DECEMBER 2023 M.Sc. in Civil Engineering İLKER KIYMIK

REPUBLIC OF TÜRKİYE

GAZİANTEP UNIVERSITY

GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

FILTER DESIGN FOR A DISPERSIVE SOIL STABILIZED BY VARIOUS ADDITIVES

M.Sc. THESIS

IN

CIVIL ENGINEERING

BY

İLKER KIYMIK

DECEMBER 2023

FILTER DESIGN FOR A DISPERSIVE SOIL STABILIZED BY VARIOUS ADDITIVES

M.Sc. Thesis

in

Civil Engineering

Gaziantep University

Supervisor

Prof. Dr. Ali Fırat ÇABALAR

by

İlker KIYMIK

December 2023

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

İlker KIYMIK

ABSTRACT

FILTER DESIGN FOR A DISPERSIVE SOIL STABILIZED BY VARIOUS ADDITIVES

KIYMIK, İlker
M.Sc. in Civil Engineering
Supervisor: Prof. Dr. Ali Fırat ÇABALAR
December 2023
152 pages

This thesis presents a series of empirical studies to define dispersibility of a base soil and its stabilization to prevent dispersibility to be able to be used as a filter. A low plastic clay (CL) with intermediate dispersibility was used as a base soil during the experimental studies. An environmentally-friendly biopolymer xanthan gum (XG) and bentonite were separately added to the base soil with the ratios of 0.5, 1, 2, 3 % by dry weight. These specimens were tested at the end of 0, 7, 14, 28 days in the pinhole, crumb and double hydrometer tests. Furthermore, narli sand (NS) and crushed sand stone (CSS) were also used in the permeability tests in order to understand the effect of different particle shape on the filter design. XG and tire waste powder (TWP) at the contents of 0%, 1%, 3% by dry weight were separately added to the NS and CSS samples in order to decrease the permeability values. The specimens were tested at the end of 0, 7, 28, 56 day curing time using the constant head permeability test. Eventually, CL type base soil with intermediate dispersibility was stabilized by using the XG. It was also found that XG and TWP additives decreased the permeability values of the sand samples substantially. XG was found to be strongly effective on the results of both testing series.

Key Words: *Filter Design, Clay, Sand, Additives, Dispersibility.*

ÖZET

ÇEŞİTLİ KATKILARLA STABİLİZE EDİLMİŞ DİSPERSİF ZEMİN İÇİN FİLTRE TASARIMI

KIYMIK, İlker
Yüksek Lisans Tezi, İnşaat Mühendisliği
Danışman: Prof. Dr. Ali Fırat ÇABALAR
Aralık 2023
152 sayfa

Bu tez bir dolgu zeminin dispersifliğini tanımlamak için bir dizi deneysel çalışmaları ve filtre olarak kullanılabilmesi için dispersifliği önlemek üzere iyileştirilmesini sunar. Deneysel çalışmalarda zemin olarak orta derecede dispersifliğe sahip düşük plastik kil (CL) kullanılmış, çevre dostu bir biyopolimer olan ksantan sakızı (XG) ve bentonit temel zeminine kuru ağırlıkça % 0,5, % 1, % 2, % 3 oranlarla ayrı ayrı eklenmiştir. Bu numuneler 0, 7, 14, 28 gün sonunda iğne deliği, kırıntı ve çift hidrometre deneylerinde test edilmiştir. Ayrıca, farklı dane şeklinin filtre tasarımına etkisini anlamak için geçirimlilik testlerinde narlı kumu (NS) ve kırma kum taşı (CSS) da kullanılmıştır. Geçirimlilik değerlerini düşürmek için NS ve CSS numunelerine kuru ağırlıkça %0, %1, %3 içeriklerinde XG ve lastik atığı tozu (TWP) ayrı ayrı ilave edilmiştir. Numuneler 0, 7, 28, 56 gün kürlenmelerinin sonunda sabit seviyeli geçirimlilik testi kullanılarak test edilmiştir. Sonuç olarak, orta derecede dispersifliğe sahip CL tipi zemin toprağı, XG kullanılarak stabilize edilmiştir. Ayrıca XG ve TWP katkılarının kullanılan kum numunelerinin hidrolik iletkenlik değerlerini önemli ölçüde azalttığı tespit edilmiştir. XG'nin her iki test serisinin sonuçları üzerinde güçlü bir şekilde etkili olduğu bulunmuştur.

Anahtar Kelimeler: *Filtre Tasarımı, Kil, Kum, Katkı Malzemeleri, Dispersiflik.*

''Dedicated to my family and loved ones''

ACKNOWLEDGEMENTS

I would like to thank a lot to my supervisor, Prof. Dr. Ali Fırat ÇABALAR for his guidance and support throughout the study. I am thankful for his encouragement and motivation. Last but not least, I am and will be always grateful and honored for him being a "lighthouse" for me and enlighten the right way. It was a delightful pleasure and journey to work with him.

I would like to express my love, respect and gratitude to my father, mother and younger brother with always best wishes and being always there for me with patience and continuous support.

I would also like to give my respect and gratitude to Research Assistant Süleyman Demir for giving me constant help and guidance, encouragement throughout the whole process.

I would like to thank my colleagues, Mr. Ahmet Taşdemir and Mr. M. Emin Yetim, Mr. Aktan Özsoy for their support and guidance, motivation.

Last but not least, I would like to state my gratitude and love to my dear friend Mr. İbrahim Halil Mestanoğlu, for his undeniable support and always being there for me, highly appreciated.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS

c	Cohesion (kPa)
C_c	Compressibility Index
Cc	Coefficient of Curvature
C_s	Swelling Index (%)
C_u	Coefficient of Uniformity
C_v	Coefficient for Consolidation
CL	Clay with Low-Plasticity
D	Dispersive
D1	Highly Dispersive
D2	Dispersive
D_{10}	Mass Size of 10% Finer Than This Value
D_{30}	Mass Size of 30% Finer Than This Value
D_{50}	Mass Size of 50% Finer Than This Value
D_{60}	Mass Size of 60% Finer Than This Value
e	Void Ratio
G_s	Specific Gravity
GP	Poorly Graded Gravel
ϕ	Internal Angle of Friction (°)
LL	Liquid Limit (%)
n	Porosity (%)
ND	Non-Dispersive
ND1	Non-Dispersive
ND2	Non-Dispersive
ND3	Moderately Dispersive
ND4	Moderately Dispersive
PI	Plasticity Index (%)

PL	Plastic Limit (%)
q	Discharge Volume Per Second (mL/sec)
R	Roundness
Rd	Relative Density
S	Sphericity
SD	Slightly Dispersive
Wc	Water Content (%)

LIST OF ABBREVIATIONS

ALM	Accumulated Loss of Mass
ASTM	American Society for Testing and Materials
BOFS	Basic Oxygen Furnace Slag
BS	Base Soil
B. V	Barely Visible
CBR	California Bearing Ratio
C. C	Completely Clear
CEC	Cation Exchange Capacity
CSD	Constriction Size Distribution
D	Dark
ELT	End-of-Life Tires
ESP	Exchangeable Sodium Percentage
FA	Fly Ash
FC	Fine Content
GBFS	Granulated Blast Furnace Slag
HET	Hole Erosion Test
MDD	Maximum Dry Density (kg/m^3)
MIP	Mercury Injection Porosity
NEF	No-Erosion Filter Test
NS	Narli Sand
OMC	Optimum Moisture Content (%)
OPC	Ordinary Portland Cement
PVA	Polyvinyl Alcohol
RSM	Rubber-Soil Mixture
SAR	Sodium Adsorption Rate
SEM	Scanning Electron Microscopy
TDS	Total Dissolved Solid
TGA	Thermogravimetric Analysis

TOC	Total Organic Carbon
TWP	Tire Waste Powder
UCS	Unconfined Compression Strength
USCS	Unified Soil Classification System
V	Visible
XG	Xanthan Gum
XRF	X-Ray Florescence
XRD	X-Ray Diffraction

CHAPTER 1
INTRODUCTION

1.1 General

In the long span of human life, the demand for accommodation and settlement sustains importance for ages. Even in the first settlement tries in the history was seen near the vicinity of water sources for various reasons. Agricultural, irrigation, sewerage are some of the reasons to comes to mind initially. For these basic reasons, people tried to save the water for the aim of using it throughout the whole year. Fluctuations in the temperature, precipitation and other natural reasons forced human being to construct water storage systems to benefit all year long.

Dams, embankments and many more water storage and irrigation systems were constructed even before 2000 B.C. Yet, these structures need perfect harmony between soil and water to be feasible and service properly (Richards and Reddy, 2007; Talukdar and Dey, 2019). Furthermore, with the limited knowledge and opportunities people struggled especially in the first trials. Moreover, as the failures happened people collected feedbacks and with the help of improving technology, better and safer constructions have been built. Major and minor parameters caused the failures in those days, are well-examined and documented with help of researchers and scientists.

With the progressive knowledge, it can be said that one of the reasons for failures in those days was imbalanced ratio and properties of the soil and water combinations which means filter design criteria (Flores-Berrones et al., 2011; Caldeira, 2019). These filters must be designed so that they should be coarse enough to pass away the water but fine enough to prevent any dissipation of the fine soils. Any careless situation in these systems, may clog the filter or let the soil move away which can be result in breaching of the structure (Coduto et al., 2011). Dedicated and precise systems have been offered by the researchers and scientists in the history of filters.

First filter designing started with the particle size distribution (PSD) ratio from the Terzaghi (in 1920s) and followed by other theories like constriction size distribution (CSD) theory of the Indraratna or modelling of the governing soil and matrix by several researchers (Raut and Indraratna, 2008; Indraratna et al., 2008).

Another mistake that seen back then and right now, is the problematic soils that may complicate the situations in building and service span of the structure. These types of soils generally risky to build on so that in most cases, these soils are removed from the construction area or they may stabilize with several contributors (e.g., chemical, biological and/or waste, by-product additives). These types of soils may be expansive, dispersive, gap-graded or they may lack of enough stability or strength to be capable of facilitate feasibility. Dispersive soils consist of very small clay particles that can be transferred in the water flow inside a soil matrix. When they are unsaturated, they have high dry density and low permeability but when they are saturated all this positive sides becomes unreliable. It may be caused by several reasons like clay minerology, clay cation type and strength, pore water minerology and etc. For these reasons, mitigating the use of these soils or stabilizing it have great importance (Vakili and Selamat, 2018).

Stabilizing the problematic soils especially dispersive ones can be done by multiple methods like using conventional additives or geotextiles/geomembranes or biological ways etc. Most of the additives or materials that are used for stabilization, have advantages and also disadvantages for number of reasons. Most of the conventional ways like fly ash (FA), cement or lime gives great strength to soils but their production processes also harm the nature by producing CO_2 which affects the greenhouse effect. Unconventional ways like biologically induced materials or precipitations, geotextiles/geomembranes etc. have similar advantages like conventional ways but their downsides are limited or none compared to conventional ways so that most of them are considered as environmentally friendly and even some of them facilitate the forestation of the greens. Being effective even with the low dosages and being costly reasonable helps the use them in a short and long term rather than conventional methods (Chang et al., 2016).

Even when the fine soil is stabilized sufficiently and properly adjusted to filter design criteria, it does not guarantee a sustainable system to run, also coarse soil inside the appliable filter zone must be selected well to balance the system. So that, even identical soils by means of PSD and mass size of 10% finer than this value (D_{10}), mass size of 30% finer than this value (D_{30}), mass size of 50% finer than this value (D_{50}), mass size of 60% finer than this value (D_{60}) parameters, may behave varied from each other inside a filter layer. These behaviors can be attributed to particle shape and characteristics (Cabalar and Akbulut, 2016a, b).

Therefore, a proper design of a stabilized problematic soil - filter design combination must contain rigorous designs of fine and coarse materials and stabilization of problematic soil with great concentration and dedication.

1.2 Aim and Significance of the Study

The main purpose of this study was examining the stabilization of a dispersive soil with additives like solely xanthan gum (XG) and solely bentonite with 0.5, 1, 2, 3 % by respective dry weights. Specimens of this combinations were tested in pinhole test, crumb test and double hydrometer test after 0, 7, 14, 28 days. After that, filter design criteria for stabilized dispersive soil were investigated. Moreover, to use in the appliable filtering zone, two types of sands (i.e., narli sand (NS) and crushed sand stone (CSS)) which have different particle shapes and characteristics were selected. Their selection was for the aim of identifying the effect of particle shape on the permeability of the soil matrix in the appliable filter zone. For this reason, these two types of sands were mixed with solely tire waste powder (TWP) and solely XG with 0, 1, 3 % by their respective weights. These combinations were tested in constant head permeability test after 0, 7, 28, 56 days. By this way, effects of the solely sands and solely mixtures can be defined substantially.

1.3 Outline of the Study

This study contains 6 chapters in which Chapter 1 it gives general aims and directions to fulfill the knowledge and it reflects significance of the study. In Chapter 2, general knowledge and past studies about the topic is shown. In Chapter 3, materials that were used is given with their properties and also experiments that conducted is shown with their regarding standards and methods. In Chapter 4, consequences of the experiments are shown. In Chapter 5, discussions and critics of the results of the tests are made in this study with respect to the past studies in this topic and general critical points are given in the conclusion. In Chapter 6, major conclusions of the study were given. In Chapter 7, general suggestions, directions for further studies are given for academical purposes.

CHAPTER 2
LITERATURE REVIEW

2.1 Dispersibility and Filter Designing

Problematic soils (e.g., dispersive, gap-graded, expansive etc.) may cause difficult situations if care is not taken. Identification of these problematic soils and taking precautions about them, have great importance to fulfill the strength, stability and sustainability expectations of the system. In case of using problematic soils, initial solution generally contains exchanging the problematic soil with a safe soil. This solution may be described as the easiest solution and also may be the cheapest one. But if this option is not available then other solution types are investigated. Filters and/or geotextiles/geomembranes are also some of the solutions to consider. Filters that are well-adjusted, fits greatly to the systems (e.g., dams, reservoirs, drainage systems, irrigation and sewerage channels etc.) and they are feasible to use in short and long terms. Especially, graded soil filtering systems are economical and also sustainable systems to conduct. Whereas conducting this system requires precise judgement and knowledge to satisfy the conditions of the system.

Lone et al. (2005) stated that, most of the previous studies gave interests about the cohesive soils but in their study, they gave effort for the cohesionless soil and created a filter design criterion for a cohesionless soil. Their effort created an empirical formula for filter design and this formula also approved by their empirical study and they found out that filter design is not only about respective ratios of gradation but also coefficient of uniformity (C_u) and packing type is also effective to preparation of the filter. This idea and formula were also approved with the experimental study with wide variety of soil types. They showed that accuracy and efficiency of the filter system depends on minimum constriction size of the particle matrix that consist the filtration layer. Their experimental stage was designed just like in real field conditions and trial of the system was satisfactory so that even in the high hydraulic gradient scenarios they observed limited washout of the base soil particles. They stated that all the process in the filter was rapid so that it took only four hours to conclude the experimental stage. After the four hours, it was non-significant and negligible to continue the tests. They showed that soils that have the same D_{15} size, might not show similarities whereas they might show differences at all. They also approved the importance of the d_{85} of the base soil gradation. Constrictions in the soil matrix is demonstrated in Figure 2.1. Instance filter design criteria was shown in Table 2.1.

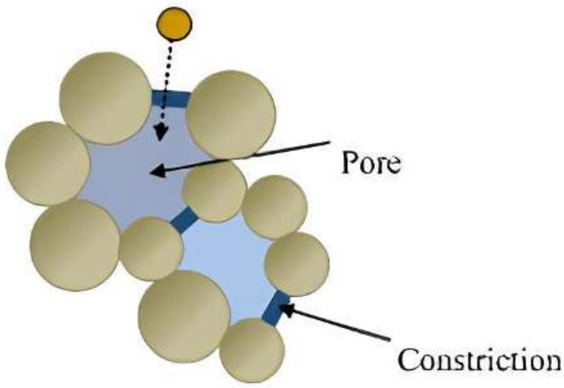


Figure 2.1 Demonstration of constrictions in the soil matrix (Seblany et al., 2021)

Table 2.1 A filter design criteria from Indraratna and Locke in 1999 (Rearranged after Indraratna et al., 2008)

	Base Soil Category	Base Soil Passing No.200 (Reduced*)	Filter Criterion
I.	Fine silt or clay	>85	$\frac{D_{15}}{d_{85R}} \leq 9$
II.	Sandy silt/clays and silty/clayey sands	40-85	D15 ≤ 0.7mm
III.	Sands, sandy gravels with few fines	<15 and $\frac{d_{95R}}{d_{75R}} \leq 7$	$\frac{D_{15}}{d_{85R}} \leq \left[5 - 0.5\left(\frac{d_{95R}}{d_{75R}}\right)\right]$
IV.	Soils intermediate between previous two categories	5-39	Extrapolate between the two previous values based on passing % of No.200

* Portion passed No.40

Indraratna and Raut (2006) introduced an enhanced criterion for retention in filters so that previous acknowledged theory of gradation ratios was disadvantages for some soil types and systems. For this reason, they aimed to get a new enhanced criteria that do not have any disadvantages especially for these soil types and systems. After the numerous studies and experiments, they offered a study based on CSD and retention of it. They satisfied this theory with regarding empirical studies and showed criteria of the Terzaghi was satisfactory with cohesionless uniform soils but on the other hand even it is appliable according to the criteria numerically, well-graded soils and gap-graded soils showed problematic behaviors. These results showed the need for better and also safer filtering systems.

Another deficient point of the theory of Terzaghi was, he expected to observe similar behaviors from the soils that have same D_{15} values but in reality, they might not behave like one all the time. This expectation was also erroneous for some base soils that have the identical d_{85} value. Moreover, they also detected that Terzaghi did not consider the effect of clogging possibility especially for long term.

They showed that real relative density of the filter and relative compaction also matters for the sake of efficiency of the filtering system. These features affect the constriction size in the soil matrix. With the progression of the study, they observed that relative density (Rd), CSD and C_u significantly affects the filtering system. They introduced a term like “self-healing” which describes the situation of, as the soil is transported with the effect of seepage forces, coarser base soil particles moves away and they stuck in the filter. With the progression of the retention of coarser particles, a layer of “cake” is created on the face of the filter so permeability is decreased. Factors that affect the permeability of the filter are porosity of the base soil and “cake” on top of the filter.

In their study, they formed CSD based on d_{c95} which stands for constriction size of the base soil which is finer than 95% by mass. They selected 95 % as 5% remaining generally consist of coarsest particles that have no effect on filter especially on well-graded soil types.

An advantage of the CSD theory over PSD theory was exchanging “ratio by mass” to “ratio by surface area”. They claimed that as they select “by mass” it would be overestimation of the coarser particles even they are fewer by quantity. On the other hand, they neither selected the "by quantity" so that in this case it would be overestimation of the finer particles even they are fewer by mass. Moreover, they selected "by surface area" as a common parameter to satisfy both conditions. CSD was offered as loosest state and densest state but optimum state was suggested. This suggestion included Rd and fine content (FC).

This theory also approved by empirical studies so that it gave realistic and also reasonable results when compared to other previous theories. Internal stability of the filtering systems was also considered in this study. Another important point of the study was, it showed that if the number of fine materials are more than the optimum value, it harms the system and reduce the efficiency. Constriction sizes in soil and filter systems are represented in Figure 2.2 and 2.3 respectively.

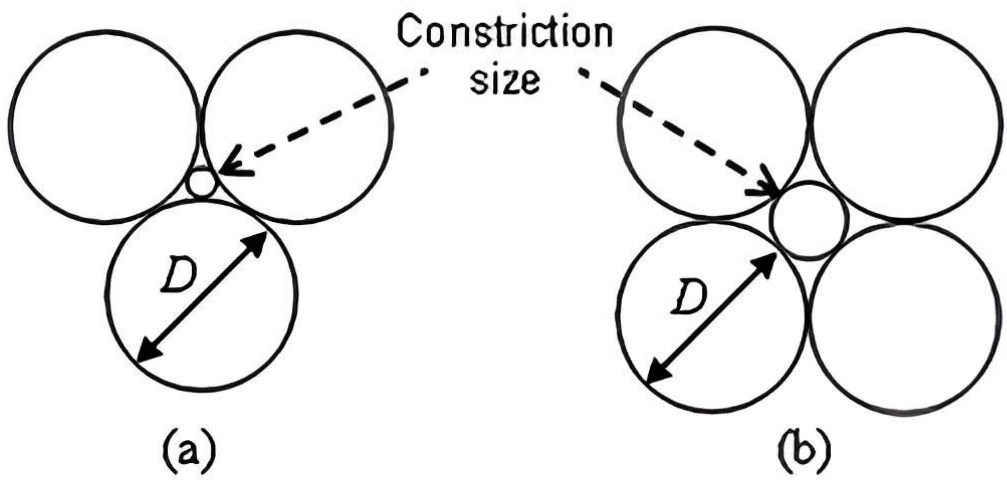


Figure 2.2 Constriction size forms in soil matrix (a) densest form (b) loosest form (Indraratna et al., 2008)

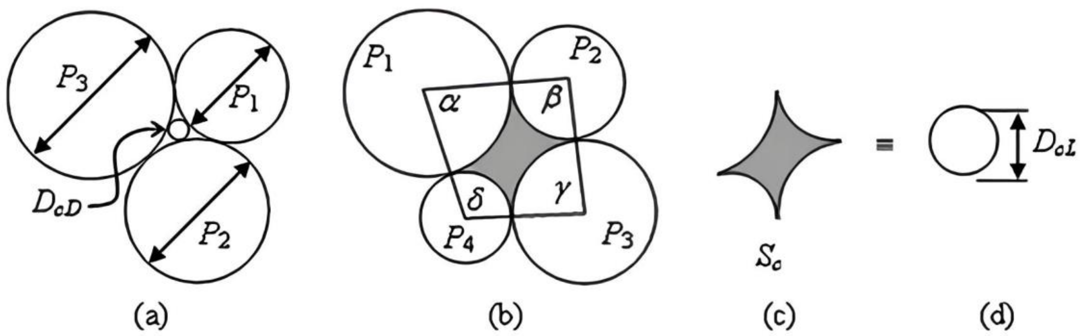


Figure 2.3 Constriction size forms in filter layer (a) densest form (b) loosest form (c) constriction area (d) equivalent size for constriction area (Indraratna et al., 2008)

Kakuturu and Reddi (2006a) investigated the seepage and leakage from the cracks and fissures occurred in earth dams and embankments. They showed that there are two types of cracks about the earth dam, one consists of central crack that reached up to downstream side, other one is "complementary" and generally contains and reaches all the cross-sectional area of the dam.

They conducted empirical studies to test the theory of PSD ratios by creating artificial cracks inside the soil strata and sustaining flow inside them. From the results of the experimental stage, it was stated that criteria and experiments are varied from each other as criteria labels one as safe but it fails in the experiment or vice versa. So, it showed the incapabilities of the theory that had proposed. Soils in the experiments were cohesionless and they had varied d_{85} values. They stated that erosion of the cohesive soils would be time-dependent and depended on some parameters like critical shear capacity, erosion interface, velocity of the fluid flow, permeabilities of the base soil and filtering layer, effective opening sizes and critical hydraulic gradient value. They expressed that to measure the efficiency of the filtering system and "tendency" for internal erosion can be calculated from no-erosion filter (NEF).

Consequently, cracks can be occurred because of differential settlement, seismic activities or varied hydraulic pressures in the soil strata. They offered that progressively erosion or self-healing can be detectable from the discharge of the flow per time and concentration of the effluent. As an instance, breaching of the Tous Dam is shown in Figure 2.4.

Figure 2.4 Breaching of the Tous Dam (Talukdar and Dey, 2019)

Minguez et al. (2006) investigated reliability of the filters by means of numerical and analytical studies. The main aim of their study was identifying the reliability of the filtering system even if filtering system completely satisfy the conditions of design criteria. They tested “risk potential” and “fail possibilities” and describing the most dominant factor to cause that. They stated that identifying this factor helps by means of economic and time management. They expressed that every scenario is unique and can have varied dominant factors specifically.

These investigations can also be used for existing structures like dams and embankments. This concept was tested on two different case and the results were reasonable. They examined two varied failure cases also and they saw that regarding failures were caused of inappropriate retention criteria and/or “homogeneity” which resulted in erosion etc. It was stated that even the system was successful in this soil/filter combination, it can be insufficient for some combinations for this reason a concept like this can be beneficial for risk management. They expressed “In case of cracking and erosion, if the filter is capable of retaining the eroded particles, then the crack will seal and the dam safety will be ensured". This concept also measures the safety of the structures so that any urgent action can be taken. They noted that this concept can be promising to measure the risk and taking precautions about them.

Kakuturu and Reddi (2006b) examined the concept of "self-healing" and how it affects the filtering system. They modeled two filtering systems based on varied self-healing types and investigated the outcomes of these systems. From the outcomes of the study, it can be said that some critical parameters exist to identify self-healing on filtering layer. These parameters can be defined as critical seepage velocity, flow length and width of the passage, dissipated particle size, conductivities of the base soil and filtering layer, geometrical characteristics of the cracks. As velocity of the flowing fluid (i.e., water) exceeds the limiting value, it can create erosion and seepage. Particle size of the dissipated soil was also described as critical because as the particle size increase, clogging or topping of the filter becomes quicker and more effective. Initiation of the erosion is harmful in one way but on the other way it is also has some upsides so that if a system has filters, erosion creates "cake" on it and reduces the discharge and limits the erosion which also triggers "self-healing". Furthermore, researchers also advised to conduct full scale test with other combinations of filter designs to establish a general knowledge. Parameters affecting the" self-healing" process was shown in Table 2.2.

Table 2.2 Parameters affecting the "self-healing" phenomena (Rearranged after Kakuturu and Reddi, 2006b)

Group	Parameter	Method of Evaluation
Base Soil Characteristics	Permeability	Falling Head Permeability Test
	Critical Hydraulic gradient	Described in that study
	Coefficient of progressive piping	Described in that study
	Critical shear stress	Explained in that study
	Mass rate of erodibility	Explained in that study
	Size distribution of eroded particles	Sedimentation Analysis
Plug Characteristics	Density	Described in that study
	Permeability	Described in that study
Filter Characteristics	Permeability	Constant Head Permeability Test
	Pore size distribution	Explained in that study
	Critical seepage velocity	Described in that study
Geometrical Parameters	Lengths of intact core and core crack	Cross-Sectional Dimensions of the earth dam
	Length of filter	
	Hydraulic head	

Indraratna et al. (2007) stated that granular filter design process started nearly in 1920s with engineering judgement and experience of the conductors and/or engineers. As the time reach the 1950s, theory of PSD with respective ratios had been using conservatively but this theory was only valid on cohesionless uniform soils. They discovered that this theory was insufficient when they face with any problematic soils (e.g., dispersive, expansive, gap-graded etc.) or they have to work with broadly graded soils. As the times goes on, they founded that especially in case of broadly graded soils, using coarse part (i.e., greater than No.4 in sieve size) was unnecessary and negligible so they rearranged the system. This system made the soil more uniform. In this study, they found that filtering of the soil depends more on restriction sizes between individual soil particles rather than the particles sizes itself. CSD created based on constriction sizes, depends on D_{c35} instead of D_{15} which stands for constriction sizes finer than 35% and d_{85SA} instead of d_{85} which also stands for constriction sizes finer than 85% by surface area. They observed that this concept was working satisfactorily.

In the empirical stage, they conducted combinations in both filter and base soil types (e.g., uniform soil and well-graded filter or vice versa or uniform soil and uniform filter or well-graded soil and well-graded filter). From the outcomes they stated that literature point was insufficient but empirical stage was satisfactory. However, they did not point on clogging of the filter systems in short or long term. They suggested to use CSD based theory instead of PSD based theory to fully investigate the filter by means of “soil geography” and geometry of the soil. By using CSD based theory, parameters like Rd and C_u, compaction characteristics can have significant effect on soil. They also gave advices for filter thickness and stability. All these processes and experiments were done on cohesionless soil. Filter-soil interface of a filtration system was shown in Figure 2.5.

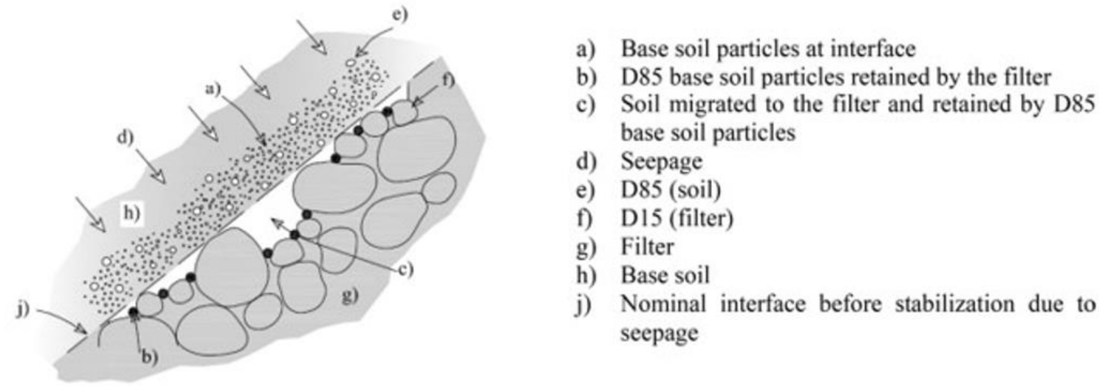


Figure 2.5 Filter-soil interface (Caldeira, 2019)

Sivakumar and Srivastava (2007) examined the PSD based theory for filtering criteria and saw that Rd and porosity of the base soil and filter matters for efficiency and sustainability of the system. They suggested to use both analytical and empirical methods for the sake of concept feasibility. They also agreed to the idea of regraded particle sizes so that materials greater than No.4 sieve size (i.e., 4.75 mm) must be regraded and added to the calculations to create more uniform and stable system to consider. They also stressed that previous studies about this topic never fully expressed the effects of Atterberg limits and cohesion factors. It is also mentioned that C_u of the filtering system affects the sustainability of it. They pointed that “soil-boiling” is also an important incident to consider when system works. It was stated that coarse particles are more dominantly affects the sake of the filter by creating self-healing. Self-healing process are more precisely defined by coarser particles rather than finer particles. Also, relationship between D_{15} and permeability value k was defined and it was shown that D_{15f} and d_{85b} are numerically related with each other. They offered a numerical relationship to avoid creating a gap-graded soil and this study was also shown analytically. At last, it was identified that sustainability of the filtering system also affected by permeabilities of the both the base soil and filtering layers. As instance, different filter design criteria are presented in Figure 2.6, Table 2.3 and Table 2.4.

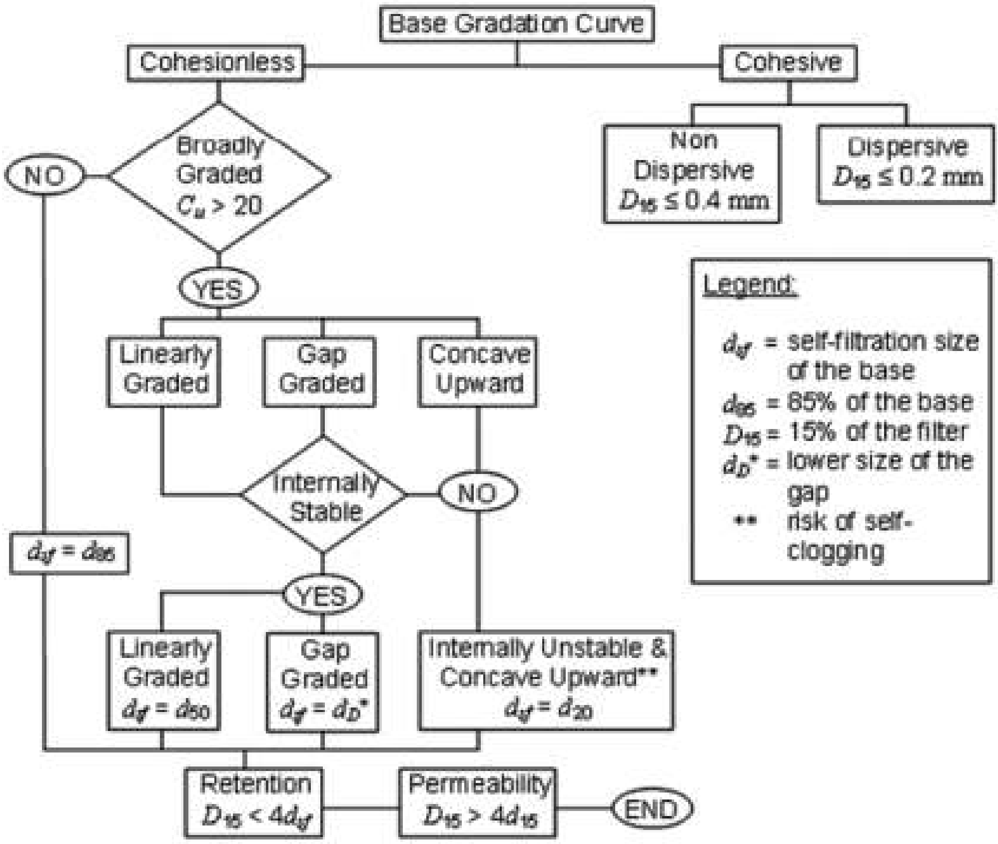


Figure 2.6 Filter design criteria from Lafleur (Indraratna et al., 2008)

Table 2.3 Filter design criteria from Sherard and Dunnigan (Rearranged after Vakili and Selamat, 2014)

Fines content of base soil (%)	Designation for base soil	Filter design criteria	Case
≥85	Group 1	$D_{15f}/d_{85} \le 9$	I
40-85	Group 2	$D_{15f} \le 0.7\text{mm}$	II
<15	Group 3	$D_{15f} \le 4d_{85}$	III
15-40	Group 4	$D_{15f} \le \left\{\left[40-(pp\% < 0.075mm)\right]\left[\frac{(4d_{85}-0.7)}{25}\right]\right\} + 0.7$	IV

Table 2.4 Filter design criteria from NRCS (Sivakumar and Srivastava, 2007)

Base soil				
Category	Description	Percent finer than No. 200 sieve (0.075 mm) after regrading, where applicable	Filtering criteria ($(D_{15f})_{max}$)	Permeability criterion ($(D_{15f})_{min}$)
1	Fine silts and clays	>85	≤9 mm but not less than 0.2 mm	For all categories, $\geq 4D_{15b}$ before regrading, but not less than 0.1 mm
2	Sands, silts, clays, and silty and clayey sands	40–85	≤0.7 mm	
3	Silty and clayey sands and gravel	15–39	$\leq \left(\frac{40-A}{40-15}\right)[(4 \times D_{85b} - 0.7\,\text{mm})] + 0.7\,\text{mm}$, where A is percent passing No. 200 sieve after regrading (if $4D_{85b} < 0.7$ mm, use 0.7 mm)	
4	Sands and gravel	<15	$\leq 4D_{85b}$ after regrading	

Richards and Reddy (2007) explained the concepts of piping and internal erosion occurred in earth dams or embankments. It was shown that terms like suffusion, heave, tunneling, internal erosion, piping are used for each other and because of this complicated using and creating a confusion about these terms, knowledge about these phenomena can be misdirected. Piping was expressed as outflow/effluent caused by concentrated leakage processed in spaces between own individual particles of the soil and internal erosion was defined as flowing away the water inside cracks and fissures in the soil matrix. These differences were not detected as the first dams were constructed in BC. 2000 but with the progression of knowledge and experience from the field, these terms were defined only in 20th century. Also, with the help of statistical science and observations erroneous applications or knowledge were detected. Especially, efforts from the Terzaghi in early 1920s helped the progression of the knowledge and experience so that these studies identified the deficiency of this system. They used these evolved ideas to solve the problems about cohesive soils and/or dispersive ones. As the dispersibility concept first defined in Australia, other countries predominantly USA gave effort theoretically and empirically to mitigate this kind of problems.

Fernando (2010) studied the effect of water quality on dispersibility and detected substantial changes as the dispersibility characteristics can change with the water quality such that a dispersive soil can be recognizable as non-dispersive depending on the water properties. It was stated that Na^+ percentage inside the pore water or surrounding soil can decide the behavior. They also expressed total dissolved solid

(TDS) percentage can also have influential effect on dispersibility behavior. As it was examined in experiments, identical conditions with only one change (i.e., water quality) could result in varied behaviors. They gave an instance about the embankment built on a local river and this embankment have never faced any trouble by means of erosion with the help of high TDS level. They identified a critical value for TDS of 105 µg/L per 25-50 µg Na^+ concentration of soil or pore water. The lower the Na^+ concentration, the lower need for TDS to make the soil stable. Yet, upper constraining value was not determined in this study. As the TDS increase, they observed smaller number of dispersive behaviors in the study. It was seen that as the Na^+ percentage increase inside the clay minerology, dispersive behavior of that soil also increases which means they observed that montmorillonite type of clay had shown more dispersive characteristic than illite type of clay. Illite type of clay also shown more dispersive characteristic than kaolinite type of clay. As they are small by mass, they are also prone to eroding. They are affected by electrochemical of the surroundings and double layer of the clay. These types of soils showed dispersive behaviors in lower cationic waters like rainwater or distilled waters.

