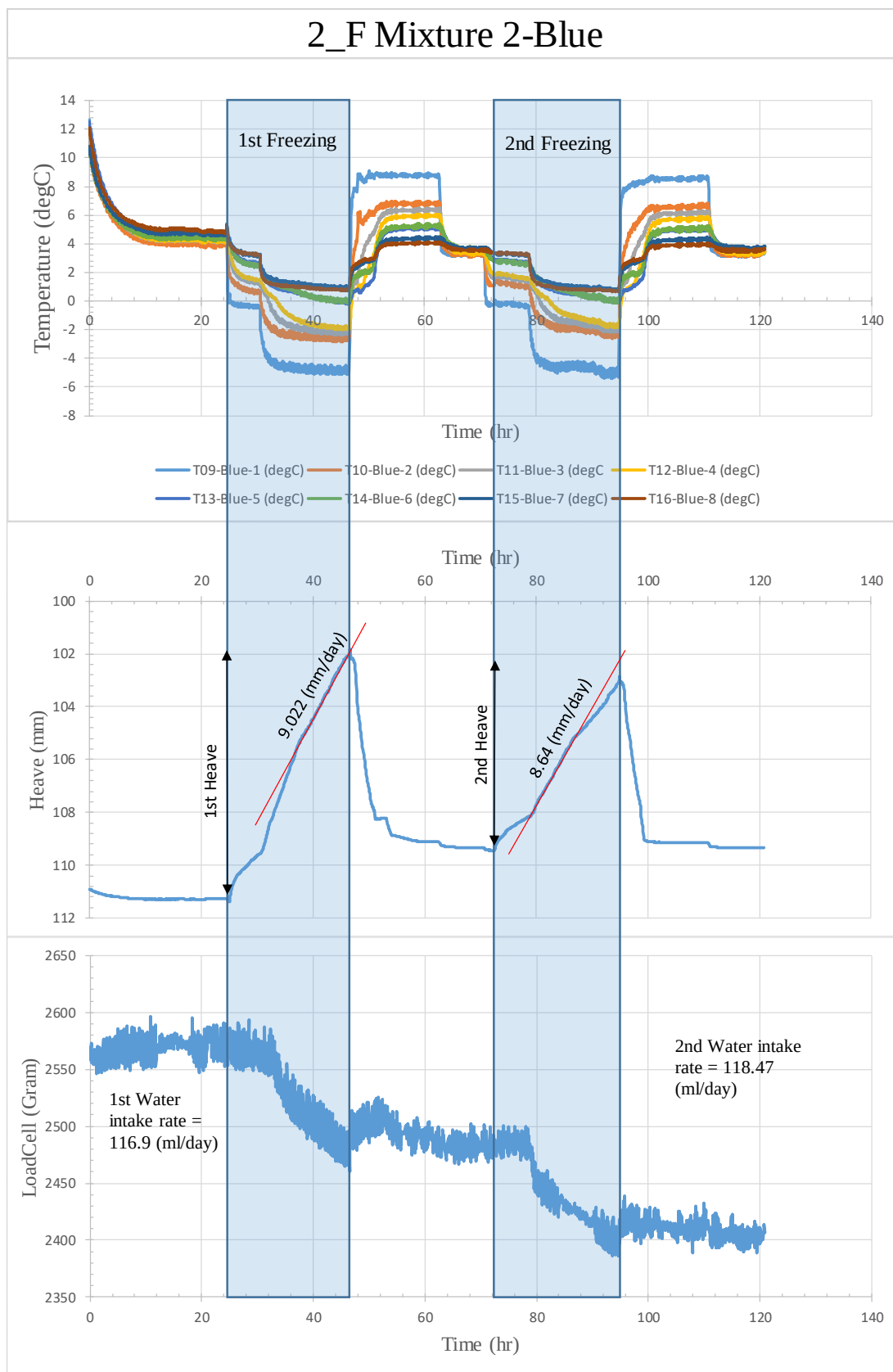


Figure C. 5 Freez-Thaw Test Results for “2_F Mix 2-Blue”

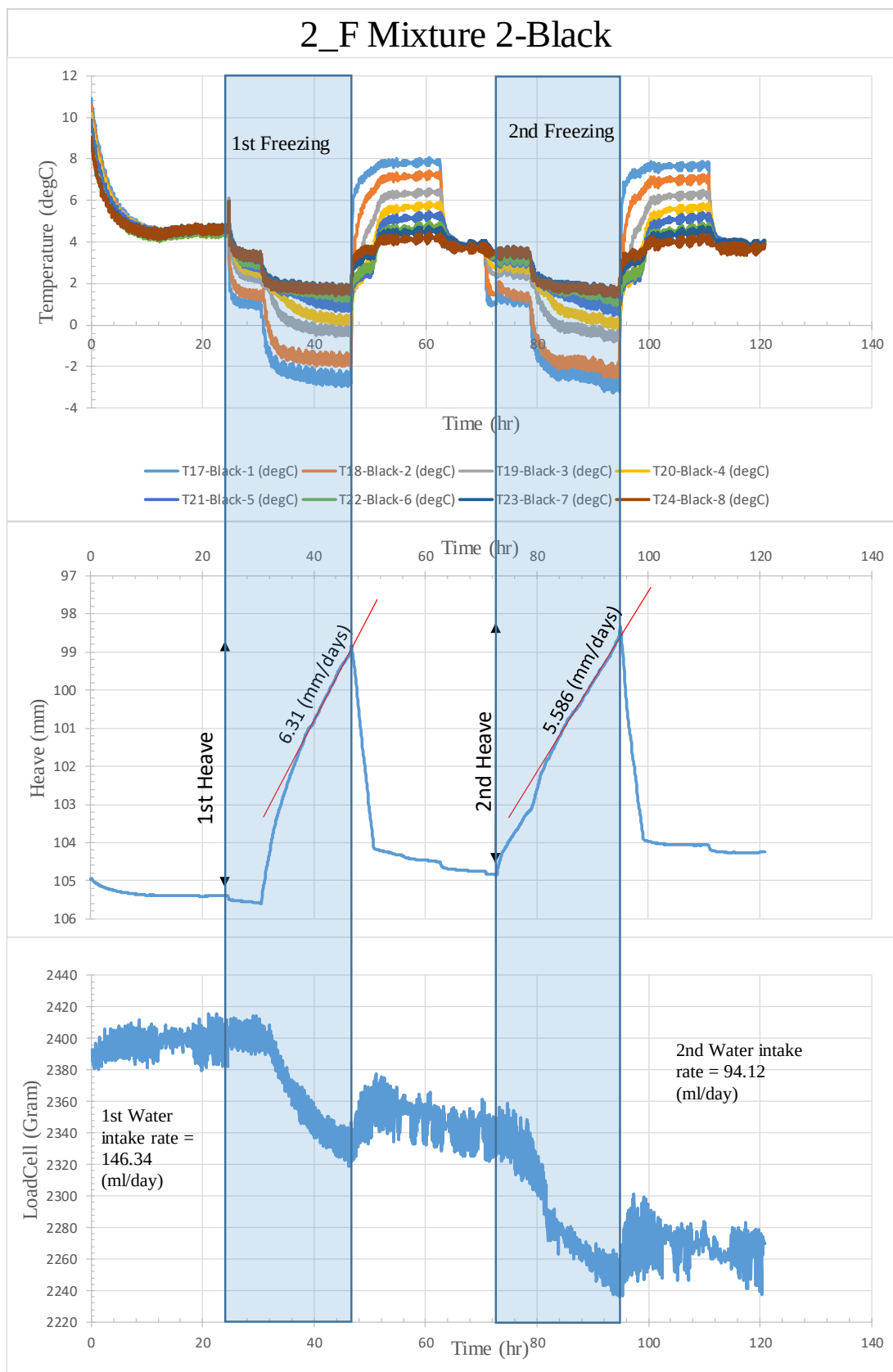


Figure C. 6 Freez-Thaw Test Results for “2_F Mix 2-Black”

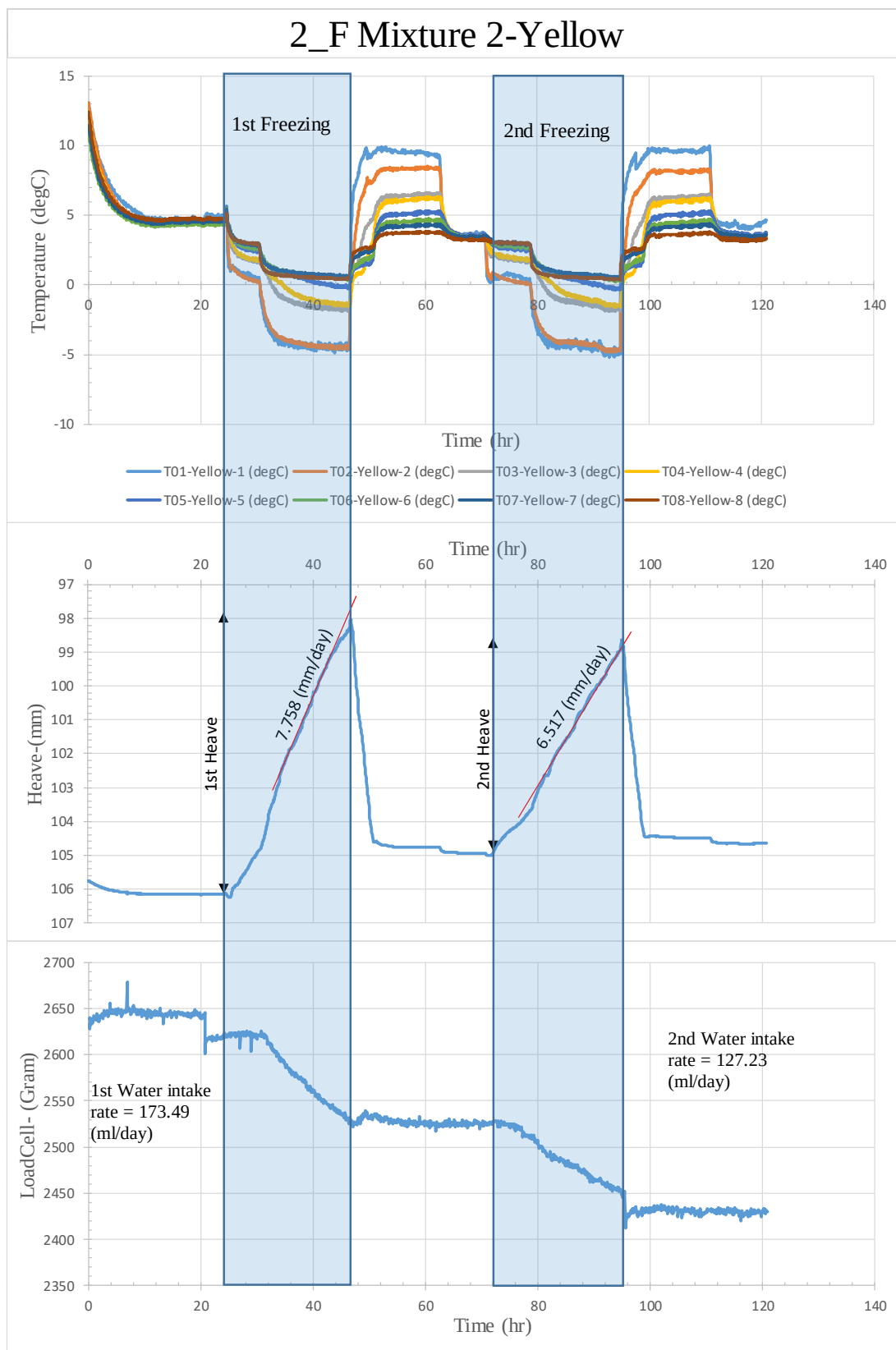


Figure C. 7 Freez-Thaw Test Results for “2_F Mix 2-Yellow”

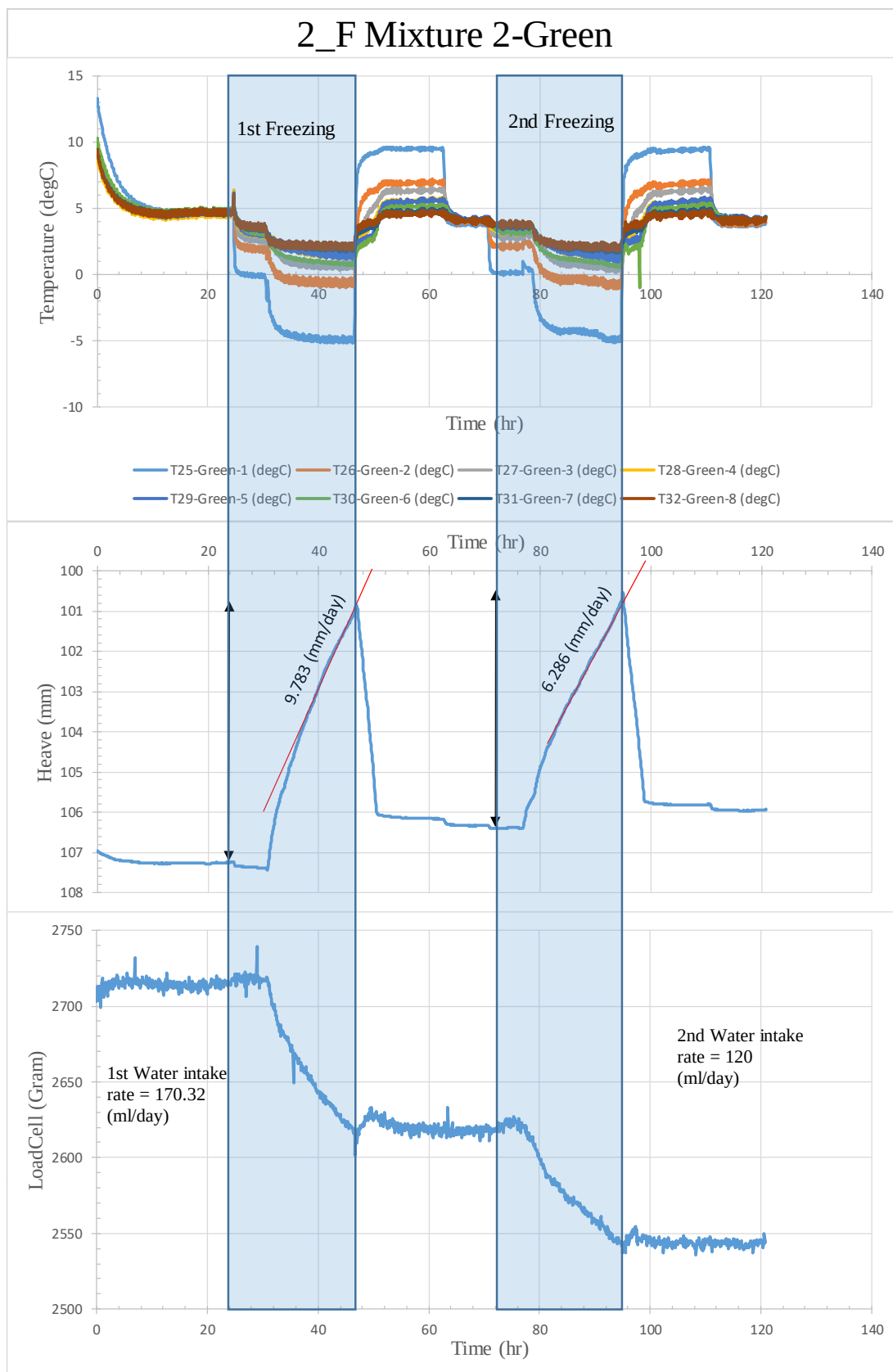


Figure C. 8 Freez-Thaw Test Results for “2_F Mix 2-Green”

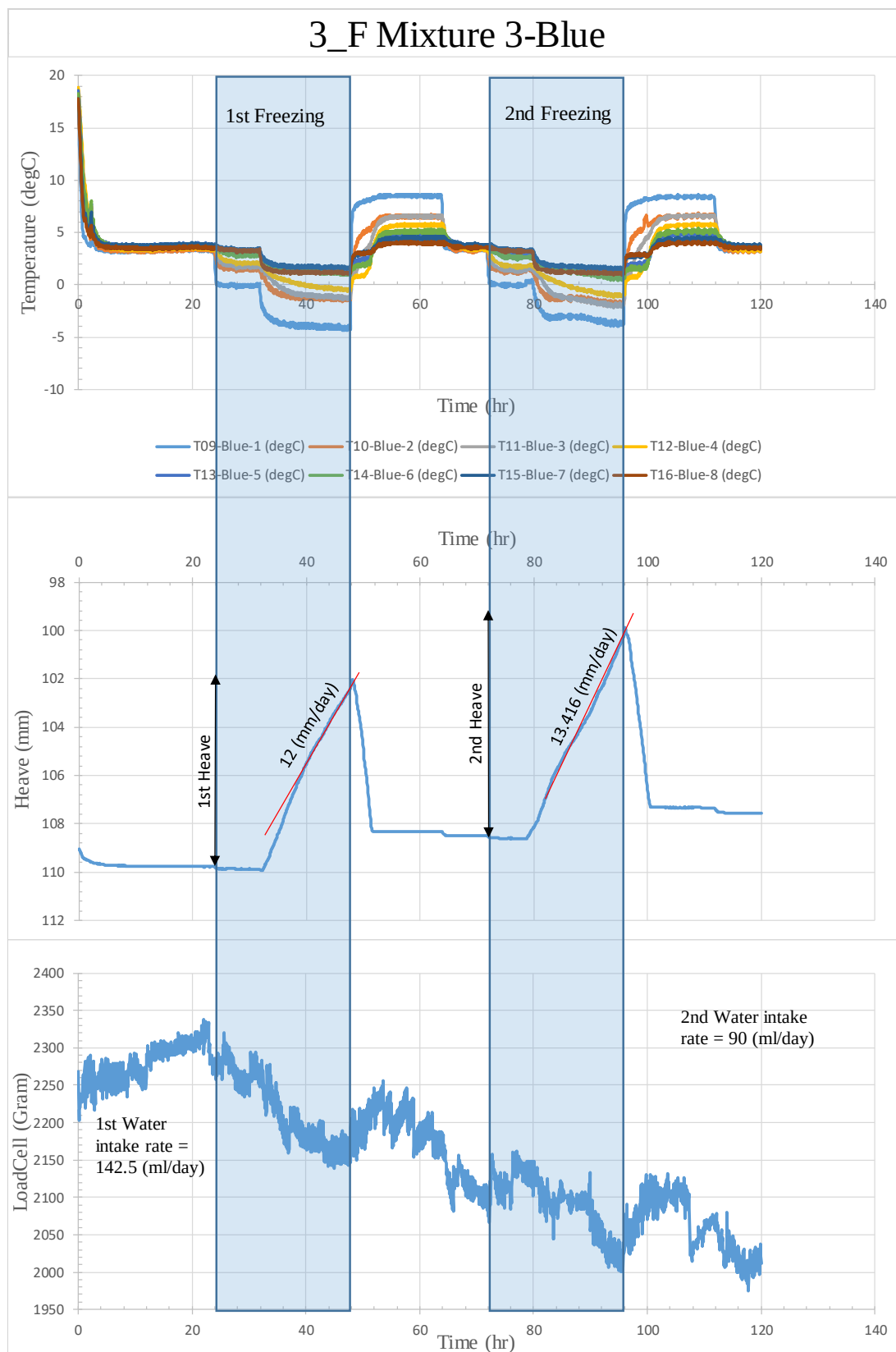


Figure C. 9 Freez-Thaw Test Results for “3_F Mix 3-Blue”

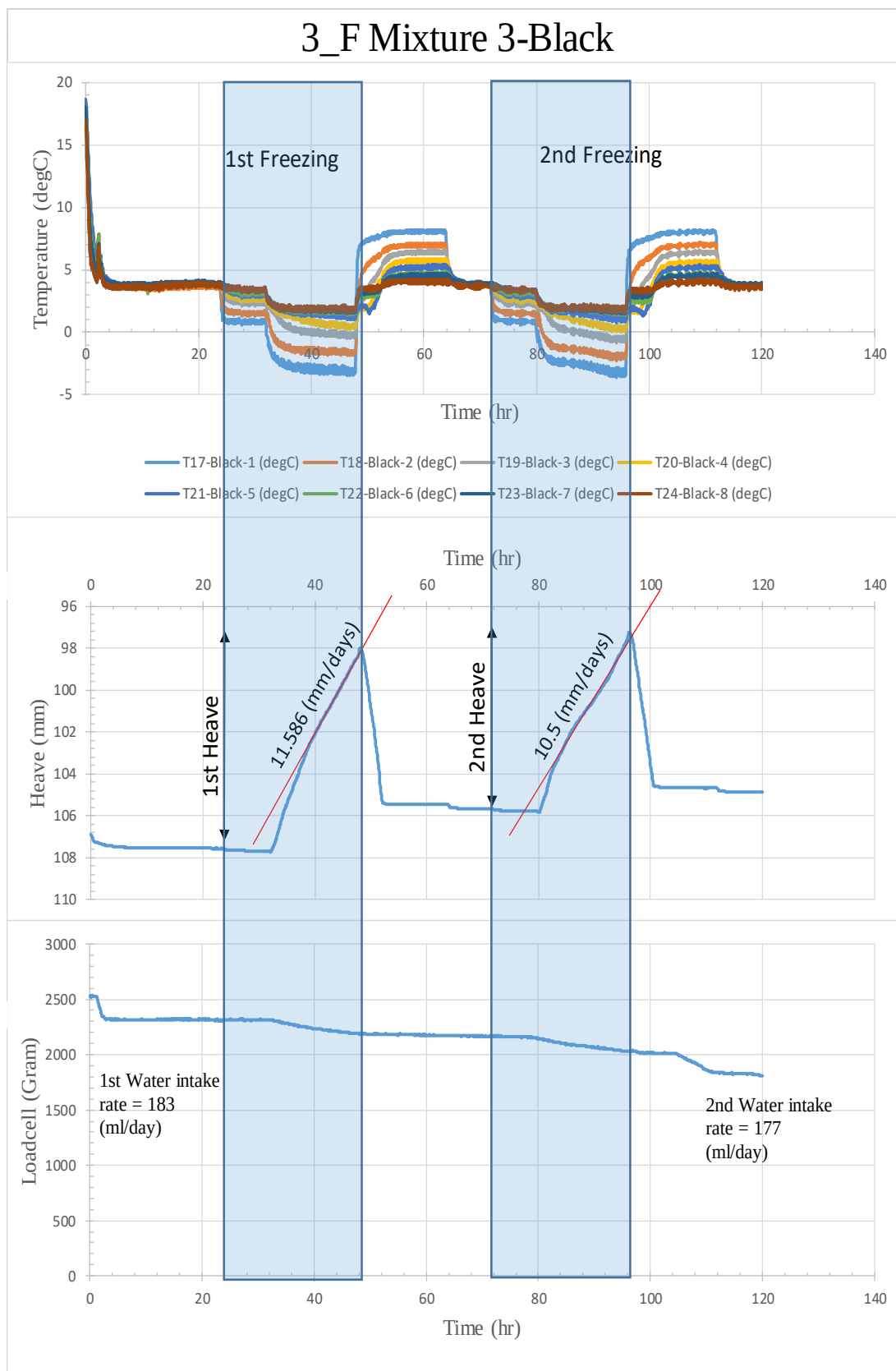


Figure C. 10 Freez-Thaw Test Results for “3_F Mix 3-Black”

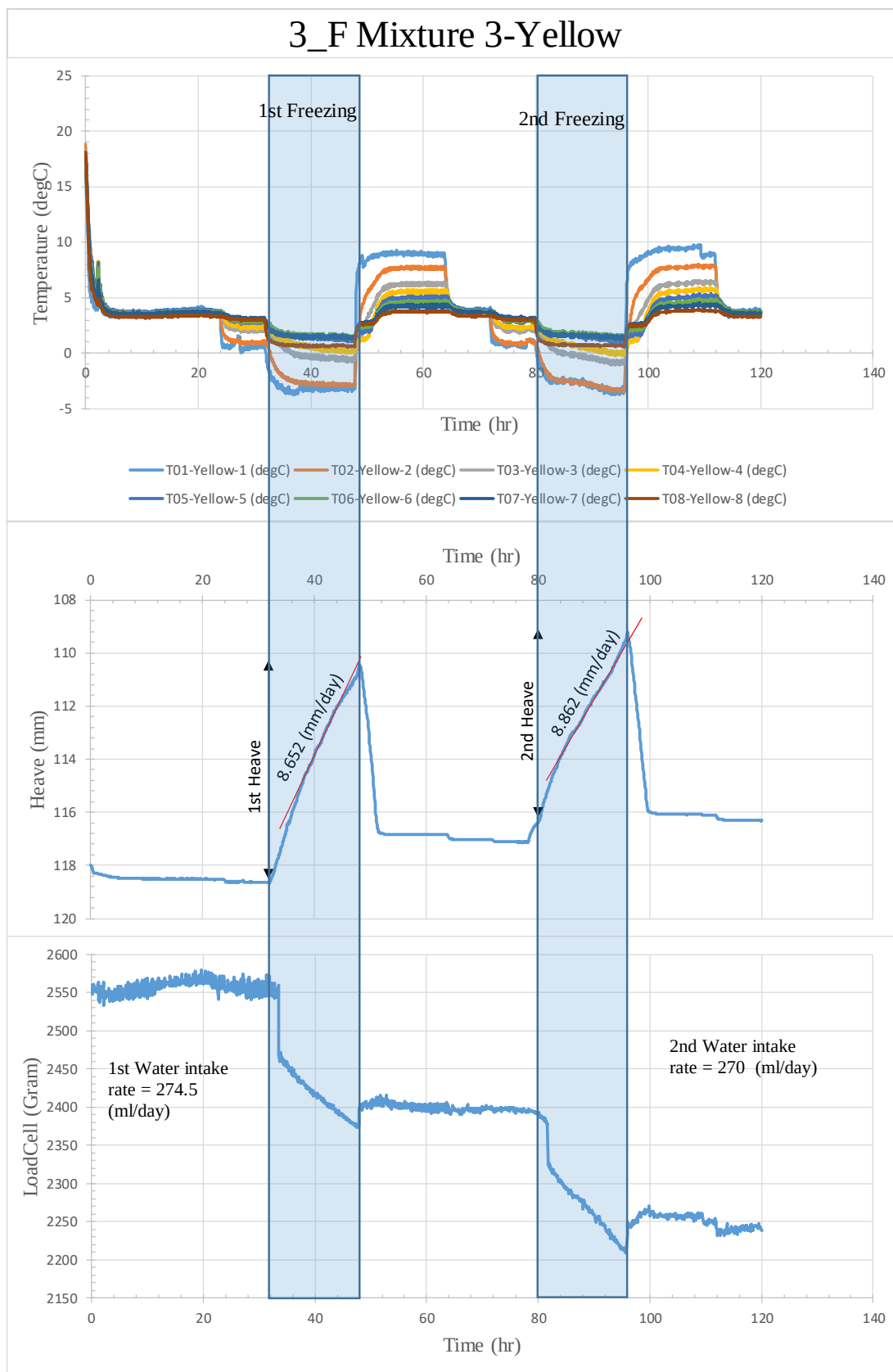


Figure C. 11 Freez-Thaw Test Results for "3_F Mix 3-Yellow"

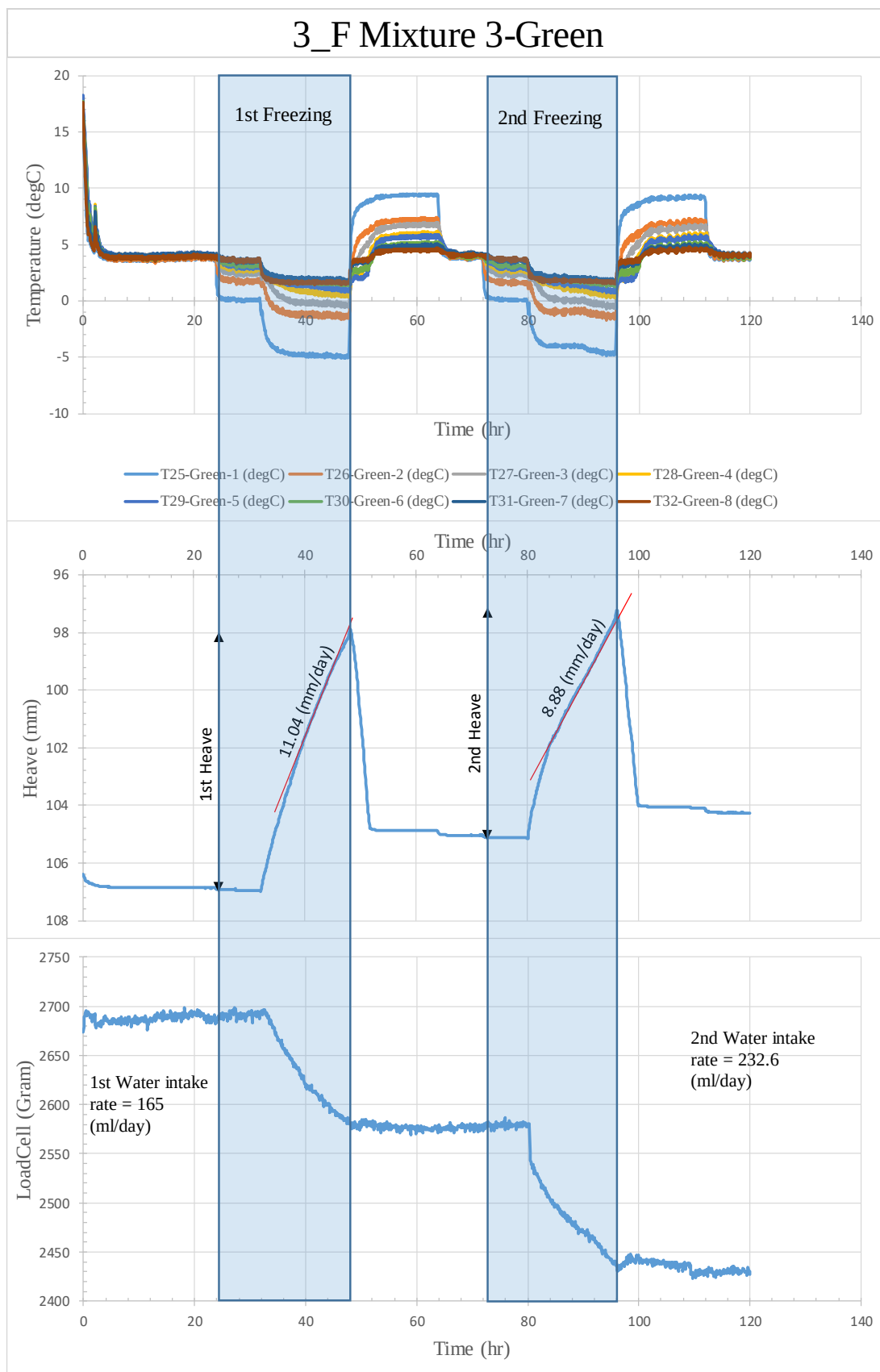


Figure C. 12 Freez-Thaw Test Results for “3_F Mix 3-Green”

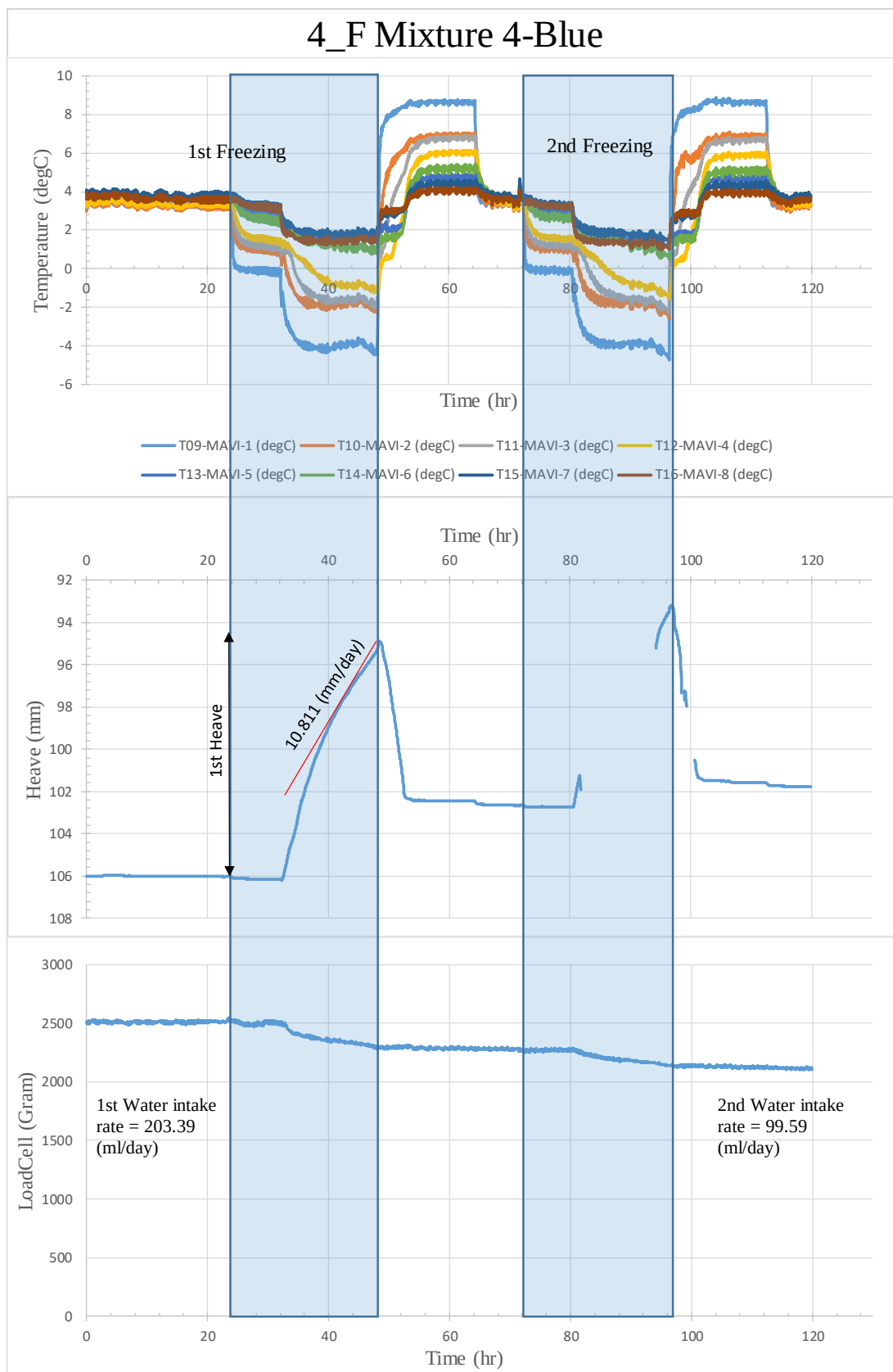


Figure C. 13 Freez-Thaw Test Results for “4_F Mix 4-Blue”

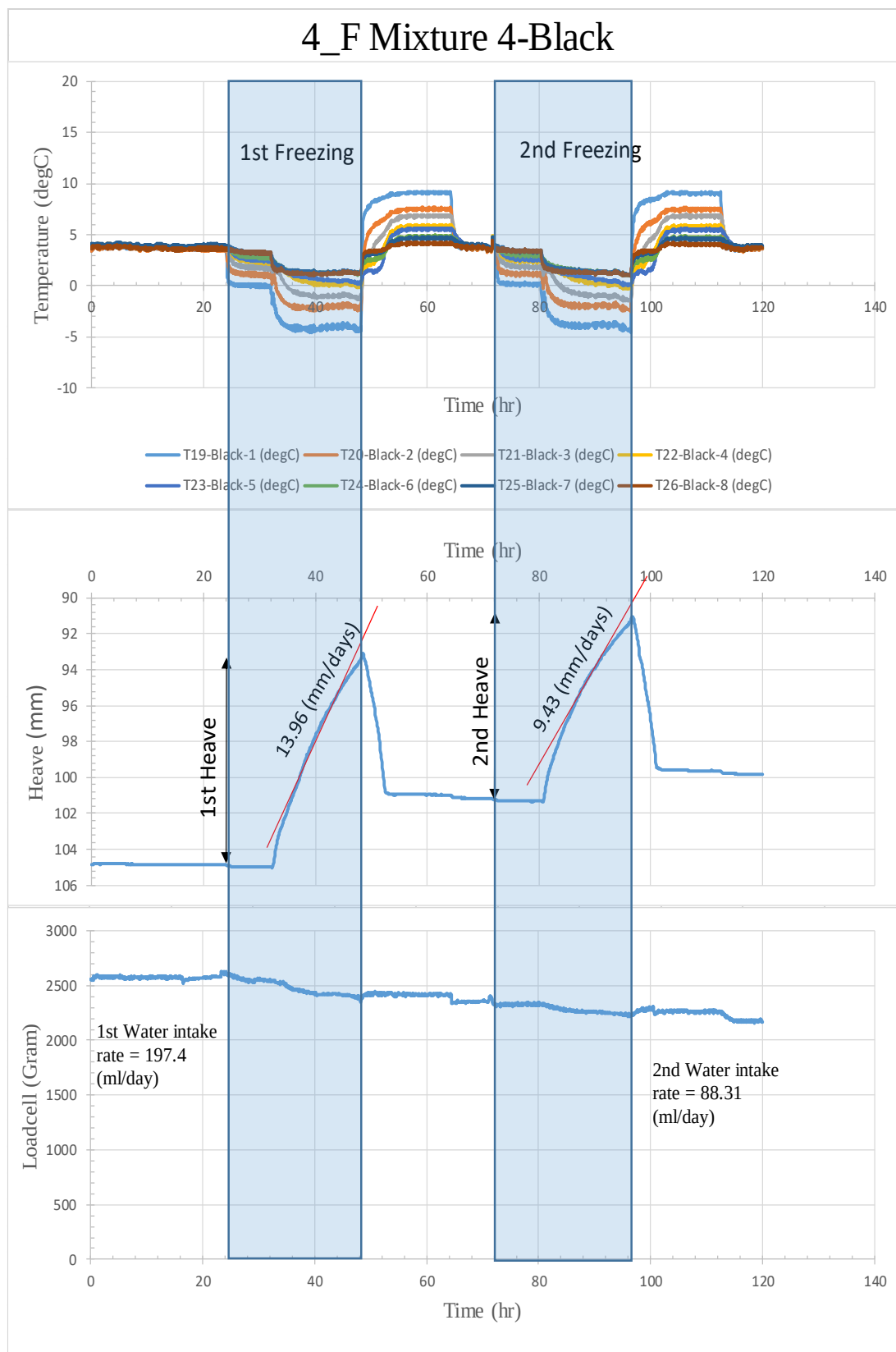


Figure C. 14 Freez-Thaw Test Results for “4_F Mix 4-Black”

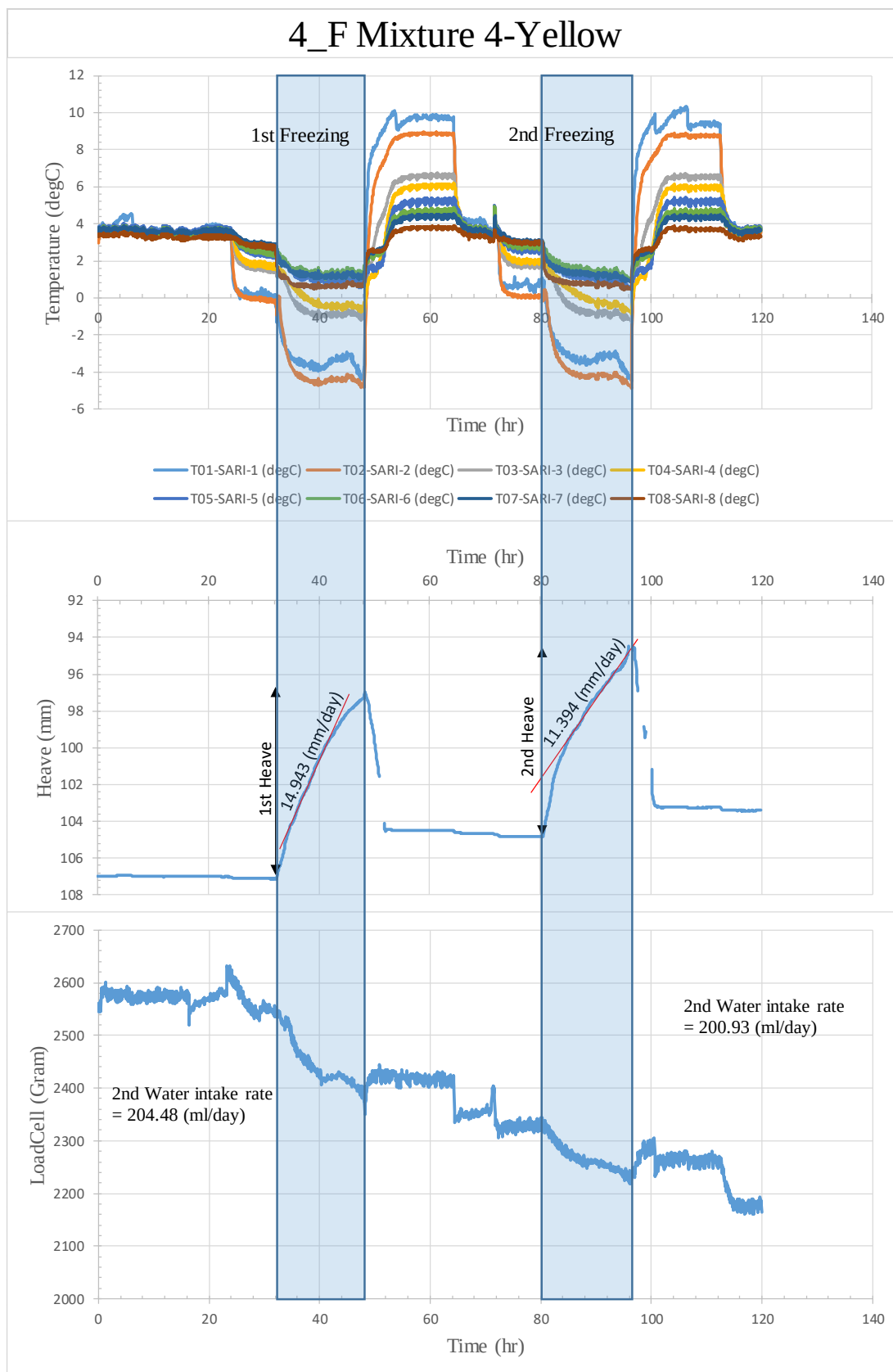


Figure C. 15 Freez-Thaw Test Results for “4_F Mix 4-Yellow”

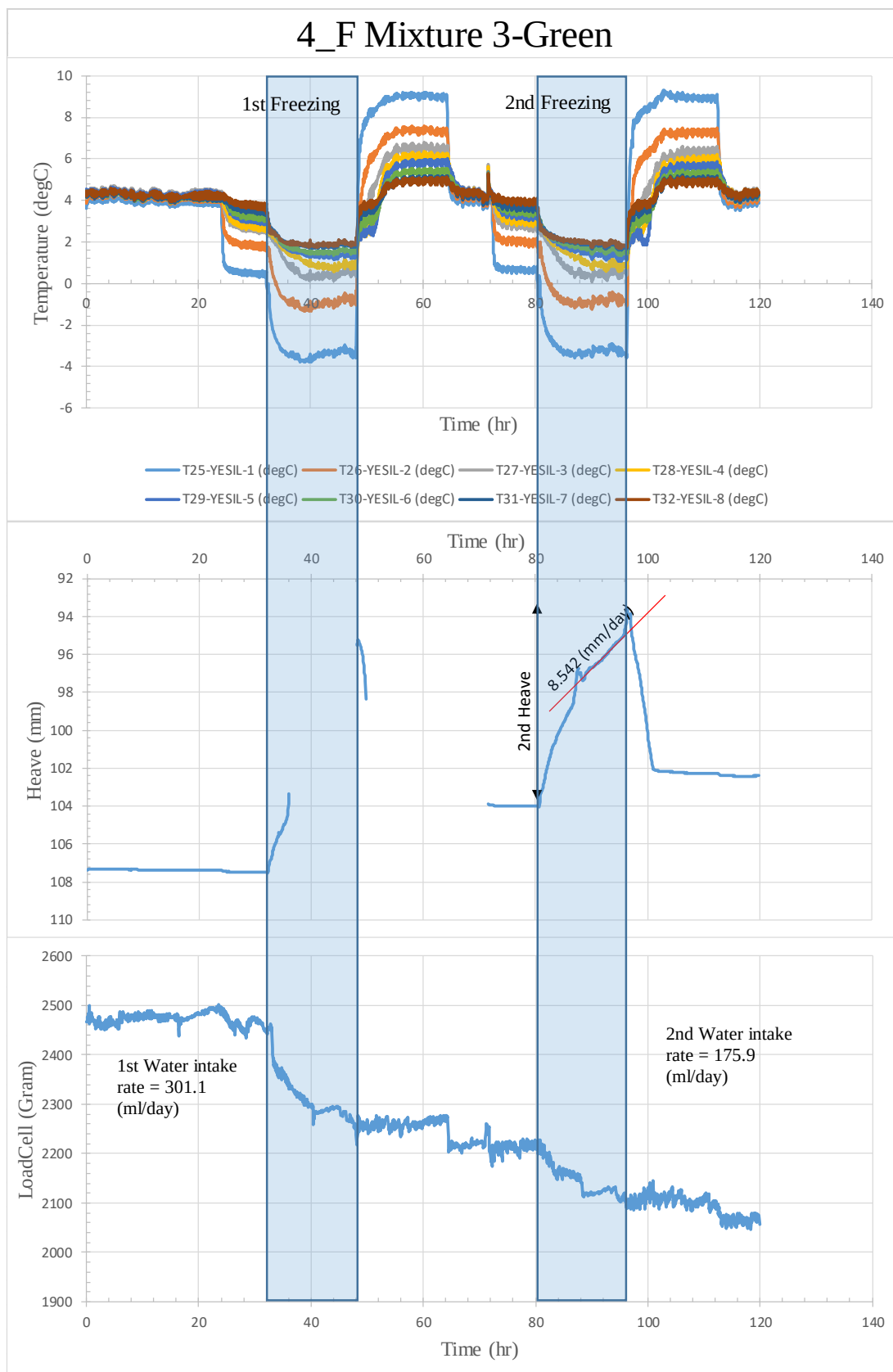


Figure C. 16 Freez-Thaw Test Results for “4_F Mix 4-Green”

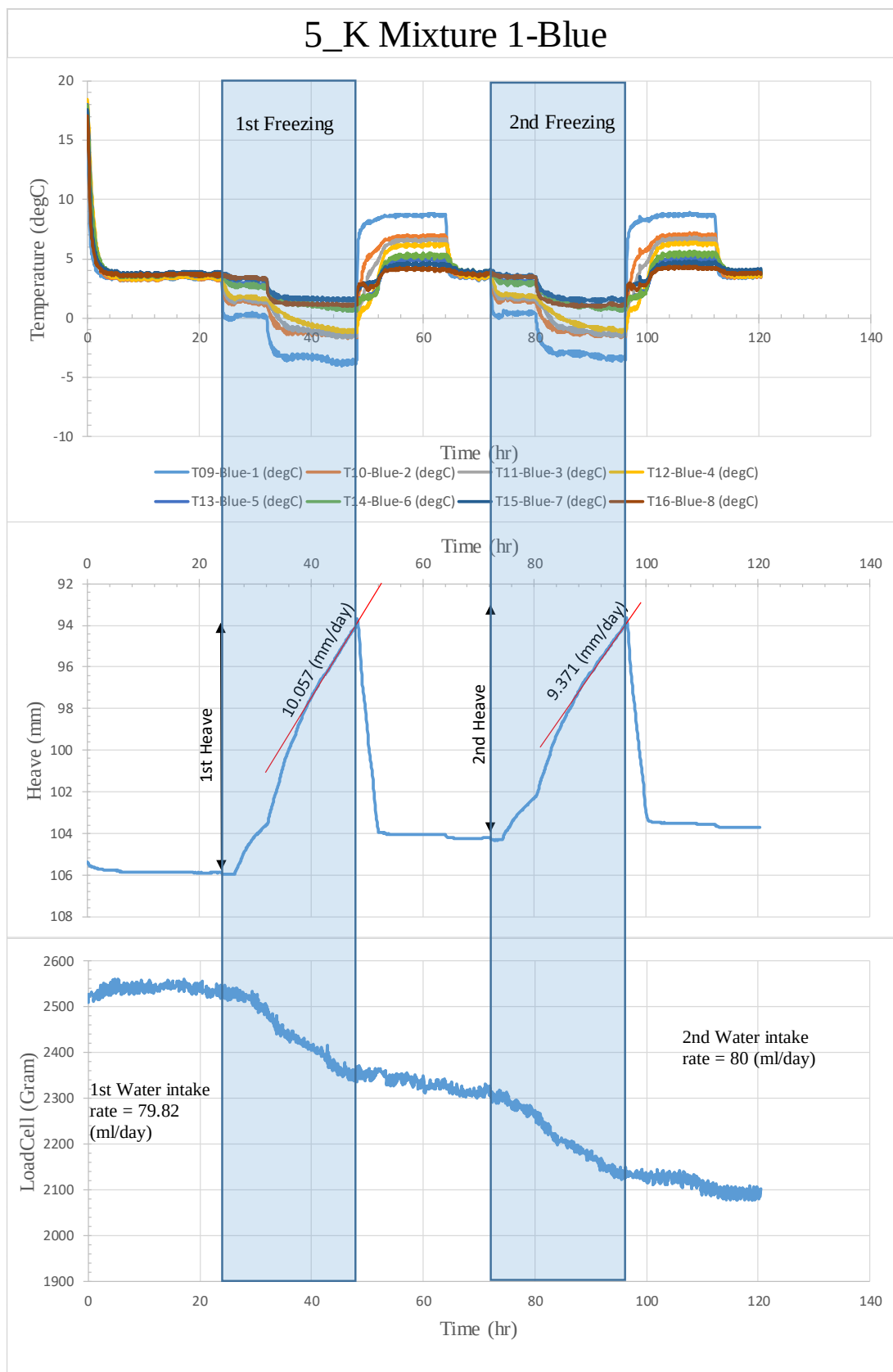


Figure C. 17 Freez-Thaw Test Results for “5_K Mix 1-Blue”

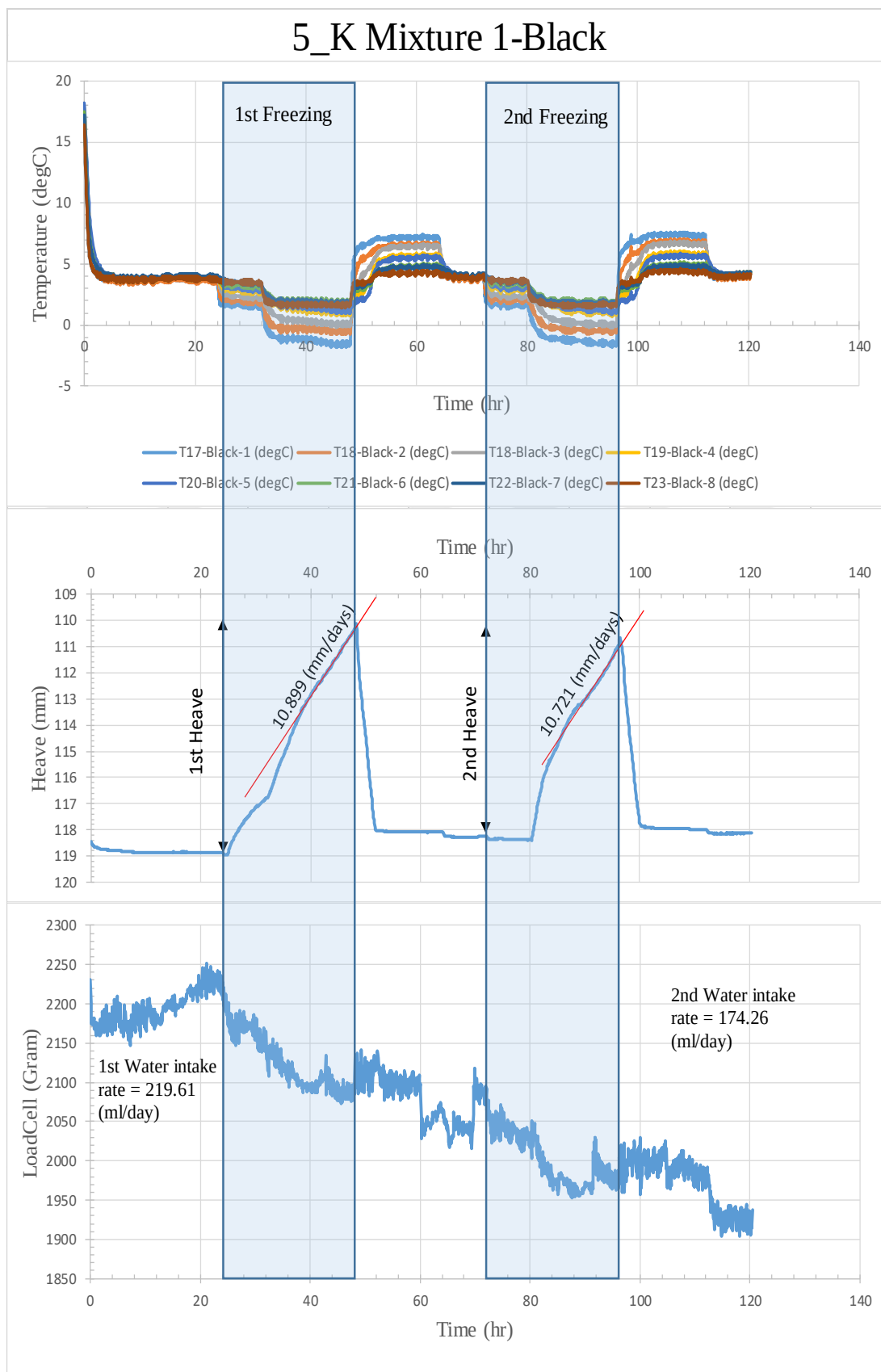


Figure C. 18 Freez-Thaw Test Results for “5_K Mix 1-Black”

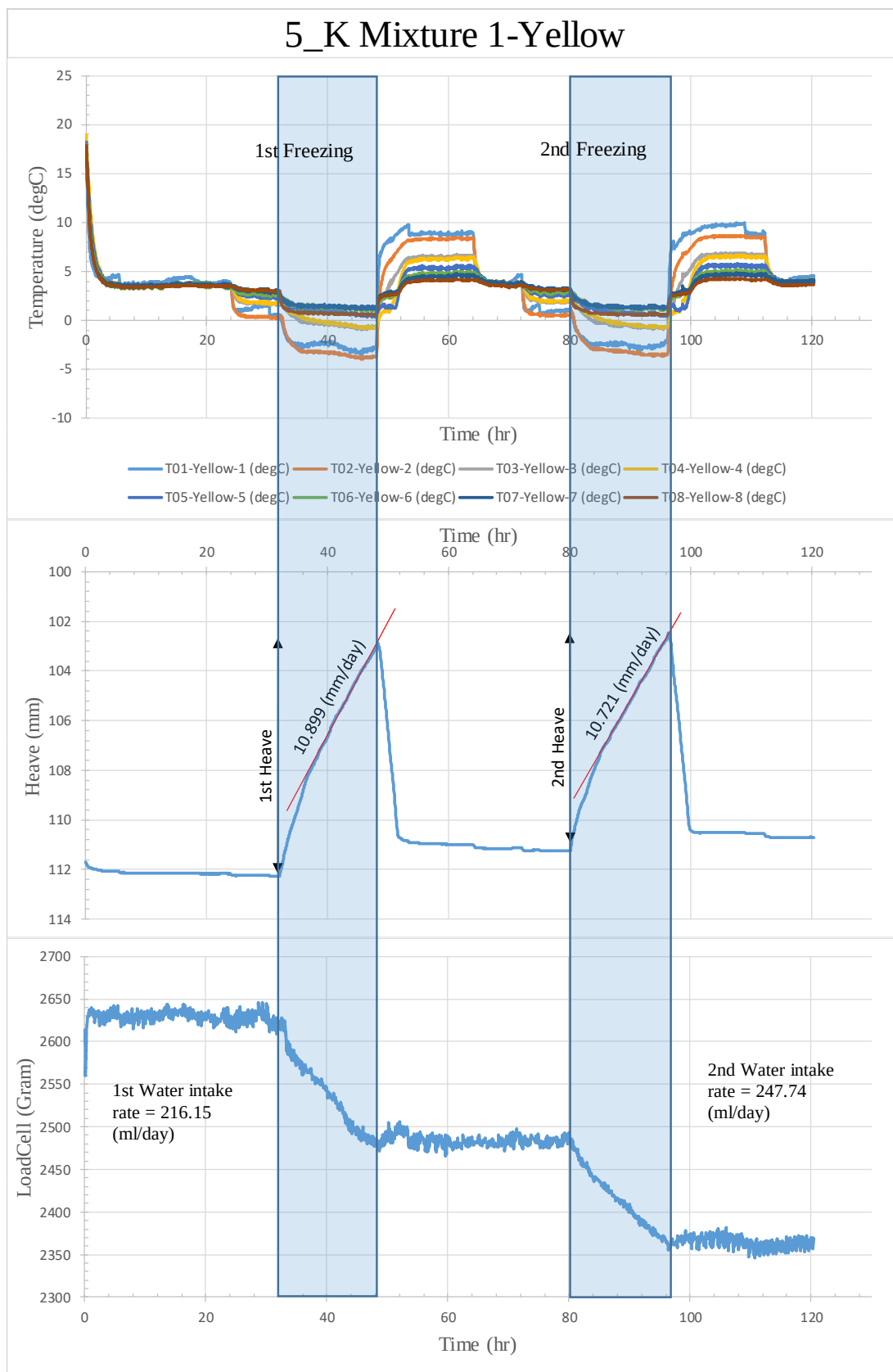


Figure C. 19 Freez-Thaw Test Results for “5_K Mix 1-Yellow”

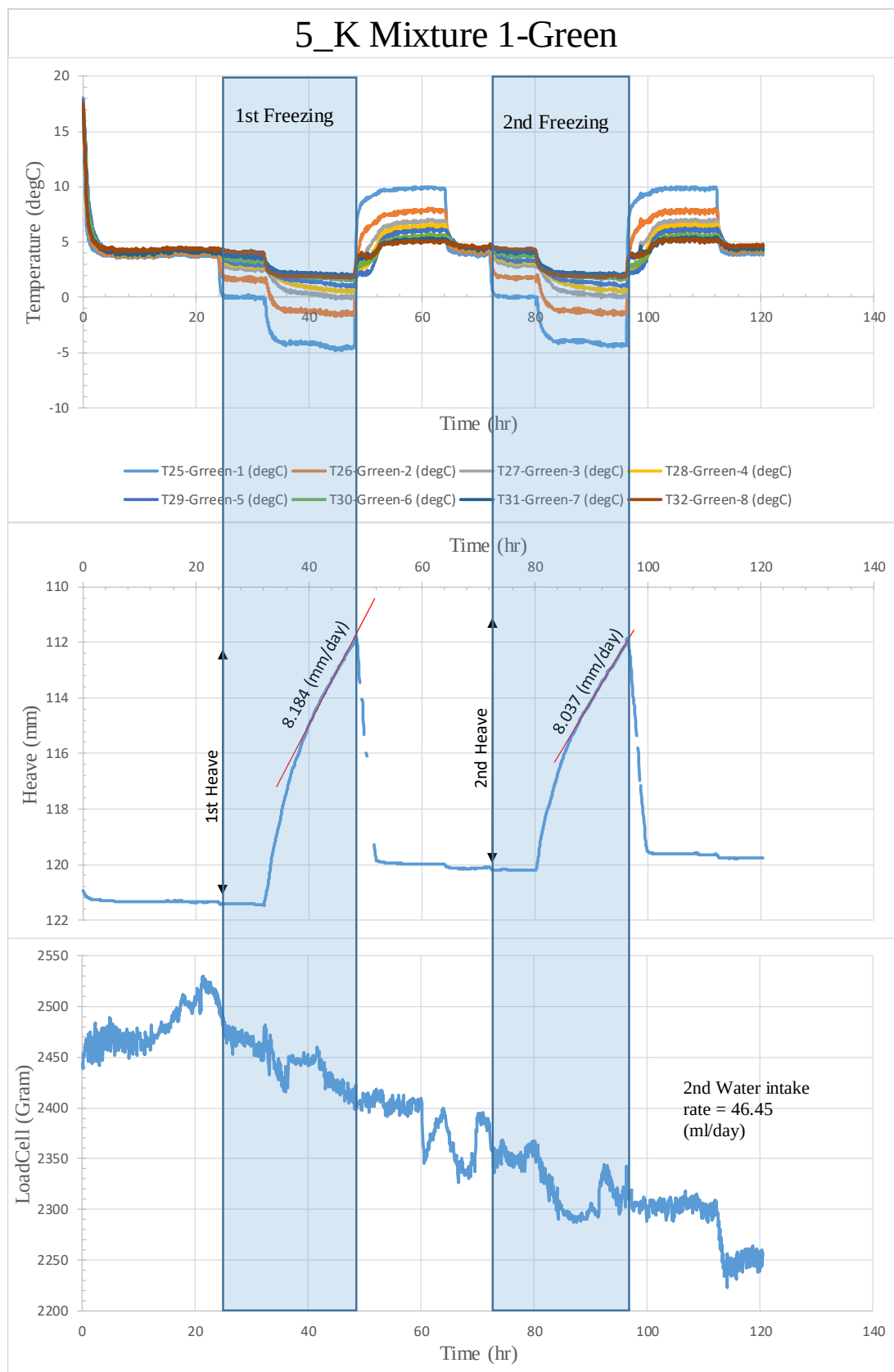


Figure C. 20 Freez-Thaw Test Results for “5_K Mix 1-Green”

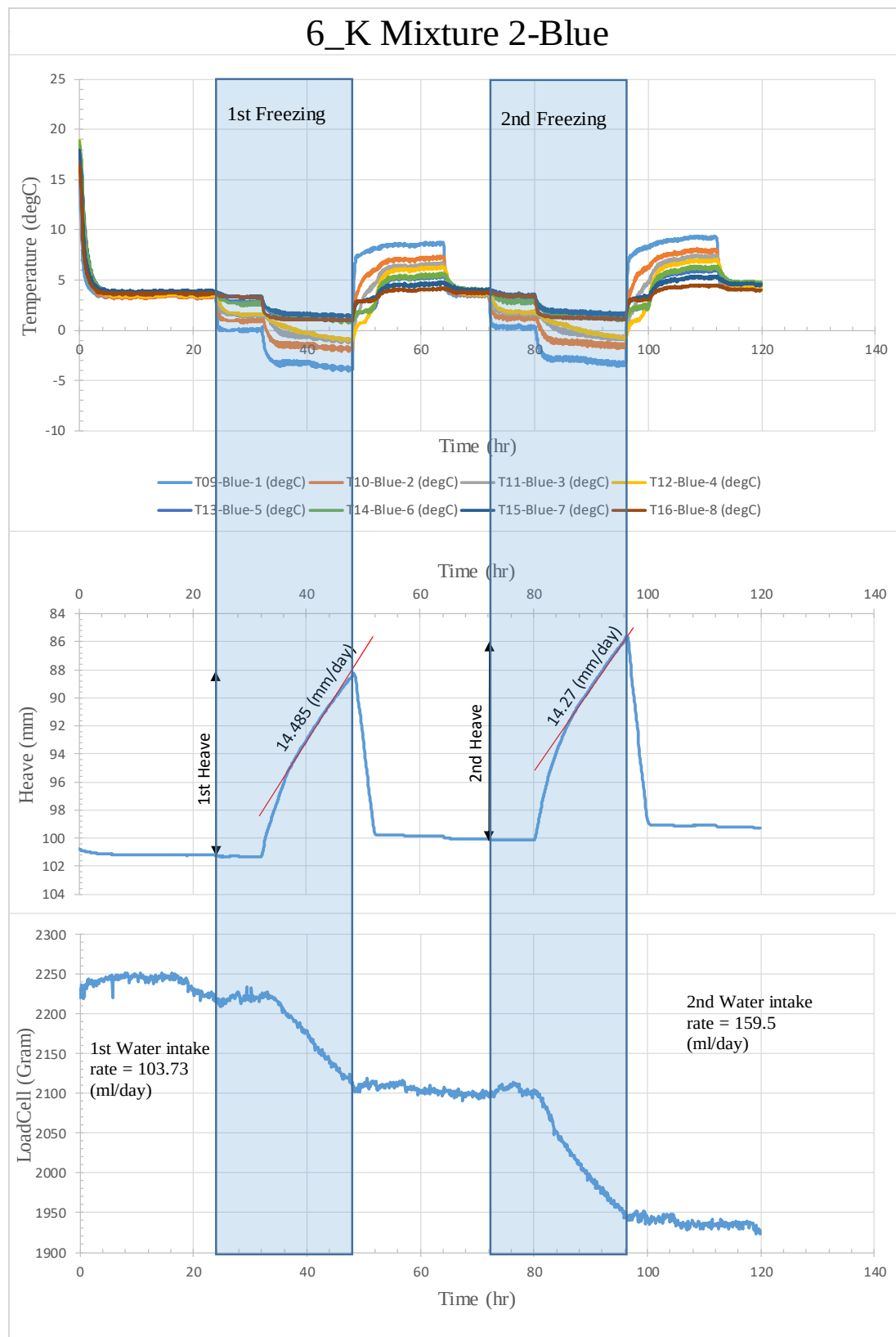


Figure C. 21 Freez-Thaw Test Results for “6_K Mix 2-Blue”

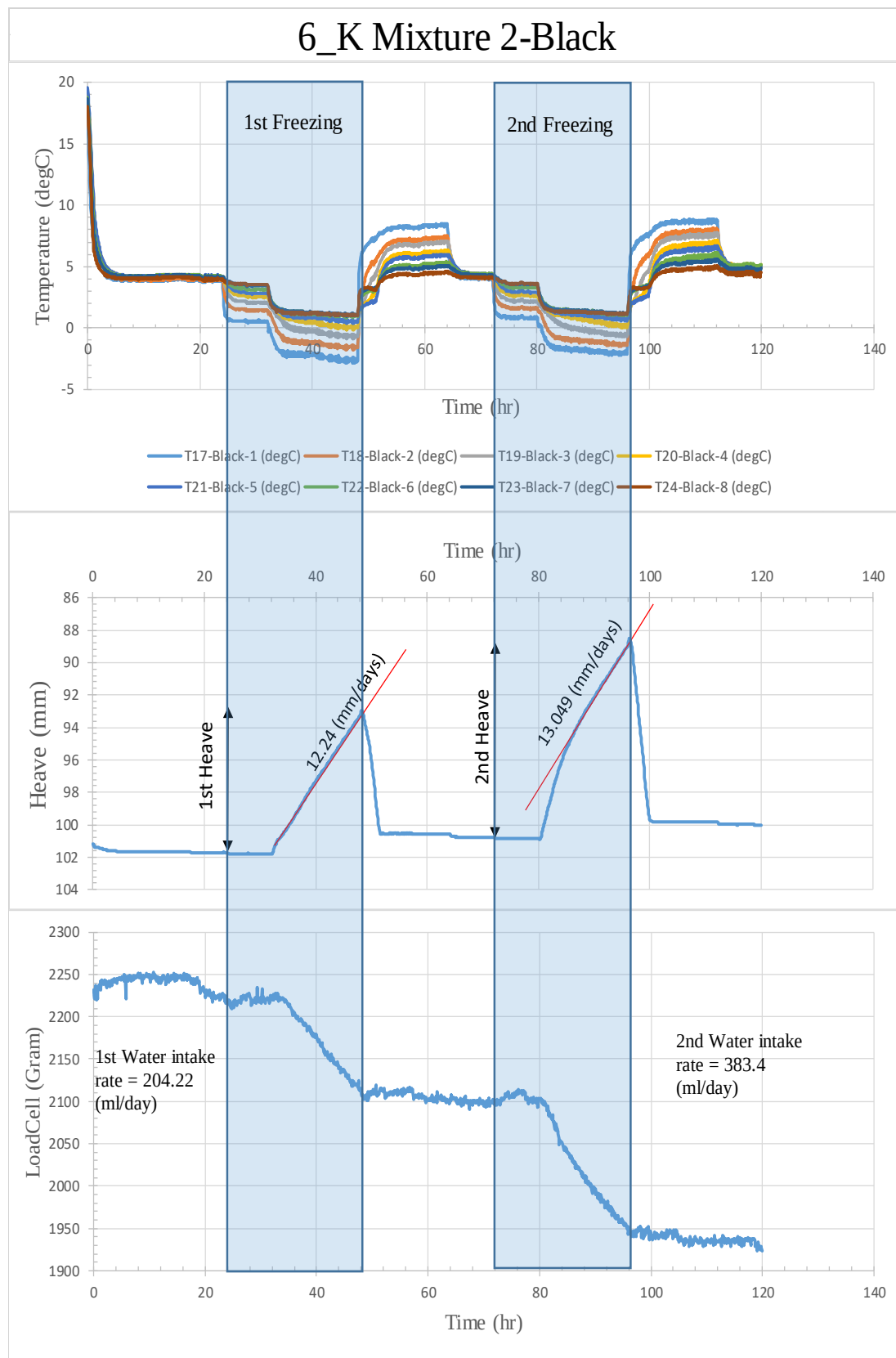


Figure C. 22 Freez-Thaw Test Results for “6_K Mix 2-Black”