Fannin (2008) investigated the importance of Karl Terzaghi for filter design. Even his profession for bachelor was not in civil engineering, his dedication and ambitions helped him to examined the surrounding and observing nature. With his skills and self-trust, he investigated soil retention processes and seepage and pathways. With the collected knowledge about these topics and field studies, he examined the process for filter designing. He implemented his theoretical knowledge to the field and constructed basic weirs and embankments. As he progressively collects his experiences, his scales for constructions got bigger and greater. His first trials for filter systems were based on basic properties like using only three layers etc. and later he developed these systems as five-layered. Yet, he only investigated similar types of filters so that any gradation differences were not examined. He leaded the way for the topics like soil retention and filtering. His ideas and knowledge defined as “improvising”.

Indraratna et al. (2008) studied the history of the filter and filter design. First trials of the filter design proposed by Terzaghi, was lack of effects of C_u, Rd, compaction, surface area etc. According to this theory, it was expected that soils that have the same D_{15} and d_{85} values, even if they were different by gradation (e.g., well-graded and poor-graded), would behave identical but in reality, it is not. Further searches showed that constriction sizes and porosities, hydraulic conductivities of the systems are major parameters to define the filters and stability of it. For these reasons, in recent years studies involves analytical, empirical and numerical studies all together to define the unique geometry of the soil matrix and pores. With the progression of the technology, terms like self-healing for base soil and self-filtration for filter layer were introduced to theories. It was expressed that self-filtration concept are especially important for well-graded soils and they are influenced by coarser particles in the system. For this reason, PSD of the well-graded soils were adjusted by using re-gradation systems. Rd and compaction parameters are especially critical for widest part in the constrictions. They identified an effective filter as similar graded to base soil but also have tolerance for using with well-graded soils.

Yet, in this study effect of clogging in short term and long term were not fully investigated. As the C_u of the system increase (i.e., becoming more well-graded), the systems generally affected harmfully (e.g., clogging). Gap-graded soils as filters, generally makes the system unsustainable as expressed in the study. It should be noted that this study was conducted on cohesionless soils and it must be thoroughly investigated for using on cohesive ones. Self-filtration study based on PSD is shown in Figure 2.7.

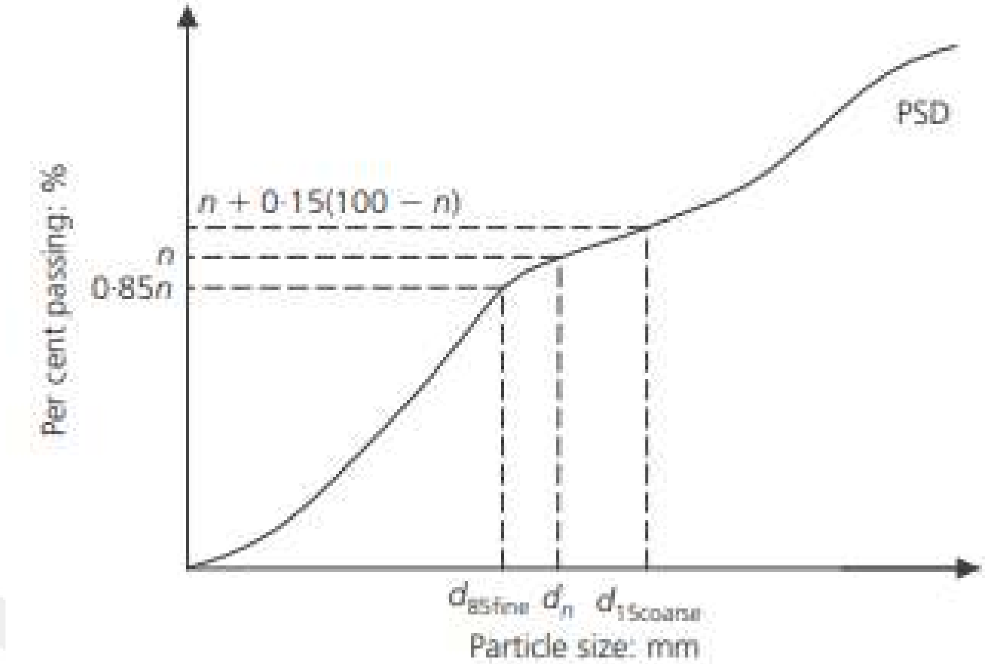


Figure 2.7 Self-filtration requirements on PSD (Vakili and Selamat, 2014)

Raut and Indraratna (2008) searched for advancements in filter design criteria for CSD theory and they founded an important disadvantage for previous theories. In previous theories, it was stated to use regradation technic for the base soil if soil have +4.75 mm particles (i.e., No.4 sieve size) but if a base soil only consists of +4.75 mm particles this solution would be insufficient. For these reasons, it would be propriate to create a new system to define a filter designing criteria. They established a theory based on CSD and this theory was tested in empirical stages. Results from these stages, were satisfactory and more precise than conventional criteria at those times. Whereas, it should be noted that most of the previous studies and this one consists of cohesionless soils and they warned to be more careful when dealing with dispersive soils and using finer filters to sustain the system. Previous studies were defined as “conservative” and this study showed more precise results. This study showed a great advantage than previous ones so that this study contains both analytical and empirical stages to define filtering system.

Zorluer et al. (2010) examined the dispersibility of a clay and expressed that even for the same soil and conditions, dispersibility identification tests (e.g., physical and/or chemical) of that soil may result varied. To justify this theory, they conducted chemical (i.e., total dissolved solid (TDS) and Na^+ % and exchangeable sodium percentage (ESP), cation exchange capacity (CEC) and physical (i.e., double hydrometer test and pinhole test) tests. They modeled the system based on “fuzzy rule” and selected inputs to show the dispersibility and stability as their output. It is stated that previous studies involved other modeling systems but these systems were more complex and they had to add specific number of inputs, also other systems were not unique to each specific case. For these reasons, they selected to apply “fuzzy rule”. This method was considered as more economic, feasible and easy to use. Consequently, they defined dispersible soils as “structurally unstable” and “highly erodible”.

Flores-Berrones et al. (2011) investigated earth-rock dams and internal erosions and remediations in these structures. In their study, core soil selected as plastic clay and as they placing the core soil appropriate compaction efforts were not given. This property decided from the water content of the core soil. It was stated that core soil was not prepared thoroughly and became non-homogenous. Homogeneity of the soil affected the internal erosion as homogeneity made it prone to internal erosion. The soil was checked for dispersibility in crumb test and it was found non-dispersive. Filter that planned according to the criteria, failed in the application and became too coarse for core soil and core soil dissipated and created internal erosion. This situation created piping and internal erosion so that magnitude of the flow reaches up to 200 L/sec. two sinkholes were seen on the body of the dam and with the help of, even being inappropriate, filter progressively decreased the discharge of effluent. They checked for the suitability of the filter for a number of theories. It was observed that in both filter layer and in base soil gradation, there were mistakes and those mistakes caused the propagation of the erosion and piping.

For solution, stored water in that area were drained by spillways and samples taken from the centers of the erosion. It was seen that samples that gathered was far from the optimum point of water content and compaction effort was insufficient also they were lack of gradation both in filter and base soil. In the next step, grouting was applied to the soil and slurry wall created. From the experiments it can be said that remediation was successful and system was saved with a limited loss of water. Furthermore, it was given that nearly 50% of the failures was directly or relatedly caused by piping and internal erosion. Moreover, it was suggested to use NEF tests to indicate the filters as sufficient or not. Particle segregation and cementation must be checked for the sake of sustainability.

Indraratna et al. (2011) studied the potential for erosion and suffusion in granular soils. In this study it was observed that for fine percentage in the soil representative size can be sufficient for a rigorous filter design and this value can be affected by Rd and gradation, compaction. Effect of Rd and compaction can be seen in Figure 2.8. They stated that ratio of the D_{c35} to D_{f85} gives insight about the potential for erosion and suffusion. This ratio can also indicate the feasibility of the system and risk potential. Suffusion in this study was defined as the dissipation of the fine particles among coarse particles in the soil matrix. At this point, stacking of the coarser particles gained importance to identify the flow.

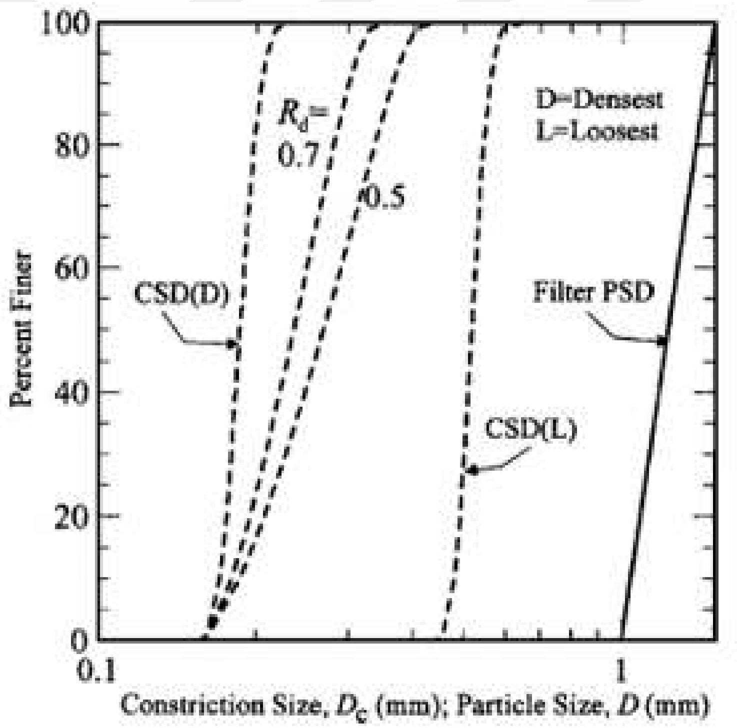


Figure 2.8 Effect of Rd and compaction on CSD (Indraratna et al., 2007)

Benahmed and Bonelli (2012) conducted hole erosion test (HET) to describe the concentrated erosion in cohesive soils. With this experiment series, the concept of piping and erosion could be understood more precisely. After taking all the results into considerations it could be said that dry density, clay type and clay content, degree of saturation affects these incidents substantially. Piping defined as creation of a “pipe” shaped passage in the soil strata from upstream to downstream so that soil particles flow away in this passage. Some properties like critical shear stress and rate of erosion can be detected by HET. With the progression of the study, it was observed that water content of soil and compaction energy also affected these incidents. As it was stated, HET has an advantage that it gives rate or probability for erosion in that system. One tricky point was that clay type can alter the attitude towards the system so further research was suggested.

Indraratna et al. (2012) studied the measurement of the permeability by constriction sizes in saturated granular soils. They also made comparisons with the previous studies to find out the reliability of the system. Constriction size technics were selected to model the soil matrix because by this way it would be enable to identify the unique combinations in that soil matrix. It was expressed that constriction sizes in a soil matrix specifically or relatively related with the Rd and compaction efforts that had given. This study was also justified by the experimental stages and results were related with the theory. The theory also satisfies the condition that it can also be applied to the wide range of soils. It was observed that theory was more effective than the conventional formulas and theories which most of them contains simplifications about the shape parameters. This study was conducted on poorly graded soils so they suggested to expand the study for well graded soils.

Abbasi and Nazifi (2013) examined the “Sherard Chemical Method” for identifying dispersibility potential for soils They observed some disagreement between the results of pinhole test and Sherard Chemical Chart Method. For this reason, it was believed that there must be some advancement or modification for Sherard Chemical Chart Method. It was widely recognized that Na^+ concentration affects the dispersibility but not only this was enough according to this theory, also anions in the soils and pore water affects this behavior. As in this study, Na^+ concentration can be leveled with Cl- concentration and this combination can create sustainability in the system. From the results, it was observed that Na^+ percentage in the mixture increase the potential for dispersibility on the other hand Cl- percentage in the mixture decreases it. They found the solution by exchanging the Na^+ / TDS to Na^+ /Cl^- in y-axis of the chart. According to the new chart, it was seen that anion type and concentration in the mixture have a huge importance for soil. Consequently, Cl^- linked to Na^+ and created NaCl, by this way they created a flocculation and reduced the potential for dispersibility. Opposite behavior can be seen by $NaCO_3$. They stated that these combinations can also be applied in situ.

Fan and Kong (2013) created an empirical equation to measure the potential for dispersibility in cohesive soils. They stressed that dispersibility of a soil is highly dependent to Na^+ concentration in soil or pore water, clay type and minerology and pH of the soil and surroundings as highly alkaline pH is an important parameter in this case. They linked the formula with liquid limit (LL), clay content, pH and concentration of Na^+ in pore water. As they were compared with the empirical results, it can be said that results are reliable with the formulation. It was stated that formula can be used for general purposes but it should be accompanied by empirical studies.

Huang et al. (2014) investigated the variance between blockage on the filter and penetration into the filter in cohesionless soil. These differences were examined in analytically (i.e., DEM and CFD methods) and compared with the numeric results of the previous studies with the same topic. Four different (by means of opening sizes) filter designs were made and these designs challenged with the cohesionless base soil. Intentionally, gap-graded soils were also selected to test the system. Outcomes of these studies were compared with the studies of Terzaghi in 1920s. Comparisons made for the parameters like discharge, permeabilities of the filters, PSD of the soils, porosity, pore water pressure etc.

From the outcomes it was observed that as the opening size greater, retention ratio decreases so this directly causes discharge to increase and both porosities of the base soil and filter also increase which resulted in increase in eroded soil mass. On the other hand, if the opening size is small, it gets smaller step by step with the retention of the eroded mass and causes limited discharge. Eroded masses in small openings increase to a limit then stays there. Porosity in these systems decreases. At the end of all systems, clogging of the filters were observed and erosion was prevented. Common point in these filters were, they both lost some masses to erosion but after a while these masses were constant. By using the DEM and CFD methods, these systems and combinations can be modeled and different combinations for filter can be created. It was stated that, this study gave insight about the modelling and “visualization” of the body and particles of the filter matrix.

Kandra et al. (2014) examined the general filtering concept and “variables” of these filters on “clogging in stormwater filters”. They searched for effect of some parameters like filter particle size, width of the filter and layering (one or multi-layered), composition of the filter (same layer system or differentiated system for per layer) and “embedding depth”. They observed that when the water contains biological, chemical or “sediment” accumulation inside it, finer filter particle types were better for filtration purposes but opposingly this action can reduce the life span of the filtration layer. If the width of the filter increase, life span of the filter increases. For the layering side, it was seen that being multi-layered helped the filtration to protect itself as all the retention in this study stuck in the upper layers. They did not observe any substantial difference between mixed-particle layers and multi uniform layers. All these empirical processes were conducted with high discharge values but for smaller discharge values these concepts can be skeptical.

Vakili and Selamat (2014) examined the filter designs by theoretical and empirically. Some of the important studies about filter design criteria are shown in Figure 2.9. Theoretically they investigated designs based on previous studies and they tested these theories in NEF tests for experimental stage. They used wide variety of soil types (e.g., dispersive, poorly graded etc.) to investigate the influence of the filters. It was observed that formulations in the literature were dominant or fully successful only for a type of soil not generally. Some of the soils showed low shear strength or dispersive behaviors or some other divergent properties so that these properties defined their success for some filter combinations. Common point of the all the studies was, they showed rough estimations to the actual value so that it signaled to use also empirical processes coordinately to ensure the stability for projects like permeable embankments or thin weirs etc. Another common point was, they were identified as “conservative” by a huge margin and they did not show precise values. They also offered to use regraded/reduced PSD for well-graded soil systems to create self-healing and self-filtration concept.

Filter design criteria proposed by	Type of base soil	Criteria for non dispersive base soil	Criteria for highly dispersive base soil
Terzaghi (1926)	Non cohesive uniform soil	$D_{15f} \leq 4.0\text{–}5.0\ d_{85}$	Not recommended
Bertram (1940)	Silt and fine sand	$D_{15f} \leq 6.0\ d_{85}$	Not recommended
Vaughan and Soares (1982)	Clay base soils	$k_f = 6.7 * 10^{-6} * d_R^{1.52}$	Not recommended
Sherard and Dunnigan (1989)	$F \geq 85$	$D_{15f} \leq 9\ d_{85}$	$D_{15f} \leq 9\ d_{85}$
	$F = 40\text{–}85$	$D_{15f} \leq 0.7$ mm	$D_{15f} \leq 0.7$ mm
Khor and Woo (1989)	$F = 40\text{–}85$	$D_{15f} \leq 12\ d^*_{85m}$	Not recommended
Lafleur et al. (1993)	Cohesive base soils	$D_{15f} \leq 0.4$ mm	$D_{15f} \leq 0.2$ mm
Indraratna et al. (1996)	$d_{85s} = 50\text{–}60$ µm	$D_{15f} \leq 5\text{–}5.5\ d_{85}$	Not recommended
	$d_{85s} = 60\text{–}80$ µm	$D_{15f} \leq 4\text{–}5\ d_{85}$	
Indraratna et al. (1996)	$d_{85s} = 40\text{–}100$ µm	$k_f = 6.3 * 10^{-4} * d_{85}^{1.25}$	Not recommended
Foster and Fell (2001)	$F \geq 85$	$D_{15f} \leq 9\ d_{85}$	$D_{15f} \leq 6.4\ d_{85}$
	$F = 35\text{–}85$	$D_{15f} \leq 0.7$ mm	$D_{15f} \leq 0.5$ mm
Locke and Indraratna (2002)	$F \geq 85$	$D_{15f} \leq 12\ d_{85reduced}$	Not recommended
	$F = 40\text{–}85$, $PI > 10$	$D_{15f} \leq 9\ d_{85reduced}$	
	$F = 40\text{–}85$, $PI < 10$	$D_{15f} \leq 4\ d_{85reduced}$	
Fell et al. (2005)	$F \geq 85$	$D_{15f} \leq 9\ d_{85}$	$D_{15f} \leq 6.0\ d_{85}$
	$F = 35\text{–}85$	$D_{15f} \leq 0.7$ mm	$D_{15f} \leq 0.5$ mm
Delgado et al. (2006)	$F \geq 40$	$k_f = 59.738 \times \exp(-0.102 \times F)$	Not recommended
Raut and Indraratna (2008)	All base soils	$D_{c35}/d^*_{85} \leq 1$	$D_{c35}/d^*_{85} \leq 1$
Shourijeh and Soroush (2009)	$F \geq 85$	$D_{15f} \leq 9\ d_{85}$	$D_{15f} \leq 7.5\ d_{85}$
	$F = 80\text{–}85$	$D_{15f} \leq$ minimum of (0.7 mm and $6.4\ d_{85}$)	$D_{15f} \leq 0.5$ mm

Figure 2.9 Some important filter design criteria studies in the history (Vakili et al., 2018)

Sharif et al. (2015) conducted empirical tests to identify the processes of piping in earth embankments. To make the tests more precise and accurate, modelling of the systems of piping and progression of the piping in the soil system were demonstrated. They created an embankment made of silt, clay and sand and tested with "image processing techniques". Their respective percentages were 29, 7 and 64 by weight. Embankment was observed in two varied systems. In one of them, it was observed from sides and bottom of the embankment on the other side it was only depicted from side views. From the results, first imaging technique was more realistic and feasible because in 2nd method, they were not able to calculate the volume of the system. With the 1st method they observed piping in width, depth and area. The depth was greatest in upstream side, width was greatest in downstream side of the embankment. One important finding was that Rd and compaction effort drastically reduced the time of progression of the piping but had limited effect on average depth of the piping phenomena. They created empirical equations for average depth, width and area and offered further studies to investigate the feasibility of this system for in situ scale.

Vakili et al. (2015) studied the filtration of the cohesive dispersive soils. Twenty-one specimens were prepared with this type of soils and they were checked for suitability for the filter design criteria in the history to if they adapt to cohesive dispersive kinds of soil. Factors like D_{15}, d_{85}, constriction size, reduced PSD and percent dispersion predominantly affect the concept in this study. They made filter design criteria for Twenty-one cohesive dispersive soil specimen and they were tested. According to the results, D_{15} value of the filter must get lower if the dispersibility increase and using CSD for well-graded soils was advised. Fine dominant filters were offered for using against dispersive soils. Yet, it was expressed that sometimes creating these very fine filters may be very difficult and complicated so these filters may be non-economical but using with NEF test may help to make filter system feasible. Percent dispersion had a huge impact on filter design criteria. For filters like these, using conservative systems were suggested.

Premkumar et al. (2016) examined the erosion failure in the pavement embankment made of dispersive clay. One of the main purposes of this study was, identifying the dispersibility inside of an embankment and detecting the steps that dispersive soils can cause erosion and preventing that. It was expressed that if soft soils are used to construct structures like embankments, it would not be sufficient by means of strength and capacity because these types of soils can not gather intense compaction efforts. They needed “soil platforms” to sustain stability and strength however generally these platforms consist of coarser particles and they can cause erosion of the finer soil particles in them. Especially these kinds of dispersive soils rapidly interact with water and they can easily flow away inside coarser particles. For this reason, type of clay and minerology of both clay and pore water must be known rigorously. It was stated that Na^{+} concentration and also Ca^{+2} concentration can cause dispersibility substantially and even if the TDS value is low, if the Ca^{+2} and Mg^{+2} concentrations are high this combination probably would behave like dispersive.

Study showed that if the water exposure time increase, dispersibility also increases and if the soil faces with high number of wetting and drying cycles, dispersibility also increases. For these reasons, it was suggested that not to use these kinds of soils in water exposed surfaces or places. Lastly, it was stressed that even a small percentage of dispersibility exist inside the soil layer, it would trigger erosion and the whole body might get harm.

Parameswaran and Sivapullaiah (2017) investigated the cation effect on dispersibility of a clayey soil. In this study, they selected to use Na^+ and Li^+ cations to identify their effect on dispersibility and they expressed that Li^+ concentration can also be influential as Na^+ ion. pH, cation type and concentration, clay type and minerology, electrochemical forces, dissolved salts and cation exchange value were classified as chemically important parameters to define dispersibility in a clayey soil. Furthermore, dry density, water content, plasticity, structure type and orientation classified as physically important parameters to define dispersibility in a clayey soil. They conducted unconfined compression strength (UCS) and shrinkage limit tests to identify dispersibility. As the individual clay particles attracts water particles, they are connected and create a “water shell”. This “water shell” can be bigger and larger if the smaller cations are selected. Water shells create distance between each soil particle and these soil particles apply repulsive forces to each other and these forces are stronger than the Van der Waals bonds of the water-clay interactions and as a result this process creates dispersibility. Even a low percentage of dispersion would be enough to concentrate the erosion. Most of the times, Li^+ does not seen frequently in the soil however Li^+ can attract more water and can create greater shells than K^+ or Na^+. This property of the Li^+ can create more significant dispersibility.

Clay minerals can adsorb great amount of water with the help of their surface area but cations can suppress these interactions. As a result, swelling and dispersibility can increase. To understand the dispersibility behavior of a soil, researchers offered to test them in saturated conditions. It was stressed that if ionic exchange value increase, dispersibility decrease. They expressed that UCS and shrinkage limit test may not be precise as conventional dispersibility detection tests for this reason, further study may be needed.

Yousif et al. (2017) studied the clogging concept in the uniformly graded soils. They conducted tests to observe the changes in permeability of the soil strata. Options were created like, using uniform/well-graded base soil or “discharge variations” or “concentration of the suspension”. As they increase the concentration of the suspension, permeability values reduced, clogging increased. This trend was also seen if the low inflow values are used. Clogging of the media was seen if the soil consists of well-graded ones. They observed three types of penetrations for flow that one of them was fully penetration, other one was limited penetration and the 3rd one was semi-penetration. These penetrations were classified based on residual that are created in/on the media. They detected that permeability reduction was directly related with D_{15} of the filtration but inversely related with C_u and d_{85} of the base soil. It was stated that the clogging may be resulted from biological, chemical or physical activities for this reason it may be multidisciplinary and further studies may be needed to understand the general behavior. Soil was intentionally selected to not to obey the rules of filter design criteria.

Vakili et al. (2018b) made a review about filter designing and criteria for dispersive base soils. It was stated that filters can be usable and preferable for all water exposed structures and regarding lifetime, economics, feasibility, capacity gained importance. In our profession field, filters generally seen in earth dams, embankments or weir, irrigation channels. Until the millennium, PSD based filter design criteria generally preferred but with the improved technology and knowledge CSD based theory almost replaced the conventional PSD based one. For conventional way, parameters like gradation, shape and characteristics, C_u, coefficient of curvature (Cc), porosity and void ratio influence the stability and capacity of the filtering system whereas "void distribution and frequency" gains importance for CSD based theory.

Common points for two theories were, creating a uniform layer and mitigating the using of gap-graded or "non-segregated" systems. Moreover, freezing-thawing cycles and chemical, biological resistance must be taken seriously as these factors can also affect the sustainability of the filtering system. It was stressed that any problematic soils must be avoided for the usage in filtering system. Creating a non-cohesive filter system was offered for general purposes. Feasibility of the filter is also important so that any fissures can cause piping, erosion or spillways even settlement in the structure. It was suggested to use NEF tests to measure the self-healing or self-filtration and stability of the system.

Talukdar and Dey (2019) studied the hydraulic failures in dams and embankments. In this study, piping, erosion, overtopping and mechanisms of these processes were investigated. They stated that first dams and embankments were constructed approximately in 2900s B.C. Piping can be seen as heave or internal erosion. The terms are very similar but they have slight variances. Filters can sustain self-filtrations and by this way sediments can be stuck on or in the filter and can reduce the permeability values of the filters but in long term they may cause clogging of the filter systems. It was detected that shrinking and swelling of the soil may cause fissures and cracks in the soil and may result as piping. “Processing time” for the piping is still not clear for general knowledge and this topic may need further studies to insight the process. Because of the fact that creating a real scale piping experiment is tough, generally studies involve laboratory scale experiments and analytical and numerical processes. Common vital parameter was detected as crucial hydraulic gradient so that if the gradient in the system exceeds this level, it may cause failures in the system. It was stated that piping resulted by “uncontrolled seepage”, excessive zonation and insufficient filtering and severe rainfall, seismic activities or fluctuated ground water table may trigger these parameters. According to the study, “progressive backward erosion” can be triggered by the initiation of the piping. In the literature it was stated that none of the dispersibility identifying tests give hundred percent accurate decisions so these tests must be combined with some other tests to give much more reasonable results. Mechanical behaviors of the soils may be affected by the internal erosion and compaction increased the time needed for the piping.

It was expressed that overtopping can be resulted from excessive rainfall, “malfunction” in the drainage or outlet etc. Overtopping can be affected by geometry of the dam, dispersibility of the base soil and critical gradient. Overtopping is caused by flowing of the water over the dam or embankment to the downstream side and this mechanism can breach the upstream side or create fissures or cracks in the downstream side. These fissures and cracks may be triggered into “steady dissipation” of the soil. They stressed that time-dependent changes can occur in the soil system so that regular inspections must be done. They suggested to increase the number of studies for cohesive and/or dispersive soils to understand the mechanism in these soils.

Caldeira (2019) studied internal erosion instances in dams and their reasons, affecting factors and remediations of them. Filters were considered as defensive lines in the dams and they are affected by optimum moisture content (OMC) and homogenous zonation. Creating a homogenous filter layer enables self-filtration by enabling fine particles to limit the dissipation of coarser particles and can help to process of self-healing in both filter layer and base soil layer. Processing of the “self-healing” is shown in Figure 2.10. They indicated that giving sufficient effort for compaction and sustaining necessary dry weights enables uniformity in base soil strata and prevents loss of capacity and feasibility in the system. Shear stress and confining stress of the base soil also matters so that any extreme values may harm the system and can create erosion or piping. They also investigated the hydraulic gradient limits and found that even a small value like “0.008” can trigger the system and create piping and internal erosion in non-plastic cohesionless soils. It was suggested to not to use much fine soils and/or cementation material in the filtration layer because these particles may clog the filter and harm the system.

As precautions, doing regular observations and inspections, checking the cloudiness of the effluent taken from the outflow can be done. If the piping and internal erosion starts in the system, later hydraulic gradient will increase so the system trigger itself to propagation for erosion and may be resulted to form of whirlpools or sinkholes. It was stated that if the filter exist in the system, whirlpools and sinkholes may be clogged with coarser particles and may sustain self-healing. Dams’ behaviors against poor or well-prepared systems are shown in Table 2.5.

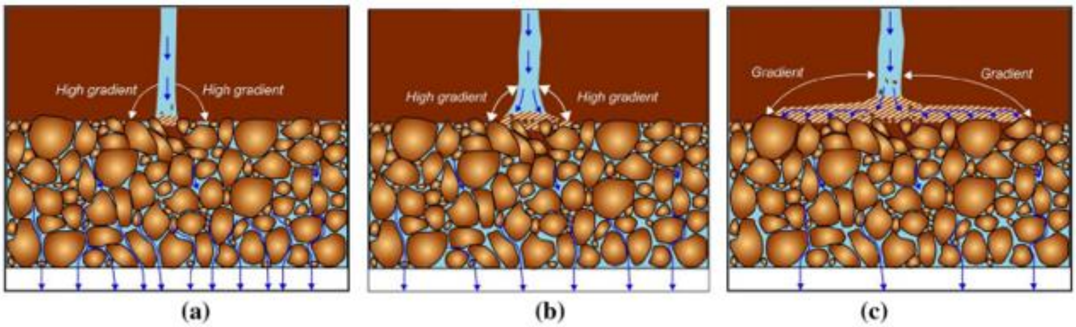


Figure 2.10 Self-healing processes in soil matrix (a) creation of accumulation (b) propagation and (c) clogging of the filter and creation of “self-healing” (Caldeira, 2019)

Table 2.5 Dams behaviors against good and poor arranged filters (Vakili et al., 2018)

Characteristic of filter	Dams with poor filter performance	Dams with good filter performance
D_{15f}	Average $D_{15f} > 1.00$ mm	Average $D_{15f} \leq 0.5$ mm
	Coarsest $D_{15f} = 7–40$ mm	Coarsest $D_{15f} = 0.5–1.5$ mm
Maximum particle size	≥ 100 mm	≤ 75 mm
Percent finer than 4.75 mm	< 40%	> 40%
Susceptibility to segregation	High	Low

Rather et al. (2021) conducted experiments to create filter design criteria for varied shapes of filters. As a recent method, CSD based theory used the assumptions as spherical particles but in reality, it is more than that so it was a need to define or modify a new theory to identify varied shapes for particles. They empirically defined relationships between varied particle shapes (e.g., roundness, sphericity, angularity etc.) and compared these relations with existing theory. From the results it can be said that using conventional formulas can be sufficient if they are modified to the varied shapes and characteristics. For this reason, researchers defined coefficients to apply on formulas. They observed that CSD also changes with the particle shape and they saw that Dc_{35} is also affected by that. This study is significant for investigating the change in CSD with non-uniform filter and also non-spherical particles. Results indicate that CSD of the non-spherical particles actually lower than the spherical particles. It was suggested to use shape coefficients derived from the formula while calculating the CSD for system. Efficiency of the CSD based study over conventional ways is shown in Figure 2.11

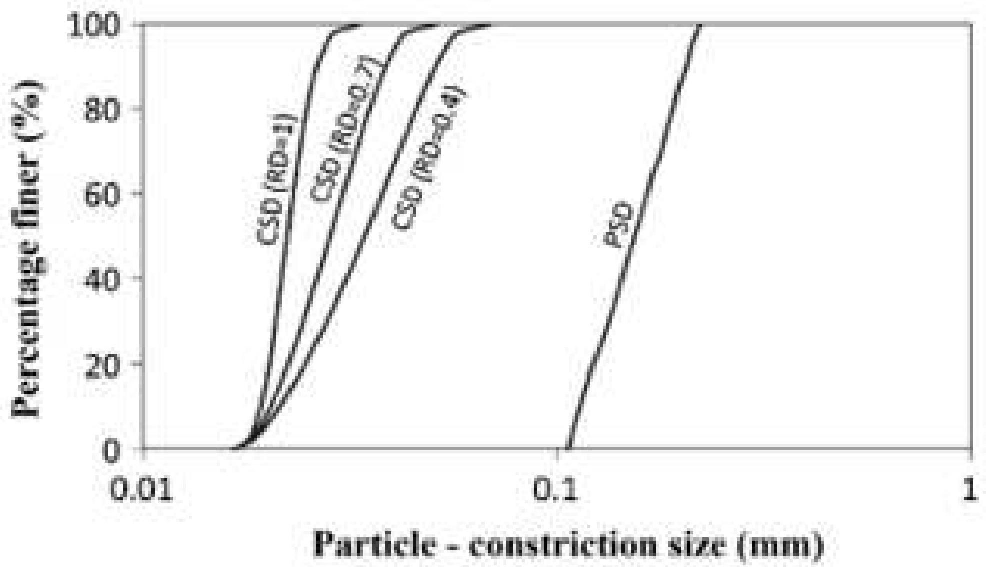


Figure 2.11 Comparison of PSD and CSD on an instance case (Vakili et al., 2018)

Seblany et al. (2021) examined the opening sizes for the filters. They stated that almost 50% of the failures occurred in dams and embankments caused from internal erosion. Internal erosion failures are closely related to the improper filters or malfunctions. It was expressed that CSD based theory is more superior than the PSD based theory because CSD based theory gives more realistic and also sustainable results than PSD based theory. According to this study, every filtration combination is unique by constriction sizes, particle matrix and pore spaces. Even the same soil from different places can give varied results based on these parameters. For this reason, studies were suggested to include analytical, numerical and experimental stage altogether. Comparisons of some filter designs are given in Table 2.6. One deficient point of the study was, they used completely spherical particles that may not give reasonable results in real life conditions. “Effective opening size” and/or “controlling constriction size” are also influential parameters to define CSD. According to the study, CSD and effective opening size can be derived from gradation and density of the soil. It was suggested to use different shape parameters to understand the behavior of the system precisely.

Table 2.6 Comparison of some filter design criteria (Rearranged after Indraratna et al., 2008)

Criteria capabilities	Terzaghi (USACE, 1953)	NRCS (1994)	D_{c95} Model (Indraratna and Raut, 2006)	D_{c35} Model (Indraratna et al., 2007)
Regrading required	Yes	Yes	No	No
Inherent internal stability analysis	No	No	Yes	No
Enhanced design certainty due to self-filtration PSD	No	No	Yes	No
Clear distinction between effective and ineffective filter	No	No	Yes	Yes
Porosity, Rd and C_u considered	No	No	Yes	Yes
Analytical principles applied	No	No	Yes	Yes

2.2 Stabilization of the Soils

Undesirable properties or deficiencies in soil properties must be treated to enable sustainability and capacity to satisfy the demands. Stabilization or remediation can be done with several ways. Easiest and generally the cheapest one contains exchanging of the soil. Current soil in the study area can be changed with vicinity desirable soils or other solutions can be applied. These solutions include biological, chemical or physical stabilization methods. By applying stabilization, soil generally submit desirable capacity, strength and permeability options. Stabilization can include biological ways by means of microbial induction or by-product inclusion from the biological reactions and wisely usage of the biological stabilizations generally results in greener and harmless way. Chemical stabilization methods include additives (e.g., lime, cement, FA etc.) and inclusion of these additives to soil strata. Chemical stabilization methods generally labeled as conventional methods but they contain environmentally concerns also. Lastly, physical stabilization usually contains compaction efforts to improve the soil property and this method can be labeled as the well-known way and the harmless way especially for flora and fauna in vicinity of the soil.

2.2.1 Stabilization by Physical and/or Chemical Methods

Moo-Young et al. (2003) investigated the physical and chemical properties of the wasted tire shreds. Different forms of wasted tires are shown in Figure 2.12. They examined the effects of sizes in physical properties. The result of this examination showed that increased compaction effort did not give any significant effect as the size of the shreds increase. Shear strength increased but compressibility decreased as the size increase. Permeability of the system increased. They conducted “column tests” and no harm was seen from the wasted tire particles contrarily it gave some increase in water quality if the particles are above the groundwater table. Whereas, if the particles are below the groundwater table and ponds are created in the soil strata, it may harm the flora. In order to mitigate this problem, filling of the ponds or drainage of the water in the system was offered.

According to the thermogravimetric analysis (TGA), tire particles are stable up to 200°C but they can give exothermic reactions so precautions must be taken. Total organic carbon (TOC) decreased and ϕ and c increased. Specific gravity (Gs) did not get affected at all to the changes in the system. Water adsorption remained constant. Shear strength increased as the density increased. It was suggested to take precautions in order to prevent ignition in the soil strata.

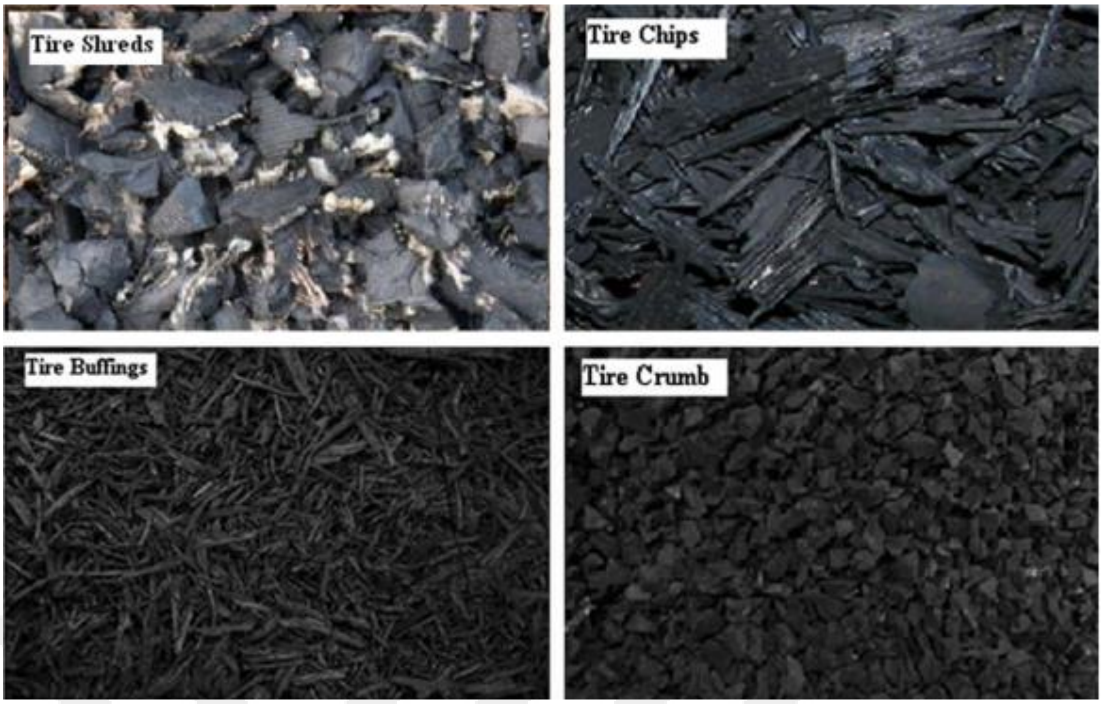


Figure 2.12 Different wasted tire forms to use (Edincliler et al., 2010)

Edincliler et al. (2004) studied the static and dynamic properties of the wasted materials for highways. Researchers studied two recycled materials namely fly ash pellets and tire buffings in highway embankment construction. They conducted large scale shear strength test and dynamic triaxial test. It was noted that to understand the effectiveness of this method in field scale, larger scales for experiments were applied. Physical, chemical and seismic/dynamic properties of the materials were investigated. According to the results, in low displacements sandy soil behaved stiff but for high displacements it behaved ductile when tire buffings were used. Shear strength increased as the tire content increased. Fly ash pellets on the other hand, increased ϕ and it reasonably matched with soil as it has low unit weight. Shear modulus when using fly ash pellets did not increase as in tire buffings. It was noted that tires, glass, plastics, fly ash have reasonable prices so using these materials would make the system feasible economically. Yet, care must be given as these materials have high porosity and low unit weight, interlocking skills.

Zornberg et al. (2004) examined the behaviors of tire-sand combinations. In the study it was mentioned that especially after industrial developments, stockpiles of end-of-life tires (ELT) have been occurred and managing these piles gained importance. For sustainability purposes, economically and environmentally utilization of these piles has been discussed. It was mentioned in the literature that at first full tires were utilized but it created problems like excessive compression and ignition in the soil layer. For this reason, researchers combined tires with sands to create a balance. Solely sand systems showed low shear strength but when tires added to these systems, these values increased. Aspect ratio and dosage of the tire shreds were affected the system and Rd of the system also affected it. Tire gained ductility to the system. Increase in aspect ratio (length/width) increased the shear strength of the combination. As the confining pressure increased shear strength decreased so system would work better especially in low bearing pressure medium.

Utilizing the renewable materials like tires, would give advantages over conventional ways. Tire systems gave thermal insulation but permeability of the system needed further investigations. Tire increased the strength in the combinations. 35% was detected as the limiting value so that over this limit would give combination to "tire shred like" behavior but under this value was described "sand like" behavior. In over this limit, no further increase in strength was observed.

Arslan and Baykal (2006) investigated the FA for using as pellet aggregates. Waste materials and by-products are offered for the usage in stabilization purposes as they give advantages in economic and environmental aspects. For this reason, FA was utilized as pellets in agglomeration and examined if they become stable and beneficial for stabilization purposes. Researchers observed the parameters like PSD, shear strength, Gs, water absorption and surface characteristics of the fly ash pellets. Moreover, results indicated that these particles can be used for several purposes and can behave like natural soils by means of ϕ. It can also be combined with cement to increase the shear strength of the system. It was noted that utilization of these particles may decrease the demand for usage of natural mineral resources and reduce the disposal costs. Water absorption, crushing strength and unit weight parameters were similar to the lightweight concrete, so these particles can work as substitute or can be combined with lightweight concrete. According to ϕ of the combination, it can be used as landfills or in embankments.

Cai et al. (2006) studied the effects of fiber and lime combinations on clayey soil. They conducted UCS, shear strength and swell-shrinkage tests on polypropylene added lime-stabilized clayey soil. As a result, it was observed that polypropylene fiber dosage and lime dosage, curing days are important for this combination. As the lime added to combination, UCS and ϕ and cohesion (c), shear strength increased but toughness, swelling, shrinkage decreased substantially. Lime adjusted the behavior as brittle. All these outcomes, especially strength effects became more significant after the curing days. Reason for all these behaviors was expressed from the chemical interactions between lime and clayey soil. On the other hand, as the fiber added to the mixture UCS and shear strength parameters, toughness, shrinkage increased but swell decreased. All these effects became more significant after the curing days also. The reason for these types of behaviors were expressed from the physical interactions and bonding between fiber and clayey soil. As the fiber content increase, combination showed more ductile behavior. It was noted that this combination system is durable and stable and can be used in projects like slope stability and foundations.

Ouhadi and Goodarzi (2006) examined the "assessment of the stability of a dispersive soil by alum". In this study, researchers dispersed a soil with a sodium sulfate and gave effort to stabilize it with aluminum sulfate (alum). It was expressed that in the literature there are many studies about the stabilization with lime and/or gypsum but there are limited number of studies with alum. For this reason, an effort was given to stabilize a dispersed soil with addition of alum with different percentages, effects of this combinations are supported with scanning electron microscopy (SEM) and XRG figures to identify the interactions between them.

They conducted double hydrometer test, consolidation test, permeability test and also Atterberg limits. It was observed that dispersibility in a soil actually related with pore water and soil chemistry, minerology. Na^+ ion affects the dispersibility of the soil so that these ions create repulsive forces in the soil and increase the dispersibility. The selected soil for this study was montmorillonite-based bentonite and bentonite can adsorb high amount of sodium sulfate then double layers of the bentonite was filled with sodium sulfate and dispersibility increased and unit volume decreased. After this operation, alum was added to this dispersed soil and these ions were replaced with Al^{+3}, as Al^{+3} have higher valency repulsive forces weakened and dispersibility decreased. As the H^+ released in the medium with this operation, pH value decreased and this operation also reduced the dispersibility. It was noted that because of the dispersibility when these soils exposed with water they can create instability for landfills, embankments and pavements. Alum was reported that it is soluble in water, less hazardous and have reasonable price.

Pore fluid chemistry and soil minerology can alter the behaviors of the soil and these changes can affect the properties of soil like permeability, strength and settlement etc. If dispersive soils are not exposed water, they show high dry strength and low compressibility but their exposure is very risky and can create fissures in the soil strata. Origin of the particle texture was oriented but this attitude was changed with the addition of the alum and converted into “aggregated or flocculated”. It was noted that low electrolyte concentrations can trigger the dispersibility and increase it.

Tang et al. (2007) studied the properties of fiber added and cemented clayey soil. In this study effort was given to investigate the UCS, shear strength, compressibility and stiffness factors of the polypropylene fiber added cement-stabilized clayey soil. Combinations were designed as solely fiber added, solely cement added and mixture of the all materials. Combined form showed increase in strength values with the help of mostly cement and ductile behavior caused by mostly fiber in this combination. Shear and tensile failures were mitigated with the addition of fibers. These effects can also be seen with the SEM images. With the inclusion of fiber stiffness decreased. Reinforcement status was affected with the factors of “bond strength” and “interface friction”. Solely fiber inclusion created interactions between fiber and clay surface but on the combined form interactions were created between fiber and clay-cement suspension. It was noted that micro mechanical behavior of the soil was related with the binding material, normal stress, contact area and surface friction. Fiber addition also caused the increase of the axial strain at the failure. Compressibility of the combination increased with the addition of fiber and behavior changed from brittle to ductile.

Tsang (2008) examined the seismic properties of the rubber-soil combinations for developing countries. Rubber - soil mixture (RSM) was investigated by creating layers of RSM and putting them under constructions to measure the seismic stability of them. It was noted that conventional isolations generally yield lateral seismic isolations but this study also contains vertical seismic isolations. This property is also satisfied with numerical and parametrical studies. Environmental and economical purpose of the study was mitigating the stockpiles of the waste tires and giving chances for developing countries without being too expensive to sustain especially when considering these systems are generally rare and have astronomic prices for their country. For feasibility five important topics were detected. These are liquefaction, settlement, non-linear soil response, soil resonance and environmental aspect. These topics creates “distributed seismic isolation system”. Most significant difference of this study was protecting a surface of “foundation contact layer” instead of conventional protecting only support points.

Park (2009) investigated the UCS and ductility of the fiber added cement stabilized sand. Researcher added fiber on cemented-sand and tested this material on UCS test. The main purpose of this study was investigation for effect of fiber dosage and distribution of this fiber in specimen. According to the results, as the fiber added to the specimen, strength value was increased. Randomly distributed five layered system gave strength values two times greater than the unreinforced one. However, if the fiber is only added to the 3rd layer (the middle one) then strength value was 1.5 times lesser than the fully added version. This express that if the added number of layer increase than strength also increase. It was noted that dosage also affects the strength of the system. It was suggested to look for both concentration and distribution for making a safe design.

Viswanadham et al. (2009) studied the swelling characteristics of the expansive soil. In this study soil was propylene fiber reinforced and investigated in consolidation test. Fiber was used with different dosages and aspect ratios in soil system. According to the results, if the dosage increase and ratio decrease heave, swelling and swelling pressure decrease. If both of them is low, system does not show any substantial differences and works properly. The reason for this kind of behavior was, a friction was occurred in the clay and fiber contact point.

Abdullah and Al-Abadi (2010) investigated stabilization of an expansive soil by electrochemical method. The main factor in this study was exchanging the cation in the expansive soil and reducing the potential for soil to show expansibility. The cation in the soil was examined to change with K^+ and Ca^{+2} ions. It was noted that because of their valency, it was expected that K^+ would give higher ϕ and strength values. One of the most significant advantages of this study was, it was shown that this system can work well and efficiently even the permeability value is very low. With the progression, it was observed that swelling potential decreased and this progress shows that cation exchange applications can be applied to the problematic soils. Plasticity of the soil system was decreased because of the reduction in Plasticity Index (PI). Non-ion substances can be transported with “electroosmosis” and for ions transportation can be done via “electromigration”. K^+ showed dominant performance over Ca^{+2}. This can be resulted from the linkage created from K^+.

Edincliler et al. (2010) studied the effect of varied processing techniques of tires. Varied processed wasted tires were added to a sandy soil and it was examined for applicability for embankment construction. They conducted large scale direct shear test. Processing techniques include tire shreds, tire buffings, tire chips and tire crumbs. Any kind of utilization of these materials would enable environmental and economical solutions. From the outcomes it can be said that tire gave shear strength to the system but percentage, processing type and normal stress were the governing factors. Processing type was the most dominant factor for the effectiveness of the test and aspect ratio also affect the processing type. If the mixture is prepared in the OMC and only allowable for low displacement then it results in stiff and low-compressible behavior but any other effect directs the behavior in ductile way. Identifying the materials properties and limitations also gave directions to the researchers. It was noted that even small percentages can affect the strength of the system and increase the ϕ also it was a great effort for embankment construction purposes.

Cabalar (2011) conducted direct shear test on tire-sand combinations. Two different types of sand (one is angular fine and the other one is rounded coarse) were used in experiments. Tire shreds were added to the sands and investigated for their strength and ϕ. It was noted that tire wastes are abundant and have reasonable unit prices. Results directs that ϕ and strength were decreased with the addition of tire shreds. Regression analysis was also conducted for strength parameters in regarding sands and r^2 was found 0.88 and 0.90 for sands. The explanation in graph was also expressed in mathematical functions for further usage. Because of the fact that combinations have low unit weight, they can be used in projects like landfills, lightweight fills etc.

Park (2011) conducted experiments to measure the UCS and ductility of a sand. In this study sand was cemented and fiber added. Fiber dosages and cement dosages were investigated for regarding effects. For fiber, polyvinyl alcohol (PVA) was selected and fiber created adherence with the cement. As the dosage of fiber increased, strength value also increased and optimum value was reached with 2% cement. With the help of fiber, axial strain increased by 5%. Researcher defined a ratio named “deformability ratio” and this ratio consist of axial strain of the fiber reinforced cemented sand to the non-fiber reinforced form of the sand. With the inclusion of fiber, this ratio showed increased and most important factor for this ratio was fiber dosage. Fiber dosage had superior effect than cement dosage in the study.

Edincliler et al. (2012) defined “triaxial compression behaviors” in sand-fiber mixtures using “neural networks”. A sand type was added solely tire buffings and solely tire crumbs and tested in triaxial tests. Triaxial tests were in two types, one of them was unconsolidated undrained and the other type was consolidated drained. The aim was measuring the shear strength of these combinations and reflect these results into neural networks. They modeled network system with the data from tire type, tire ratio, tire content, confining stress and test type, axial strain as their input and output was deviatoric stress. After the tests, they compared the accuracies of the modeling network and empirical stage. Outcomes showed that model of the system showed relatable results with the empirical stage and equations were created for further studies. Solely sand yielded greater peak strength values than tire added versions but tire additions elongated the axial strain values at the failure. Tire buffings yielded greater strength values than tire crumbs and greater aspect ratio showed increase in strength also. Dosage of fiber increased the strength values up to 5% but no further significant increase in strength value was recorded.

Estabragh et al. (2012) examined the behavior of fiber added cement stabilized clay (CL). It was expressed that the significant of this study was related with the addition of fiber to the clay because in the previous studies fiber or cement was generally added to the sandy soils. Cement and fiber addition to clay was relatively new because previously generally lime and gypsum were added to the clayey soils. Results indicated that cement increased the strength of the mixture and fiber did not give significant contribution about this property. On the other hand, fiber increased the ductility and axial strain at failure but cement increased the brittleness.

According to the UCS results, optimum fiber value was 1%. It was noted that solely cement usage in the soil stabilization systems can cause exothermic reactions and create fissures of shrinkage cracks especially if cement is in high percentages but in this study this deficiency was solved with addition of fiber. Generally, this interaction between cement and soil results in increase of strength and brittleness. It was suggested to distribute the fiber randomly to prevent creating failure lines inside the soil. Fibers also increased the tensile strength of the soil system.

Edincliler and Cagatay (2013) examined the enhancement of the weak subgrade with addition of fiber. The experiment consists of fiber addition to a sand (SP) and investigating this mixture in the california bearing ratio (CBR) test. Options in this study were selected on, aspect ratios of tires, particle shapes, tire types, dosages. Outcomes of this experiment indicate that all these parameters were effective on the soil behavior. For particle shape, granulated type of tire showed greater CBR values than fiber type tire. Also, granulated type of tire decreased the compressibility of the soil. As the dosage increase all the strength values also increased. However, fiber type of tire showed greater strength values than granulated type of tire. For aspect ratio it was seen that, greater aspect ratio yields greater CBR values and the reason for this kind of behavior was noted as the intact surface area increase, CBR value also increase. These operations can also be used for weak soil stabilization systems to yield greater stability and settlement aspects. It was expressed that strength isotropy was seen in the soil strata because of the randomly distribution of fibers. Tensile strength required for traffic loads were also satisfied in the study and with this design the need for lower pavement thickness will also be satisfied and it will also decrease the costs for construction.

Indraratna et al. (2013) studied the lignosulfonate treatment for silty sand and measurement of the rate of erosion for this soil. This study was prepared with erodible silty sand and stabilization of this erodible silty sand with lignosulfonate was examined. This combination was also modeled and checked for erosion. Important parameters for defining soil combination were packing style of soil particles, “mean flow velocity”, “mean particle diameter” and Gs. It was noted that erosion is created from breaking of the interparticle bonds of the soil particles with the force of hydrodynamic pressure and continues with the suspension of these particles in the water flow. Finally, these particles flow away from the original place.

From the results it was observable that lignosulfonate strengthen these interparticle bonds and limited the erosion and increased shear capacity of the soil according to the direct shear tests. Modelling was related with the empirical results and rate of erosion measured with this way. Stiffness and shear strength increased with the increase in dosage. It was noted that erosion particularly surface erosion and internal erosion are some of the most important types of erosion especially water exposed structures. Maximum flow velocity and hydraulic gradients for these kinds of structures can define the erosion status. For further usage in situ, an equation was proposed.

Masoumi et al. (2013) studied the improvement of problematic soil with fiber and PVA. The aim for this study was improving the soft soil with polypropylene fiber and polyvinyl acetate resin. With the addition of these materials to sandy soft soil, CBR test was conducted on these specimens. The decision for using these materials was done intentionally especially considering their unit price. CBR test was conducted both in saturated and non-saturated form. Results showed that in both forms, CBR values increased. Researchers expected that PVA would be less effective in saturated form so they combined PVA with fiber. It was noted that this kind of study may be beneficial for projects like pavement beds etc. especially considering this study can be effective for mitigation of "dust generation" and preventing erosion. Saturated form was described as the optimum and effective form for the sustainability of the system.

Turkoz and Vural (2013) studied "the effects of cement and natural zeolite additives on problematic clay soils". Two types of clay were investigated for their behavior with the addition of cement and zeolite additives. They conducted UCS, swelling, swell pressure, compaction and dispersibility tests to identify these parameters. 3% of cement was constant for the whole experiment process. These clays showed expansive and dispersive behaviors. To define dispersibility also sodium adsorption rate (SAR) and exchangeable sodium percentage (ESP) tests also conducted. After the curing days it was observed that, as the zeolite percentage increase strength value also increase until to a constant level, no further increase in strength was observed as the zeolite dosage increase. The reason for that was explained as, as the cement percentage is constant, interactions between zeolite and cement can only reach a constant level. Low plastic clays showed immediate effect in 0-7 days whereas high plastic clays showed effect after 28-day curing time.

This combination also mitigated or limited the dispersibility and also swell and swell pressure also decreased with the increase in dosage until a constant level. Researchers noted that low plastic clays showed low swell and swell pressure until the ESP is high and SAR is low but if soil satisfy these conditions, then it showed high swell and swell pressure. Therefore, they indicate that dispersibility may increase expansibility or swelling properties.

Blanck et al. (2014) examined soils treated with organic unconventional additives. Low plastic silty soil was tested with the addition of organic additives and they examined for their behaviors against UCS and bearing capacity. Three organic additives were added to the specimens namely enzymatic solution (ES), calcium lignosulfonate and acid solution. Test results showed that strength was increased with the addition of organic additives and OMC in compaction was decreased. Swelling also decreased and soil became stiffer. In the micro scale, SEM images and mercury injection porosity (MIP) test were conducted. Curing days did not show significant effect as the specimens showed immediate effect only. Acid solution and enzymatic solution did not affect anything harmfully in long-term whereas these materials made the mixture biodegradable. It was noted that care must be given to detect if the calcium lignosulfonate can create leachate with water in the soil strata. Some of the materials showed surfactant behavior which can affect the behavior in compaction.

Cabalar et al. (2014) investigated stabilization of a clay soil with wasted tire and lime. In this study low plastic clay soil was stabilized with tire buffings and lime then tested in UCS and CBR test. Utilization of tire buffings was reported as beneficial because utilization of these materials enables mitigating the stockpiles of tires and their regarding disposal cost. As tire buffings dosage increased in the specimens OMC decreased and also maximum dry density (MDD) decreased however this behavior was completely opposite with the usage of lime, as the lime percentage increase MDD and OMC increased. Tire buffings decreased the values for CBR and UCS whereas lime increased both parameters. Optimum combination was seen with the usage of both materials, when they were combined but if tire dosage increases then OMC decreased but if lime dosage increases then OMC increased. The reason for this kind of behavior was explained from the adsorption capacity of the lime and lime was used for “pozzolanic reaction” purposes. Lime created bonding with the clay particles. When they were combined, if lime dosage increases MDD decreased but CBR increased.

Turkoz et al. (2014) investigated the effect of $MgCl_2$ solution on problematic behavior of clay soil. Researchers conducted compaction, consolidation, unconsolidated undrained triaxial test, Atterberg limits and dispersibility tests on $MgCl_2$ added clay soil. Results indicate that as the $MgCl_2$ solution percentage increase in the soil, OMC decreased MDD increased, swelling and swell pressure decreased, LL, PL and PI also decreased. Soil loses plasticity in these experiments. From the triaxial test results, c increased but ϕ decreased. For dispersibility, crumb tests and pinhole tests were conducted and with the optimum $MgCl_2$ percentage dispersibility decreased in the soil mixture. Further addition of $MgCl_2$ that exceeds the optimum value showed decrease in MDD whereas increase in OMC. As the dosage increase, swell pressure decreased. After the curing days especially after seven days, strength parameters increased significantly. SEM images showed that with the increase in percentage of solution, continuous texture of the soil was converted into non-continuous type and holes were created and grain size increased. Flocculation of the soil particles were observable in the SEM images. It was suggested that a material originally used for anti-icing agent for pavements and humidity, dust stabilizer can be used for stabilization of clay soil.

Cabalar and Karabash (2015) conducted CBR test on tire added cemented gravel. Sub-base gravel was tested in CBR after the addition of tire buffings and cement. Addition of tire buffings decreased MDD and OMC whereas addition of cement increased both of them. Reason for cement interaction was explained as cement need water for hydration reaction. Solely tire addition decreased CBR and solely cement increased it. Combined form of the tire buffings and cement gave the best results in term of mixtures. It was suggested to utilize this kind of projects for road pavement constructions etc.

Correia et al. (2015) studied the fiber added stabilized soft soil and properties of this soil. Polypropylene fiber added stabilized soft soil was tested in this study. Mixture was tested in UCS and tensile strength, flexural strength test, split tensile strength test. A combination of soft soil and binders without fibers showed brittle behavior, UCS and tensile strength tests of this combination showed improvement. A combination of soft soil and fibers without binders showed ductile behavior and lost strength. Combined version (fiber and binder added) showed improvement in strength and showed ductile behavior. Lesser values than the optimum dosage for fiber, showed reduction in strength parameter but optimum and greater values showed increment in strength.

Goodarzi and Salimi (2015) studied the addition of slags on dispersibility characteristics of a problematic clay soil. In this study, dispersibility characteristics of a problematic clay soil was stabilized with two types of slags namely granulated blast furnace slag (GBFS) and basic oxygen furnace slag (BOFS). Combinations were tested for dispersibility and strength after the curing days. Selection for these materials was done intentionally for the reason that these materials are by-products, utilization of these materials would help in environmentally and economical way. Results indicated that, both of the slags were effective for dispersibility but GBFS was found more dominant than BOFS. These effects became more significant after the curing days especially after seven days. The most optimum value was submitted by using 5-10% GBFS after seven days. Strength parameters also affected by the additions and they increased. The reason for this kind of behavior was explained as particle cementation and granulation caused by slags. Plasticity decreased and electrical conductivity was found as non-dispersive soils yielded greater values for electrical conductivity. Ion exchange processes may affect the system and pozzolanic reaction caused by ion exchange may also alter the behavior. As the slag dosage in the mixture increase, electrical conductivity value also increased. Investigation in micro scale directed that flocculation was occurred in the matrix because of the creation of cementation minerals. Investigation in micro scale was done with SEM and XRG images.

Karabash and Cabalar (2015) examined shear parameters of the tire added cemented sandy soils. In this study, tire crumb added cemented sandy soil was subjected to unconsolidated undrained (UU) test. Compressibility, strength, modulus of elasticity (E) and pore water pressure was examined. As a result, with the addition of tire, ductility and axial strain at failure, pore water pressure increased but stress and modulus of elasticity decreased. On the other hand, cement addition increased strength and brittleness, modulus of elasticity but decreased ductility. Energy adsorption capacity increased with the addition of cement but compressibility decreased. To understand the inside mechanisms further study was proposed.

Yilmaz (2015) investigated FA and fiber added clayey soil and properties of this mixture. FA and fiber added clayey soil was examined for regarding compaction and strength parameters. Two types of fiber with two varied ratio and two different dosages were used with the FA. Previous studies about FA, showed that FA increase the strength and unit weight, brittleness but decrease the OMC. Previous studies about fibers, showed that fibers slightly decrease strength but increase the shear strength, ductility and post-peak strength. Researcher expected to combining these materials would give the benefits for each material. Results showed that combination of these materials, increased strength and made the combination more ductile. It was suggested to use randomly distribution method for not to create any specific failure lines. After the curing days it was observed that with the addition of FA, strength increased and OMC decreased. FA showed superior behavior than the fibers. In the combined form, as the fiber dosage increase UCS strength value also increased. Behaviors of c and ϕ were not stable so further study was advised.

Savas (2016) studied characteristics of stabilized dispersive soil. In this study, dispersive soil stabilized with lime and zeolite. Consolidation, compaction and swell characteristics of the stabilized dispersive soil was tested. Tests were conducted on a mixture that was consisted of constant level lime and varied percentages of natural zeolite. Results indicate that addition of these materials decreased the dispersibility and compressibility, swell potential. It was expected to show high swell potential because of the fact that soil consist of high plasticity clay but this combination decreased this potential. Decrease in dispersibility was caused by replacing of the Na^+ ions. Decrease in compressibility was caused by creation of pozzolanic reaction between lime-soil and zeolite.

Wiszniewski and Cabalar (2016) conducted permeability, consolidation and shear tests on sand mixtures. Sand mixtures were consisted of sand with wasted tire crumbs. Environmentally grown concerns about the stockpiles of wasted tire and their utilization, caused several studies about them and some of them were on soil stabilizations. Results of the test system showed that with the addition of tire crumbs, permeability and direct shear strength increased and soil behaved more elastic. In the lower dosages, ϕ value increased but with the further addition ϕ values constantly decreased. Peak shear strength did not change substantially. Compression of the soil mixture increased with the addition of tire crumbs. A parameter defined in the study which is called “inter-granular ratio” so that it was detected as a good indicator between sand and tire particles.

Cabalar and Mustafa (2017) investigated the sand-clay combinations and their applicability for using as subgrade. NS and clay were mixed and tested in UCS and CBR, compaction tests. As the NS dosage increase, UCS and OMC, swell potential decreased but CBR and MDD increased. It was noted that NS particles are nearly rounded and system must be expanded with other various form of sands and combinations to fully understand the potential.

Consoli et al. (2017) investigated properties of “fiber-reinforced compacted gold tailings-cement” mixture. This study was prepared for the aim of measuring durability and strength parameters of the gold tailings-soil mixtures with fiber added and cemented. Fiber and ordinary portland cement (OPC) added mixture was tested in wetting-drying cycles and mass loss was recorded for the aim of measuring durability. For strength measurement, a ratio was defined as porosity/cement as both of these parameters were thought as effective on the behavior. In UCS test, expectations were met and importance of these parameters were observed.

Results showed that fiber addition increased the durability and reduced mass loss which indicates it is strong against wetting-drying cycles. ALM (accumulated loss of mass) was heavily related with porosity/cement ratio and this parameter was found effective for both strength and durability. Dry density of the mixture was found influential and for weakly compacted systems, fiber showed superior for strength and durability properties. For reinforced and/or non-reinforced systems, ALM, number of cycles, and the ratio was strongly found influential for the sustainability of the systems.

Ta’negonbadi and Noorzad (2017) investigated stabilization of a clayey soil. In this study a clayey soil was subjected to lignosulfonate for treatment purposes. Clayey soil was tested in UCS, compaction, durability, compression and secant modulus. Results indicated that plasticity of the soil decreased but brittleness slightly increased with the addition of lignosulfonate. OMC increased but MDD decreased. UCS increased to

0.75% lignosulfonate by dry weight, exceeding levels reduced the UCS. Secant modulus also increased. Durability increased as soil stand tougher than the untreated one in the wetting-drying cycles. Stiffness increased in the soil.

From the inspections of micro scale in SEM, untreated soil had flaky granular structure and had voids in the texture but addition contributed to electrostatic forces and created aggregations and granulations were observable. It was noted that most of the traditional stabilization additives make the soil brittle so this material has advantages over them so using this material on airport pavements and railway embankments can be suggested.

Vakili et al. (2017) examined the stabilization of a dispersive soil by ZELIAC. Dispersive clay soil was tested in dispersibility tests, compaction, UCS, compressibility, permeability and PI after the addition of ZELIAC. With the addition of ZELIAC soil mixture showed decrease in dispersibility, MDD, compressibility and PI, increase in strength and OMC, permeability. Decrease in dispersibility caused by exchanging of Na^{+} ions in the clay with the Ca^{+2} ions in the additive. With the exchange, distance and forces between double layer decreased and this triggered the adsorption capacity of the clay and reduce the dispersibility. For strength, with the addition of optimum value of ZELIAC (i.e., 8% by dry weight), strength increased almost 700%. Reason for this behavior was explained as additive covered the individual soil particles and decreased the fine percentage in the soil so gave the system more strength and brittleness so that even in soaked conditions soil almost retain most of the strength. It was noted that substance was non-toxic and environmentally friendly. All these effects became more observable with the curing days and results were supported with SEM, x-ray diffraction (XRD) and x-ray fluorescence (XRF).

Vakili et al. (2018a) examined fiber added, stabilized dispersive soil for erosion potential. Polypropylene fiber added and lignosulfonate treated dispersive clay soil was tested for internal erosion characteristics. Combinations of lignosulfonate and fiber were tested with different percentages in UCS, pinhole, double hydrometer and hole erosion experiments. It was noted that lignosulfonate has wide range of usage from agricultural purposes to industrial stage and it is acidic, powder formed material recently used for stabilization purposes. Properties like being non-toxic and environmentally friendly, non-corrosive are some of the advantages of the lignosulfonate. It was expressed that in the literature there are serious numbers of studies with cohesionless soils combined with lignosulfonate but only a limited number of studies with dispersive soils. Similar attitudes were observed with the studies of fibers so that these studies showed that fibers can limit swelling-compression behavior and increase shear strength, ductility and tensile strength of the soils.

Results showed that solely additions of fiber and lignosulfonate increased UCS but optimum values were reached with combined form (up to 2541% after 28 days). Similar behaviors were seen in pinhole test especially with 2% lignosulfonate and 0.35% polypropylene after seven days of curing time. Specifically, this combination type showed great response by reducing surface erosion. Double hydrometer test showed similar responses as in pinhole test. Compaction and hole erosion test showed improvement with the addition of lignosulfonate and polypropylene. Erosion rate index in the hole erosion test increased with the addition of solely particles but optimum status was reached with combined form. Hole erosion test even it does not have any standards is generally accepted test for determining erosion rate and shear capacity and it can give insight about the total breaching time. Decrease in dispersibility was caused by reducing of repulsive forces in the soil with ion exchange and filling of the soil pores.

Chemical resolution and SEM images showed that addition of lignosulfonate increased the attraction forces in the soil and decrease the Na^+ percentage in total dissolved salts. Optimum level of fiber also showed similar behaviors but higher dosages would harm the system by creating lubricant effect on individual particles. It was noted that chemical status of the three different medium is important for dispersibility and erosion, clay minerology, pore water minerology and externally flowing water minerology. SEM images showed that flocculations, aggregations were seen in the soil medium with the addition of additives.

Andrew (2018) stated CO_2 releases of the countries by cement production. Cement prices of the 2015 is shown in Table 2.7. It was expressed that one third of the CO_2 production of the total world caused by cement production. This rate has been increasing significantly every year and using fossil fuels and abandoning the use of wood or soil for basic construction material also triggers this situation. Fossil fuel and cement production can be seen in Figure 2.15. The lack of confirmed data for emissions is also a problem and this problem also limits the precautions and restrictions. It was stated that 4% of the CO_2 production created by fossil fuels was belongs to cement in 2016. 66% of the CO_2 production between 1928 and 2016 was resulted after 1990. Some countries like USA, China, Türkiye, Vietnam and India are the biggest producers of the CO_2 by cement production. Greatest producers of the cement are shown in Figure 2.16. China even produced 57% of the cement and released 52% CO_2 only by itself in 2016.

Table 2.7 Cement prices in different countries in 2015 (Chang et al., 2015)

Continents	Countries	Cement price (USD/ton)	Continents	Countries	Cement price (USD/ton)
Africa	Niger	280	Asia	South Korea	68
	Kenya	190		China	57
	Mali	203		Japan	125
	Mozambique	160		India	98
	Nigeria	223		Pakistan	106
	Cameroon	200		Bangladesh	112
	Rwanda	200		Indonesia	125
	Morocco	150	America	Peru	202
	Egypt	65		United States	91
Middle East	Yemen	214	Europe	Russia	89
	Afghanistan	91		Germany	93
	Iraq	120		France	132
	Kuwait	74		UK	102

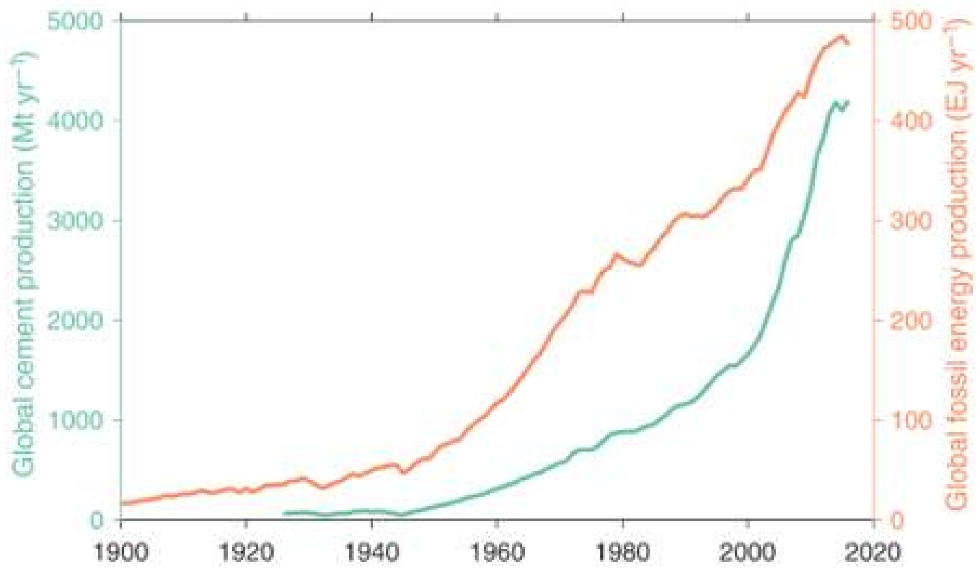


Figure 2.13 Global fossil fuel and cement production until 2016 (Andrew, 2018)

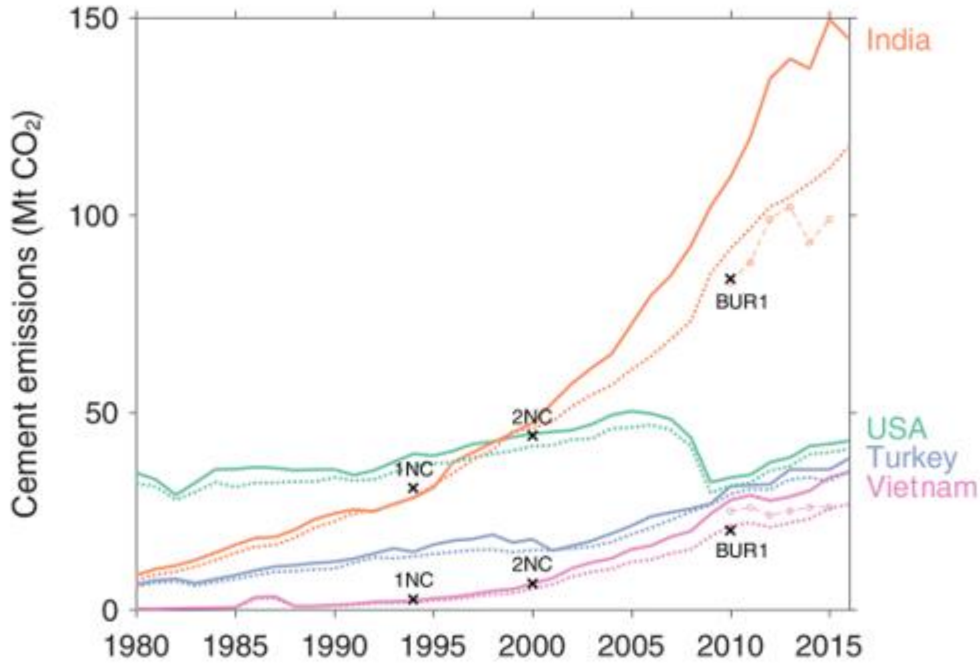


Figure 2.14 Top four greatest cement producers in the world after China (Andrew, 2018)

Liu et al. (2020) investigated characteristics of the tire added soil mixtures geotechnically. It was noted that annually one billion ton was discarded and their recycling and/or utilization gain importance. Wasted tire and solely sand or soil was investigated in physical, chemical, thermal and permeability, leachate aspects. Study was conducted with still water so for improved reality, flowing water is offered. For leachate, mixture released small amount of Zn, Pb and SO_4 to the water that was placed. It was expressed that no harm would be received from these materials. Shear strength and permeability increased with the addition of tires. In casual temperatures, tire does not get affected but with the increase in temperature further studies were advised. Soil mixture showed elastic deformations. Critical gradient, relative density and dosage for permeability must be studied for understand the mechanisms clearly. For thermal investigation, SEM found insufficient and better visualization technics like heat tracing was offered. Usage in backfills for embankments, retaining walls and highway was suggested.