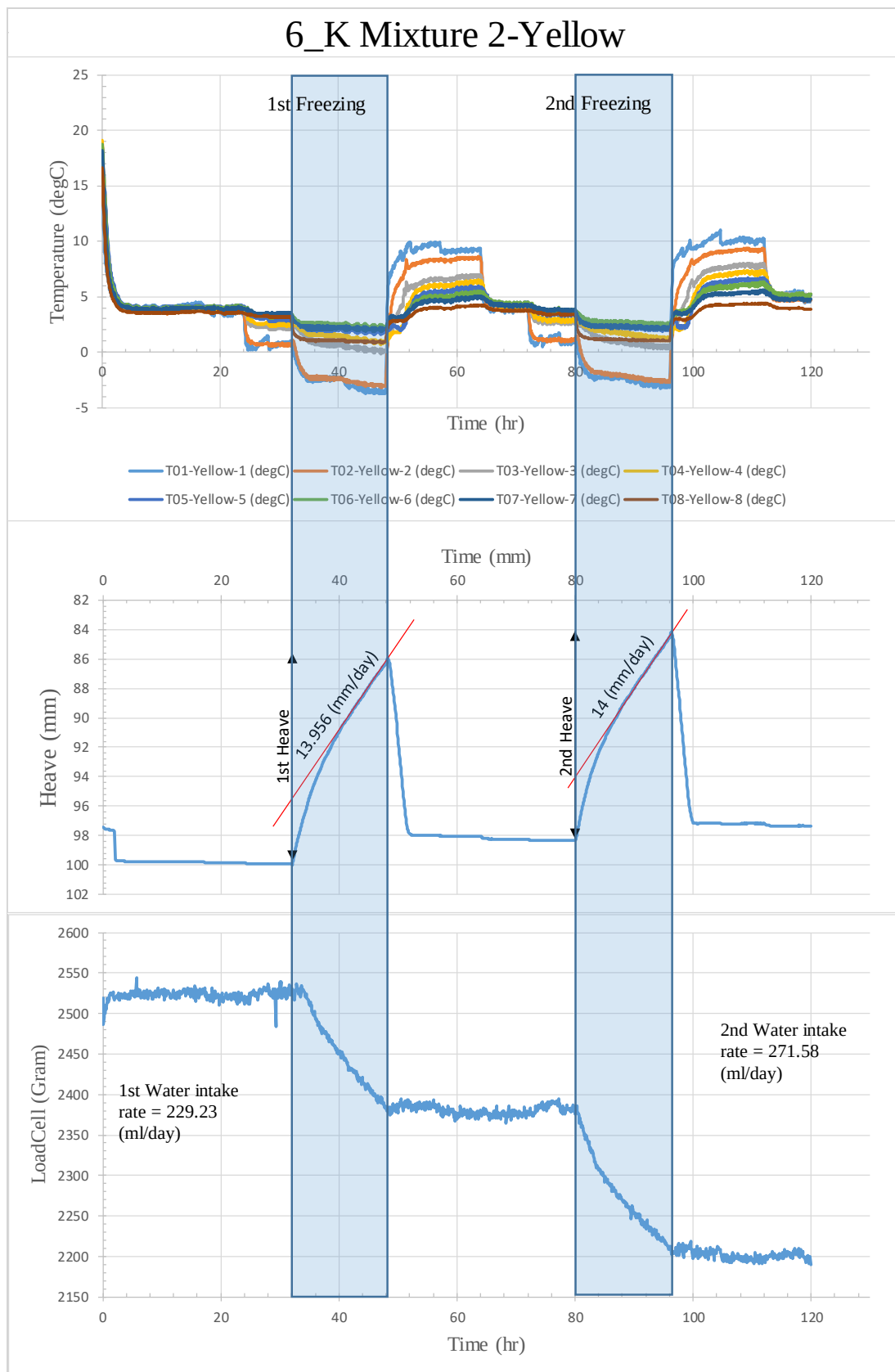


Figure C. 23 Freez-Thaw Test Results for “6_K Mix 2-Yellow”

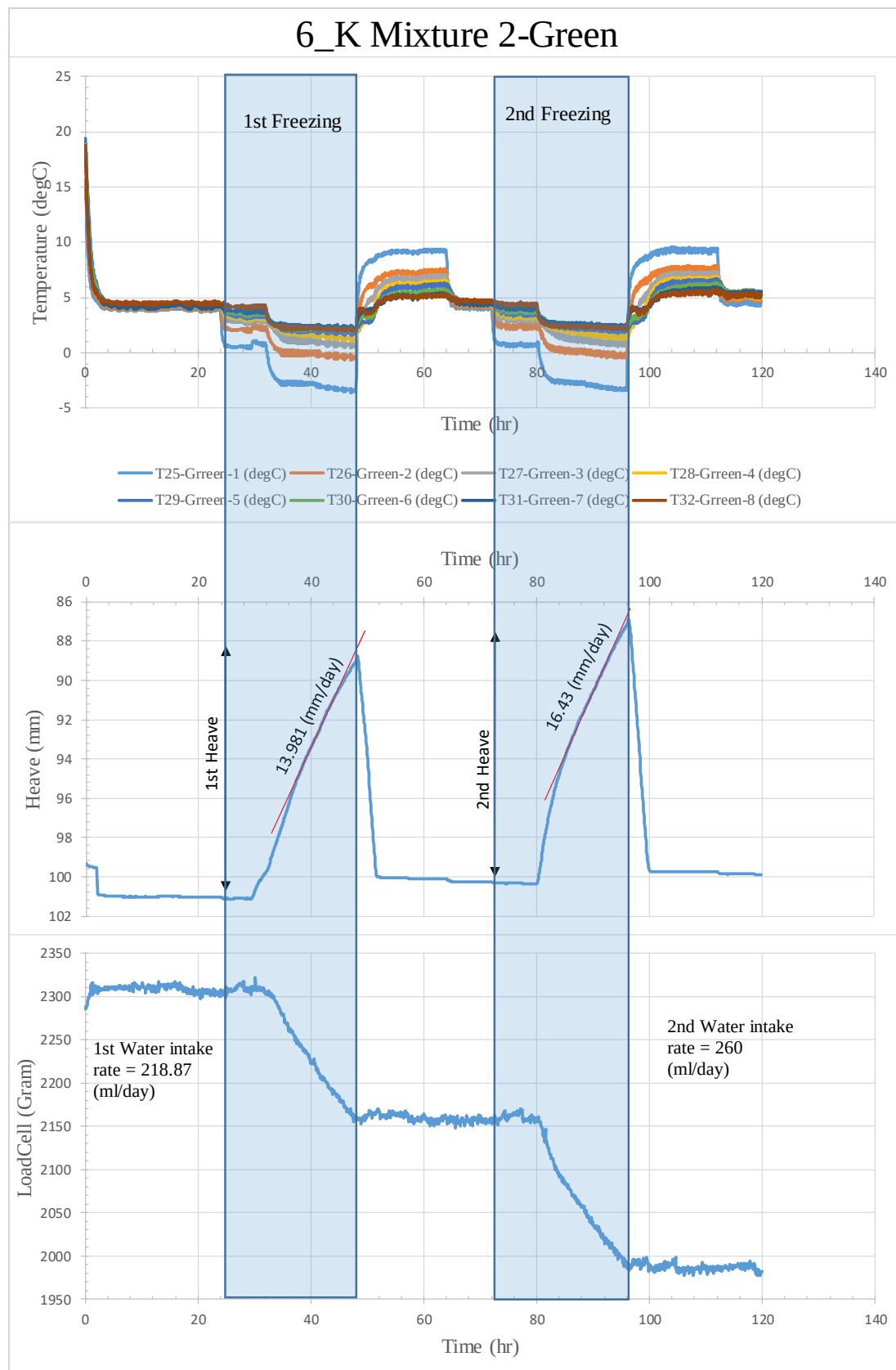


Figure C. 24 Freez-Thaw Test Results for “6_K Mix 2-Green”

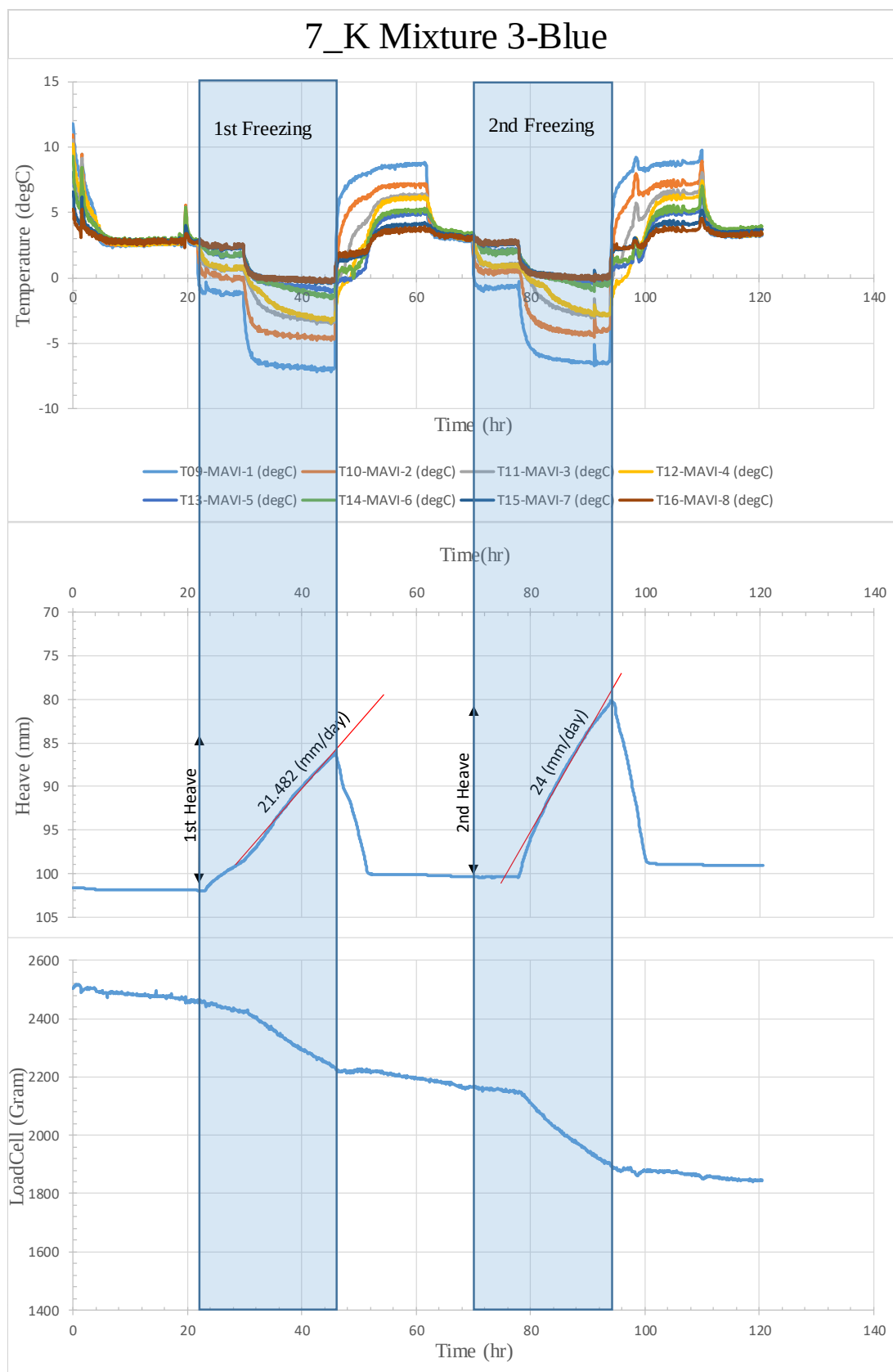


Figure C. 25 Freez-Thaw Test Results for “7_K Mix 3-Blue”

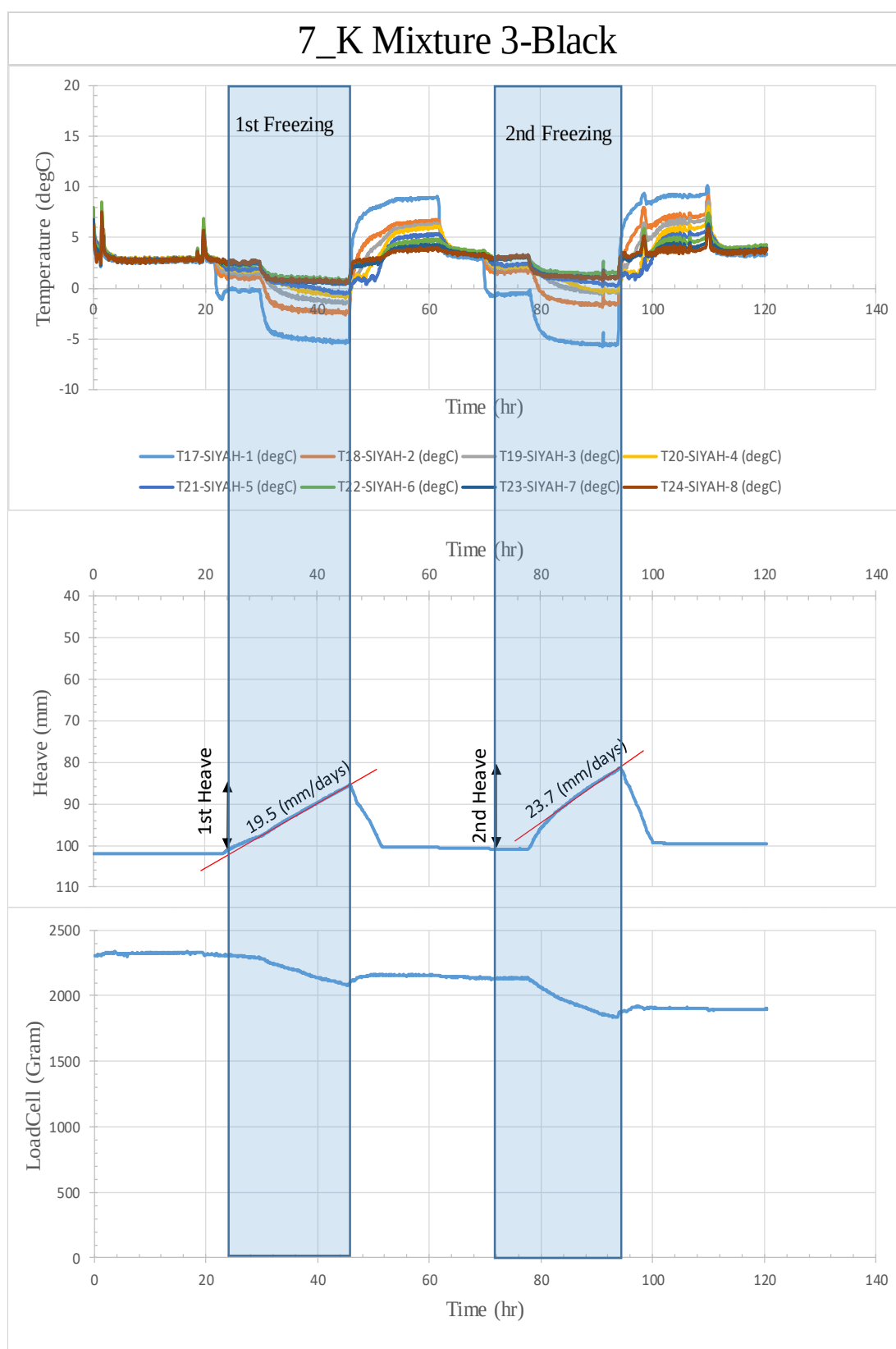


Figure C. 26 Freez-Thaw Test Results for “7_K Mix 3-Black”

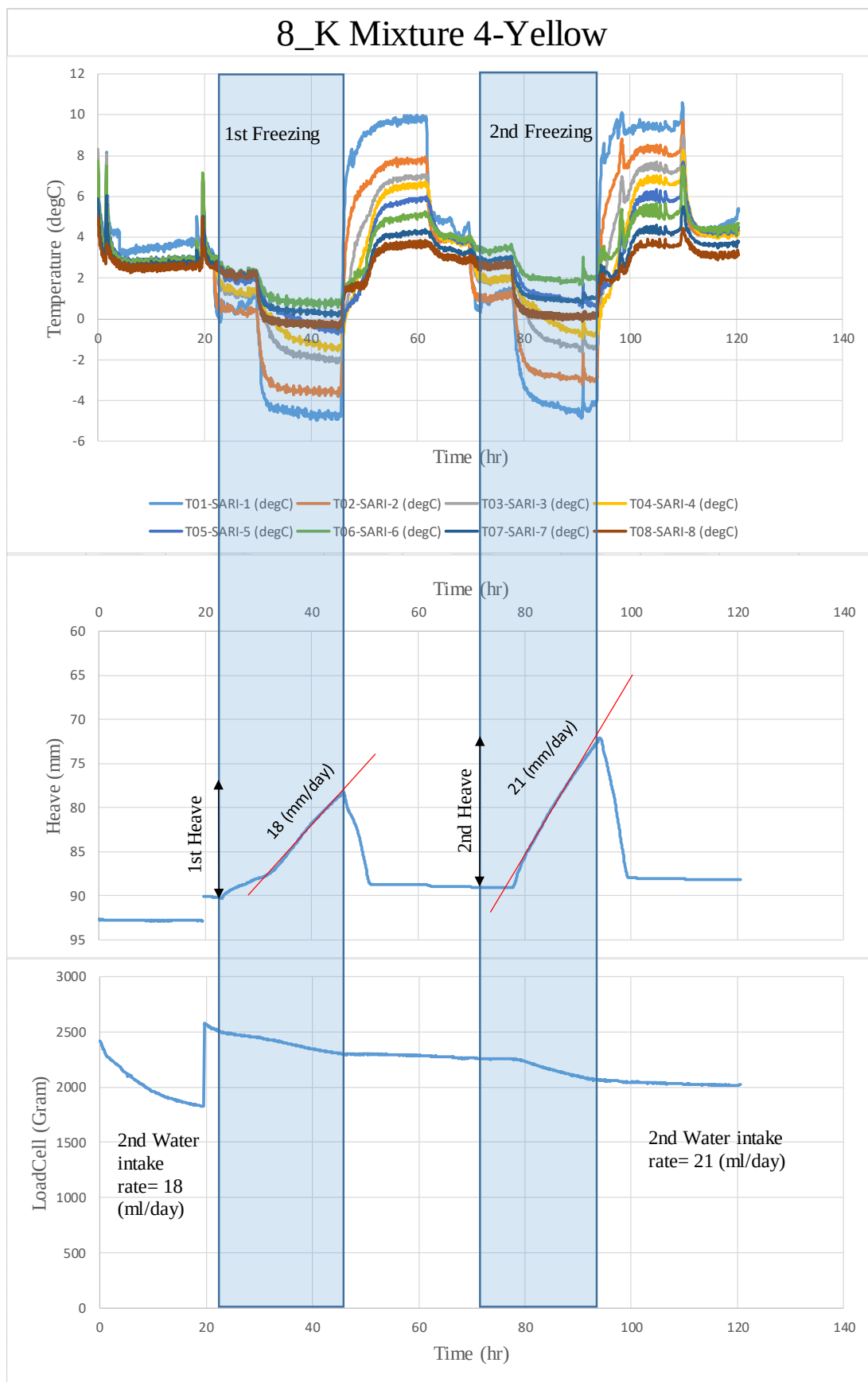


Figure C. 27 Freez-Thaw Test Results for “8_K Mix 4-Yellow”

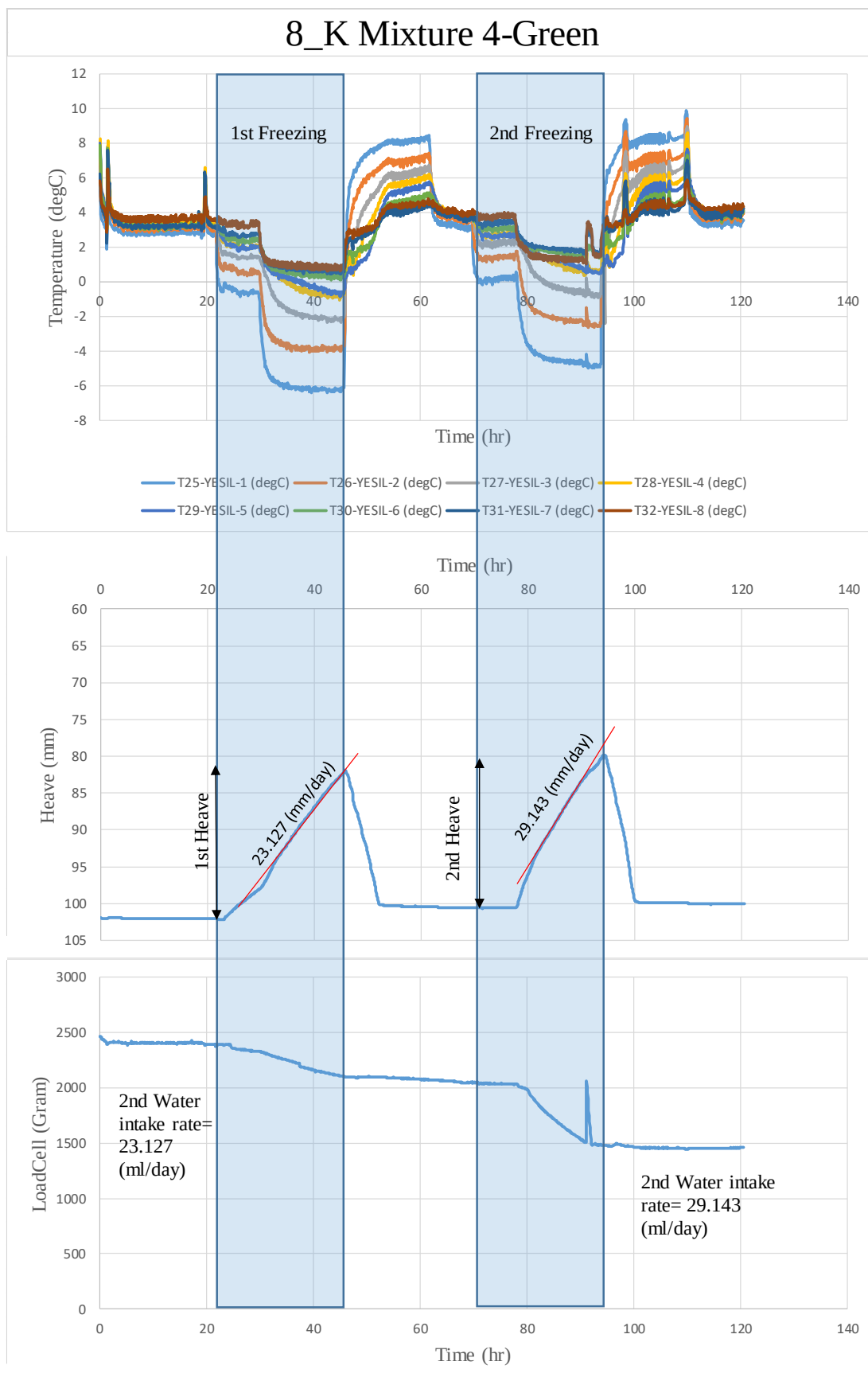


Figure C. 28 Freez-Thaw Test Results for “8_K Mix 4-Green”

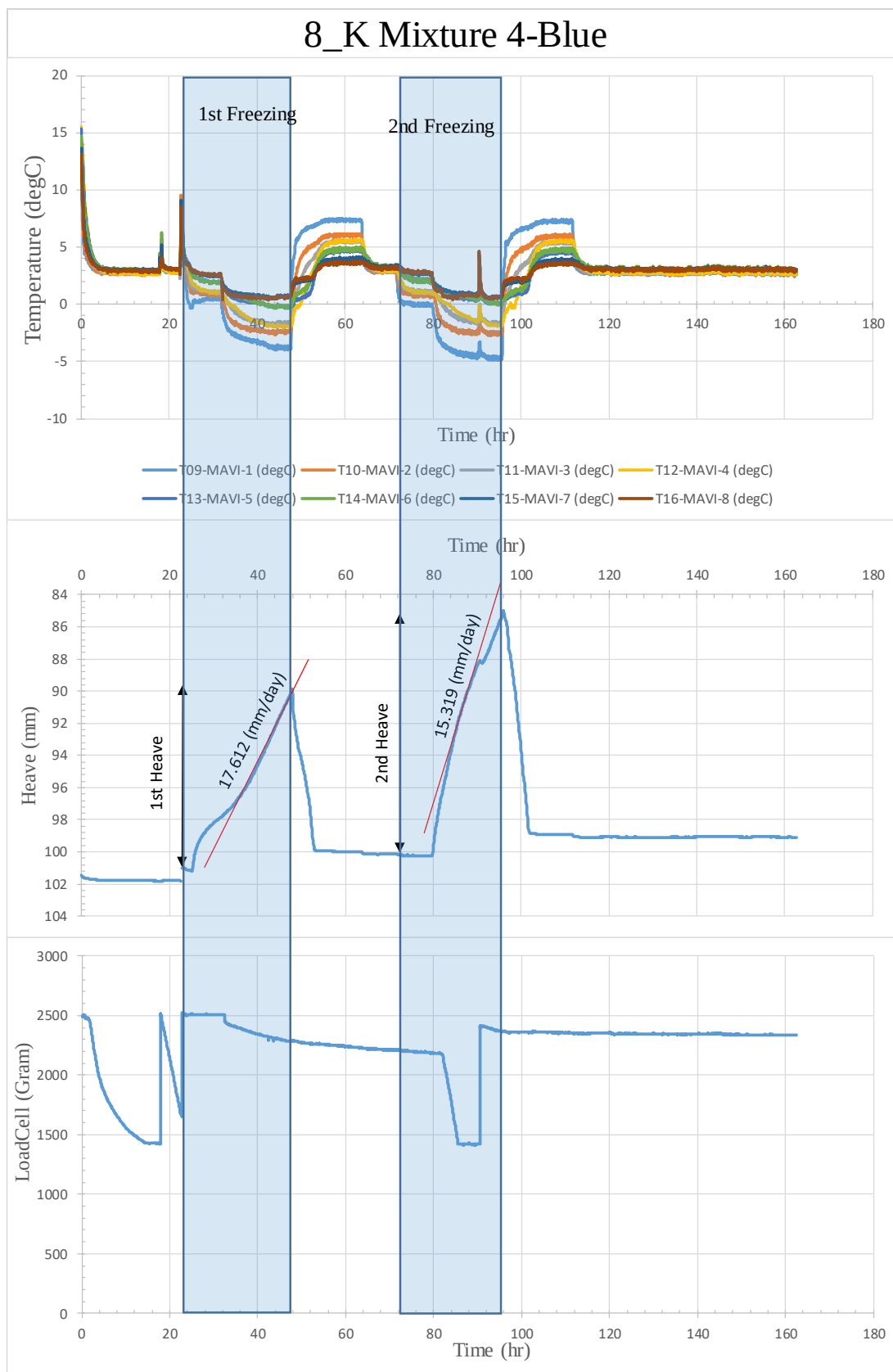


Figure C. 29 Freez-Thaw Test Results for “8_K Mix 4-Blue”

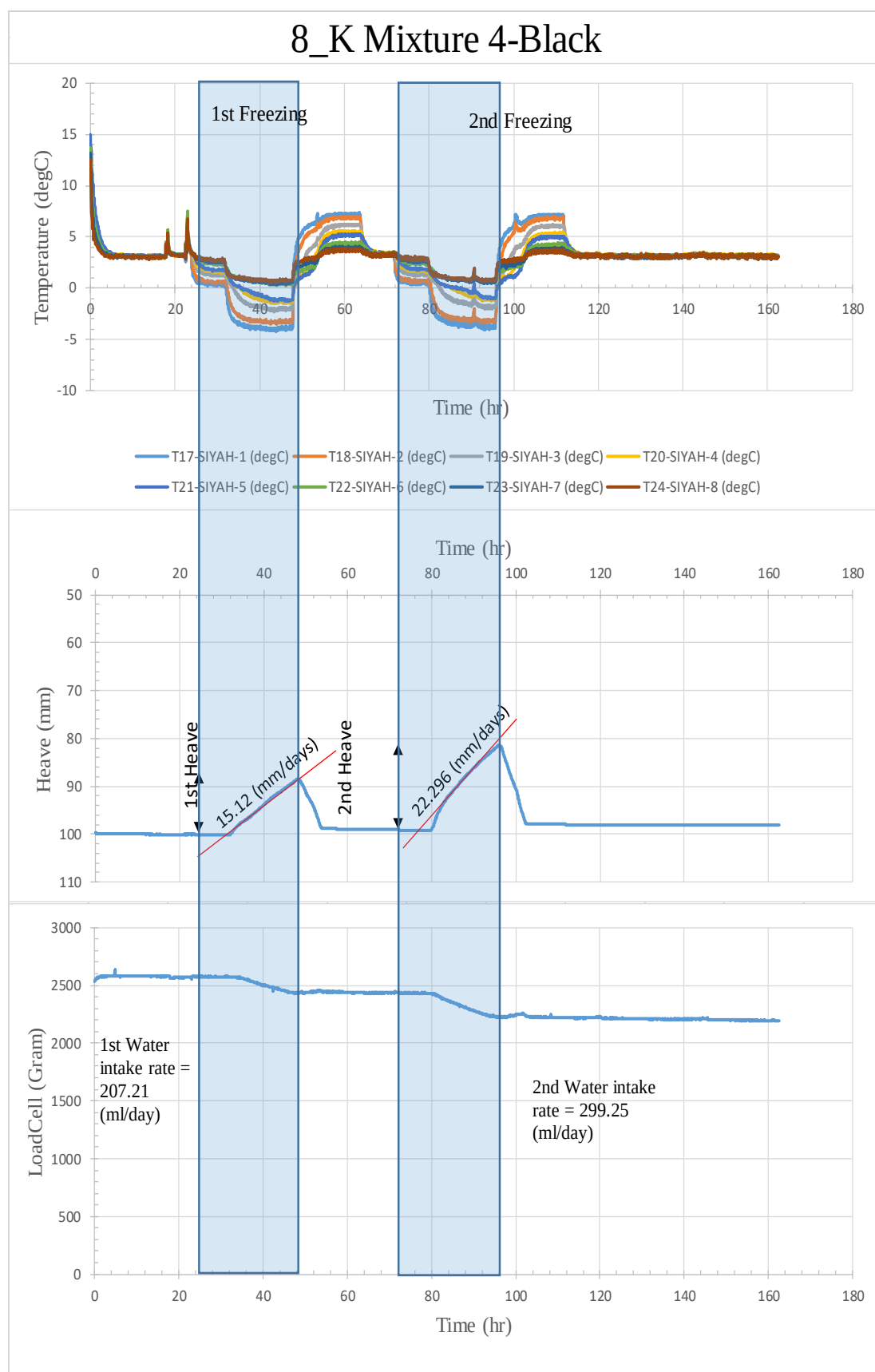


Figure C. 30 Freez-Thaw Test Results for “8_K Mix 4-Black”

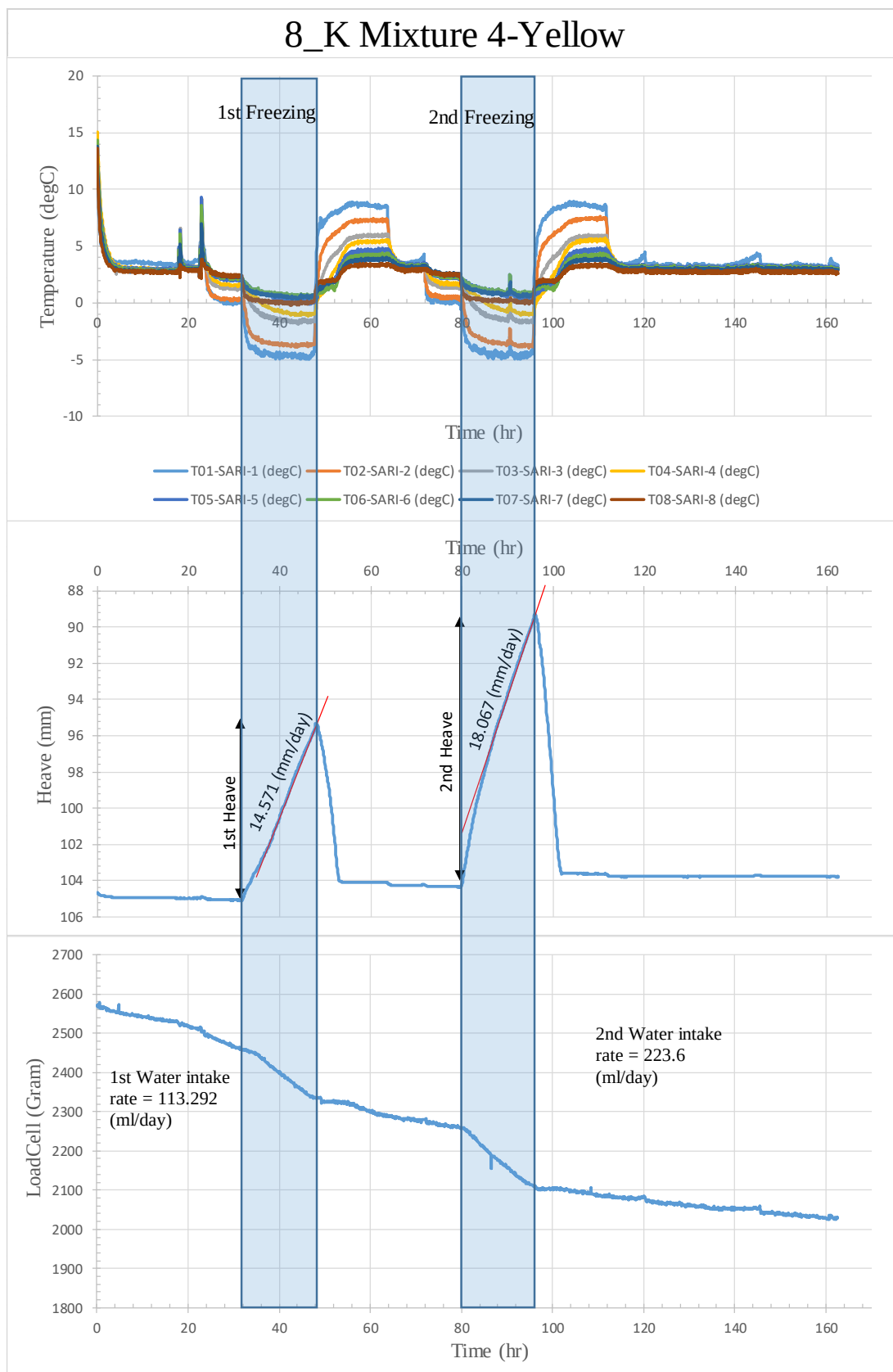


Figure C. 31 Freez-Thaw Test Results for “8_K Mix 4-Yellow”

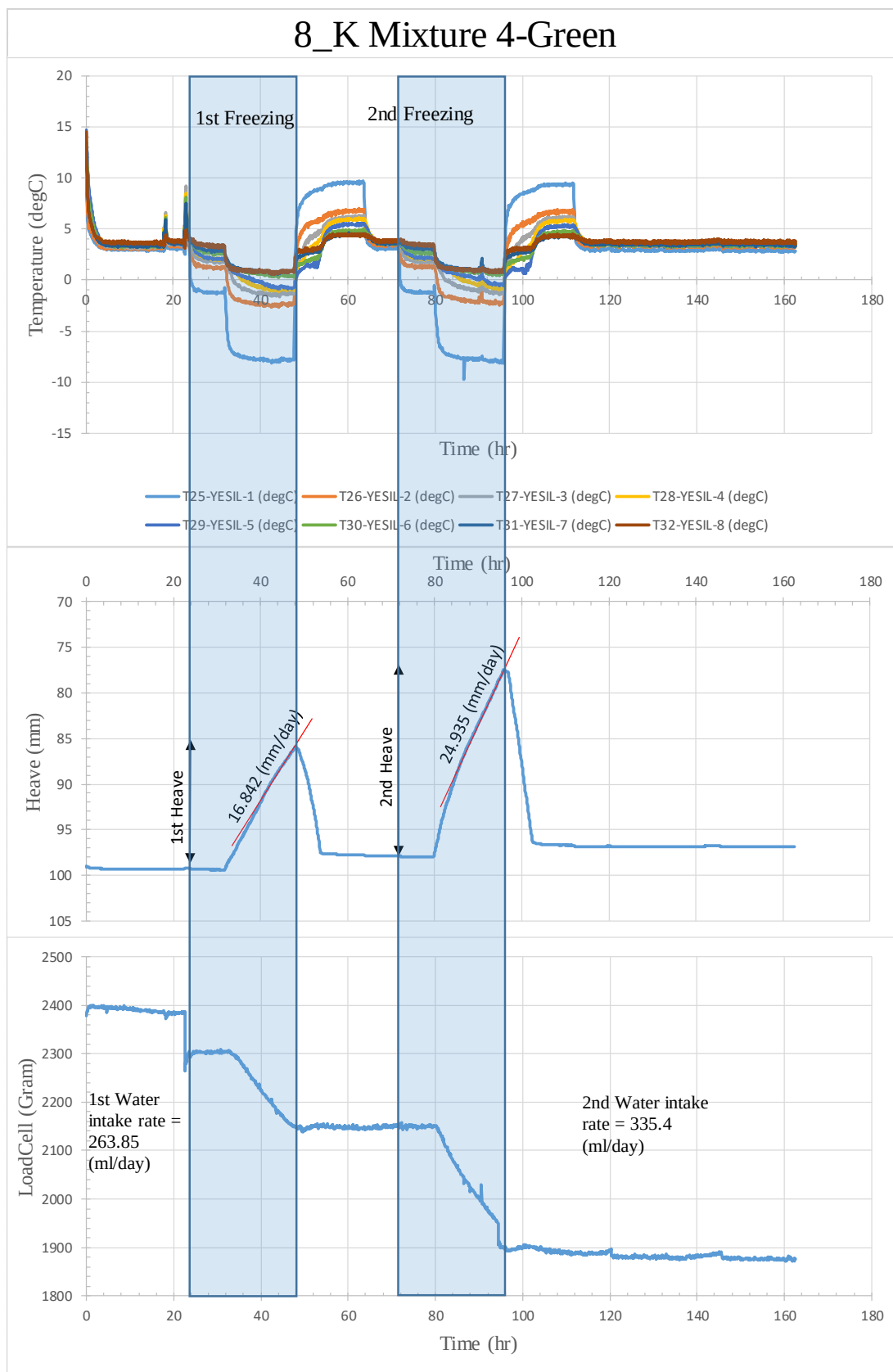


Figure C. 32 Freez-Thaw Test Results for “8_K Mix 4-Green”

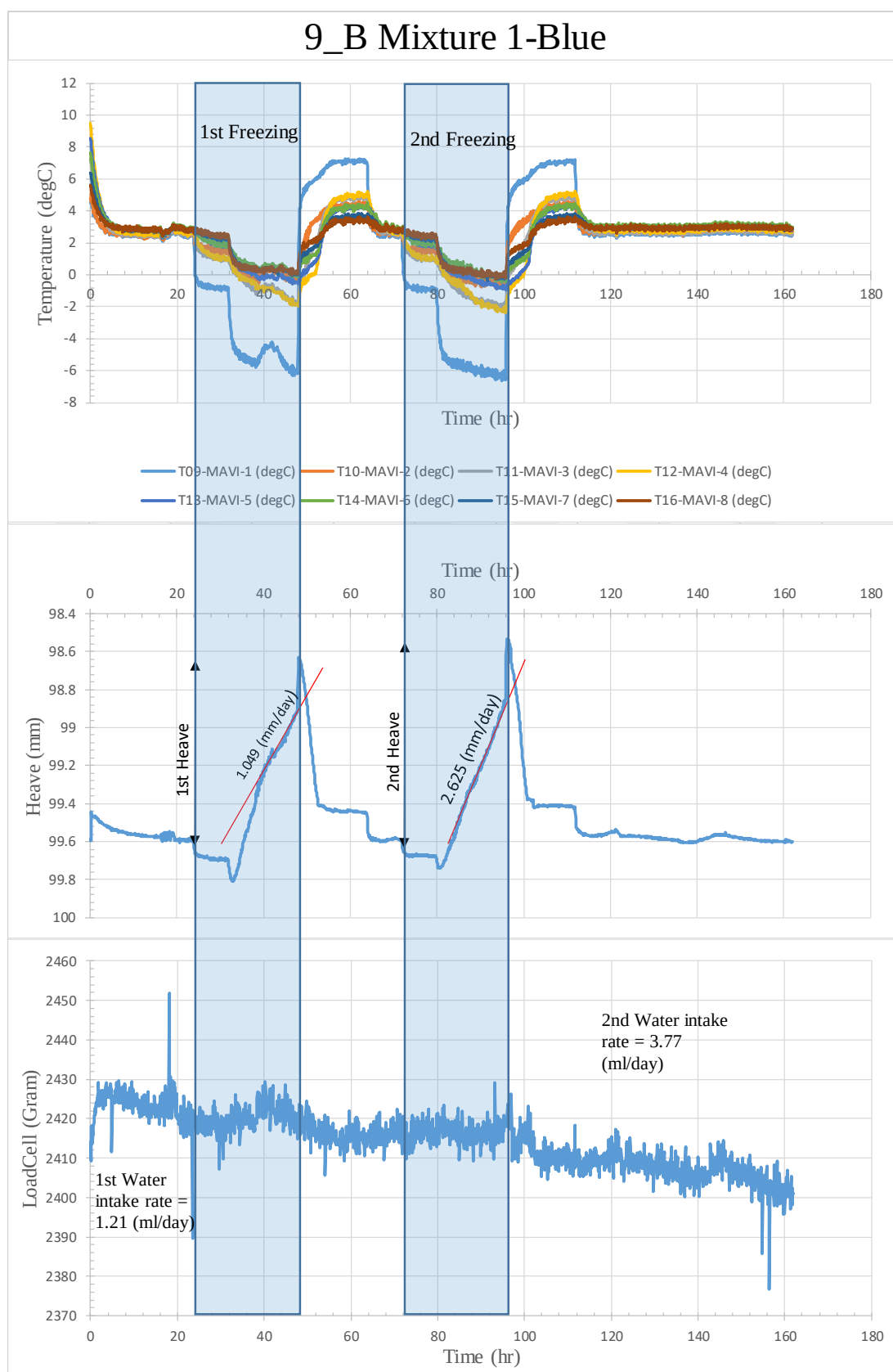


Figure C. 33 Freez-Thaw Test Results for “9_B Mix 1-Blue”

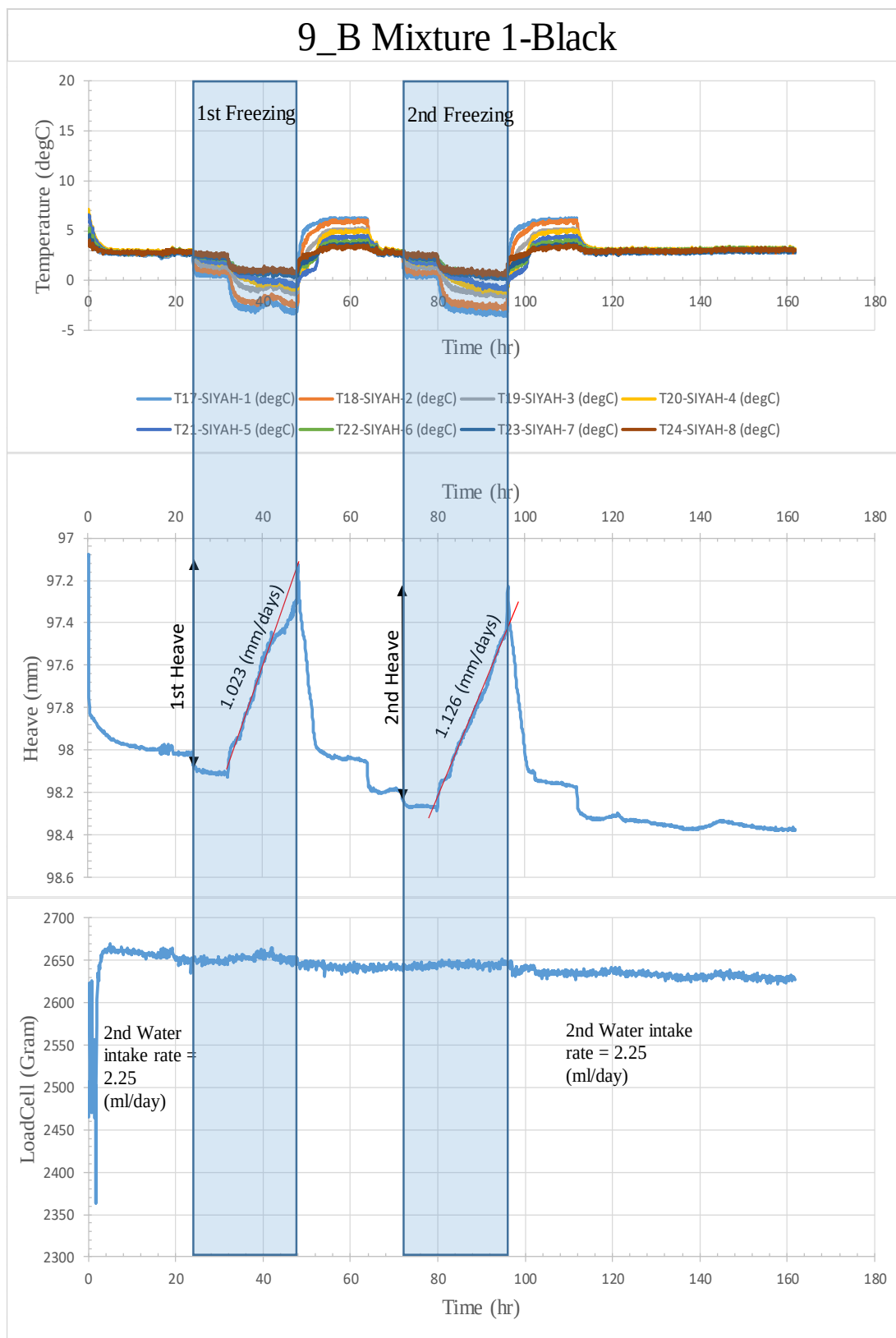


Figure C. 34 Freez-Thaw Test Results for “9_B Mix 1-Black”

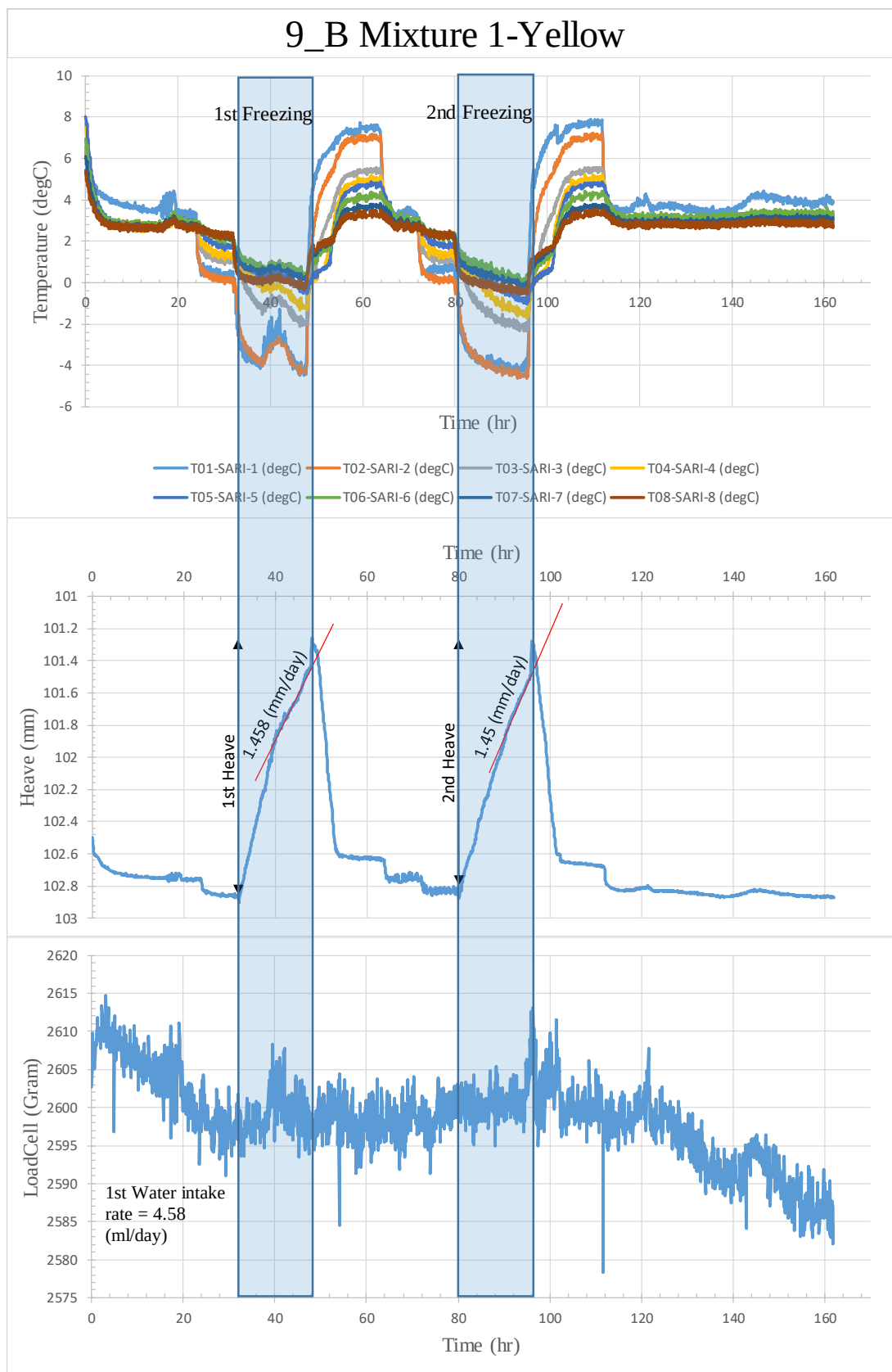


Figure C. 35 Freez-Thaw Test Results for “9_B Mix 1-Yellow”

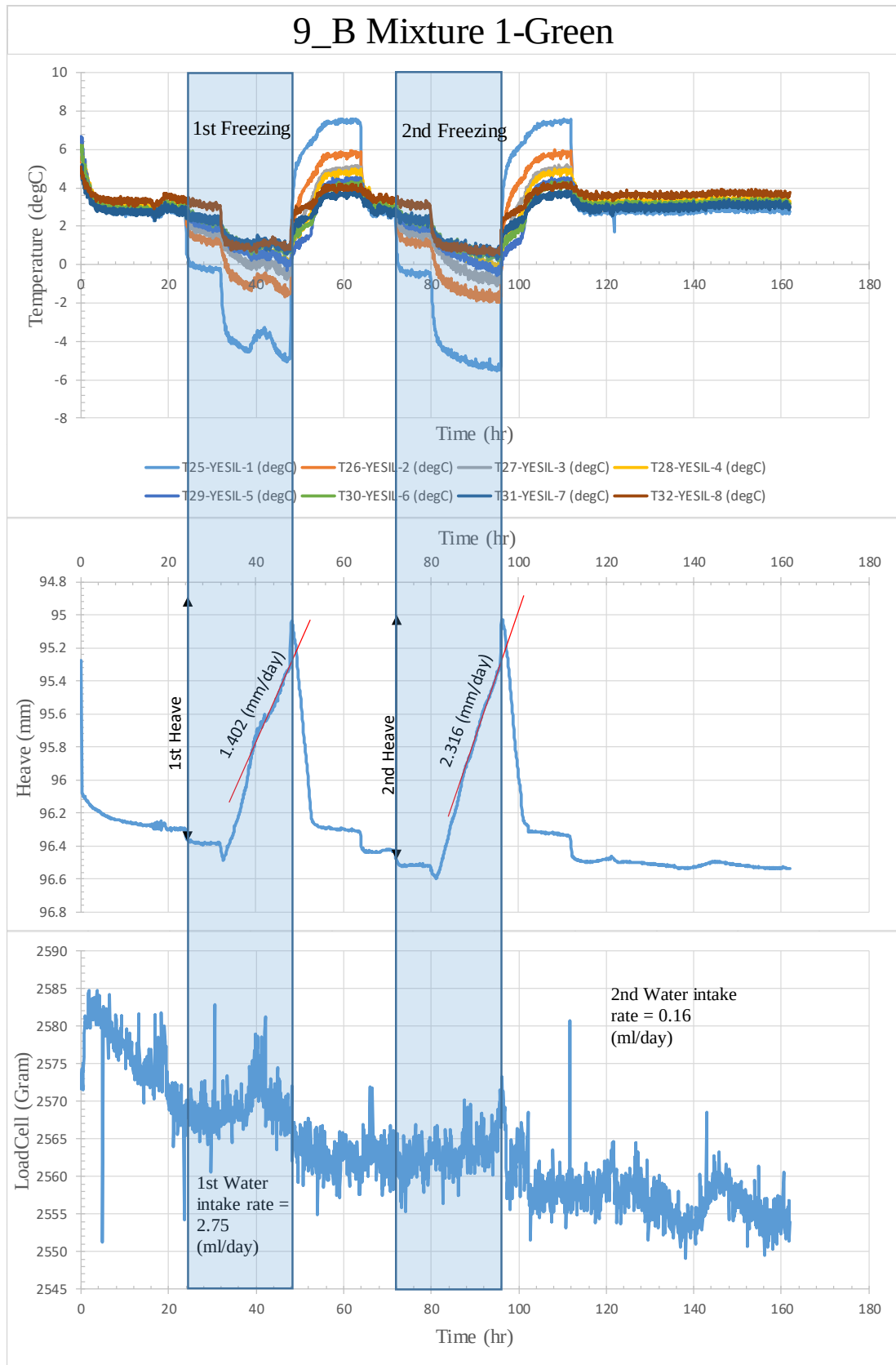


Figure C. 36 Freez-Thaw Test Results for “9_B Mix 1-Green”

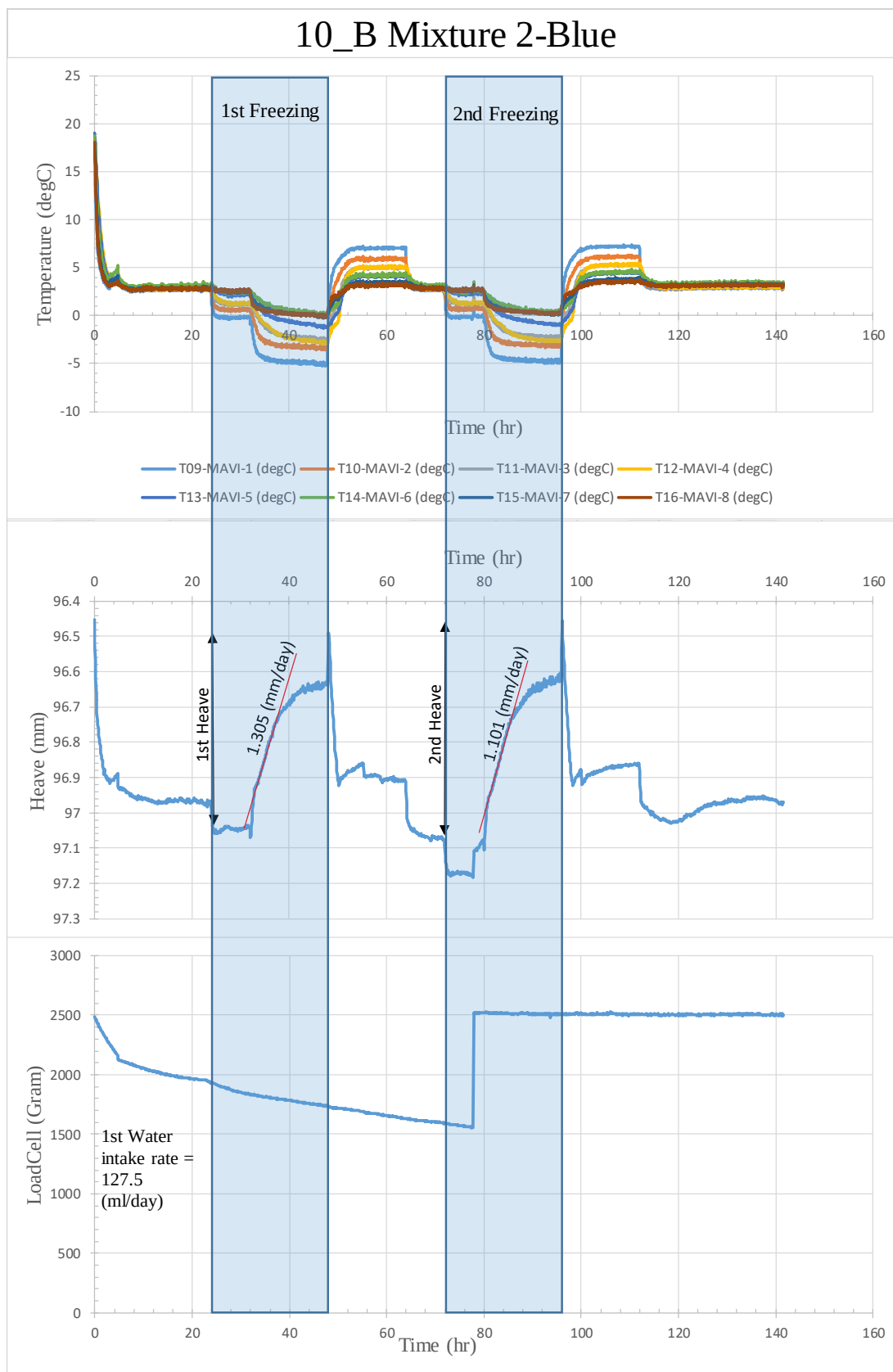


Figure C. 37 Freez-Thaw Test Results for “10_B Mix 2-Blue”

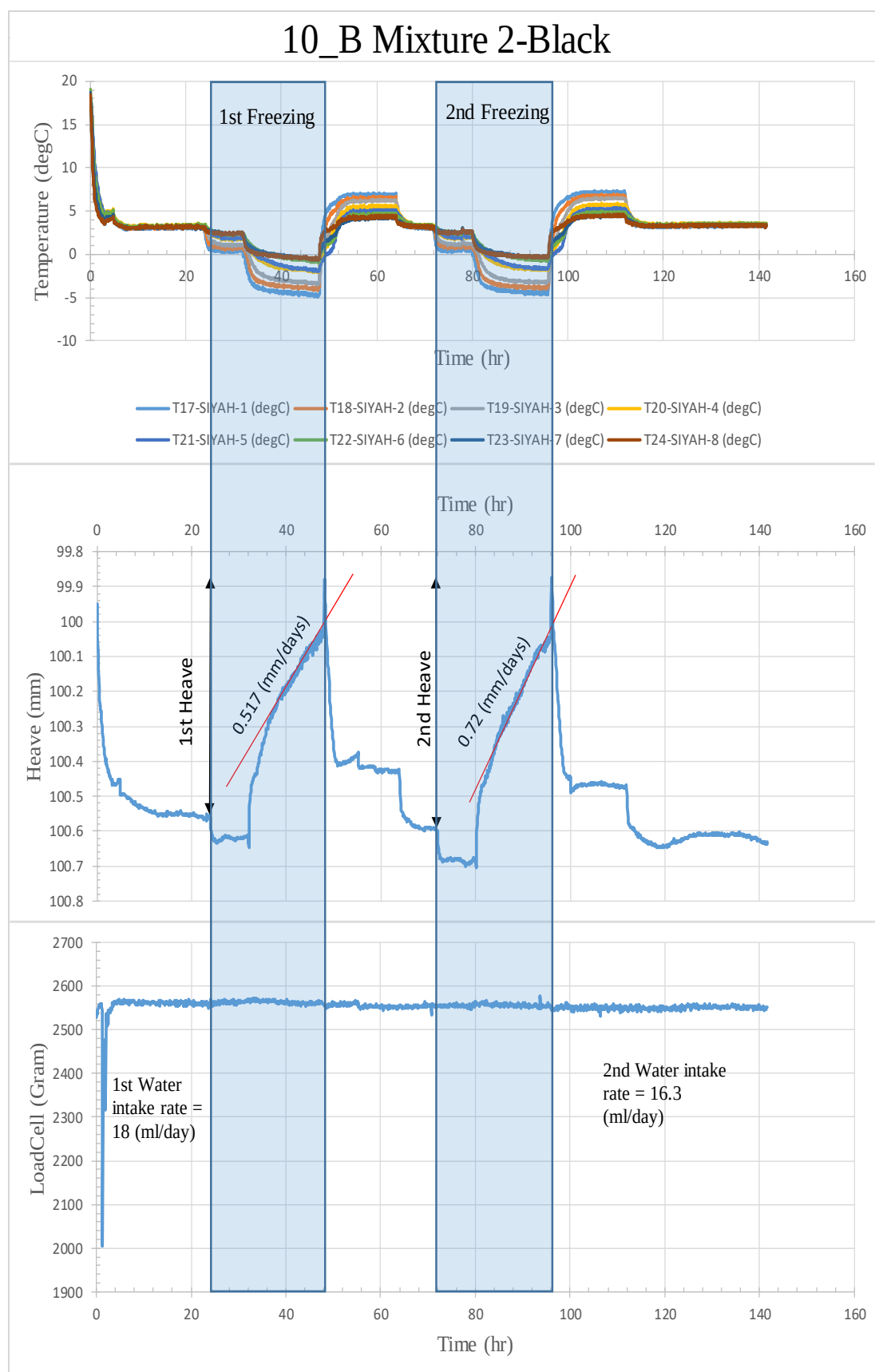


Figure C. 38 Freez-Thaw Test Results for “10_B Mix 2-Black”

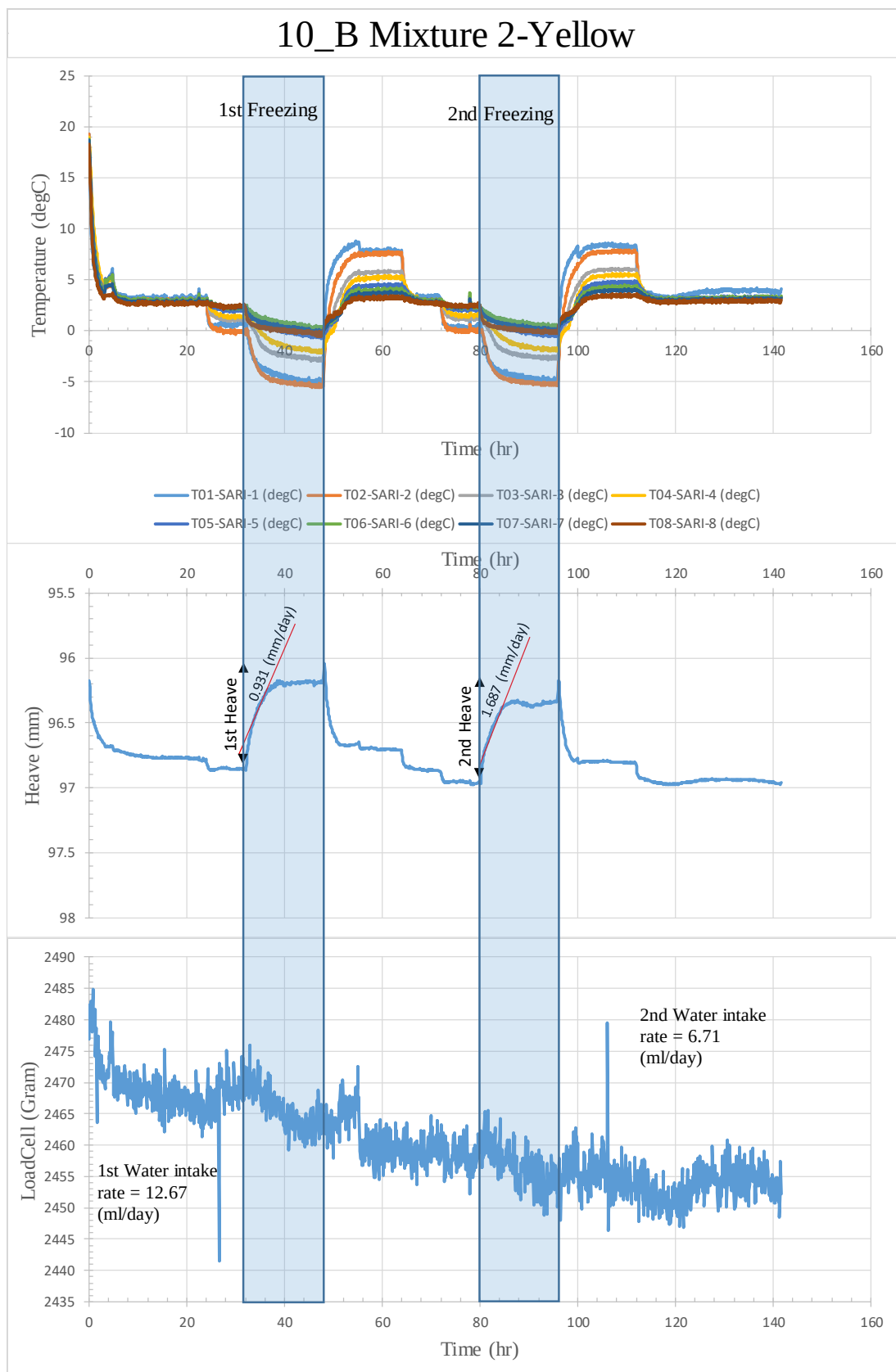


Figure C. 39 Freez-Thaw Test Results for “10_B Mix 2-Yellow”

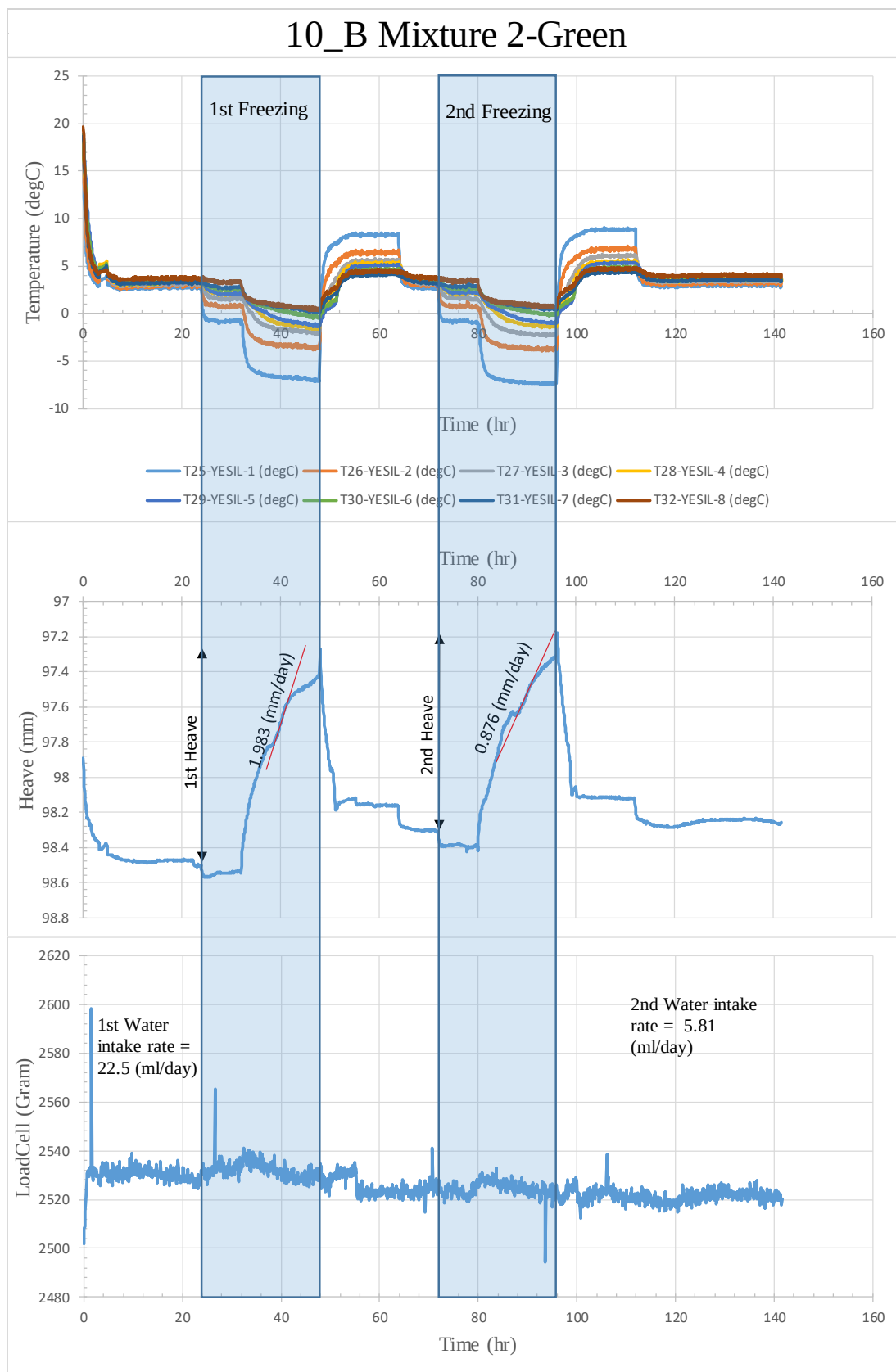


Figure C. 40 Freez-Thaw Test Results for “10_B Mix 2-Green”

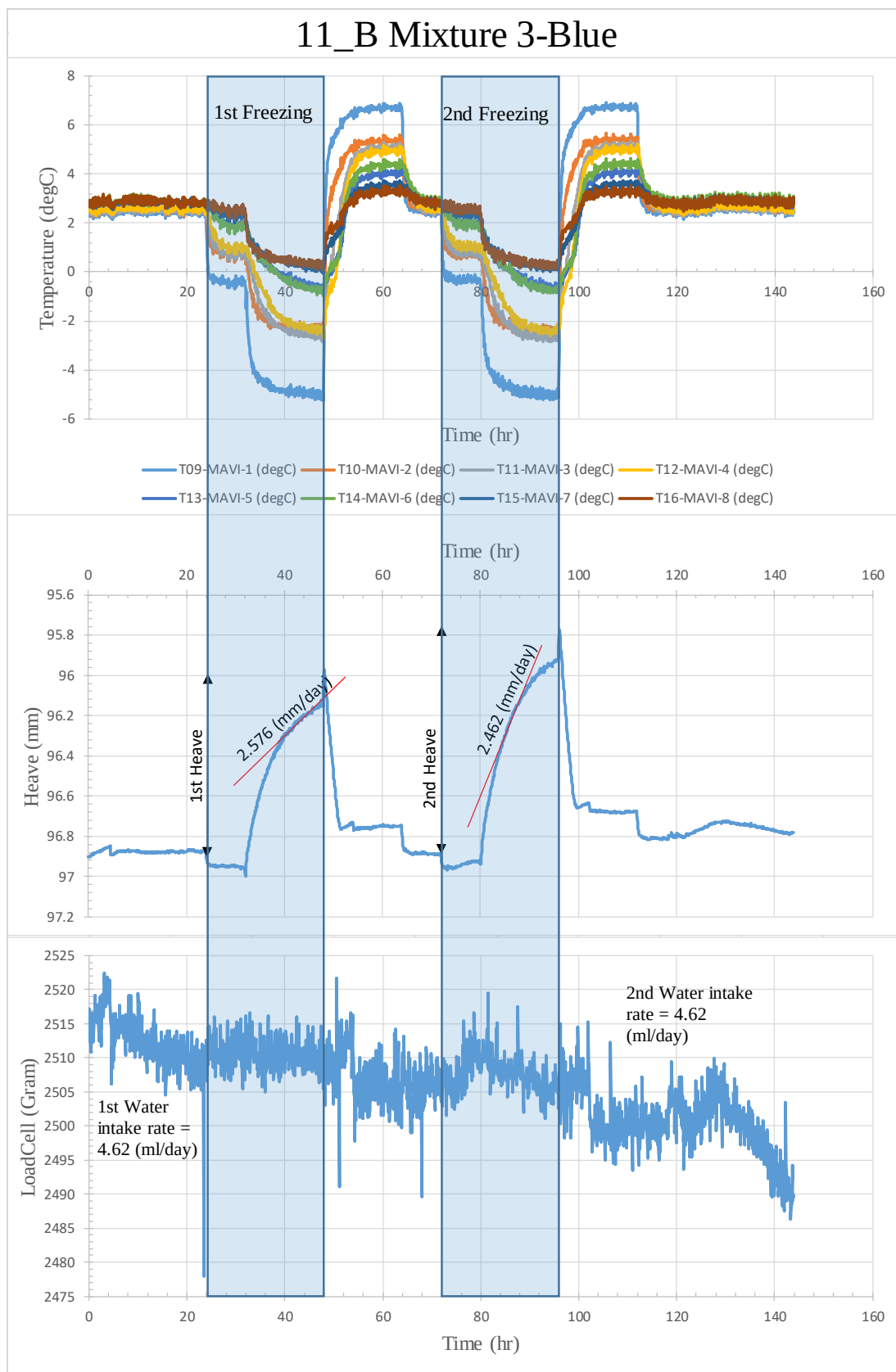


Figure C. 41 Freez-Thaw Test Results for “11_B Mix 3-Blue”

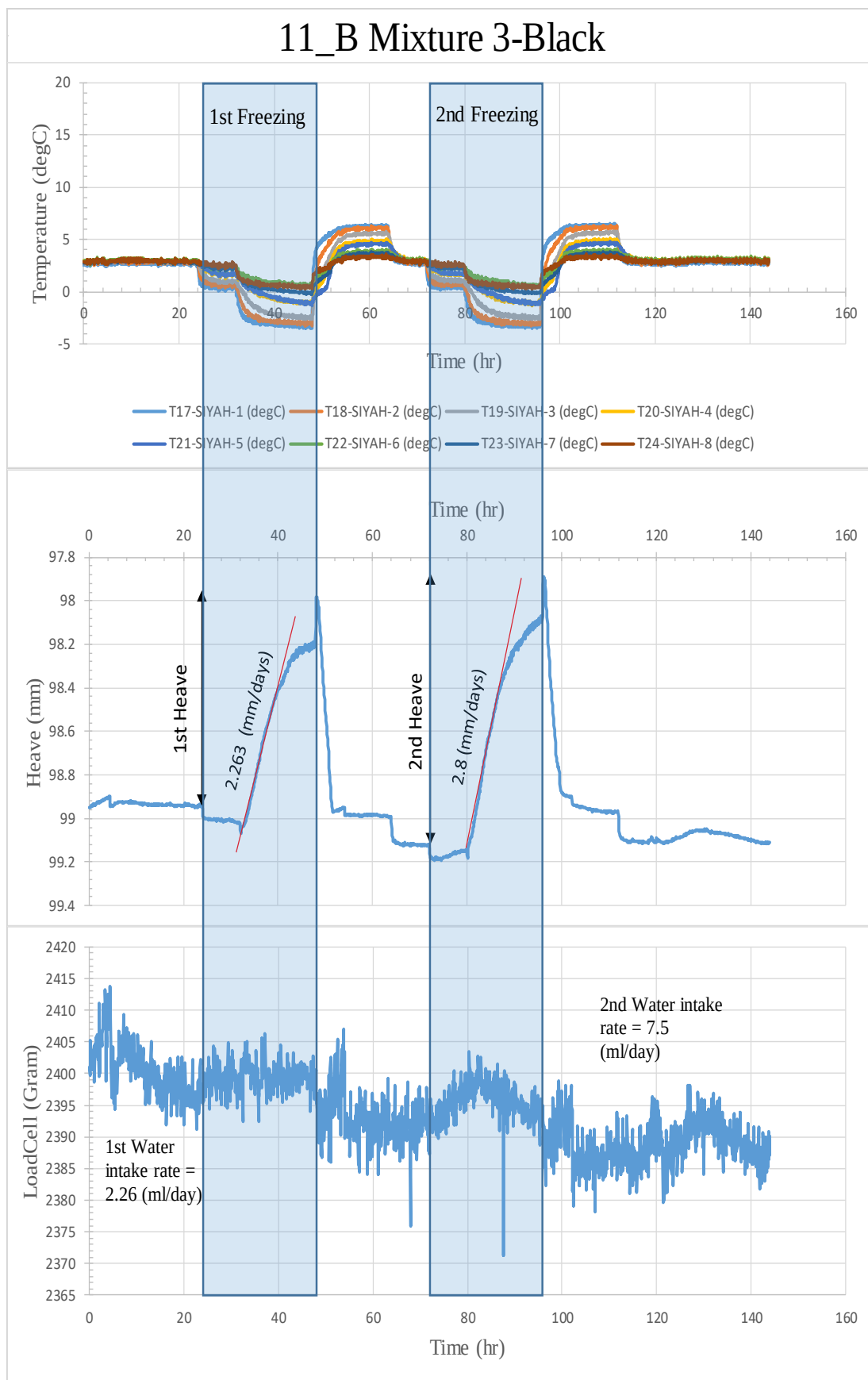


Figure C. 42 Freez-Thaw Test Results for “11_B Mix 3-Black”

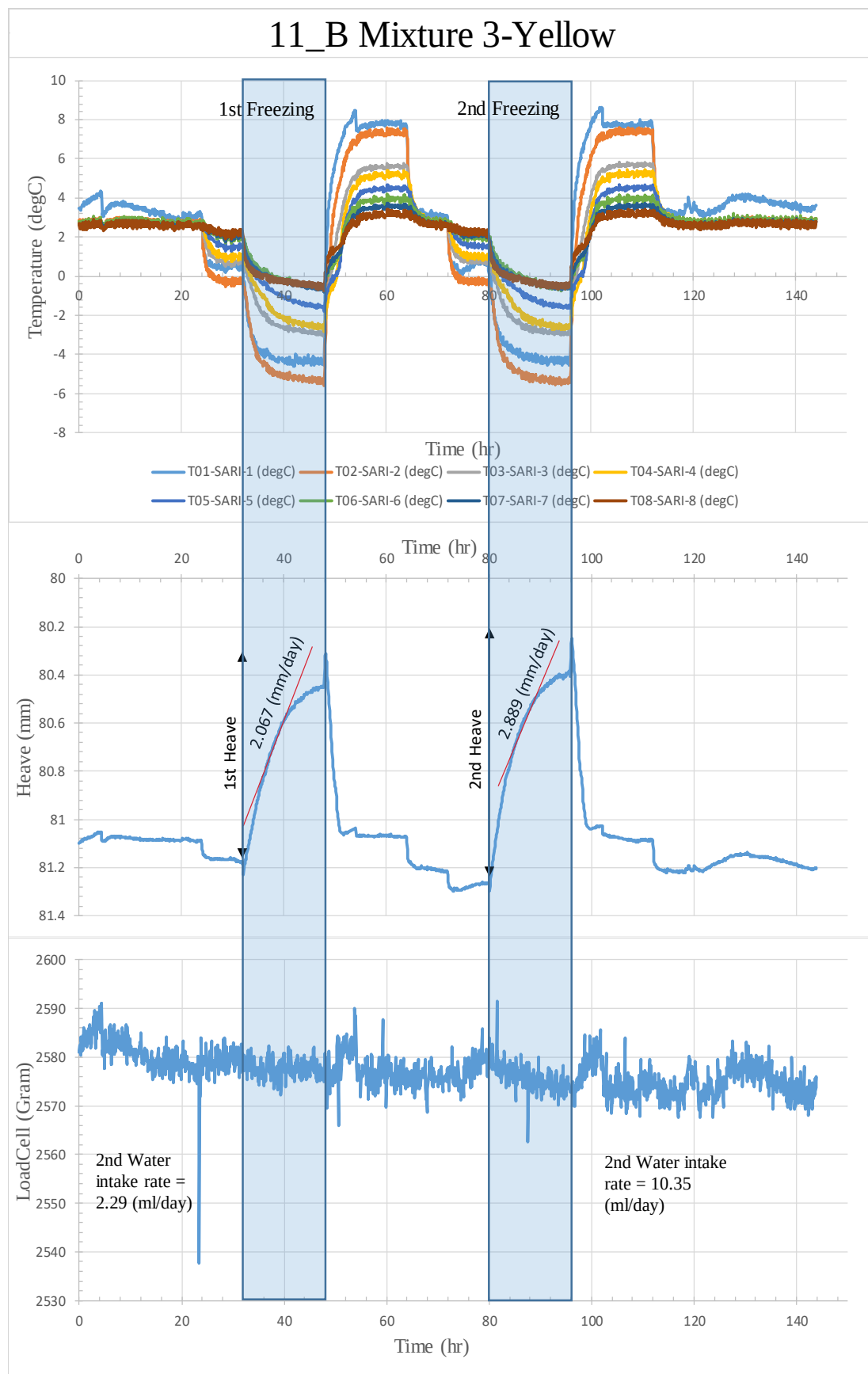


Figure C. 43 Freez-Thaw Test Results for “11_B Mix 3-Yellow”

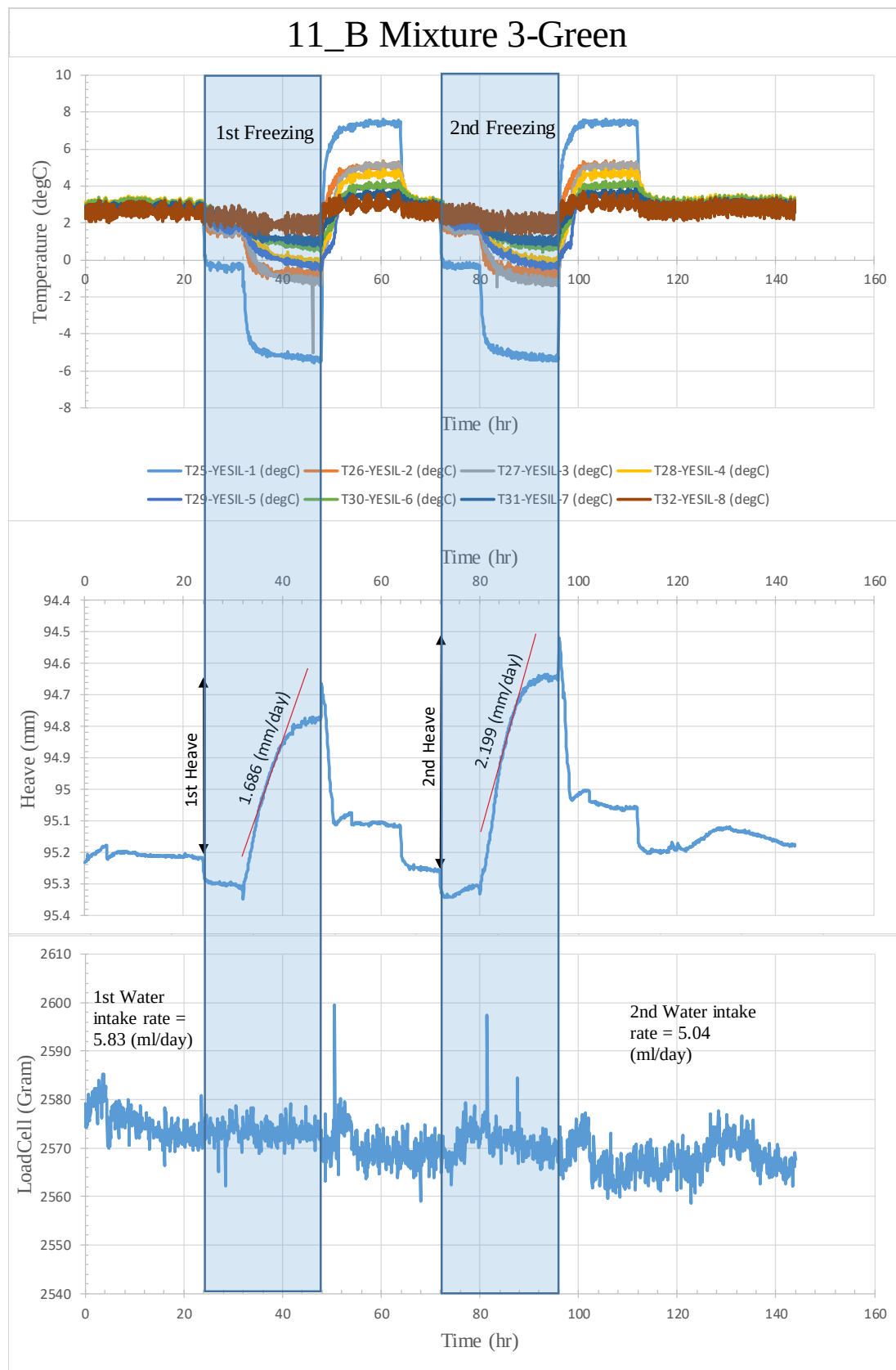


Figure C. 44 Freeze-Thaw Test Results for “11_B Mix 3-Green”

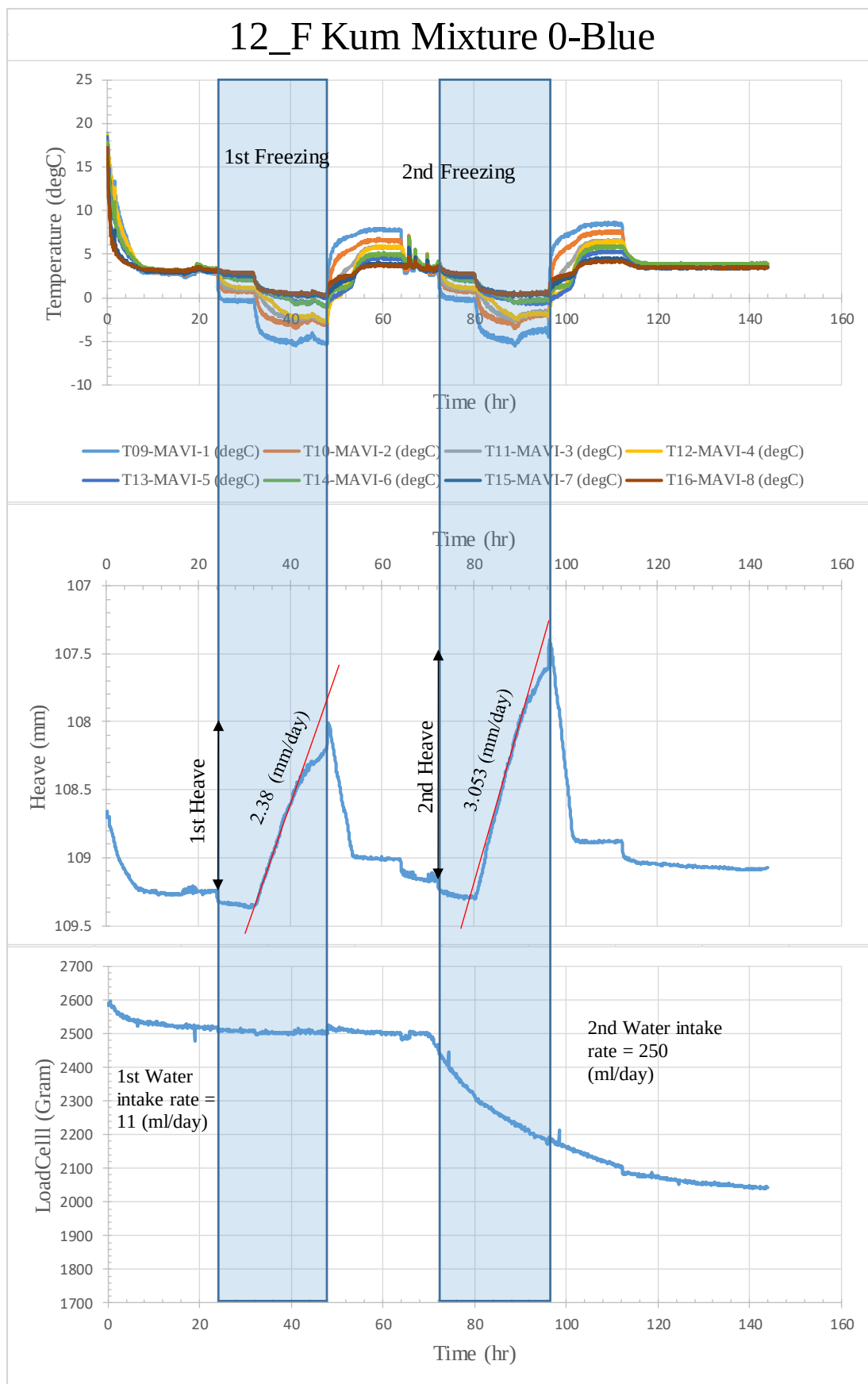


Figure C. 45 Freez-Thaw Test Results for “12_F Kum Mix 0-Blue”

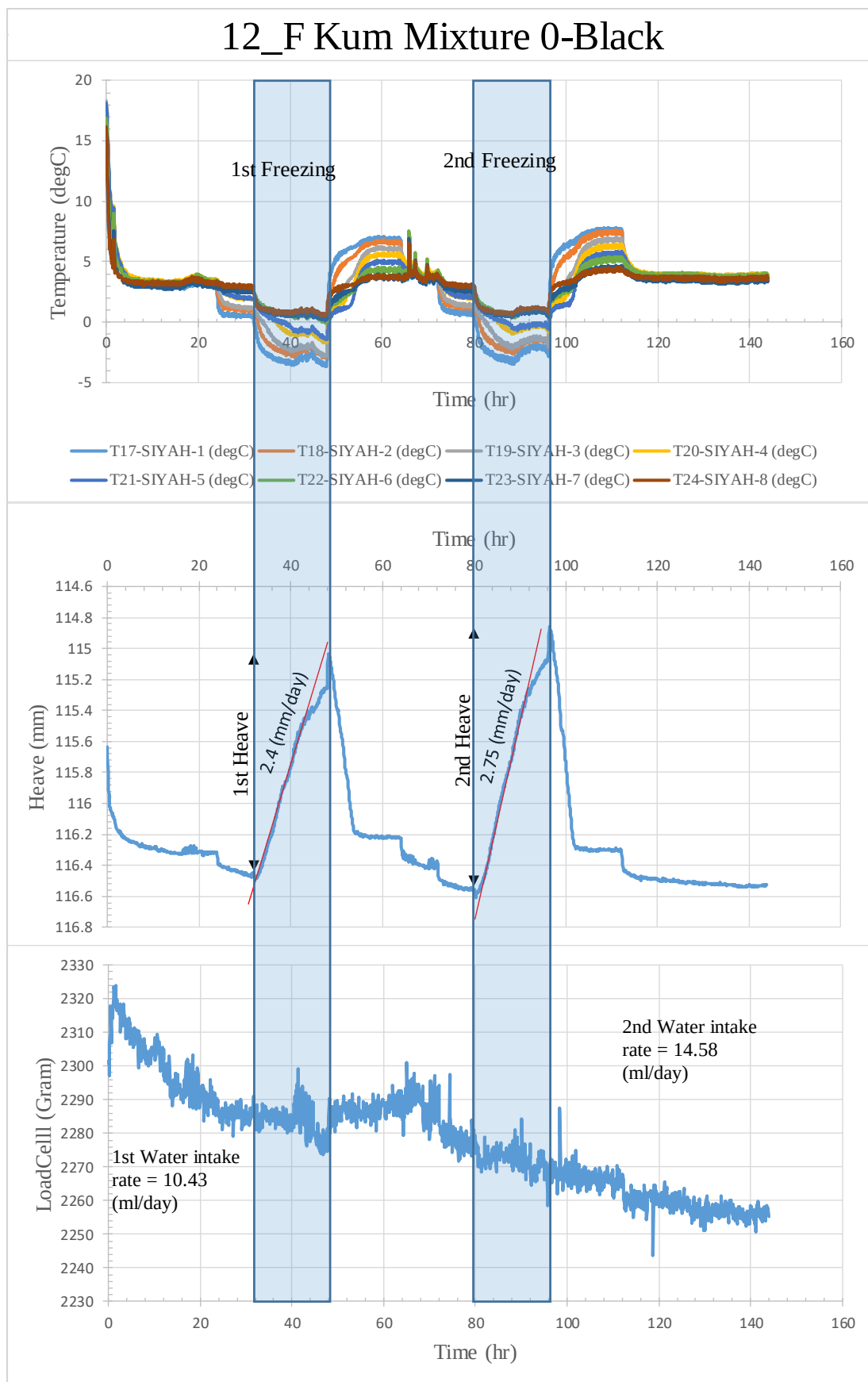


Figure C. 46 Freez-Thaw Test Results for "12_F Kum Mix 0-Black"

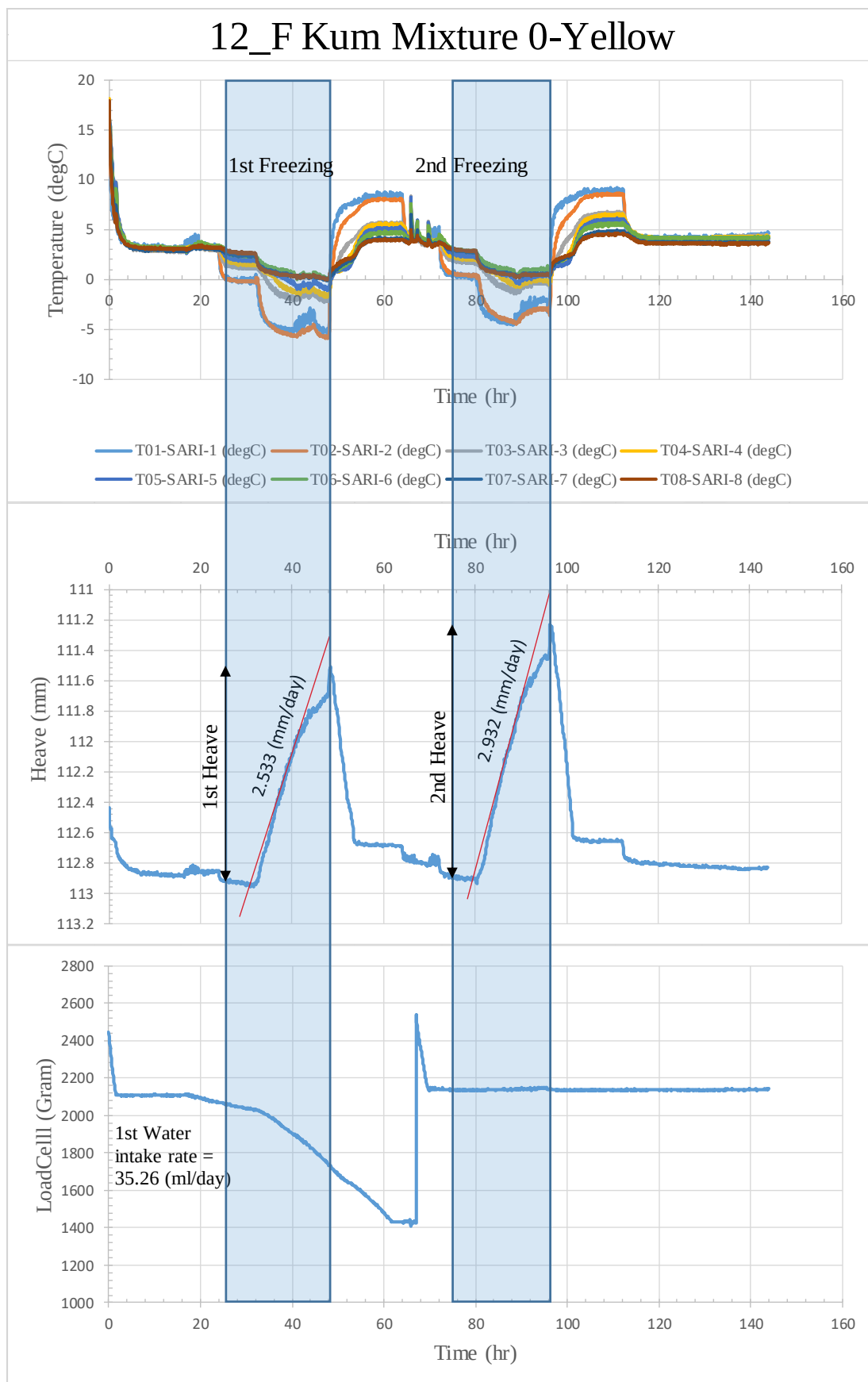


Figure C. 47 Freez-Thaw Test Results for “12_F Kum Mix 0-Yellow”

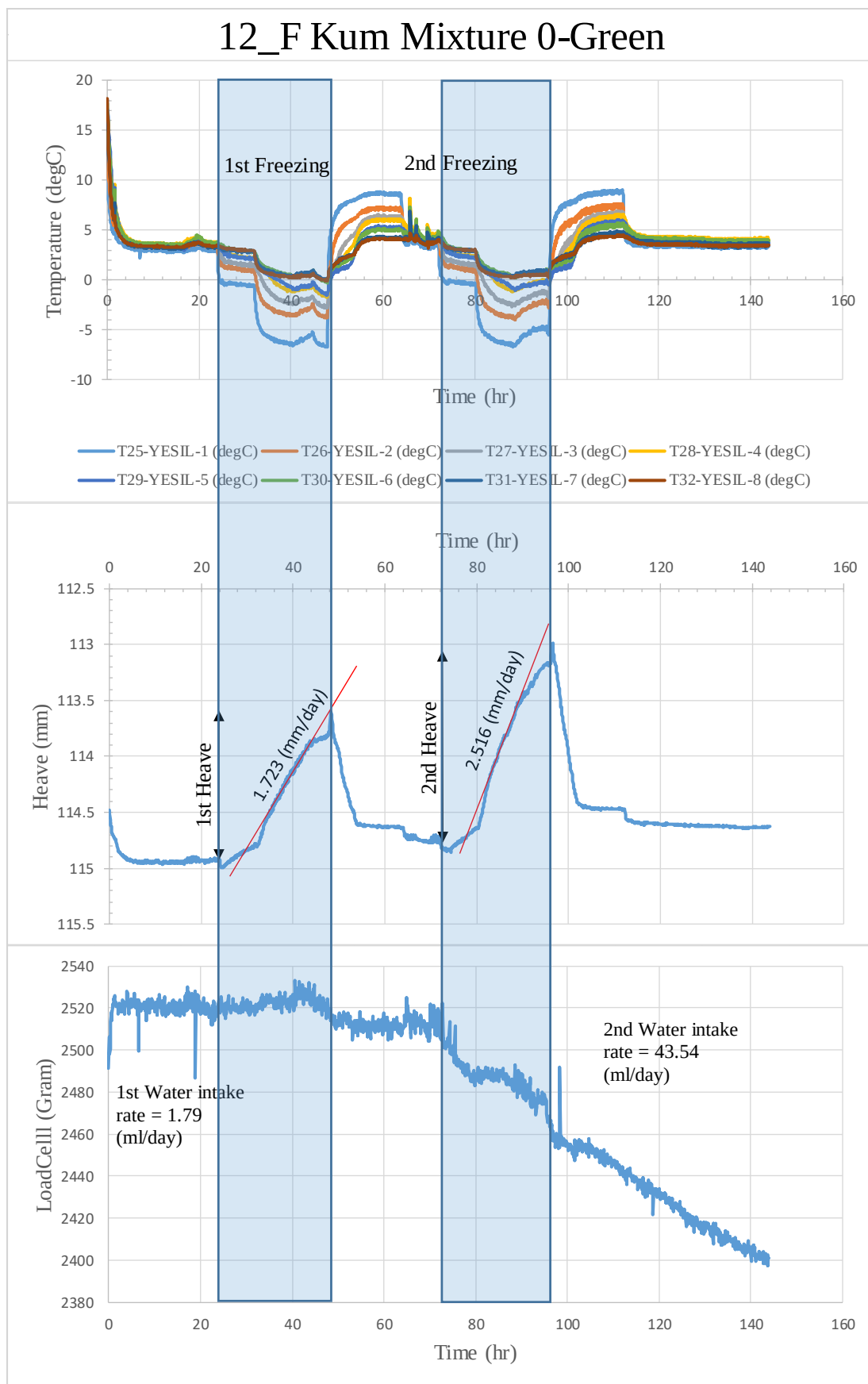


Figure C. 48 Freez-Thaw Test Results for “12_F Kum Mix 0-Green”

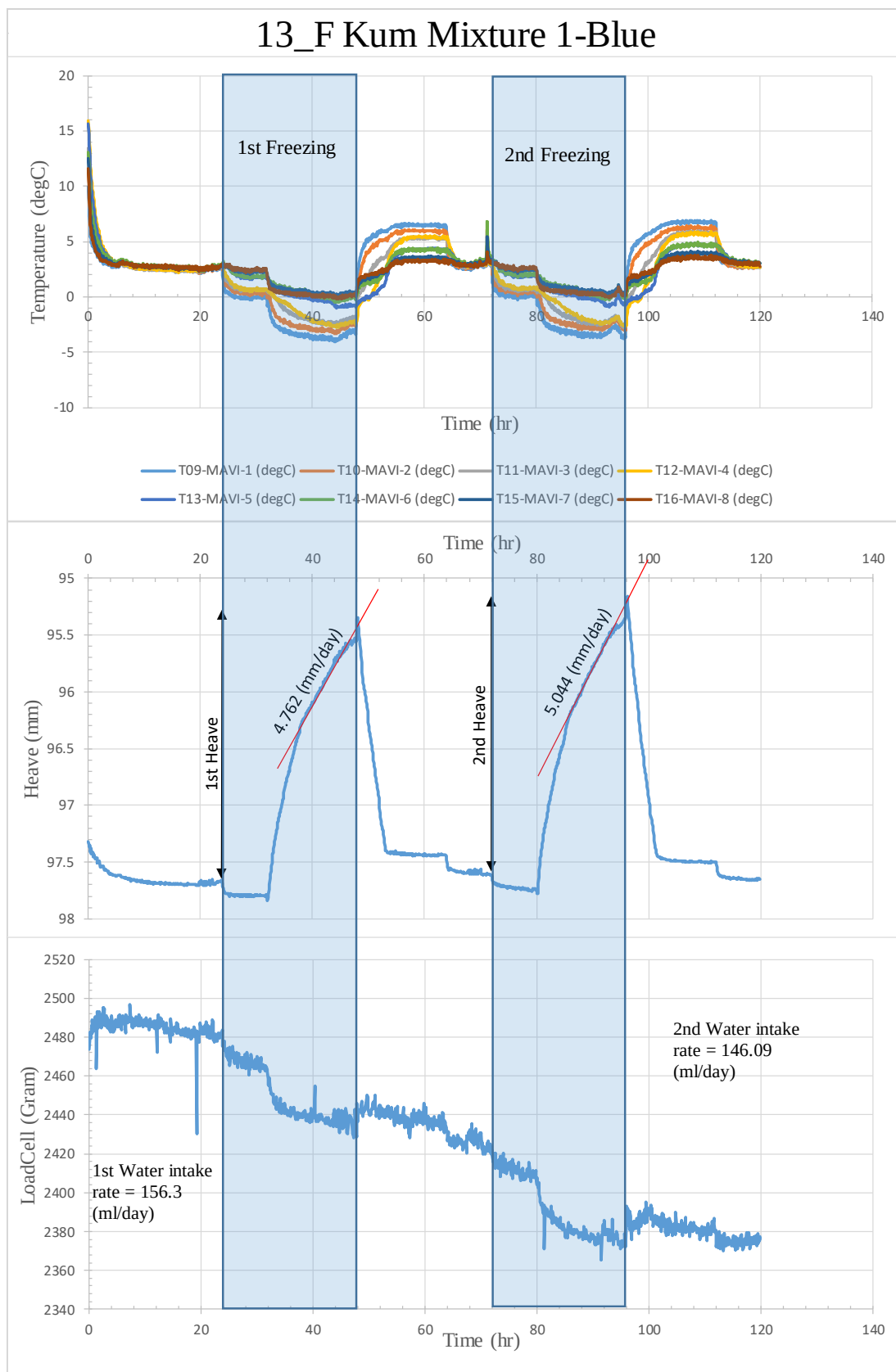


Figure C. 49 Freez-Thaw Test Results for “13_F Kum Mix 1-Blue”

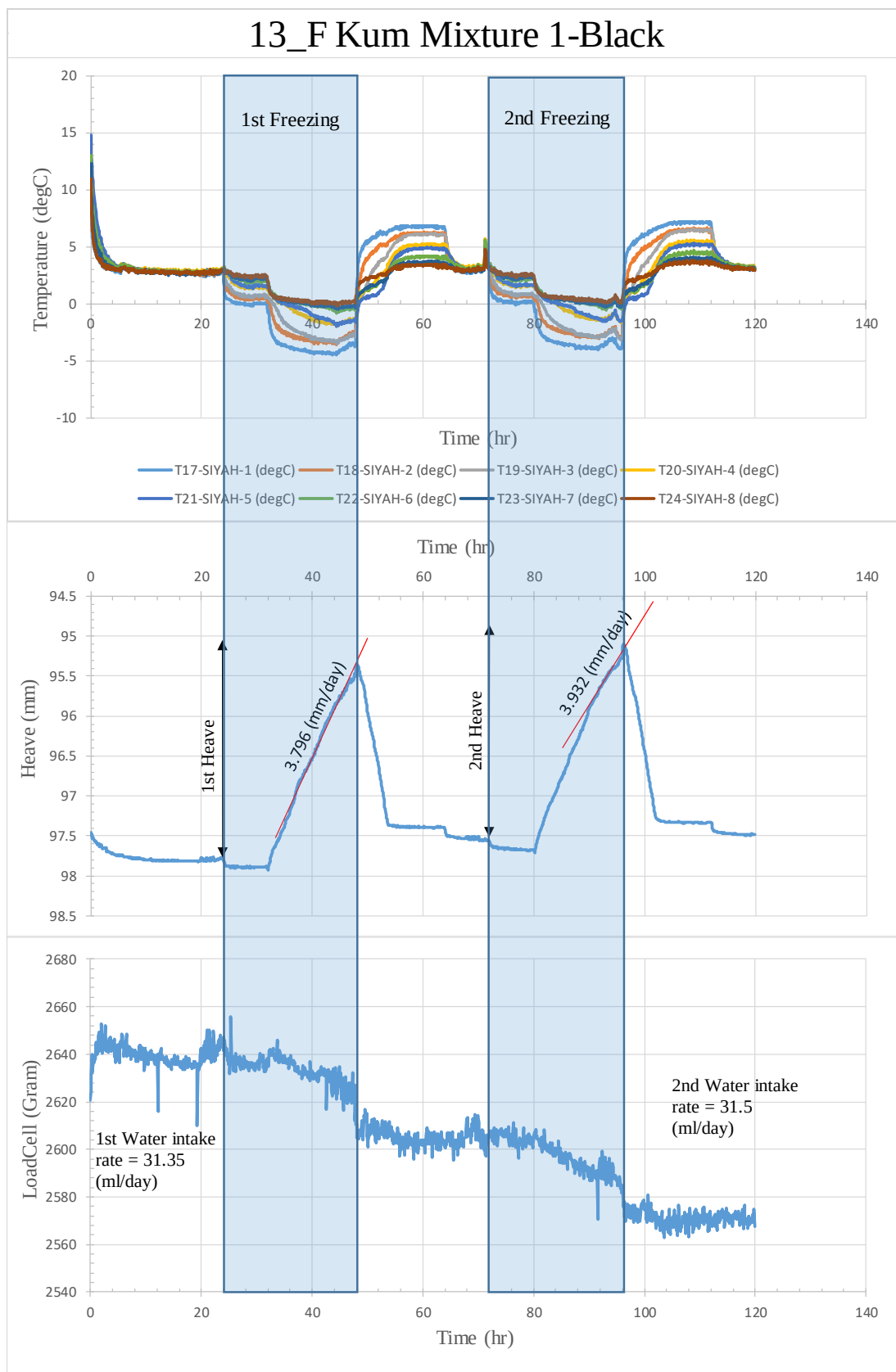


Figure C. 50 Freez-Thaw Test Results for “13_F Kum Mix 1-Black”

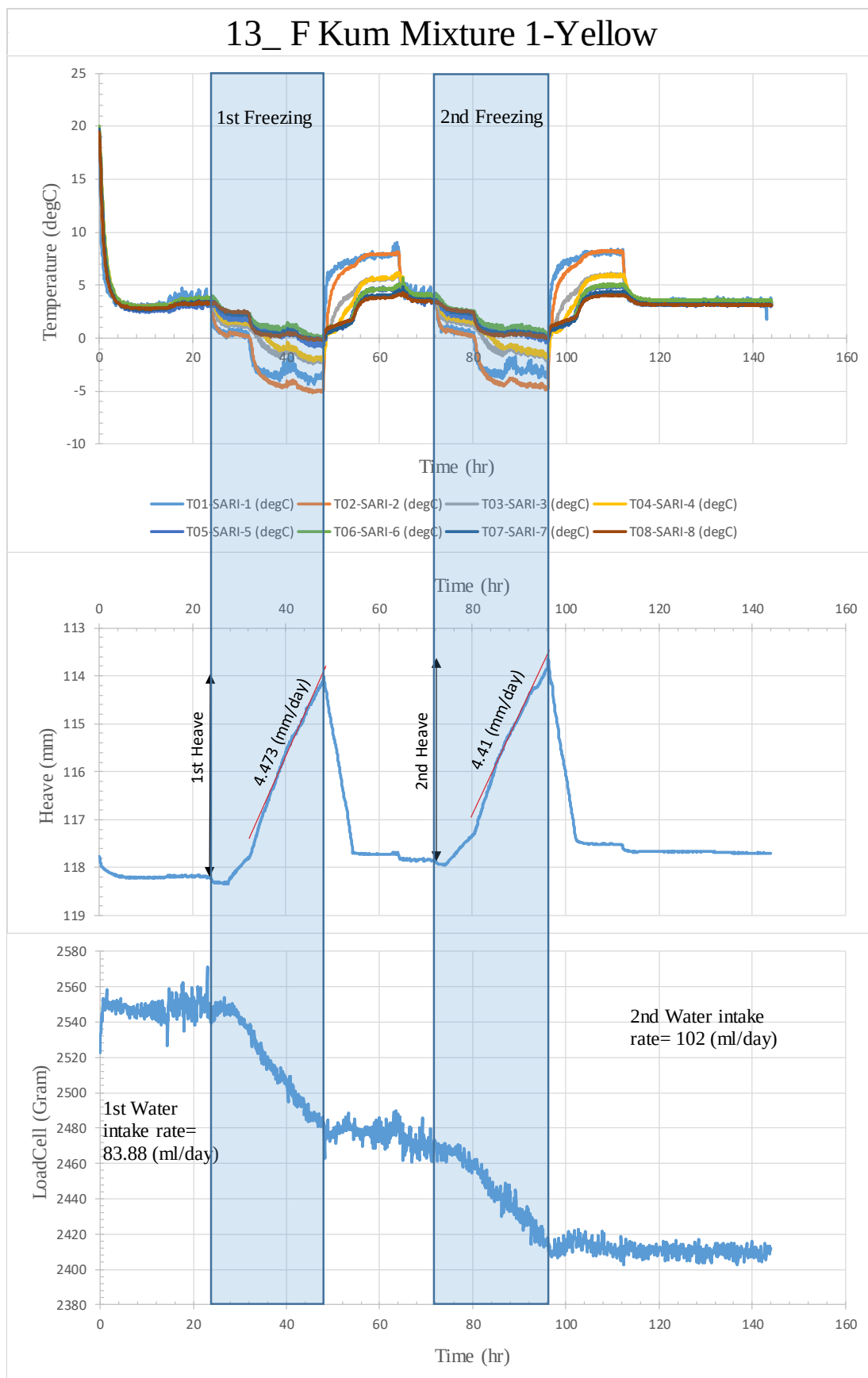


Figure C. 51 Freez-Thaw Test Results for “13_F Kum Mix 1-Yellow”

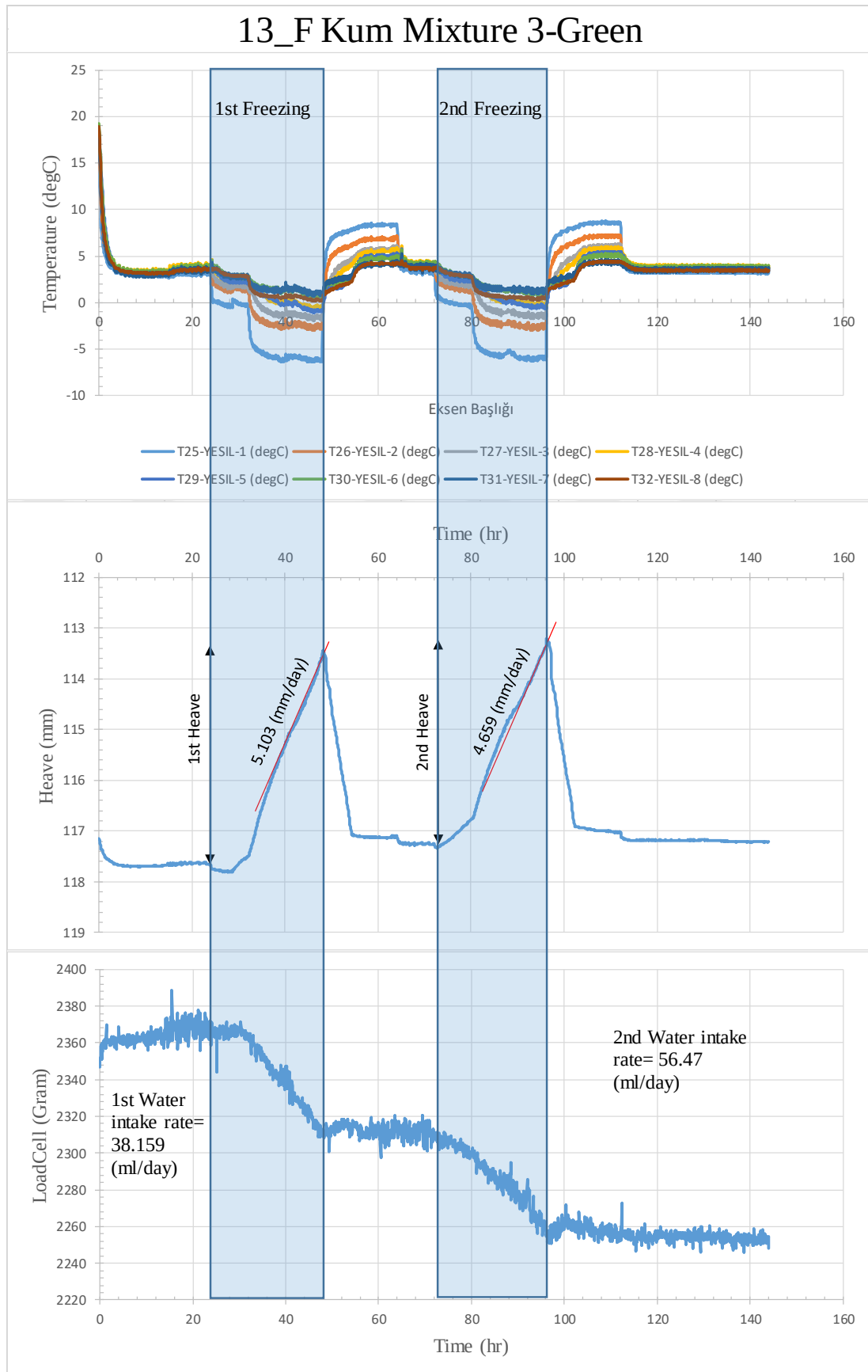


Figure C. 52 Freez-Thaw Test Results for "13_F Kum Mix 1-Green"

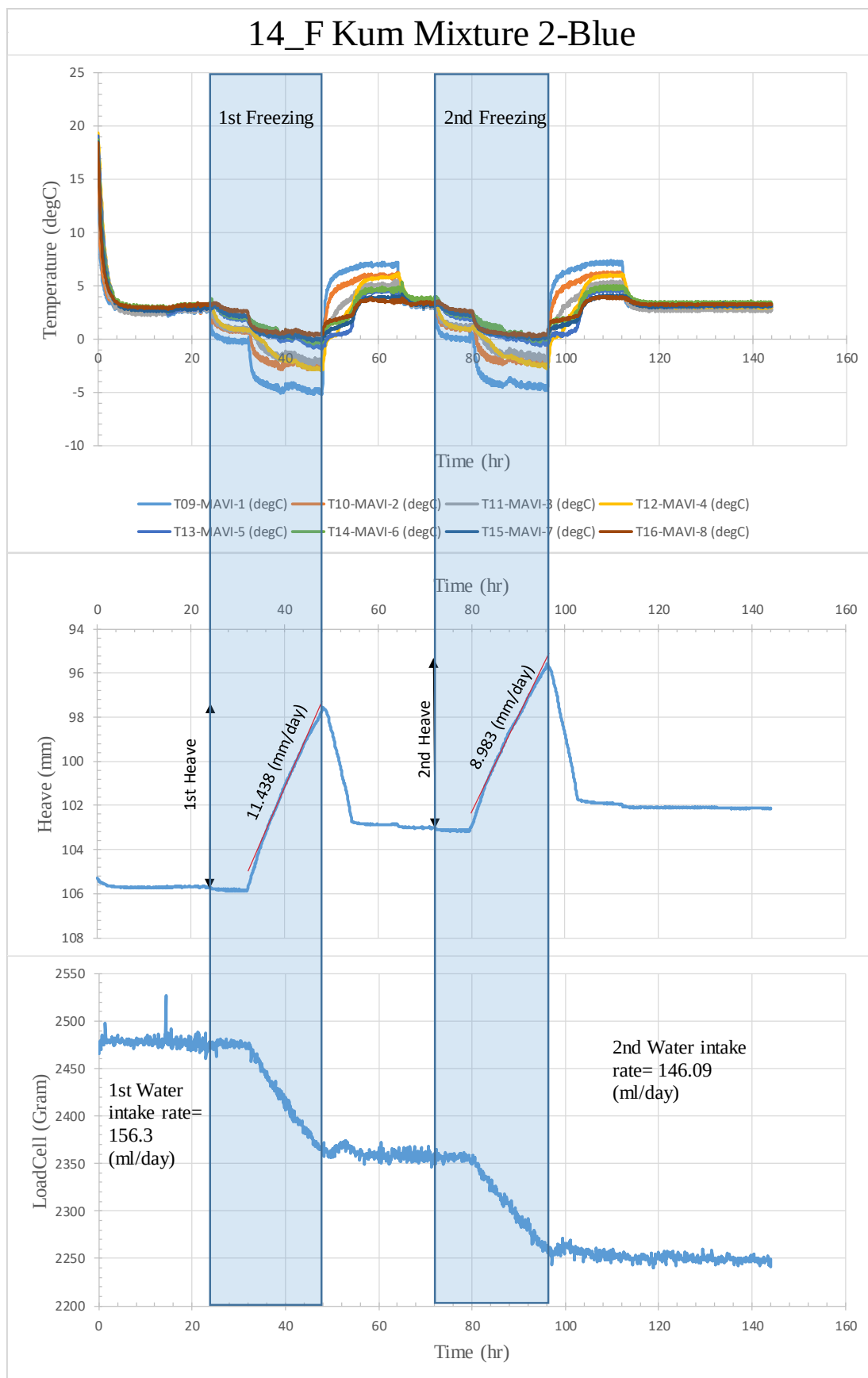


Figure C. 53 Freez-Thaw Test Results for “14_F Kum Mix 2-Blue”

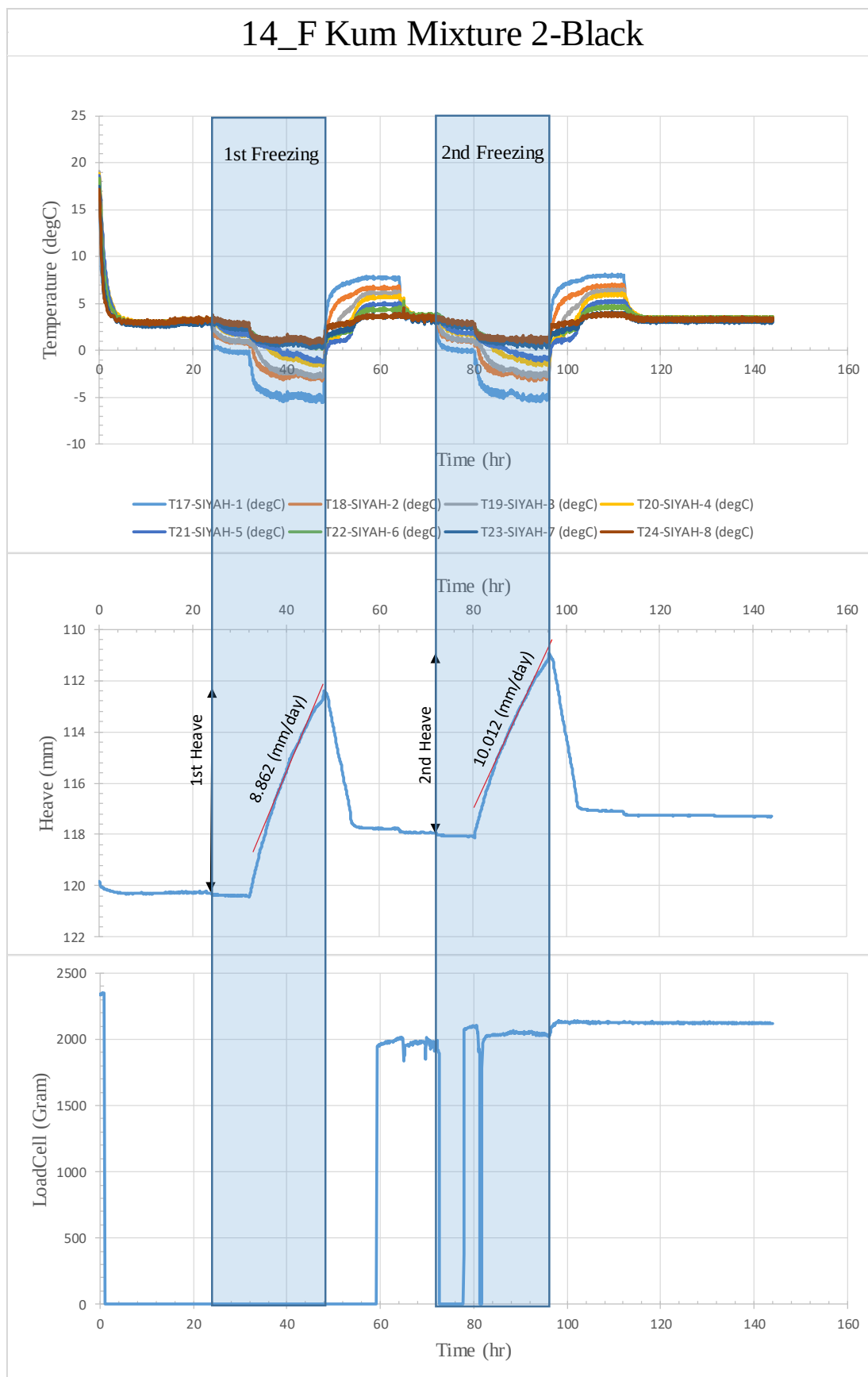


Figure C. 54 Freez-Thaw Test Results for "14_F Kum Mix 2-Black"

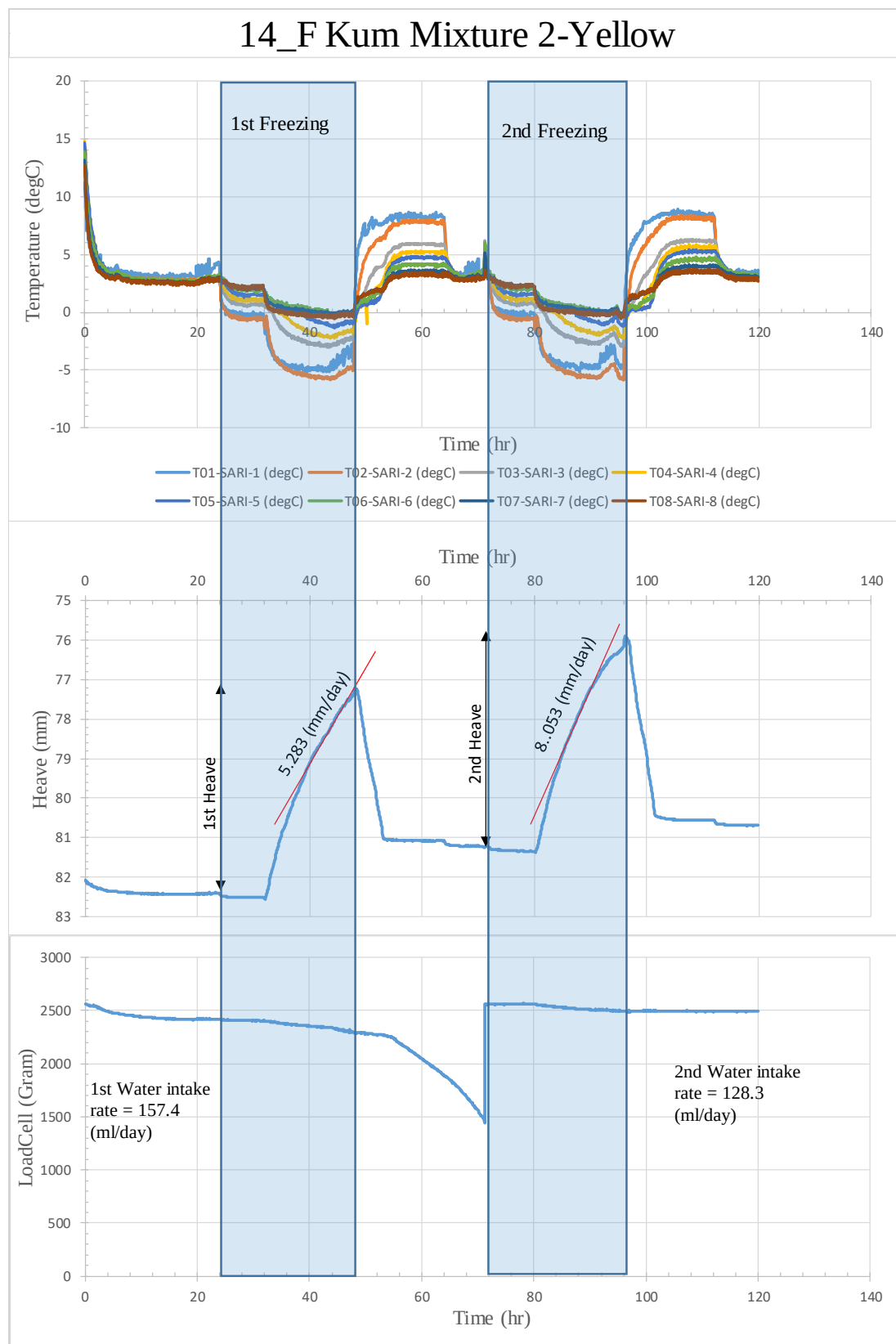


Figure C. 55 Freez-Thaw Test Results for “14_F Kum Mix 2-Yellow”

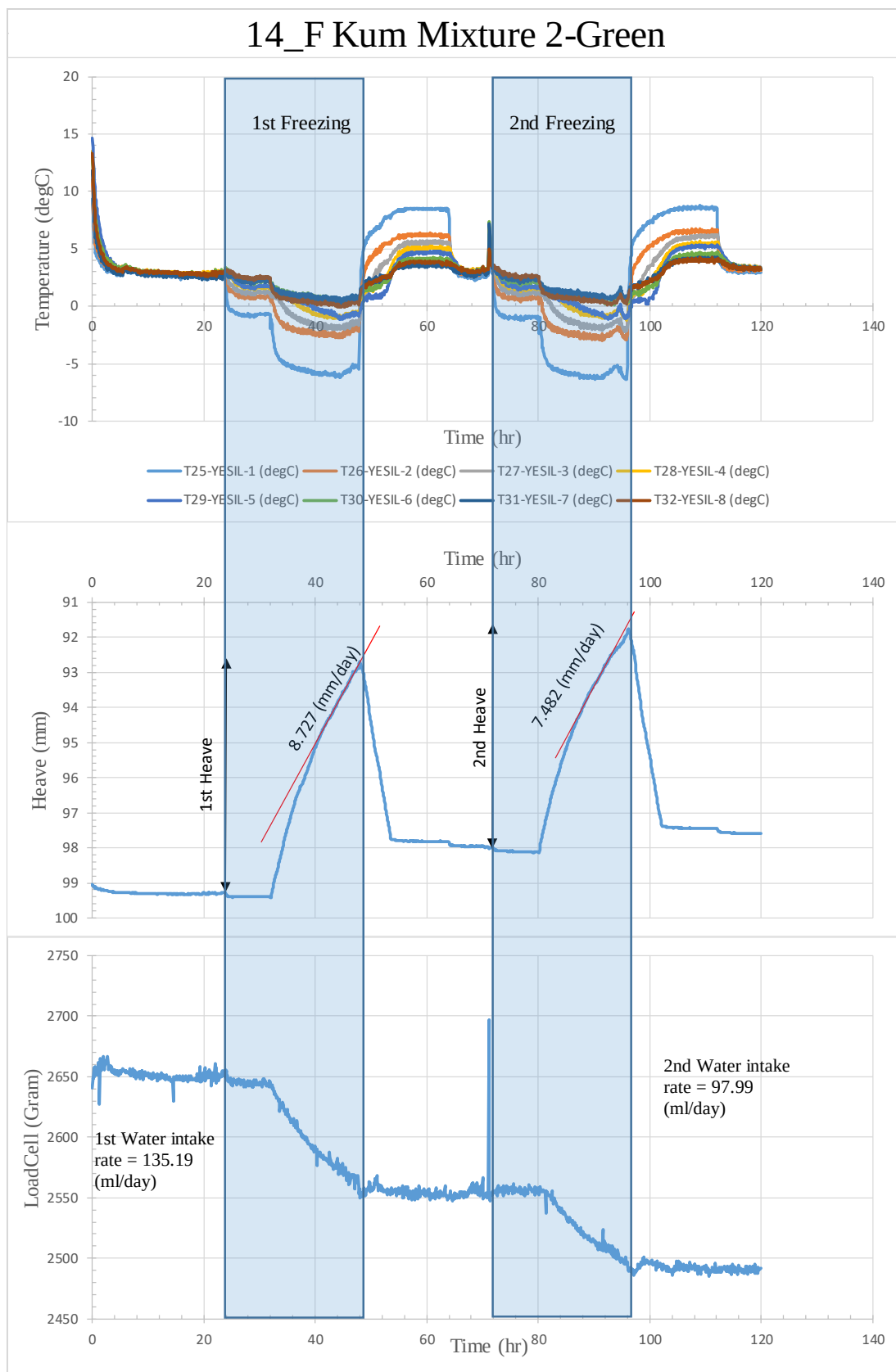


Figure C. 56 Freez-Thaw Test Results for “14_F Kum Mix 2-Green”

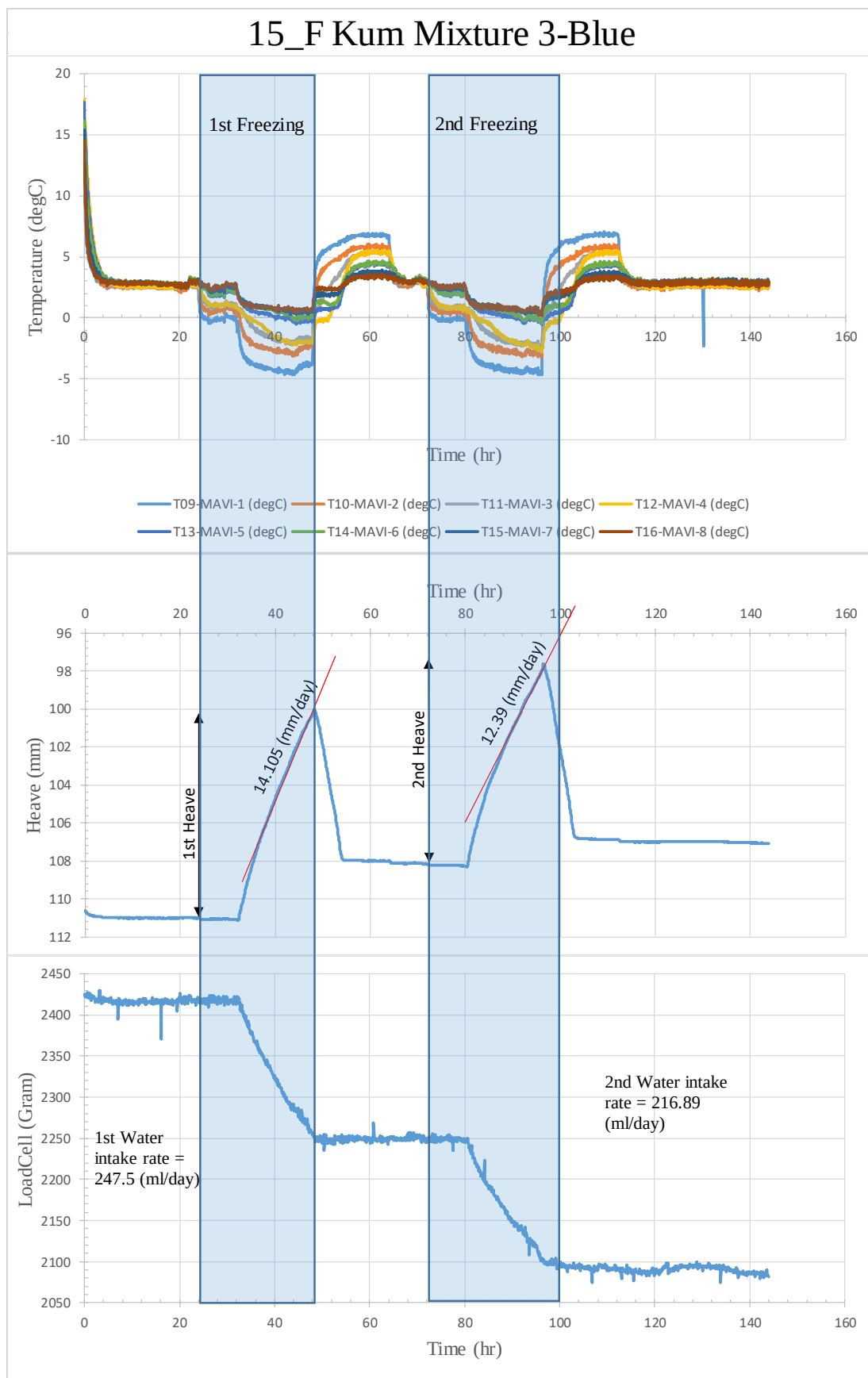


Figure C. 57 Freez-Thaw Test Results for “15_F Kum Mix 3-Blue”

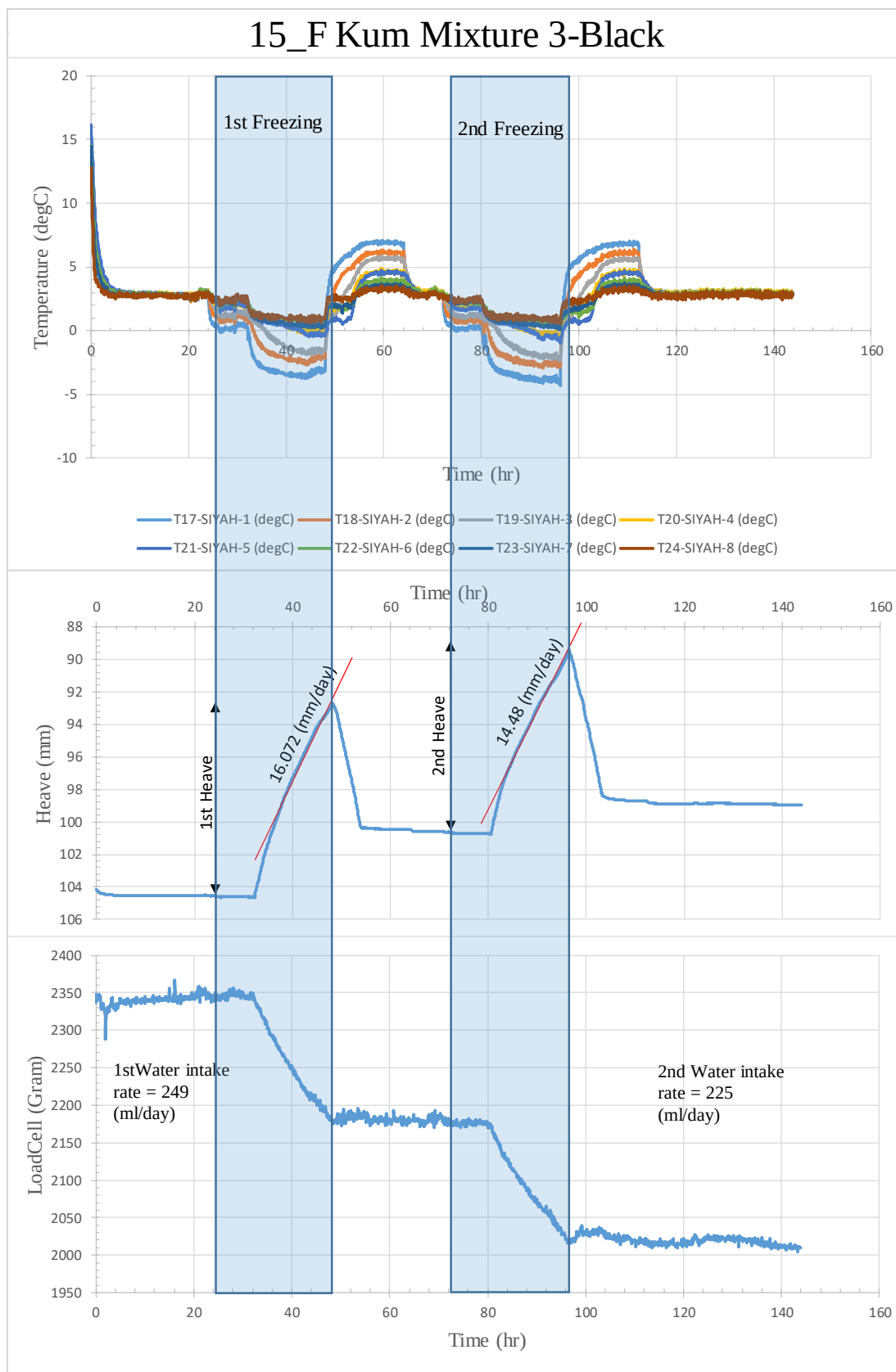


Figure C. 58 Freez-Thaw Test Results for “15_F Kum Mix 3-Black”