B.r et al. (2021) investigated characteristics of the sand-tire combinations. In this study a sand was mixed with tire shreds and tested in UCS, direct shear and permeability tests. Results indicated that addition of tire shreds, strength and permeability, ϕ decreased but strain and ductility increased. Permeability decreased because of the fact that tire shreds showed hydrophobic behavior. Compressibility of the mixture increased. Value of ϕ decreased until 30% usage of tire shreds. Soaked or unsoaked form of mixture did not change the status of compressibility.

Kiymik and Cabalar (2023) examined the permeability of the tire added sand mixture. In this study, wasted tire powder was added on two types of uniform poorly graded sands (i.e., NS and CSS) and they were tested in permeability test. Test results indicated that permeability of the NS decreased with the addition whereas permeability of the CSS increased. The results implicated as the CSS had inconsistent individual shape and created "passage" for water to flow with ease. However, TWP as in powder form filled the pores of the NS particles.

2.2.2 Stabilization by Biological Methods

Ivanov and Chu (2008) introduced the applications of biological microorganisms and their engineering behaviors in situ. Researchers explained that biological induced systems are relatively new to adopt these systems to in situ applications and these applications can be divided into two concepts. One of them was biocementation and the other one is bioclogging. Bioclogging was expressed as creating jelly materials and grouting the pores of the soil matrix with them. Bioclogging results in decrease in permeability. Whereas, biocementation creates bonding between soil particles and biological substance in the sandy soils. Biocementation enables increase in strength and stiffness. These two concepts have wide range of usage (e.g., water retention purposes, slope stability, liquefaction mitigation) in the civil engineering context.

This system consists of multidisciplinary studies so wisely options must be searched. It was stated that for large scale studies "facultative anaerobic" and "microaerophilic bacteria" should be chosen. This biological induced stabilization systems were defined non-toxic and have reasonable prices and these properties give advantage over conventional ways. Main disadvantages can be given as being a slow process, need for nutrition and careful observation for pH.

Bouazza et al. (2009) investigated the permeability of biopolymer treated sand. The sand in this study was silty sand. Three types of biopolymers were selected to apply on silty sand. These biopolymers were XG, guar gum and sodium alginate. It was noted that biopolymers are "biologically induced viscous suspensions" and they contain “long chains of basic sugars” (i.e., polysaccharide) and water. At the end of these long chains, hydroxyl and carboxyl groups are located and these materials create bonds with soil particles. The substances they created, plug the pores and reduce the permeabilities of the systems. As the dosage and curing days increase, permeabilities decreased.

Cabalar and Canakci (2011) conducted direct shear test on XG treated sand. Researchers added XG biopolymer to a sand and investigated the changes in direct shear test. Curing days were also applied for specimens and from the results it was observed that for low dosages strength values were decreased but as the dosage increase strength values also increased. Curing days did not yield substantial differences in the experiments. It was noted that this kind of application can also be done in situ conditions.

Khatami and O’Kelly (2013) examined the properties of the biopolymer added sands. In this study cohesionless soil (i.e., sand) was combined with agar gum and starch. The combinations were tested for regarding strength and stiffness. Most of the biopolymers have positive green effect and feasibility so utilization of these materials is highly proposed from the researchers. UCS and triaxial compression tests were conducted with these combinations and as a result strength parameter was increased. This kind of behavior was expected from the increase in c value. Triaxial compression tests results indicated that stiffness of the system increased with the addition of biopolymers. Effects of agar gum was superior than the effects of starch so that agar gum gave higher strength and stiffness results and these effects were observable with the dosage changes.

Akbulut and Cabalar (2014) examined the behaviors of a biopolymer stabilized sand. In this study a clay-sand mixture was tested in UCS and CBR tests after the addition of XG biopolymer. After the curing days results indicate that XG can enhance the UCS and CBR values of the clay-sand mixture. These effects were significantly observable especially after the curing days. Strength and bearing capacity parameters were also investigated in this study and according to the results increase in pressure also increase the strength and bearing capacity of the mixture.

Wiszniewski and Cabalar (2014) conducted tests to measure the permeability of the XG-treated sand. Highly permeable sand was treated with XG biopolymer and subjected to permeability test. From the results of the test it can be said that permeability decreased with the addition of the XG biopolymer. Effects of the addition became clearly observable with the progression of curing days and dosage. The reason for this behavior was explained as XG interacted with the water and created viscous suspension. This suspension filled the soil and created an impermeable layer.

It was noted that XG has advantages like having reasonable unit price and being non-toxic but further study was offered because of the fact that various soil types and percentages must be examined to fully discover the potential of the application. It was suggested that operation like this can be applied on projects like underground structures and water exposed structures (e.g., water treatment centers or sewerage systems etc.)

Chang et al. (2015a) investigated XG and effects of it on strength parameters of soils. It was expressed that XG can increase UCS and have a reasonable unit price and also labeled as non-toxic. XG was highly influential on sands and fine soils. If XG is used with poorly graded sands then addition of a fine material into the sands is highly recommended. This interaction was explained as XG creates hydrogen bonding between XG particles and soil particles, this bonding can be affected by water and clay minerology, electrochemical status of the surroundings. Optimum level was detected as 1.5% by weight and exceeding levels made the combination highly viscous. This behavior can be altered by XG dosage, soil type, mixture type and water content etc.

Biopolymers and biological induced materials were labeled as “promising” because of the fact that they have superior advantages and limited disadvantages over conventional ways. Rheological modifiers like XG may be used for treatments of soils. XG increased the c value and made the soil more brittle. It was noted that XG did not lose any significant effect by the time and it did not “decompose”.

Chang et al. (2015b) investigated biological binders for underdeveloped countries. In this study researchers compared OPC and biopolymers (XG and gellan gum). This comparison based on price and functionality of these materials. It was expressed that for 2nd and 3rd world countries their cement price per income was detected high and maybe for this reason 50% of the structures made from earth. However, top world countries already settled and almost completed urbanization process and most of them use green-friendly applications so their usage rate is varied than the others. From the investigations it was observed that 10% cement give almost same strength performance with 0.5% XG so lesser material mass can give almost same result for strength parameters also XG has superior advantages especially for environmentally aspect. Progressively, unit price of the XG has been decreasing and "commercialization", "local producing centers" can contribute to this decrease. Global price of the XG is shown in Figure 2.13. If the usage of this materials become more common, demand for OPC can reduced.

One of the main disadvantages of biopolymers, they can reduce up to 10% of their strength when they exposed to water and humidity so further studies are advised. If mass production and recycling rate can increase, more local supplier can be created and this method would also increase the rate of reduction for unit price of XG. This concept is important for 2nd and 3rd world countries as they mostly use earth-based structures whereas most of the earth-based structures are vulnerable to water exposure and seismic interactions. It was stressed that in initial stage of mixing biopolymers tend to adsorb water and create hydrogels, these hydrogels expand the holes when molding and with the desiccation of this water, hydrogels create strong matrices of soil-biopolymer combinations.

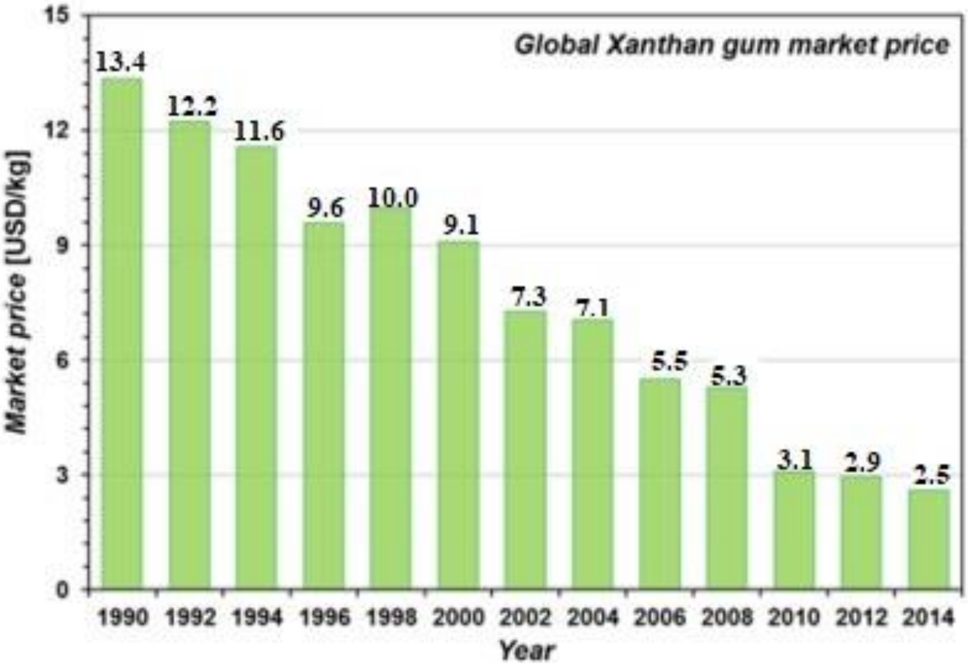


Figure 2.15 Price of XG throughout the years (Rearranged after Chang et al., 2016)

Chang et al. (2015c) studied "thermo-gelation biopolymers" and their behaviors on soils. Two types of soil (one is fine grained, other is coarse grained) were mixed with agar gum and gellan gum. Thermo-gelation processes are activated in the high temperatures (80-90 °C) and creates suspensions and when the temperatures decrease to 50-60 °C they become gel. This gel-based material creates matrices in the soil and strengthen the soil. UCS test results indicated that both gum types were effective for strength parameters and they increased it. Gellan gum was more dominant than the agar gum especially in high dosages. Curing days did not show significant effect on parameters. FC of the soil was detected as an important parameter because gel of the biopolymer creates hydrogen bonds with clay particles and makes it stiffer.

Other important parameters were found as water content, clay type and minerology, biopolymer dosage and gum type. Two types of form were tested as one of them water immersed and the other one is dry. Water immersed form can be more effective if combination air-dried and thermally-activated prior to the immersion. İmmersed form was found more effective than the dry form. Strength increased when the water content decreased and thermal activation gave higher results in strength and stiffness parameters. It was observed that thermally-activated combinations were more stable and durable in the immersion form. It was suggested to conduct further studies especially for wetting-drying cycles of the combinations.

Chang et al. (2016) introduced biopolymers for treatment purposes. Conventional ways like stabilizing with cement, lime, gypsum, ash become less frequent because of the new technologies and the demand for green-friendly applications as production of most of the conventional materials increase the greenhouse effect. The progression of the building materials is shown in Figure 2.14. Researchers gave importance to seek for new methods and concepts to replace deficient conventional ways and find harmless substances.

Geotextile, microbially induced systems, biopolymer, geopolymer, geosynthetics, less-hazardous chemical additives were found after these efforts. Most of these substances effective (especially for strength parameter) even in low dosages and nearly all of them do not have any side effect for environment. These additives are especially effective for combined fine-grained and coarse-grained systems/combinations. Reason was explained as these additives affects the friction between coarser particles and creating cementation between fine particles resulting in increase in c and ϕ parameters. In immersed conditions, polysaccharide-based substances create gel-like materials and fill the interparticle pores causing increase in strength and stiffness.

In dry conditions, these materials generally interact with clay minerology(ions) and increase the strength. Especially biopolymers have high tensile strength. Parameters like durability or biologically decomposition need further studies. To compare, total advantages of the recently developed systems are superior (even the economically it can still progress), especially for environmental and feasibility aspects than the conventional ways. Treatment ways for soils are shown in Table 2.7. It was noted that biopolymers are prone to interact with alkali and earth-alkali soil. A comparison between XG and cement is shown in Table 2.8.

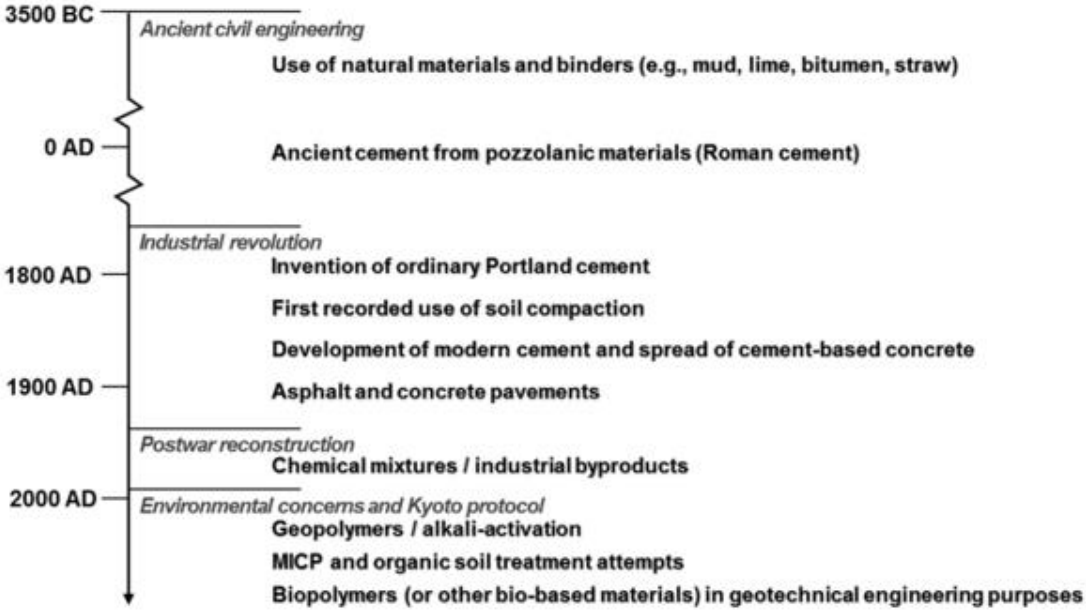


Figure 2.16 Timeline of the building materials and additives (Chang et al., 2016)

Table 2.8 General properties of the stabilization methods (Chang et al., 2016)

Properties	Cement	Chemicals	Geosynthetics	Geopolymer	MICP	Biopolymer
Soil Competitiveness	Course grained soils Fine grained soils	Course grained soils	Course grained soils	Course grained soils Fine grained soils	Course grained soils	Course grained to Fine grained soils
Method/Construction	Deep mixing, injection, grouting, direct mixing spray	Injection, grouting, spray	*In-situ* installation	Deep mixing, injection grouting, direct mixing Spray	Direct microbe and nutrient injection in to ground	Direct mixing, injection, spraying exo-cultivated biopolymers
Main Materials	Cement Water	Chemically synthesized polymers	Various synthesized materials	Pozzolanic materials, water, cement	Micro-organisms urea, starch	Biopolymers, water
Major Reactions	Hydration	Solidification, chemical bonding	Tensile reinforcement	Pozzolanic reactions	Biological calcite precipitation	Hydrogen-/ionic-bonding, gelation
Advantages	Strong, durable Numerous case studies	Strong, durable Quick isolation Numerous case studies	Quick, Easy to use	Strong, durable Good waste sink Lower carbon footprint than cement	No carbon footprint Possible use with material remediation	Environment-friendly Smaller concentrations Stronger in fine soils
Disadvantages/ Challenges	Large carbon footprint Disruption of local ecosystem. Disposal Problems	High price Environmental impacts. Washout and durability problems	Heterogeneous method Use limited to shallow depths	Similar environmental problems as cement	Ammonia byproduct Limitations in fine soils	High price High sensitivity (hydrophilic) to presence of water

Table 2.9 General comparison between cement and XG (Rearranged after Chang et al., 2016)

Soil Treatment Material	Cement	Xanthan Gum
Market price of material	98.5 USD/ton	2,700 USD/ton
Required amount for 1 ton soil treatment (≥ 2.5 MPa)	100 kg (10% to soil 1 ton)	5 kg (0.5% to soil 1 ton)
Material price for 1 ton soil treatment	9.85 USD	13.50 USD
CO_2 emission per 1 kg material production (kg CO_2)	+1.25	−4.97
CO_2 emission related to 1 ton soil treatment (kg CO_2)	+125	−24.85
CO_2 emission trade related to 1 ton soil treatment [c]	+2.75 USD	−0.55 USD
Total cost for 1 ton soil treatment (with carbon trade exchange considerations)	12.50 USD	12.95 USD

Wiszniewski et al. (2016) conducted experimental stages to determine the permeability of the sand-biopolymer combinations. In this study empirical stage was conducted with XG added sand. After the curing days mixture showed decrease in permeability. Dosage of the XG was found effective to define the behavior to create "impervious barriers" in the soil mixture. Effect of curing days was slight so it did not change the peak strength drastically. Being non-toxic and having reasonable unit price are one of the most attractive points for usage. It was stressed that in water exposed structures (e.g., waste disposals, irrigation channels and drainage systems) wetting and drying cycles can be influential for feasibility of the system.

Ayeldeen et al. (2017) investigated the characteristics of a problematic soil and treating them with two biopolymers. A collapsible soil was treated with two different biopolymers (i.e., XG and guar gum) and tested in experiments. The reason for choosing these materials was they have reasonable unit prices and in most of the situations they conserve their stable behavior. Shear strength test was prepared in two varied forms one is soaked and other one is unsoaked and collapse test was also prepared in two form one is wet mix the other one is dry mix. Empirical study was supported with numerical one with simulation modeled.

Results indicated that collapsibility potential was decreased 9% to 1% and c value and strength increased. These effects became more observable after the curing days. For shear strength and collapsibility, guar gum was found more dominant than XG. MDD decreased, OMC increased with the addition of biopolymers. Dry mix for collapsibility was found effective but wet mixing was found more effective than the dry one. Collapsibility decreased with the addition of biopolymers. Internal friction angle ϕ

decreased slightly with the addition. According to the numerical model, bearing capacity increased and settlement decreased so the system would work on flooding scenario.

Cabalar et al. (2017) conducted several tests to define the effect of XG on some behaviors of a sand. XG biopolymer was mixed with a sand and this mixture was tested in UCS, consolidation, permeability and triaxial shear strength test. Results of these tests showed that XG decreased the permeability, compressibility whereas increased shear strength, stiffness, compressive strength for the system. 1.5% XG increased the strength approximately two times than the untreated from. It was noted that even in situ applications can be possible especially for cohesionless soils.

Latifi et al. (2017) studied the stabilizing of problematic soils with a non-toxic stabilizer. Bentonite type clay and kaolinite type clay are generally considered as problematic soils, the reason for that is they generally become unstable when they are exposed to water and they are highly compressible, have low shear strength. This clay types were added XG and tested in UCS, direct shear, consolidation. Results were supported with XRD and SEM images. After the curing days tests gave results like, as the XG concentration increase in the mixture, compression strength and shear strength increased and compressibility decreased. These results were significantly observable especially in first 28 days, after the 28 days until the end of experimental stage (i.e., 90 days) only slight changes were seen. Even low dosages affected the system in first 7 days.

The mechanism of these changes was observed as in the microscale, XG interacted with soil particles and filled their voids which gave the system strength. It was noted that after the interaction, external surface area decreased. Creating almost none CO_2 for producing stage, being non-toxic and environmentally friendly are some of the advantages of biopolymers over conventional ways (e.g., cement, lime, gypsum, FA).

Wiszniewski et al. (2017) studied some properties of the biopolymer stabilized medium sand. Medium sand stabilized with XG was tested in UCS and Triaxial tests. Bio-substance like XG can affect the system in three varied methods. One of them is biocementation, biocementation increase the shear strength of the soil that is applied. Another one is bioclogging, bioclogging decrease the permeability of the soil that is applied. Last one is biogas, biogas is consisted of microbially induced gasses and it alters the saturation degree of the soil that is applied. It was expressed that biopolymers are long-lasting, biologically decomposed and renewable. For these reasons, they are trendy materials for environmentally sustainable plans and projects. Another important point is that most of them remain stable for a change in pH and temperature. They have “plugging effect” and “binding ability” for soil particles by “creating cross-linking networks” etc.

These performances can be done with injection of bacteria or microbially induced substance (e.g., XG, guar gum, agar gum, sodium alginate etc.) to the soil. Previous studies highlighted XG for the ability of increasing strength, c value and affecting the cohesion, stiffness, conductivity and compressibility. Previous studies generally used cohesive soils so in this study sandy soil was intentionally selected. It was noted that XG made the sandy soil cohesive and proper for UCS test.

Chang et al. (2019) studied consistency and micro scale characteristics of the stabilized soil. In this study XG added soil was examined for consistency and micro scale characteristics with pore fluid differentiation. Four types of soil (i.e., sand, silty soil, montmorillonite and kaolinite), were interacted solely with XG and tested for their interactions with XG. Interactions were investigated if they caused by individual particles or pore water and LL was used to insight it. Three varied pore fluid were used in this study (i.e., de-ionized water, kerosene and brine). Their affection would be either decrease the LL and creating aggregations and increasing permeability or increase the LL and creating hydrogels and filling/topping of the pore spaces. When de-ionized water was used, dominant factor was clay type and kerosene did not show significant changes.

For brine, in the lower dosages (lesser than 1%) LL decreased and created aggregations but in the higher values (greater than 1%) LL increased and hydrogels formed. This situation was explained as in first stage clay type was the dominant factor but in second stage pore water was the dominant factor.

For silty soil, de-ionized water made LL increased and created hydrogels as the pore water was the dominant factor. In kaolinite, LL started to increase until the 1%, after this level LL started to decrease so both stages were seen in this instance. In montmorillonite, LL decreased as the dosage increase. Furthermore, it was observed that for kerosene and brine, pore water was the dominant factor in most of the situations. It was noted that aggregations can reduce the “overall electrical sensitivity”. Effect of XG on sand and clay specimens are shown in Figure 2.17 and Figure 2.18 respectively. Regarding interactions and inside mechanisms are shown in Figure 2.19.

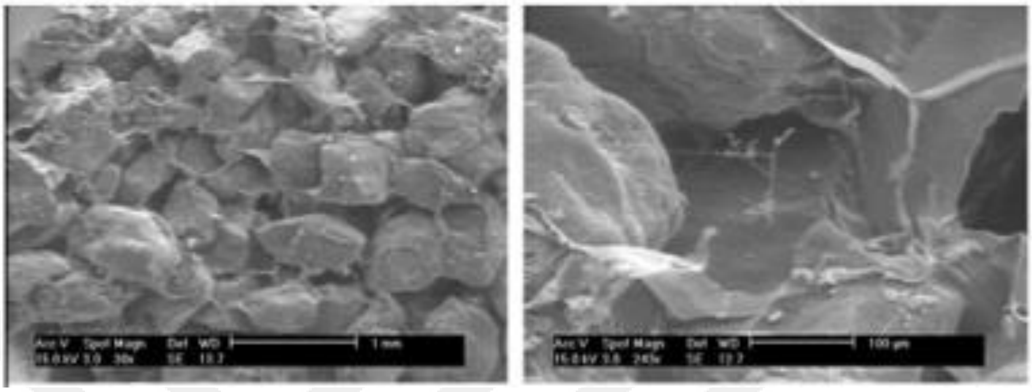


Figure 2.17 Effect of XG on sand specimen (Chang et al., 2015)

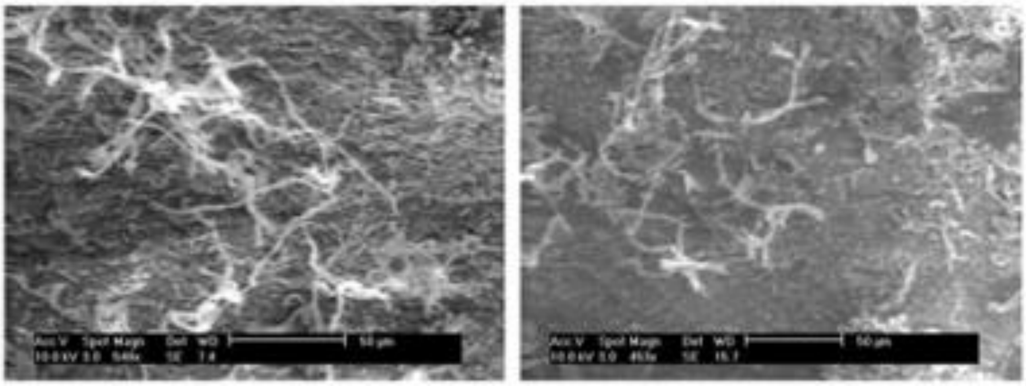


Figure 2.18 Effect of XG on clay specimen (Chang et al., 2015)

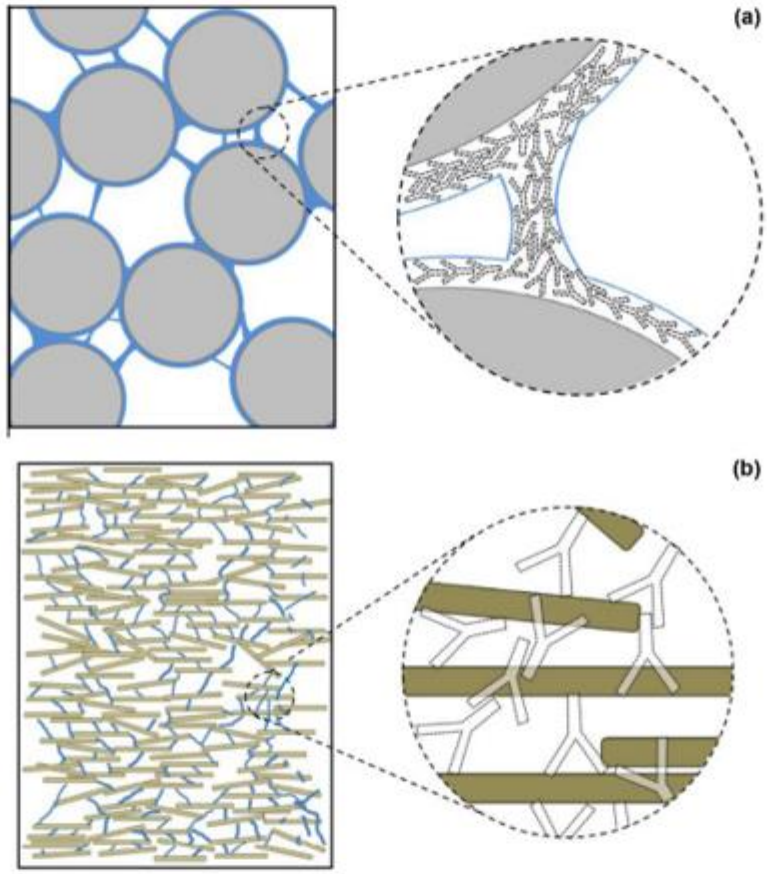


Figure 2.19 Interaction of XG with (a) coarse grains (b) fine grains (Chang et al., 2015)

Joga and Varaprasad (2019) examined the stabilization of an expansive soil with biopolymer. Expansive clay soil was stabilized with XG biopolymer and tested in UCS, compaction, consolidation and direct shear test. Results showed that UCS, OMC and shear strength parameters increased but MDD and compressibility decreased. Significant improvements were seen with the progression of curing days. Even using small percentages, immediate effects were seen after only 7 days. Optimum timeline was determined as 7-28 days, only slight differences were observed after 28 days. SEM images showed that XG addition made granulations in the soil and linked particles together, topping the pores and made the soil stiffer.

Sujatha and Saisree (2019) investigated characteristics of a soil stabilized with guar gum. A cohesive soil was added guar gum (a non-ionic polysaccharide) and tested in UCS, compaction, Atterberg limits, permeability, consolidation and durability. Immediate effects were seen in the results of the tests so that UCS, MDD and LL, PL increased, OMC and permeability, e value decreased. Permeability decreased because guar gum interacted with clay and created hydrogen bonding and gel. This gel filled the pores and made the soil stiffer and reduced the gaps. For consolidation and durability, swell and compressibility also compressibility index (C_c), coefficient for consolidation (C_v) and swelling index (C_s) decreased but shrinkage, stiffness modulus increased. Deterioration was not seen in the empirical process (almost 90 days). Durability was tested in wetting-drying cycles and it resulted below the allowable limit (14%). After all the tests, optimum value was found as 2% of guar gum by dry weight of the soil.

Joga and Varaprasad (2020) examined XG and behavior of the XG on dispersibility. Two types of dispersive soils were added XG in different percentages and tested in UCS, consolidation, permeability and dispersibility tests. It was observed that XG filled the interparticle pores and covered the soil particles which mitigate the repulsive forces that is applied by clay minerology. Accumulation of soil particles was seen. UCS of the system increased whereas swelling and compression, erosion rate, surface erosion and permeability decreased. Decrease in permeability resulted from filling of spaces and creation of “threads” in the pores. These effects became clearer with the progression of curing days and can be seen in SEM images. For compaction, MDD decreased but OMC increased, this behavior caused by viscous characteristics of the XG. 1% XG was determined as the optimum value for sustainability of the system.

Reddy and Varaprasad (2021) studied a biopolymer treated dispersive soil. A dispersive soil was treated with XG and checked for durability and Atterberg limits and UCS. It was stated that dispersive soils have high dry density but when they are exposed, they lose most of this property and erosion start. Generally, most of these processes occurs rapidly so reaction time is limited in most cases. researchers suggested to use polysaccharides, a class from biopolymers, because they are abundant and easy to find. XG increased LL and shear strength, UCS. XG biopolymer can also contribute to the forestation of the green areas. Their use with cement can mitigate the cracks in concrete and they are non-flammable and non-corrosive. Effect of XG on specimens can be seen in Figure 2.20.

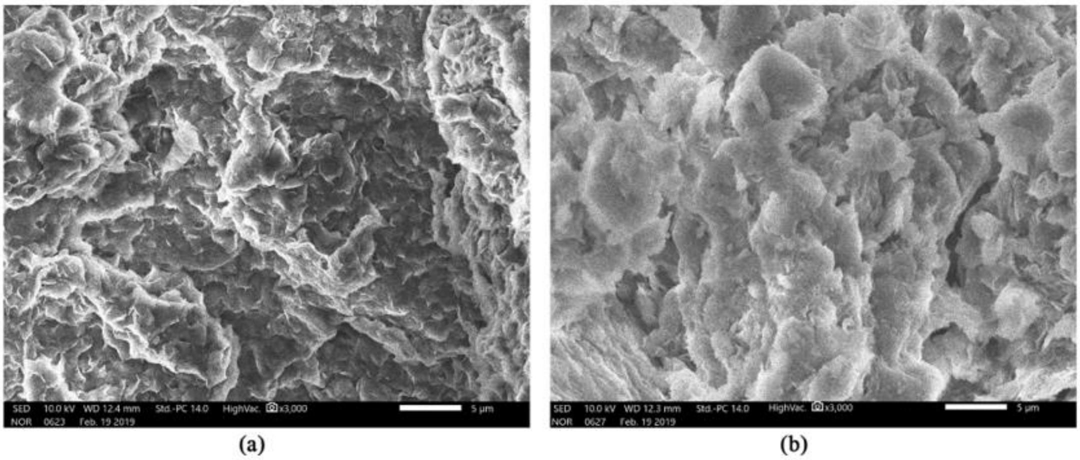


Figure 2.20 Effect of XG addition on sample (a) original (b) 28 day after (Reddy and Varaprasad, 2021)

2.3 Effects of Particle Shape on Soil Properties

Particle shape is a crucial parameter to define the behaviors of the soils. So that, if two identical soils with different shape and characteristics examined in experiments most of them would submit varied results. Particle shapes can be defined as their regarding sphericity, roundness and angularity. These particles can be ranged fully rounded to fully angular and these changes can affect most of the properties of the governing soils. Strength, capacity, permeability, cohesion and more can be altered with the change in these properties. Some vital parameters like spaces between particles or friction between particles or deposition types can decide the dominant behavior of them. Importance of these parameters and properties are getting recognized with time.

Odong (2007) studied seven empirical formulas based on PSD and shape parameters to define permeability of that soil. These estimations were compared with the actual empirical studies and approximation of the formulas were found. Even for the same soil type, some of the formulas gave varied results. Some of them made “overestimation” and some of them made “underestimation” when defining hydraulic conductivities. An important point to consider was, acceptable/appliable ranges of the formulas and specifications must be taken seriously to satisfy sustainable study. Formula from the study of Terzaghi gave the best accurate results for the defined soil in this study and least accurate formula was from USBR. Formula from Slitcher made an underestimation when dealing with permeability. Most well-known studies and equations are shown in Table 2.10.

Table 2.9 Permeability formulations with shape parameters (Cabalar and Akbulut, 2016)

Researcher/organization	Equation	Limitations
Hazen	$k = 6 \times 10^{-4} \times \frac{g}{v} \times [1 + 10(n - 0.26)] \times (d_{10})^2$	$C_u < 5$ $0.1 < d_{10} < 3.0$
Kozeny-Carman	$k = 8.3 \times 10^{-3} \times \frac{g}{v} \times \left[\frac{n^3}{(1-n)^2}\right] \times (d_{10})^2$	$0.5 < d_{10} < 4.0$
Terzaghi	$k = 0.0084 \times \frac{g}{v} \times \left[\frac{n-0.13}{\sqrt[3]{1-n}}\right]^2 \times (d_{10})^2$	–
Chapuis	$k = 1.5 \times (d_{10})^2 \times \frac{e^3}{1+e} \times \frac{1+e_{max}}{(e_{max})^3}$	–
Slitcher	$k = 1 \times 10^{-2} \times \frac{g}{v} \times n^{3.287} \times (d_{10})^2$	$0.01 < d_{10} < 5.0$
USBR	$k = 4.8 \times 10^{-3} \times \frac{g}{v} \times (d_{20})^{0.3} \times (d_{20})^2$	$C_u < 5$
NAVFAC	$k = 10^{1.291e-0.6435} \times (d_{10})10^{(0.5504-0.2937e)}$	$2 < C_u < 12$ $0.1 < d_{10} < 2.0$ $0.3 < e < 0.7$ $1.4 < \frac{d_{10}}{d_5}$
Alyamani and Sen	$k = 1300 \times [I_0 + 0.025(d_{50} - d_{10})]^2$	–
Breyer	$k = 6 \times 10^{-4} \times \frac{g}{v} \times \log\left[\frac{500}{C_u}\right] \times (d_{10})^2$	$0.06 < d_{10} < 0.6$ $1 < C_u < 20$

Li and Fannin (2008) examined two criteria for internal stability of a granular soil system. They defined that internal instability is dissipation of the soil particles inside the flow of water. It was observed that there are two common factors in these criteria which is PSD and shape factors. They defined criteria based on slope of PSD. One of them was Kezdi method and the other one was Kenney and Lau method. Kenney and Lau method can be seen in Figure 2.21. The first one is the well-known ratio of $D15/d_{85}$ and the other one is "stability index" H/F = 1. H stands for increase in mass and F is for fine mass. According to the empirical stage of this study, it was seen that Kezdi method is more suitable for gap-graded soils but for well-graded soils Kenney and Lau method is more preferable. For F=15%, this critical condition satisfies the both method in this regard. The indications can give substantial result for detecting if the system is stable or not. Below level than the critical value is more conservative for Kezdi method and above of the level is more conservative for Kenney and Lau method.

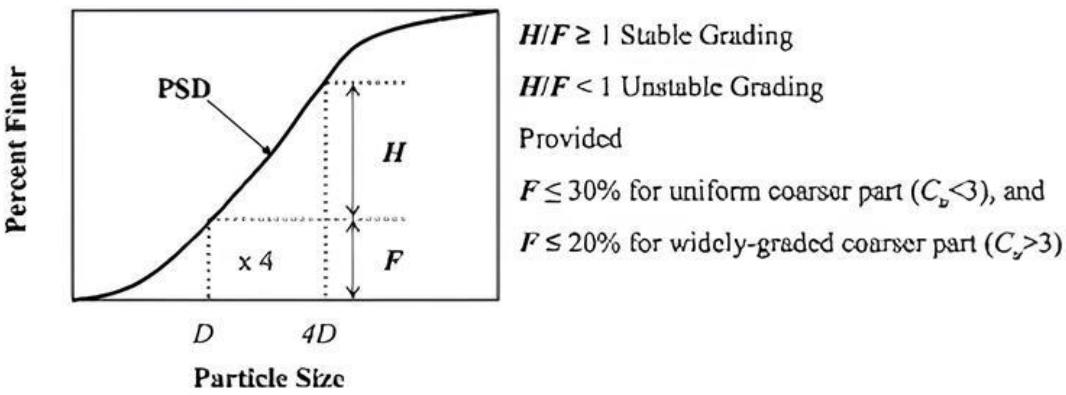


Figure 2.21 Kenney and Lau method for internal stability (Indraratna and Raut, 2006)

Clayton et al. (2009) defined a method for estimation the shape of the coarse particles. Basic particle shape properties can be seen in Figure 2.22. According to the literature, they defined three methods to identify the shape of the coarse particles. These methods were form, sphericity and roundness. Previous propositions about this topic includes 2-D studies but in reality, defining in 2-D is lack of perspective. 3-D studies were also not feasible and complicated to run the system. Therefore, they defined an ellipsoid with same volume and it was accurate according to comparison systems. It was important to see that mechanical behaviors of the soil systems were affected by the presence of the platy particles.