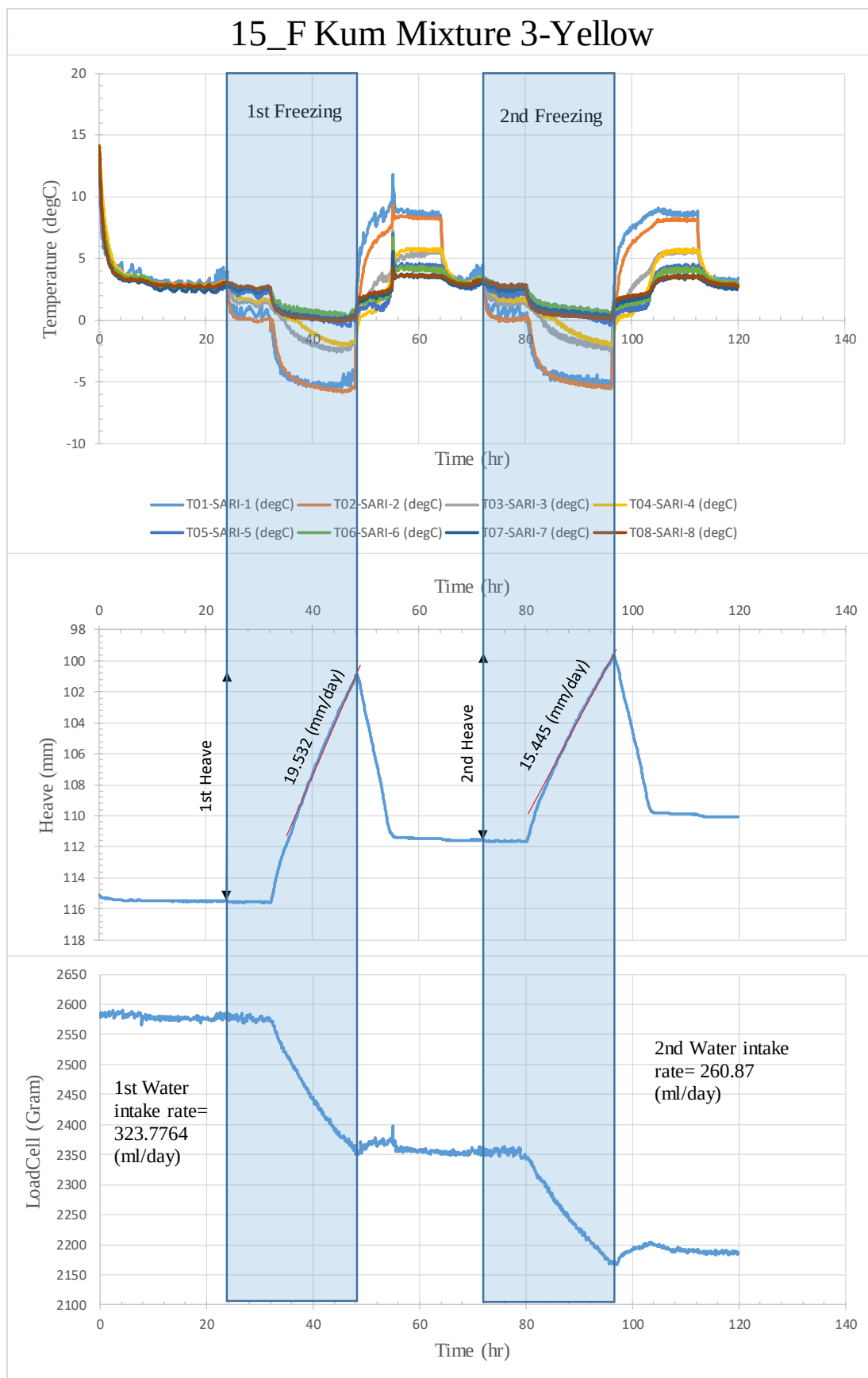


Figure C. 59 Freez-Thaw Test Results for “15_F Kum Mix 3-Yellow”

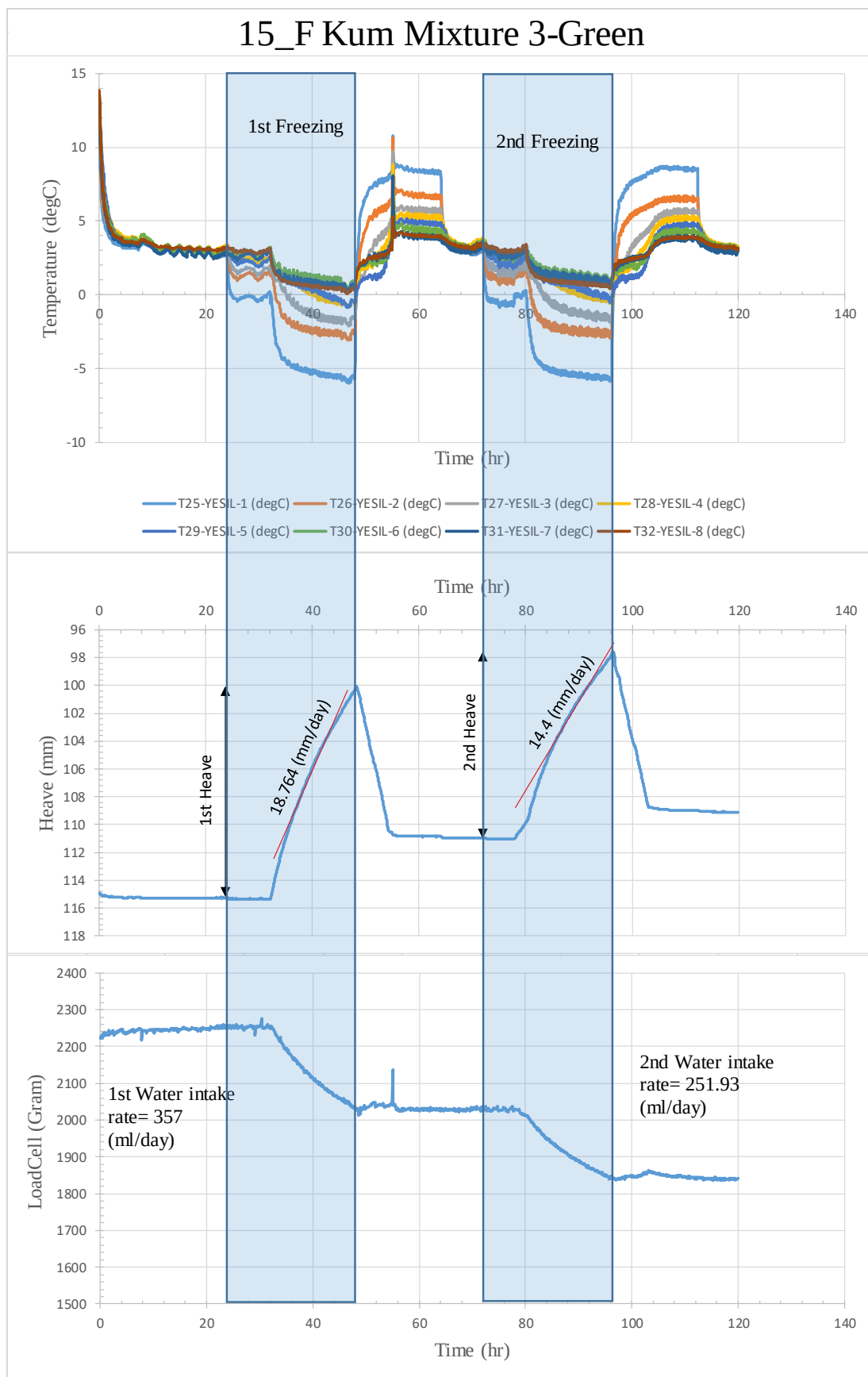


Figure C. 60 Freez-Thaw Test Results for “15_F Kum Mix 3-Green”

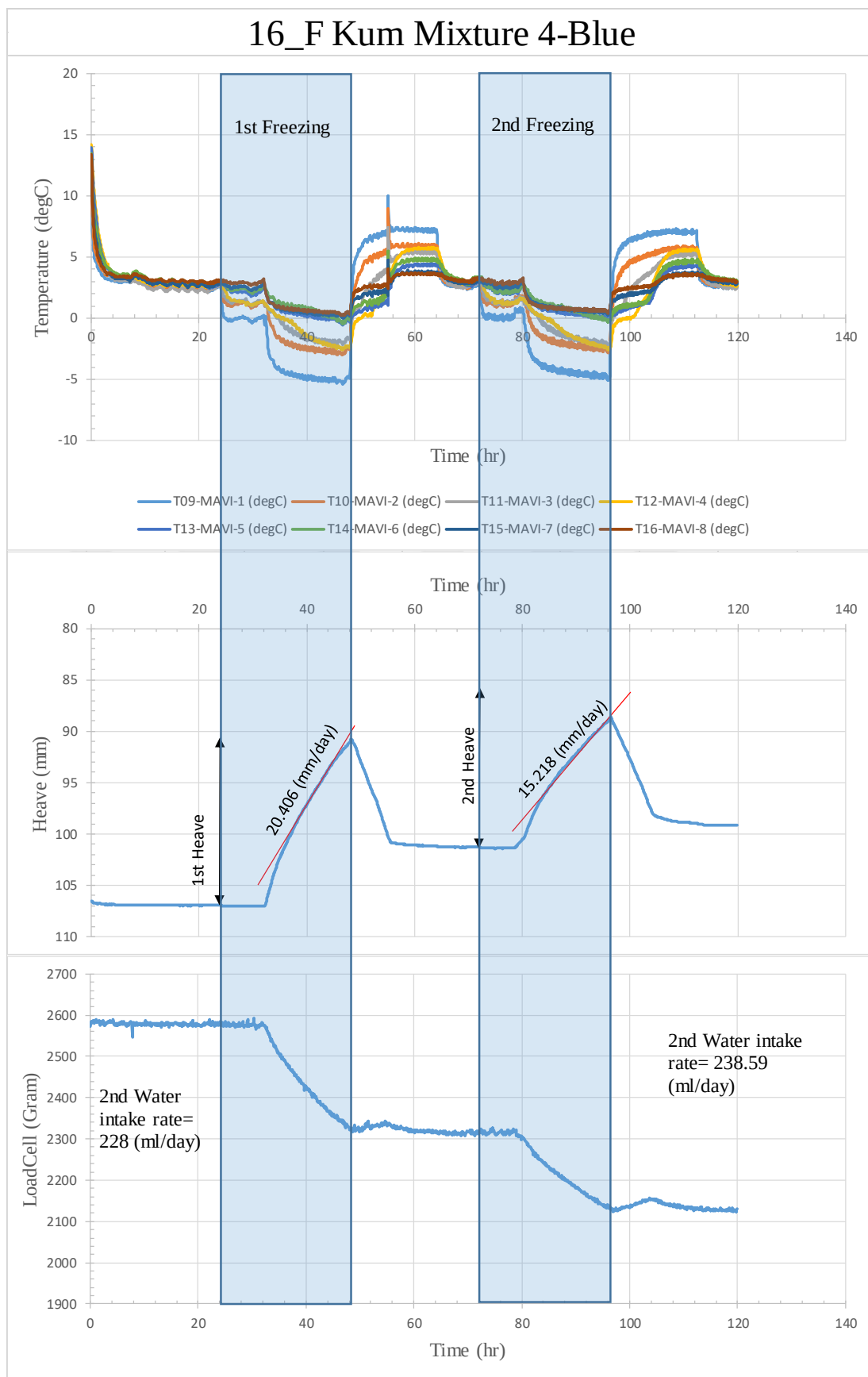


Figure C. 61 Freez-Thaw Test Results for “16_F Kum Mix 4-Blue”

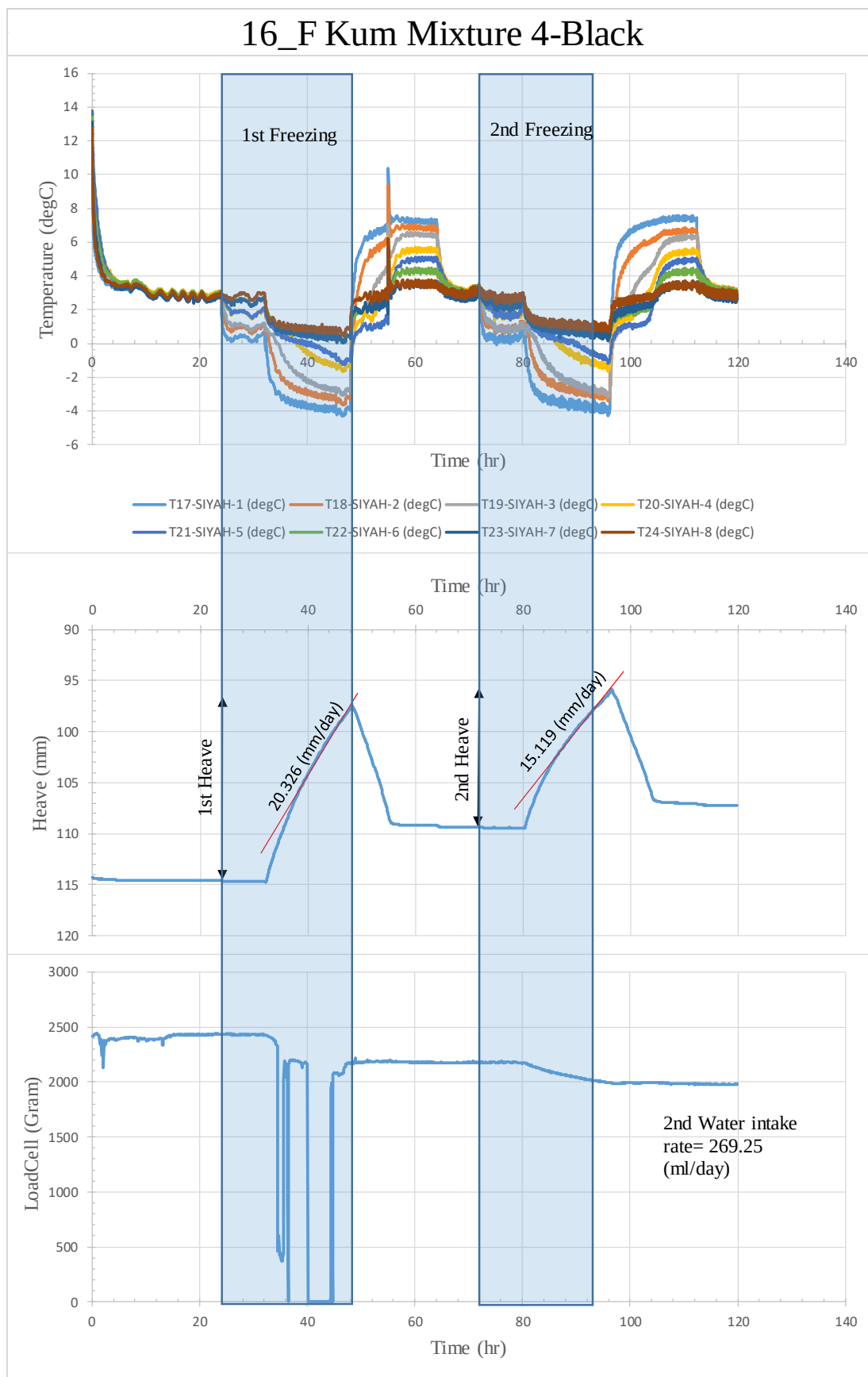


Figure C. 62 Freez-Thaw Test Results for "16_F Kum Mix 4-Black"

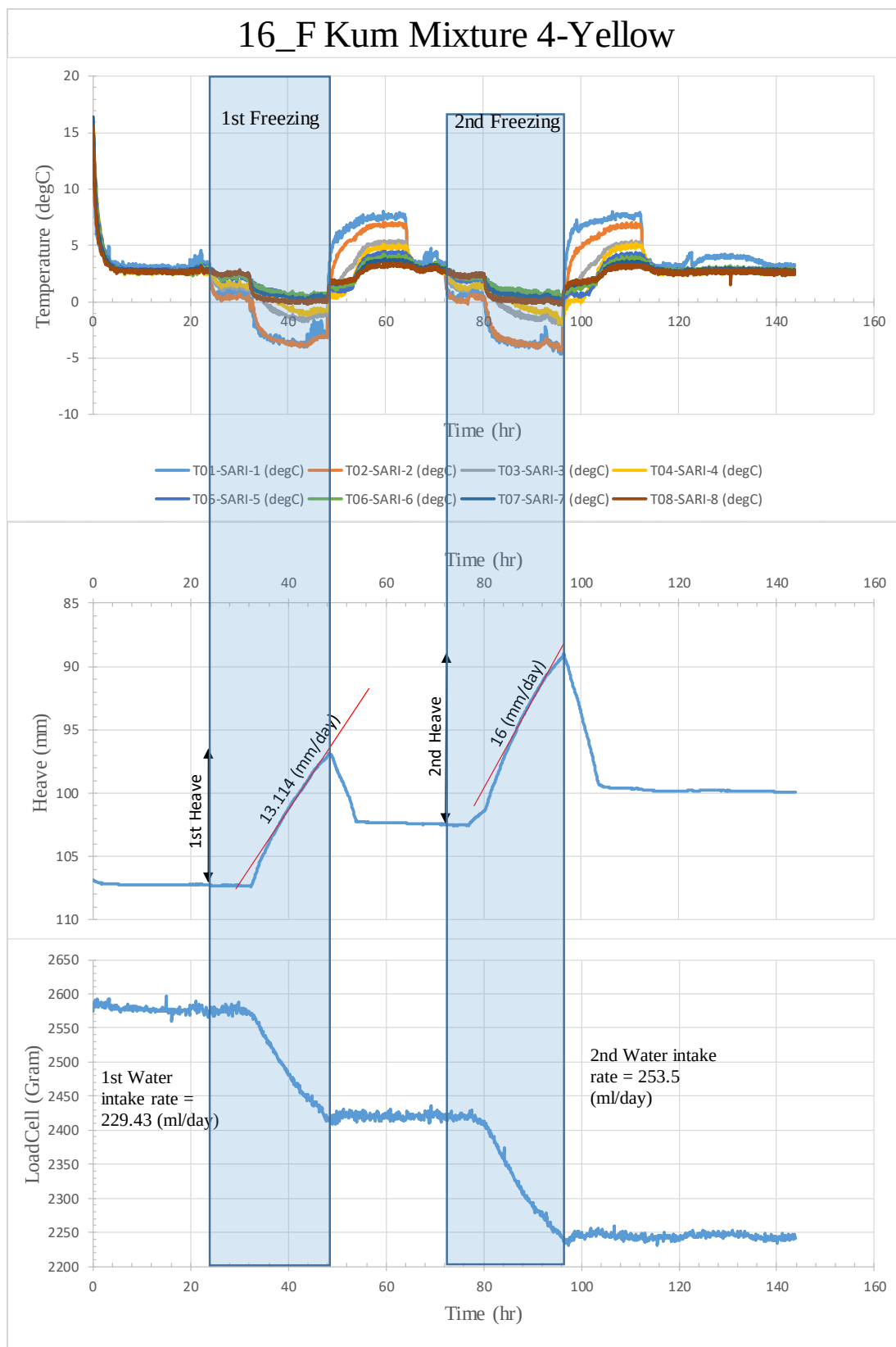


Figure C. 63 Freez-Thaw Test Results for “16_F Kum Mix 4-Yellow”

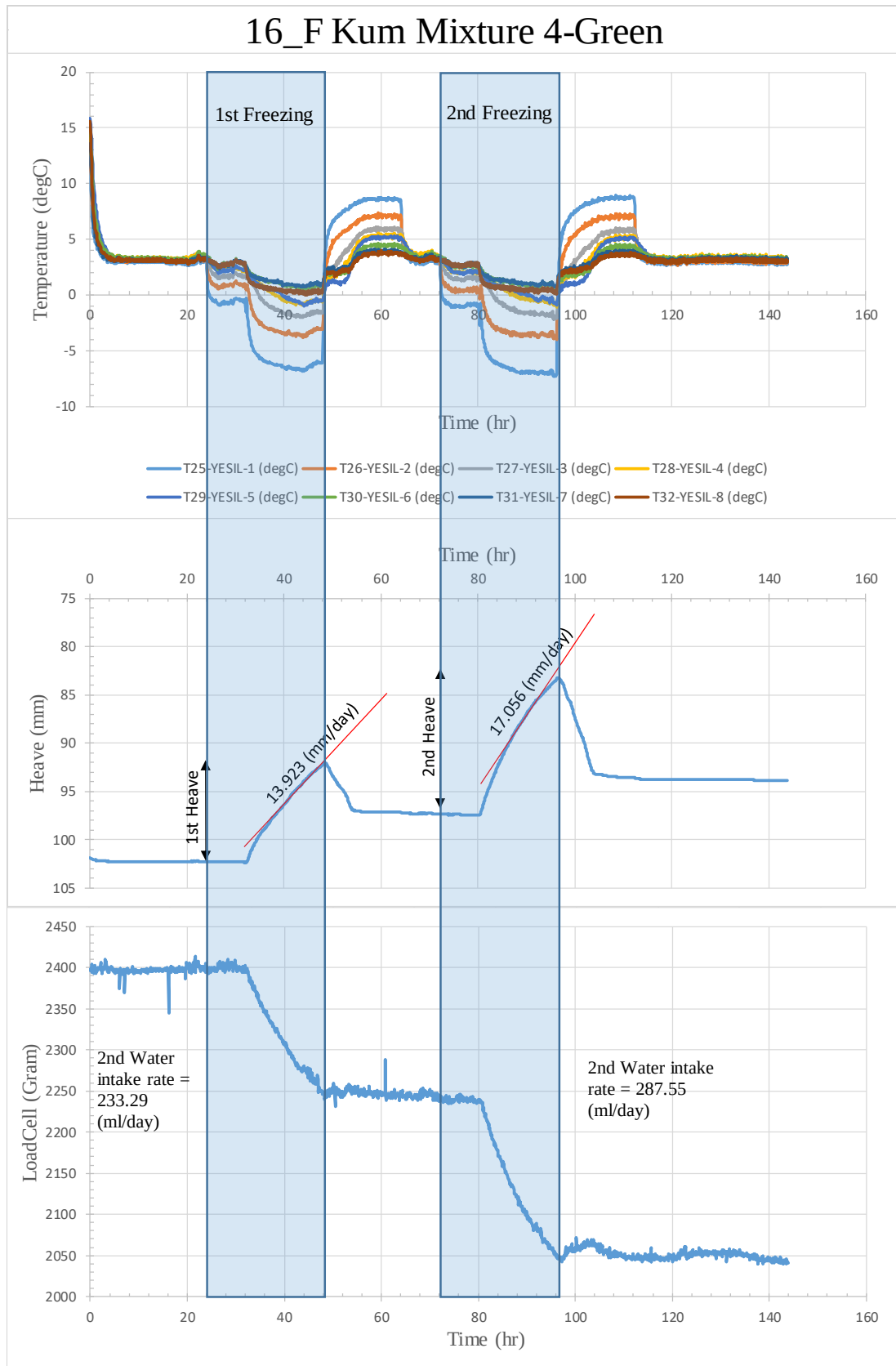


Figure C. 64 Freez-Thaw Test Results for “16_F Kum Mix 4-Green”

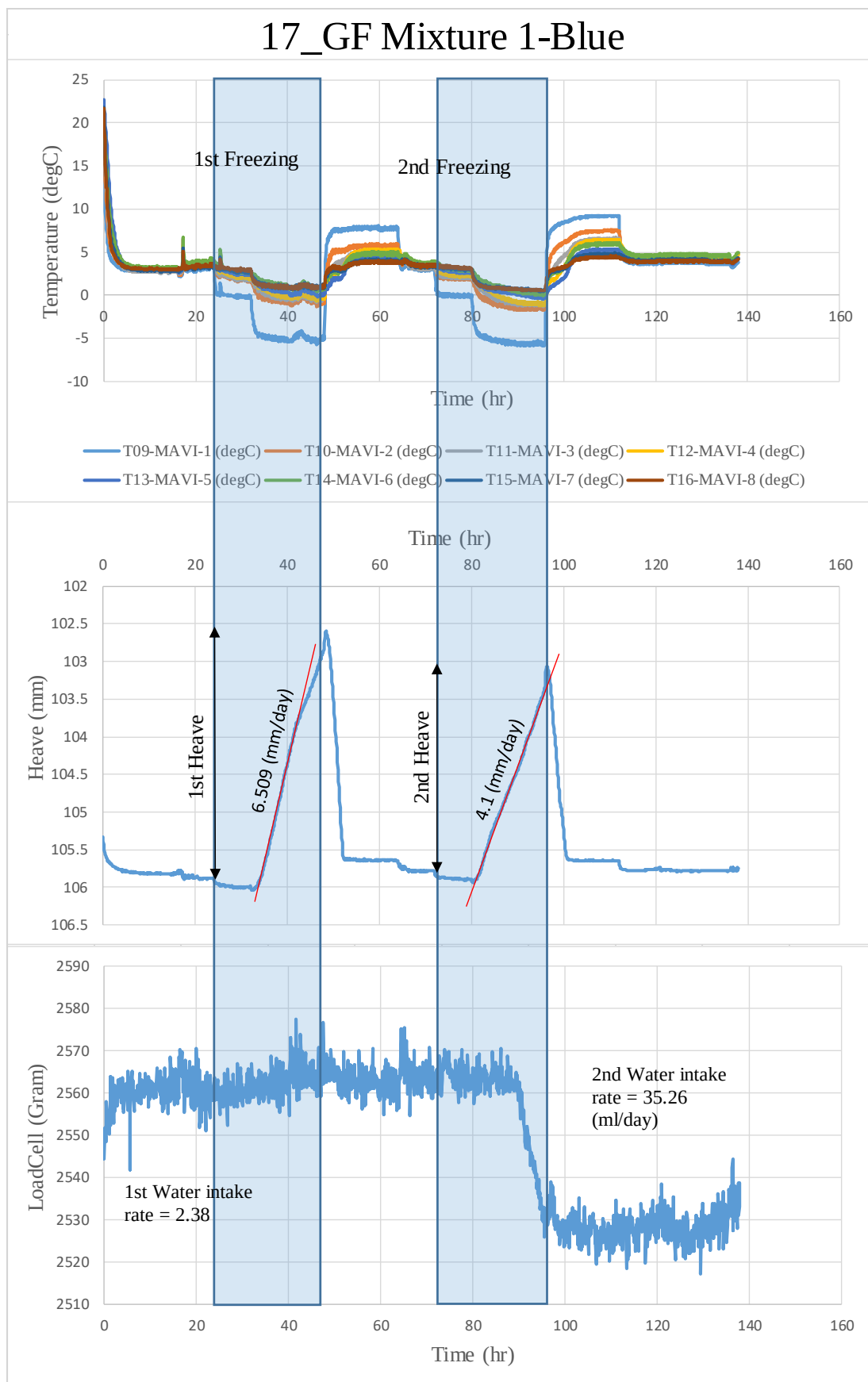


Figure C. 65 Freez-Thaw Test Results for “17_GF Mix 1-Blue”

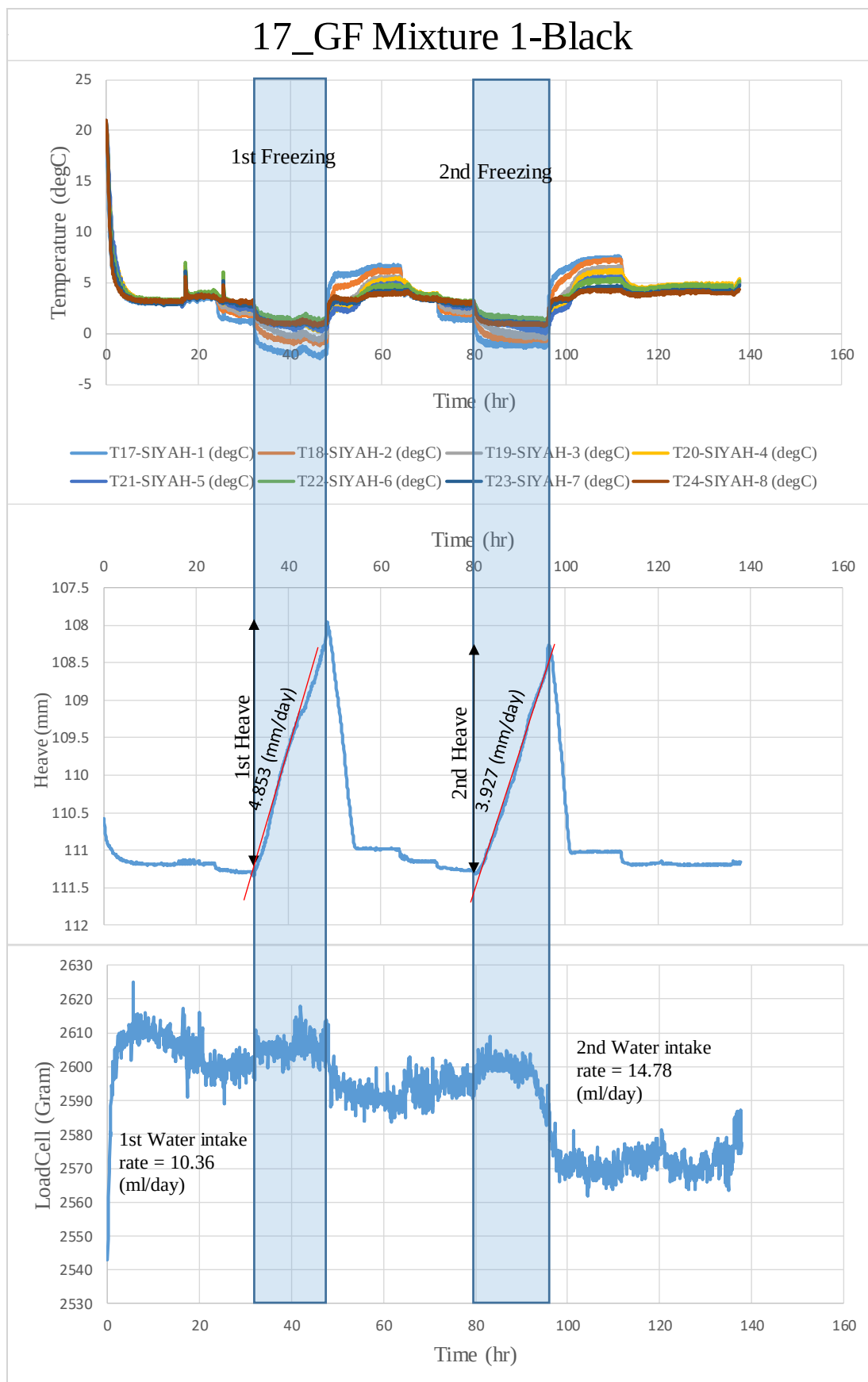


Figure C. 66 Freez-Thaw Test Results for “17_GF Mix 1-Black”

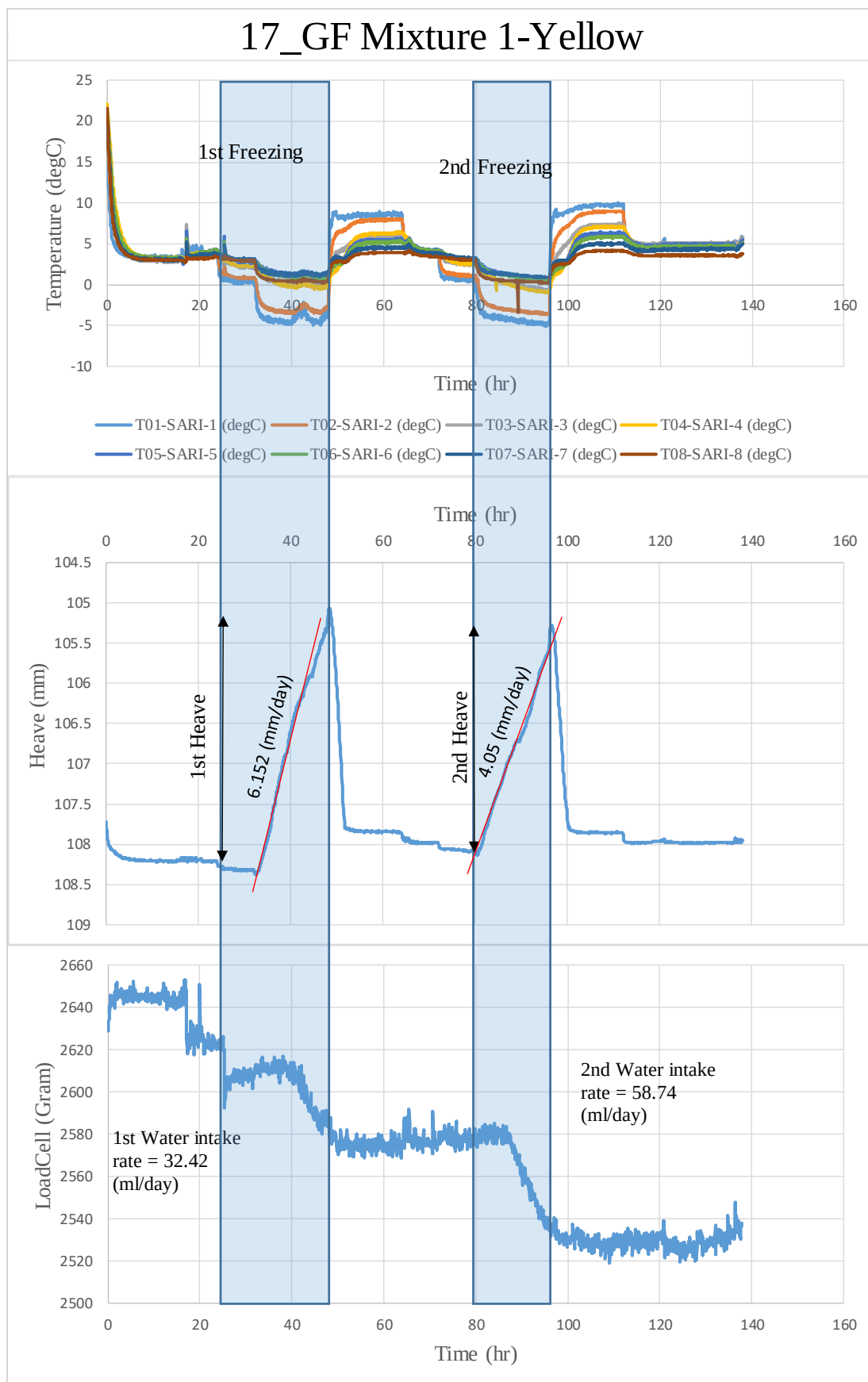


Figure C. 67 Freez-Thaw Test Results for "17_GF Mix 1-Yellow"

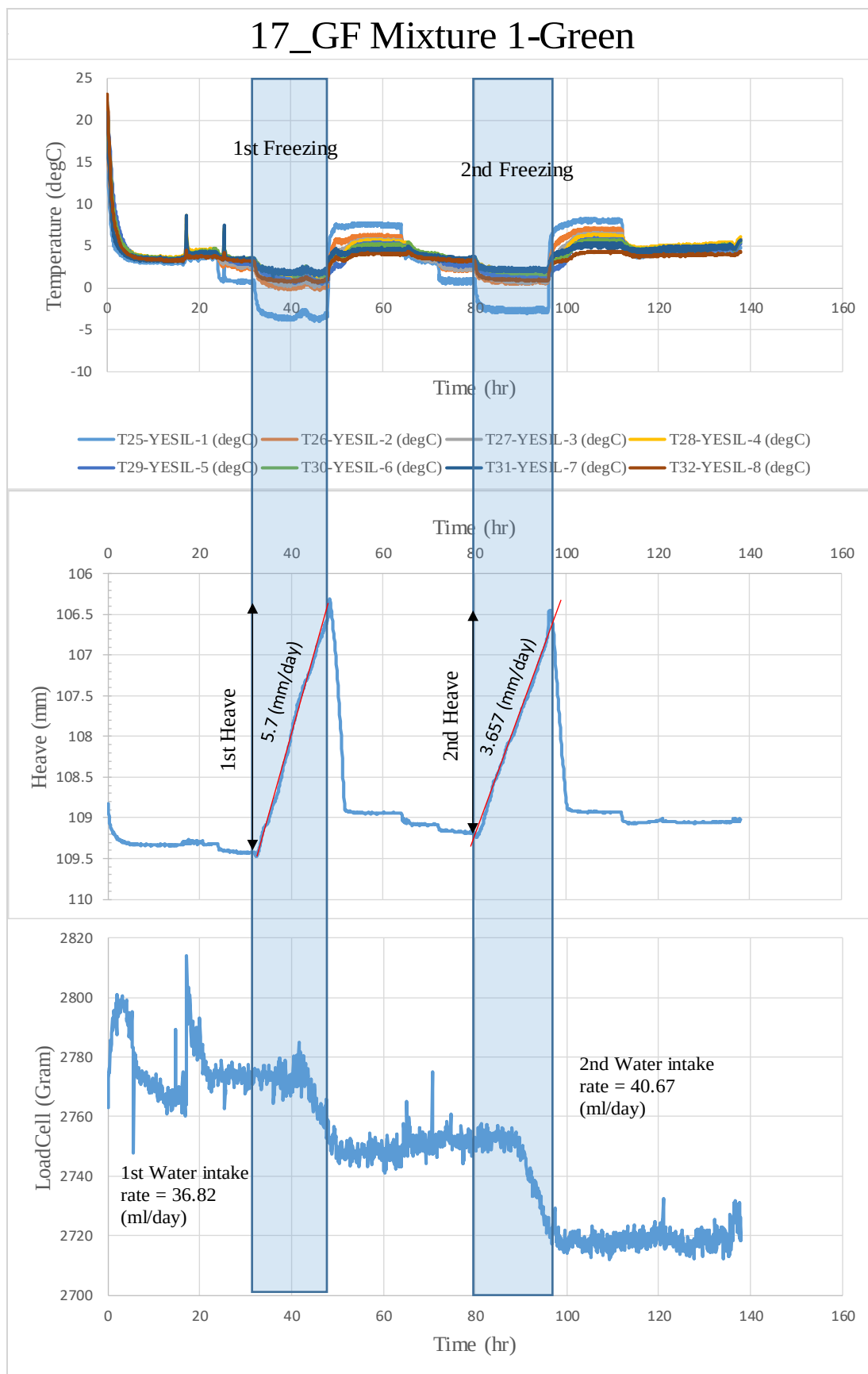


Figure C. 68 Freez-Thaw Test Results for “17_GF Mix 1-Green”

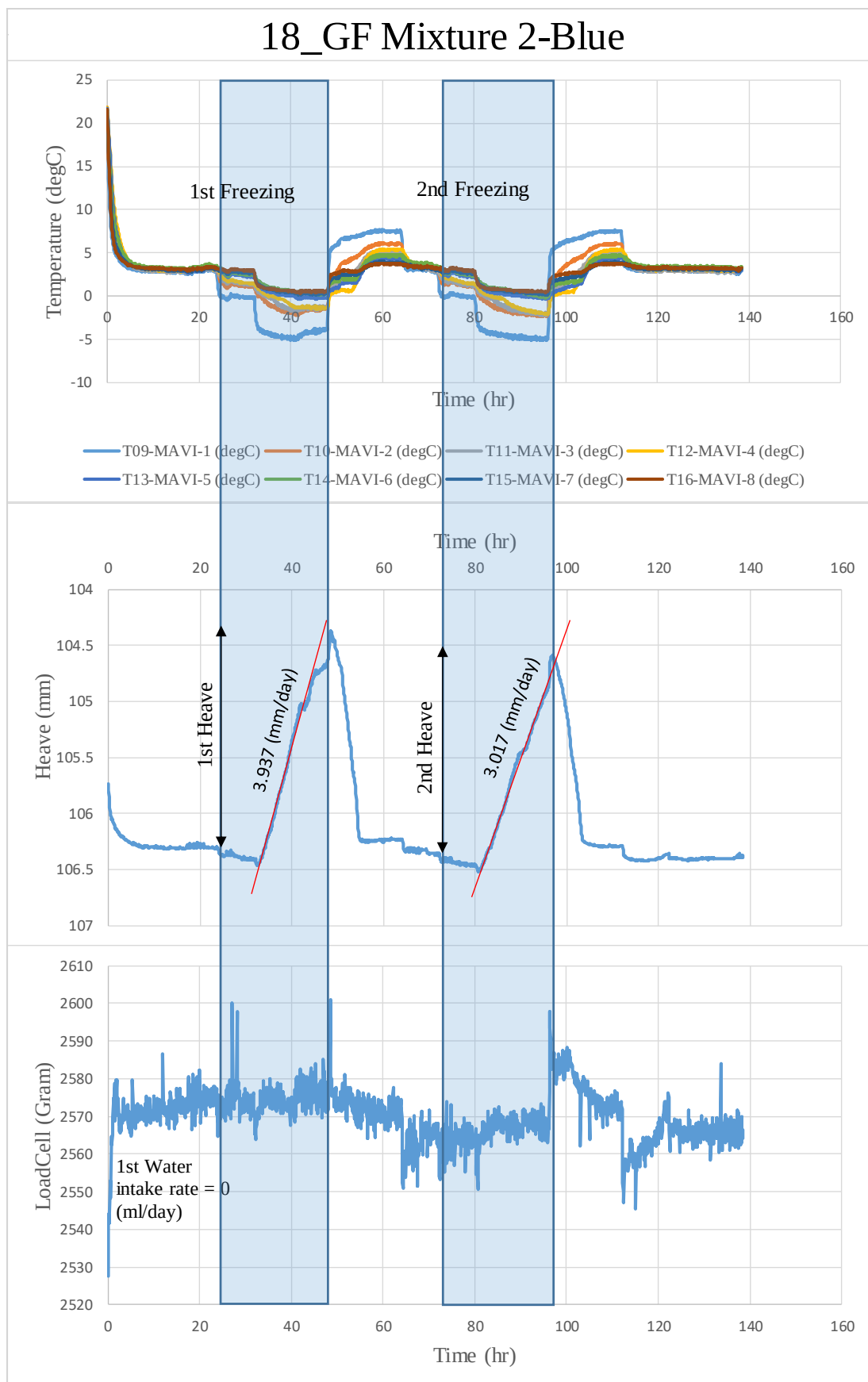


Figure C. 69 Freez-Thaw Test Results for “18_GF Mix 2-Blue”

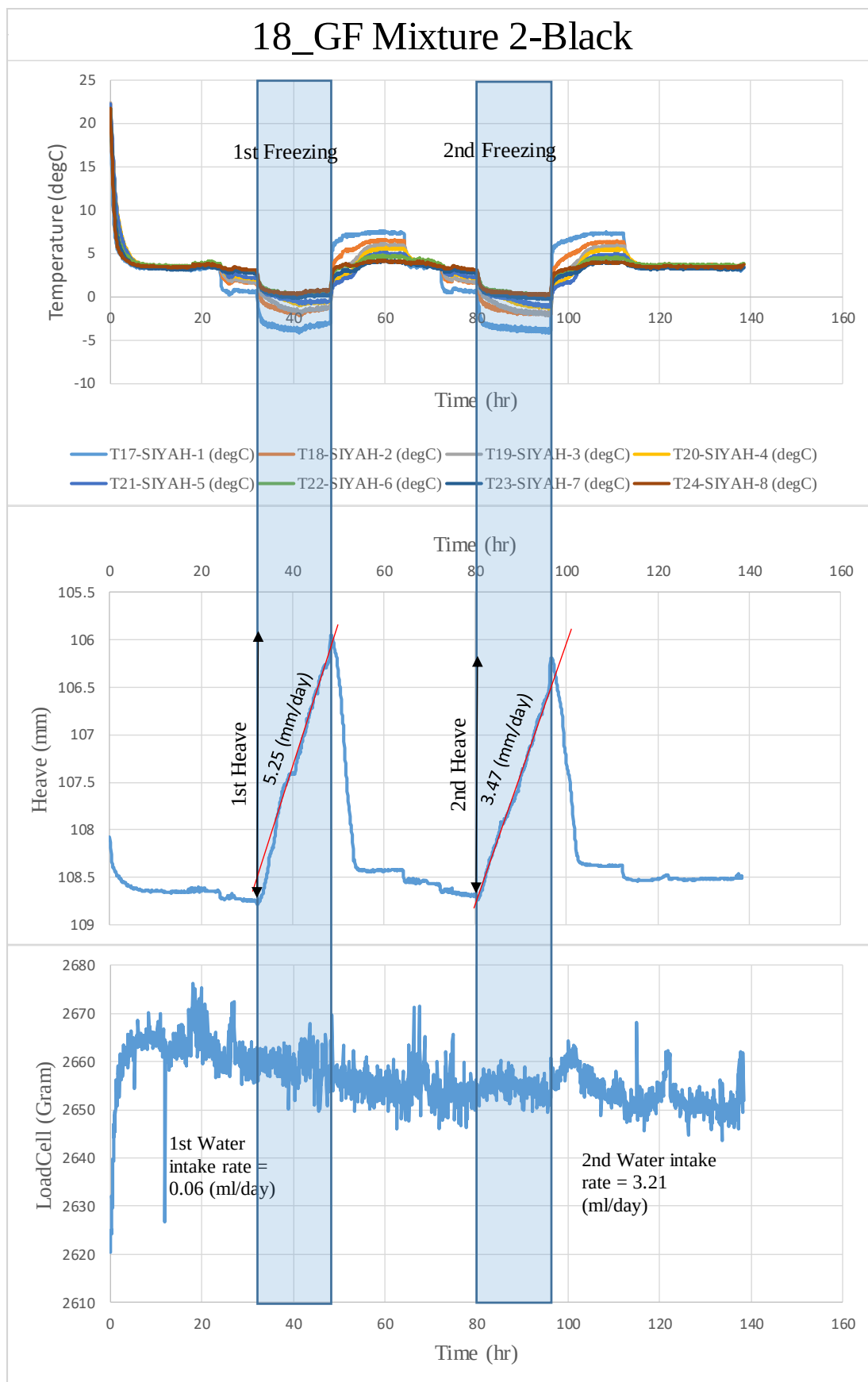


Figure C. 70 Freez-Thaw Test Results for “18_GF Mix 2-Black”

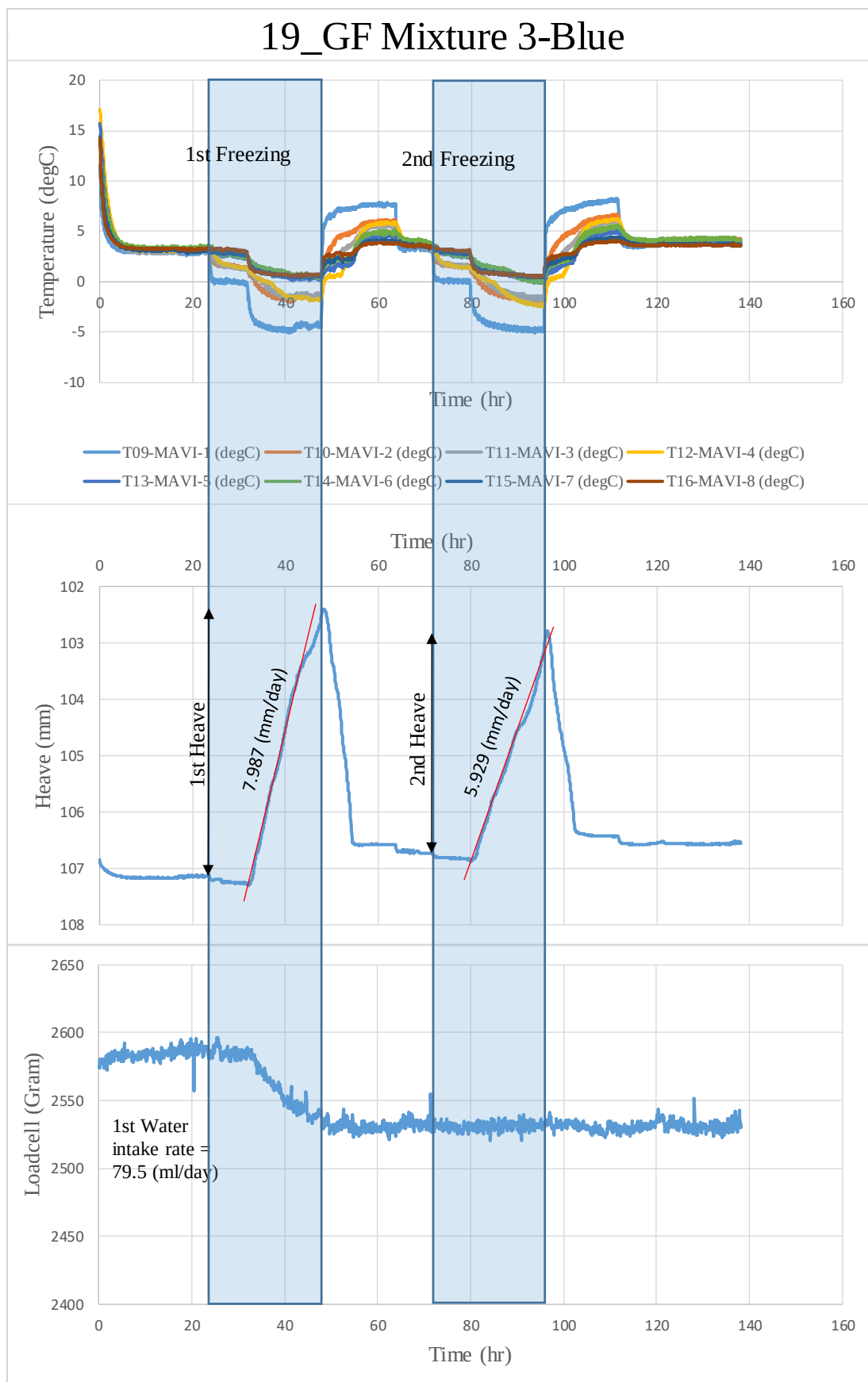


Figure C. 71 Freez-Thaw Test Results for “19_GF Mix 3-Blue”

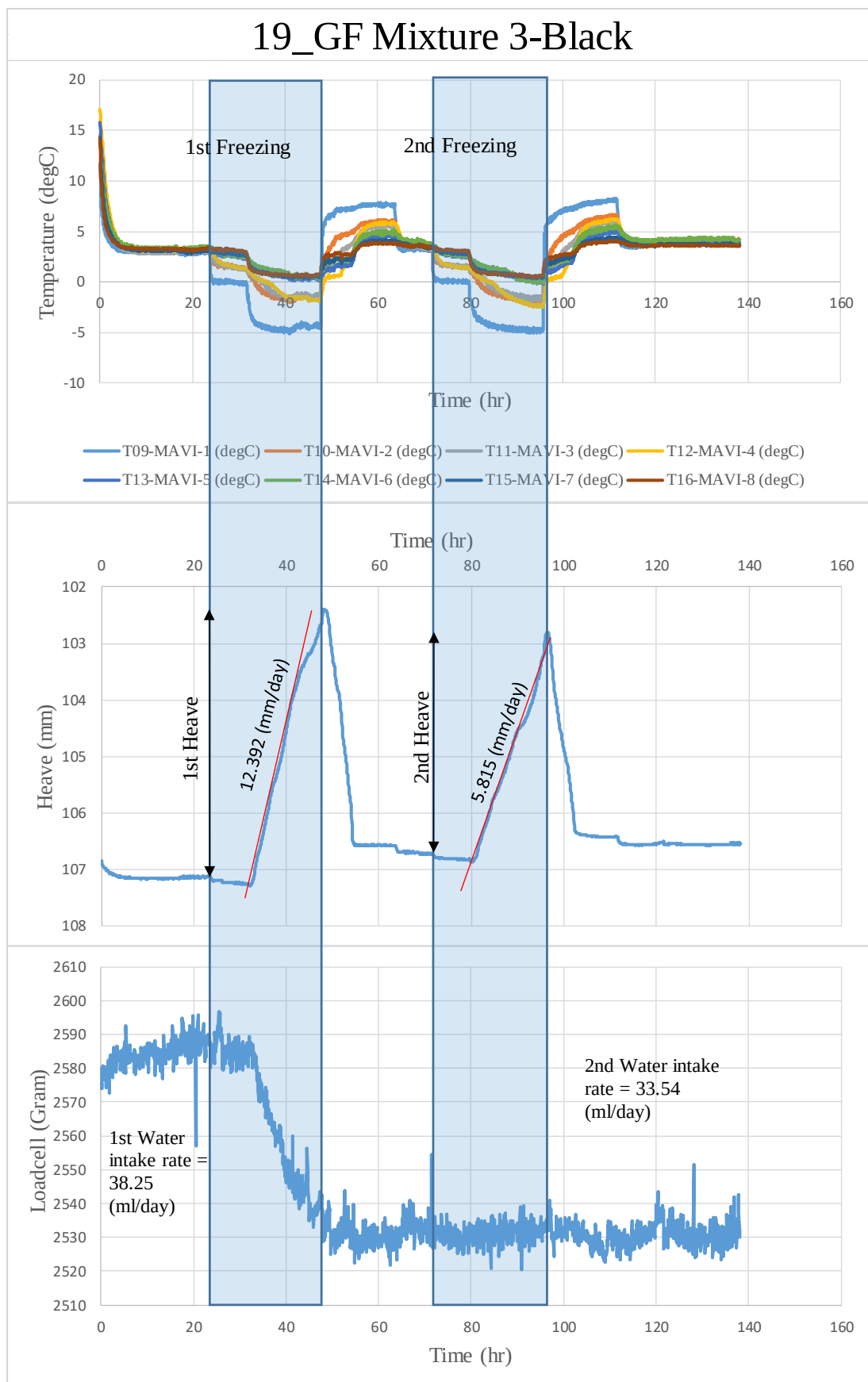


Figure C. 72 Freez-Thaw Test Results for “19_GF Mix 3-Black”

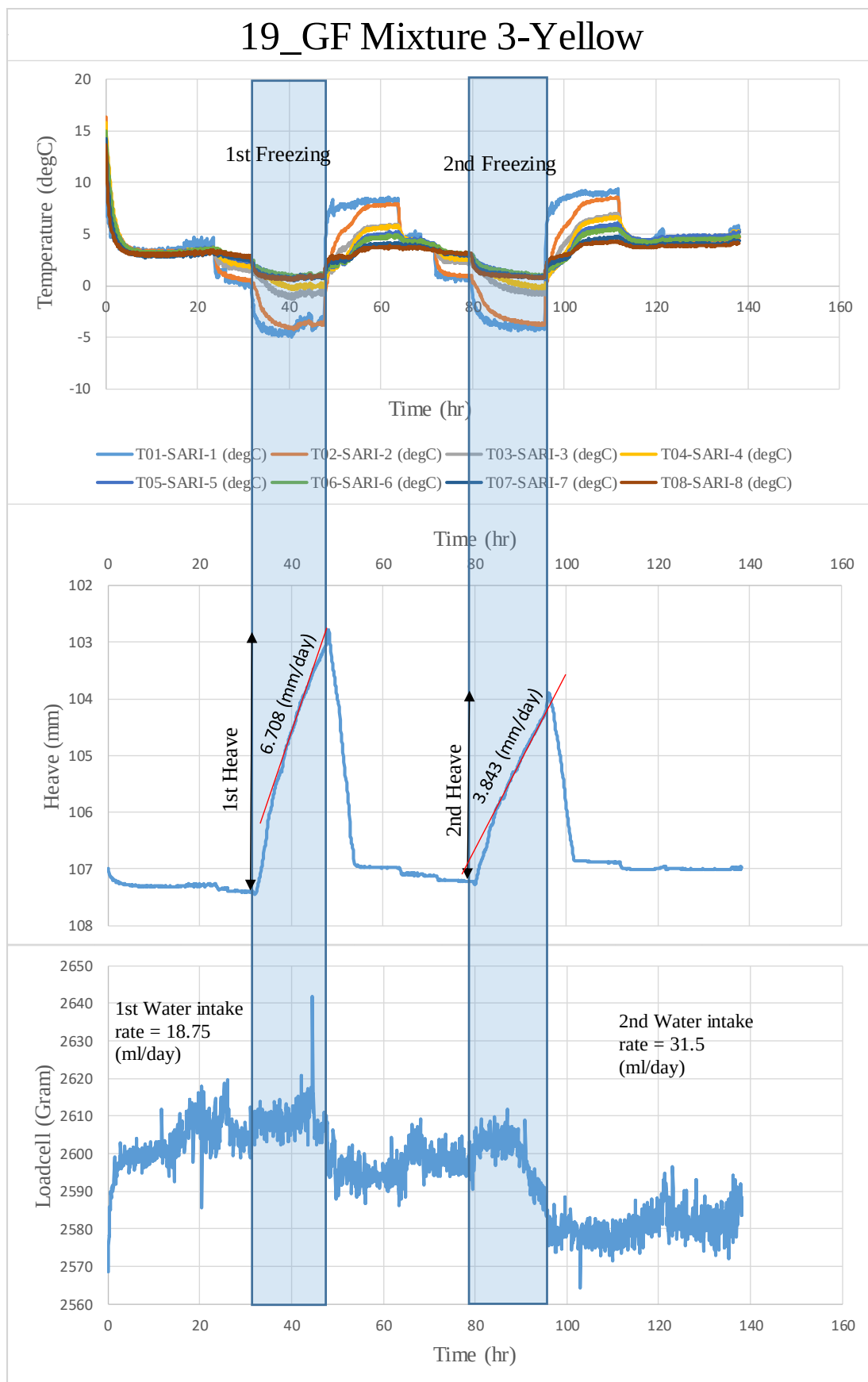


Figure C. 73 Freez-Thaw Test Results for "19_GF Mix 3-Yellow"

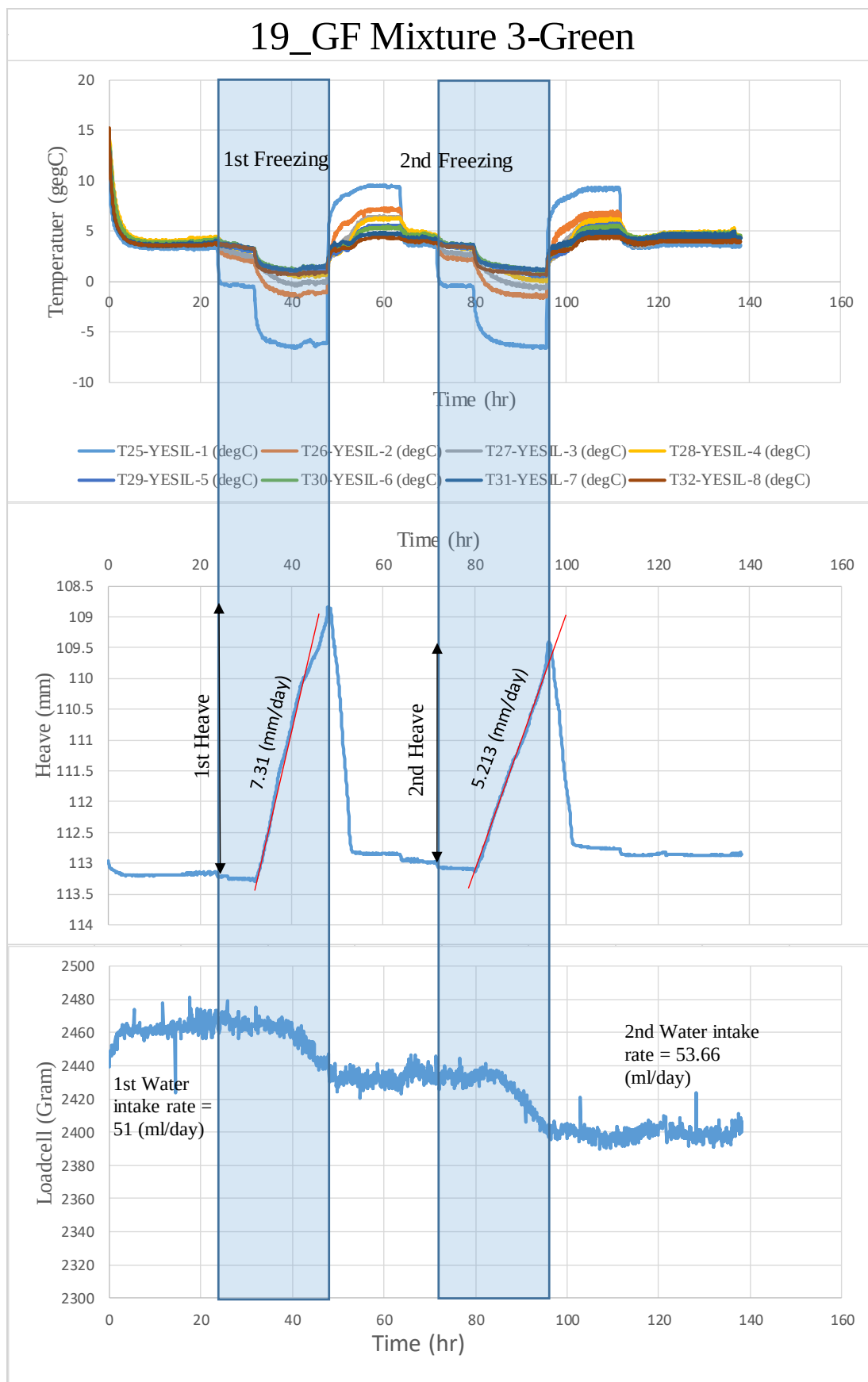


Figure C. 74 Freez-Thaw Test Results for “19_GF Mix 3-Green”

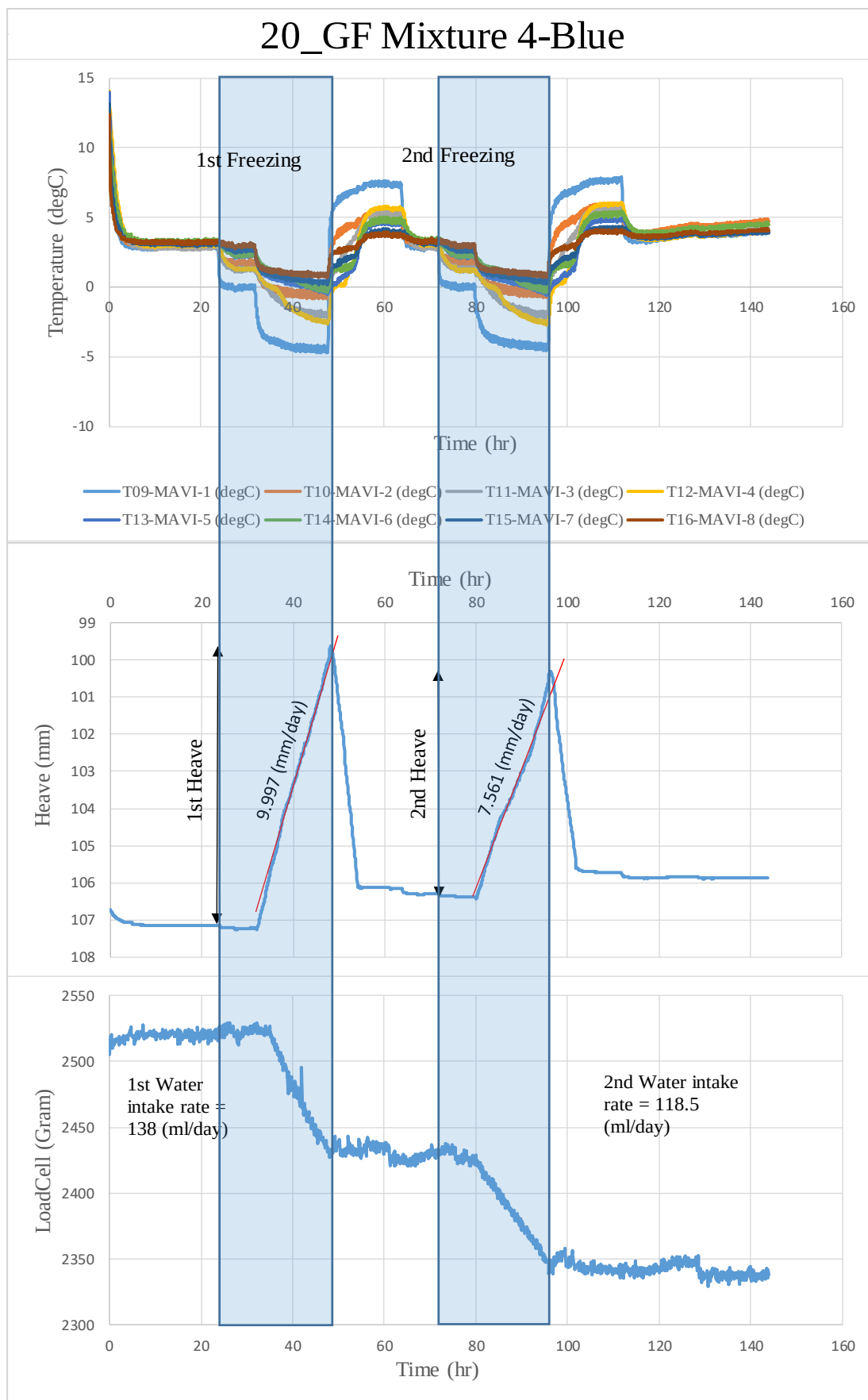


Figure C. 75 Freez-Thaw Test Results for “20_GF Mix 4-Blue”

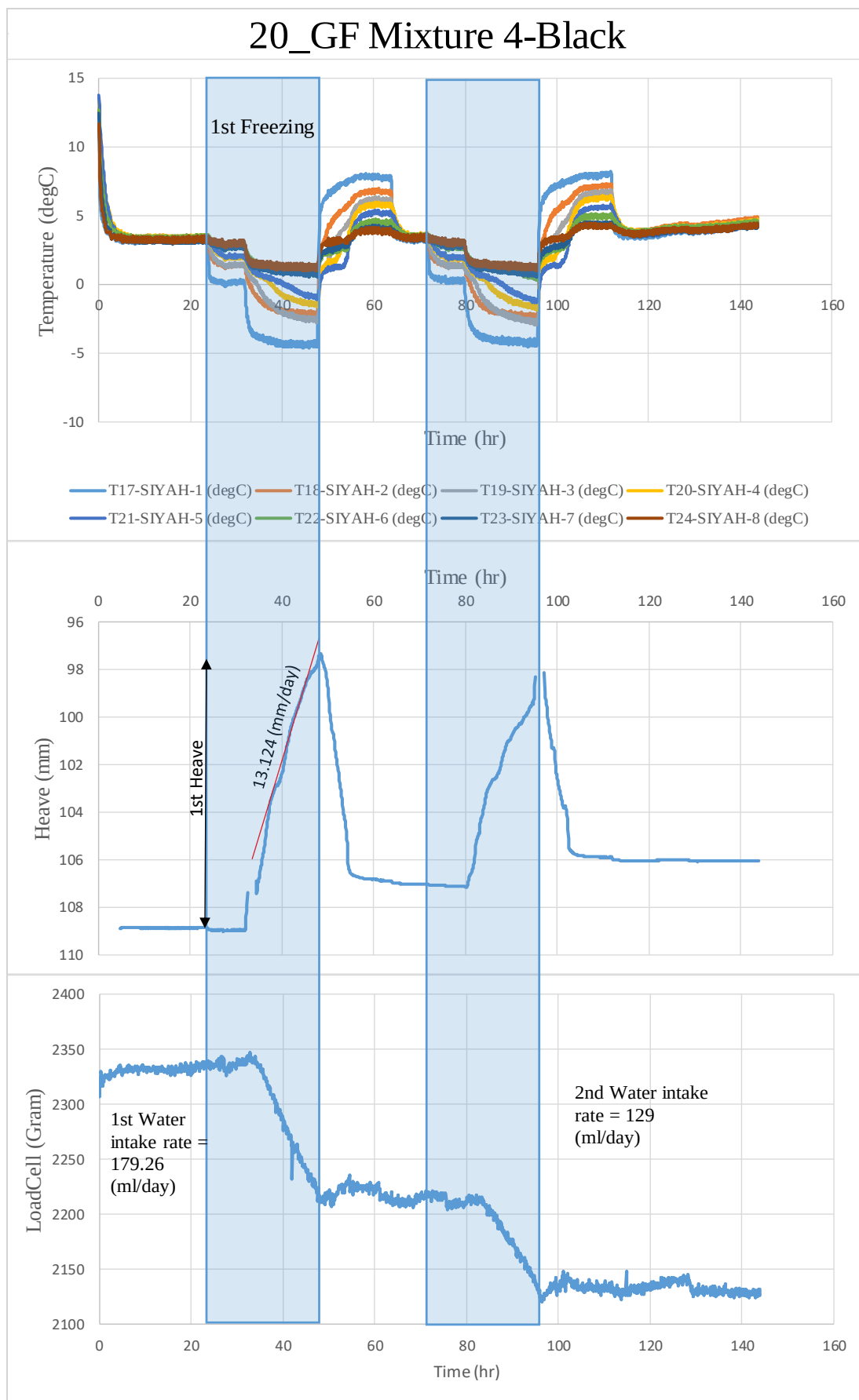


Figure C. 76 Freez-Thaw Test Results for “20_GF Mix 4-Black”