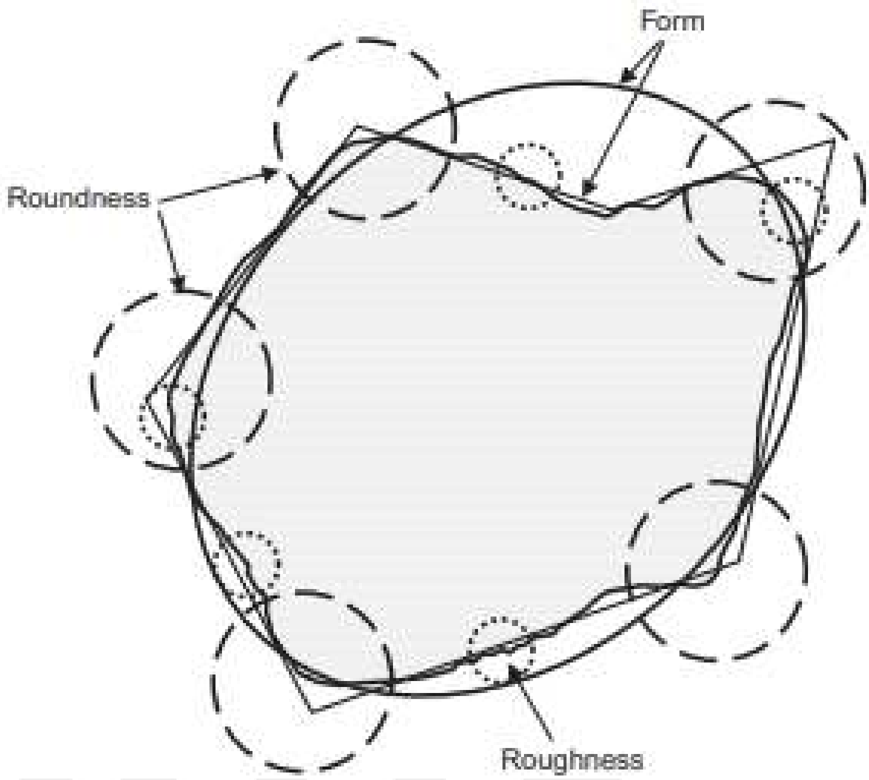


Figure 2.22 Particle shape properties (Clayton et al., 2009)

Abbireddy et al. (2009) studied the methodology for estimation the shape of fine particles. Previous studies about the topic were reviewed and 2-D studies were not approved to use because these studies were lack of real-life estimations and geometry for third dimension. 3-D studies lead to two different formulations but it was stated that in reality, there are so much irregular shaped particles so applying these conditions would be complicated and tough. Because of the fact that it is almost impossible to measure sphericity and roundness of the fine particles, only numerical study was conducted. They scanned the previous studies and generally found studies based on SEM visuals. Yet, these methods can be so subjective and erroneous. Another study based on turbidity and laser refractions gave reasonable results on most of the specimens and these relations also justified with the SEM images.

Göktepe and Sezer (2010) examined the influence of the shape characteristics on density and permeability of the sands. They conducted constant head permeability test and compaction tests. They defined shape characteristics on sphericity and roundness of the particles and they observed that roundness is effective for compaction/density and permeability. Gradation of the sands in this study were relatively similar to each other and there was no cohesion factor at all, these factors can be defined as the deficiency of the study. These systems were compared with the previous studies and empirical formulas and it was found effective. Formulas that include PSD parameters and roundness of a system, worked well with this study. Researchers also defined empirical formula according to this system. It was stated that Rd can also be defined from these formulas. Rd and permeability of this system can also be found from fractal explanations and statistical studies.

They also conducted a formula includes Kozeny-Carman equation and roundness parameters with respect to empirical stage of this study. It was expressed that defining an irregular shaped particle with the “fractal dimension concept” is possible and this concept converts this parameter into roundness and characterize the soil system. This concept also can give insights about the permeability and density of the soil. It was suggested to use this system also for determining the strength and capacity of the soil system. It was stressed that, this concept is not sufficient to use in situ yet but with the progression and inclusion of the data it may be in the near future.

Ishaku et al. (2011) investigated the process for creating an empirical formula to measure the permeability of the system based on PSD. This study compared 7 different formulas based on shape factor and their regarding PSD. Formulas were compared according to the similarity with the empirical results. To compare with the empirical results, Kozeny-Carman equation was the most realistic one, Hazen followed the Kozeny-Carman for accuracy. Alyamani and Sen formulation was highly dependent on the PSD shape. Breyer formulation was found reasonable with the “highly heterogenous” soils and Slitcher, Terzaghi and USBR formulations were labeled underestimated with respect to researcher.

Chapuis (2012) investigated the measurement of the permeability of soils. Researcher examined forty-five formulas which measures permeability, to define the limitations of them. Permeability of some soil types and drainage characteristics are shown in Table 2.11. Three of them were found suitable for non-plastic soils, two of them were found suitable for plastic soils and one of them was found suitable for compacted plastic soils. Researcher defined minimum requirement parameters and these forty-five formulas were examined by means of these parameters. Fourteen common mistakes were also detected for projects like this. This study was prepared with a care to not to do these fourteen mistakes. Previously created formulas and calculations in this topic in the literature, were examined. Another point worth to mention is that even if the study is numerical based, modelling based or network-based project, assumptions that consider all the factors are scalar, can be misdirecting. It would be very rare to expect a particles behavior same in all directional ways. For this reason, researcher suggested to use vectoral concepts to make the calculations and formulas more accurate. It was suggested to use correction factors to adjust temperature to in situ conditions and more studies are needed to investigate these systems.

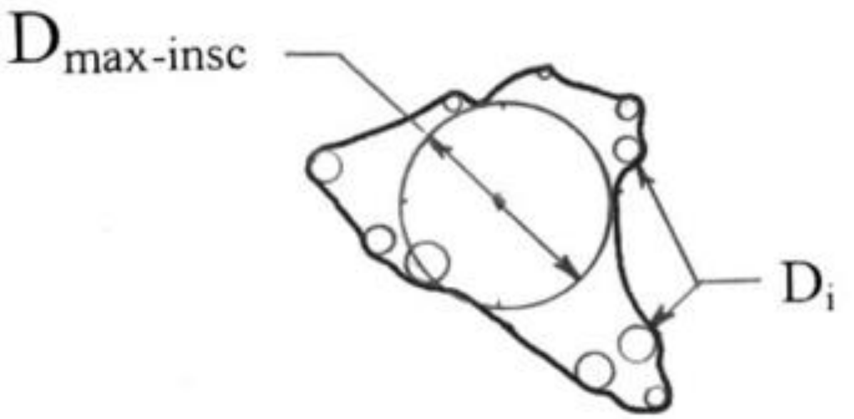
Table 2.10 Permeability of some soil types (Cabalar and Akbulut, 2016b)

Permeability (m/s)	10^{0}	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}
Drainage	Good						Poor		Practically impervious			
Soil Types	Clean gravel		Clean sands, cleansand & gravel mixtures			Very fine sands, organic & inorganic silts, mixtures of sand silt & clay, glacial till, stratified clay deposits, etc.				Impervious soils e.g., homogeneous clays below zone of weath-ering		
					"Impervious" soils modified by effects of vegetation & weathering							

Muszynski and Vitton (2012) compared the visual and automated methods for identifying particle shape factors in uniform sands. It was expressed that even though there are some technics to identify shape factors, most of them not objective and accurate. There are some technics to identify shape factors and some of them are automatic, manual, visual etc. These properties predominantly affect the coarse grain materials (i.e., sands and gravels). It was expressed that visual method is generally used for rough estimations especially when the particle size does not matter.

Yet, if a precise calculation is needed then automated or more qualified methods are offered. Even though automated calculations are more precise, R, S or angularity properties must be given as input correctly so that any kind of erroneous move can result in rough values. It was stated that if angularity is high, then it gives min and max void ratios also high and results larger friction angle, yields higher compressibility so any kind of mistake in angularity would give undesirable results. It was observed that even this concept works well on the coarser sands, it may not work well on fine sands or materials that have quartz minerals. It was reported that it may also not be efficient for very angular materials or crushed sands.

However, automatic systems still give advantages for being time-efficient and feasible. Automatic systems for coarse grained materials are reported that they are actually in use and their usage sustainable and advantageous. R and S parameters of an individual particle can be seen in Figure 2.23 and Figure 2.24 respectively.



$$R = (\Sigma r_i/N)/r_{max\text{-}insc} = (D_{i\ ave})/D_{max\text{-}insc}$$

Figure 2.23 Demonstration of the roundness parameter (Muszynski et al., 2012)

Salarashayeri and Siosemarde (2012) investigated the making predictions for permeability from PSD. It was expressed that hydraulic conductivities of the systems may be predicted from PSD of the regarding soils and some specific diameter sizes. These predictions were satisfied with the empirical studies and the results were related with each other. They conducted experiments with twenty-five sets of specimens and they accumulated these results with “regression analysis”. The results indicate that R^2 = 0.52 and important sizes were D_{10}, D_{50}, and D_{60}. However, calculations were closely dependent with D_{10} particle size.

Cabalar and Akbulut (2016a) studied the effects of shape factors and regarding sizes of the sands on permeabilities. It was noted that permeabilities are influential parameters for strength, settlements and drainage for soil systems. Specific particle sizes, C_u, Cc, S and R etc. values can affect the permeabilities of a system. Researchers expressed that even though there are numerous formulas to measure permeability, only a limited of them include these parameters. Gradationally, it was expected that particle sizes and indirectly e values affect the permeabilities.

According to the study it was observed that, roundness is the biggest influential parameter to consider hydraulic conductivities. Sphericity was lesser dominant than roundness. When comparing roundness, if the soil is more angular it would enable flow to pass the soil matrix with ease and give higher permeability values.

For sphericity, when comparing if the R value is high then this parameter is not that important but if the R value is low then increase in S gives substantial effects and increase the permeability values. It was suggested to give more effort for this topic to create a clear understanding especially for interparticle scale. Combined R and S table can be seen in Figure 2.25.

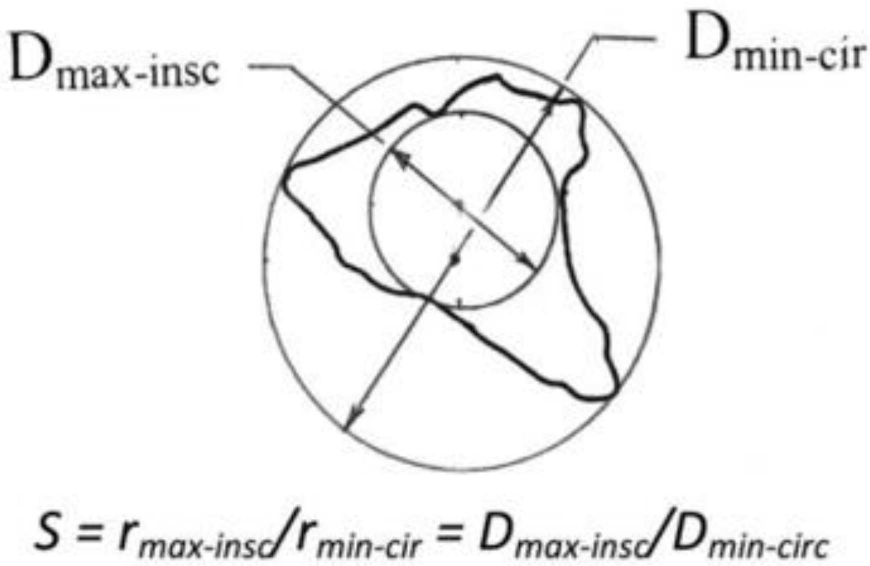


Figure 2.24 Demonstration of the sphericity parameter (Muszynski et al., 2012)

Cabalar and Akbulut (2016b) compared the actual and estimate measurement of the permeabilities of sands with varied size and shape factors. Gradations of a soil directly affects the permeability of that soil because of the e value. Parameters like D_{10}, D_{50}, D_{60}, D_{85} and also C_u, Cc, n were found influential on the permeability of the soil systems. It was also noted that formulations can give close results but it would be more precise and realistic to also conducting empirical stages. It was suggested to examine these parameters more detailed and rigorously to establish a clear understanding and knowledge.

Cabalar et al. (2022) conducted experiments for clay-gravel combinations. The main aim of the study was investigating the usage of locally found rounded gravel particles instead of manufactured angular particles in road and pavement design. Comparisons were made based on the results of the experiments (i.e., UCS, consolidation, CBR and compaction). Previous studies about the topic showed that particle shape and characteristics, additive dosage have influential effects on the behaviors. It was noted that density, liquefaction, strength etc. parameters directly affected by these effects.

Results showed that using locally available rounded particles instead of manufactured, angular aggregates is suitable and CBR, UCS values increased. MDD increased and OMC decreased in compaction test. Consolidation test showed that e value decreased with the usage of rounded particles instead of angular particles. The reason for this behavior explained as rounded particles reached higher load capacity and clay particles filled the pores of the rounded particles with ease. It was expressed that particle shape is more dominant factor than the size of the particles on behavior. Shape of the particles were defined with two basic properties, S and R. They defined a boundary condition called “transitional gravel content” which decides the system working as fine dominant or coarse dominant. Further study about the “transitional gravel content” was advised.

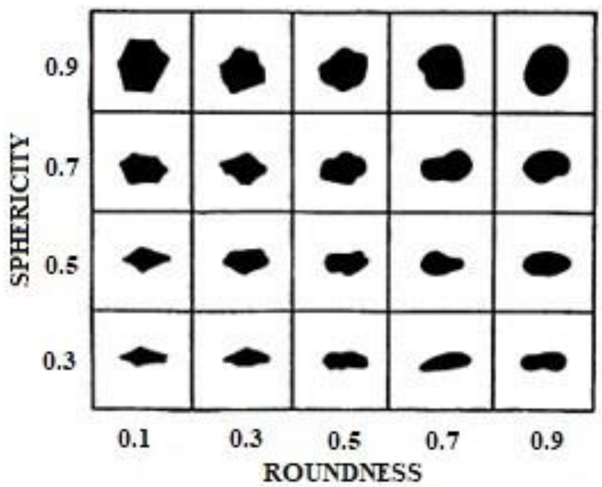


Figure 2.25 Combined chart for S and R (Rearranged after Cabalar and Akbulut, 2016)

CHAPTER 3
MATERIAL and METHOD

3.1 Materials

In this study materials that were processed are divided into two sub-classes as grain sizes. In initial class it is fine grain materials which consist of clay-based base soil (BS), Bentonite type of clay, an industrial by-product named TWP and a biopolymer named XG is introduced at this part. In the second part coarse grain materials that were used, are introduced as a drainage toe of a dam with CS, mining quarries of CSS and local river sand of NS.

3.1.1 Fine-Grain Materials

3.1.1.1 Base Soil (BS)

Base soil of this study was gathered from the campus of the Gaziantep University. BS consist of clay with low-plasticity (CL) according to unified soil classification system (USCS). Gs of the base soil is determined as 2.67 according to regarding American Society for Testing and Materials standard (ASTM C128-15). LL, PL and PI of the BS are determined as 34, 21 and 13 respectively regarding to ASTM D4318-17. OMC of the BS is determined as 18.5 % by its dry weight regarding to ASTM D2216-19. SEM image and figure are given in Figure 3.1 and Figure 3.2 respectively. PSD of the BS is given in Figure 3.12.

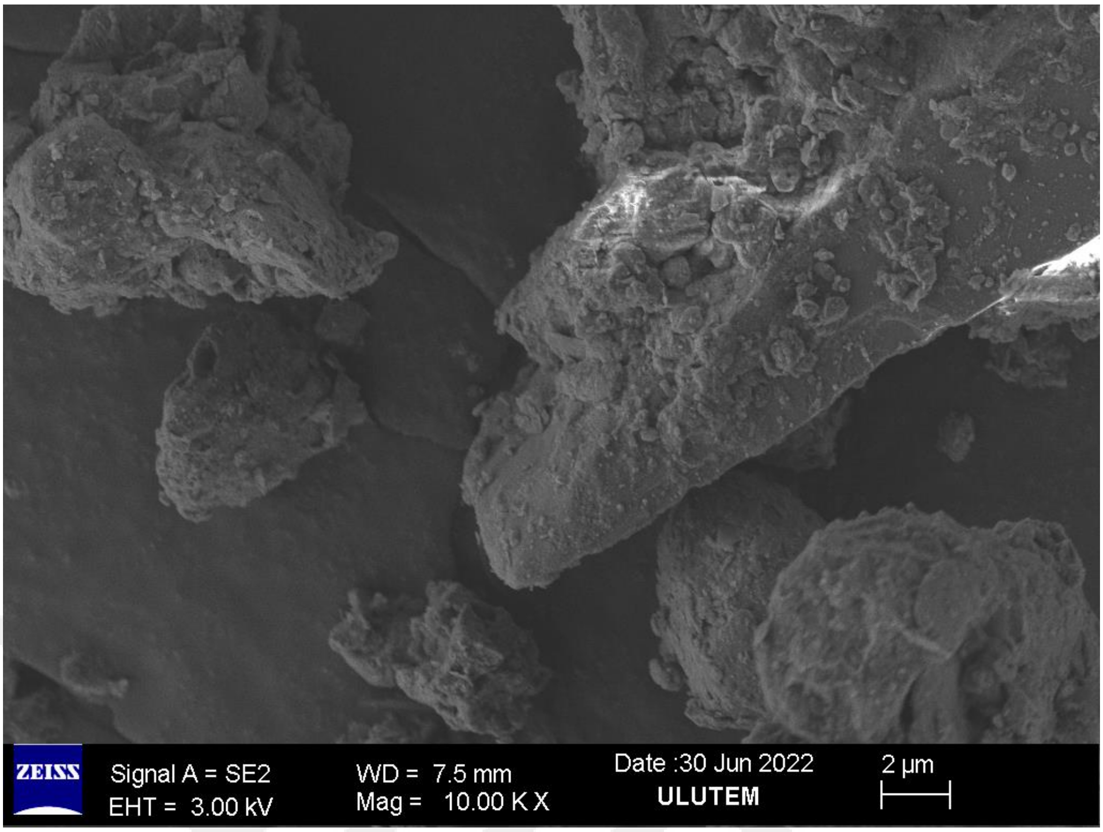


Figure 3.1 SEM image of the base soil

Figure 3.2 A view of the base soil

3.1.1.2 Bentonite

Bentonite is a unique soil that based on montmorillonite type of clay. Montmorillonite type of clay is generally known because of special properties like having enormous ratio for surface area to volume. For this reason, it can adsorb and absorb huge amount of water inside these double layers so that in can be problematic for some projects especially for water front structures (e.g., dams, embankments etc.). Bentonite in this project was delivered from Karakaya Bentonite Company in Türkiye. Gs of the bentonite was determined as 2.67 and LL, PL and PI of bentonite were found as 27, 15, 12 respectively. Gs of the bentonite and Atterberg Limits of it were determined just like in the standards (ASTM C128-15 and ASTM D4318-17 respectively). Chemical composition of the bentonite is given in Table 3.1. Figures and SEM images of the bentonite is shown in Figure 3.3 – Figure 3.4. PSD of the bentonite is also shown in Figure 3.12.

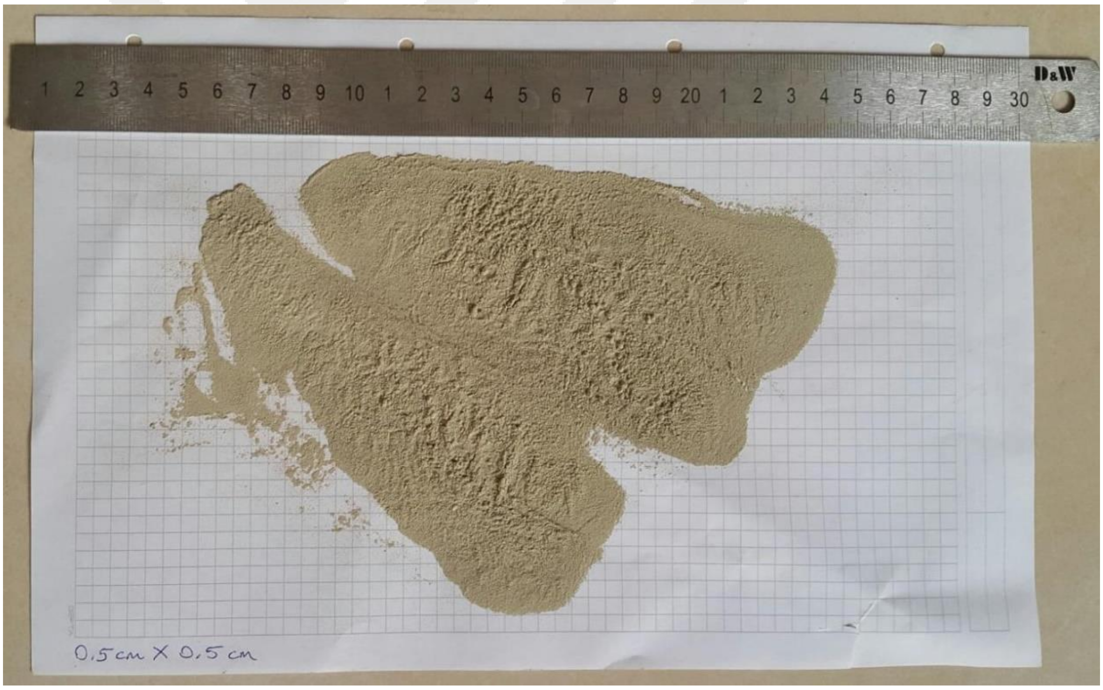
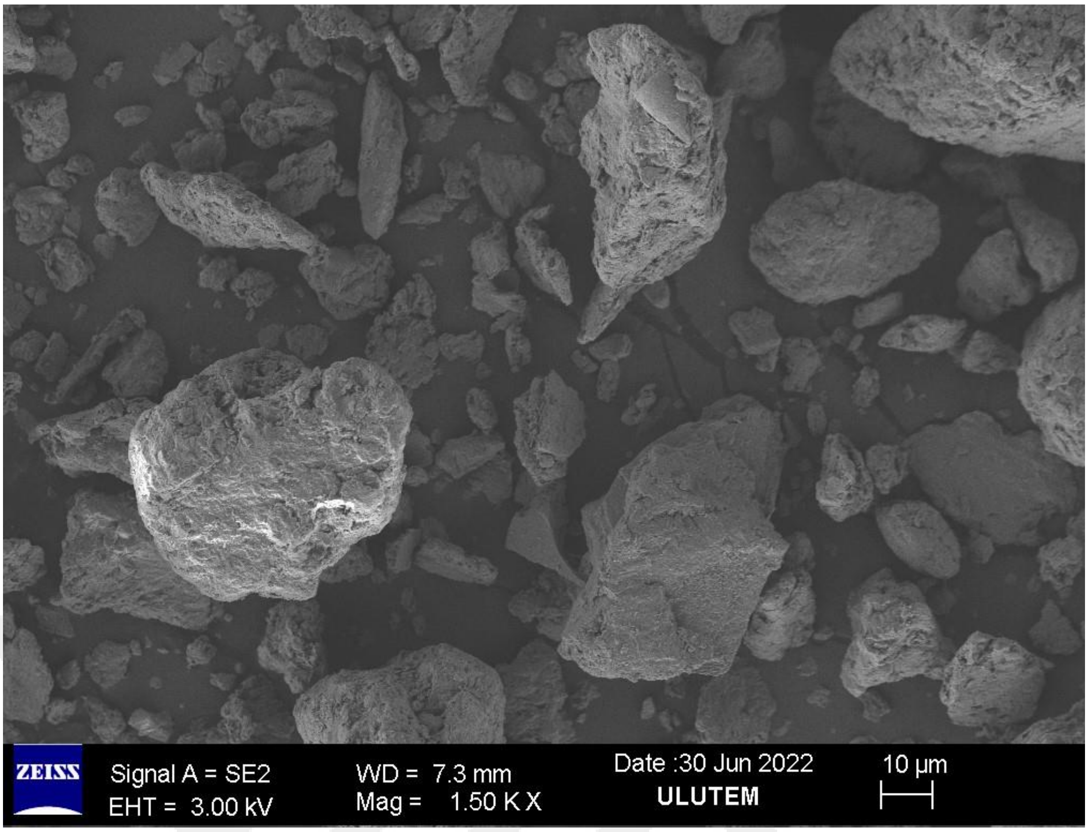
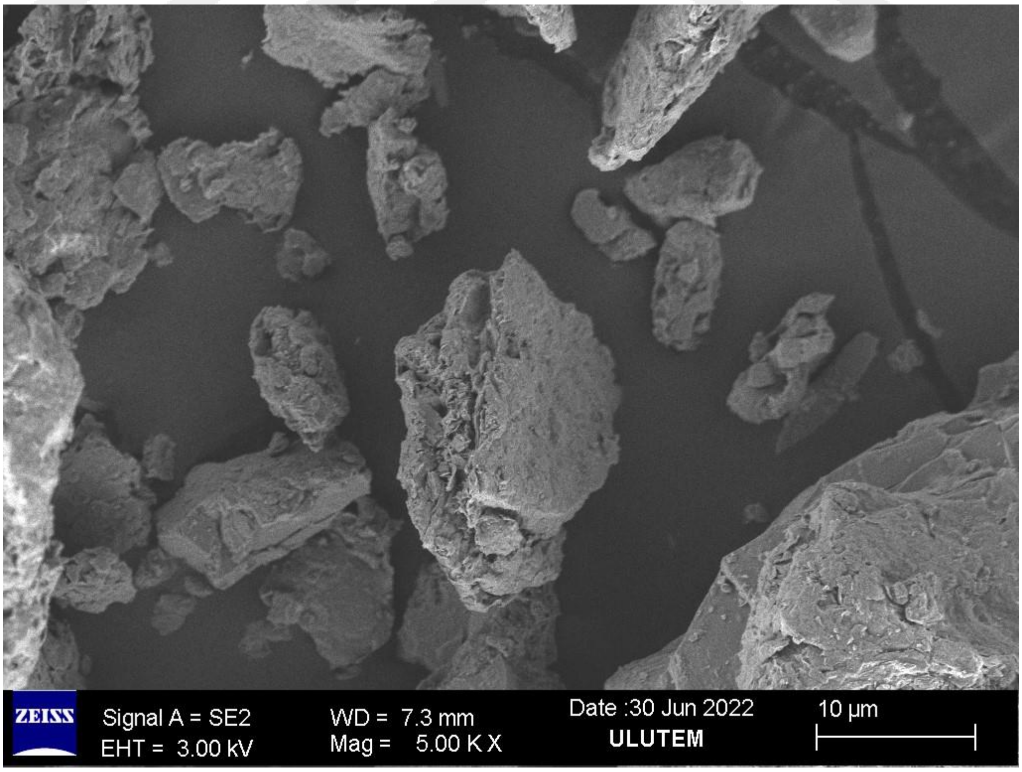


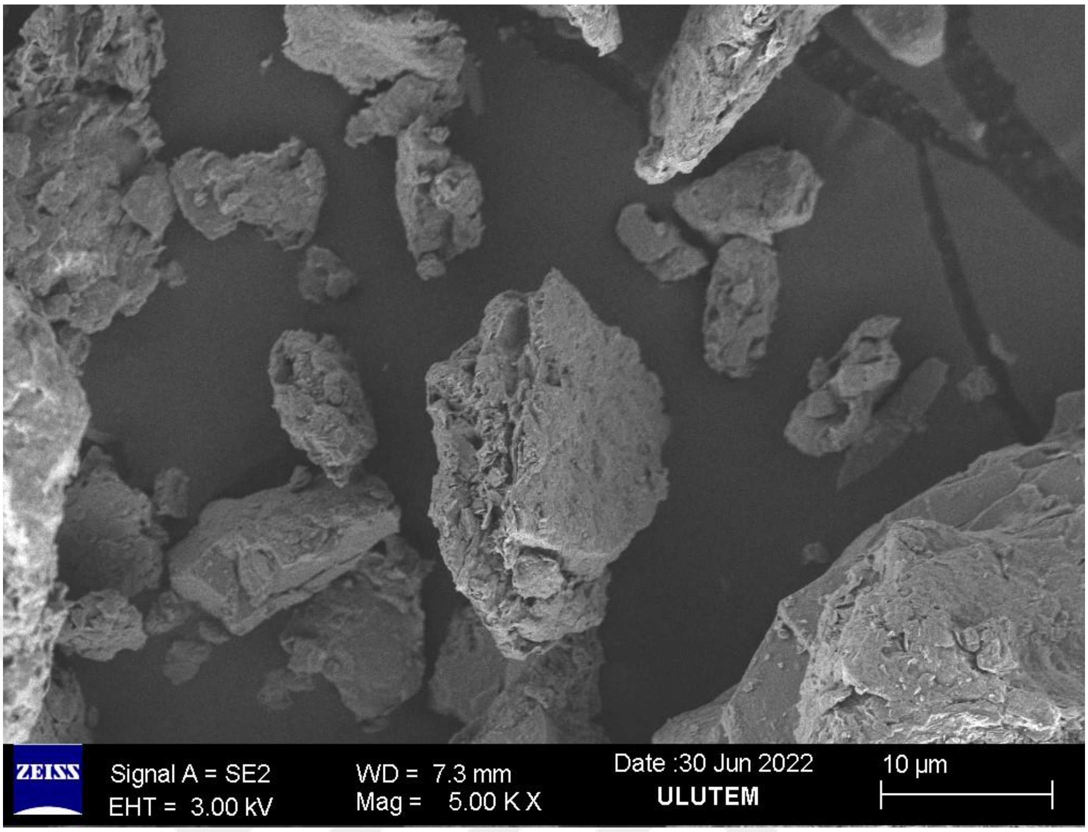
Figure 3.3 A view of the bentonite


ZEISS
Signal A = SE2
EHT = 3.00 kV
WD = 7.3 mm
Mag = 1.50 K X
Date :30 Jun 2022
ULUTEM
10 µm

(a)


ZEISS
Signal A = SE2
EHT = 3.00 kV
WD = 7.3 mm
Mag = 5.00 K X
Date :30 Jun 2022
ULUTEM
10 µm

(b)



(c)

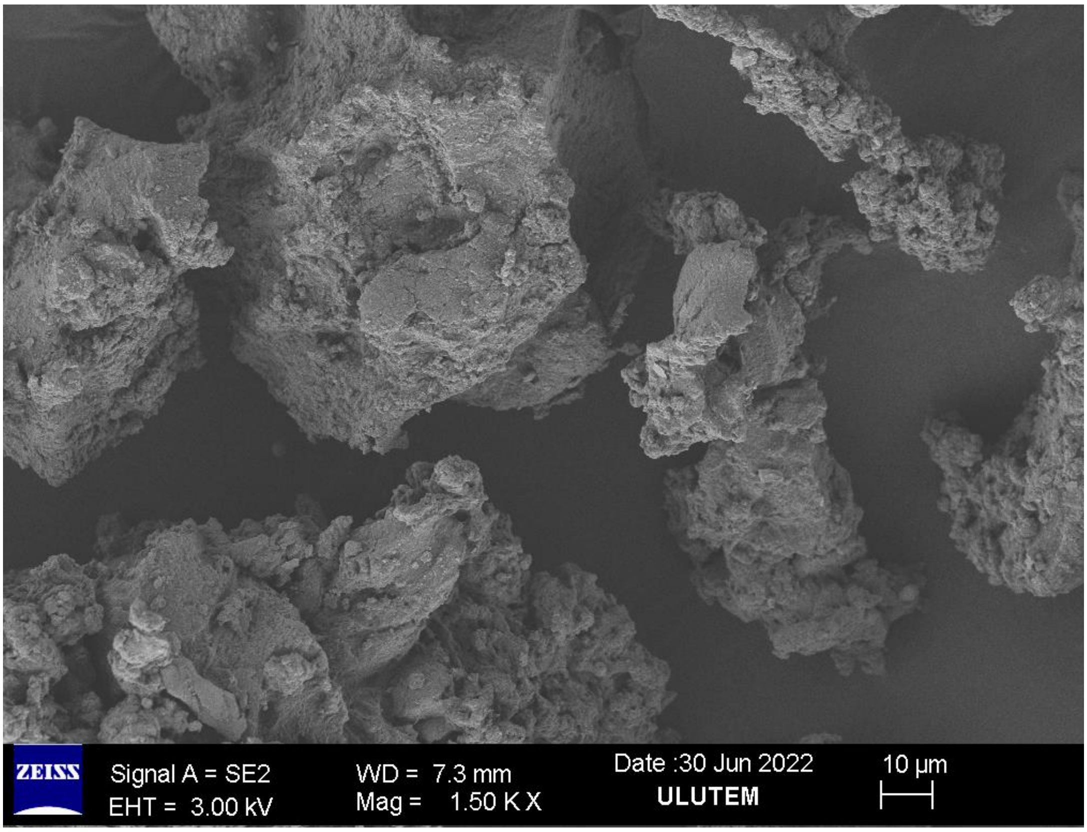
Figure 3.4 SEM images of the bentonite

Table 3.1 Chemical composition of the bentonite (According to Karakaya Bentonite Company)

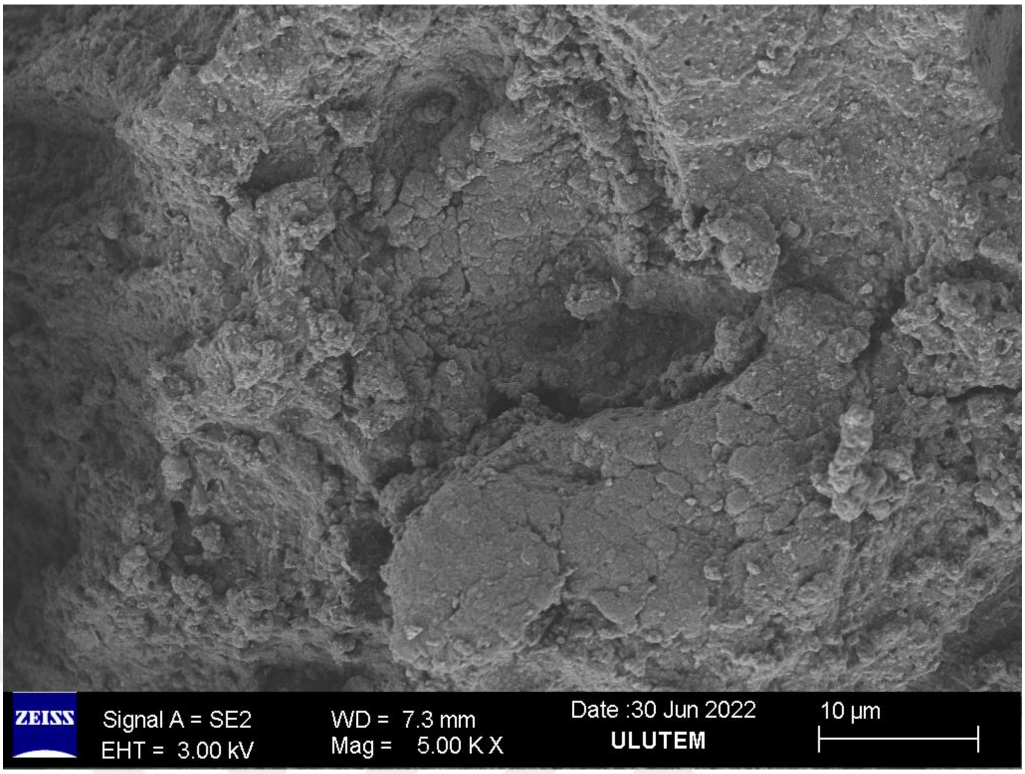
SiO_2	61.20%
Al_2O_3	18.60%
Fe_2O_3	7.31%
Na_2O	7.27%
MgO	3.35%
CaO	2.27%

3.1.1.3 Tire-Waste Powder (TWP)

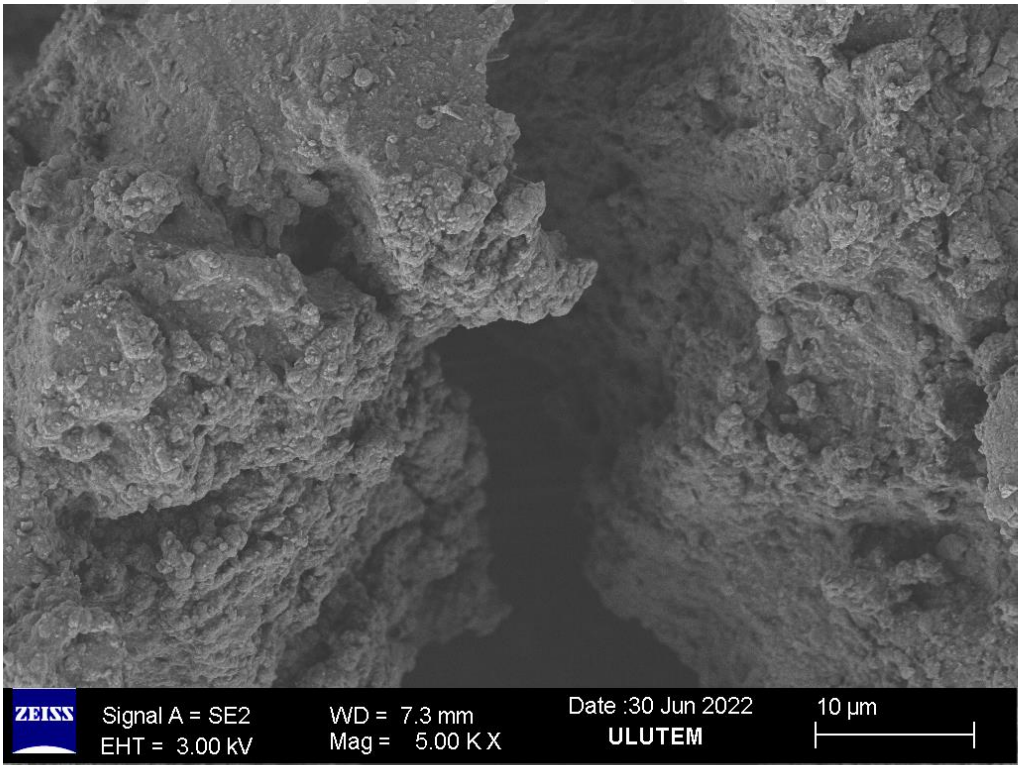
TWP is an industrial by-product which becomes a rising topic for using in soil stabilization and geotechnical projects (e.g., lightweight fills, road pavement designs etc.). Tire wastes are becoming critical issues for environmental aspects. These materials are discarded in huge amounts per year so that they create huge stockpiles in areas. Their disposal costs and efforts have been problematic for long time so that utilization becomes important. Tire-wastes can be gathered with reasonable prices from utilization centers and recycling facilities. PSD of the TWP can be found in Figure 3.12. Figures and SEM images are shown in Figure 3.5 – Figure 3.6.