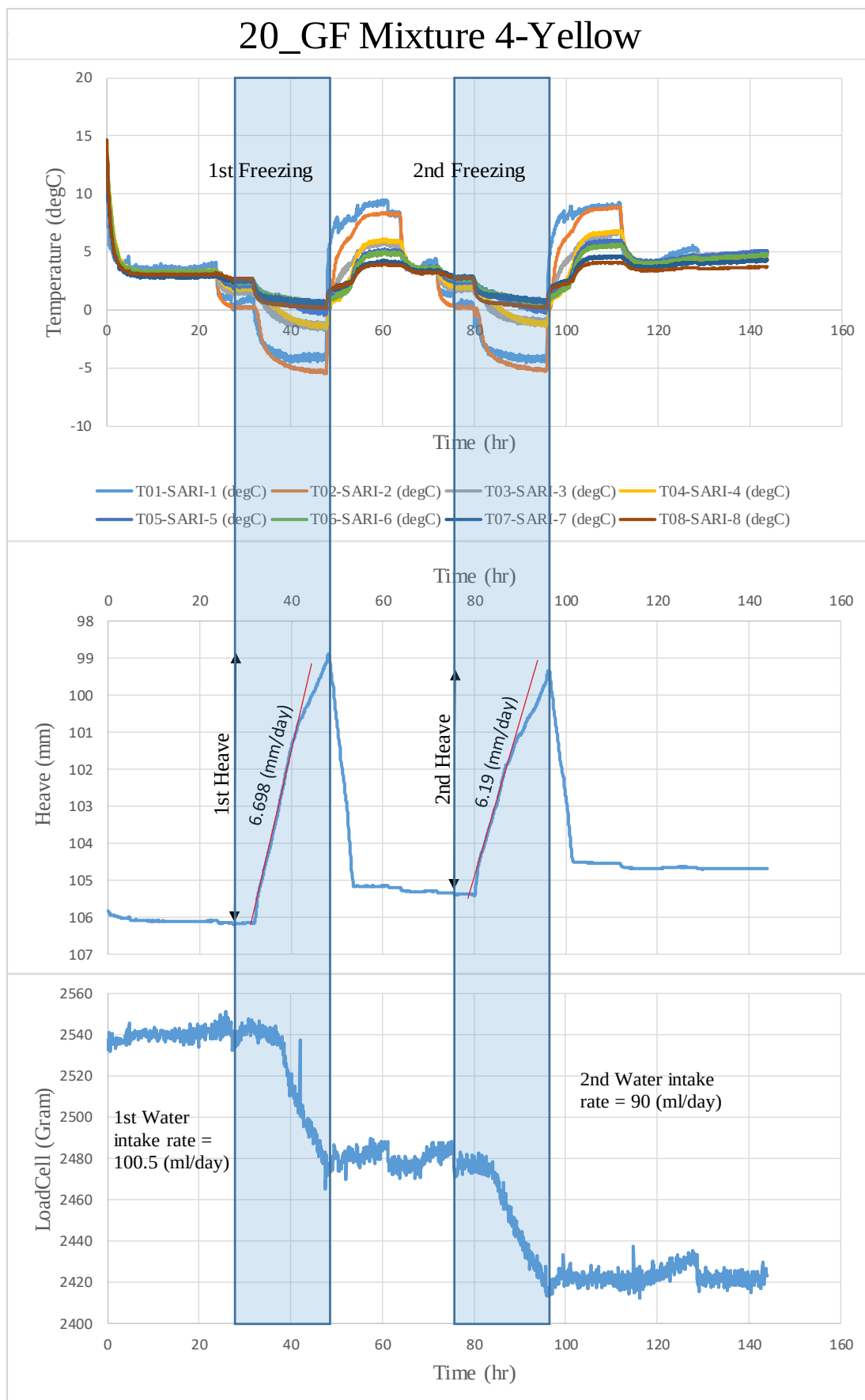


Figure C. 77 Freez-Thaw Test Results for “20_GF Mix 4-Yellow”

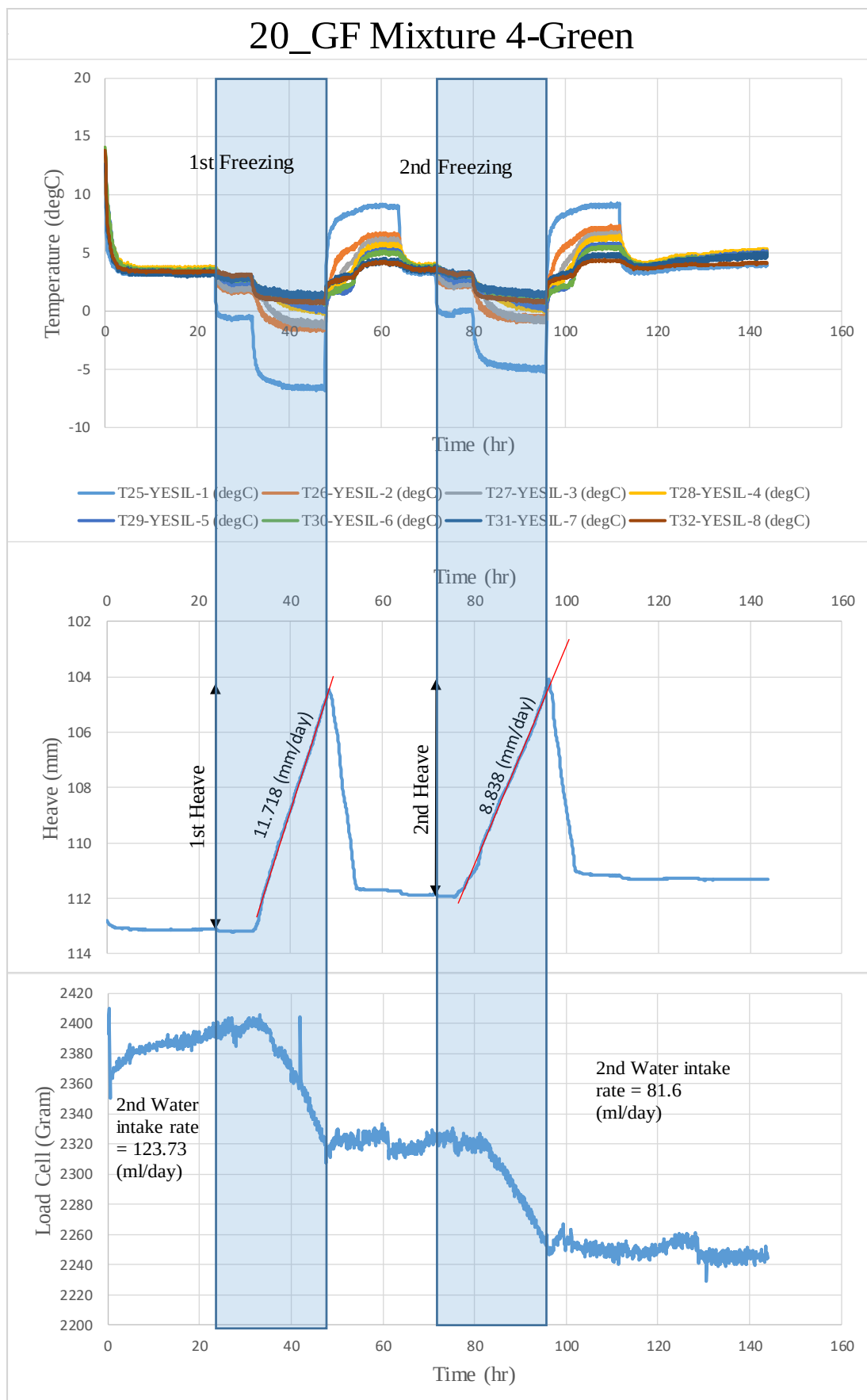


Figure C. 78 Freez-Thaw Test Results for “20_GF Mix 4-Green”

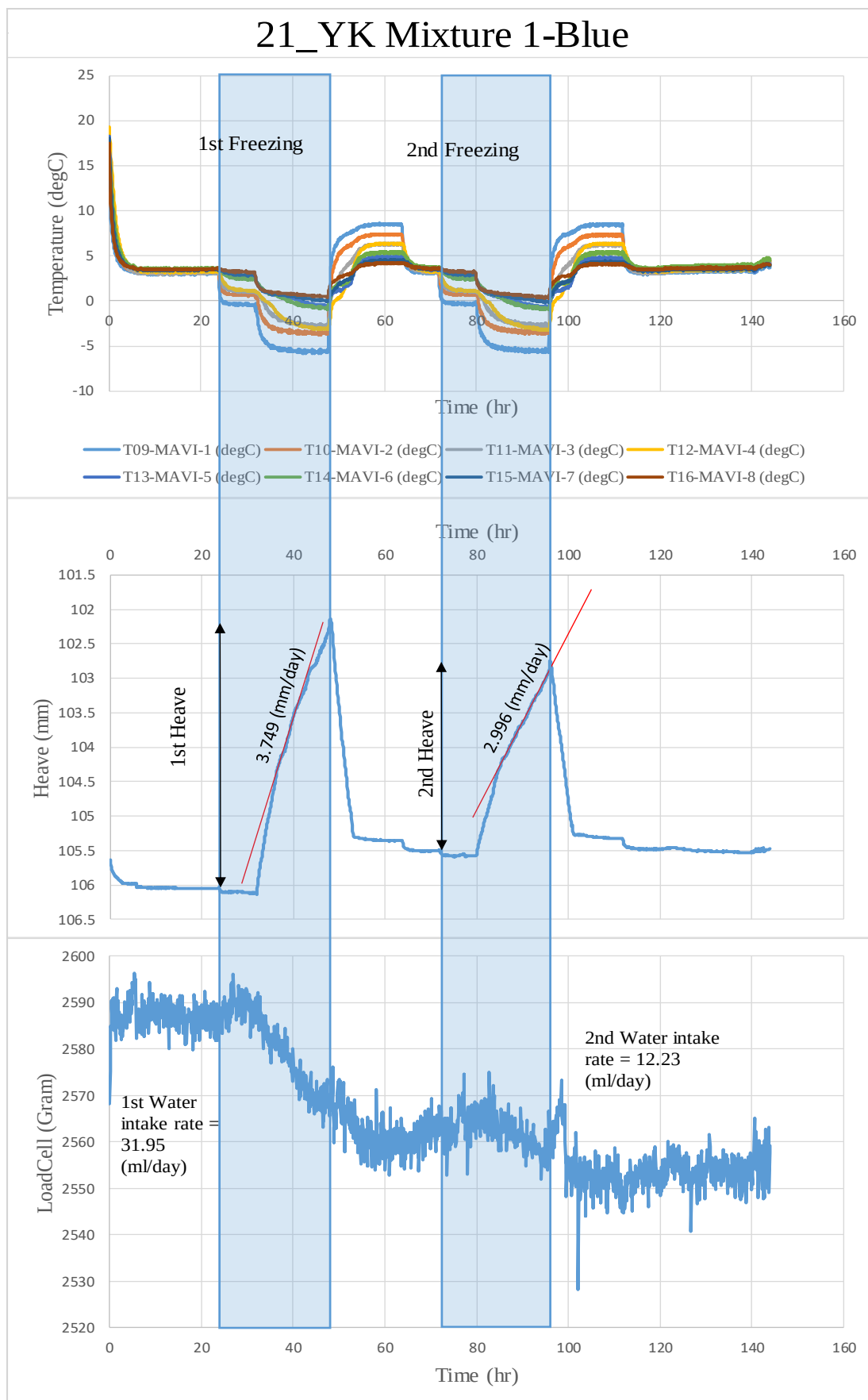


Figure C. 79 Freez-Thaw Test Results for “21_YK Mix 1-Blue”

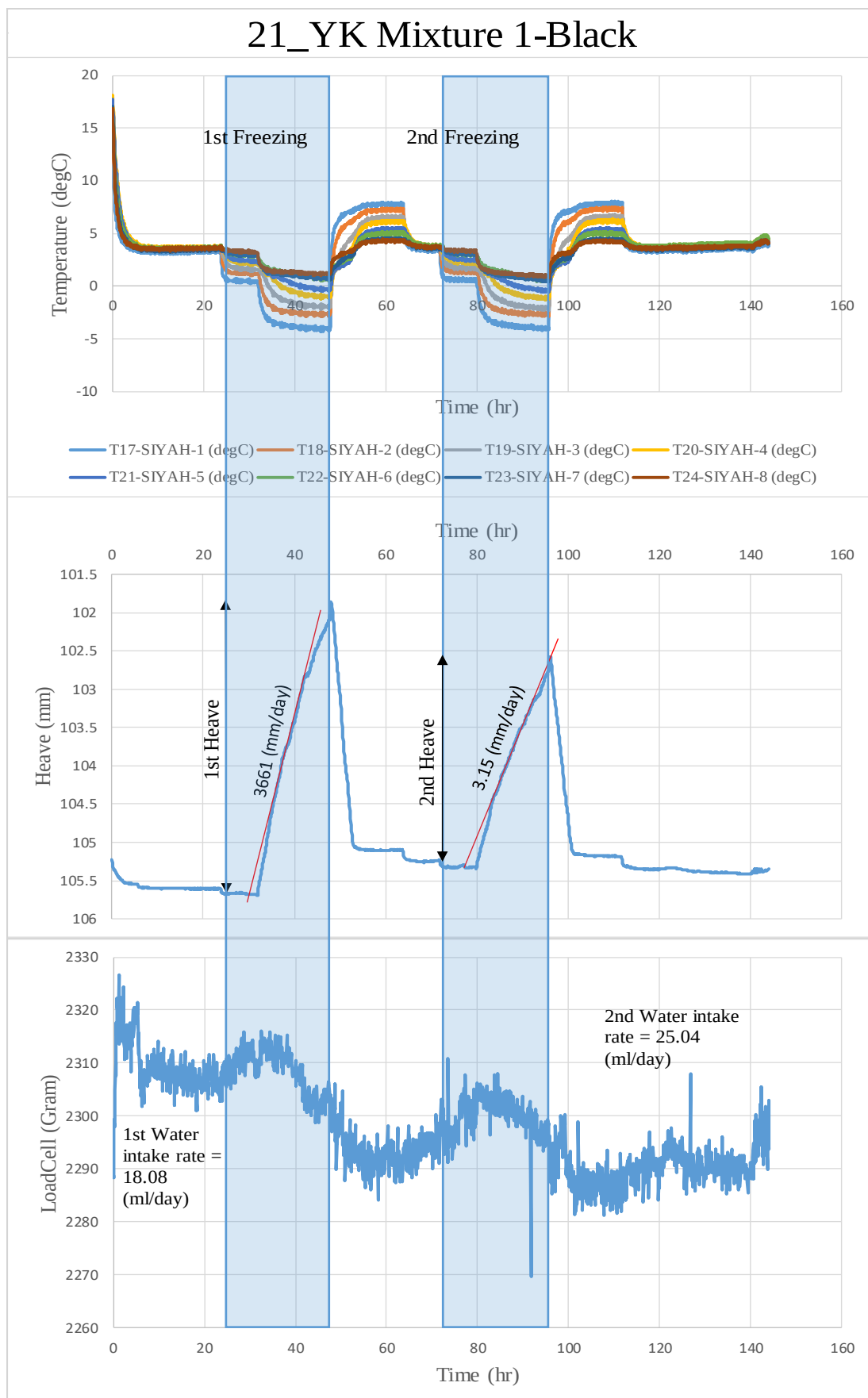


Figure C. 80 Freez-Thaw Test Results for “21_YK Mix 1-Black”

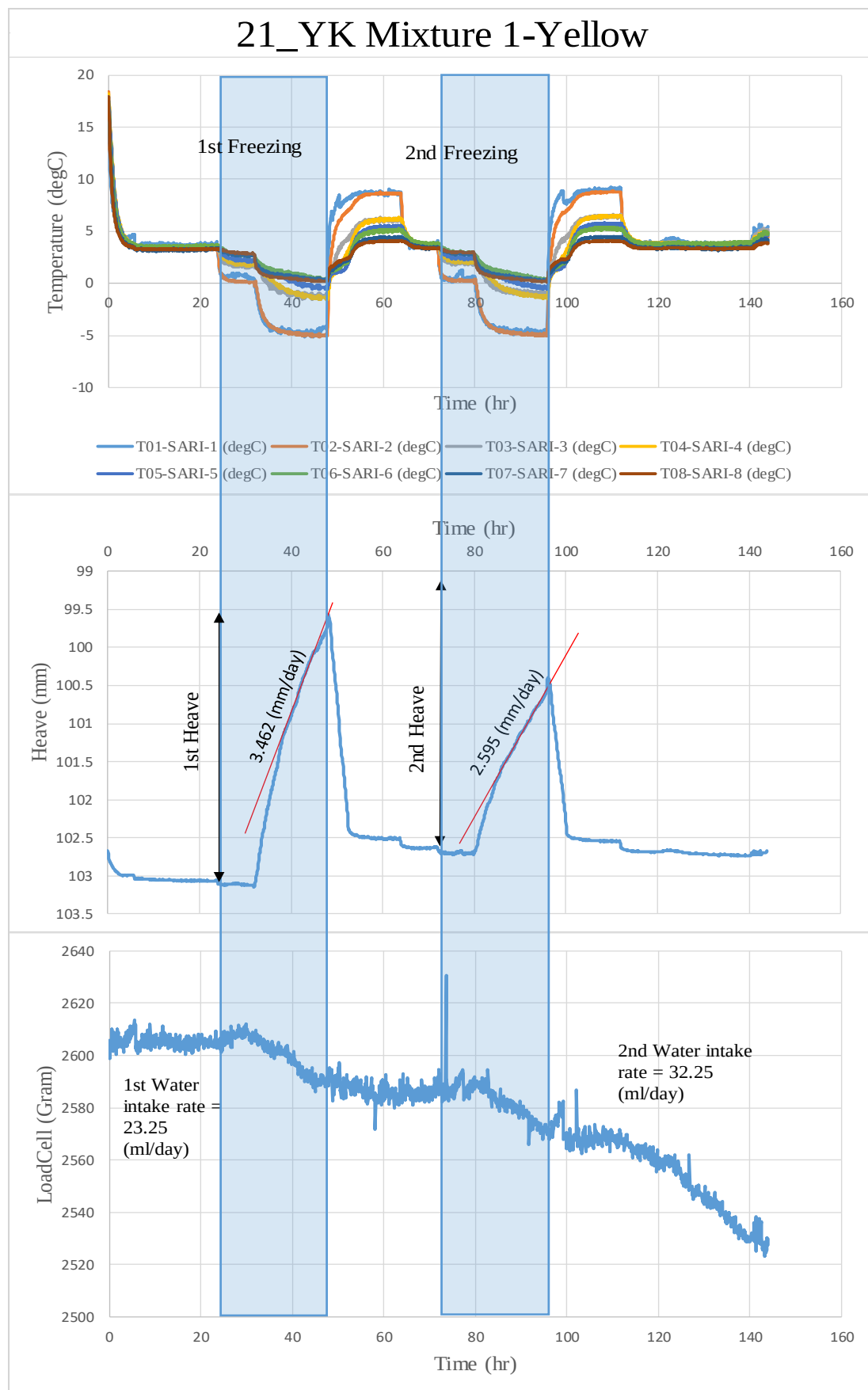


Figure C. 81 Freez-Thaw Test Results for “21_YK Mix 1-Yellow”

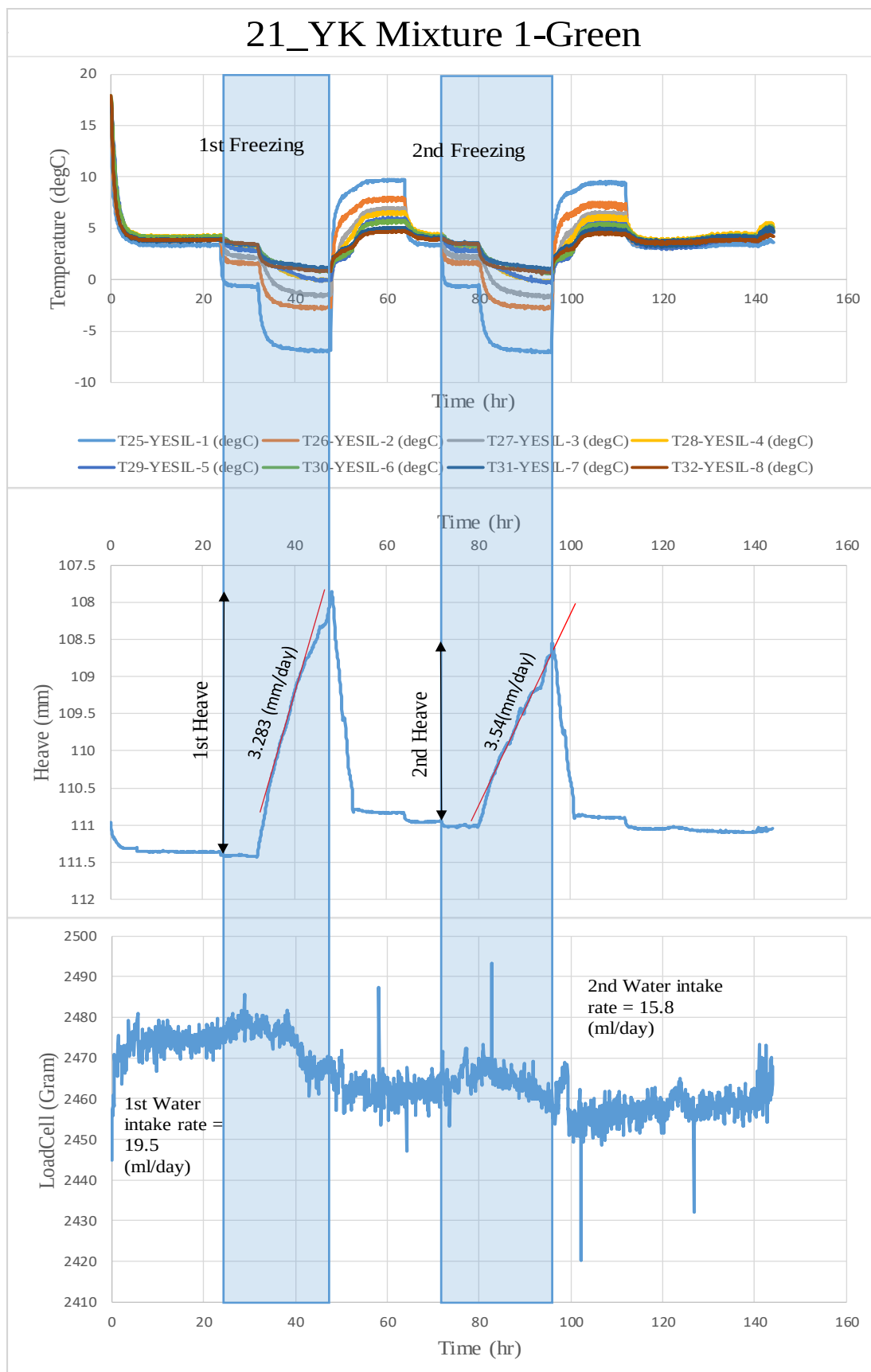


Figure C. 82 Freez-Thaw Test Results for “21_YK Mix 1-Green”

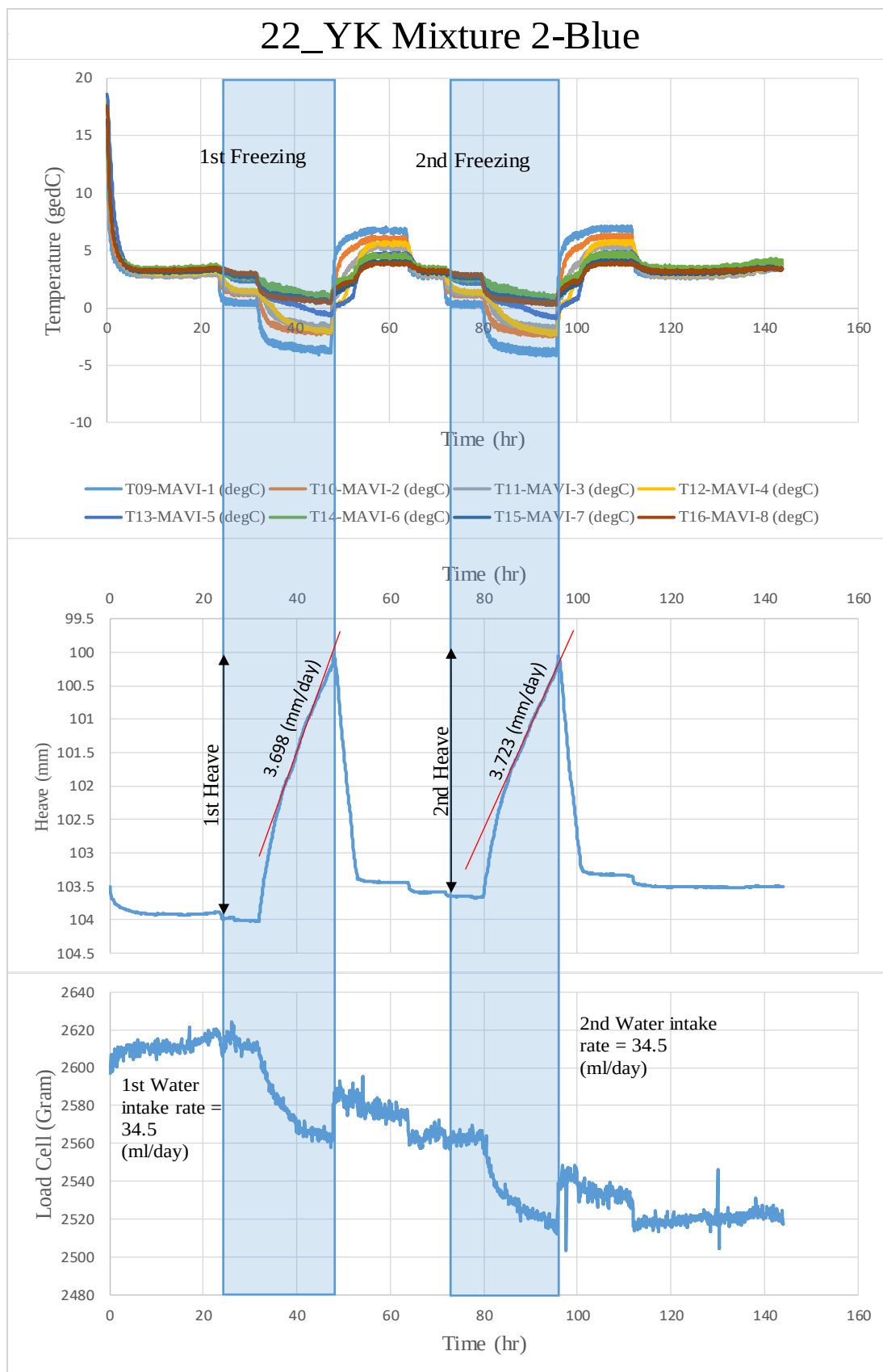


Figure C. 83 Freez-Thaw Test Results for “22_YK Mix 2-Blue”

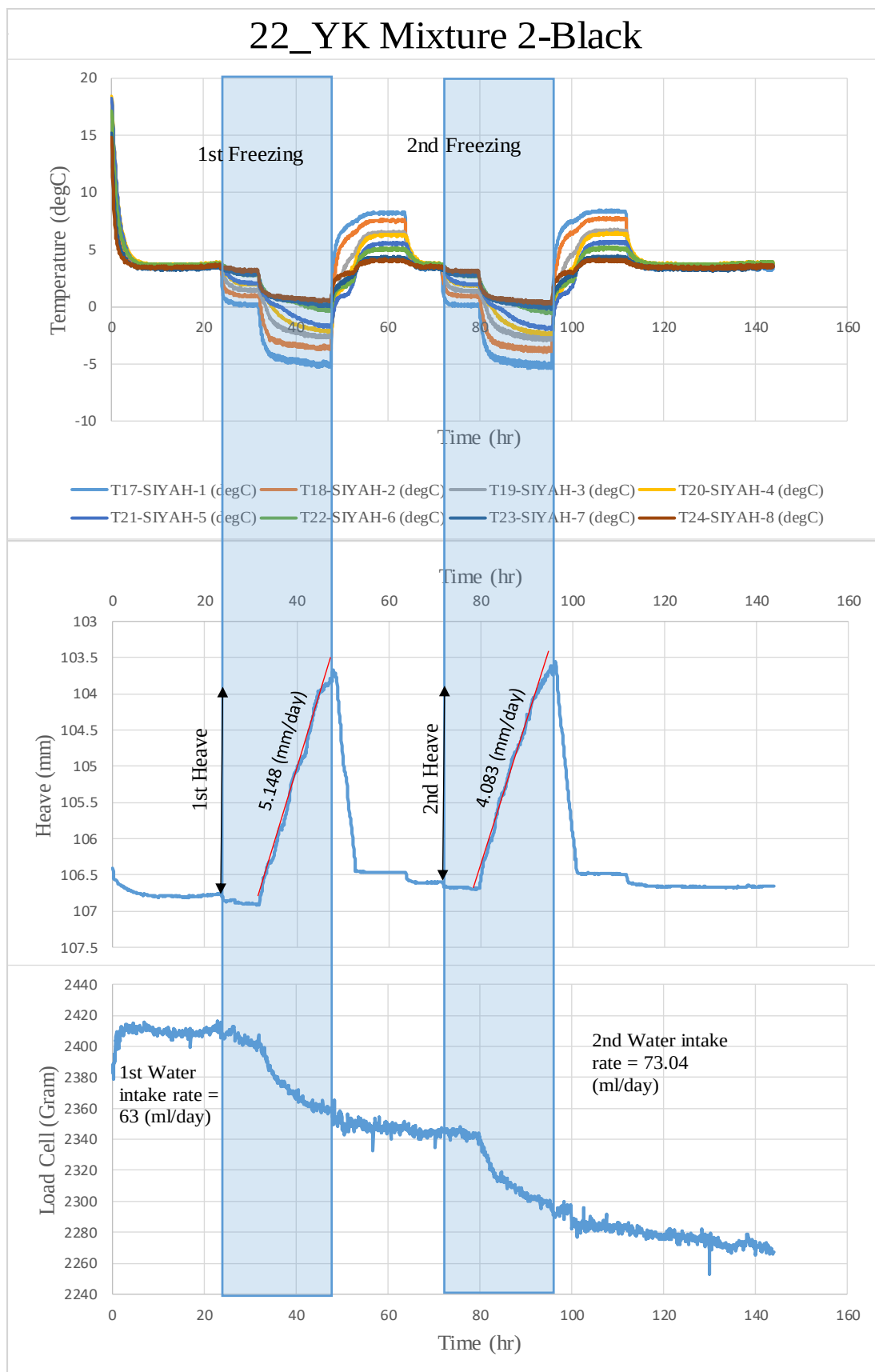


Figure C. 84 Freez-Thaw Test Results for “22_YK Mix 2-Black”

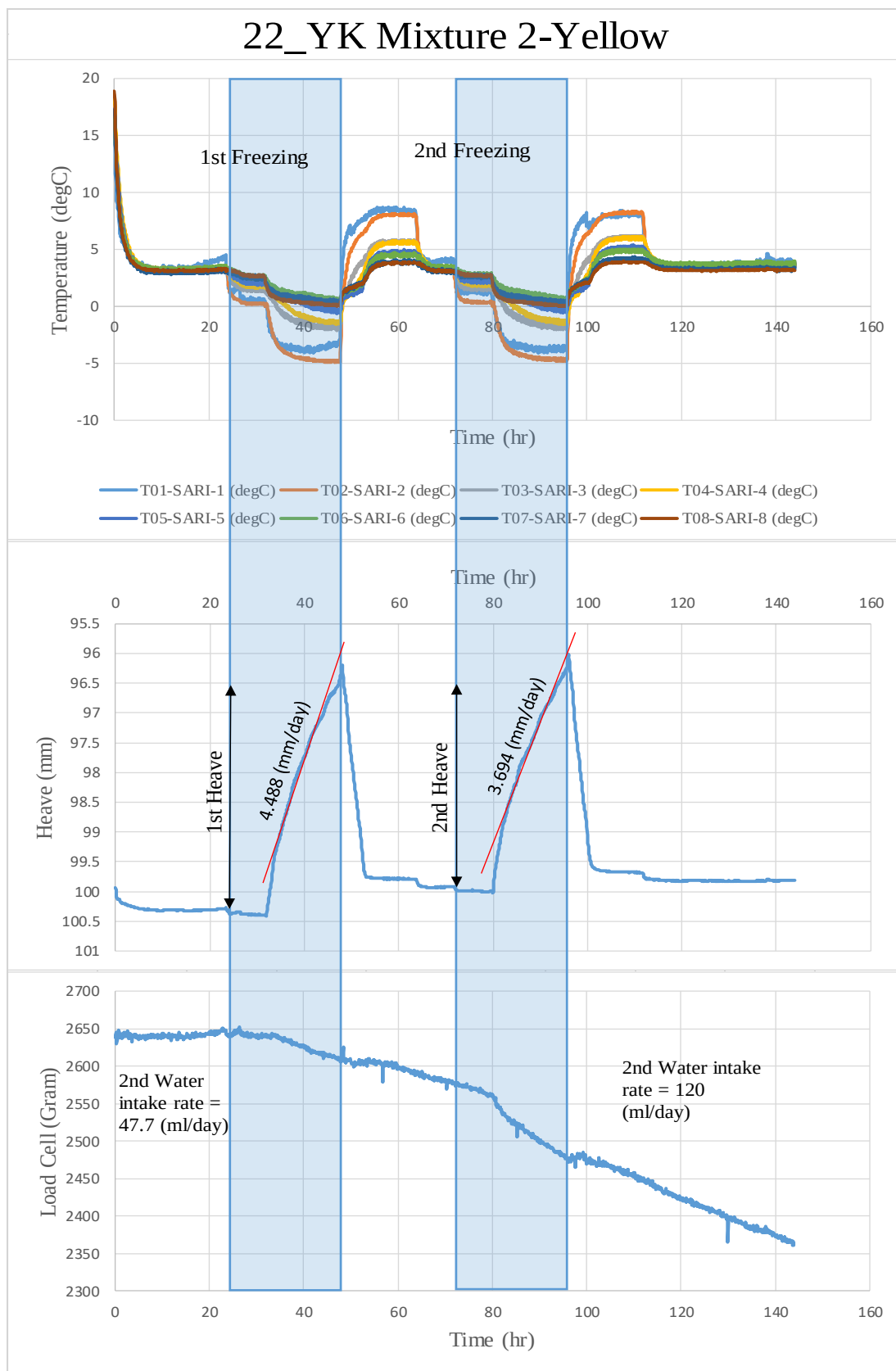


Figure C. 85 Freez-Thaw Test Results for “22_YK Mix 2-Yellow”

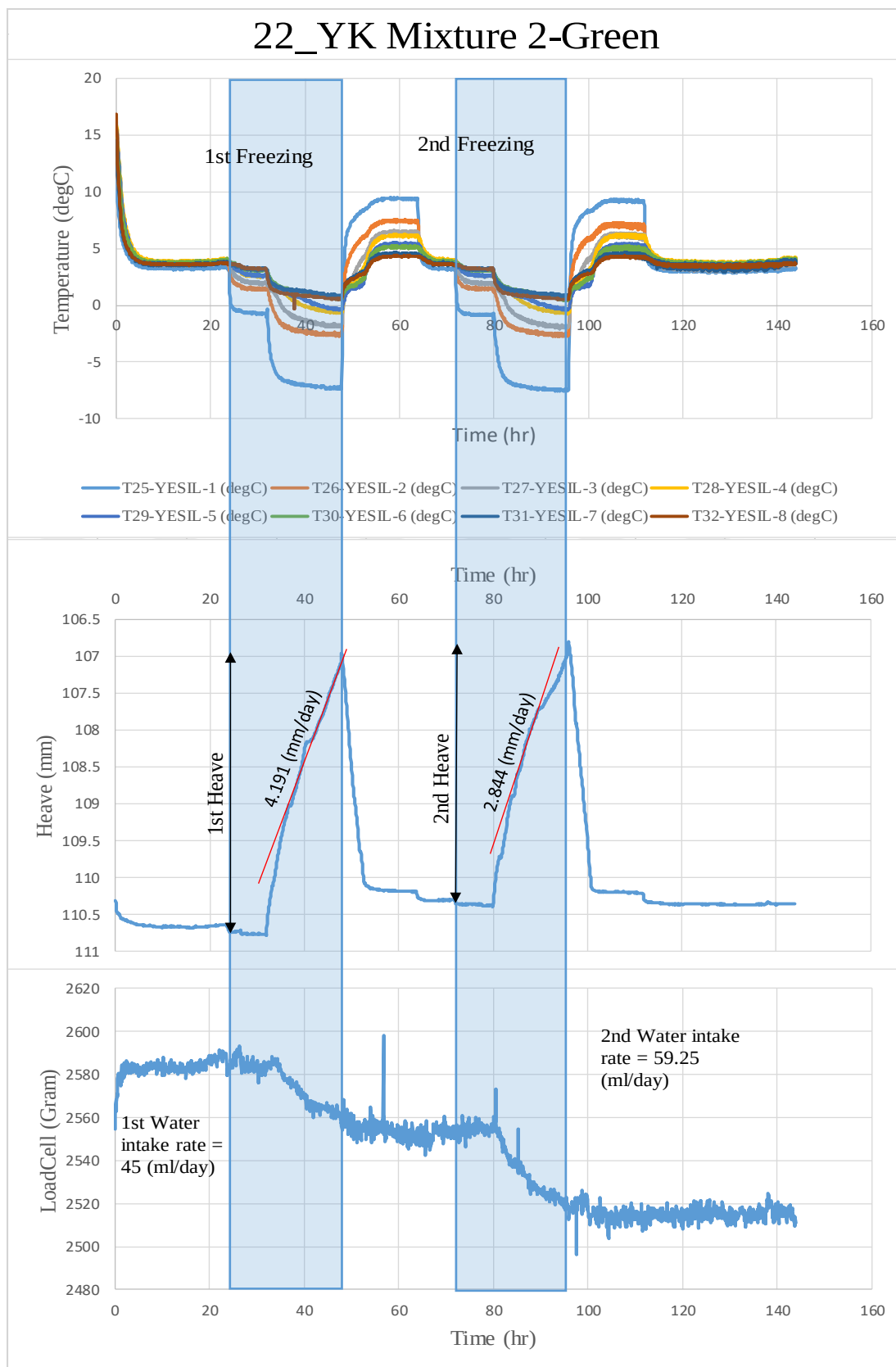


Figure C. 86 Freez-Thaw Test Results for "22_YK Mix 2-Green"

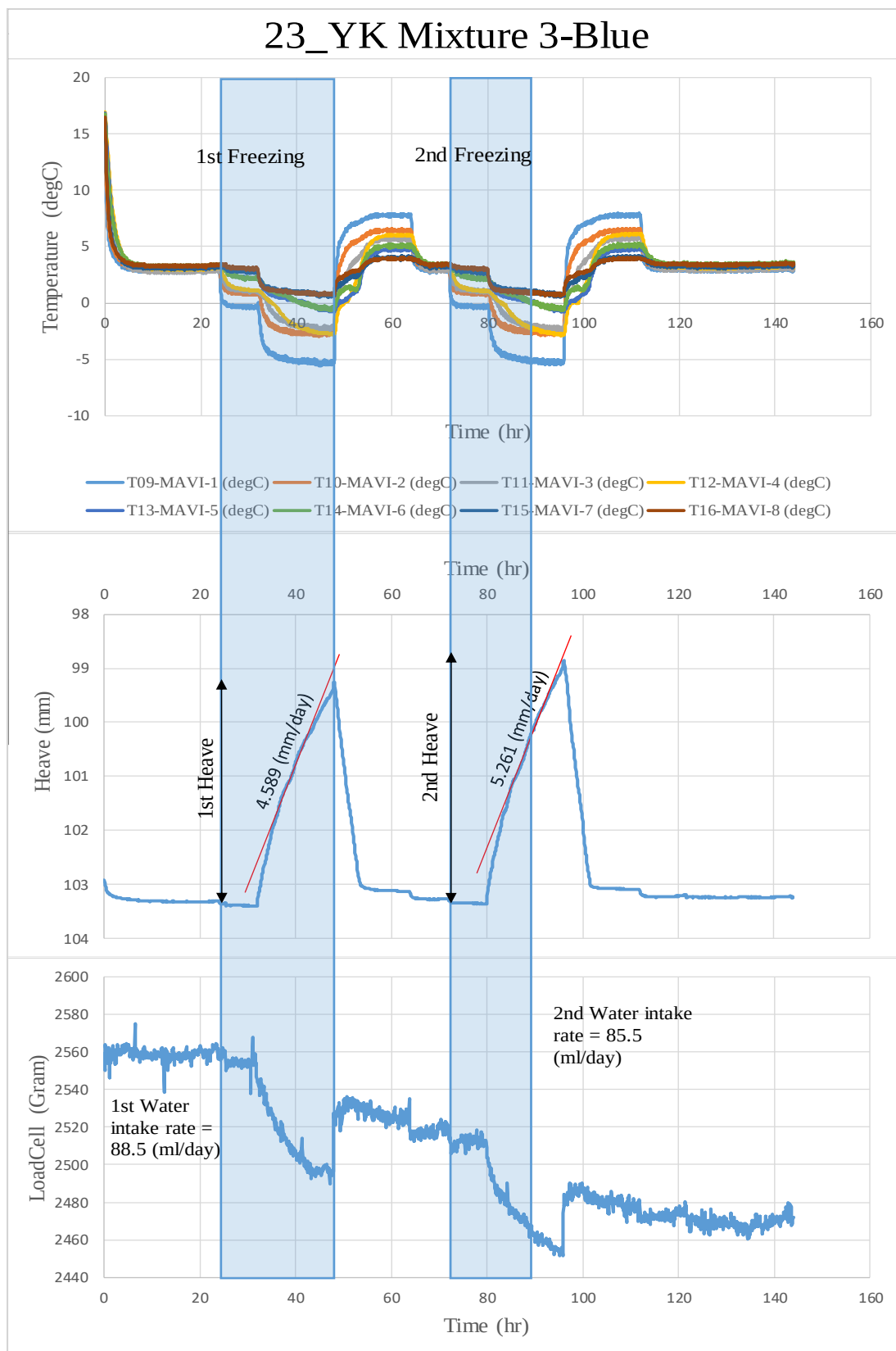


Figure C. 87 Freez-Thaw Test Results for “23_YK Mix 3-Blue”

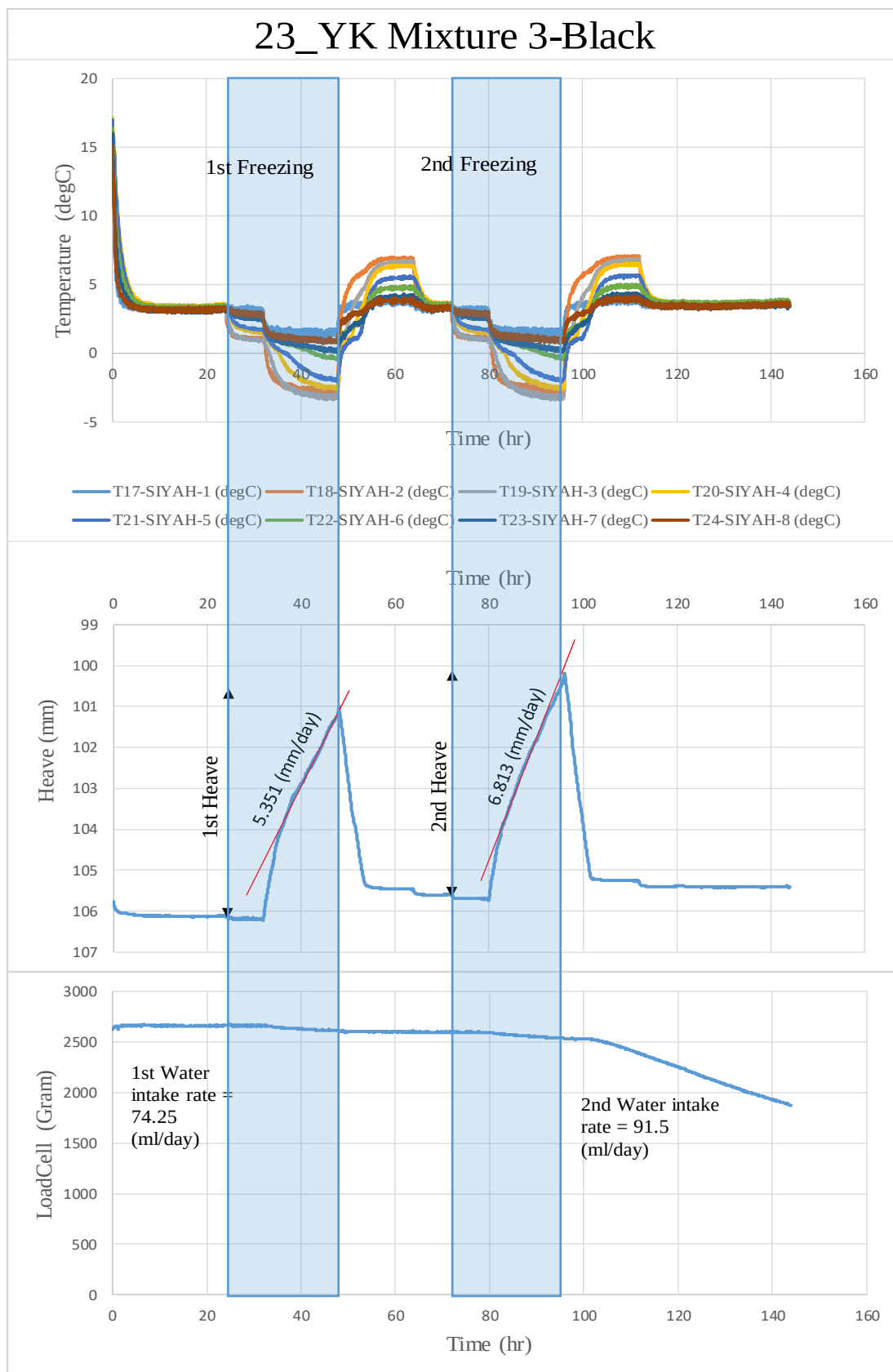


Figure C. 88 Freez-Thaw Test Results for “23_YK Mix 3-Black”

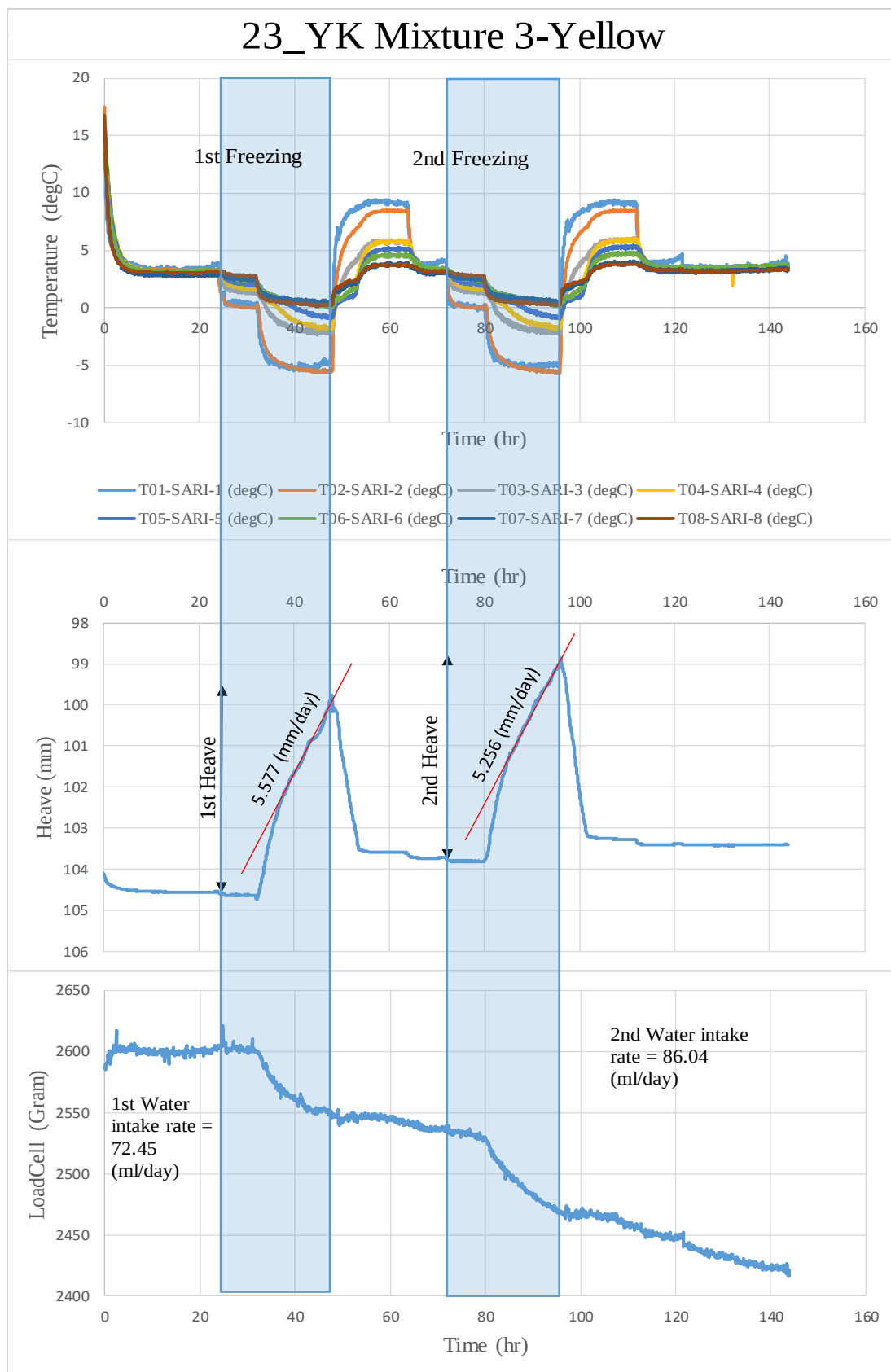


Figure C. 89 Freez-Thaw Test Results for “23_YK Mix 3-Yellow”

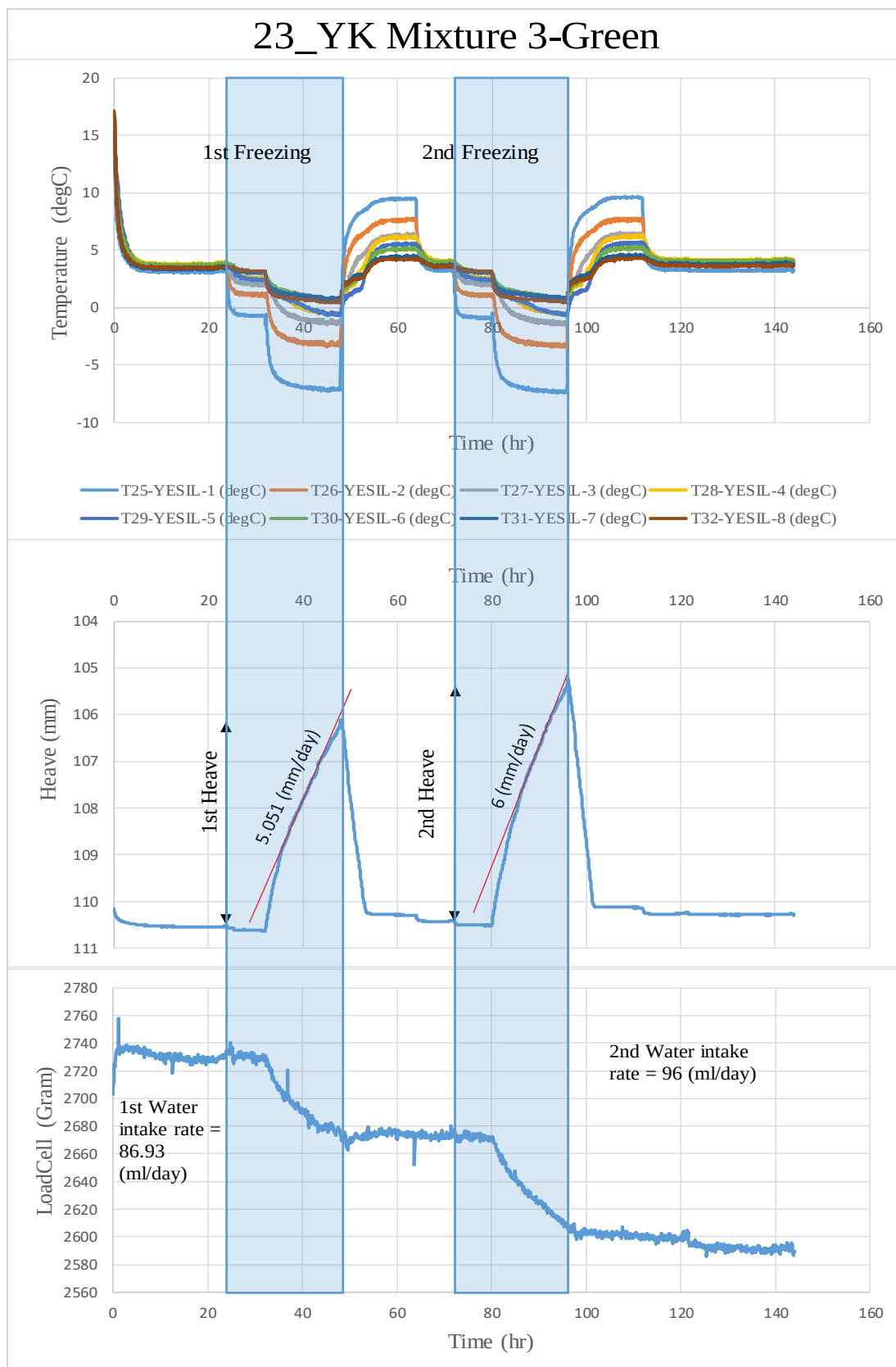


Figure C. 90 Freez-Thaw Test Results for "23_YK Mix 3-Green"

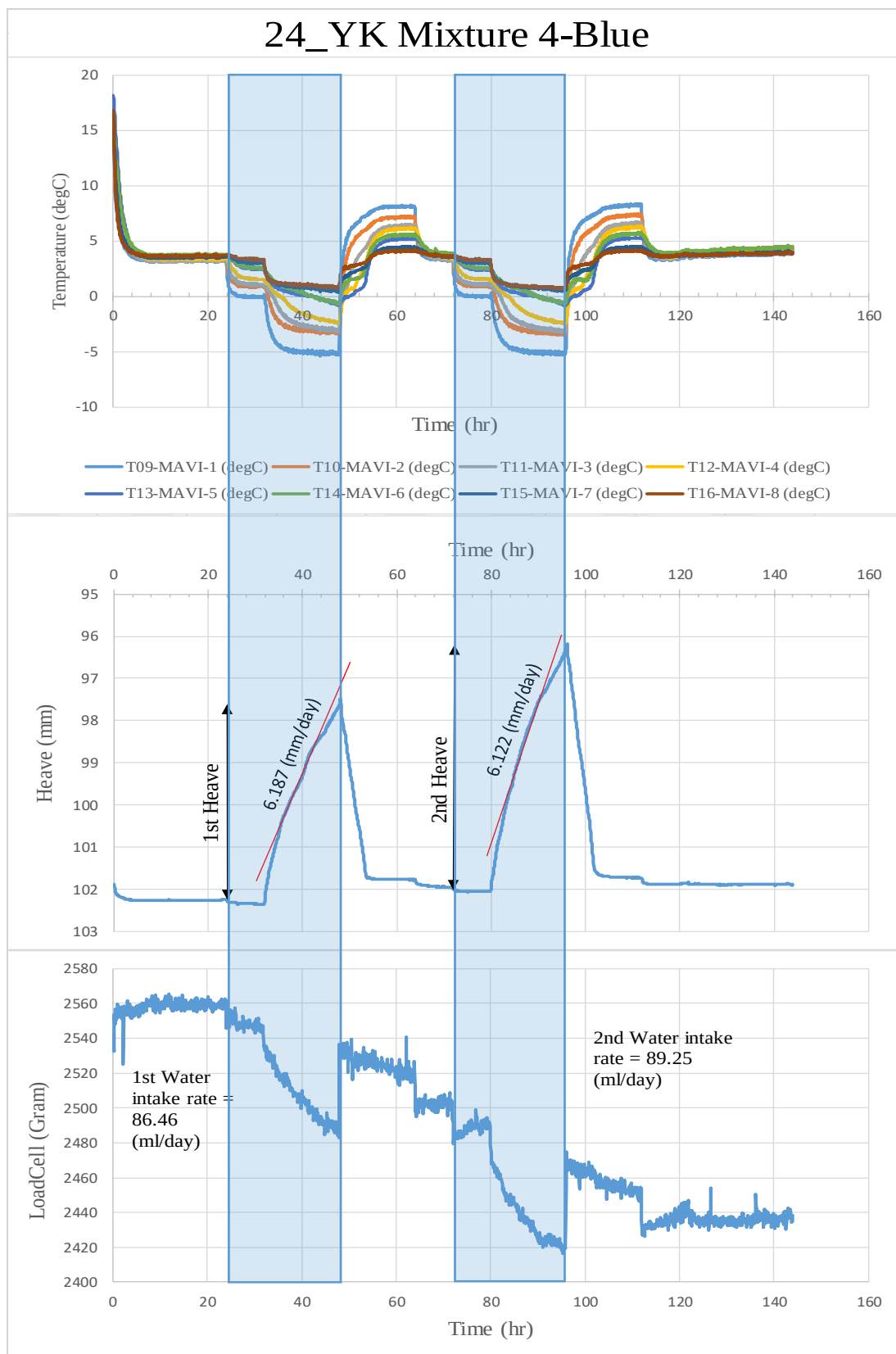


Figure C. 91 Freez-Thaw Test Results for “24_YK Mix 4-Blue”

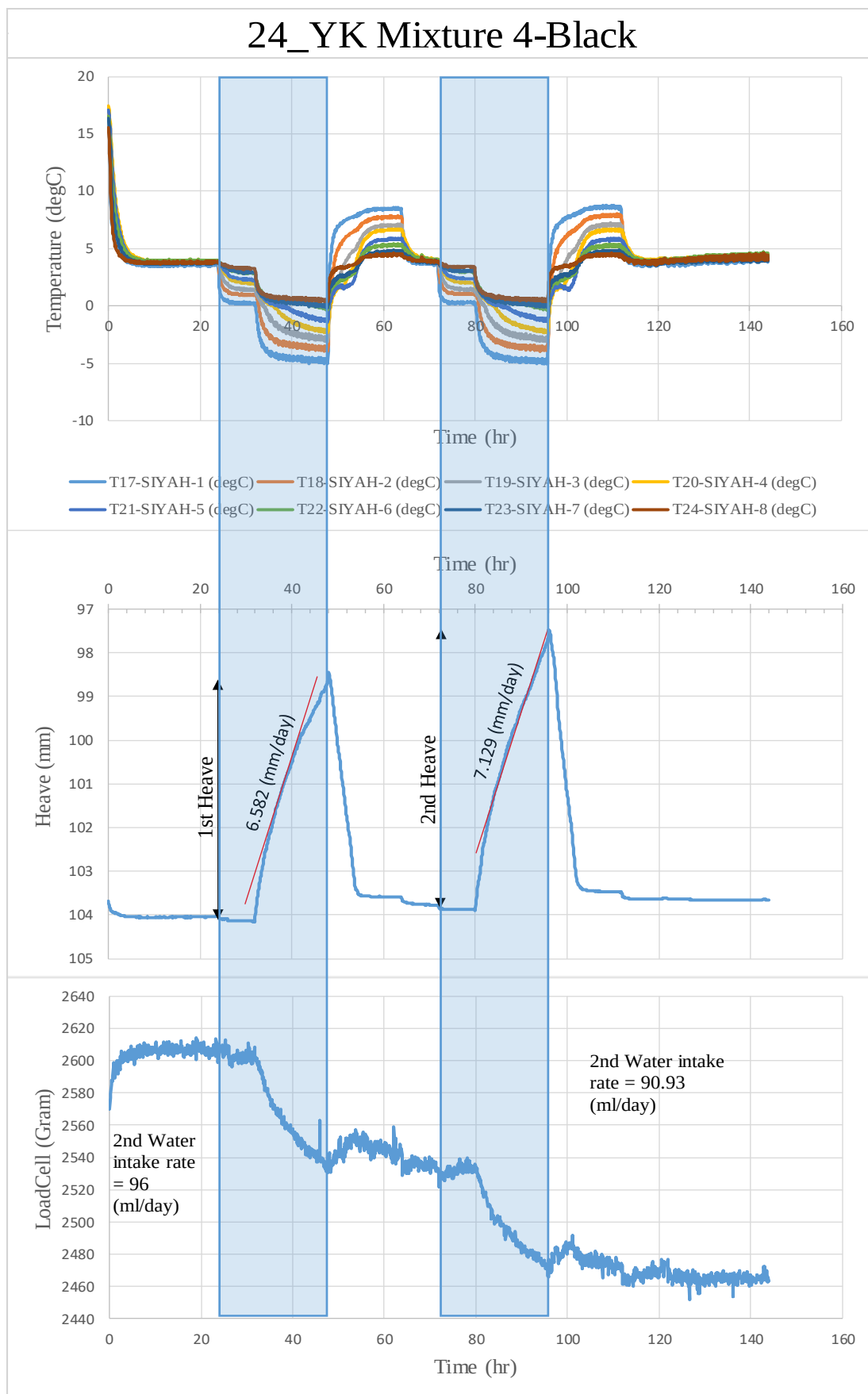


Figure C. 92 Freez-Thaw Test Results for “24_YK Mix 4-Black”

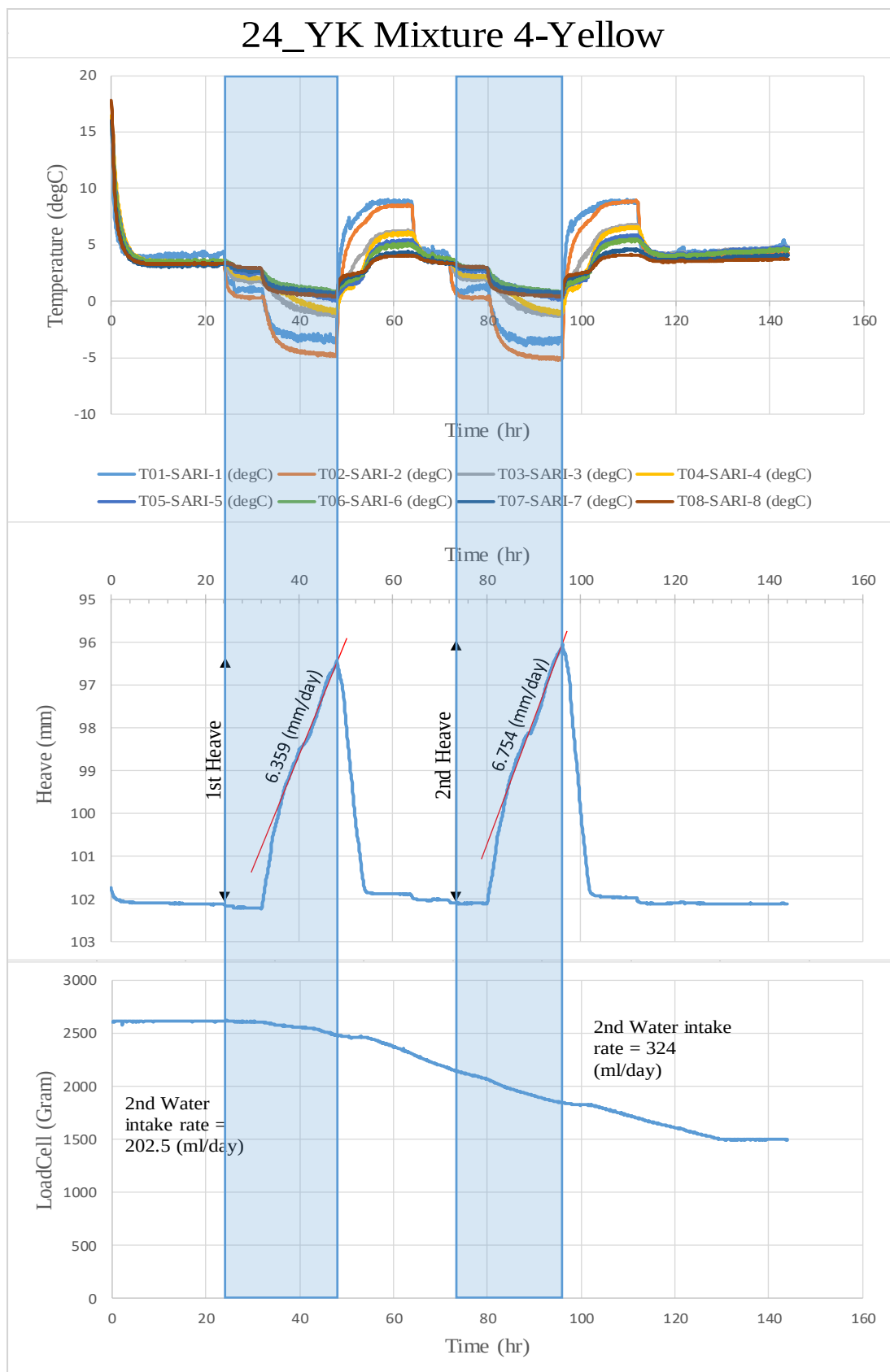


Figure C. 93 Freez-Thaw Test Results for “24_YK Mix 4-Yellow”

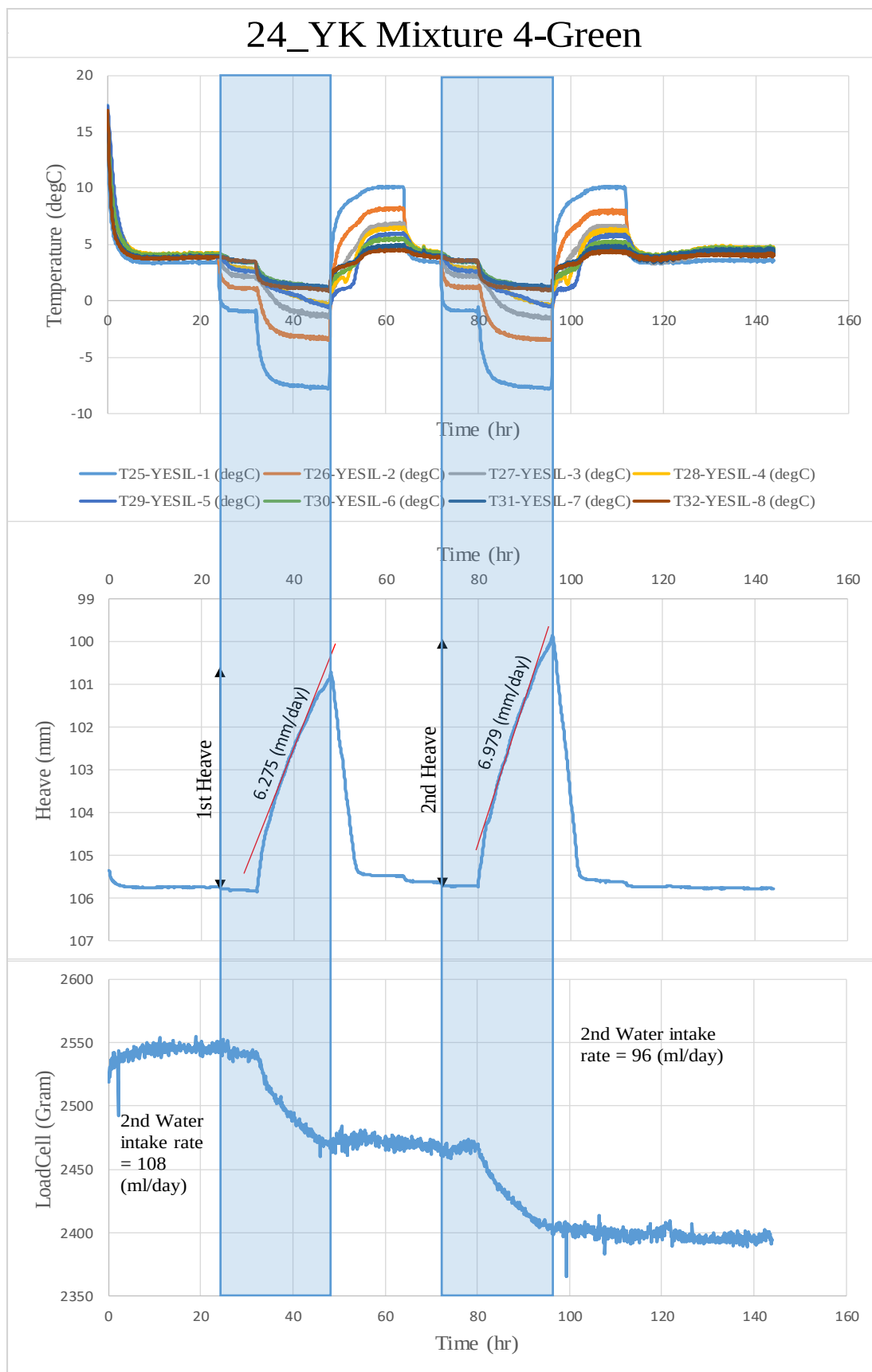
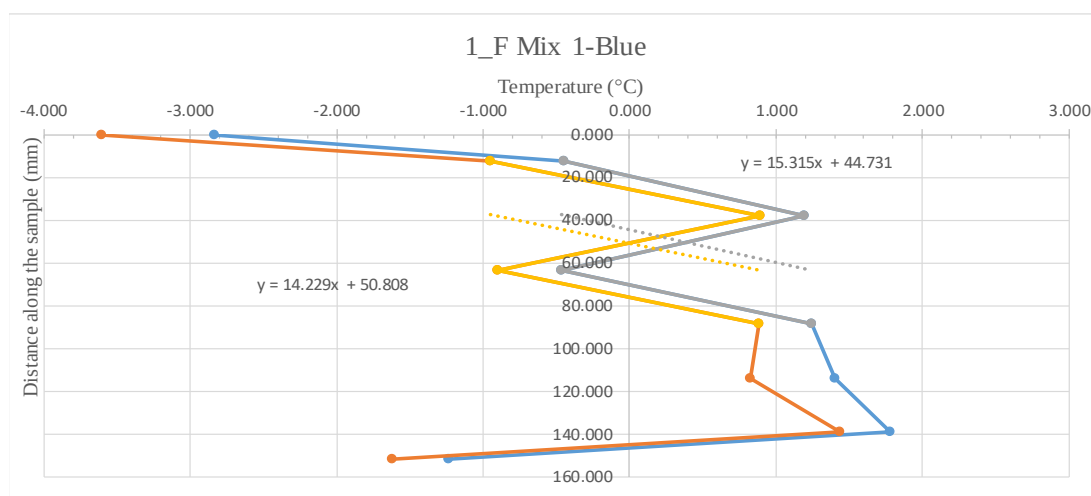


Figure C. 94 Freez-Thaw Test Results for “24_YK Mix 4-Green”

Appendix D: Temperature Profile of Samples & Temperature Gradient at Steady State Condition