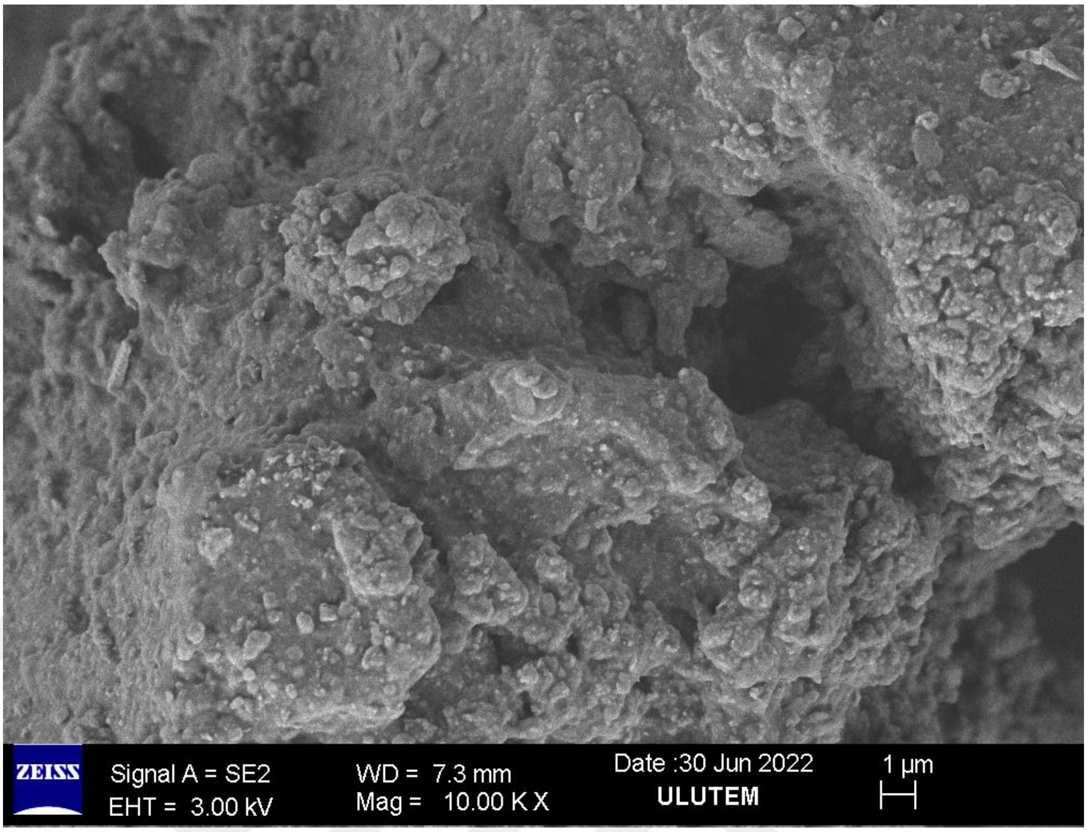
(a)


Signal A = SE2
EHT = 3.00 kV
WD = 7.3 mm
Mag = 5.00 K X
Date :30 Jun 2022
ULUTEM
10 µm

(b)


Signal A = SE2
EHT = 3.00 kV
WD = 7.3 mm
Mag = 5.00 K X
Date :30 Jun 2022
ULUTEM
10 µm

(c)



(d)

Figure 3.5 SEM images of the TWP

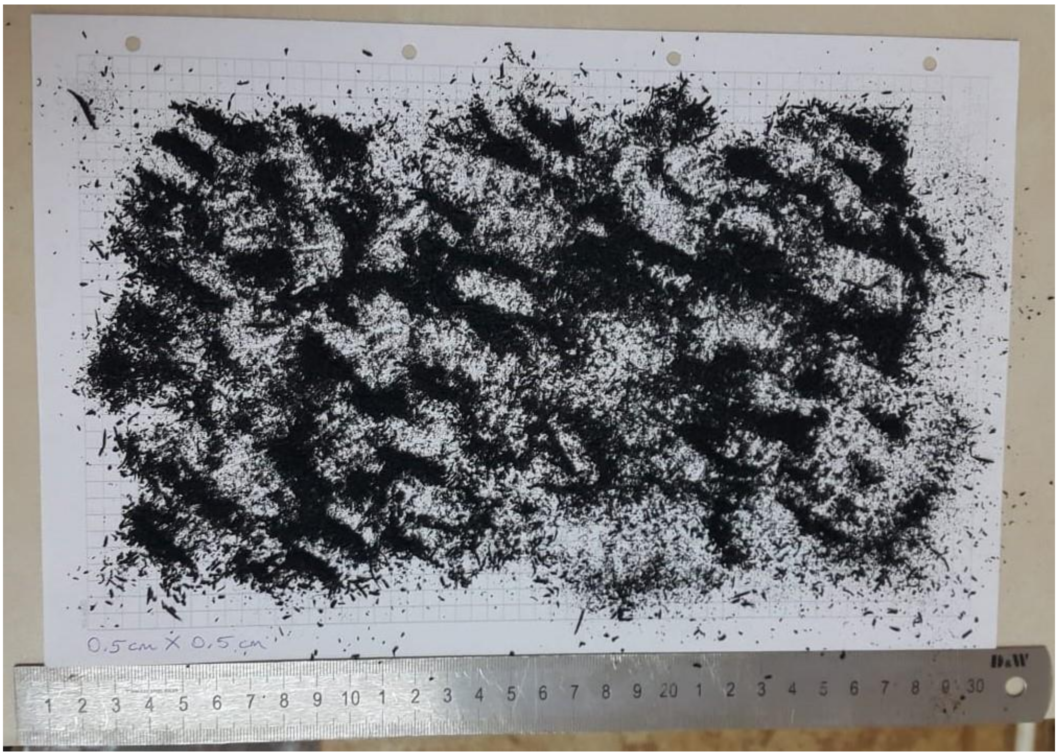
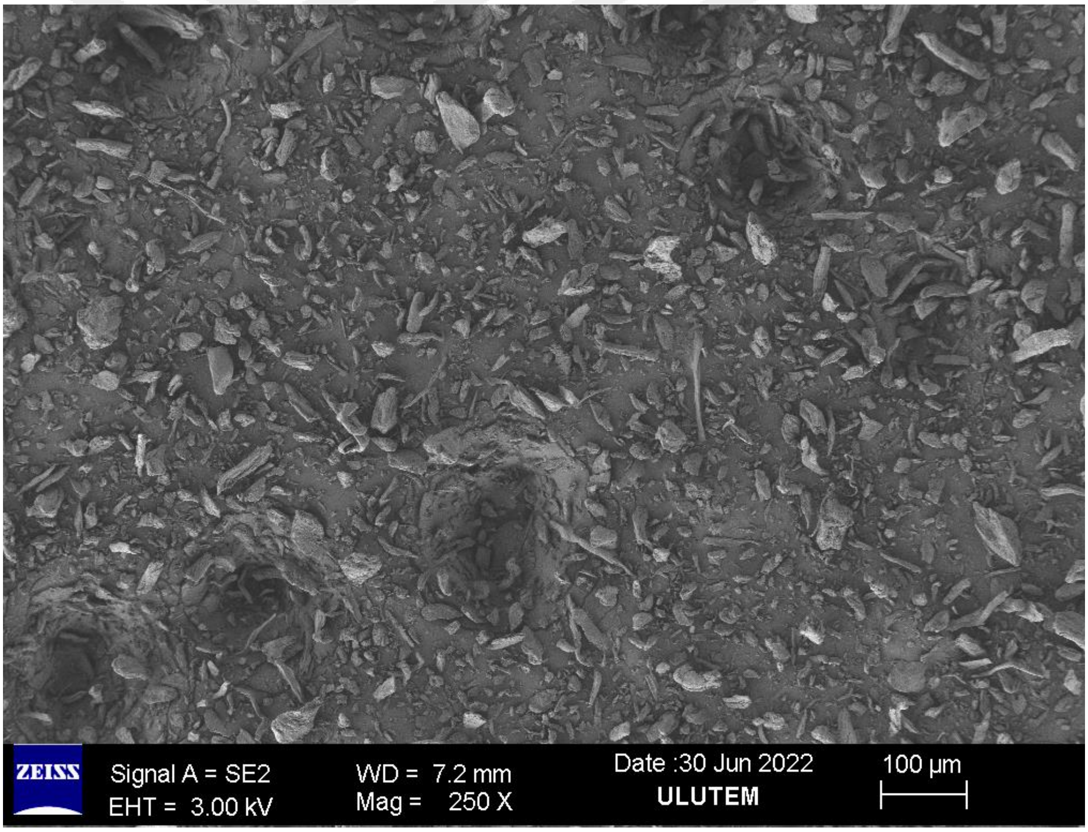


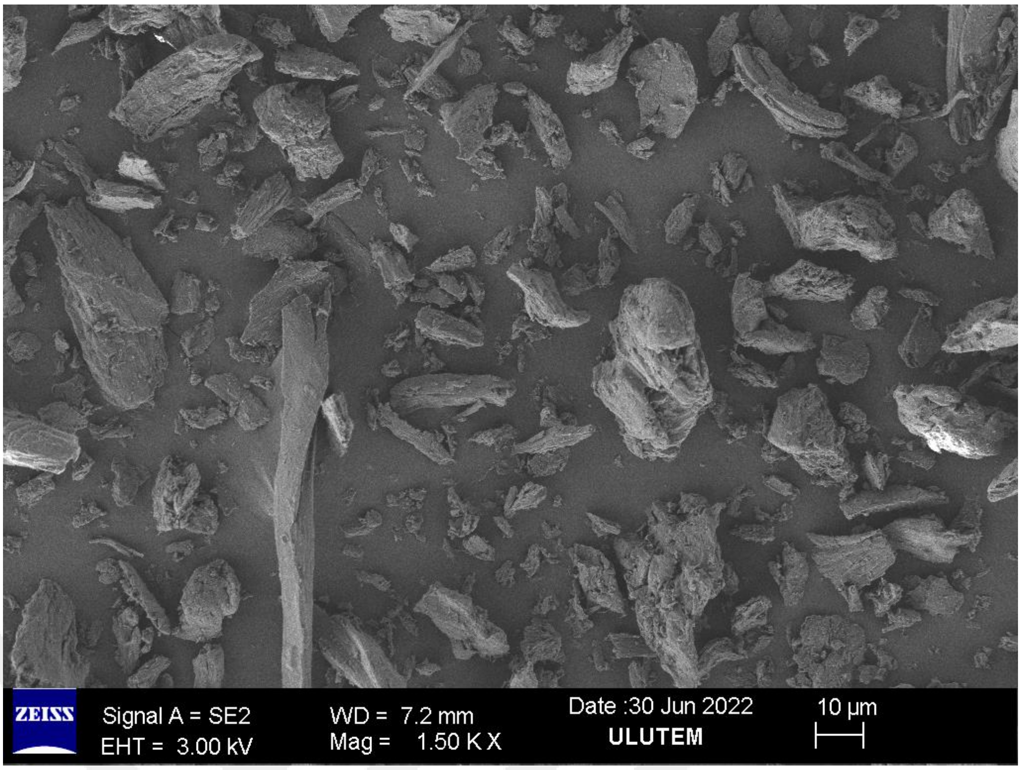
Figure 3.6 A view of the TWP

3.1.1.4 Xanthan Gum (XG)

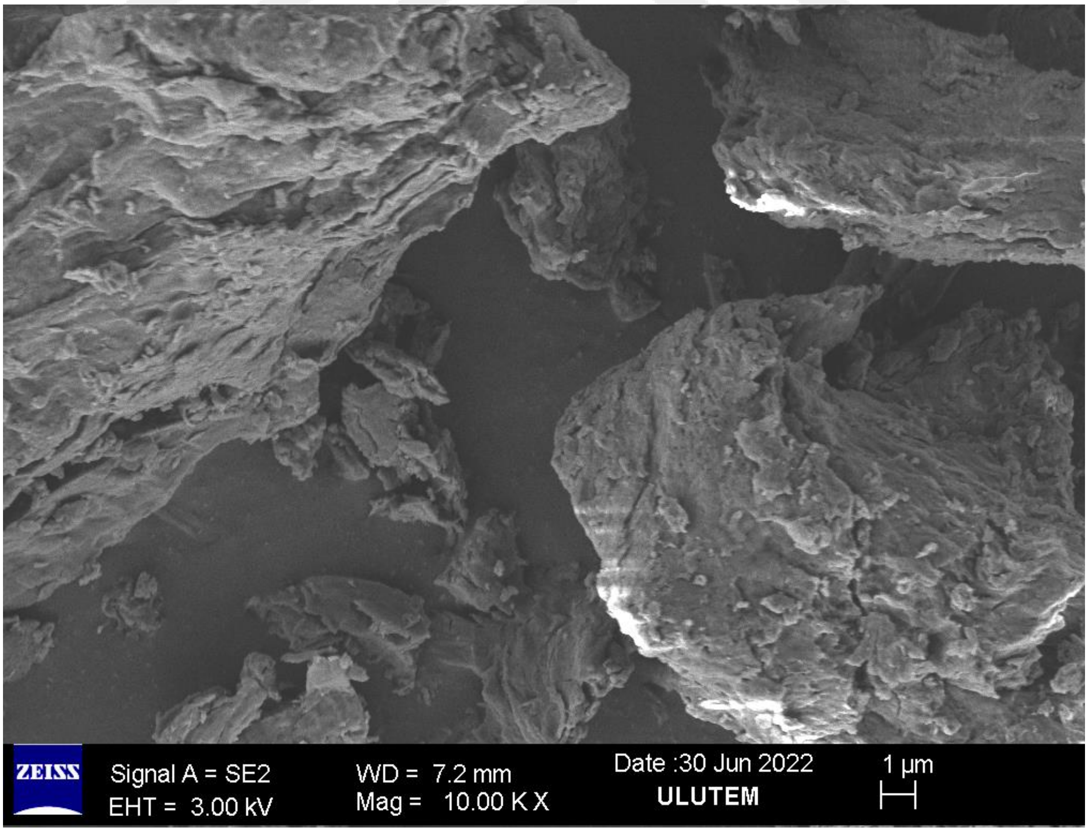
XG is a biopolymer that is precipitated from bacteria of *Xanthomonas campestris.* This material is gathered by microbial induction and has a variety of usage from cuisines to soil stabilization systems. XG is distinguishable with its unique odor and texture especially when saturated. It is considerably effective especially in suspension form and it can create hydrogels or cover the individual particles that can result in increase in stiffness and strength. Biopolymers specifically XG can be effective even in low dosages so it gives advantage over conventional additives (e.g., lime, cement, FA etc.). Unit price of XG progressively becomes more reasonable for utilization as it gets more recognition. XG can be found commercially available. Figures and SEM images are shown in Figure 3.7 – Figure 3.8.



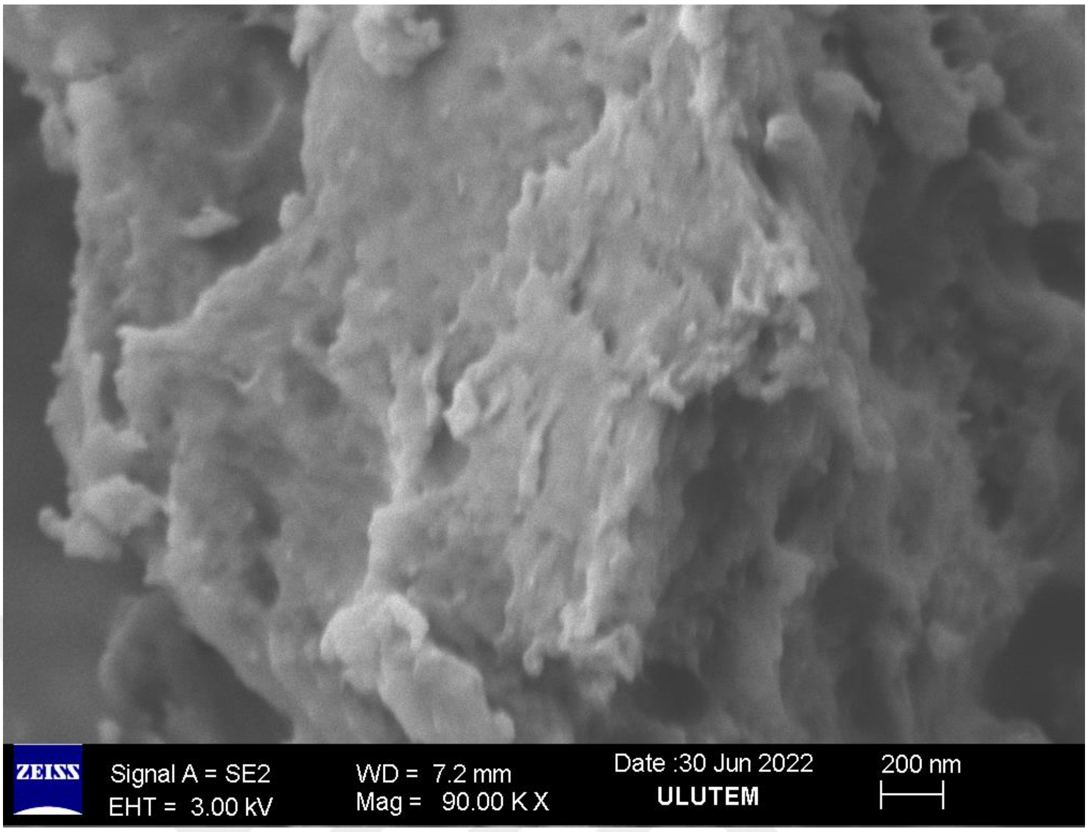
(a)


ZEISS
Signal A = SE2
EHT = 3.00 kV
WD = 7.2 mm
Mag = 1.50 K X
Date :30 Jun 2022
ULUTEM
10 µm

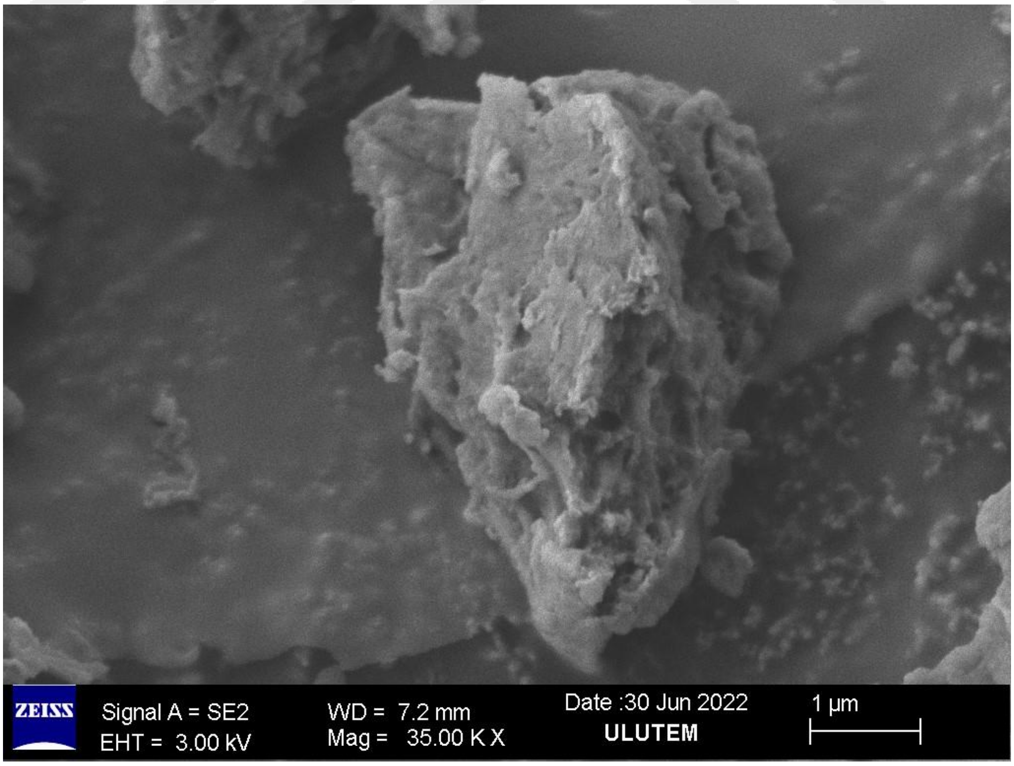
(b)


ZEISS
Signal A = SE2
EHT = 3.00 kV
WD = 7.2 mm
Mag = 10.00 K X
Date :30 Jun 2022
ULUTEM
1 µm

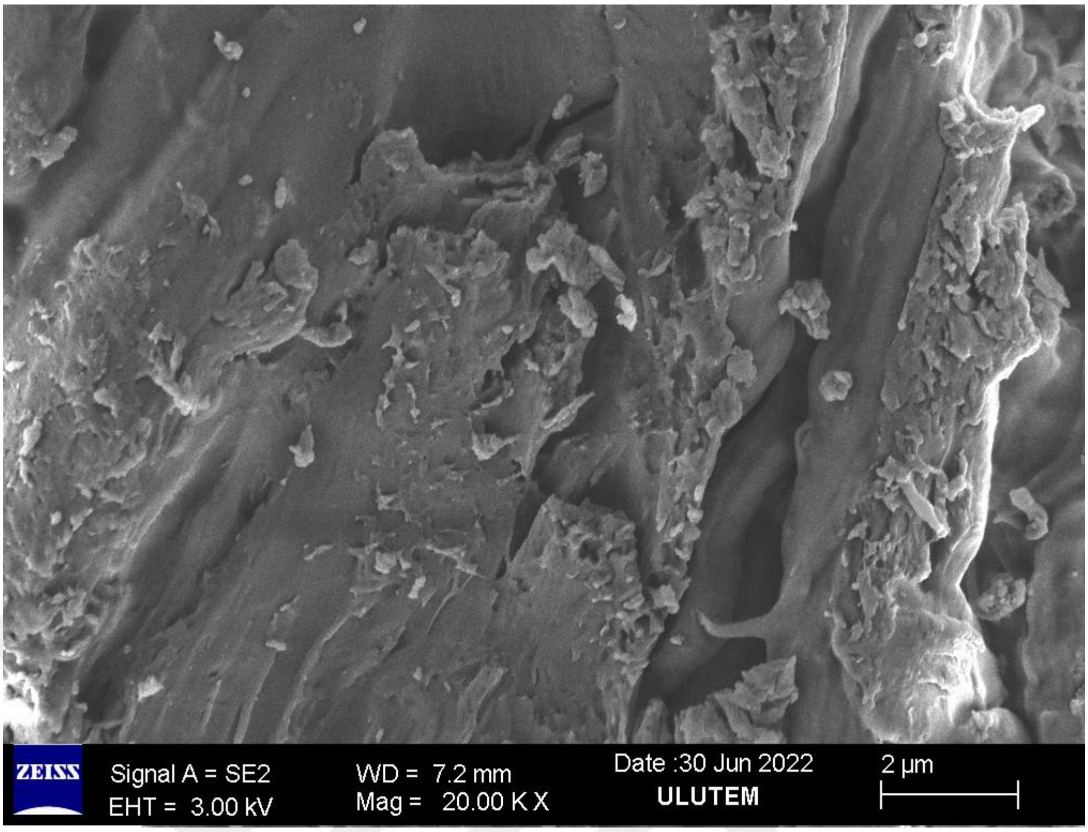
(c)


ZEISS
Signal A = SE2
EHT = 3.00 kV
WD = 7.2 mm
Mag = 90.00 K X
Date :30 Jun 2022
ULUTEM
200 nm

(d)


ZEISS
Signal A = SE2
EHT = 3.00 kV
WD = 7.2 mm
Mag = 35.00 K X
Date :30 Jun 2022
ULUTEM
1 µm

(e)



(f)

Figure 3.7 SEM images of the XG

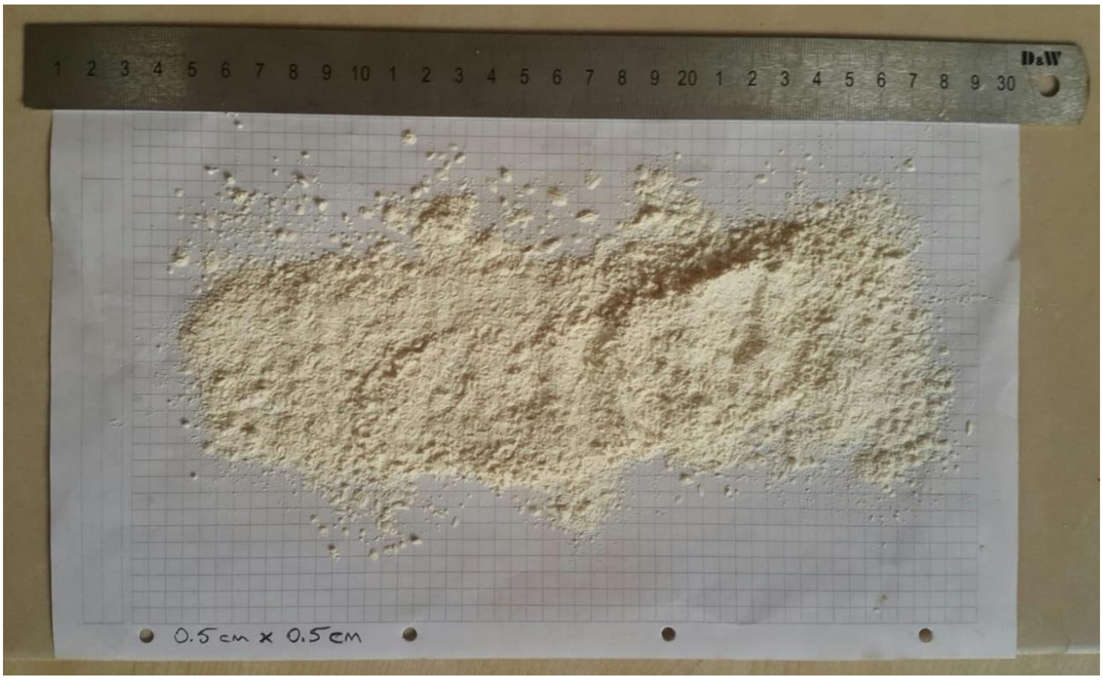


Figure 3.8 A view of the XG

3.1.2 Coarse-Grain Materials

3.1.2.1 Coarse Soil (CS)

Coarse soil in this study was gathered from the campus of Gaziantep University. CS in this study, was intentionally selected as a demonstration of a drainage toe of an earth-based dam. According to the USCS, soil is classified as poorly graded gravel (GP). Figure is given in Figure 3.9. PSD of the CS is given in Figure 3.12.

Figure 3.9 A view of the coarse soil

3.1.2.2 Crushed Sand Stone (CSS)

CSS is a uniform sand that processed from the parent rock of sand stone. Sand stone is a sedimentary rock majorly consist of quartz and other minerals. Sand stones can be collectable from mining facilities and stone/rock processing factories. Individual particle shape of the CSS is detected as angular. R and S values of the CSS were taken from the study of (Cabalar and Akbulut, 2016a, b). R, S and Gs values are given in Table 3.3. Some characteristic parameters of the CSS are shown in Table 3.2. Figure of the CSS is given in Figure 3.10. PSD of the CSS is in Figure 3.12.

Figure 3.10 A view of the CSS

3.1.2.3 Narli Sand (NS)

NS is a local river sand that was gathered from Narli region in the city of Kahramanmaraş, Türkiye. NS can be obtainable from the local utilization facilities. Particle shape of the NS was detected as rounded. Some characteristic parameters of the NS are shown in Table 3.2. R, S and Gs values are given in Table 3.3. R and S values of the NS were taken from the study of (Cabalar and Akbulut, 2016a, b). PSD of the NS is in Figure 3.12. Figures of the NS are given in Figure 3.11.

Figure 3.11 A view of the NS

Table 3.2 Some characteristic parameters of the materials used

	Base soil	Bentonite	NS	CSS	Coarse soil
D_{10} (mm)	0.002	0.005	4.15	4	16.5
D_{30} (mm)	0.005	0.0015	6.25	5.54	18.75
D_{50} (mm)	0.018	0.0037	7.67	6.6	19.98
D_{60} (mm)	0.078	0.0045	8.5	7.15	26
C_u	39	0.9	2.048	1.788	1.575
Cc	0.160	0.1	1.107	1.073	0.819

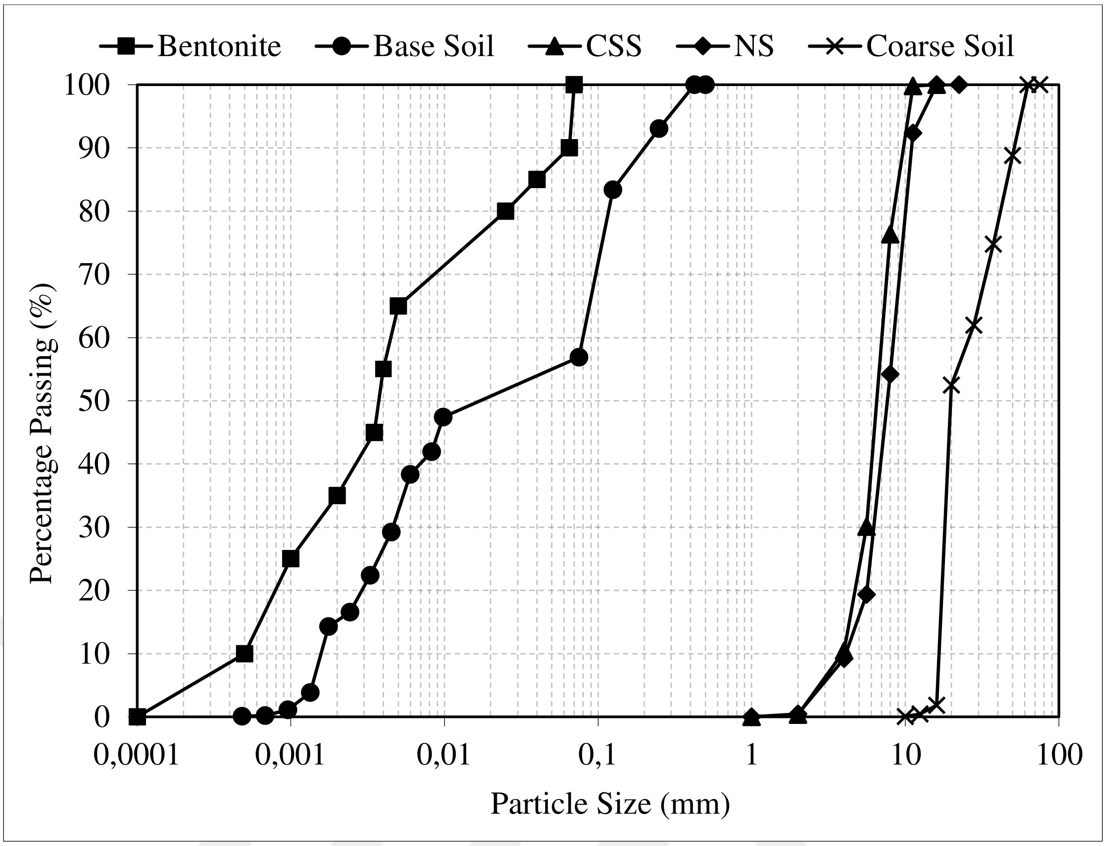


Figure 3.12 PSD of BS and CS, Bentonite, NS and CSS

Table 3.3 Gs, R and S values of the CSS and NS

CSS		NS	
Gs	2.56	Gs	2.63
R	0.16	R	0.43
S	0.55	S	0.67

3.2 Methods

In this study an effort was given to detect the dispersiveness of a stabilized dispersive soil. For that, conventional and well-known tests for observing dispersibility namely pinhole test, crumb test and double hydrometer test were conducted. After satisfying the stabilization of the dispersive soil, its regarding filter design criteria were made. To use in the appliable filter zone, two types of sands were selected. Because of their varied particle shape and characteristics, they were expected to behave different from each other in soil matrix in the filtering layer. To investigate this expectation, their regarding hydraulic conductivities were tested in constant head permeability test.

3.2.1 Constant Head Permeability Test

Constant head permeability test is conducted for defining hydraulic conductivities for coarse grain soils. In this study this test was conducted for determining the hydraulic conductivities for NS and CSS. With the help of "constant head" and differences between the selected manometers and their regarding water level, it is appliable to define a relationship between hydraulic gradient and soil layers. Constant head tank and manometers, specimen cell can be seen in Figure 3.13. To satisfy a precise test, saturation of the regarding tubes and pipes are critical for the sake of experiment. In this test, NS and CSS solely and with the mixtures of XG and TWP were tested in this experiment. Solely NS and solely CSS mixed with 0, 1, 3 % of solely XG and solely TWP with respect to their dry weights. These specimens were tested after 0, 7, 28 and 56 days of curing times. The all processes in this experiment were directly done according to regarding standard of ASTM D2434-19.

(a) (b)

Figure 3.13 (a) Constant head permeability test manometers and water tank (b) constant head permeability cell

3.2.2 Crumb Test

Crumb test is a reliable test for examining the dispersibility of a soil. From the previous studies, it is accepted as crumb test is a good indicator if the soil is not dispersive. In the crumb test, a 1-1.5 cm cubic specimen is prepared with the help of thumb and index fingers. After then, 125 mL distilled water is poured on leveled surfaced plate or pan. Equipment of the test is shown in Figure 3.14. Gently, this specimen is placed into the water, at the bottom of the plate. An instance specimen can be seen in Figure 3.15. Without creating any disturbance in still water, changes against the time (i.e., after 2m, 1h, 6h) are recorded. Cloudiness of the mixture is observed according to the time. With the help of effluence, classifications can be made. All these procedures were also strictly followed in this study with the help of ASTM D6572-21. In this study, BS was mixed with solely XG and solely Bentonite with 0.5, 1, 2, 3 % by respective dry weights. Specimens were tested after 0, 7, 28 and 56 days. Identical specimens were created for two times, one with the stretch film and one without it. The reason for that was, observing the change in the state of the specimens as one of them is air-drying (i.e., open to air) and the other one is conserving the moisture of the specimen.