1_F Mixture 1

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 40.5 hr	Temperature (°C)	-2.83	-0.45	1.20	-0.46	1.24	1.41	1.78	-1.23
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.833 hr	Temperature (°C)	-3.60	-0.95	0.89	-0.90	0.89	0.83	1.43	-1.62
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 39.917 hr	Temperature (°C)	-1.55	-2.06	-0.64	0.31	0.85	1.30	1.40	1.45
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 87.917 hr	Temperature (°C)	-2.25	-3.12	-1.56	-0.49	0.12	0.71	0.97	1.03
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

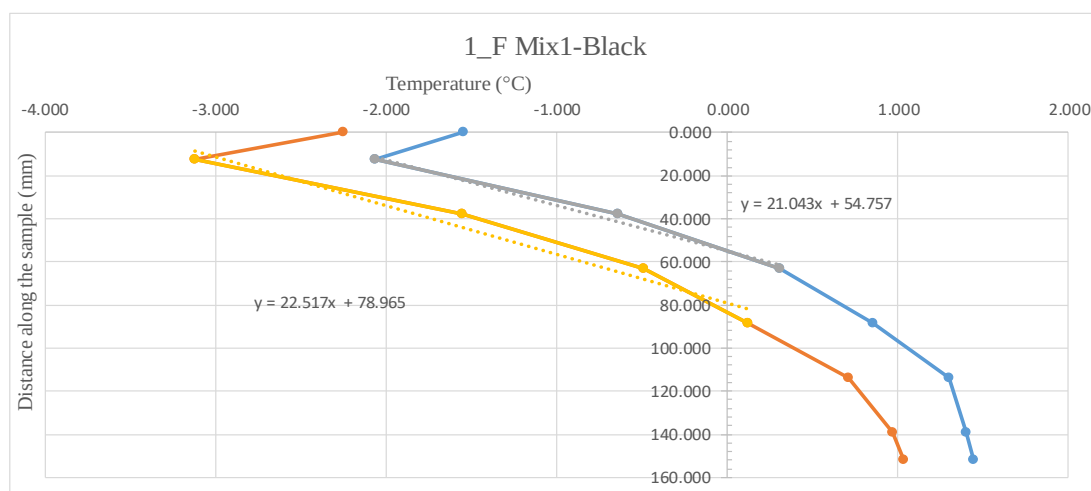
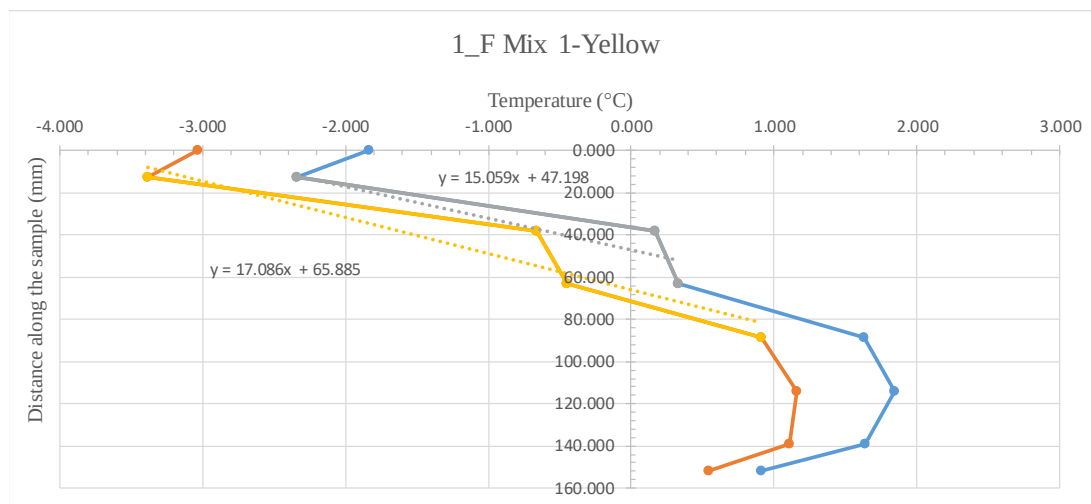


Figure D. 1 Temperature profile for “1_F Mix 1-Blue & Black” samples

1_F Mixture 1

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 39.75 hr	Temperature (°C)	-1.84	-2.34	0.17	0.33	1.63	1.84	1.64	0.91
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.8 hr	Temperature (°C)	-3.03	-3.38	-0.66	-0.45	0.91	1.16	1.11	0.55
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 41.58 hr	Temperature (°C)	-4.63	-0.04	0.25	0.82	1.23	1.73	1.99	1.63
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 90.917 hr	Temperature (°C)	-5.04	-0.24	-0.05	0.46	0.75	1.40	1.75	1.49
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

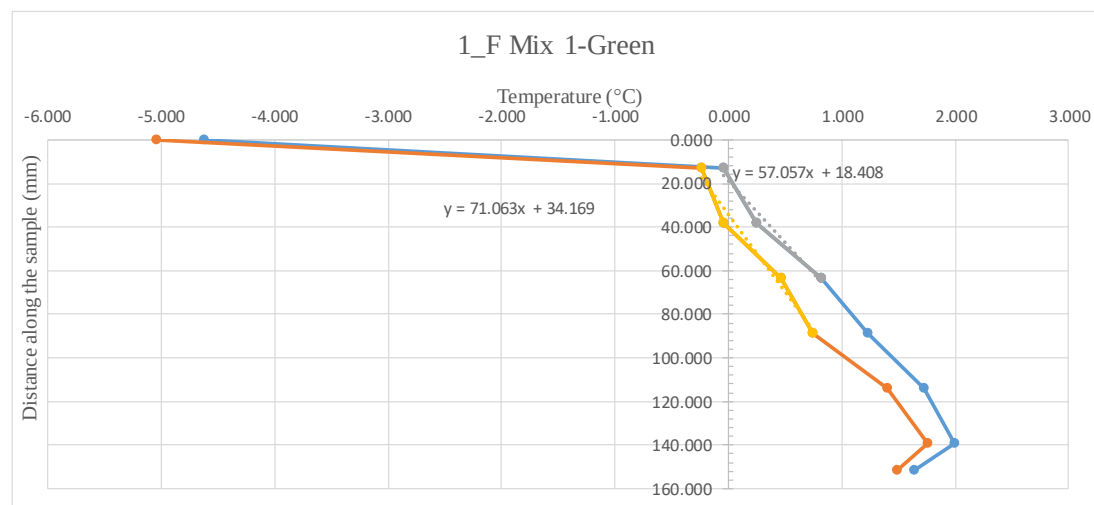
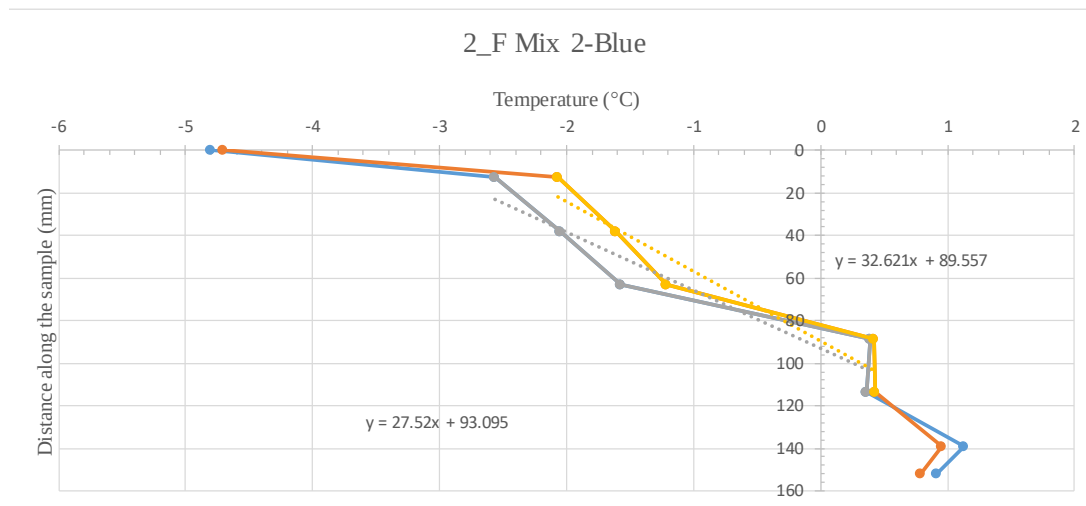


Figure D. 2 Temperature profile for “1_F Mix 1-Yellow & Green” samples

2_F Mixture 2

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 37.67 hr	Temperature (°C)	-4.804	-2.559	-2.045	-1.574	0.393	0.358	1.135	0.918
	Distance (mm)	0.000	12.645	37.935	63.225	88.515	113.805	139.095	151.740
2nd 87.083 hr	Temperature (°C)	-4.706	-2.070	-1.613	-1.209	0.425	0.432	0.960	0.789
	Distance (mm)	0.000	12.645	37.935	63.225	88.515	113.805	139.095	151.740



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 39.5 hr	Temperature (°C)	-2.664	-1.805	-0.345	0.335	1.038	1.450	1.659	1.621
	Distance (mm)	0.000	12.645	37.935	63.225	88.515	113.805	139.095	151.740
2nd 87.25 hr	Temperature (°C)	-1.994	-1.501	0.053	0.687	1.420	1.884	2.069	1.985
	Distance (mm)	0.000	12.645	37.935	63.225	88.515	113.805	139.095	151.740

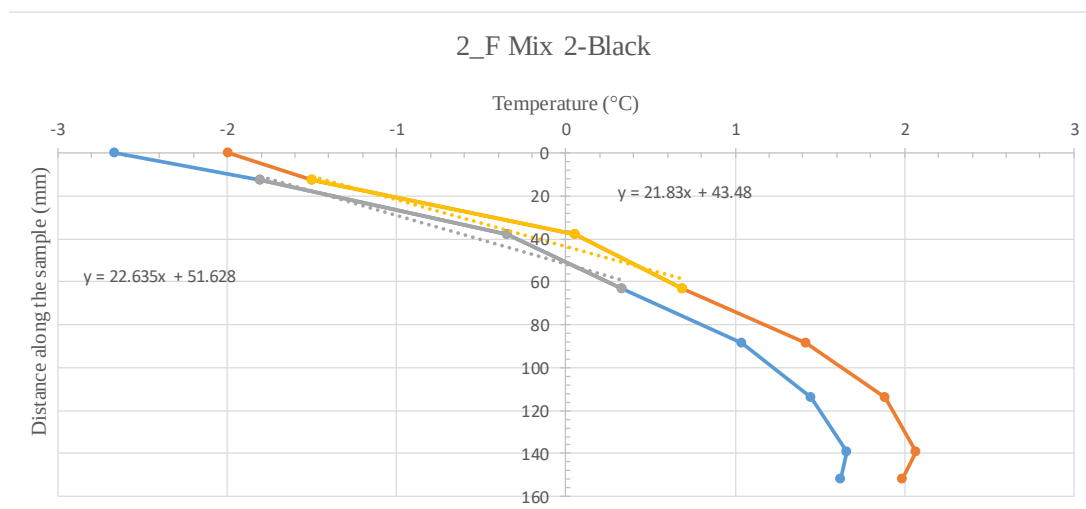
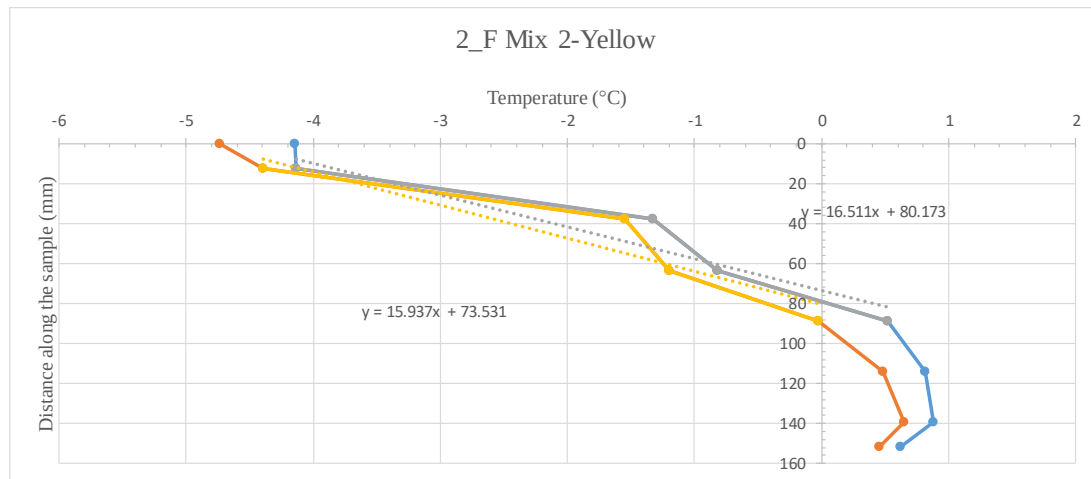


Figure D. 3 Temperature profile for “2_F Mix 2-Blue & Black” samples

2_F Mixture 2

Yellow Sample - 3									
Freezing Cycles	Parameters	T01-SARI-1 (degC)	T02-SARI-2 (degC)	T03-SARI-3 (degC)	T04-SARI-4 (degC)	T05-SARI-5 (degC)	T06-SARI-6 (degC)	T07-SARI-7 (degC)	T08-SARI-8 (degC)
1st 38.583 hr	Temperature (°C)	-4.15	-4.13	-1.33	-0.82	0.52	0.82	0.88	0.62
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.9167 hr	Temperature (°C)	-4.74	-4.39	-1.55	-1.20	-0.02	0.48	0.65	0.45
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25-Green-1 (°C)	T26-Green-2 (°C)	T27-Green-3 (°C)	T28-Green-4 (°C)	T29-Green-5 (°C)	T30-Green-6 (°C)	T31-Green-7 (°C)	T32-Green-8 (°C)
1st 40.3 hr	Temperature (°C)	-5.11	-0.98	0.37	1.25	1.32	0.92	1.79	1.86
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.75 hr	Temperature (°C)	-4.21	-0.18	1.01	1.87	1.78	1.05	2.29	2.37
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

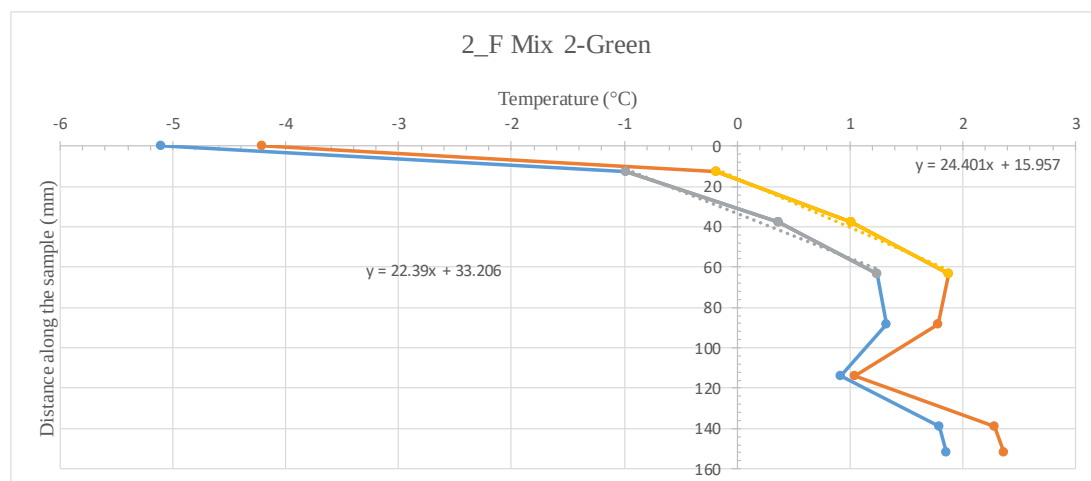
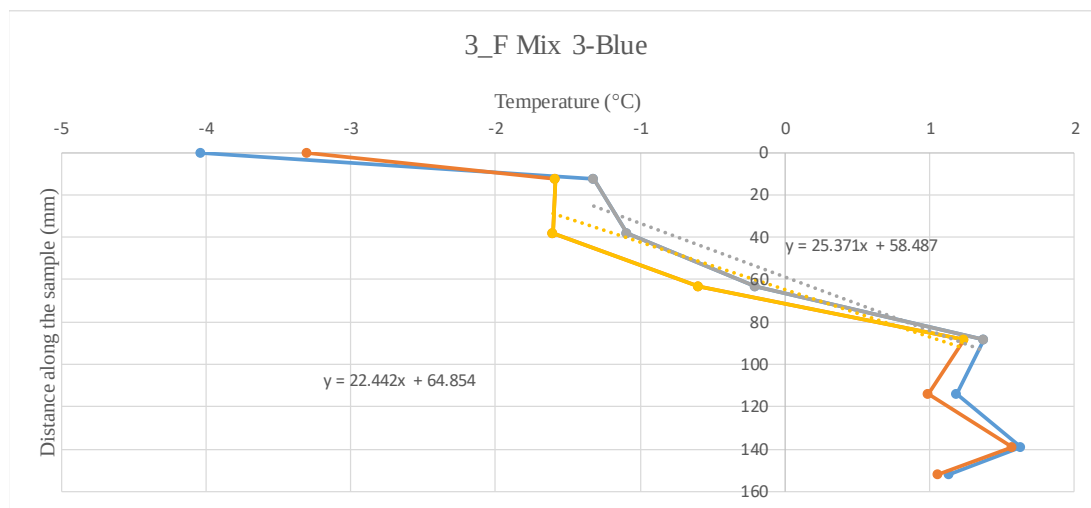


Figure D. 4 Temperature profile for “2_F Mix 2-Yellow &Green” samples

3_F Mixture 3

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 41.083 hr	Temperature (°C)	-4.04	-1.32	-1.09	-0.21	1.37	1.19	1.63	1.14
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.83 hr	Temperature (°C)	-3.30	-1.59	-1.60	-0.59	1.24	0.99	1.57	1.06
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 40.8 hr	Temperature (°C)	-3.01	-1.61	-0.12	0.66	1.38	1.61	1.70	1.79
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89 hr	Temperature (°C)	-2.37	-1.26	0.09	0.98	1.65	2.08	2.03	2.23
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

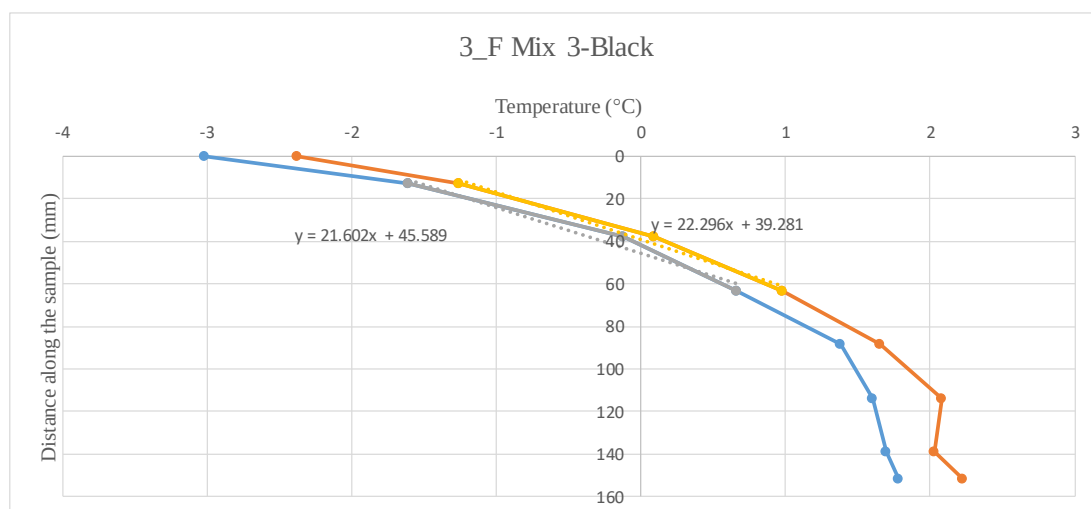
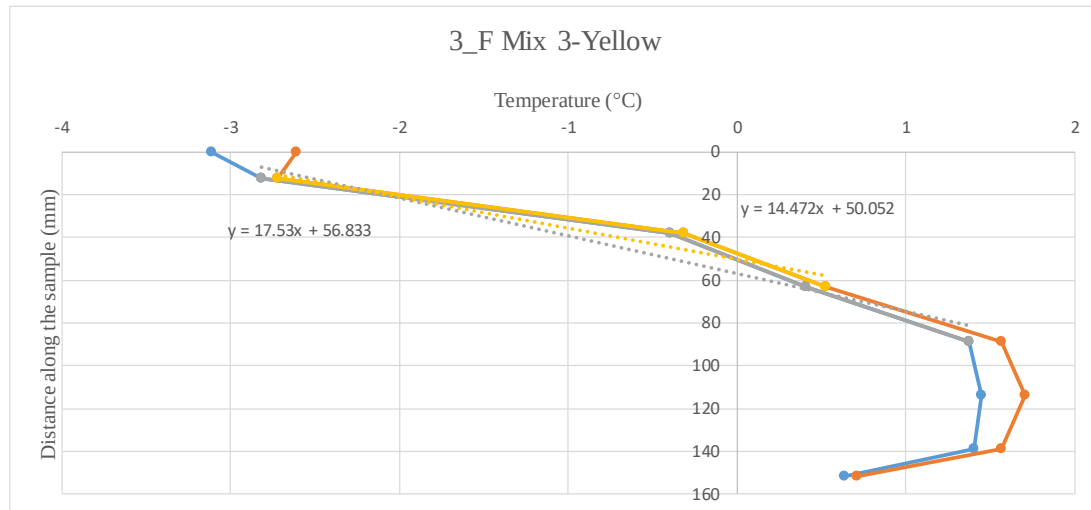


Figure D. 5 Temperature profile for “3_F Mix 3-Blue & Black” samples

3_F Mixture 3

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.83 hr	Temperature (°C)	-3.11	-2.82	-0.40	0.41	1.38	1.45	1.40	0.64
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.67 hr	Temperature (°C)	-2.61	-2.72	-0.32	0.53	1.56	1.71	1.56	0.71
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 41.5 hr	Temperature (°C)	-4.71	-1.05	-0.06	0.90	1.44	1.83	2.08	1.74
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.4 hr	Temperature (°C)	-3.97	-0.82	0.10	1.02	1.46	1.82	2.07	1.80
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

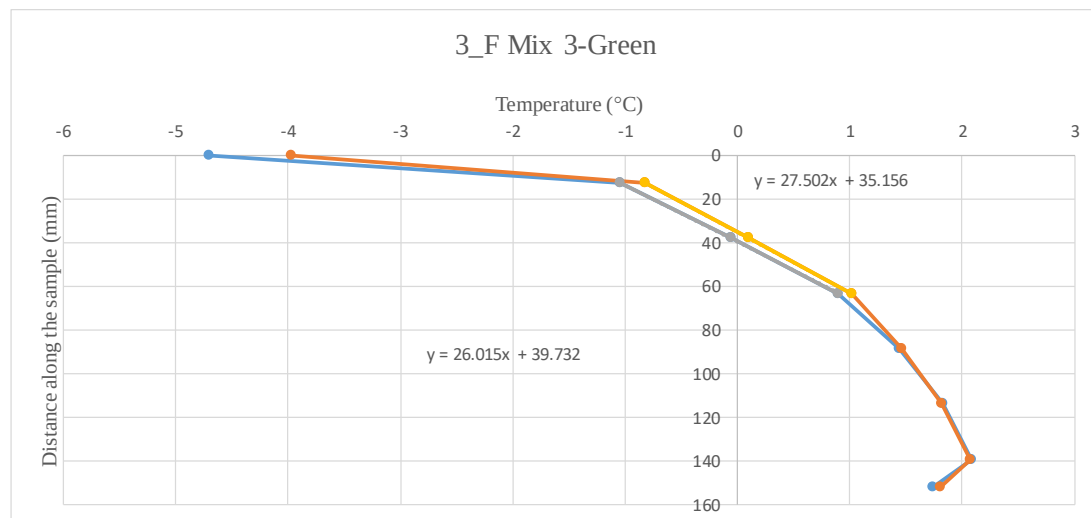
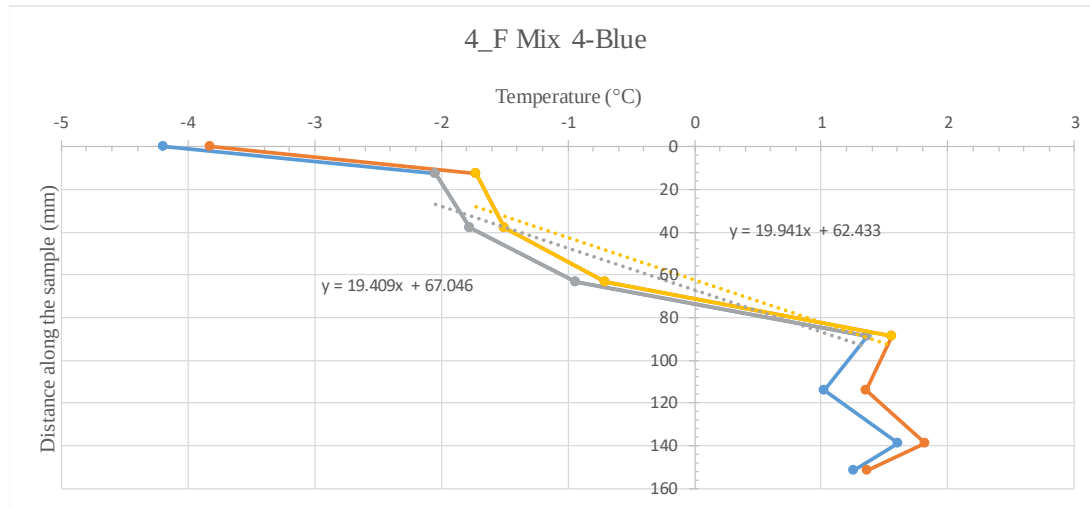


Figure D. 6 Temperature profile for “3_F Mix 3-Yellow & Green” samples

4_F Mixture 4

Blue Sample - 1									
Freezing Cycles	Parameters	T09- Blue-1 (°C)	T10- Blue-2 (°C)	T11- Blue-3 (°C)	T12- Blue-4 (°C)	T13- Blue-5 (°C)	T14- Blue-6 (°C)	T15- Blue-7 (°C)	T16- Blue-8 (°C)
1st 41 hr	Temperature (°C)	-4.194	-2.049	-1.775	-0.938	1.369	1.023	1.603	1.254
	Distance (mm)	0.000	12.645	37.935	63.225	88.515	113.805	139.095	151.740
2nd 89.583 hr	Temperature (°C)	-3.824	-1.729	-1.501	-0.707	1.559	1.353	1.824	1.360
	Distance (mm)	0.000	12.645	37.935	63.225	88.515	113.805	139.095	151.740



Black Sample - 2									
Freezing Cycles	Parameters	T17- Black-1 (°C)	T18- Black-2 (°C)	T19- Black-3 (°C)	T20- Black-4 (°C)	T21- Black-5 (°C)	T22- Black-6 (°C)	T23- Black-7 (°C)	T24- Black-8 (°C)
1st 41 hr	Temperature (°C)	-4.37	-2.28	-1.10	0.12	0.61	1.14	1.24	1.07
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.583 hr	Temperature (°C)	-3.72	-1.91	-0.96	0.25	0.75	1.37	1.38	1.29
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

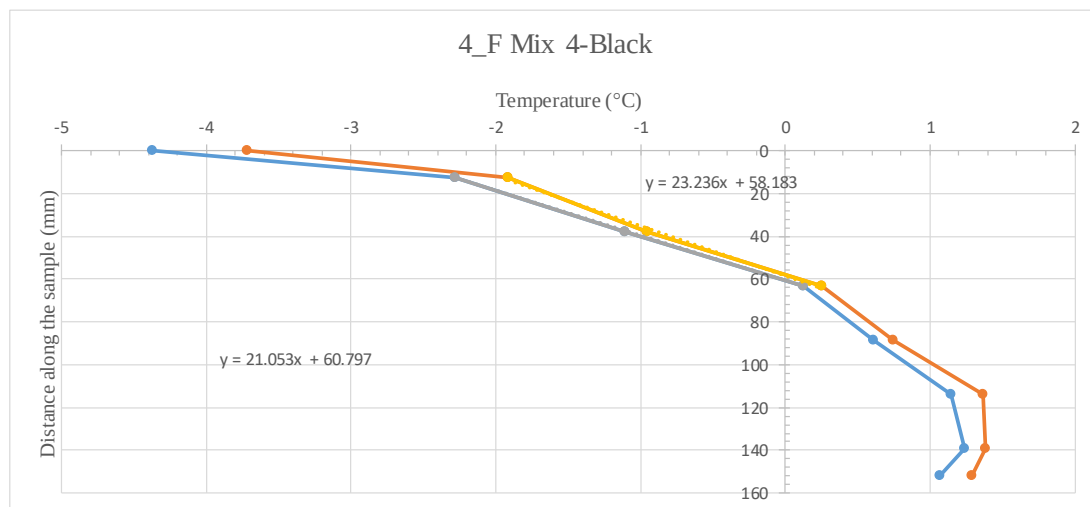
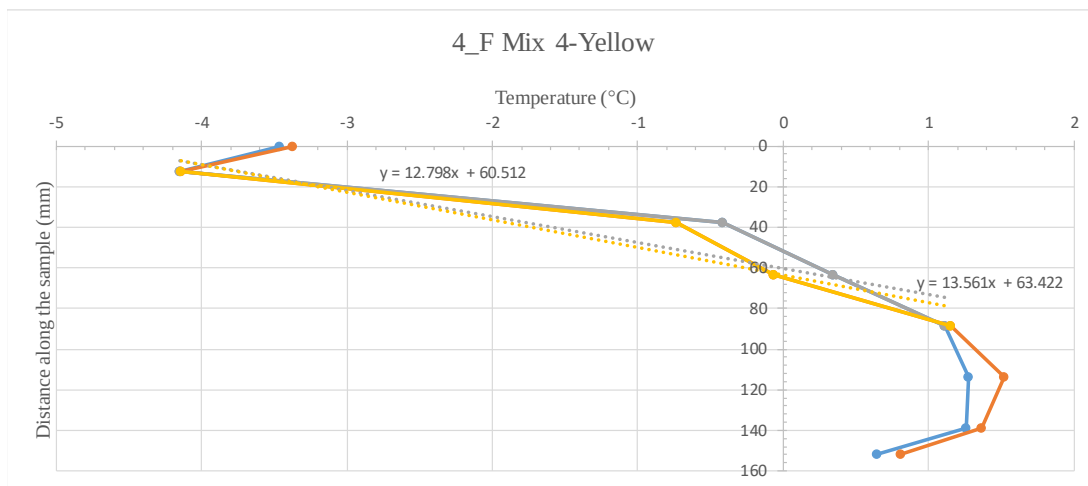


Figure D. 7 Temperature profile for “4_F Mix 4-Blue & Black” samples

4_F Mixture 4

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 35.83 hr	Temperature (°C)	-3.47	-4.15	-0.42	0.35	1.12	1.28	1.26	0.65
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.167 hr	Temperature (°C)	-3.37	-4.14	-0.73	-0.07	1.15	1.52	1.37	0.81
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 41.83 hr	Temperature (°C)	-3.42	-0.96	0.39	0.84	1.33	1.52	1.80	1.86
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 90.33 hr	Temperature (°C)	-3.48	-1.14	0.21	0.70	1.21	1.46	1.69	1.76
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

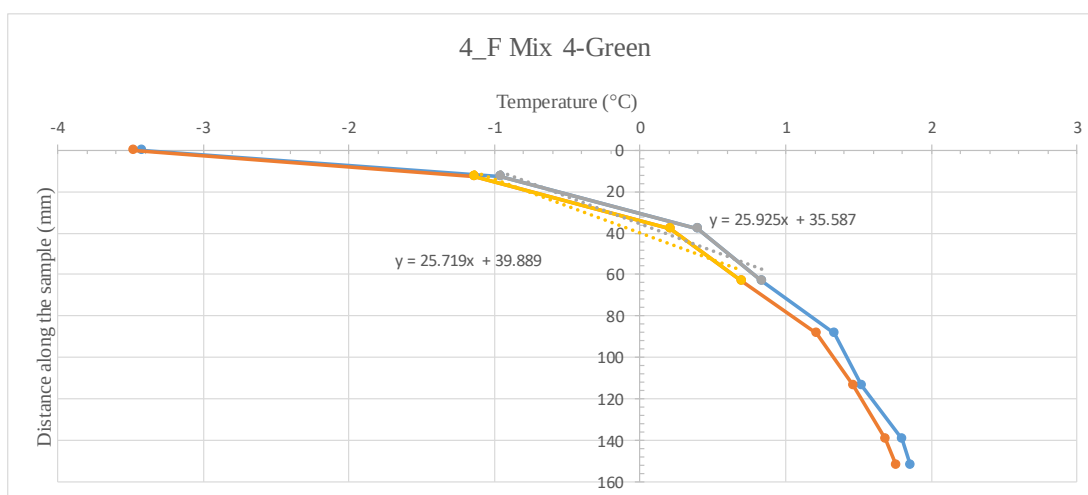
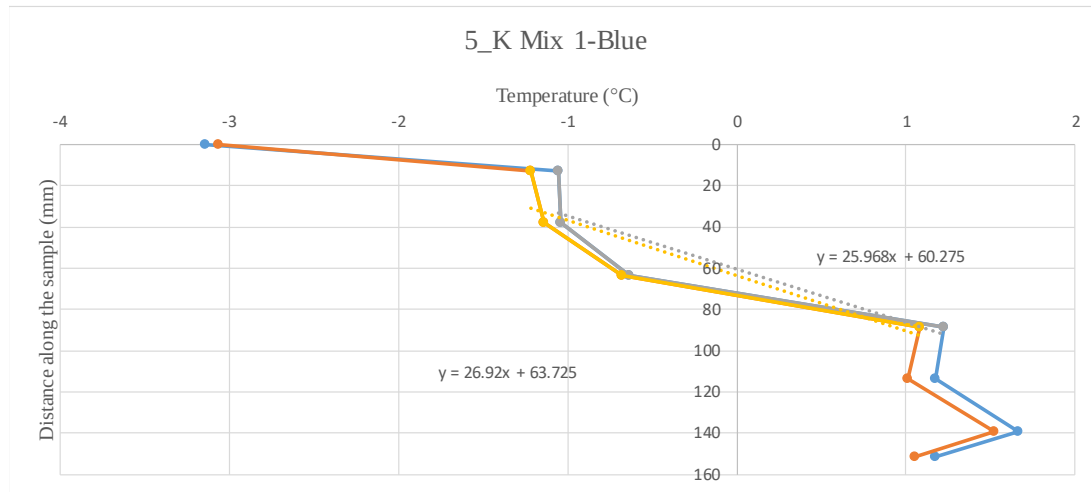


Figure D. 8 Temperature profile for “4_F Mix 4-Yellow & Green” samples

5_K Mixture 1

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 40.83 hr	Temperature (°C)	-3.14	-1.05	-1.04	-0.63	1.23	1.17	1.66	1.18
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.25 hr	Temperature (°C)	-3.06	-1.22	-1.14	-0.68	1.08	1.01	1.52	1.05
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 41.5 hr	Temperature (°C)	-1.23	-0.30	0.27	1.18	1.41	1.95	1.87	1.67
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 90.5 hr	Temperature (°C)	-1.14	-0.15	0.30	1.32	1.50	2.09	1.97	1.76
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

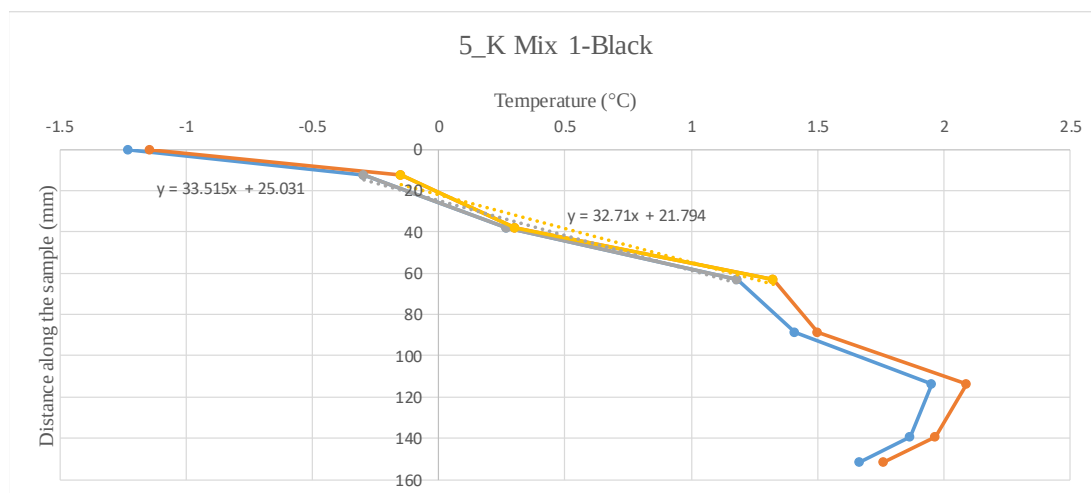
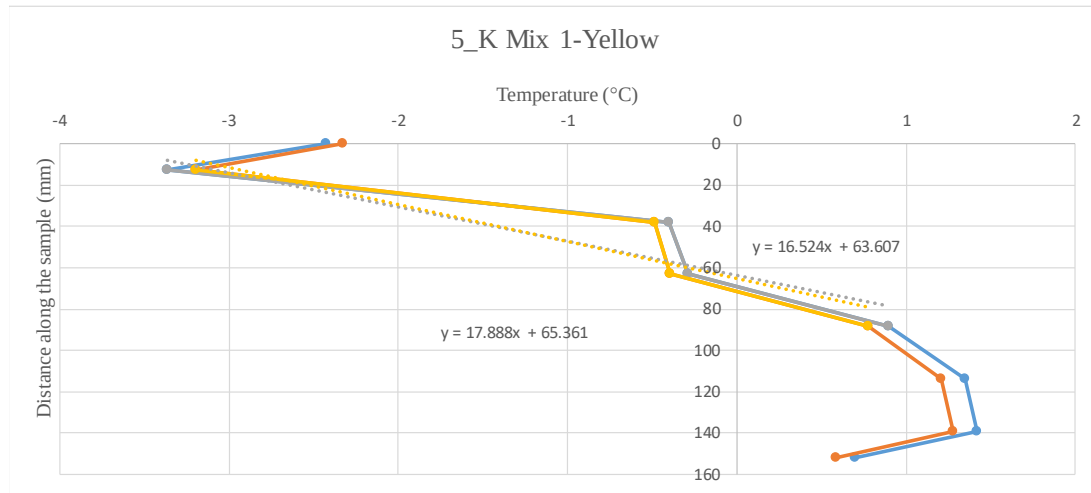


Figure D. 9 Temperature profile for “5_K Mix 1-Blue & Black” samples

5_K Mixture 1

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.667 hr	Temperature (°C)	-2.42	-3.36	-0.40	-0.29	0.90	1.35	1.42	0.70
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.83 hr	Temperature (°C)	-2.33	-3.20	-0.49	-0.40	0.77	1.21	1.28	0.59
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 41.167 hr	Temperature (°C)	-4.10	-1.17	0.38	0.95	1.49	1.91	2.25	1.95
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.5 hr	Temperature (°C)	-4.03	-1.30	0.32	0.89	1.40	1.83	2.15	1.92
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

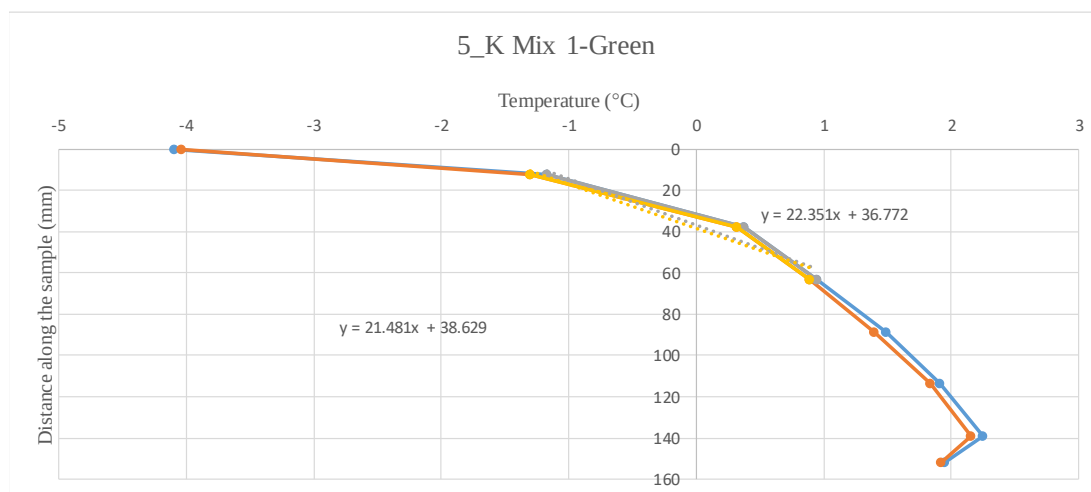
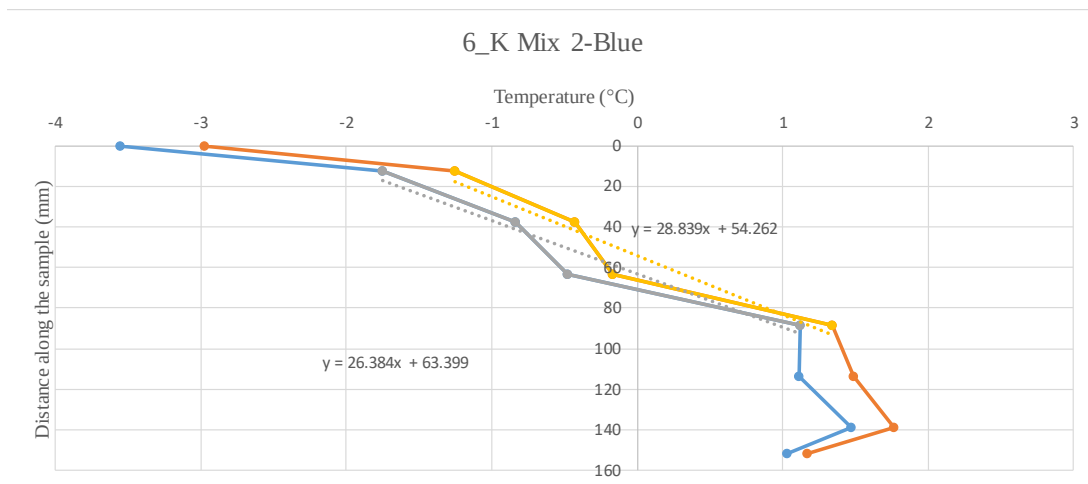


Figure D. 10 Temperature profile for “5_K Mix 1-Yellow & Green” samples

6_K Mixture 2

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 40.9167 hr	Temperature (°C)	-3.56	-1.75	-0.84	-0.47	1.12	1.12	1.47	1.03
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.25 hr	Temperature (°C)	-2.98	-1.26	-0.43	-0.17	1.35	1.49	1.76	1.17
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 41.583 hr	Temperature (°C)	-2.51	-1.42	-0.52	0.21	0.72	1.07	1.13	1.13
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.83 hr	Temperature (°C)	-1.75	-1.01	-0.13	0.73	1.11	1.43	1.41	1.31
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

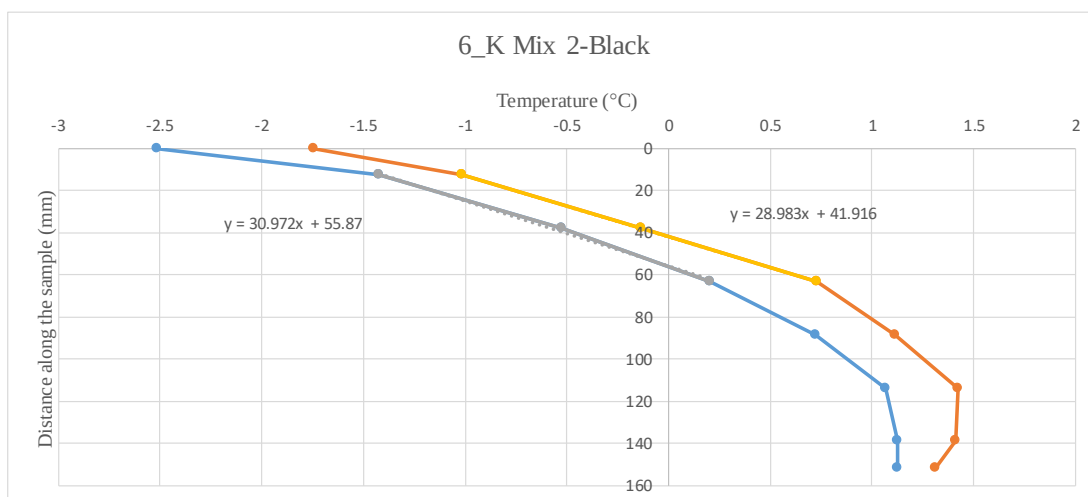
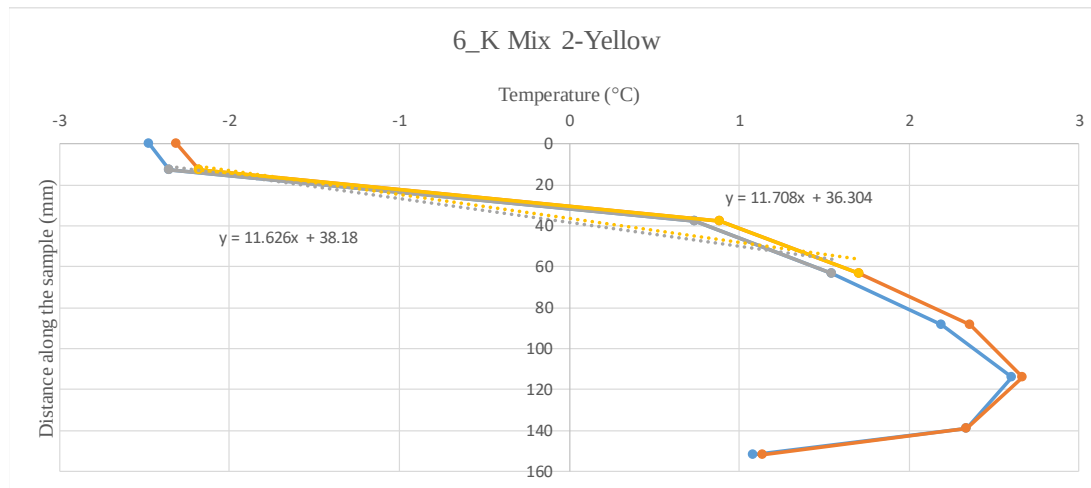


Figure D. 11 Temperature profile for “6_K Mix 2-Blue & Black” samples

6_K Mixture 2

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.83 hr	Temperature (°C)	-2.48	-2.35	0.74	1.55	2.19	2.60	2.34	1.09
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.167 hr	Temperature (°C)	-2.31	-2.18	0.89	1.71	2.36	2.67	2.34	1.14
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 42.4167 hr	Temperature (°C)	-3.03	-0.13	0.95	1.56	2.00	2.23	2.35	2.21
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 92.67 hr	Temperature (°C)	-3.23	-0.25	0.81	1.41	2.05	2.27	2.39	2.23
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

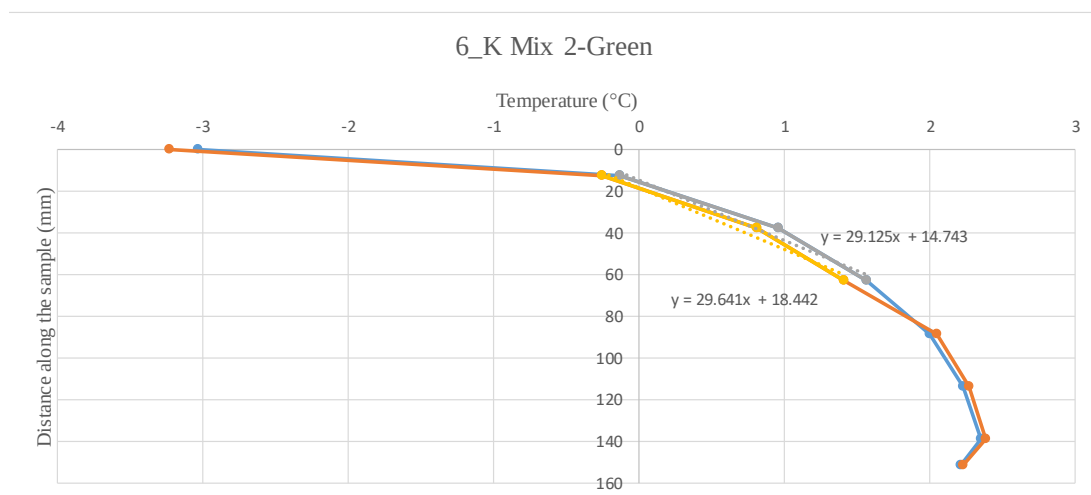
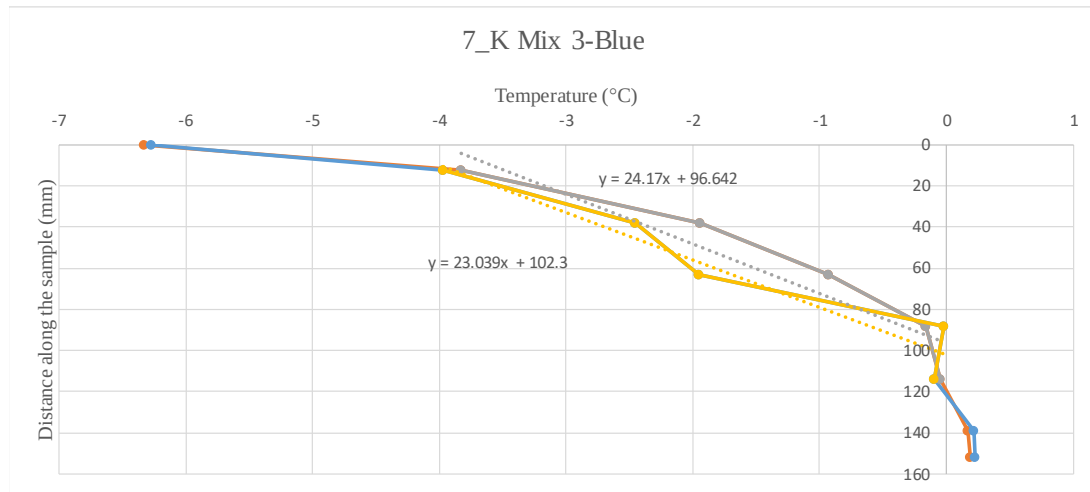


Figure D. 12 Temperature profile for “6_K Mix 2-Yellow & Green” samples

7&8_K Mixture 3&4

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 33.75 hr	Temperature (°C)	-6.33	-3.83	-1.94	-0.93	-0.17	-0.05	0.17	0.19
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 86.5 hr	Temperature (°C)	-6.27	-3.97	-2.45	-1.95	-0.02	-0.09	0.22	0.23
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 38.67 hr	Temperature (°C)	-5.03	-2.09	-0.97	-0.30	0.15	1.01	0.68	0.72
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 87.583 hr	Temperature (°C)	-5.46	-1.53	-0.26	0.09	0.69	1.44	1.08	1.12
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

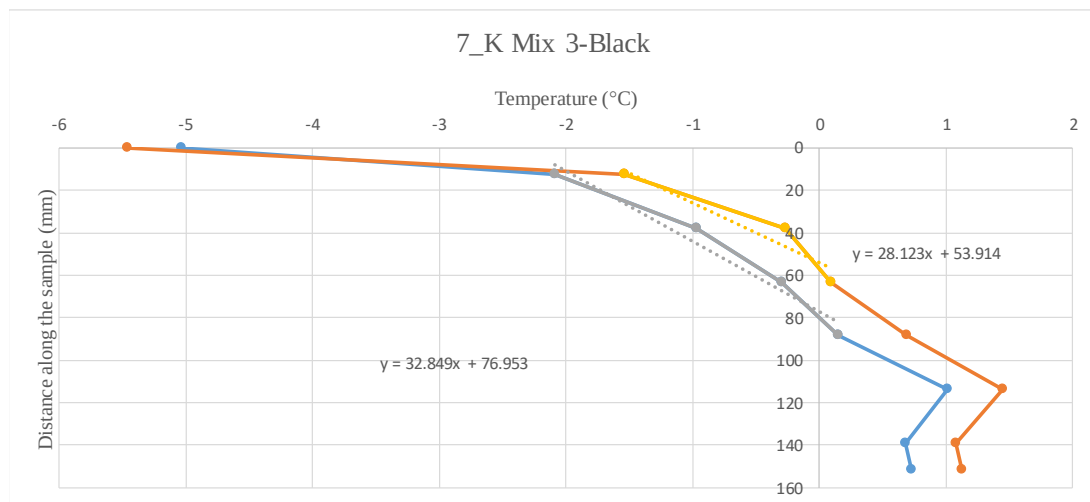
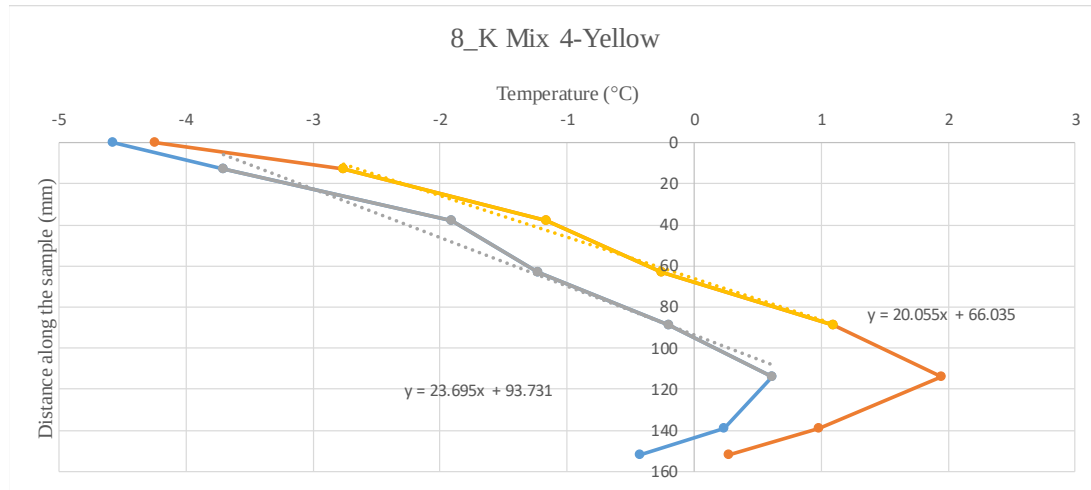


Figure D. 13 Temperature profile for “7_K Mix 3-Blue & Black” samples

7&8_K Mixture 3&4

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 38 hr	Temperature (°C)	-4.58	-3.71	-1.91	-1.23	-0.20	0.62	0.24	-0.43
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 86.583 hr	Temperature (°C)	-4.25	-2.76	-1.16	-0.26	1.10	1.95	0.98	0.27
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 38.167 hr	Temperature (°C)	-6.25	-3.97	-1.96	-0.61	-0.16	0.33	0.46	0.78
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 87 hr	Temperature (°C)	-4.71	-2.38	-0.58	0.65	1.05	1.45	1.72	1.17
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

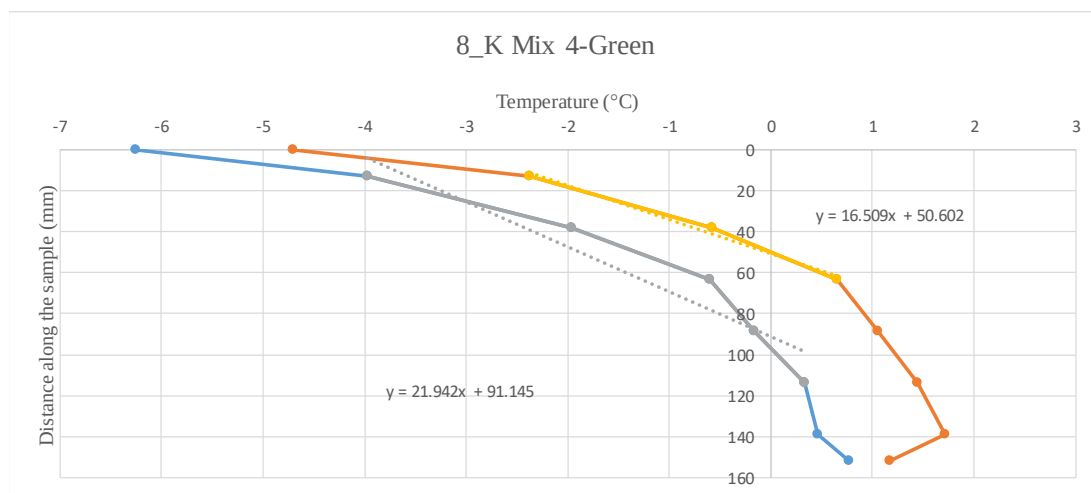
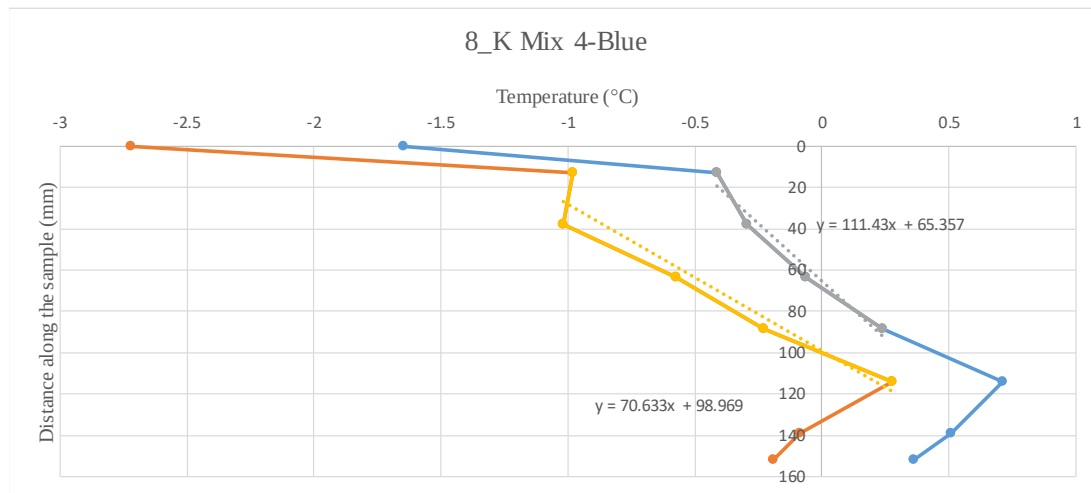


Figure D. 14 Temperature profile for “8_K Mix 4-Yellow & Green” samples

8_K Mixture 4-Unused

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 32.167 hr	Temperature (°C)	-1.65	-0.41	-0.29	-0.06	0.24	0.71	0.51	0.36
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 80.083 hr	Temperature (°C)	-2.72	-0.98	-1.02	-0.57	-0.23	0.28	-0.09	-0.19
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 32 hr	Temperature (°C)	-1.97	-0.62	0.09	0.78	0.45	0.94	0.53	0.77
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 79.67 hr	Temperature (°C)	-0.38	0.40	0.19	1.11	0.84	1.51	0.91	1.11
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

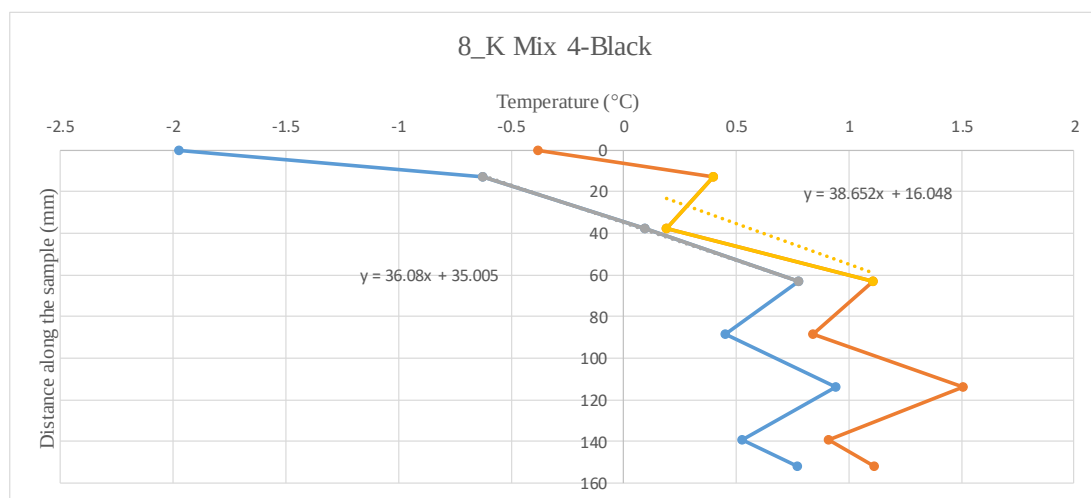
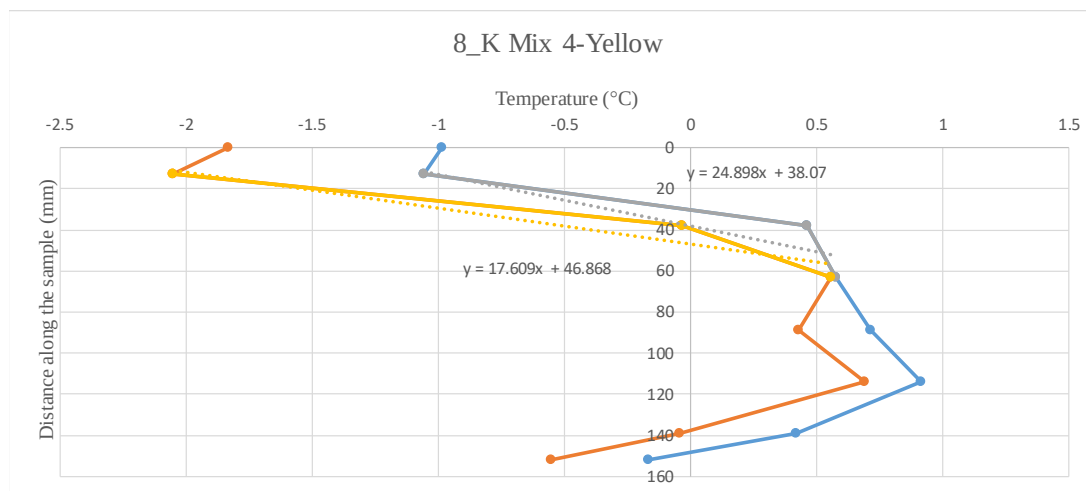


Figure D. 15 Temperature profile for “8_K Mix 4 Unused-Blue & Black” samples

8_K Mixture 4-Unused

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 32.167 hr	Temperature (°C)	-0.99	-1.05	0.46	0.58	0.71	0.92	0.42	-0.17
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 80.83 hr	Temperature (°C)	-1.83	-2.05	-0.03	0.56	0.43	0.69	-0.04	-0.55
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 32 hr	Temperature (°C)	-2.17	0.62	0.79	1.31	0.82	1.27	1.03	1.17
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 79.583 hr	Temperature (°C)	-1.70	0.61	0.71	1.35	0.89	1.48	1.29	1.53
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

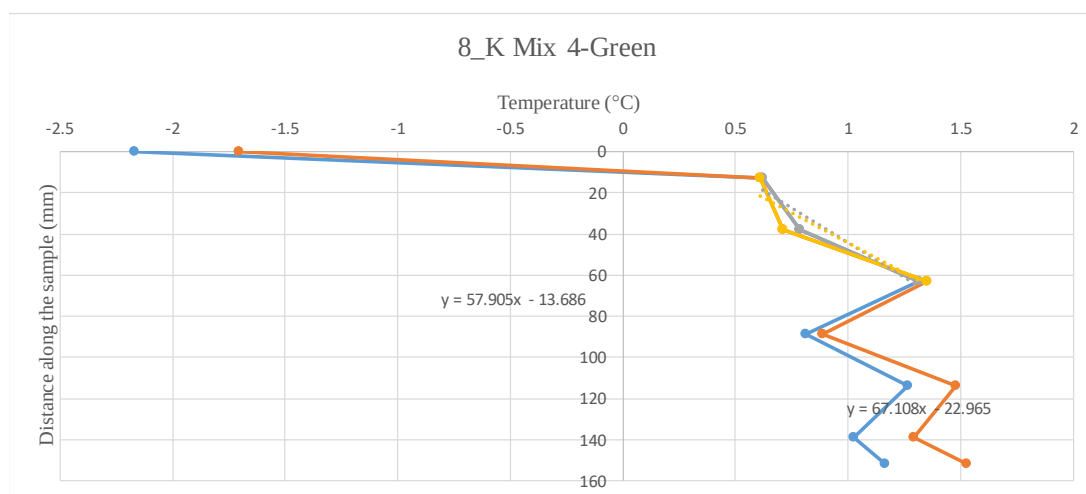
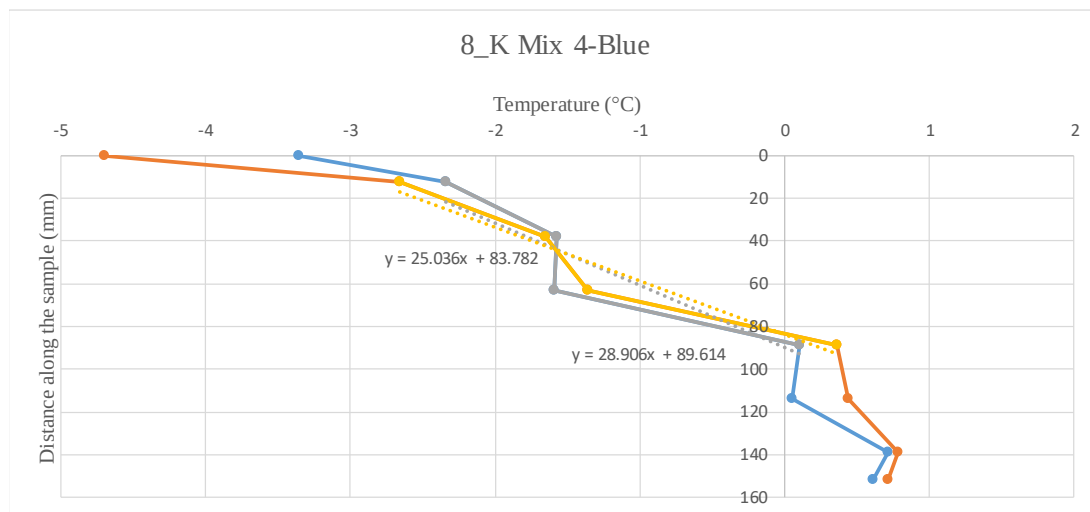


Figure D. 16 Temperature profile for “8_K Mix 4 Unused-Yellow & Green” samples

8_K Mixture 4

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 40.4167	Temperature (°C)	-3.35	-2.34	-1.57	-1.59	0.10	0.05	0.71	0.61
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.67 hr	Temperature (°C)	-4.70	-2.66	-1.65	-1.36	0.36	0.44	0.78	0.71
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 40.3 hr	Temperature (°C)	-3.86	-3.27	-1.81	-1.14	-0.80	0.60	0.61	0.77
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.5 hr	Temperature (°C)	-3.55	-3.04	-1.37	-0.61	-0.18	0.80	0.80	0.86
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

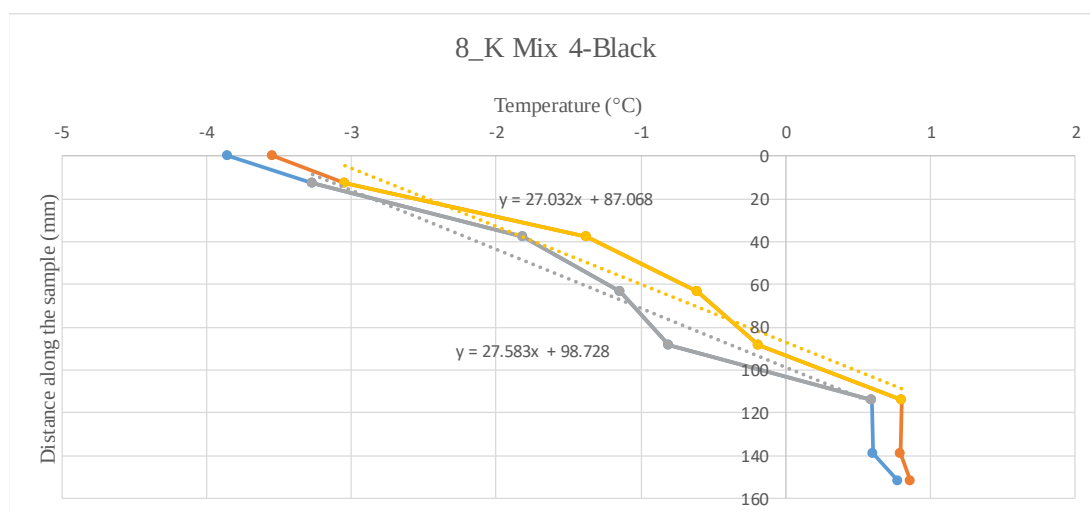
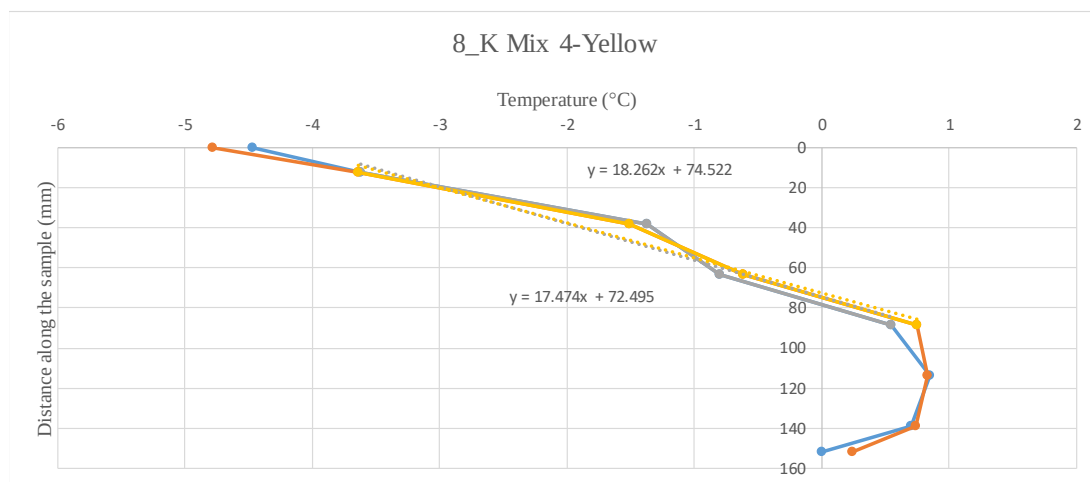


Figure D. 17 Temperature profile for “8_K Mix 4 Used-Blue & Black” samples

8_K Mixture 4

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.3 hr	Temperature (°C)	-4.47	-3.62	-1.37	-0.80	0.55	0.85	0.70	0.00
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.4167 hr	Temperature (°C)	-4.78	-3.64	-1.51	-0.62	0.75	0.83	0.74	0.24
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 40.4167 hr	Temperature (°C)	-7.76	-2.41	-1.38	-0.74	-0.28	0.66	0.88	0.98
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.5 hr	Temperature (°C)	-7.63	-2.01	-0.85	-0.35	0.28	0.77	1.02	0.92
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

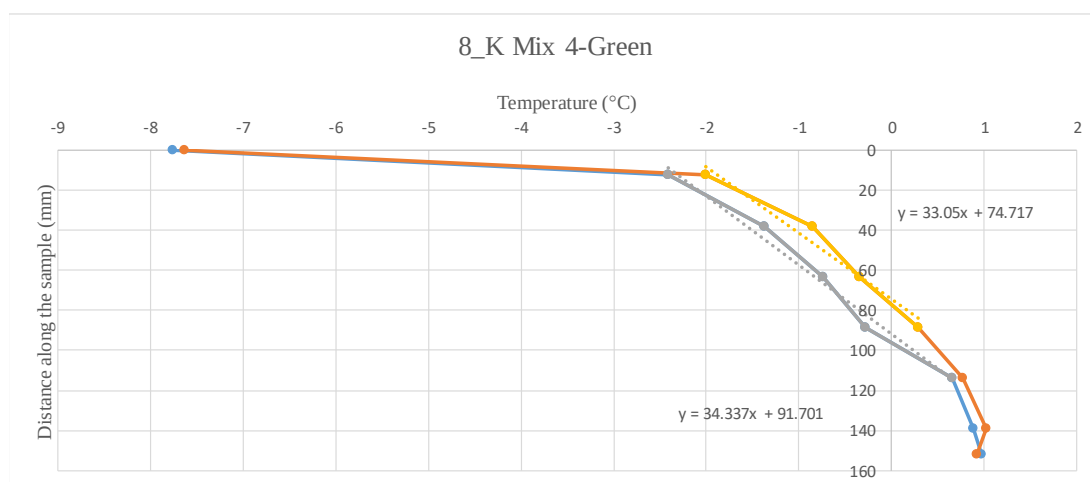
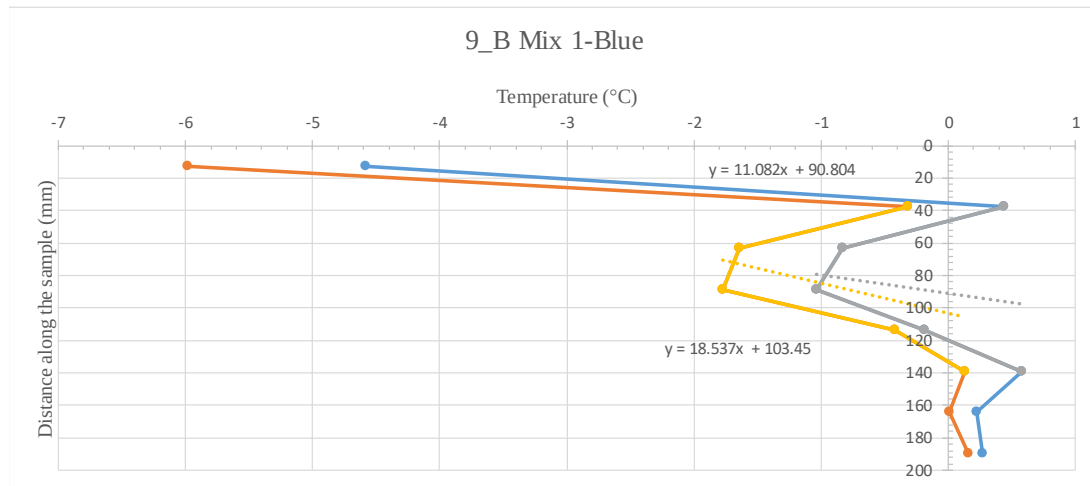


Figure D. 18 Temperature profile for “8_K Mix 4 Used-Yellow & Green” samples

9_B Mixture 1

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 42.4167 hr	Temperature (°C)	-4.58	0.44	-0.83	-1.03	-0.19	0.58	0.22	0.27
	Distance (mm)	12.65	37.94	63.23	88.52	113.81	139.10	164.39	189.68
2nd 90.583 hr	Temperature (°C)	-5.98	-0.32	-1.64	-1.77	-0.42	0.13	0.01	0.16
	Distance (mm)	12.65	37.94	63.23	88.52	113.81	139.10	164.39	189.68



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 40.75 hr	Temperature (°C)	-2.13	-1.59	-0.43	-0.22	0.15	1.10	0.95	1.20
	Distance (mm)	12.65	37.94	63.23	88.52	113.81	139.10	164.39	189.68
2nd 88.67 hr	Temperature (°C)	-2.89	-2.37	-1.10	-0.71	-0.17	0.85	0.63	0.88
	Distance (mm)	12.65	37.94	63.23	88.52	113.81	139.10	164.39	189.68

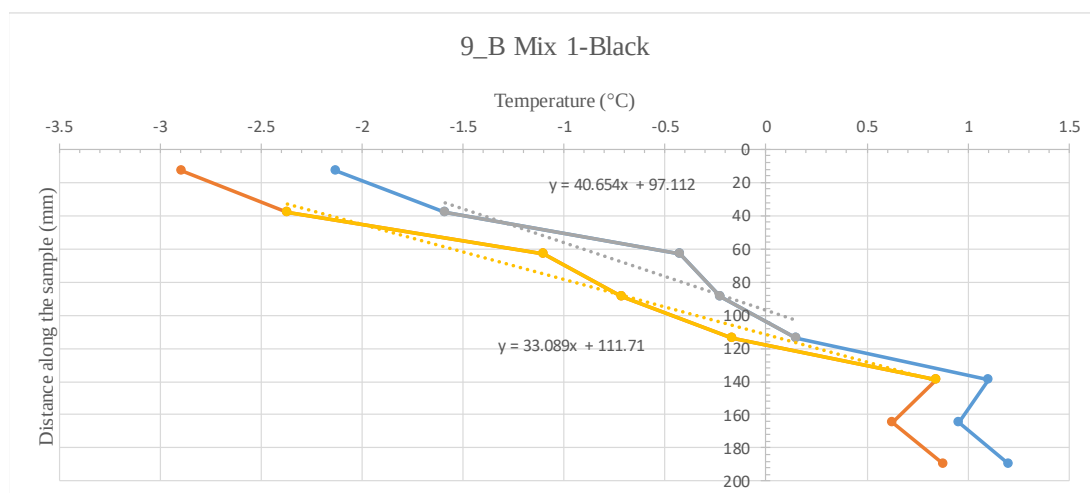
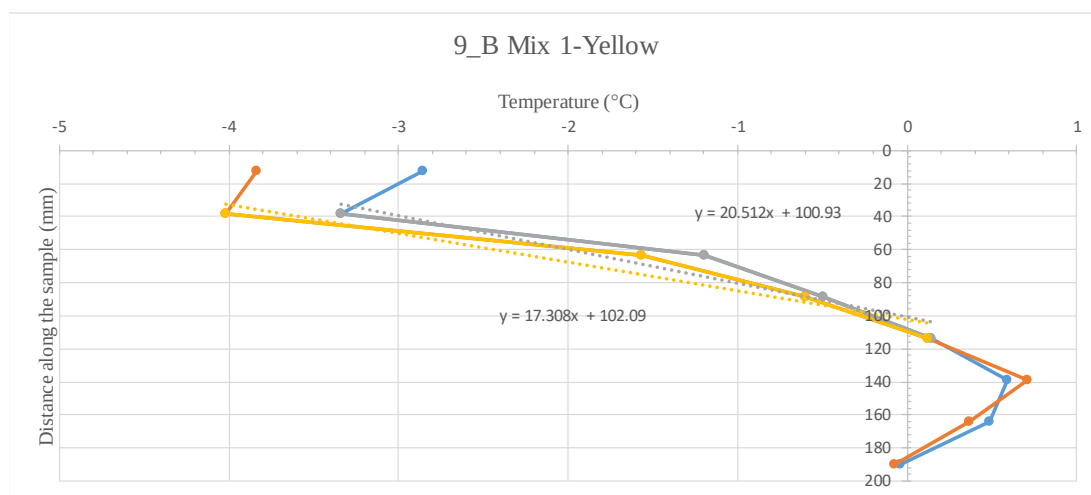


Figure D. 19 Temperature profile for “9_B Mix 1-Blue & Black” samples

9_B Mixture 1

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40 hr	Temperature (°C)	-2.86	-3.34	-1.19	-0.50	0.14	0.59	0.49	-0.04
	Distance (mm)	12.65	37.94	63.23	88.52	113.81	139.10	164.39	189.68
2nd 88.083 hr	Temperature (°C)	-3.83	-4.02	-1.57	-0.60	0.12	0.71	0.37	-0.08
	Distance (mm)	12.65	37.94	63.23	88.52	113.81	139.10	164.39	189.68



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 41 hr	Temperature (°C)	-3.64	-0.81	-0.03	0.69	0.43	0.85	0.97	1.11
	Distance (mm)	12.65	37.94	63.23	88.52	113.81	139.10	164.39	189.68
2nd 88.83 hr	Temperature (°C)	-5.08	-1.42	-0.32	0.34	0.31	0.89	0.95	0.68
	Distance (mm)	12.65	37.94	63.23	88.52	113.81	139.10	164.39	189.68

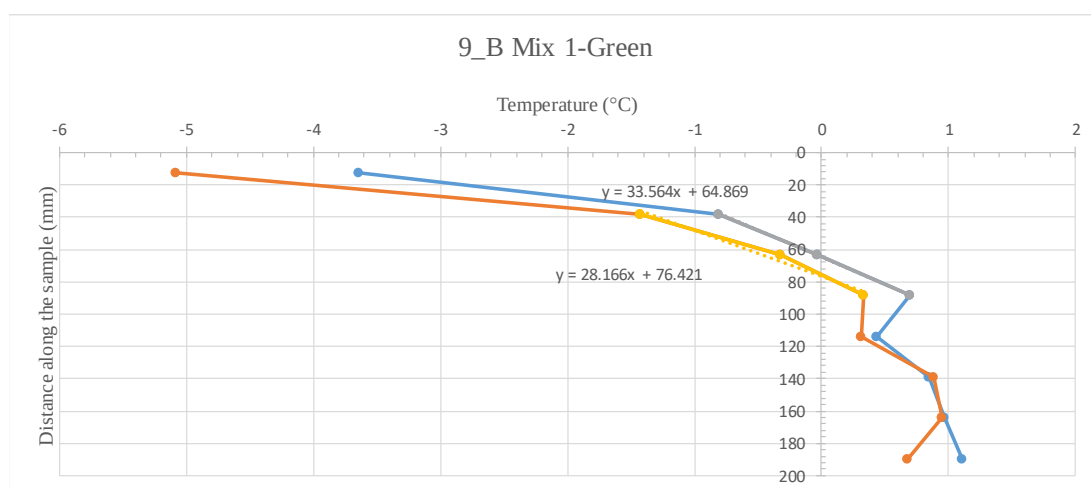
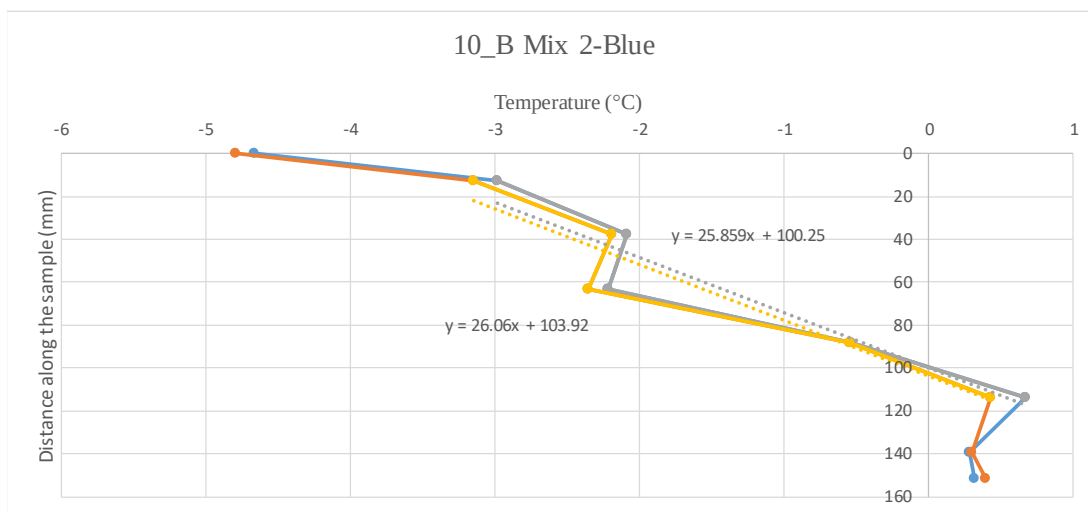


Figure D. 20 Temperature profile for “9_B Mix 1-Yellow & Green” samples

10_B Mixture 2

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 40.5 hr	Temperature (°C)	-4.67	-2.99	-2.09	-2.22	-0.54	0.67	0.28	0.32
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.583 hr	Temperature (°C)	-4.80	-3.15	-2.19	-2.35	-0.55	0.43	0.30	0.40
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 40.67 hr	Temperature (°C)	-4.30	-3.62	-2.99	-1.55	-1.37	-0.29	-0.14	-0.22
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.75 hr	Temperature (°C)	-4.42	-3.79	-3.09	-1.63	-1.38	-0.42	-0.14	-0.29
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

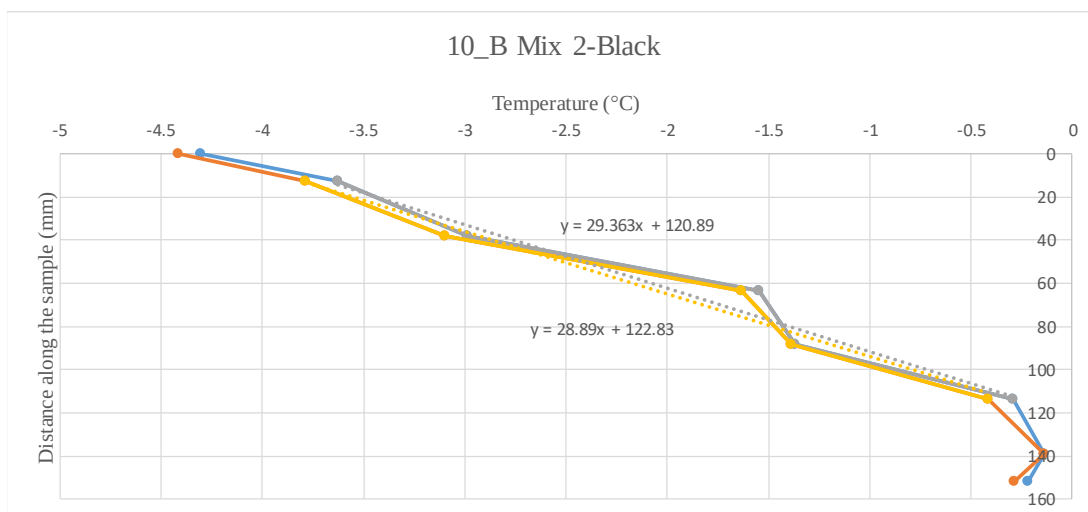
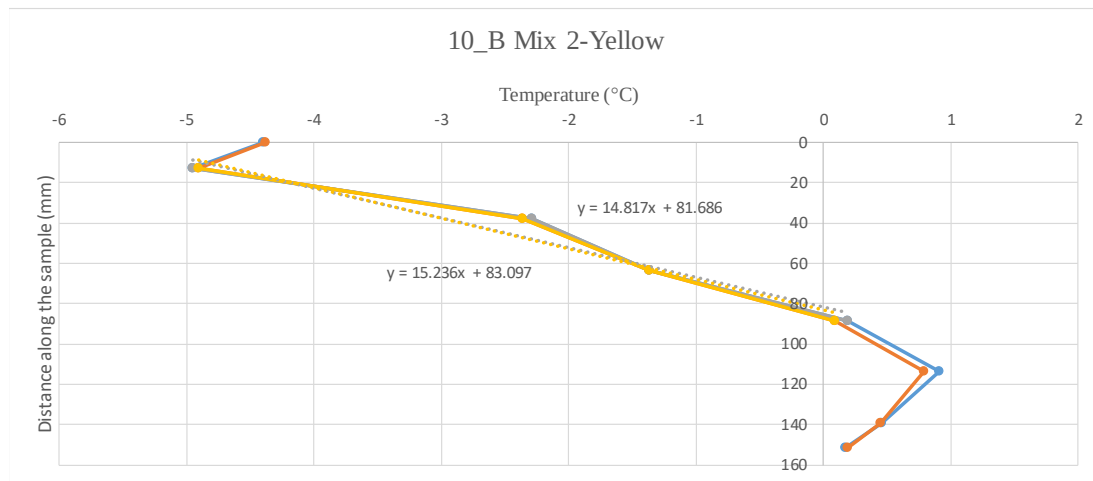


Figure D. 21 Temperature profile for “10_B Mix 2-Blue & Black” samples

10_B Mixture 2

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.5 hr	Temperature (°C)	-4.39	-4.95	-2.28	-1.36	0.20	0.91	0.46	0.17
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.4167 hr	Temperature (°C)	-4.38	-4.90	-2.36	-1.37	0.09	0.79	0.45	0.19
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 40.583 hr	Temperature (°C)	-6.84	-3.46	-1.76	-1.19	-0.74	0.12	0.58	0.67
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.583 hr	Temperature (°C)	-7.27	-3.76	-2.22	-1.04	-0.55	0.42	0.80	1.13
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

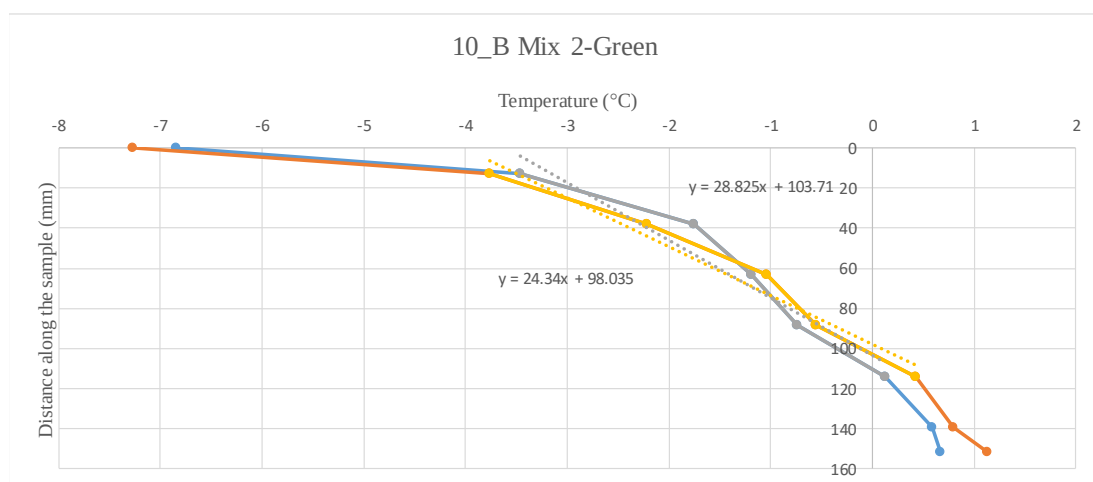
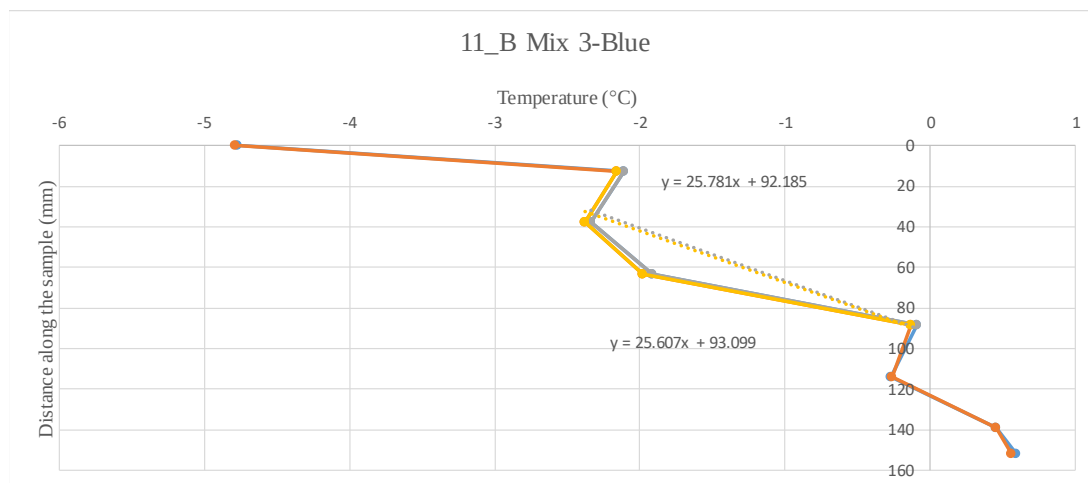


Figure D. 22 Temperature profile for “10_B Mix 2-Yellow & Green” samples

11_B Mixture 3

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 40.583 hr	Temperature (°C)	-4.77	-2.11	-2.34	-1.92	-0.09	-0.27	0.46	0.59
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.5 hr	Temperature (°C)	-4.78	-2.16	-2.37	-1.98	-0.13	-0.26	0.46	0.56
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 40.4167 hr	Temperature (°C)	-3.04	-2.78	-2.15	-0.68	-0.54	0.89	0.20	0.69
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.5 hr	Temperature (°C)	-2.98	-2.79	-2.12	-0.66	-0.57	0.95	0.20	0.72
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

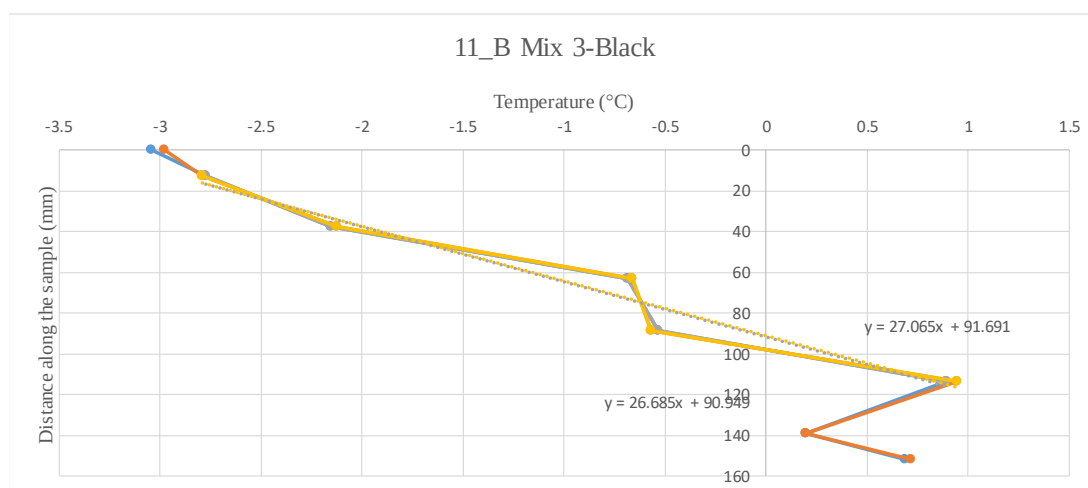
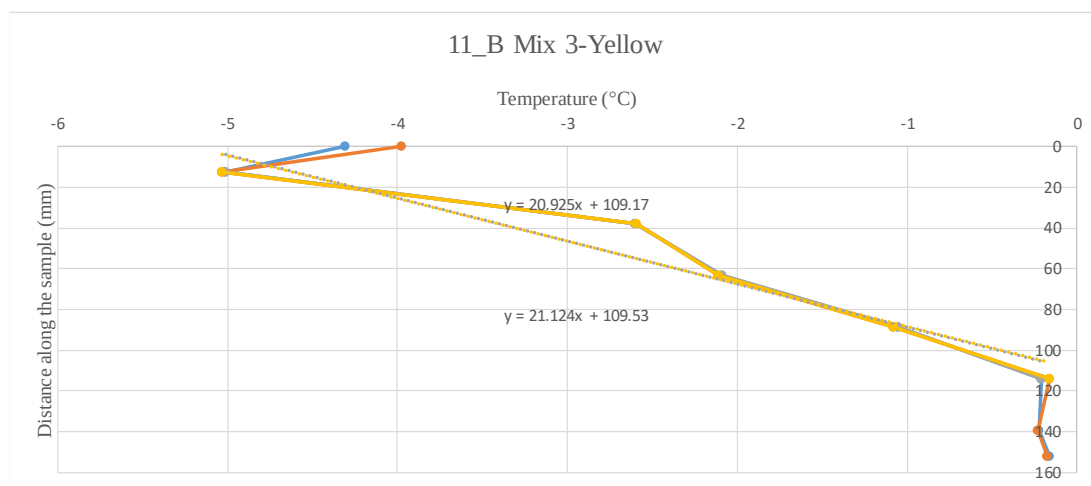


Figure D. 23 Temperature profile for “11_B Mix 3-Blue & Black” samples

11_B Mixture 3

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.083 hr	Temperature (°C)	-4.31	-5.01	-2.60	-2.09	-1.05	-0.21	-0.22	-0.16
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.3 hr	Temperature (°C)	-3.97	-5.03	-2.59	-2.11	-1.08	-0.16	-0.23	-0.17
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 41.167 hr	Temperature (°C)	-5.23	-0.78	-0.97	0.11	-0.04	0.77	1.10	1.65
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.9167 hr	Temperature (°C)	-5.24	-0.78	-1.11	0.03	-0.18	0.78	0.97	1.50
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

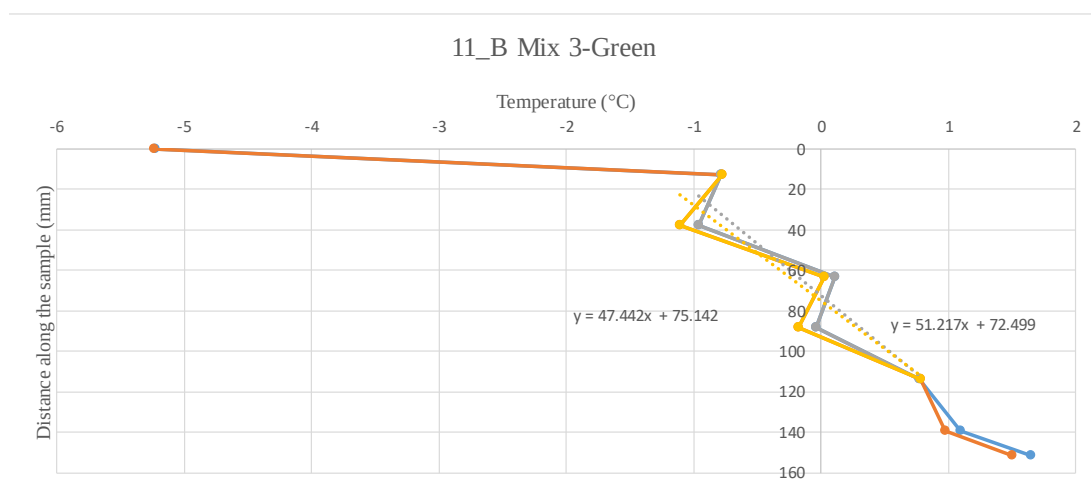
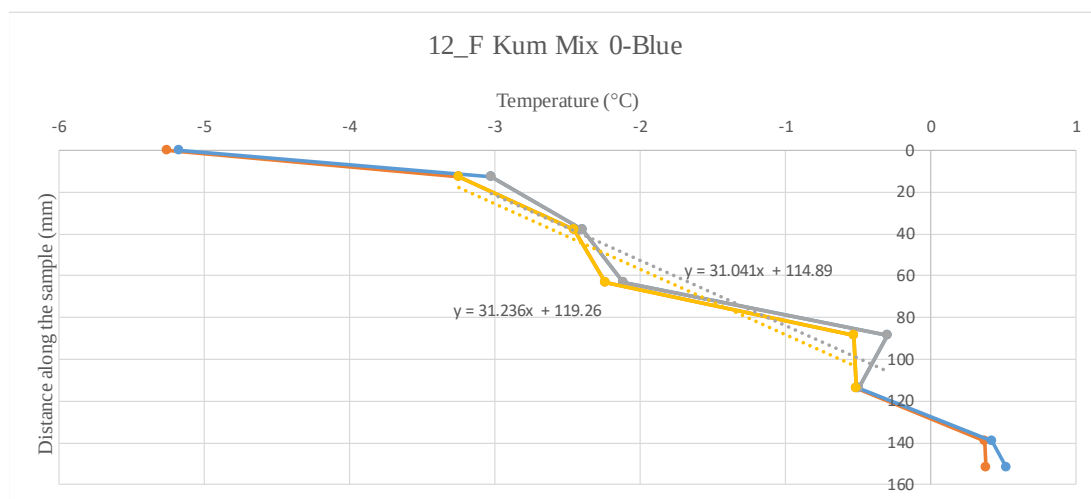


Figure D. 24 Temperature profile for “11_B Mix 3-Yellow & Green” samples

12_F Kum Mixture 0

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 40.583 hr	Temperature (°C)	-5.18	-3.03	-2.39	-2.11	-0.29	-0.50	0.42	0.52
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.67 hr	Temperature (°C)	-5.26	-3.25	-2.45	-2.24	-0.53	-0.51	0.38	0.38
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 41 hr	Temperature (°C)	-3.25	-2.60	-2.19	-0.95	-0.66	0.56	0.70	0.96
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.25 hr	Temperature (°C)	-2.94	-2.17	-1.82	-0.63	-0.42	0.69	0.84	1.04
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

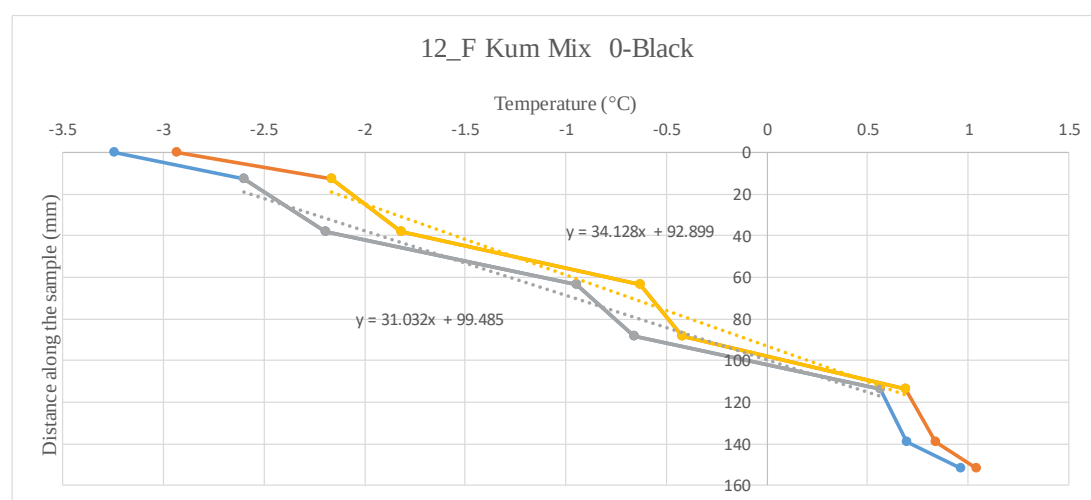
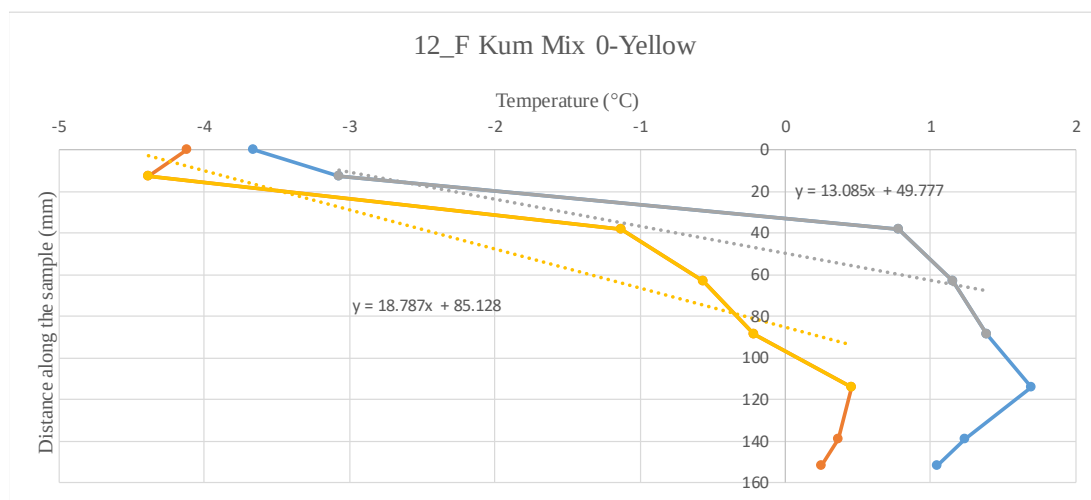


Figure D. 25 Temperature profile for “12_F Kum Mix 0-Blue & Black” samples

12_F Kum Mixture 0

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 33.5 hr	Temperature (°C)	-3.66	-3.07	0.78	1.15	1.39	1.69	1.24	1.05
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.83 hr	Temperature (°C)	-4.12	-4.38	-1.13	-0.56	-0.21	0.46	0.37	0.25
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 40.4167 hr	Temperature (°C)	-6.59	-3.60	-2.41	-1.19	-0.93	0.34	0.36	0.25
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.67 hr	Temperature (°C)	-6.55	-3.85	-2.45	-1.10	-0.94	0.28	0.44	0.26
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

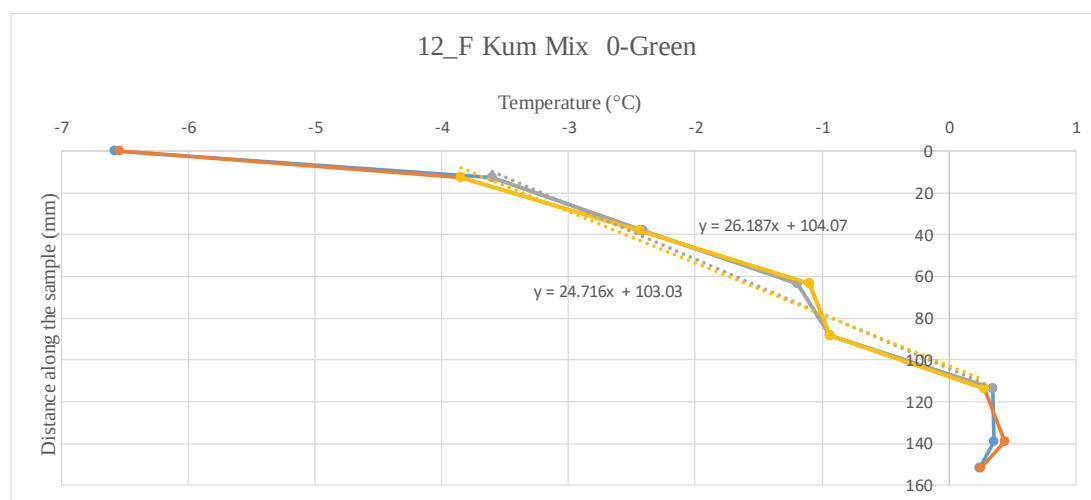
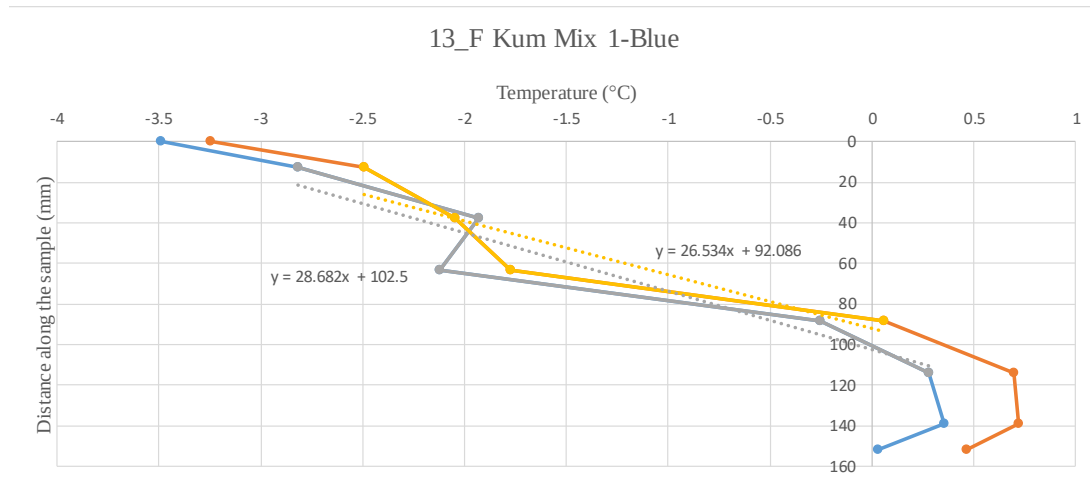


Figure D. 26 Temperature profile for “12_F Kum Mix 0-Yellow & Green” samples

13_F Kum Mixture 1

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 40 hr	Temperature (°C)	-3.49	-2.82	-1.93	-2.12	-0.25	0.28	0.36	0.03
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.167 hr	Temperature (°C)	-3.25	-2.50	-2.05	-1.77	0.06	0.70	0.72	0.46
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 40.4167 hr	Temperature (°C)	-4.28	-3.22	-2.99	-1.43	-1.03	-0.09	-0.08	0.20
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.75 hr	Temperature (°C)	-3.72	-2.69	-2.59	-1.01	-0.74	0.23	0.15	0.50
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

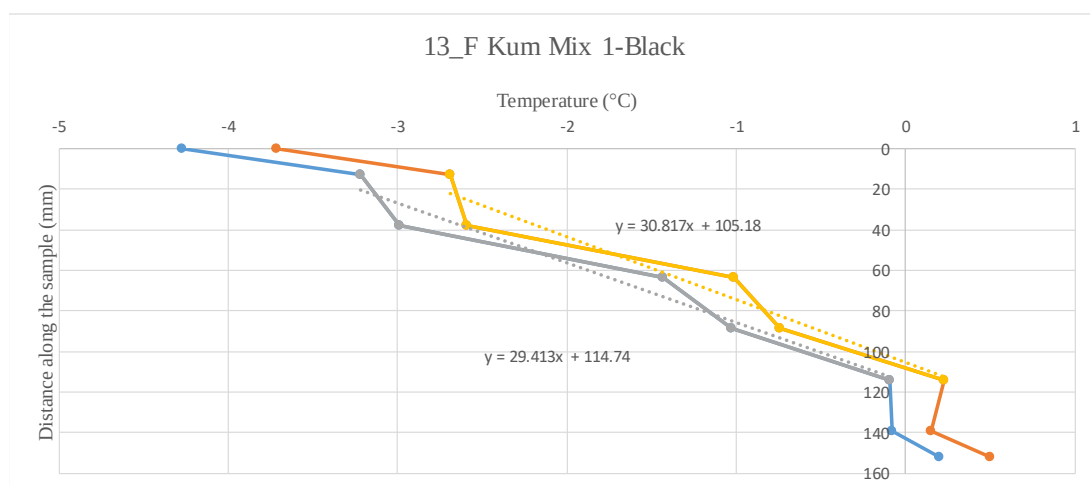
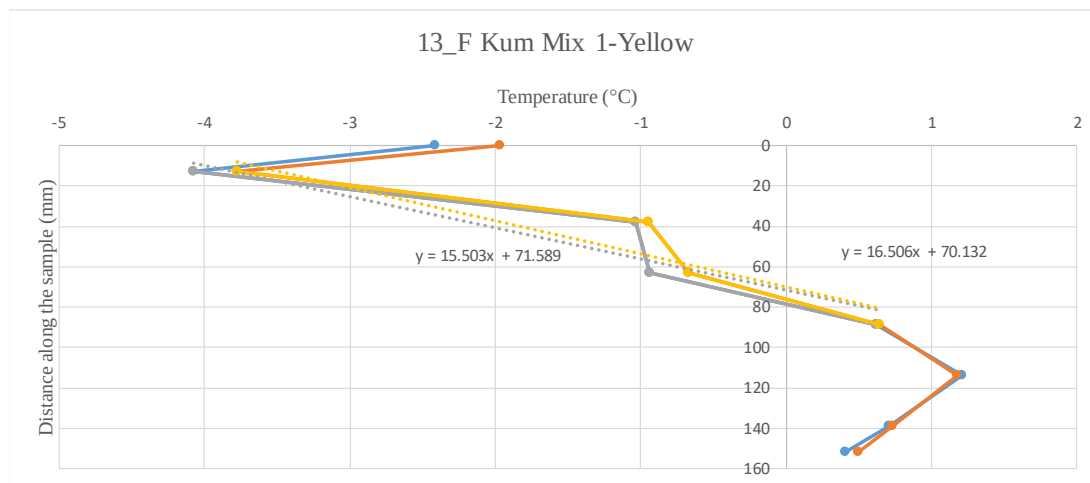


Figure D. 27 Temperature profile for “13_F Kum Mix 1-Blue & Black” samples

13_F Kum Mixture 1

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 41.83 hr	Temperature (°C)	-2.41	-4.07	-1.03	-0.94	0.62	1.21	0.71	0.41
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.4167 hr	Temperature (°C)	-1.96	-3.77	-0.94	-0.67	0.64	1.18	0.74	0.50
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 40.583 hr	Temperature (°C)	-5.69	-2.18	-0.98	0.24	-0.04	1.63	1.76	0.75
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.583 hr	Temperature (°C)	-5.38	-2.19	-0.93	0.33	0.19	1.43	1.53	0.62
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

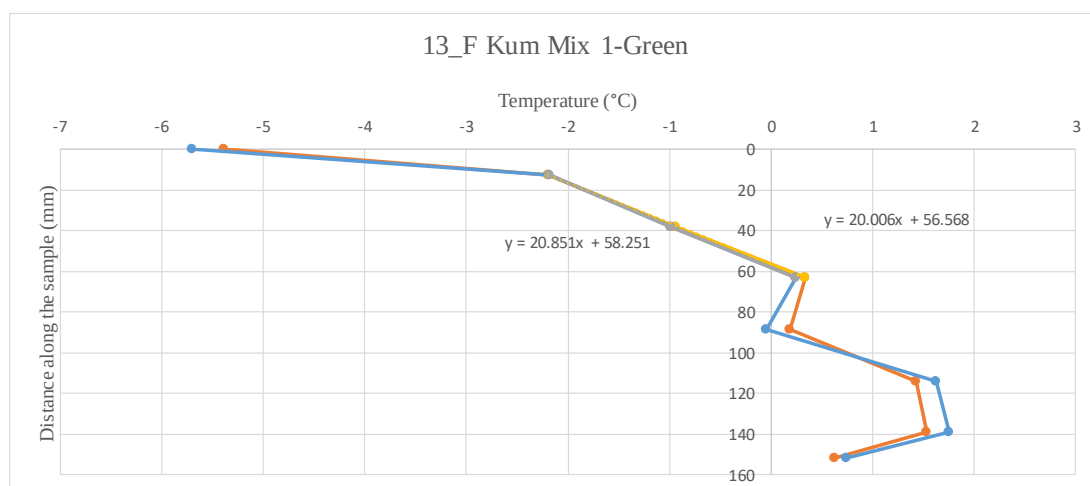
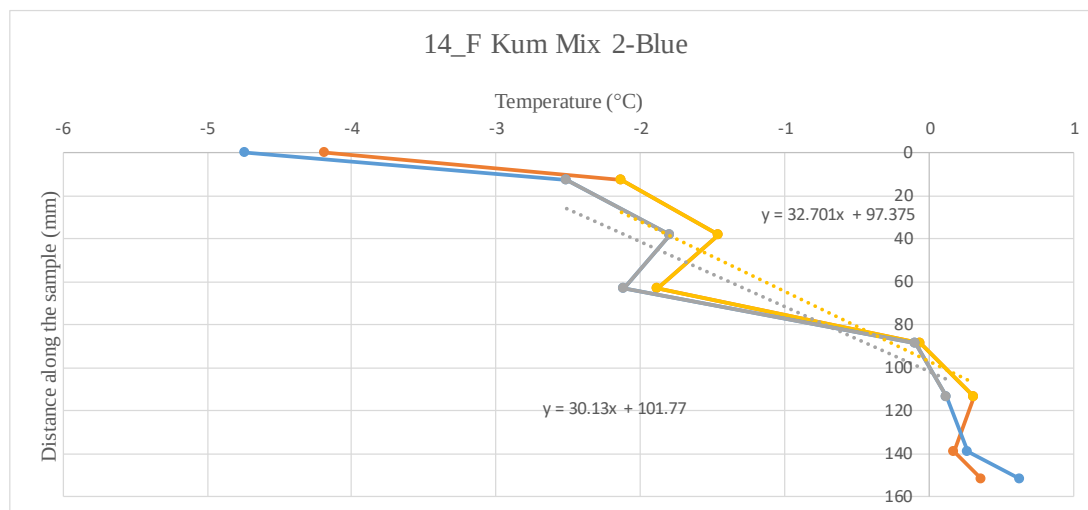


Figure D. 28 Temperature profile for “13_F Kum Mix 1-Yellow & Green” samples

14_F Kum Mixture 2

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 40.67 hr	Temperature (°C)	-4.73	-2.51	-1.80	-2.12	-0.09	0.12	0.26	0.63
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.83 hr	Temperature (°C)	-4.18	-2.13	-1.46	-1.88	-0.06	0.31	0.17	0.36
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 40.83 hr	Temperature (°C)	-4.81	-2.55	-2.22	-0.82	-0.34	1.03	0.86	1.34
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89 hr	Temperature (°C)	-4.77	-2.70	-2.26	-0.96	-0.41	0.82	0.64	1.05
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

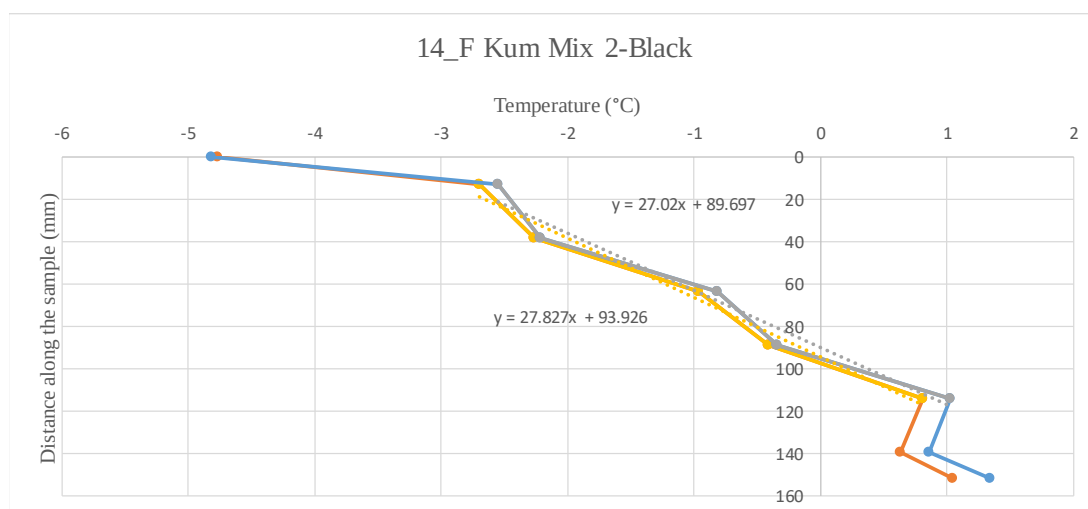
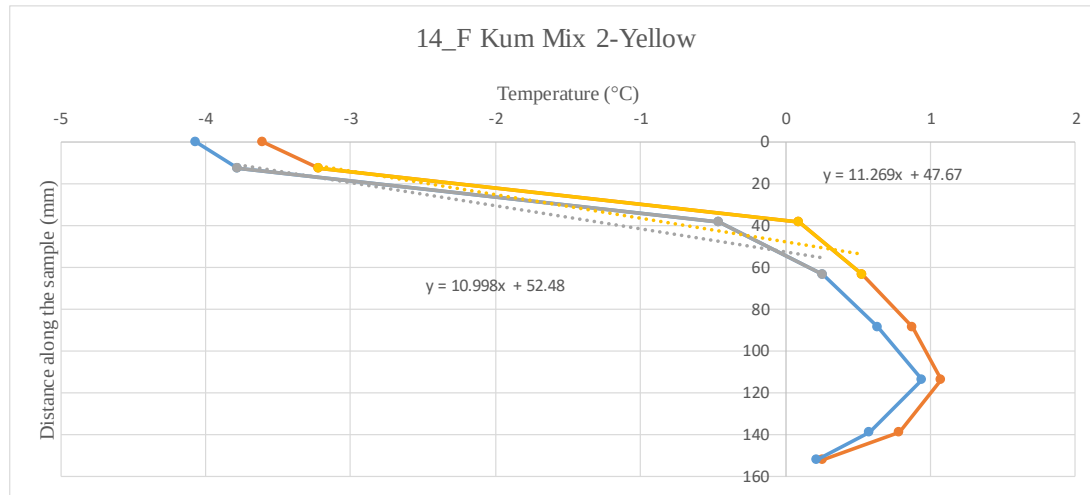


Figure D. 29 Temperature profile for “14_F Kum Mix 2-Blue & Black” samples

14_F Kum Mixture 2

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 33.83 hr	Temperature (°C)	-4.06	-3.78	-0.45	0.26	0.64	0.94	0.58	0.22
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 81.5 hr	Temperature (°C)	-3.61	-3.22	0.10	0.53	0.88	1.08	0.79	0.26
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 40.583 hr	Temperature (°C)	-5.77	-2.26	-1.52	-0.67	-0.17	0.84	0.89	0.24
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.75 hr	Temperature (°C)	-6.00	-2.34	-1.53	-0.49	-0.17	1.00	1.14	0.66
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

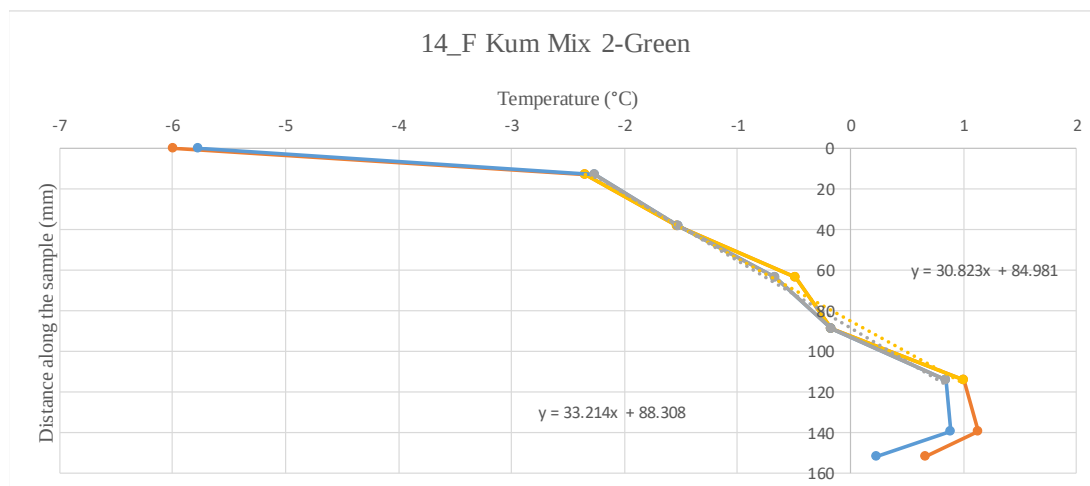
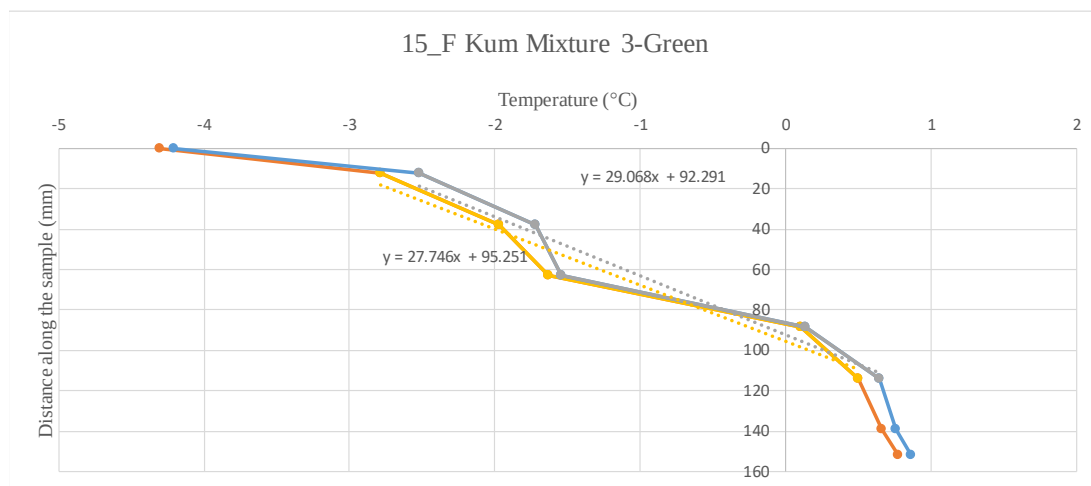


Figure D. 30 Temperature profile for “14_F Kum Mix 2-Yellow & Green” samples

15_F Kum Mixture 3

Blue Sample - 1									
Freezing Cycles	Parameters	T09- Blue-1 (°C)	T10- Blue-2 (°C)	T11- Blue-3 (°C)	T12- Blue-4 (°C)	T13- Blue-5 (°C)	T14- Blue-6 (°C)	T15- Blue-7 (°C)	T16- Blue-8 (°C)
1st 40.75 hr	Temperature (°C)	-4.21	-2.52	-1.72	-1.54	0.13	0.65	0.76	0.86
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.4167 hr	Temperature (°C)	-4.31	-2.78	-1.97	-1.63	0.11	0.50	0.66	0.78
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17- Black-1 (°C)	T18- Black-2 (°C)	T19- Black-3 (°C)	T20- Black-4 (°C)	T21- Black-5 (°C)	T22- Black-6 (°C)	T23- Black-7 (°C)	T24- Black-8 (°C)
1st 41.25 hr	Temperature (°C)	-3.36	-2.21	-1.32	0.39	0.36	0.97	0.58	1.12
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.5 hr	Temperature (°C)	-3.56	-2.35	-1.52	0.31	0.29	0.92	0.58	1.12
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

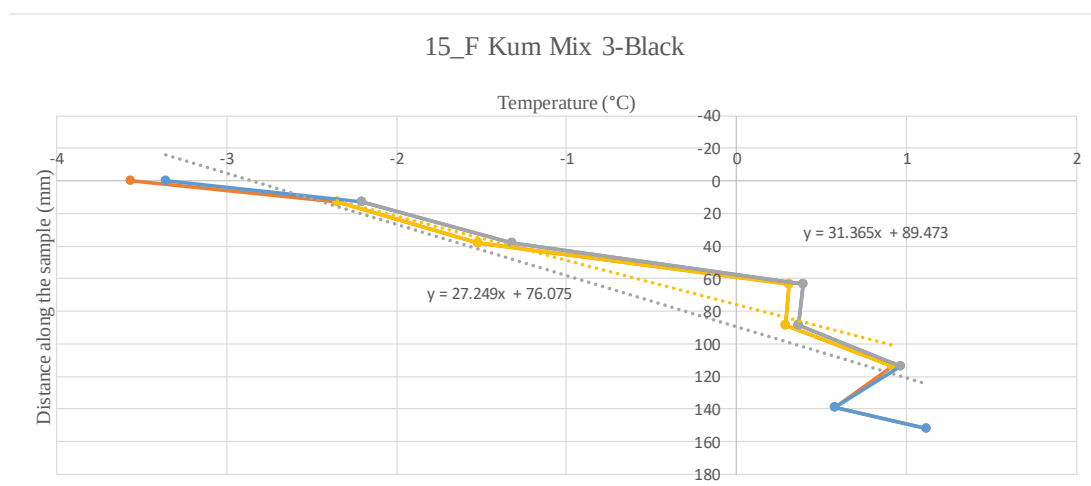
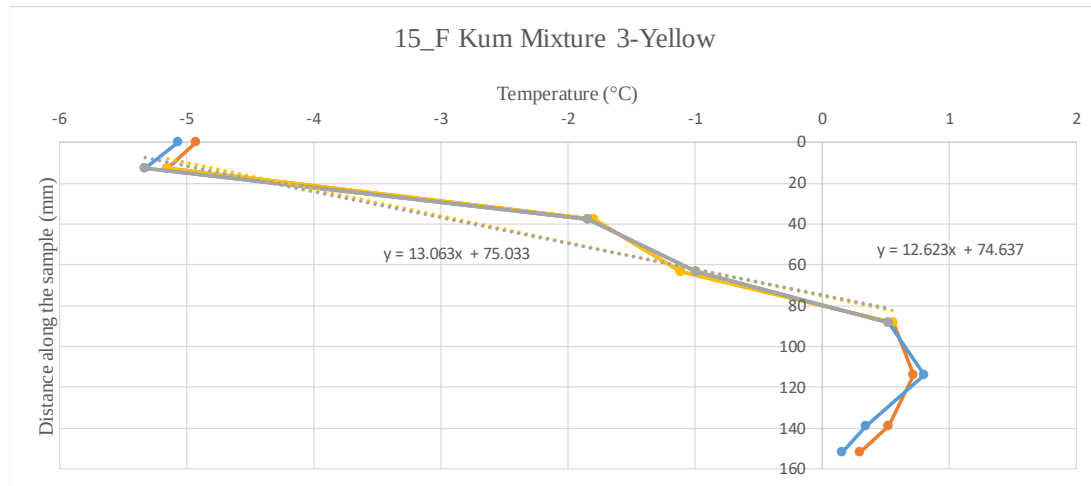


Figure D. 31 Temperature profile for “15_F Kum Mix 3-Blue & Black” samples

15_F Kum Mixture 3

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.167 hr	Temperature (°C)	-5.06	-5.32	-1.84	-0.99	0.52	0.80	0.35	0.16
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.25 hr	Temperature (°C)	-4.93	-5.15	-1.79	-1.11	0.56	0.73	0.52	0.30
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 41.083 hr	Temperature (°C)	-5.40	-2.69	-1.62	-0.19	0.18	0.89	0.63	0.58
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.083 hr	Temperature (°C)	-5.51	-2.69	-1.38	0.12	0.51	1.18	1.04	0.82
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

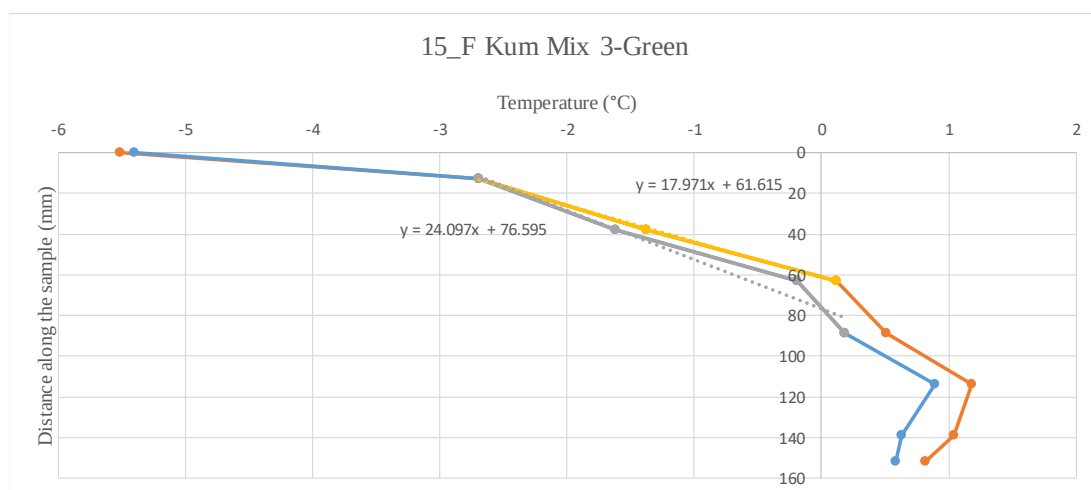
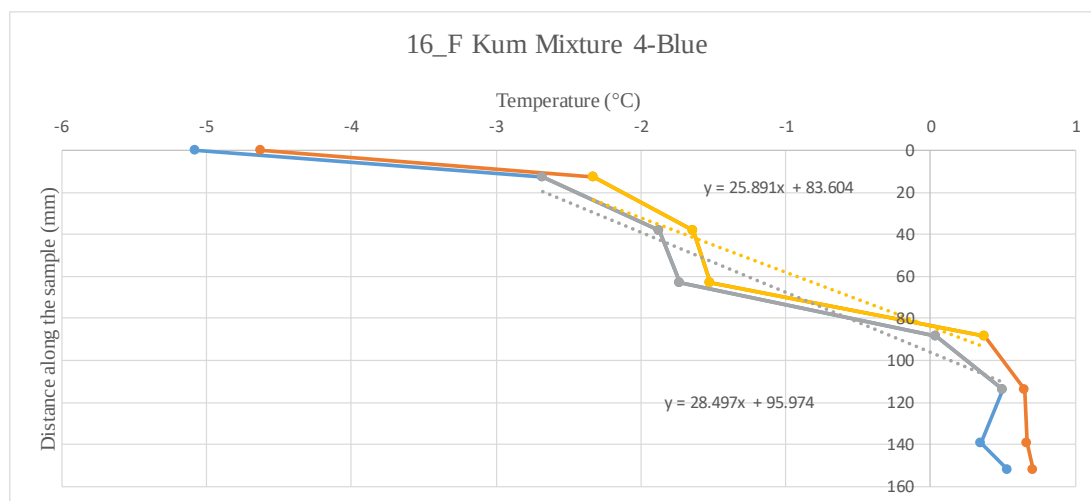


Figure D. 32 Temperature profile for “15_F Kum Mix 3-Yellow & Green” samples

16_F Kum Mixture 4

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 41 hr	Temperature (°C)	-5.07	-2.68	-1.88	-1.73	0.04	0.50	0.35	0.54
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.3 hr	Temperature (°C)	-4.62	-2.32	-1.64	-1.52	0.38	0.65	0.67	0.71
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 41 hr	Temperature (°C)	-3.90	-3.12	-2.43	-0.88	-0.19	0.45	0.32	0.72
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.3 hr	Temperature (°C)	-3.74	-2.86	-2.36	-0.70	0.02	0.79	0.60	0.98
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

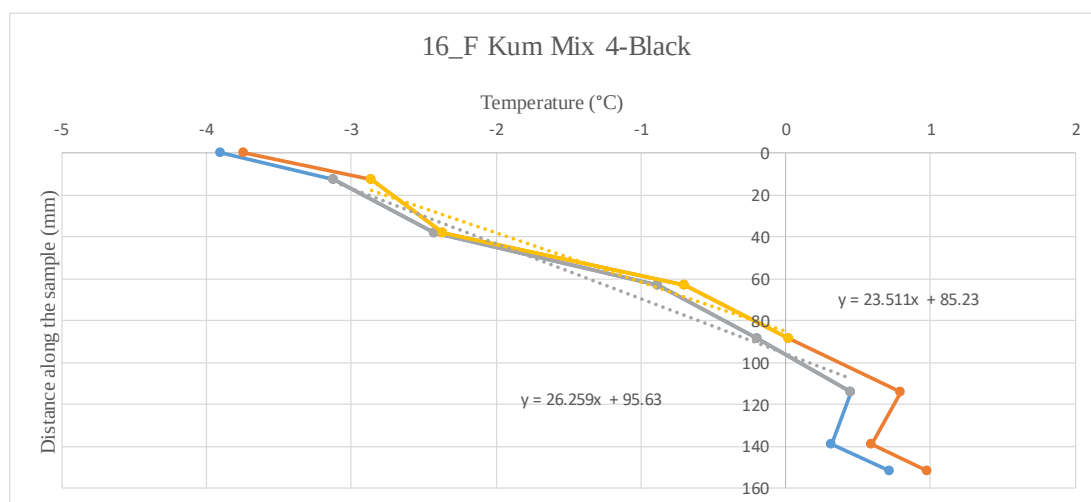
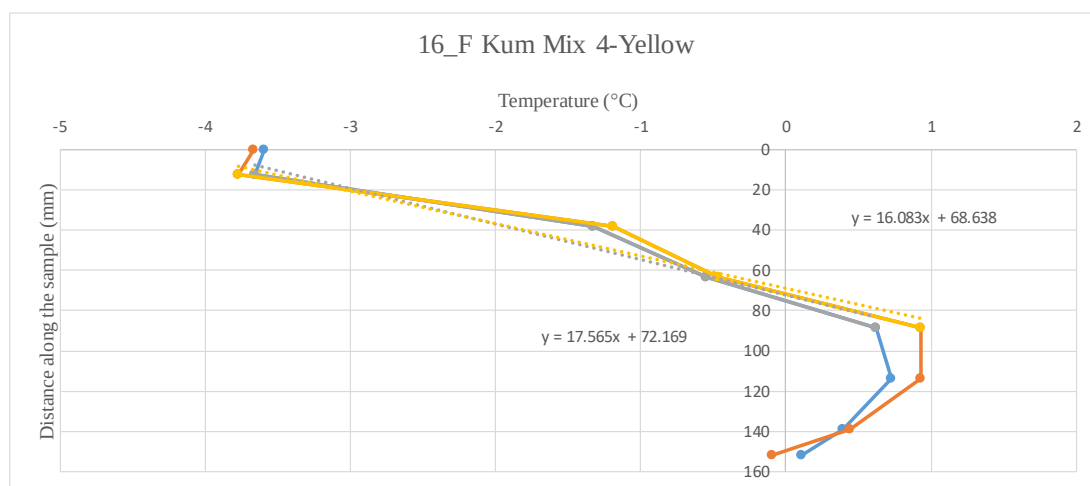


Figure D. 33 Temperature profile for “16_F Kum Mix 4-Blue & Black” samples

16_F Kum Mixture 4

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.167 hr	Temperature (°C)	-3.59	-3.66	-1.33	-0.55	0.62	0.73	0.40	0.11
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.5 hr	Temperature (°C)	-3.67	-3.77	-1.19	-0.47	0.93	0.93	0.45	-0.09
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 40.83 hr	Temperature (°C)	-6.46	-3.40	-1.69	-0.43	-0.23	0.93	0.99	0.41
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.4167 hr	Temperature (°C)	-6.93	-3.60	-1.63	-0.23	0.28	0.99	1.03	0.56
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