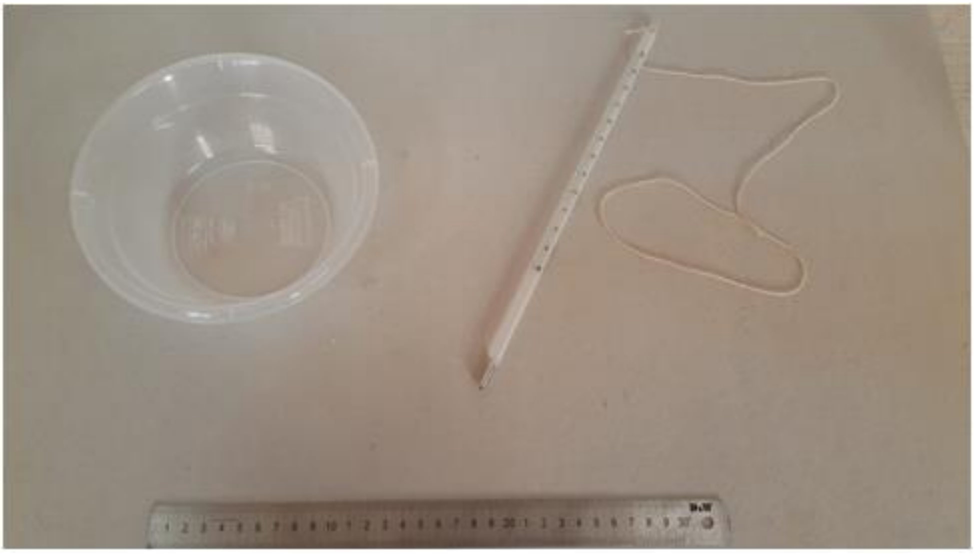
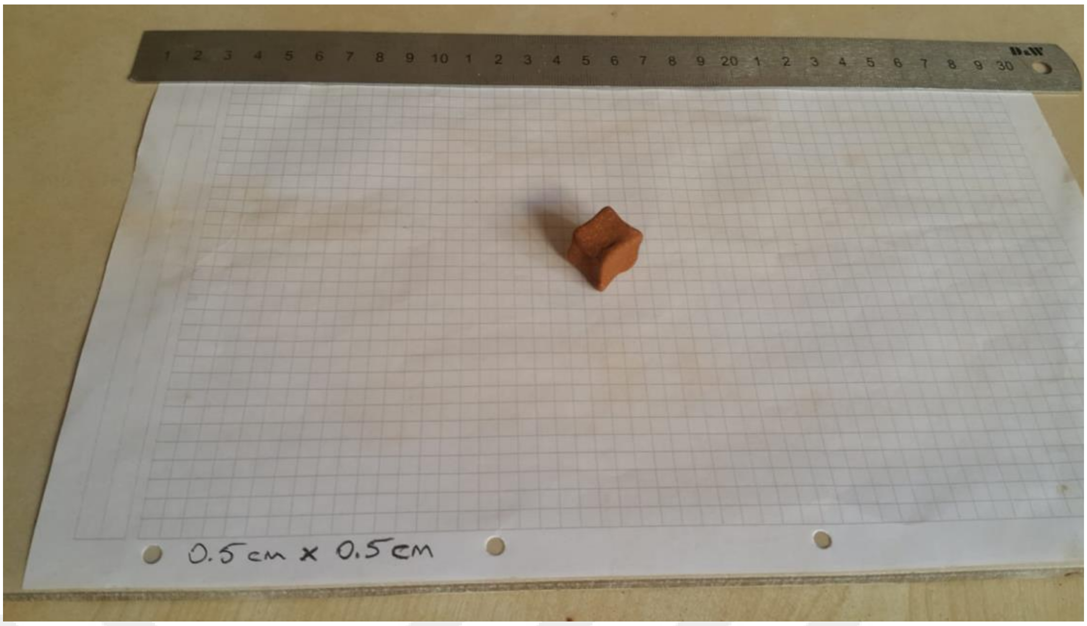
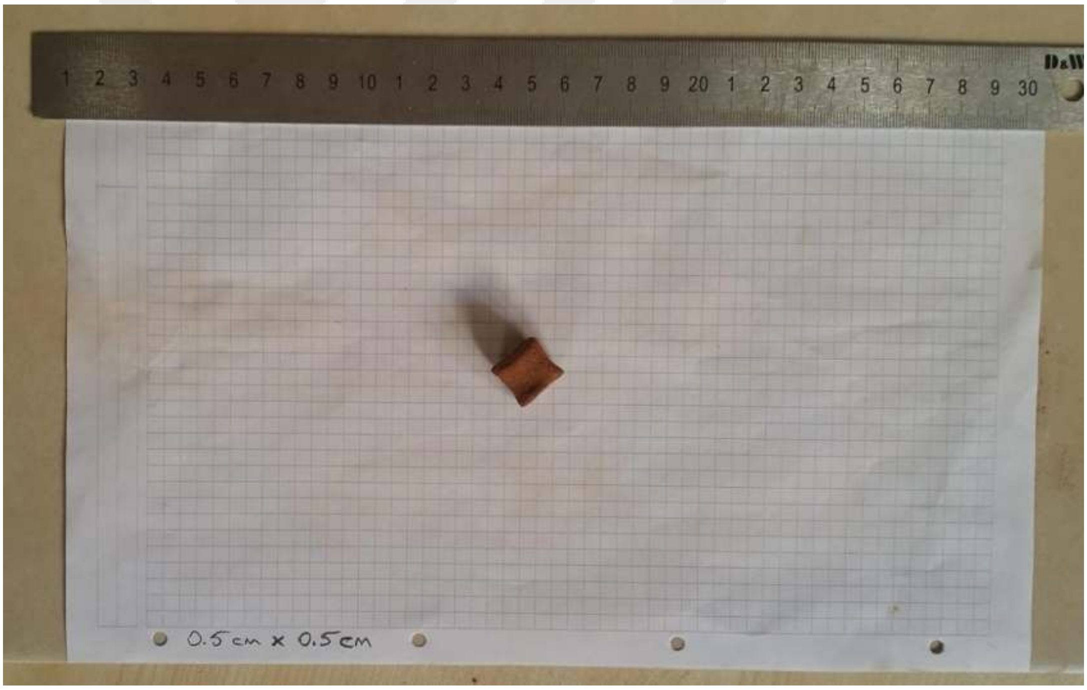


Figure 3.14 Crumb test apparatus



(a)



(b)

Figure 3.15 Crumb test specimen

3.2.3 Double Hydrometer Test

Double hydrometer test is a well-known test for identifying dispersibility in the soil. General procedure of the test is very similar to the hydrometer test which can be conducted for gradation purposes. Only major difference can be described as, in double hydrometer test procedure involves chemically and mechanically dispersion of the sample and creating a ratio between dispersed sample and non-dispersed sample. In this study, as a chemical dispersive agent sodium hexametaphosphate was selected. Specimens were created solely BS and their mixtures. As of mixtures, solely XG and solely Bentonite added to specimens with a percentage of 0.5, 1, 2, 3 with respect to their dry weights. Calculations were made after the specimens stayed in the oven for an overnight. All the procedures were strictly followed as in ASTM D4221-18. Equipment and sodium hexametaphosphate disperser can be seen in Figure 3.16 and 3.17 respectively.

Figure 3.16 Double hydrometer test apparatus

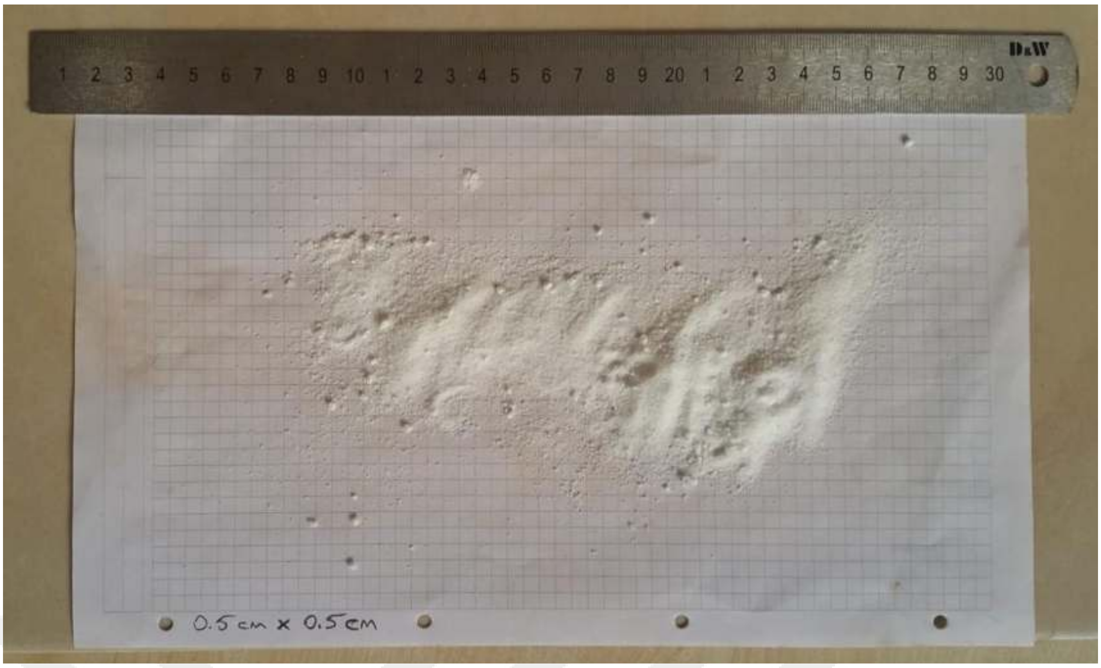


Figure 3.17 Sodium hexametaphosphate

3.2.4 Pinhole Test

Pinhole test is a well-known and also reliable test for detection of dispersion. In this test, dispersive soil particles suspend in the flowing water inside the specimen and they flow away from the specimen which creates dispersion and erosion. For this reason, pinhole test is a good indicator if the soil is dispersive. Procedures of mixing the soil with additives thoroughly and compacting it, breaking it down and compacting it again for evenly distribution of water inside the soil, were done step by step for the preparation of the sample. In this stage, all the meshes and caps must be placed up and down on the sample. After then, sand particles were placed also up and down. With the help of the needle, pinhole groove was created in the soil specimen. By placing the pipes for connection and with the saturation of these pipes, procedure was completed.

Getting the proper time readings at 10, 25, 50, 100 mL from outflow of the specimen under the 5, 18, 38 and 102 cm heads, it was possible to define a relationship between q and dispersion from the standard. Also, cloudiness of the outflow gave insight about the dispersion of the sample so that both q and cloudiness directed reasonable results for a specimen.

In this study, solely BS and mixtures of BS were processed in this test. For that reason, BS was mixed with solely XG and solely bentonite with the percentages of 0.5, 1, 2, 3. Specimens of the solely BS and mixtures of it, were tested after 0, 7, 14, 28 days of curing. Identical specimens were created and tested for the aim of testing it under with and without stretch film. By this way, it would enable to understand the effect of moisture conserving so that specimen with the film would conserve the moisture and humidity inside the specimen and the one without film would lose that. All the procedures of ASTM D4647/D4647M-13(2020) vigorously followed in this experiment. Pinhole test equipment can be seen in Figure 3.18.

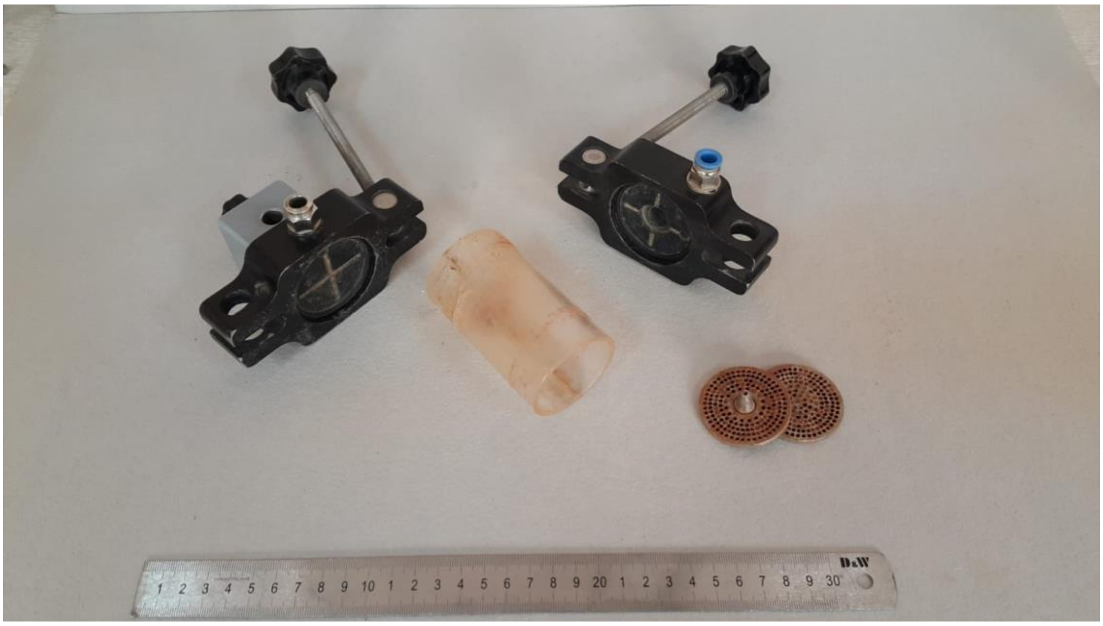


Figure 3.18 Pinhole test apparatus

Table 3.4 Testing Program

	Pinhole	**Constant Head**	**Crumb**	**Double Hydrometer**
XG	0.5, 1, 2, 3 %	0, 1, 3 %	0.5, 1, 2, 3 %	0.5, 1, 2, 3 %
Tire-Waste	-	0, 1, 3 %	-	-
Bentonite	0.5, 1, 2, 3 %	-	0.5, 1, 2, 3 %	0.5, 1, 2, 3 %
Curing	0, 7, 14, 28 days	0, 7, 28, 56 days	0, 7, 14, 28 days	-

CHAPTER 4
RESULTS

4.1 Crumb Test

Crumb test was conducted on base soil and mixture of the base soil with XG and bentonite. 0, 0.5, 1, 2, 3 % of additives were solely added to base soil and tested after curing days (i.e., 0, 7, 28, 56). Humidity and water conservation effect on specimens was also tested in the experiment with the application of stretch film on an identical sample for each specimen. Crumb test is known as a good indicator if soil is not dispersive so that addition of XG showed this effect in immediate and long-term. Even though, bentonite made the soil dispersive in short-term, dispersibility of the specimens slightly increased with the progression of curing days.

Results showed that even though they did not make any difference on dispersibility, humidity and water conservation (stretch film) caused slight differences on behavior of the specimen in the water. Using of stretch film and curing days made the specimens behave varied even though these variations did not change the ultimate decisions on dispersibility. Behaviors of the XG and bentonite can be explained by, XG as a polysaccharide, created viscous suspension in saturated form and fill the pores of the clay particles and suspension of XG and water mitigated the repulsive forces of the clay particles that they applied on each other as it can be resulted from exchanging of the cation in the clay. On the other hand, bentonite as a montmorillonite-based clay type, increase the dispersibility as montmorillonite can adsorb and absorb huge amount of water with regard to unit volume and induce the electrochemical status of the base soil clay particles by triggering repulsive forces by minerology. Concentration of cation in the clay particles of bentonite with base soil increase the dispersibility. Based on results, remediated base soil can be useable in filter calculations. Results of the tests are given in Table 4.1 to Table 4.4.

Table 4.1 Final results of the XG added specimens (stretch film on)

Stretch	Day	%	Final Degree	Result
+	0	0	DG2	Intermediate
+	0	0.5	DG1	Non - Dispersive
+	0	1	DG1	Non - Dispersive
+	0	2	DG1	Non - Dispersive
+	0	3	DG1	Non - Dispersive
+	7	0	DG2	Intermediate
+	7	0.5	DG1	Non - Dispersive
+	7	1	DG1	Non - Dispersive
+	7	2	DG1	Non - Dispersive
+	7	3	DG1	Non - Dispersive
+	28	0	DG2	Intermediate
+	28	0.5	DG1	Non - Dispersive
+	28	1	DG1	Non - Dispersive
+	28	2	DG1	Non - Dispersive
+	28	3	DG1	Non - Dispersive
+	56	0	DG2	Intermediate
+	56	0.5	DG1	Non - Dispersive
+	56	1	DG1	Non - Dispersive
+	56	2	DG1	Non - Dispersive
+	56	3	DG1	Non - Dispersive

Table 4.2 Final results of the XG added specimens (stretch film off)

Stretch	Day	%	Final Degree	Result
-	0	0	DG2	Intermediate
-	0	0.5	DG1	Non - Dispersive
-	0	1	DG1	Non - Dispersive
-	0	2	DG1	Non - Dispersive
-	0	3	DG1	Non - Dispersive
-	7	0	DG2	Intermediate
-	7	0.5	DG1	Non - Dispersive
-	7	1	DG1	Non - Dispersive
-	7	2	DG1	Non - Dispersive
-	7	3	DG1	Non - Dispersive
-	28	0	DG2	Intermediate
-	28	0.5	DG1	Non - Dispersive
-	28	1	DG1	Non - Dispersive
-	28	2	DG1	Non - Dispersive
-	28	3	DG1	Non - Dispersive
-	56	0	DG2	Intermediate
-	56	0.5	DG1	Non - Dispersive
-	56	1	DG1	Non - Dispersive
-	56	2	DG1	Non - Dispersive
-	56	3	DG1	Non - Dispersive

Table 4.3 Final results of the bentonite added specimens (stretch film on)

Stretch	Day	%	Final Degree	Result
+	0	0	DG2	Intermediate
+	0	0.5	DG3	Dispersive
+	0	1	DG3	Dispersive
+	0	2	DG3	Dispersive
+	0	3	DG3	Dispersive
+	7	0	DG2	Intermediate
+	7	0.5	DG3	Dispersive
+	7	1	DG3	Dispersive
+	7	2	DG3	Dispersive
+	7	3	DG3	Dispersive
+	28	0	DG2	Intermediate
+	28	0.5	DG4	Highly - Dispersive
+	28	1	DG4	Highly - Dispersive
+	28	2	DG4	Highly - Dispersive
+	28	3	DG4	Highly - Dispersive
+	56	0	DG2	Intermediate
+	56	0.5	DG4	Highly - Dispersive
+	56	1	DG4	Highly - Dispersive
+	56	2	DG4	Highly - Dispersive
+	56	3	DG4	Highly - Dispersive

Table 4.4 Final results of the bentonite added specimens (stretch film off)

Stretch	Day	%	Final Degree	Result
-	0	0	DG2	Intermediate
-	0	0.5	DG2	Intermediate
-	0	1	DG2	Intermediate
-	0	2	DG2	Intermediate
-	0	3	DG2	Intermediate
-	7	0	DG2	Intermediate
-	7	0.5	DG2	Intermediate
-	7	1	DG2	Intermediate
-	7	2	DG2	Intermediate
-	7	3	DG2	Intermediate
-	28	0	DG2	Intermediate
-	28	0.5	DG4	Highly - Dispersive
-	28	1	DG4	Highly - Dispersive
-	28	2	DG4	Highly - Dispersive
-	28	3	DG4	Highly - Dispersive
-	56	0	DG2	Intermediate
-	56	0.5	DG4	Highly - Dispersive
-	56	1	DG4	Highly - Dispersive
-	56	2	DG4	Highly - Dispersive
-	56	3	DG4	Highly - Dispersive

4.2 Double Hydrometer Test

Double hydrometer test was conducted with base soil and combination of the base soil with XG and bentonite with varied percentages. 0, 0.5, 1, 2, 3 % of solely XG and solely bentonite mixed with base soil and tested in the experiment. Test results showed that addition of XG decreased the dispersibility whereas addition of bentonite increased it. Increase in percentages also affected the dispersibility so that as the XG percentage increase dispersibility significantly decreased on the other hand as the bentonite dosage increase dispersibility drastically increased also. The reason for these behaviors, XG weaken the repulsive forces on clay minerals and by this way attraction forces between suspension and clay particles become more dominant and reduce the dispersibility. However, bentonite strengthen these repulsive forces with contribution on cation percentage and made the mixture more dispersible. So, improved base soil can be applicable for filter calculations. Results of the combinations are given in Table 4.5.

Table 4.5 Percent of dispersion with addition of XG and bentonite

Percent of Dispersion		
%	XG	Bentonite
0	34	34
0.5	33	51
1	31	61
2	33	69
3	29	76

4.3 Pinhole Test

Pinhole test is a good indicator for dispersibility of a soil and for most of the time it is considered the most accurate one among all the dispersibility tests. For this reason, the test was conducted with base soil and mixture of the base soil with solely XG and solely bentonite. 0, 0.5, 1, 2, 3 % of solely XG and solely bentonite was added to the mixture and examined in the test. Specimens were prepared with identical two specimens as one of them was with stretch film and the other one is not. After the curing days (i.e., 0, 7, 14, 28) specimens were tested and results indicated that addition of XG decreased the dispersibility but bentonite increased it. Decrease of dispersibility caused from the addition of XG, limited the outflow and affected the cloudiness of the effluent also bentonite increased the outflow and made the cloudiness darker which signals that some masses are eroded and existed in the effluence. Effects of the mixtures became more clearer with the curing days and it is showed that treated base soil can be used for filter application. Specimens without stretch film was too tough to operate so they were not evaluated. Results of the tests are shown in Table 4.6 to Table 4.9.

Table 4.6 Final parameters of the test with XG (stretch film on)

Stretch	Day	%	Final Cloudiness	Final Diameter (mm)	Final Flow Rate (mL/sec)
+/-	0	0	C. C	1.5	3.167
+/-	0	0.5	C. C	1.5	3.733
+/-	0	1	C. C	1.5	3.050
+/-	0	2	C. C	1.5	0.250
+/-	0	3	C. C	1	0.900
+	7	0	C. C	1	3.917
+	7	0.5	C. C	1.1	1.967
+	7	1	C. C	1.2	1.833
+	7	2	C. C	1.1	2.083
+	7	3	C. C	1.2	2.767
+	14	0	C. C	1.5	4.467
+	14	0.5	C. C	1.5	4.833
+	14	1	C. C	1.5	3.333
+	14	2	C. C	1.5	4.417
+	14	3	Visible (V)	1.5	4.000
+	28	0	C. C	1.5	6.583
+	28	0.5	C. C	1.5	3.500
+	28	1	C. C	1.5	4.333
+	28	2	C. C	1	1.667
+	28	3	C. C	1	0.950

Table 4.7 Results of the test with XG (stretch film on) by 3 different methods

Stretch	Day	%	Method A	Method B	Method C
+/-	0	0	ND4	SD	ND3
+/-	0	0.5	ND3	SD	ND2
+/-	0	1	ND4	SD	ND2
+/-	0	2	ND4	SD	Non-Defined
+/-	0	3	ND1	ND	Non-Defined
+	7	0	ND2	ND	Non-Defined
+	7	0.5	ND1	ND	Non-Defined
+	7	1	ND1	ND	Non-Defined
+	7	2	ND1	ND	ND2
+	7	3	ND1	ND	ND1
+	14	0	ND3	SD	Non-Defined
+	14	0.5	ND3	SD	Non-Defined
+	14	1	ND3	SD	ND3
+	14	2	ND3	SD	ND2
+	14	3	ND3	SD	ND2
+	28	0	ND3	ND	ND3
+	28	0.5	ND3	ND	ND4
+	28	1	ND3	ND	ND3
+	28	2	ND1	ND	ND1
+	28	3	ND1	ND	Non-Defined

Table 4.8 Final parameters of the test with bentonite (stretch film on)

Stretch	Day	%	Final Cloudiness	Final Diameter (mm)	Final Flow Rate (mL/sec)
+/-	0	0	Barely Visible (B. V)	1.5	3.167
+/-	0	0.5	B. V	1.5	3.100
+/-	0	1	B. V	1.5	0.933
+/-	0	2	B. V	1.5	4.333
+/-	0	3	Dark (D)	1.5	5.167
+	7	0	B. V	1	3.917
+	7	0.5	D	2	5.500
+	7	1	D	2	4.833
+	7	2	D	2	10.833
+	7	3	B. V	1.5	3.600
+	14	0	B. V	1	4.467
+	14	0.5	D	1	5.433
+	14	1	B. V	1.5	4.800
+	14	2	D	1	4.767
+	14	3	D	1.5	4.250
+	28	0	B. V	1.5	6.583
+	28	0.5	B. V	1	1.567
+	28	1	B. V	1.4	4.333
+	28	2	B. V	1.4	3.267
+	28	3	D	1.5	4.200

Table 4.9 Results of the test with bentonite (stretch film on) by 3 different methods

Stretch	Day	%	Method A	Method B	Method C
+/-	0	0	ND3	SD	ND3
+/-	0	0.5	ND4	SD	Non-Defined
+/-	0	1	ND4	SD	Non-Defined
+/-	0	2	ND4	SD	ND3
+/-	0	3	(Dispersive) D2	D	ND4
+	7	0	ND3	ND	Non-Defined
+	7	0.5	(Highly Dispersive) D1	D	ND4
+	7	1	D1	D	ND3
+	7	2	D1	D	ND4
+	7	3	ND4	SD	ND3
+	14	0	ND4	SD	Non-Defined
+	14	0.5	ND4	SD	ND4
+	14	1	ND3	ND	ND3
+	14	2	ND4	SD	ND3
+	14	3	ND3	SD	ND3
+	28	0	ND3	SD	ND3
+	28	0.5	ND3	SD	Non-Defined
+	28	1	ND3	SD	ND3
+	28	2	ND3	SD	ND1
+	28	3	ND3	SD	ND2

4.4 Constant Head Permeability Test

Constant head permeability test was conducted to examine the permeability of the specimens. Specimens were designed with solely NS and solely CSS and their respective combinations with solely XG biopolymer and solely TWP industrial by-product/waste. Experiments were conducted after curing days (i.e., 0, 7, 28, 56) with different percentages (i.e., 0%, 1%, 3%). Results of the tests showed that rounded NS particles yielded lower permeability values than angular CSS particles. So, any filter system consist of NS or CSS would give varied results although their PSD are almost equal to each other. Therefore, any combination must be verified with experimental stages to satisfy the filter criteria. Moreover, addition of XG immediately affected the combination and reduced the permeability values of both sands and the system showed stable behavior for all the process of experiment. The reduction was affected with curing days so that hydraulic conductivities of the systems progressively decreased in almost all cases. The reason for this kind of behavior may be caused from filling of the pores of the particles with suspension (water and XG) and creation of gel material inside there. Addition of TWP decreased the permeability values, the reason for that may be TWP also filled the interparticle holes. TWP is in powder form so settling among particle holes can be effortless and filling of these pores with the tapping efforts can provide stiff and impervious bodies in there. 0% in this study was taken from the previous study of Kiymik and Cabalar (2023). Effects of the addition of TWP and XG on sands became clearer with the progression of curing days. Results with day-based and material-based are shown in Figure 4.1 to Figure 4.8.