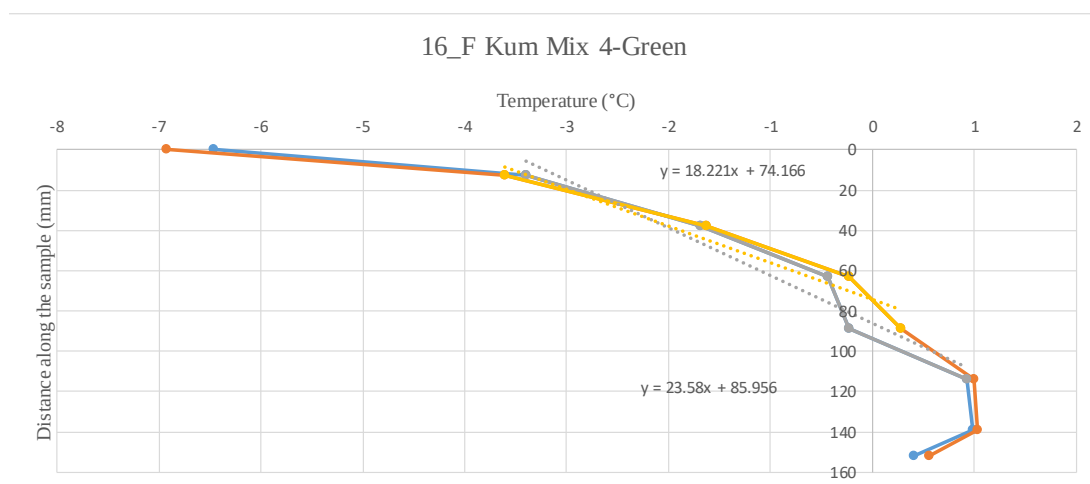
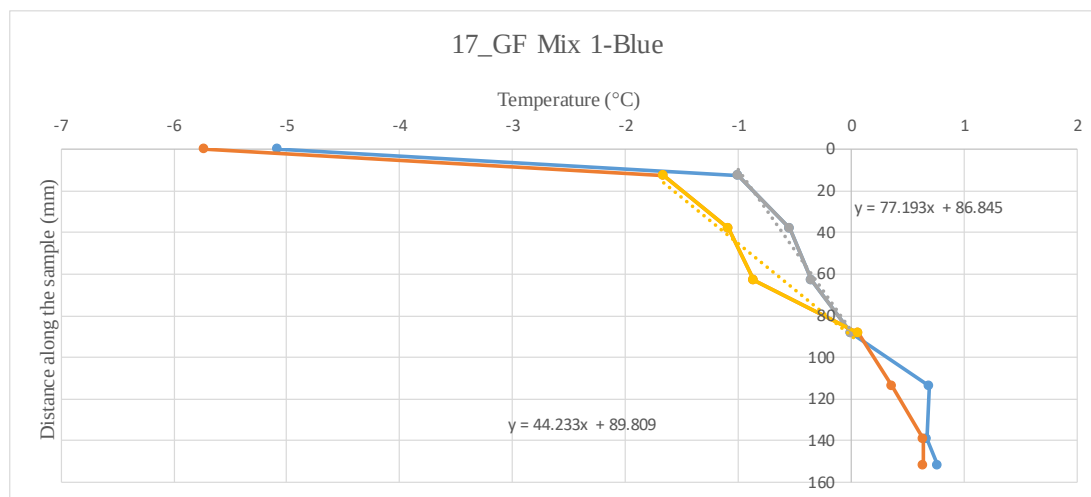


Figure D. 34 Temperature profile for “16_F Kum Mix 4-Yellow & Green” samples

17_GF Mixture 1

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 41.5 hr	Temperature (°C)	-5.08	-1.00	-0.54	-0.34	0.00	0.70	0.67	0.77
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.583 hr	Temperature (°C)	-5.73	-1.66	-1.08	-0.86	0.06	0.36	0.64	0.64
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 41.83 hr	Temperature (°C)	-1.86	-0.77	-0.24	0.69	0.51	1.23	0.91	0.99
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 90 hr	Temperature (°C)	-0.89	-0.37	-0.02	0.91	0.74	1.60	1.15	1.03
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

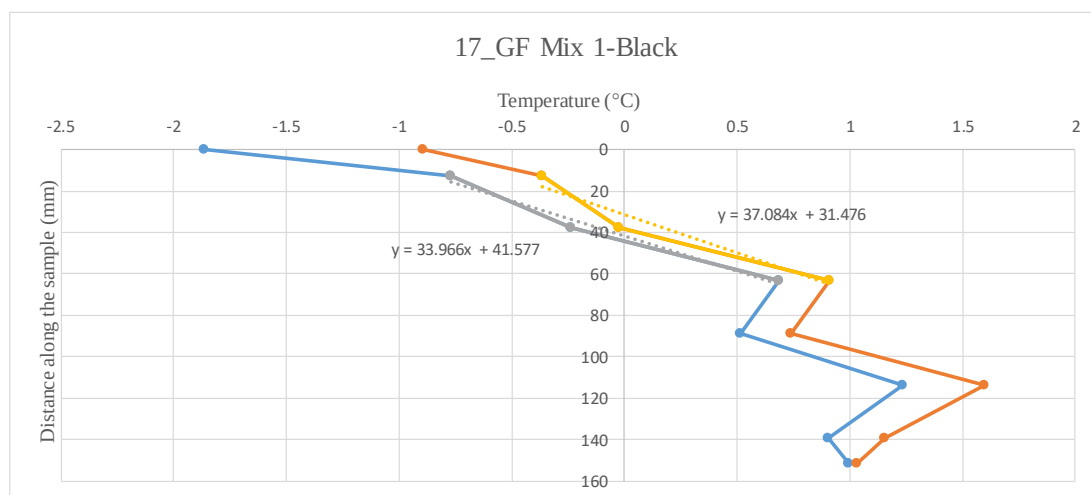
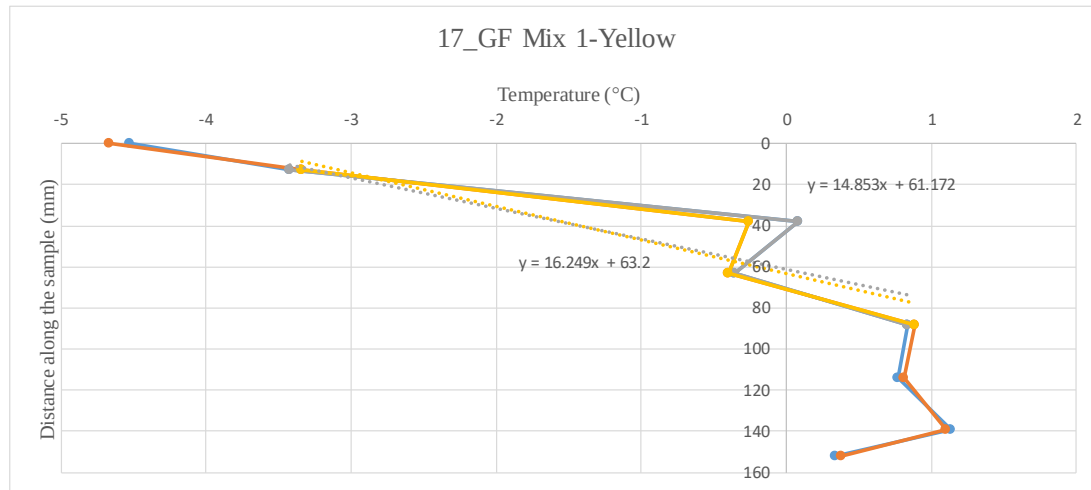


Figure D. 35 Temperature profile for “17_GF Mix 1-Blue & Black” samples

17_GF Mixture 1

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.5 hr	Temperature (°C)	-4.52	-3.42	0.08	-0.36	0.84	0.77	1.13	0.34
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.583 hr	Temperature (°C)	-4.67	-3.34	-0.25	-0.40	0.89	0.81	1.10	0.38
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 44.5 hr	Temperature (°C)	-3.67	0.01	0.30	1.33	0.93	1.76	1.74	0.85
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.167 hr	Temperature (°C)	-2.88	0.62	0.84	1.74	1.32	1.85	1.97	0.94
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

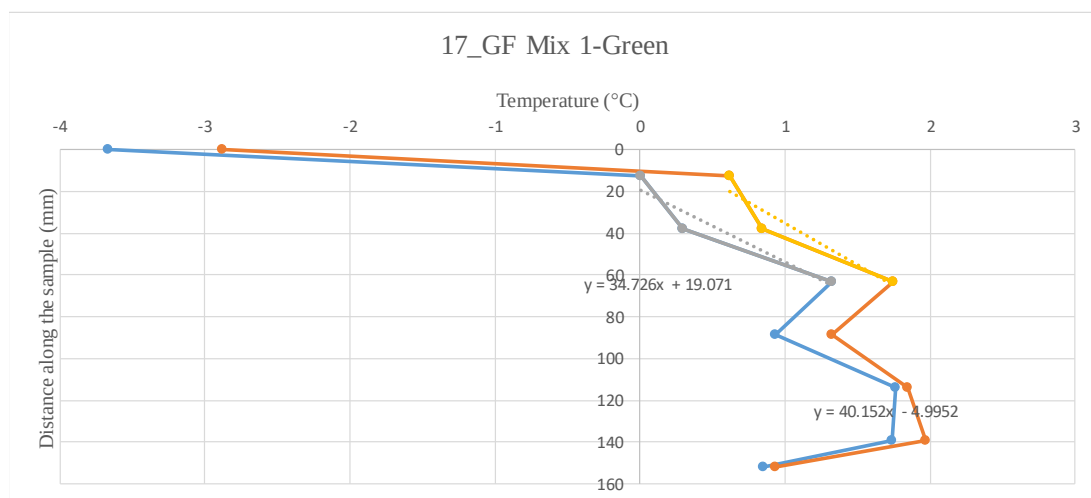
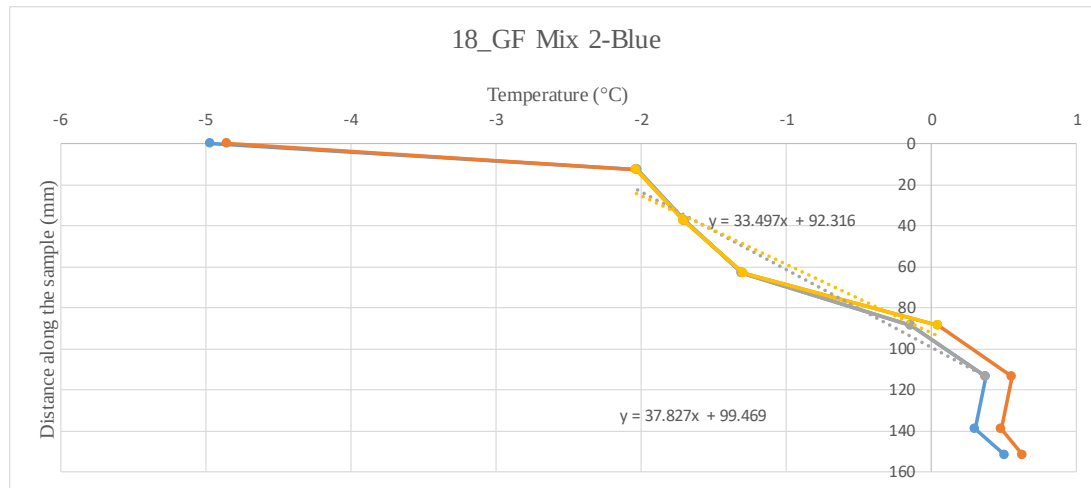


Figure D. 36 Temperature profile for “17_GF Mix 1-Yellow & Green” samples

18_GF Mixture 2

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 41 hr	Temperature (°C)	-4.96	-2.03	-1.70	-1.30	-0.14	0.38	0.30	0.50
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.083 hr	Temperature (°C)	-4.85	-2.03	-1.71	-1.29	0.05	0.55	0.48	0.63
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 40.75 hr	Temperature (°C)	-3.53	-1.60	-1.45	-0.60	-0.33	0.44	0.10	0.44
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.9167 hr	Temperature (°C)	-3.94	-1.93	-1.80	-0.95	-0.67	0.17	-0.11	0.34
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

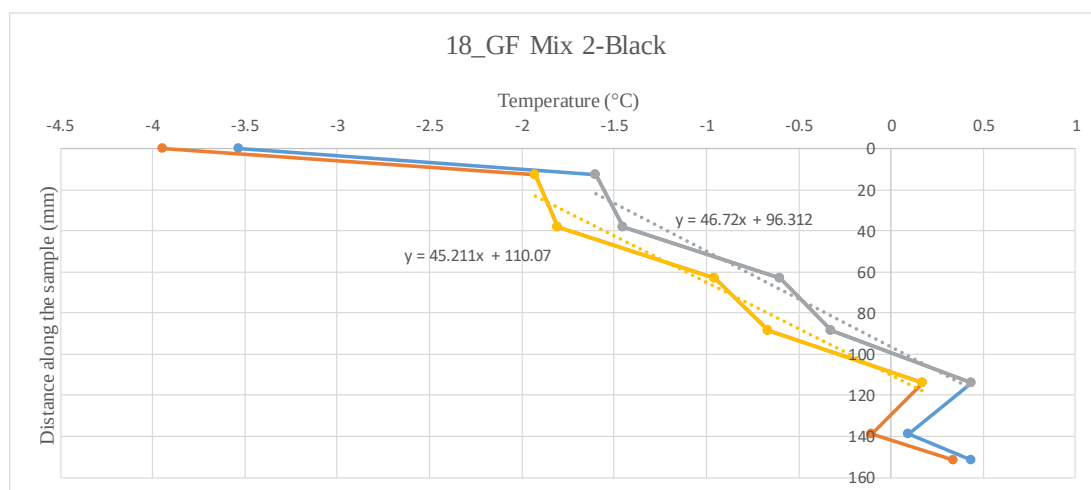
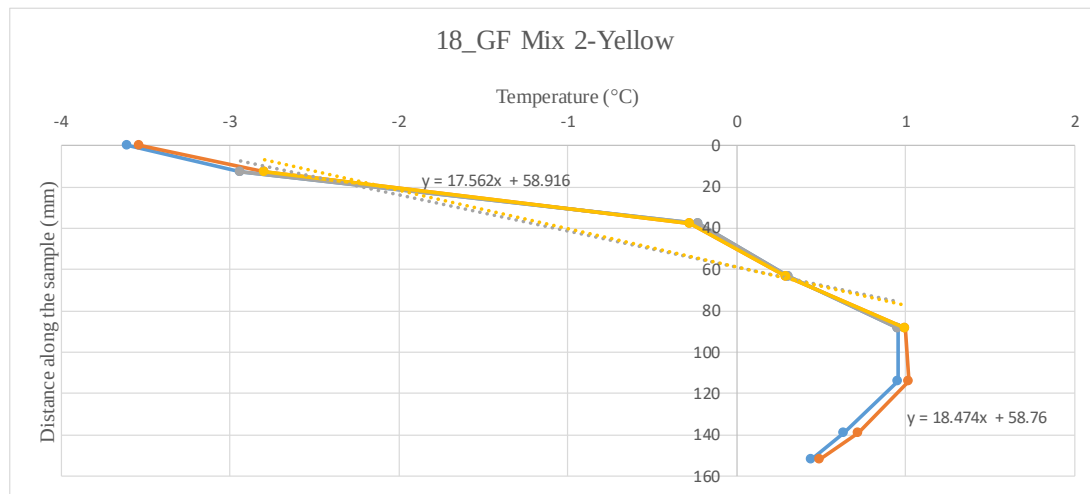


Figure D. 37 Temperature profile for “18_GF Mix 2-Blue & Black” samples

18_GF Mixture 2

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.167 hr	Temperature (°C)	-3.60	-2.94	-0.23	0.31	0.96	0.95	0.64	0.44
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.583 hr	Temperature (°C)	-3.53	-2.79	-0.28	0.30	1.00	1.02	0.72	0.49
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 41.583 hr	Temperature (°C)	-6.91	-1.14	-0.04	0.62	0.75	1.32	0.91	0.54
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.67 hr	Temperature (°C)	-6.92	-1.32	-0.24	0.34	0.74	1.35	0.89	0.60
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

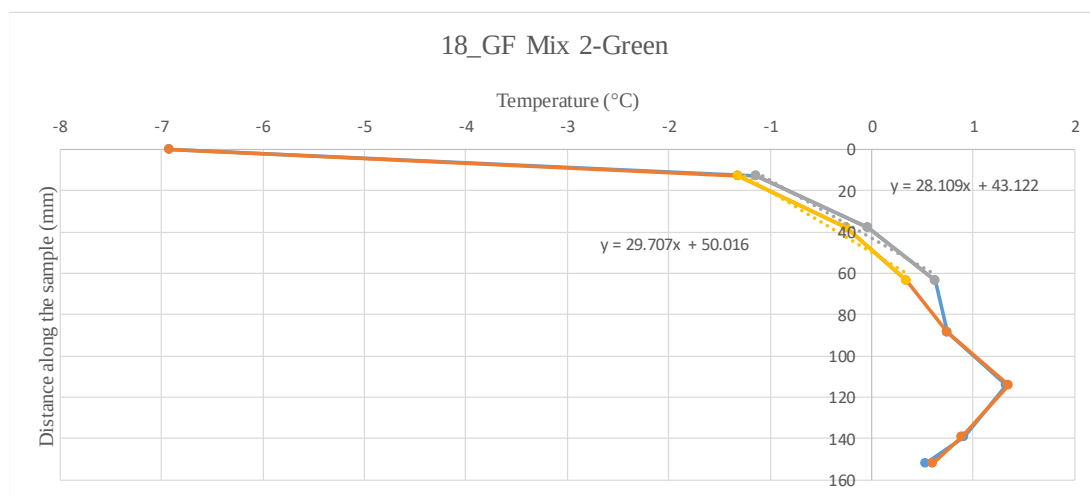
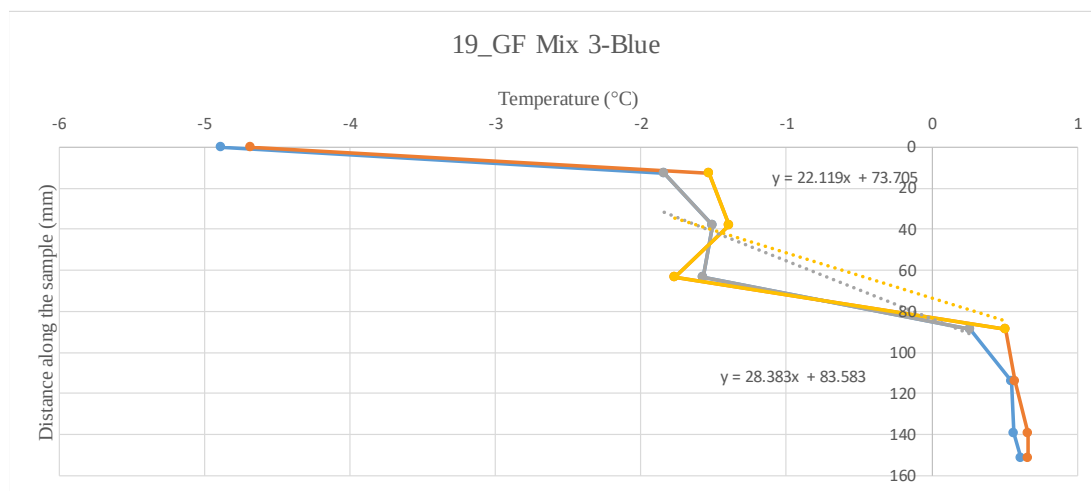


Figure D. 38 Temperature profile for “18_GF Mix 2-Yellow & Green” samples

19_GF Mixture 3

Blue Sample - 1									
Freezing Cycles	Parameters	T09-Blue-1 (°C)	T10-Blue-2 (°C)	T11-Blue-3 (°C)	T12-Blue-4 (°C)	T13-Blue-5 (°C)	T14-Blue-6 (°C)	T15-Blue-7 (°C)	T16-Blue-8 (°C)
1st 41.4167 hr	Temperature (°C)	-4.89	-1.84	-1.51	-1.57	0.27	0.55	0.56	0.61
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.583 hr	Temperature (°C)	-4.68	-1.53	-1.39	-1.77	0.50	0.57	0.66	0.66
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17-Black-1 (°C)	T18-Black-2 (°C)	T19-Black-3 (°C)	T20-Black-4 (°C)	T21-Black-5 (°C)	T22-Black-6 (°C)	T23-Black-7 (°C)	T24-Black-8 (°C)
1st 42.167 hr	Temperature (°C)	-2.95	-0.83	-0.99	0.15	0.49	1.33	0.88	1.54
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 90.3 hr	Temperature (°C)	-3.03	-0.90	-1.02	0.09	0.50	1.51	1.04	1.64
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

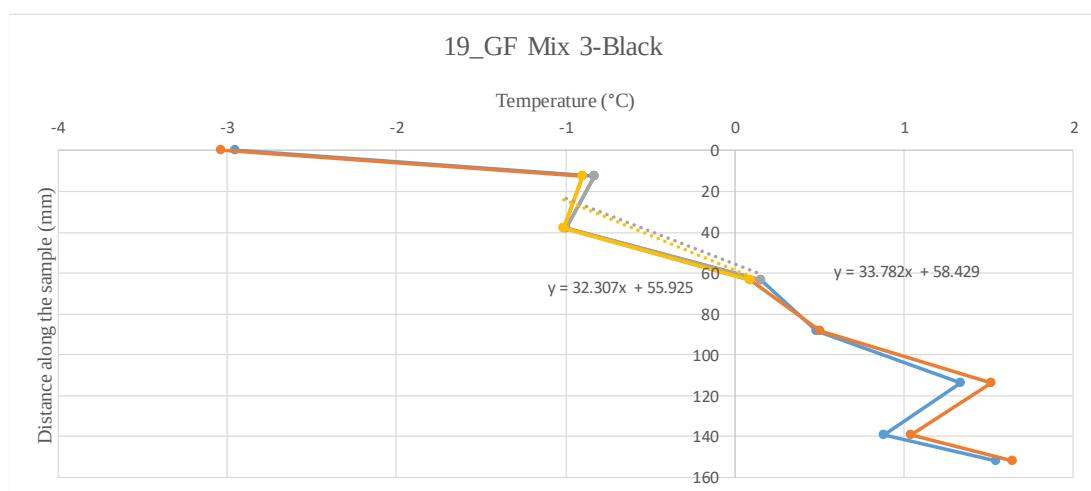
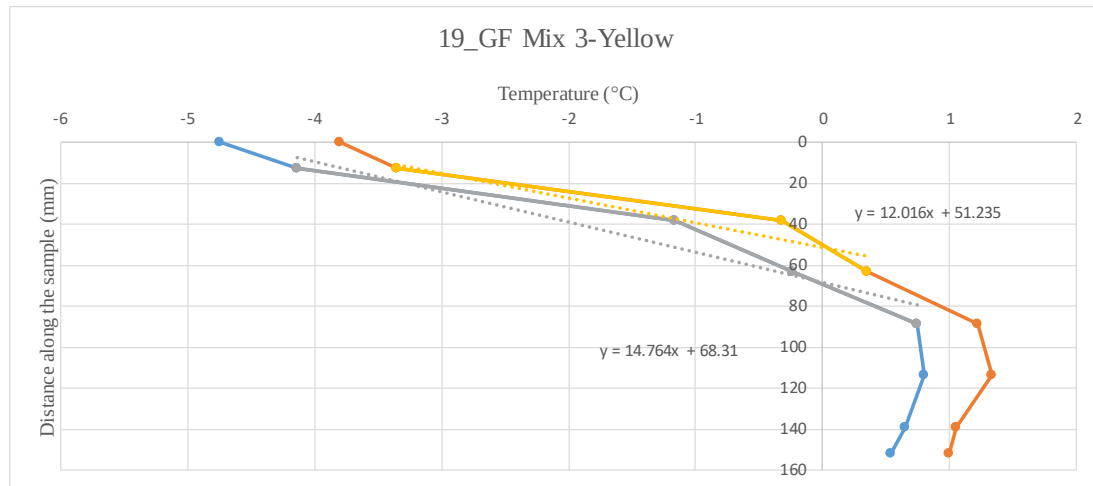


Figure D. 39 Temperature profile for “19_GF Mix 3-Blue & Black” samples

19_GF Mixture 3

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.25 hr	Temperature (°C)	-4.74	-4.14	-1.17	-0.24	0.74	0.80	0.65	0.54
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.67 hr	Temperature (°C)	-3.80	-3.35	-0.32	0.35	1.22	1.33	1.05	0.99
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 41.75 hr	Temperature (°C)	-6.48	-1.45	-0.34	0.45	0.80	1.16	1.16	0.69
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 90.167 hr	Temperature (°C)	-6.34	-1.31	-0.36	0.30	0.83	1.30	1.33	0.81
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

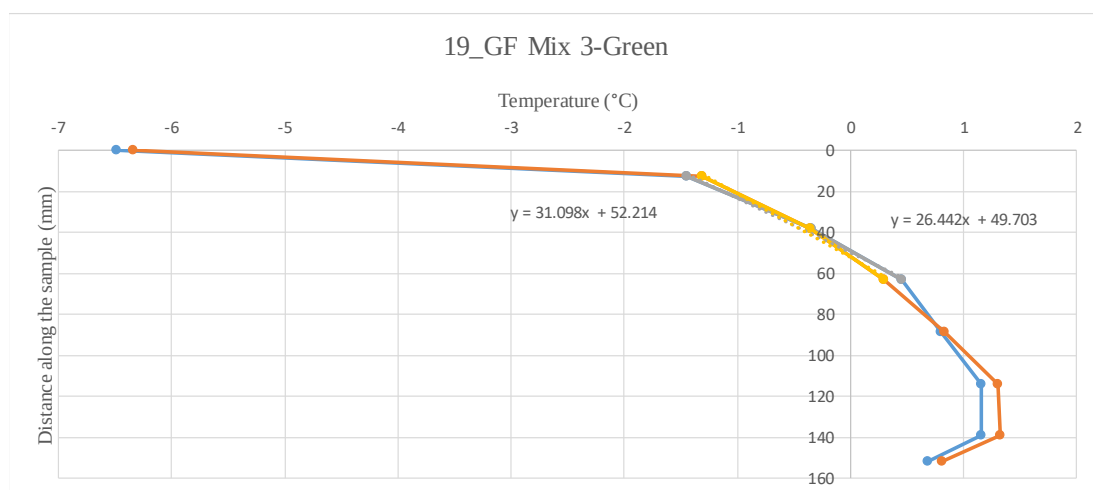
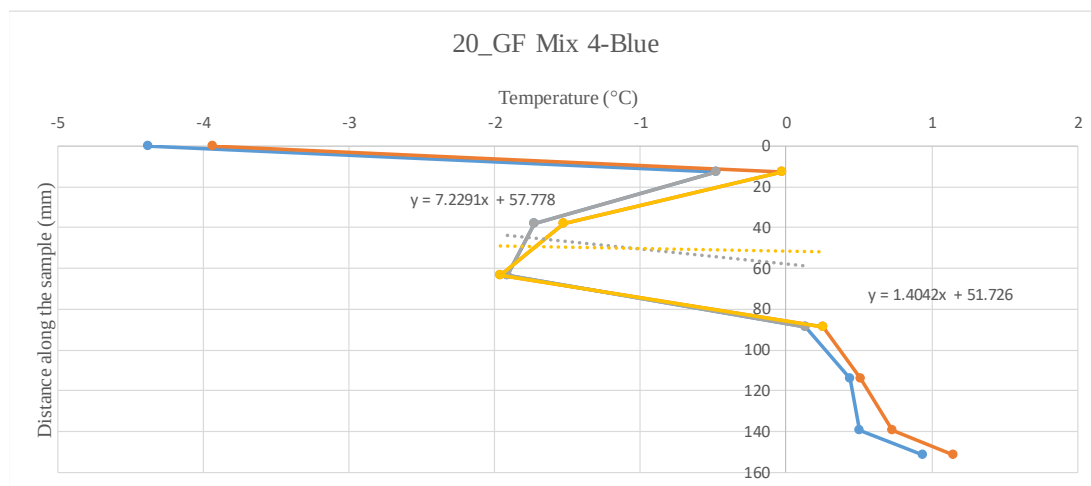


Figure D. 40 Temperature profile for “19_GF Mix 3-Yellow & Green” samples

20_GF Mixture 4

Blue Sample - 1									
Freezing Cycles	Parameters	T09- Blue-1 (°C)	T10- Blue-2 (°C)	T11- Blue-3 (°C)	T12- Blue-4 (°C)	T13- Blue-5 (°C)	T14- Blue-6 (°C)	T15- Blue-7 (°C)	T16- Blue-8 (°C)
1st 41.67 hr	Temperature (°C)	-4.38	-0.48	-1.72	-1.91	0.13	0.44	0.50	0.94
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 90.5 hr	Temperature (°C)	-3.93	-0.03	-1.53	-1.96	0.25	0.51	0.73	1.15
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17- Black-1 (°C)	T18- Black-2 (°C)	T19- Black-3 (°C)	T20- Black-4 (°C)	T21- Black-5 (°C)	T22- Black-6 (°C)	T23- Black-7 (°C)	T24- Black-8 (°C)
1st 40.75 hr	Temperature (°C)	-4.13	-1.84	-2.00	-0.76	0.11	1.29	1.06	1.49
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.9167 hr	Temperature (°C)	-3.88	-1.93	-2.15	-0.97	-0.32	1.32	1.19	1.59
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

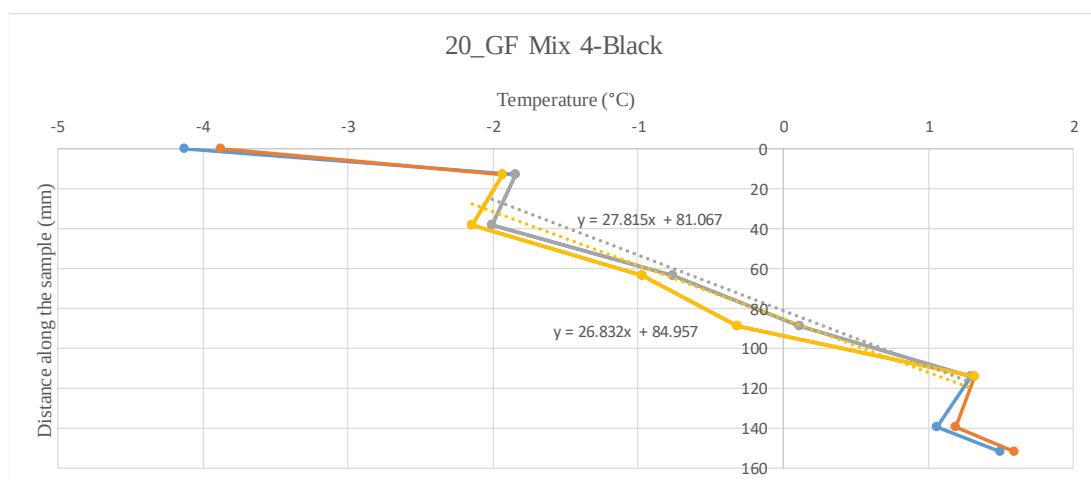
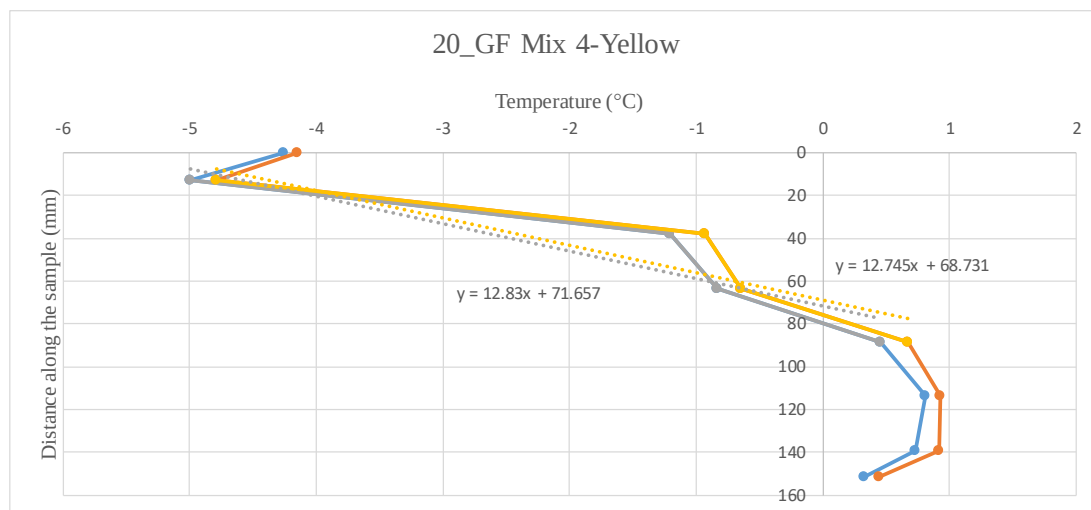


Figure D. 41 Temperature profile for “20_GF Mix 4-Blue & Black” samples

20_GF Mixture 4

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.5 hr	Temperature (°C)	-4.25	-4.99	-1.20	-0.83	0.46	0.81	0.73	0.33
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88 hr	Temperature (°C)	-4.15	-4.78	-0.93	-0.65	0.67	0.93	0.92	0.45
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 41.67 hr	Temperature (°C)	-6.53	-1.37	-0.92	0.36	0.58	1.11	1.43	0.85
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 90.5 hr	Temperature (°C)	-4.71	-0.36	-0.37	0.60	0.85	1.36	1.79	1.00
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

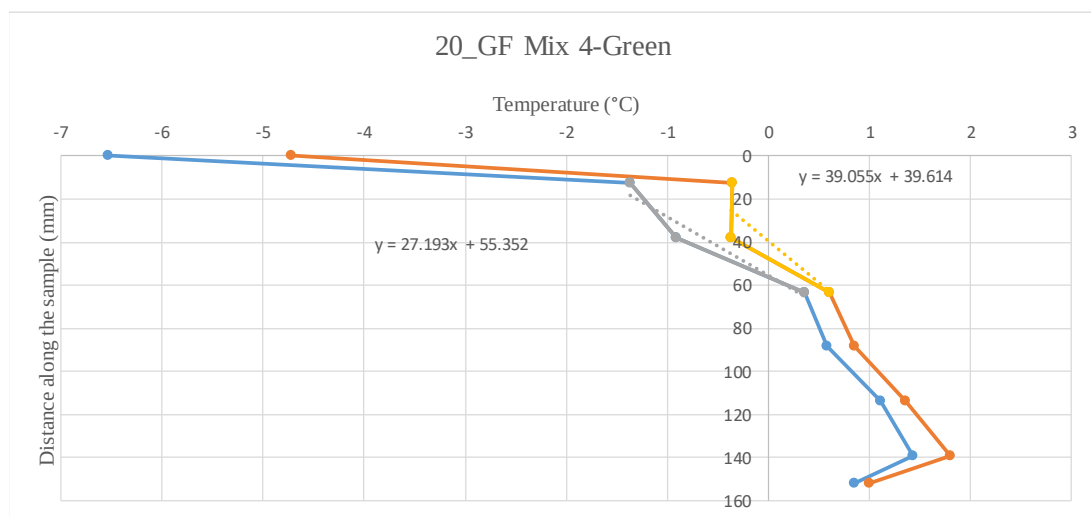
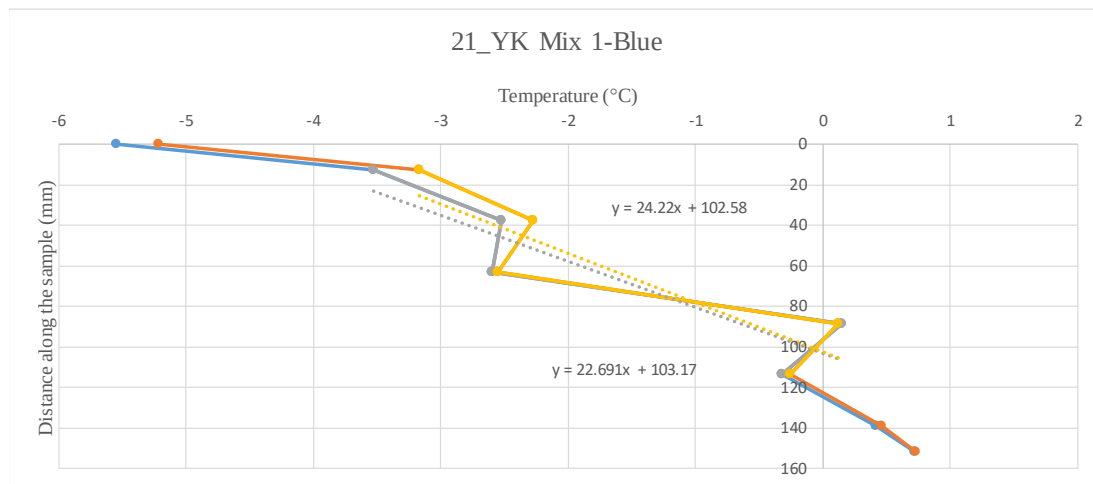


Figure D. 42 Temperature profile for “20_GF Mix 4-Yellow & Green” samples

21_YK Mixture 1

Blue Sample - 1									
Freezing Cycles	Parameters	T09- Blue-1 (°C)	T10- Blue-2 (°C)	T11- Blue-3 (°C)	T12- Blue-4 (°C)	T13- Blue-5 (°C)	T14- Blue-6 (°C)	T15- Blue-7 (°C)	T16- Blue-8 (°C)
1st 40.67 hr	Temperature (°C)	-5.54	-3.52	-2.52	-2.59	0.15	-0.32	0.42	0.72
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.4167 hr	Temperature (°C)	-5.22	-3.17	-2.27	-2.55	0.12	-0.26	0.46	0.73
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17- Black-1 (°C)	T18- Black-2 (°C)	T19- Black-3 (°C)	T20- Black-4 (°C)	T21- Black-5 (°C)	T22- Black-6 (°C)	T23- Black-7 (°C)	T24- Black-8 (°C)
1st 40.4167 hr	Temperature (°C)	-3.90	-2.54	-1.68	-0.63	0.11	1.18	0.99	1.34
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.75 hr	Temperature (°C)	-3.82	-2.55	-1.85	-0.80	-0.03	1.05	0.80	1.10
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

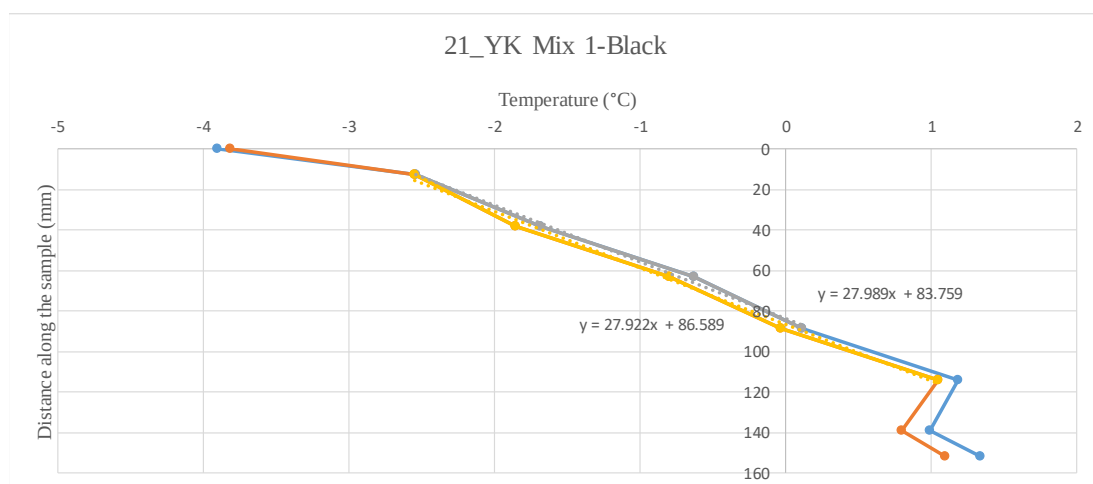
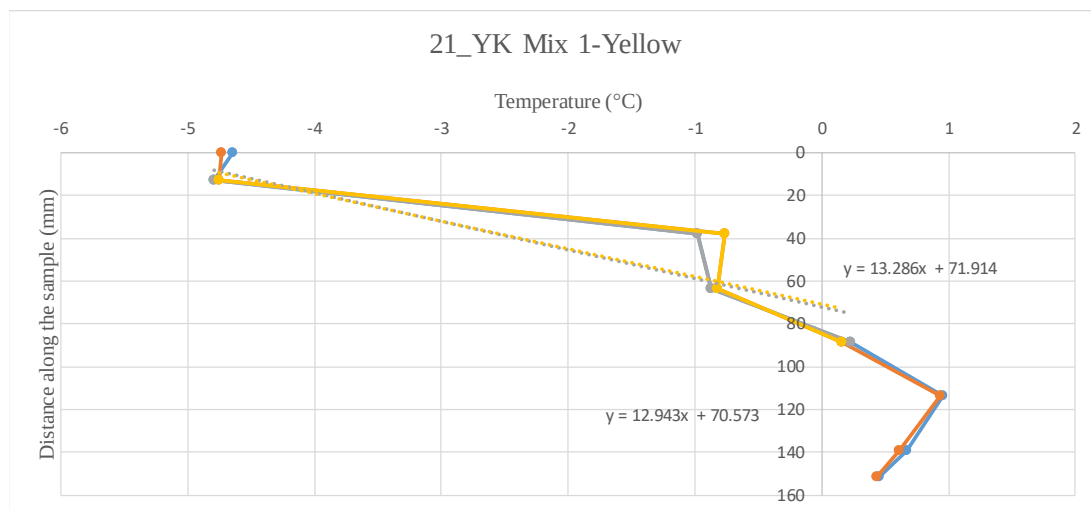


Figure D. 43 Temperature profile for “21_YK Mix 1-Blue & Black” samples

21_YK Mixture 1

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.25 hr	Temperature (°C)	-4.64	-4.79	-0.98	-0.87	0.22	0.96	0.67	0.46
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd F 88.3 hr	Temperature (°C)	-4.73	-4.76	-0.76	-0.82	0.16	0.94	0.61	0.44
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st F 40.83 hr	Temperature (°C)	-6.85	-2.71	-1.36	0.27	0.39	1.25	1.32	1.03
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd F 88.83 hr	Temperature (°C)	-6.83	-2.54	-1.23	0.27	0.33	1.25	1.39	1.00
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

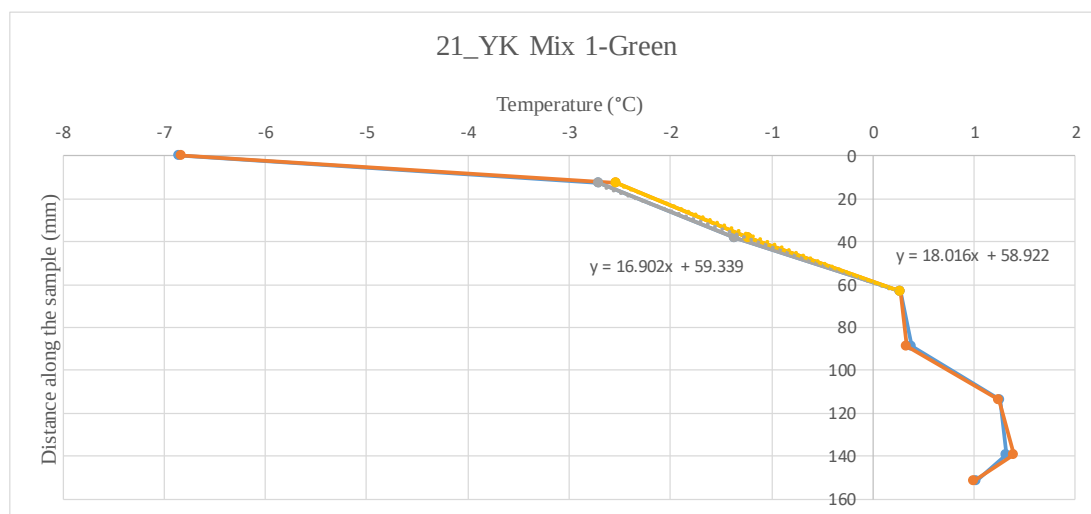
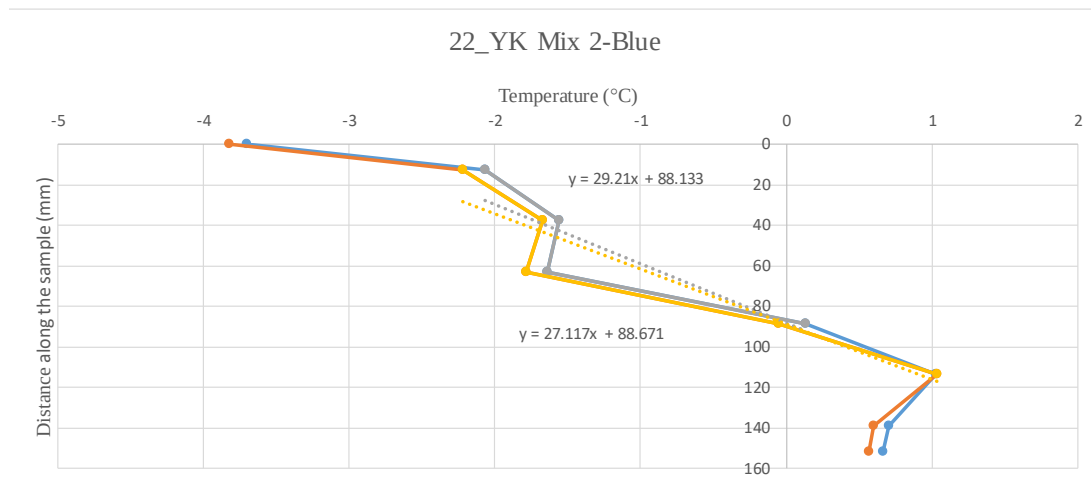


Figure D. 44 Temperature profile for “21_YK Mix 1-Yellow & Green” samples

22_YK Mixture 2

Blue Sample - 1									
Freezing Cycles	Parameters	T09- Blue-1 (°C)	T10- Blue-2 (°C)	T11- Blue-3 (°C)	T12- Blue-4 (°C)	T13- Blue-5 (°C)	T14- Blue-6 (°C)	T15- Blue-7 (°C)	T16- Blue-8 (°C)
1st 40.83 hr	Temperature (°C)	-3.71	-2.07	-1.56	-1.64	0.13	1.03	0.70	0.66
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.9167 hr	Temperature (°C)	-3.82	-2.22	-1.67	-1.78	-0.05	1.04	0.60	0.57
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17- Black-1 (°C)	T18- Black-2 (°C)	T19- Black-3 (°C)	T20- Black-4 (°C)	T21- Black-5 (°C)	T22- Black-6 (°C)	T23- Black-7 (°C)	T24- Black-8 (°C)
1st 40.4167 hr	Temperature (°C)	-4.56	-3.29	-2.14	-1.59	-0.92	0.35	0.56	0.79
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.4167 hr	Temperature (°C)	-4.84	-3.49	-2.38	-1.83	-1.19	0.18	0.28	0.59
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

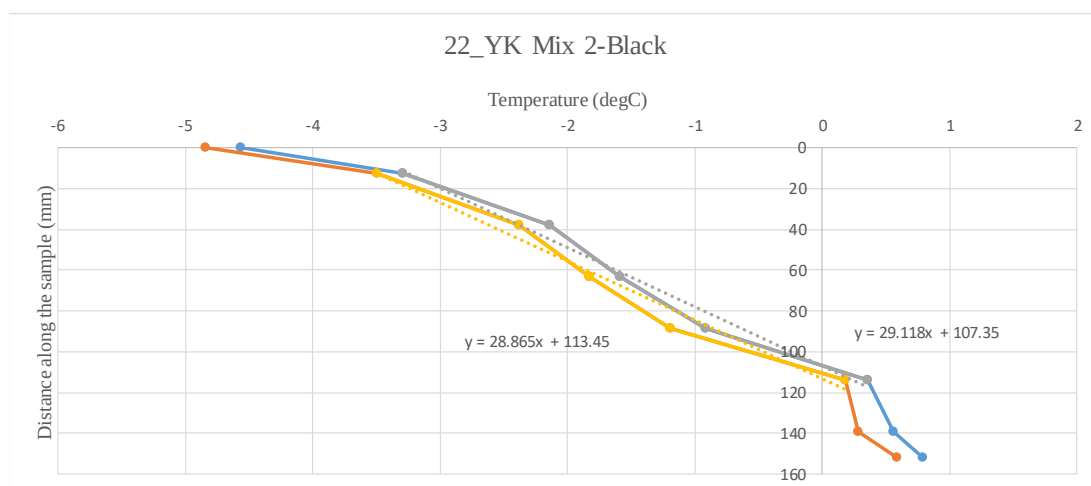
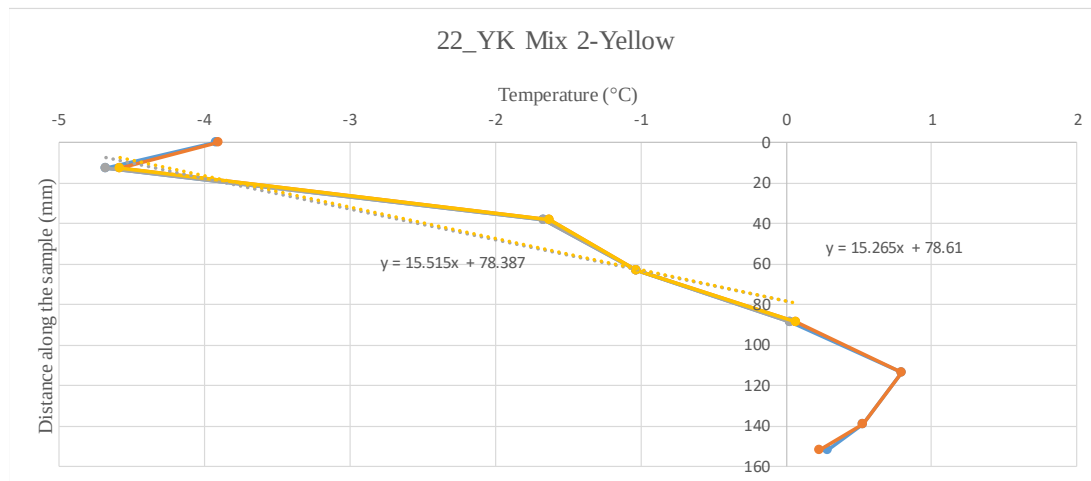


Figure D. 45 Temperature profile for “22_YK Mix 2-Blue & Black” samples

22_YK Mixture 2

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.3 hr	Temperature (°C)	-3.92	-4.68	-1.67	-1.03	0.03	0.79	0.52	0.29
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.5 hr	Temperature (°C)	-3.90	-4.58	-1.63	-1.03	0.07	0.80	0.53	0.23
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 41 hr	Temperature (°C)	-7.10	-2.37	-1.46	-0.18	0.31	1.10	1.17	0.80
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.9167 hr	Temperature (°C)	-7.36	-2.50	-1.62	-0.25	0.21	0.99	1.00	0.72
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

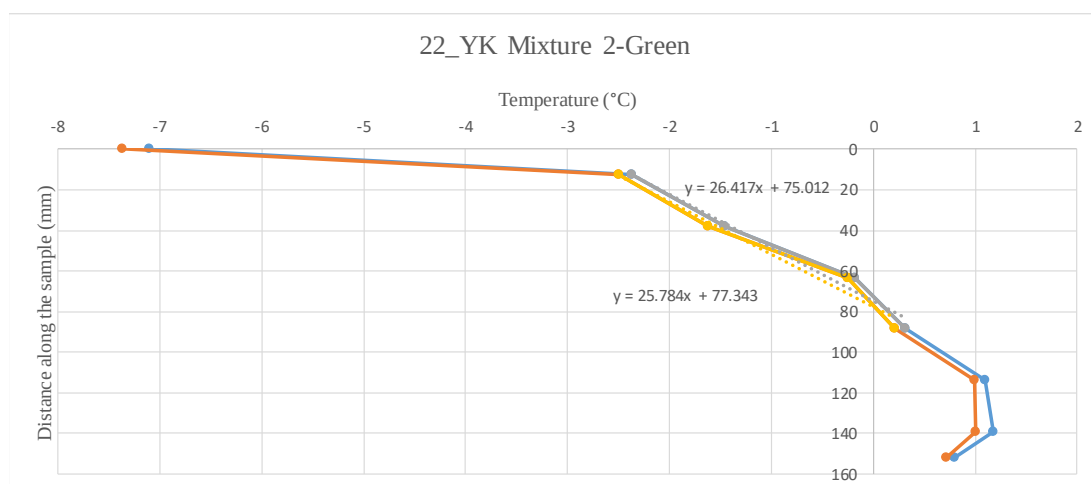
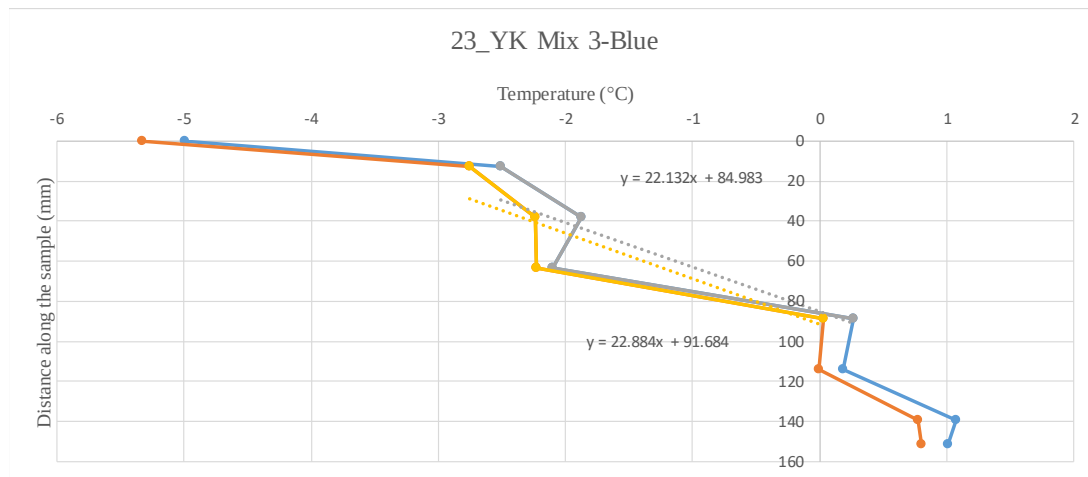


Figure D. 46 Temperature profile for “22_YK Mix 2-Yellow & Green” samples

23_YK Mixture 3

Blue Sample - 1									
Freezing Cycles	Parameters	T09- Blue-1 (°C)	T10- Blue-2 (°C)	T11- Blue-3 (°C)	T12- Blue-4 (°C)	T13- Blue-5 (°C)	T14- Blue-6 (°C)	T15- Blue-7 (°C)	T16- Blue-8 (°C)
1st 40.583 hr	Temperature (°C)	-4.99	-2.51	-1.87	-2.10	0.26	0.18	1.07	1.01
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.67 hr	Temperature (°C)	-5.32	-2.75	-2.23	-2.23	0.03	-0.01	0.77	0.80
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17- Black-1 (°C)	T18- Black-2 (°C)	T19- Black-3 (°C)	T20- Black-4 (°C)	T21- Black-5 (°C)	T22- Black-6 (°C)	T23- Black-7 (°C)	T24- Black-8 (°C)
1st 41.3 hr	Temperature (°C)	1.73	-2.52	-2.86	-2.02	-1.23	0.25	0.60	1.08
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.4167 hr	Temperature (°C)	1.66	-2.41	-2.85	-1.99	-1.23	0.38	0.69	1.26
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

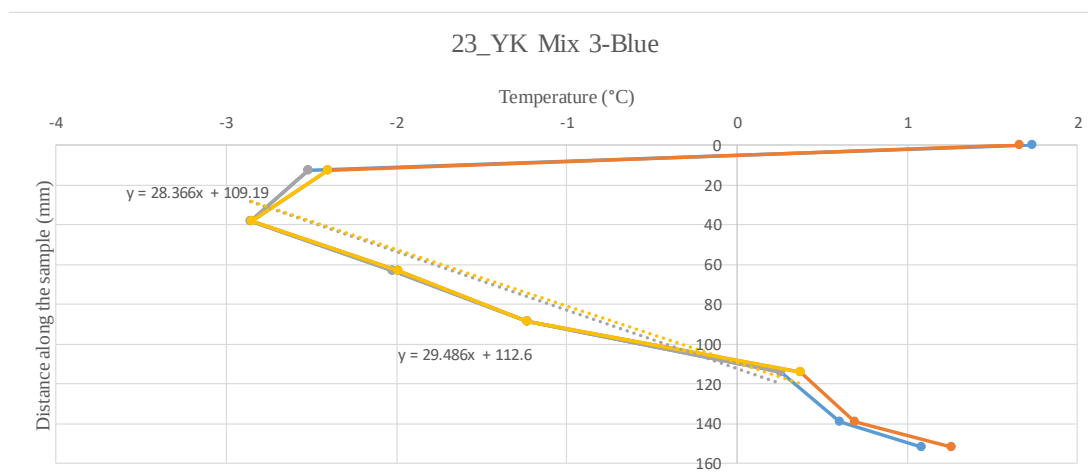
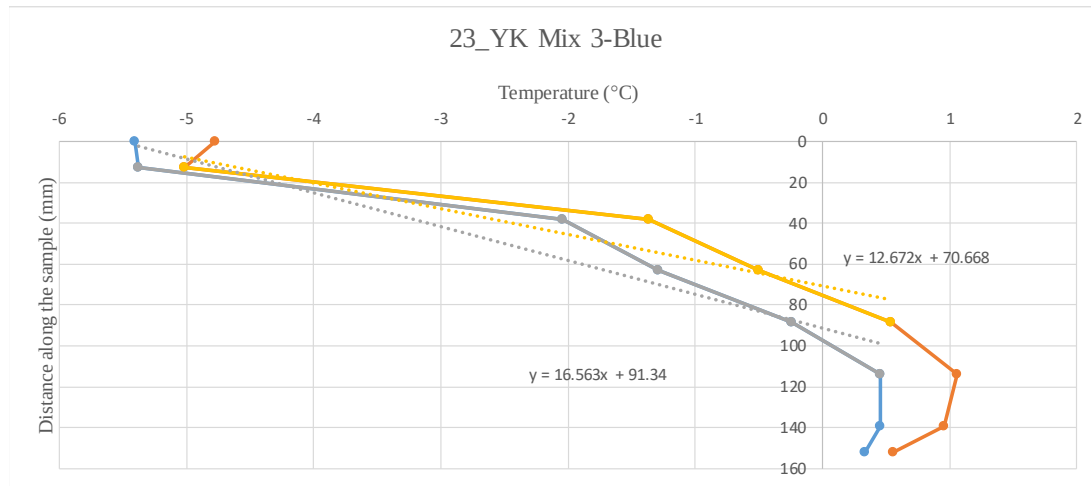


Figure D. 47 Temperature profile for “23_YK Mix 3-Blue & Black” samples

23_YK Mixture 3

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.4167 hr	Temperature (°C)	-5.41	-5.37	-2.05	-1.29	-0.24	0.46	0.45	0.33
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 86.3 hr	Temperature (°C)	-4.78	-5.01	-1.37	-0.50	0.54	1.06	0.96	0.56
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 40.67 hr	Temperature (°C)	-7.01	-3.13	-1.15	-0.22	0.01	1.02	0.90	0.68
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.67 hr	Temperature (°C)	-7.23	-3.22	-1.21	-0.15	0.10	1.11	1.00	0.71
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

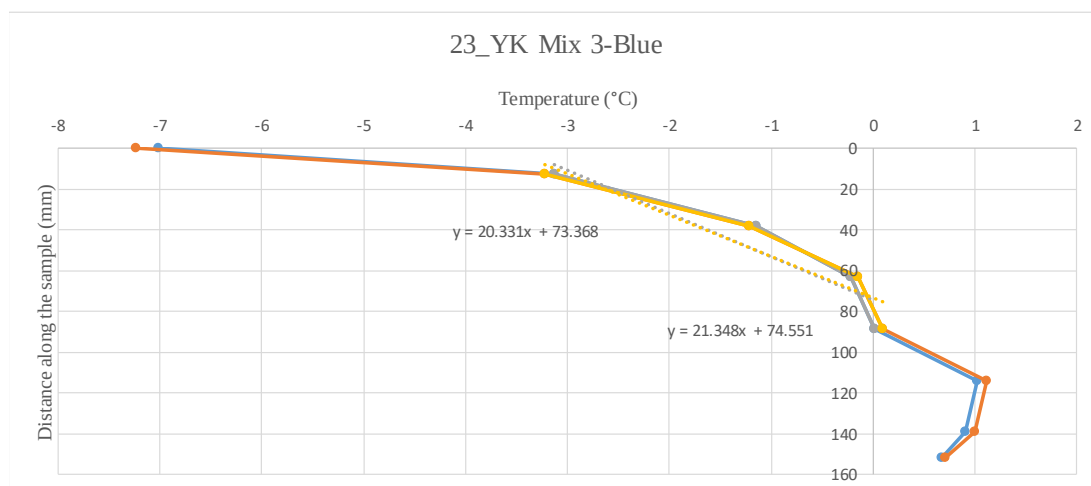
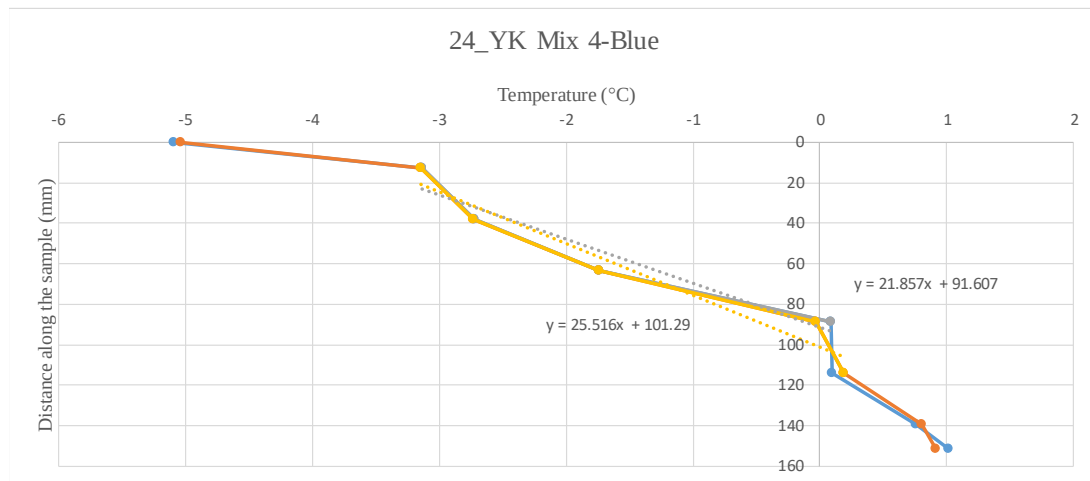


Figure D. 48 Temperature profile for “23_YK Mix 3-Yellow & Green” samples

24_YK Mixture 4

Blue Sample - 1									
Freezing Cycles	Parameters	T09- Blue-1 (°C)	T10- Blue-2 (°C)	T11- Blue-3 (°C)	T12- Blue-4 (°C)	T13- Blue-5 (°C)	T14- Blue-6 (°C)	T15- Blue-7 (°C)	T16- Blue-8 (°C)
1st 40.9167 hr	Temperature (°C)	-5.09	-3.13	-2.72	-1.74	0.08	0.09	0.76	1.01
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.9167 hr	Temperature (°C)	-5.03	-3.15	-2.73	-1.74	-0.03	0.19	0.80	0.91
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Black Sample - 2									
Freezing Cycles	Parameters	T17- Black-1 (°C)	T18- Black-2 (°C)	T19- Black-3 (°C)	T20- Black-4 (°C)	T21- Black-5 (°C)	T22- Black-6 (°C)	T23- Black-7 (°C)	T24- Black-8 (°C)
1st 40.75 hr	Temperature (°C)	-4.55	-3.40	-2.38	-1.48	-0.53	0.31	0.31	0.69
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.83 hr	Temperature (°C)	-4.53	-3.36	-2.42	-1.53	-0.46	0.37	0.36	0.71
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

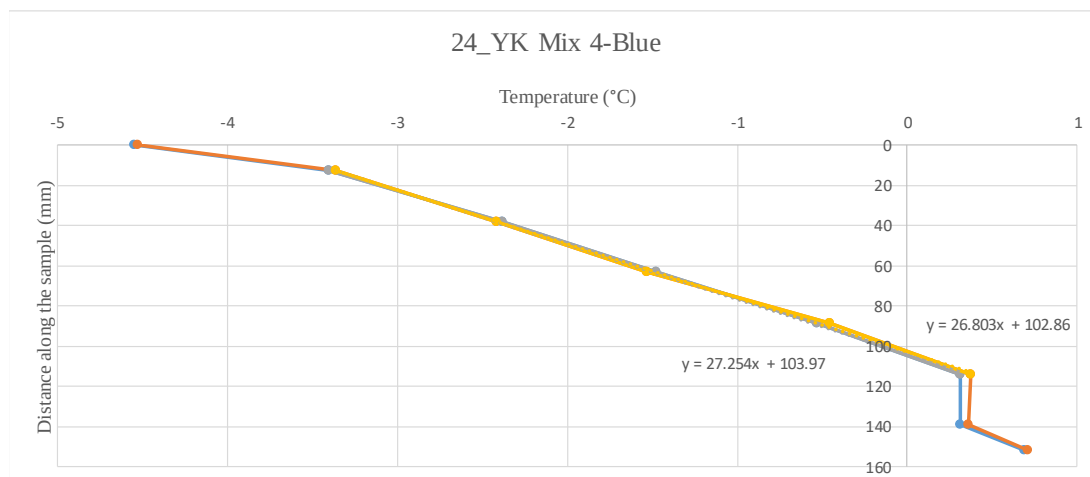
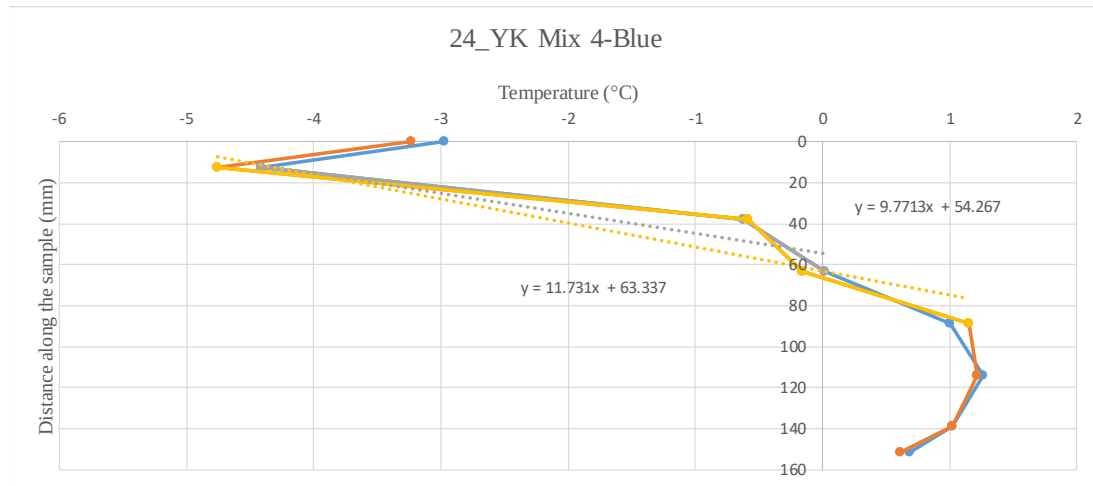


Figure D. 49 Temperature profile for “24_YK Mix 4-Blue & Black” samples

24_YK Mixture 4

Yellow Sample - 3									
Freezing Cycles	Parameters	T01- Yellow- 1 (°C)	T02- Yellow- 2 (°C)	T03- Yellow- 3 (°C)	T04- Yellow- 4 (°C)	T05- Yellow- 5 (°C)	T06- Yellow- 6 (°C)	T07- Yellow- 7 (°C)	T08- Yellow- 8 (°C)
1st 40.583 hr	Temperature (°C)	-2.97	-4.41	-0.62	0.02	1.00	1.26	1.02	0.69
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 88.67 hr	Temperature (°C)	-3.23	-4.75	-0.59	-0.16	1.15	1.21	1.02	0.61
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74



Green Sample - 4									
Freezing Cycles	Parameters	T25- Green-1 (°C)	T26- Green-2 (°C)	T27- Green-3 (°C)	T28- Green-4 (°C)	T29- Green-5 (°C)	T30- Green-6 (°C)	T31- Green-7 (°C)	T32- Green-8 (°C)
1st 40.9167 hr	Temperature (°C)	-7.54	-3.13	-0.99	0.35	0.46	1.48	1.42	1.18
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74
2nd 89.083 hr	Temperature (°C)	-7.50	-3.20	-1.01	0.33	0.50	1.49	1.48	1.20
	Distance (mm)	0.00	12.65	37.94	63.23	88.52	113.81	139.10	151.74

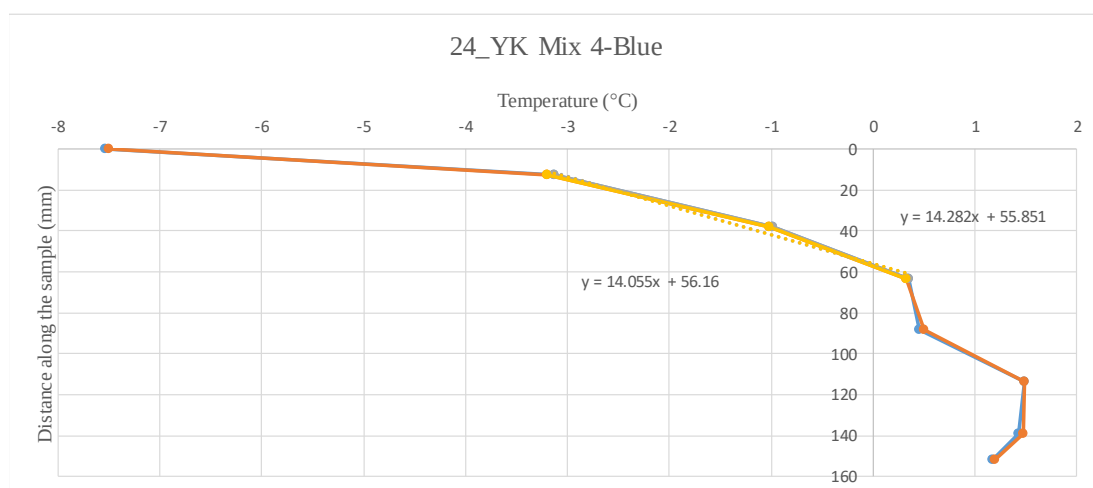


Figure D. 50 Temperature profile for “24_YK Mix 4-Yellow & Green” samples

If the source numbers follow each other, the first and last numbers are written with a hyphen (-). For example, if a paragraph is made from sources 4 to 9, this is shown in the text