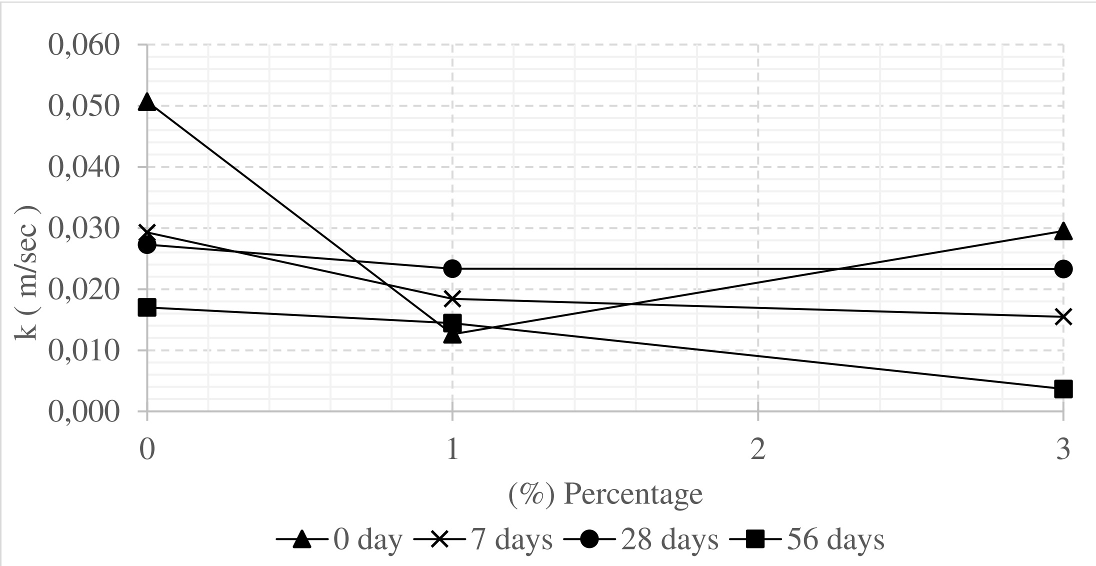


Figure 4.1 Permeability values combined days for NS and TWP

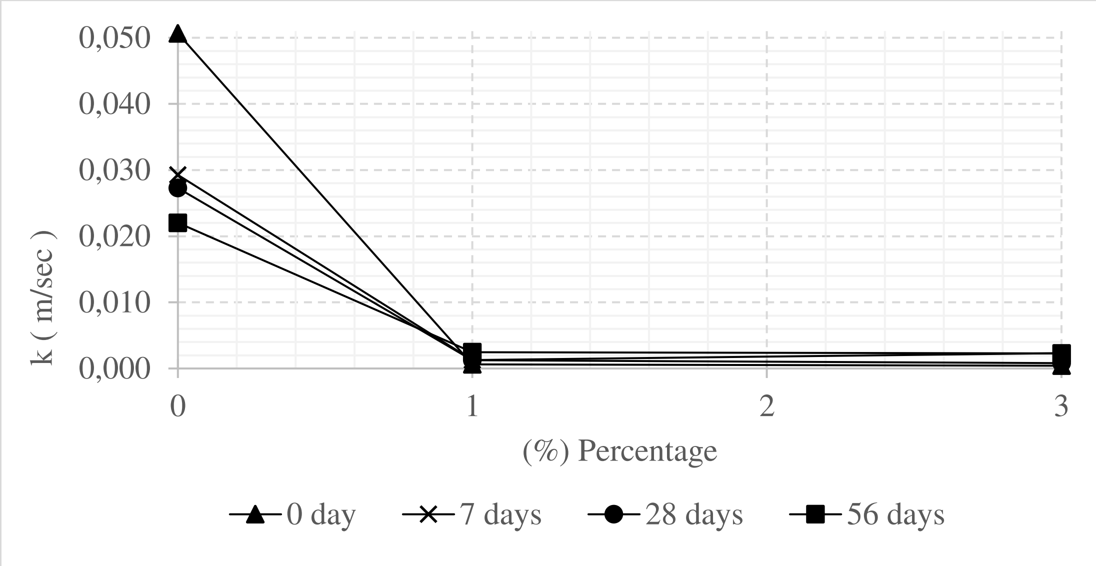


Figure 4.2 Permeability values combined days for NS and XG

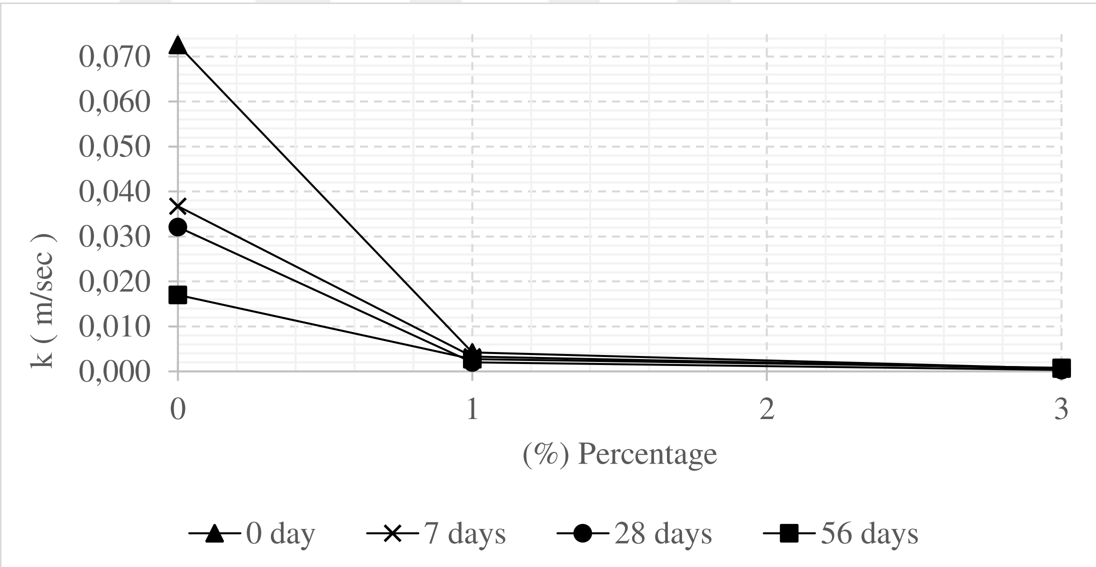


Figure 4.3 Permeability values combined days for CSS and TWP

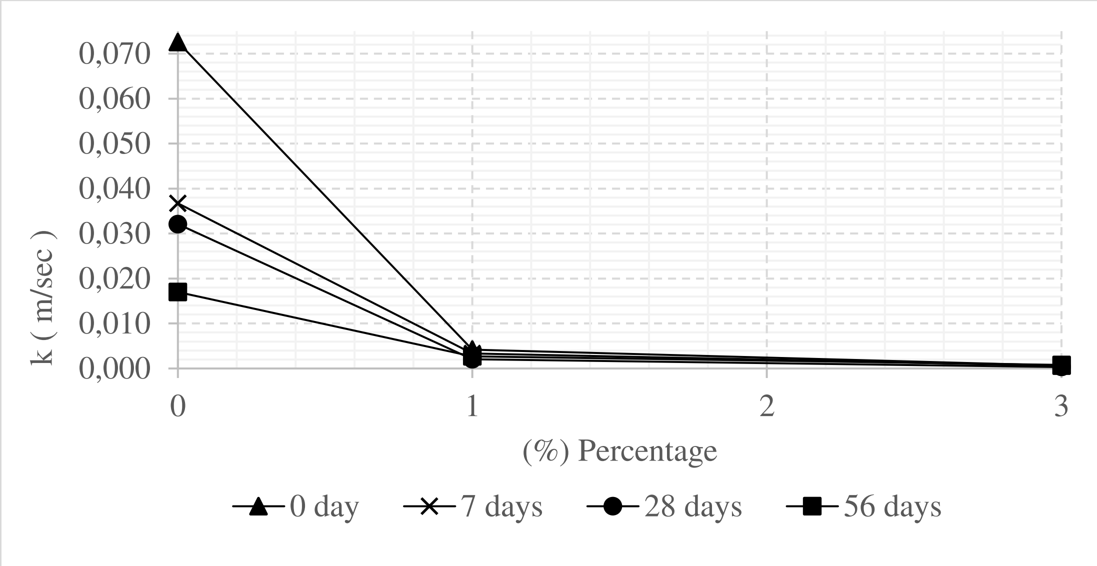


Figure 4.4 Permeability values combined days for CSS and XG

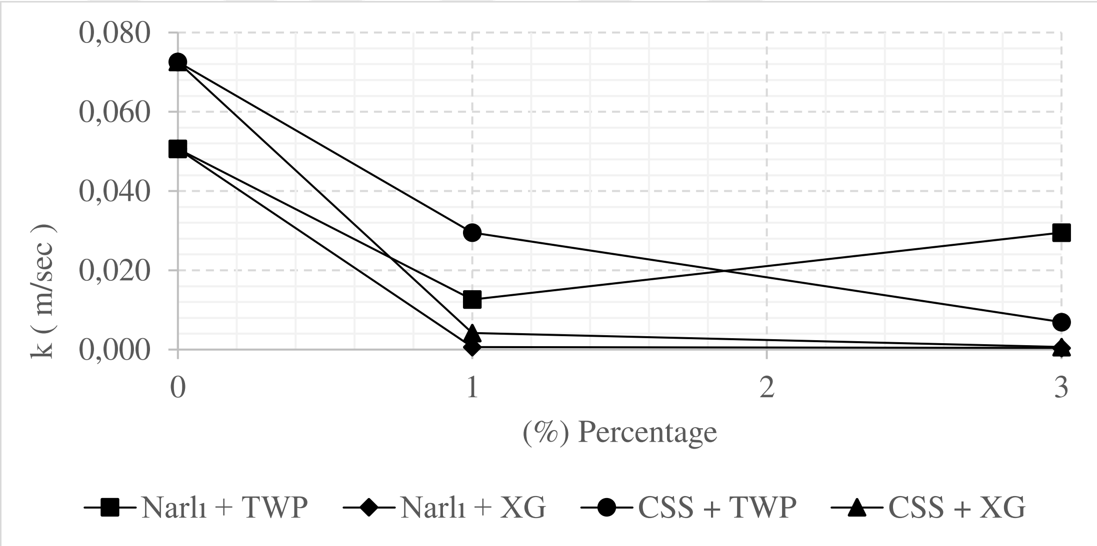


Figure 4.5 Permeability values of the materials after 0 day

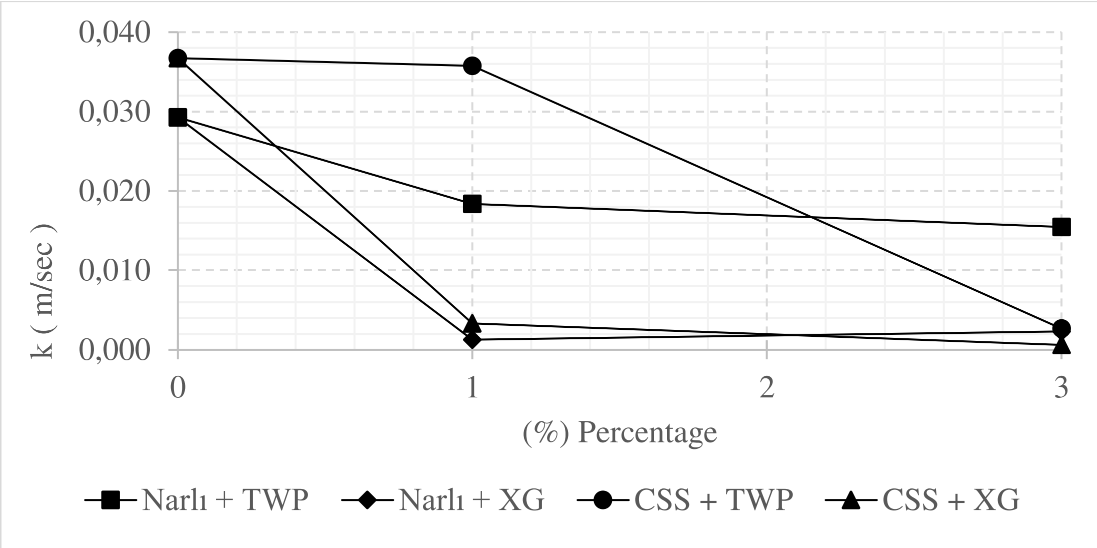


Figure 4.6 Permeability values of the materials after 7 days

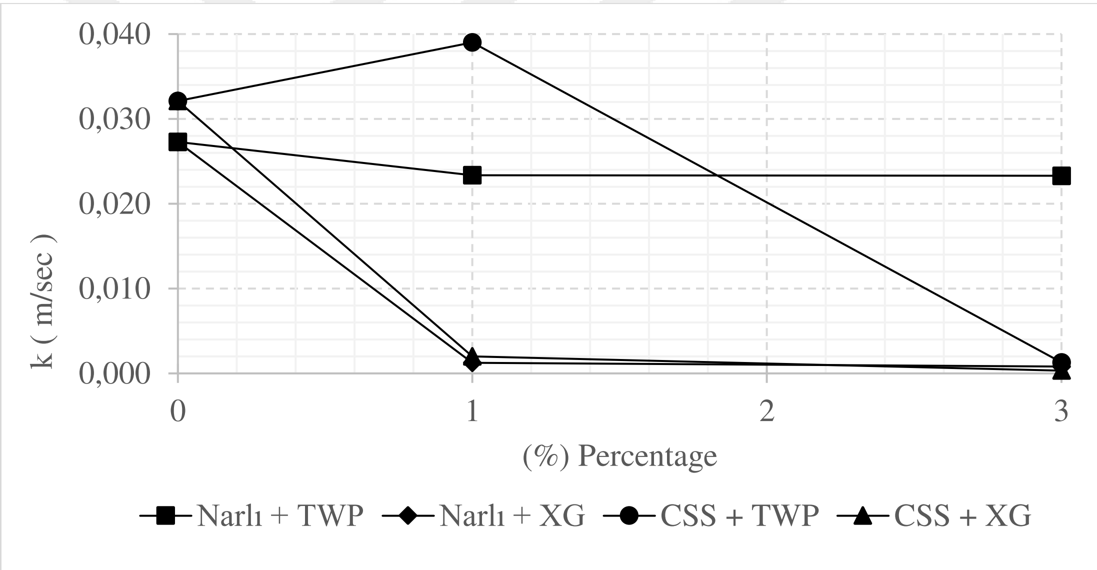


Figure 4.7 Permeability values of the materials after 28 days

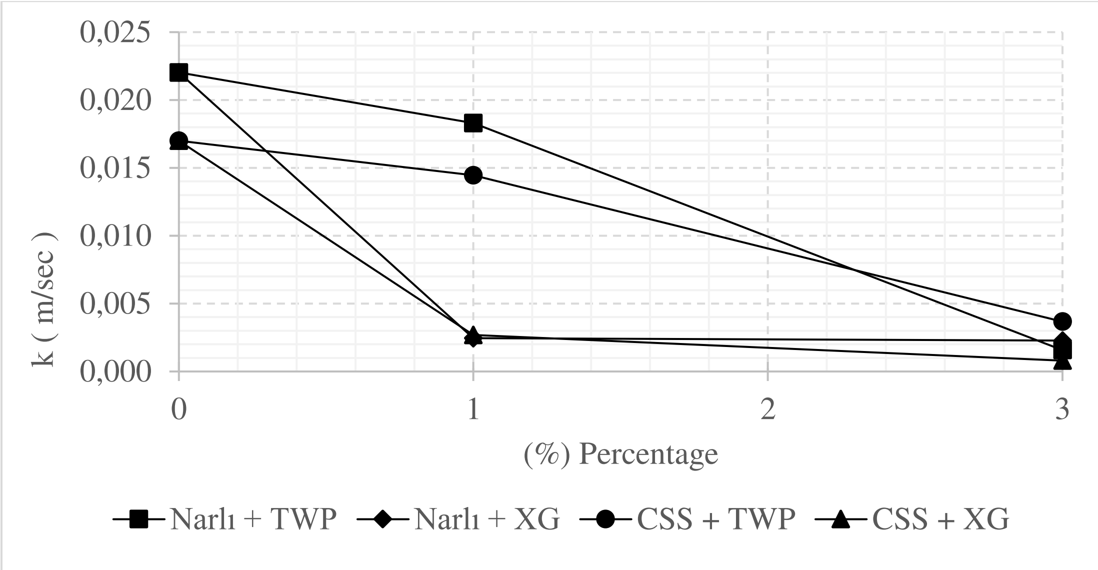


Figure 4.8 Permeability values of the materials after 56 days

4.5 Filter Design

As the base soil converted to a "safe" soil and none of the particle size properties significantly altered, filter design for this base soil can be defined. Several studies regarding the filter design criteria were conducted but there are limitations and restrictions in almost all of them to make the design in "safe" region. For instance, a study from Terzaghi in 1920s was limited only for non-cohesive soils so that this application gave best results within this class. One of the most recent studies was conducted from Vakili et al., (2015). In this study, researchers defined filter design criteria for non-dispersive soils as

$$D_{15f}/d_{85} = 0.6037(d_{85})^{-0.66}$$

Figure 4.9 Filter design criteria formulation for non-dispersive soils (Vakili et al., 2015)

As the base soil in this study have d_{85} value as approximately 0.13 mm, formulation gives the ratio of 2.381 and all the calculations and graphics were designed according to this ratio. Ratio defines the appliable zone as in Figure 4.10.

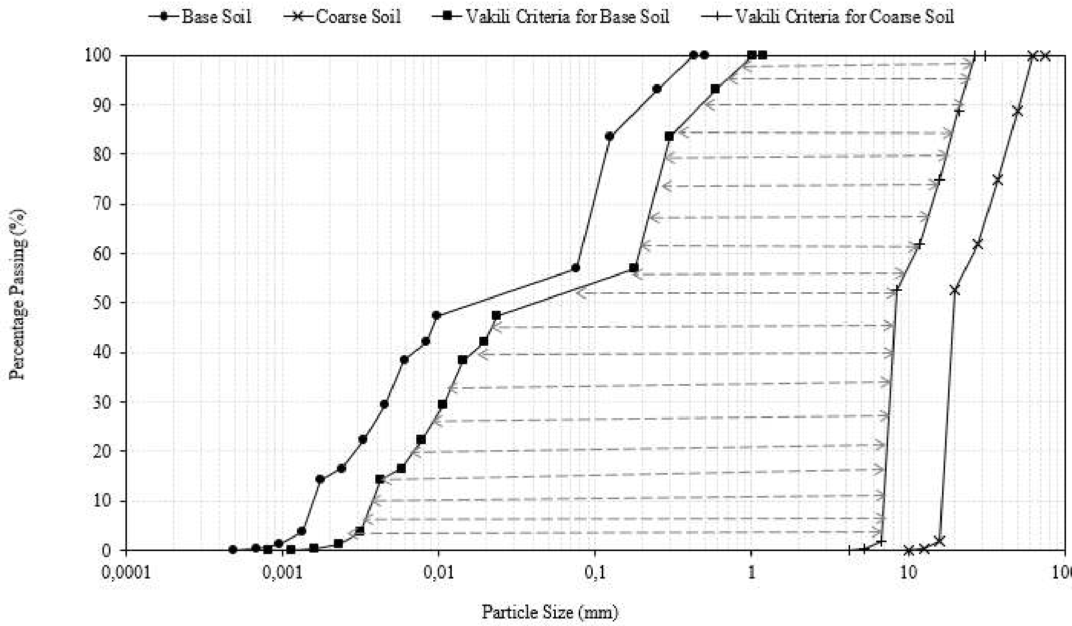


Figure 4.10 Applicable filter zone by the defined ratio

So, any filter combination must be between these limits in order to be sufficient to satisfy the system needs. It was suggested that creating well-graded mixtures within these limits would satisfy both retention and drainage needs of the system better. NS and CSS are both satisfying the regarding conditions to employ in appliable filter zone so that they were chosen in this regard. Systems can be seen in Figure 4.11.

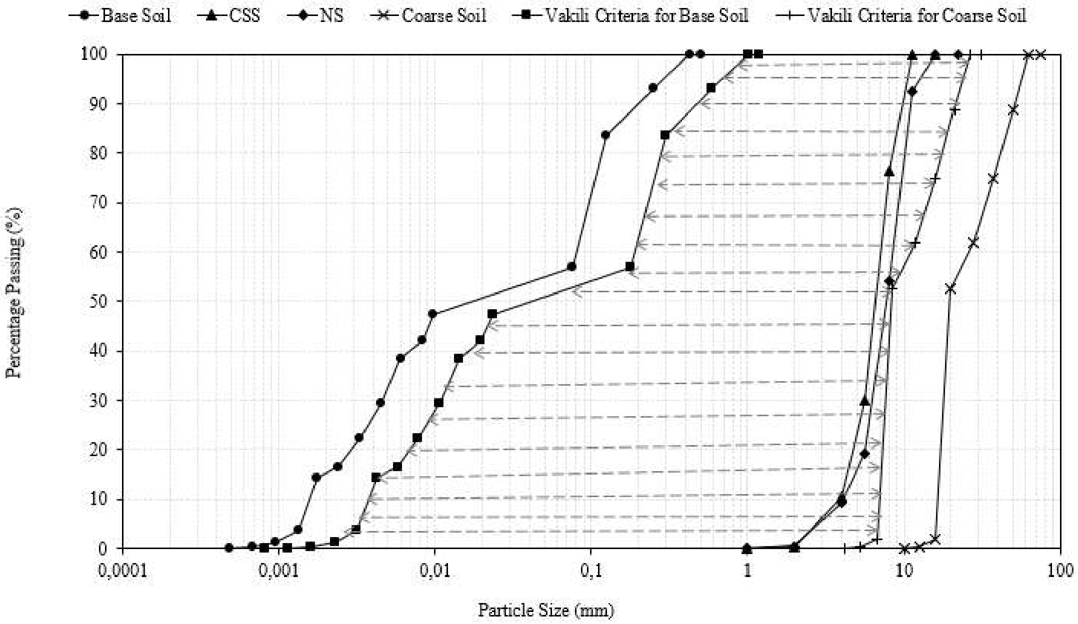


Figure 4.11 Place of NS and CSS in the appliable filter zone

CHAPTER 5
DISCUSSION

5.1 Dispersibility and Filter Designing

In this study soil was found intermediate dispersive (34%) unlike Flores-Berrones et al. (2011), they found their base soil as non-dispersive. In case of Zorluer et al. (2010), it was dispersive and behavior of the soil was predicted with “fuzzy rule method” Remediation of the base soil in this case made the soil applicable for employing in filter design applications. Curing days effect on specimens did not change the eventual decision on dispersibility but showed varied behavior during the process (e.g., some of them showed quick slaking etc.).

Lone et al. (2005) and Indraratna et al. (2008) found that C_u parameter strongly affects the sustainability of the filtering system, this study also showed similar intentions and justified this intention with the design for the filtering zone. As Indraratna and Raut (2006) stated there are some problematic soils to consist filtering system and base soil in this study initially was problematic also but stabilization of this soil made it applicable for usage in filtering systems. They suggested to use CSD theory instead of PSD theory but to create a fundamental understanding about the topic and filtering systems more basic and preliminary theory (PSD theory) was chosen.

In the next stages, as the basic steps for establishing knowledge about these topics was completed, more advanced theories like CSD can be applied for better resolution. As Indraratna et al. (2007) expressed, if the soil is unsuccessful for stabilization purposes and remained dispersive then creating filtering systems and expecting it to be safe will be non-sense and pointless. Even if they worked on cohesionless soils, looking for clogging process in (CL) type base soil in this study still can be examined. Sivakumar and Srivastava (2007) suggested to look for Atterberg Limits of the consisting soils in systems and in this study this effect was not investigated and for further studies this can be done. Indraratna et al. (2008) and Yousif et al. (2017) defined the importance of the permeabilities of the basic consisting parts of a filtering system (i.e., base soil and filtering zone) and permeability of the filtering zone was investigated thoroughly in this study also. Raut and Indraratna (2008) offered to use many methods as possible but in this study only empirical efforts were given and analytical stages can be done for further studies.

Fernando (2010), Fan and Kong (2013) and also Parameswaran and Sivapullaiah (2017) expressed the importance of the Na^+ percentage inside the soil and pore water also in this study same concept was mentioned and dispersion of the base soil was mitigated with the help of XG so that XG affected the chemical balance inside the soil strata. Zorluer et al. (2010) expressed that even for same soil dispersibility identification tests may give varied results so that in this study they also give minimally varied results. Benahmed and Bonelli (2012) and Premkumar et al. (2016) stressed the importance of clay type so that varied type of clays can give varied behaviors and attitudes against identical situations just like in this study, in this study (CL) type of clay showed difference with bentonite in the dispersibility perspective. Abbasi and Nazifi (2013) adjusted the behavior of a soil and compared with chemical test and identified that none of the dispersibility tests are enough to create a precise study so results must be validated with other tests so this procedure was followed in this study.

Filter design for stabilized base soil was conducted and the creation design was taken from the study of Vakili et al. (2015). They defined the calculations for non-dispersive and/or dispersive base soil and the ratio was taken from that calculation. Appliable filter zone was defined by these limitations and ratio. Vakili and Selamat (2014) suggested to use also empirical efforts instead of only using formulations to investigate the filter designing so that these formulations give approximate results and they are mostly rough and conservative, for more precise expectations empirical stages were offered and, in this thesis, empirical efforts were given for more precise results. Particle shape and effects of it on filter designing were one of the other purposes of this study. This effect was tested on constant head permeability test with NS and CSS as they have varied shape properties. Results indicated that NS (rounded) showed lesser permeability values than CSS (angular) so that particles that have almost same particle size distribution trends may show varied attitudes in the filter systems. Rather et al. (2021) investigated this concept but Seblany et al. (2021) did not give much attention and Rather et al. (2021) observed similar trends as particle shape was effective on filtering systems.

5.2 Stabilization of the Soils

5.2.1 Stabilization by Physical and/or Chemical Methods

Edincliler et al. (2004) stressed the importance of unit prices of the tire wastes and this was one of the reasons to use them in this study. Tsang (2008), Edincliler and Cagatay (2013), Cabalar et al. (2014) pointed that tire can be found as waste and can be utilized so that this utilization may aid the stockpile problems of wasted tires in most environmentally way, for this reason this material was also utilized in this study.

Many research was based on problematic soils, Viswanadham et al. (2009) studied expansive soils, Turkoz et al. (2014) examined dispersive soils and Correia et al. (2015) studied soft soils. Turkoz et al. (2014) used $MgCl_2$ and improve the dispersibility but bentonite addition made it worse. Vakili et al. (2018) also applied similar methodology on dispersive soil and in that case, soil was treated with lignosulfonate and remediated. Optimum value was found as 2% of lignosulfonate in that case but in this case, it was 3% of XG. As in case of Ouhadi and Goodarzi (2006), they added “alum” into the mixture and soil mixture showed improvement. Vakili et al. (2018) and Ta’negonbadi and Noorzad (2017) used lignosulfonate, Turkoz and Vural (2013) utilized cement and zeolite, Goodarzi and Salimi (2015) used varied types of slags (as optimum value was reached with 5-10% GBFS after 7 days) as stabilizer instead of XG that was used in this study but all the methods were effective for remediation purposes. Masoumi et al. (2013) stabilized a problematic soil with PVA and fiber. Savas (2016) used zeolite and lime to cure dispersibility and results were satisfactory, in that study lime was on a constant level and zeolite was increasing in percentage and dispersibility gradually decreased with this treatment.

Some other researches focused on different stabilization methods and detected the importance of cations especially Na^+ because cations generally become reason for dispersibility as in the study of Abdullah and Al-Abadi (2010), Goodarzi and Salimi (2015) and in this study dispersibility was remediated so this concept also altered with the empirical efforts in this study.

Moo-Young et al. (2003) detected increase in permeability when tire added but this may be resulted as they used tire shreds whereas in this study tire was used in "powder" form so that it can easily fill the interparticle pores. Zornberg et al. (2004) also investigated the parameters for tires but they suggested to look for regarding permeabilities also. Wiszniewski and Cabalar (2016) also worked on hydraulic conductivities of the sand systems that tire added. They observed that permeability of the system increased unlike in this study, variance between Wiszniewski and Cabalar (2016) and this study may cause from particle shape as they used tire crumbs but in this study powder form was used also they used sand but in this study (CL) type clay was used. As the particle grain size increase, it may create greater spaces/holes in the mixture so B.r et al. (2021), Kiymik and Cabalar (2023) observed this kind of response.

Vakili et al. (2017) used ZELIAC as additive to test the permeability and additive increased the permeability of the system unlike in TWP of this case. Liu et al. (2020) also detected increase in permeability when tire added. B.r et al. (2021) also observed reduction in permeability when tire added and they implicated that used tire was hydrophobic.

Curing days in most of the studies showed effect just like in Turkoz et al. (2014) but also in most of the cases this situation generally depended on materials and methods that were followed as in this study. Effects may alter the ultimate decision on parameters but on the other hand it may only alter the process not ultimate decision as happened in this study. Durability in these systems also another important point so studies may cover this topic just like in Ta'negonbadi and Noorzad (2017), they found that their treatment with lignosulfonate increased the durability of the system. In this study this kind of concern was not processed so in further studies similar effect can be investigated.

5.2.2 Stabilization by Biological Methods

Ivanov and Chu (2008) and Wiszniewski et al. (2017) introduced biological methods to stabilize systems and one of the methods of it (bioclogging) was seen in the constant head permeability test and resulted in reduction of the permeabilities in this study. XG biopolymer addition to base soil improved the dispersibility in this case, just like in Turkoz et al. (2014). In this study, base soil was improved with XG and got worse with bentonite additions. Bouazza et al. (2009) also studied with XG to reduce the permeability and they also succeed to decrease the permeability. Wiszniewski and Cabalar (2014), Wiszniewski et al. (2016), Cabalar et al. (2017) also used XG but it was mixed with sand, results indicated that XG also managed to limit the permeability of the sand with creating viscous suspension in pores. Sujatha and Saisree (2019) investigated permeability of a system that guar gum added and guar gum yielded similar results with XG as they both decreased the permeabilities. Joga and Varaprasad (2020) also used XG on dispersive soils and system was successfully improved with the addition of XG by means of permeability.

Joga and Varaprasad (2019) stabilized a problematic soil (expansive soil) with XG as used in this study so it was shown that XG can also be used effectively on expansive soils. Cabalar and Canakci (2011), Akbulut and Cabalar (2014) and Chang et al. (2015a) showed that XG can also improve the strength of the system that was applied, this concept was not studied in this study but for further studies this section can be examined.

Chang et al. (2015a) also mentioned the reasonable unit prices of this biopolymer and easy-to-get status of the XG so this was one of the reasons to conduct studies with this biopolymer. Chang et al. (2015b) mentioned the green effect of the biopolymer so that usage of these materials can even benefit the forestation process in the vicinity soil as this property was one of the other reasons to conduct studies with this biopolymer. Latifi et al. (2017) showed that XG can give strength to the bentonite type of clay so that in further studies their relationship about these parameters can be investigated as both of these materials were investigated separately in this study. Interparticle microscale changes leading to these major attitudes can be implicated from the study of Chang et al. (2019).

5.3 Effects of Particle Shape on Soil Properties

Constant head permeability test was conducted in this study to identify permeabilities of the solely NS and solely CSS. Results showed that shape property is a factor that have influence on permeability, just like in the study of Göktepe and Sezer (2010). In that study, shape factors especially roundness found closely relative with the permeability. In this study, angular CSS particles yielded greater permeability values than rounded NS particles.

Shape definitions that were used in this study gathered from the studies of Abbireddy et al. (2009) and Clayton et al. (2009), in those studies sphericity (S) and roundness (R) terminologies were defined and used in this study. Muszynski and Vitton (2012) studied to give more objective and precise measurements for R and S for coarse particles so that in further studies especially for NS (because it was not suggested for crushed sands) shape parameters can be measured more precisely and thoroughly.

Odong (2007) and Ishaku et al. (2011) studied seven formulations (Terzaghi, Slitcher, USBR, Hazen, Kozeny-Carman, Alyamani and Sen, Breyer) about permeability and compared them based on reliabilities in those studies, results showed that estimations and formulations must include shape parameters for better resolutions just like in this study. Ishaku et al. (2011), Salarashayeri and Siosemarde (2012) used PSD to create formula for detecting permeability also in this study PSD was utilized for filter designing process. Salarashayeri and Siosemarde (2012) also stated the importance of some specific diameter sizes.

Cabalar and Akbulut (2016a), Cabalar and Akbulut (2016b) investigated the effects of shape on permeability and they also justified the effect on permeability so that angular particles in that study also yielded greater permeability values just like in this case. In the study of Cabalar and Akbulut (2016a), they stressed the importance of roundness (R) parameter so that it was observed as dominant factor over than sphericity (S) in their studies. They also pointed to effect of parameters like Cc, C_u and specific particle sizes and in this study, they are shown in Table 3.2. Effect of the differences of the R, S and angularity between NS and CSS was observed in the results of permeability tests of these materials. Cabalar and Akbulut (2016b) indicated the importance of n and e parameters for permeability of sands which was not used in this study specifically but for further studies examination of these parameters can be beneficial. They also stated that formulations for measuring permeability would be lack of precision alone so empirical stages would be favorable to add for better resolution and precision just like it was done in this study.

Chang et al. (2019) investigated the effect of pore fluid on permeability and received varied results. Cabalar et al. (2022) studied angular and rounded particles and observed that for some specific circumstances (i.e., consolidation test, UCS test etc.) shape of the particle can even be more dominant factor than the size of the particle so investigation of the shape of the particles like in this study can be beneficial and influential for further studies.

CHAPTER 6
CONCLUSION

In this study, an effort was given to find out the dispersibility of a base soil and stabilizing this base soil. In varied percentages (i.e., 0%, 0.5%, 1%, 2%, 3%) different additives (i.e., XG and bentonite) were added to treat this clay soil and expectations were satisfied. To use in appliable filter zone, two types of poorly graded sands (i.e., NS and CSS) were selected. With the aim of investigating the hydraulic conductivities of these sands, permeability tests were conducted. These tests included solely NS and solely CSS with varied percentages (i.e., 0%, 1%, 3%) of different additives (i.e., XG and TWP). Crucial points of the study were given as,

- In the crumb test soil was detected as intermediate dispersive and did not show any change with timelapse but addition of XG biopolymer improved this property and made the soil non-dispersive. Improving of this property progressed with the curing days. On the other hand, bentonite type clay made the base soil more dispersive and this effect was significant as the dosage increase. Curing days did not give any improvement in this case whereas increase in curing days made the soil more dispersive.
- In the double hydrometer test, trend was similar with the crumb test so that solely base soil yielded dispersive outcomes but with the addition of XG this property improved, 34% percent dispersion of the solely base soil decreased to the 29% as the dosage increase. However, addition of bentonite to the soil system made the combination more dispersive so that 34% percent dispersion of the solely base soil increased up to 76% as the dosage increase. This outcome shows that bentonite was more dominant than the XG by means of changing the base soil.

- For pinhole test, similar trend with crumb and double hydrometer tests was observable. For XG addition, in almost all cases increase in dosage resulted improvement in dispersibility and this improvement supported with curing days whereas bentonite addition made the cases worse so that increase in dosage regardless of curing time, made the soil more dispersive. Progression in curing days propagated this situation and did not show any improvement at all. These outcomes were relatable with all three different methods to measure the dispersibility.
- The reason for results for all dispersibility tests may be explained as base soil was intermediate or slightly dispersive in initial condition but addition of XG improved the soil by filling of the pores of the clay particles and changed the repulsive forces between clay particles to more mild condition with exchanging the cations in clay minerology. Water - XG suspension altered the electrochemical status of the combination and made the attractive forces exist, by this way domination of the repulsive forces mitigated and soil improved. In another way, bentonite addition made the soil worse for dispersibility so that addition of montmorillonite-based bentonite clay to the mixture contributed to the repulsive forces that is applied and adsorb and absorb huge amount of water with respect to volume of particles. Interaction of pore water and/or external water and clay propagated this situation and increase the concentration of cation and also increased the dispersibility of the system.
- Constant head permeability test resulted as solely NS and solely CSS yielded different permeability values even, they have almost same PSD. This situation reflected that particle shape affected the mixture and conduct of water in soil matrix. Angular CSS particles submitted greater permeability values than rounded NS particles. Reason for this kind of behavior may be better settling of the rounded particles and these particles applied more friction to the water flow.
- Addition of XG and TWP in the constant head permeability test submitted similar trends. As both of them in powder form, they both reduced the permeabilities so that XG added NS and CSS showed reduction and TWP added NS and CSS also showed similar trend. In almost all cases 3% addition of XG yielded lowest permeability results. For addition of TWP, also 3%

submitted lowest values but interaction process took longer time for TWP comparing with the XG. XG reduced the permeability values 99% for NS and CSS on the other hand TWP reduced the permeability values 42% for NS and 90% for CSS.

- The reason for XG addition reduced the permeability values, may be XG suspension filled the pores of the NS and CSS and created impervious layers and chemically interacted with the particles, by this way conduction of the water limited. Furthermore, addition of TWP also reduced the permeability values and it may be resulted from also filling of the interparticle spaces but in this time no chemical interaction was observed. For these reasons XG was superior for restricting the water flow rather than TWP.
- Filter design criteria that were proposed from Vakili et al. (2015) was applied in this study. This criterion is based on ratio of the predetermined grain sizes and formulation is available for non-dispersive soils. For this reason, this criterion was used to create a filter layer and regarding limits of this filter layer. Parameter of d_{85} was used to assign the regarding parameters. As the base soil was remediated, can be available to use as base soil and also NS and CSS materials were also available to use in appliable filter zone.

CHAPTER 7
SUGGESTIONS

In this study a slightly/intermediate dispersive soil was examined for dispersibility so in further studies dispersibility level can be adjusted to create greater difference. Stabilization of this dispersive soil with XG and bentonite was investigated with different percentages and under the effect of curing days. In further studies different additives can be selected and dosage may also vary. To detect the changes curing days were applied but in next stage longer days or specific timelines can be arranged. Filter design criteria for this stabilized soil was studied. To employ in appliable filter zone, two types of poorly graded sands were selected. To investigate the effect of variety in gradation, well-graded soils can be used or soils with different PSD can be arranged. These two types of poorly graded soils were tested in permeability tests and investigated to understand the effect of particle shape and characteristics. So, in other studies, more variation can be added by means of particle shape. To investigate the effect of addition of TWP and XG on regarding permeabilities, varied percentages of XG and TWP added on specimens and these specimens tested after curing days. It was suggested to use varied materials with different percentages and may be different curing days can also be applied.

REFERENCES

Abbasi, N., and Nazifi, M. H. (2013). Assessment and Modification of Sherard Chemical Method for Evaluation of Dispersion Potential of Soils. *Geotechnical and Geological Engineering*, 31(1), 337–346. https://doi.org/10.1007/s10706-012-9573-7

Abbireddy, C. O. R., Clayton, C. E., and Huvenne, V. A. (2009). A Method of Estimating the Form of Fine Particulates. *Geotechnique*, 59(6), 503–511. https://doi.org/10.1680/geot.2008.p.009

Abdullah, W. S., and Al-Abadi, A. M. (2010). Cationic-electrokinetic Improvement of an Expansive Soil. *Applied Clay Science*, 47(3–4), 343–350. https://doi.org/10.1016/j.clay.2009.11.046

Akbulut, N., and Cabalar, A. F. (2014). Effects of Biopolymer on Some Geotechnical Properties of a Sand. *New Frontiers in Geotechnical Engineering,* 28-37. https://doi.org/10.1061/9780784413456.004

Andrew, R. M. (2018). Global CO_2 Emissions from Cement Production. *Earth System Science Data*, 10(1), 195–217. https://doi.org/10.5194/essd-10-195-2018

Arslan, H., and Baykal, G. (2006). Utilization of Fly Ash as Engineering Pellet Aggregates. *Environmental Geology*, 50(5), 761–770. https://doi.org/10.1007/s00254-006-0248-7

ASTM C127-15. American Society for Testing and Materials (2015). *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate. West Conshohocken, PA: ASTM International.* https://doi.org/10.1520/C0127-15

ASTM C128-15. American Society for Testing and Materials (2015). *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate. West Conshohocken, PA: ASTM International.* https://doi.org/10.1520/C0128-15

ASTM D4318-17. American Society for Testing and Materials (2017). *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. West Conshohocken, PA: ASTM International.* https://doi.org/10.1520/D4318-17

ASTM D4221-18. American Society for Testing and Materials (2018). *Standard Test Method for Dispersive Characteristics of Clay Soil by Double Hydrometer. West Conshohocken, PA: ASTM International.* https://doi.org/10.1520/D4221-18

ASTM D2216-19. American Society for Testing and Materials (2019). *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and*

Rock by Mass. West Conshohocken, PA: ASTM International. https://doi.org/10.1520/D2216-19

ASTM D2434-19. American Society for Testing and Materials (2019). *Standard Test Method for Permeability of Granular Soils (Constant Head). West Conshohocken, PA: ASTM International.* https://doi.org/10.1520/D2434-19

ASTM D4647/D4647M-13(2020). American Society for Testing and Materials (2020). *Standard Test Methods for Identification and Classification of Dispersive Clay Soils by the Pinhole Test. West Conshohocken, PA: ASTM International.* https://doi.org/10.1520/D4647_D4647M-13R20

ASTM D6572-21. American Society for Testing and Materials (2021). *Standard Test Methods for Determining Dispersive Characteristics of Clayey Soils by the Crumb Test. West Conshohocken, PA: ASTM International.* https://doi.org/10.1520/D6572-21

ASTM D7928-21. American Society for Testing and Materials (2021). *Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis. West Conshohocken, PA: ASTM International.* https://doi.org/10.1520/D7928-21

Ayeldeen, M., Negm, A., El-Sawwaf, M., and Kitazume, M. (2017). Enhancing Mechanical Behaviors of Collapsible Soil Using Two Biopolymers. *Journal of Rock Mechanics and Geotechnical Engineering*, 9(2), 329–339. https://doi.org/10.1016/j.jrmge.2016.11.007

Benahmed, N., and Bonelli, S. (2012). Investigating Concentrated Leak Erosion Behaviour of Cohesive Soils by Performing Hole Erosion Tests. *European Journal of Environmental and Civil Engineering*, 16(1), 43–58. https://doi.org/10.1080/19648189.2012.667667

Blanck, G., Cuisinier, O., and Masrouri, F. (2014). Soil Treatment with Organic Non-Traditional Additives for The Improvement of Earthworks. *Acta Geotechnica*, 9(6), 1111–1122. https://doi.org/10.1007/s11440-013-0251-6

Bouazza, A., Gates, W. P., and Ranjith, P. G. (2009). Hydraulic Conductivity of Biopolymer-Treated Silty Sand. *Geotechnique*, 59(1), 71–72. https://doi.org/10.1680/geot.2007.00137

B.r, M., Boominathan, A., and Banerjee, S. (2021). Engineering Properties of Sand–Rubber Tire Shred Mixtures. *International Journal of Geotechnical Engineering*, 15(9), 1078–1092. https://doi.org/10.1080/19386362.2019.1617479

Cabalar, A. F. (2011). Direct Shear Tests on Waste Tires–Sand Mixtures. *Geotechnical and Geological Engineering*, 29(4), 411–418. https://doi.org/10.1007/s10706-010-9386-5

Cabalar, A. F., and Akbulut, N. (2016a). Effects Of the Particle Shape and Size of Sands on The Hydraulic Conductivity. *Acta Geotechnica Slovenica*, 2(4), 83–93.

https://www.researchgate.net/publication/311929184_Effects_of_the_particle_shape_and_size_of_sands_on_the_hydraulic_conductivity

Cabalar, A. F., and Akbulut, N. (2016b). Evaluation Of Actual and Estimated Hydraulic Conductivity of Sands with Different Gradation and Shape. *SpringerPlus*, 5(1). https://doi.org/10.1186/s40064-016-2472-2

Cabalar, A. F., and Canakci, H. (2011). Direct Shear Tests on Sand Treated with Xanthan Gum. *Proceedings of the Institution of Civil Engineers: Ground Improvement*, 164(2), 57–64. https://doi.org/10.1680/grim.800041

Cabalar, A. F., and Karabash, Z. (2015). California Bearing Ratio of a Sub-Base Material Modified with Tire Buffings and Cement Addition. *Journal of Testing and Evaluation*, 43(6), 1279–1287. https://doi.org/10.1520/jte20130070

Cabalar, A. F., and Mustafa, W. (2017). Behaviour Of Sand–Clay Mixtures for Road Pavement Subgrade. *International Journal of Pavement Engineering*, 18(8), 714–726. https://doi.org/10.1080/10298436.2015.1121782

Cabalar, A. F., Hama, S. O., and Demir, S. (2022). Behaviour of a Clay and Gravel Mixture. *Baltic Journal of Road and Bridge Engineering*, 17(1), 98–116. https://doi.org/10.7250/bjrbe.2022-17.553

Cabalar, A. F., Karabash, Z., and Mustafa, W. S. (2014). Stabilising A Clay Using Tyre Buffings and Lime. *Road Materials and Pavement Design*, 15(4), 872–891. https://doi.org/10.1080/14680629.2014.939697

Cabalar, A. F., Wiszniewski, M., and Skutnik, Z. (2017). Effects of Xanthan Gum Biopolymer on the Permeability, Odometer, Unconfined Compressive and Triaxial Shear Behavior of a Sand. *Soil Mechanics and Foundation Engineering*, 54(5), 356–361. https://doi.org/10.1007/s11204-017-9481-1

Cai, Y., Shi, B., Ng, C. W. W., and Tang, C. (2006). Effect Of Polypropylene Fibre and Lime Admixture on Engineering Properties of Clayey Soil. *Engineering Geology*, 87(3–4), 230–240. https://doi.org/10.1016/j.enggeo.2006.07.007

Caldeira, L. (2019). Internal Erosion in Dams: Studies and Rehabilitation. *International Journal of Civil Engineering*, 17(4), 457–471. https://doi.org/10.1007/s40999-018-0329-5

Chang, I., Im, J., and Cho, G. (2016). Introduction of Microbial Biopolymers in Soil Treatment for Future Environmentally-Friendly and Sustainable Geotechnical Engineering. *Sustainability*, 8(3), 251. https://doi.org/10.3390/su8030251

Chang, I., Im, J., Prasidhi, A. K., and Cho, G. C. (2015a). Effects of Xanthan Gum Biopolymer on Soil Strengthening. *Construction and Building Materials*, 74, 65–72. https://doi.org/10.1016/j.conbuildmat.2014.10.026

Chang, I., Jeon, M., and Cho, G. (2015b). Application of Microbial Biopolymers as an Alternative Construction Binder for Earth Buildings in Underdeveloped Countries. *International Journal of Polymer Science*, 2015, 1–9. https://doi.org/10.1155/2015/326745

Chang, I., Kwon, Y., Im, J., and Cho, G. (2019). Soil Consistency and Interparticle Characteristics of Xanthan Gum Biopolymer–Containing Soils with Pore-Fluid Variation. *Canadian Geotechnical Journal*, 56(8), 1206–1213. https://doi.org/10.1139/cgj-2018-0254

Chang, I., Prasidhi, A. K., Im, J., and Cho, G. C. (2015c). Soil Strengthening Using Thermo-Gelation Biopolymers. *Construction and Building Materials*, 77, 430–438. https://doi.org/10.1016/j.conbuildmat.2014.12.116

Chapuis, R. P. (2012). Predicting the Saturated Hydraulic Conductivity of Soils: A Review. *Bulletin of Engineering Geology and the Environment*, 71(3), 401–434. https://doi.org/10.1007/s10064-012-0418-7

Clayton, C. E., Abbireddy, C. O. R., and Schiebel, R. (2009). A Method of Estimating the Form of Coarse Particulates. *Geotechnique*, 59(6), 493–501. https://doi.org/10.1680/geot.2007.00195

Coduto, D., Yeung, M., and Kitch, W. (2011). *Geotechnical Engineering: Principles and Practices*. 2nd edition. Pearson.

Consoli, N. C., Nierwinski, H. P., Peccin da Silva, A., and Sosnoski, J. (2017). Durability and Strength of Fiber-Reinforced Compacted Gold Tailings-Cement Blends. *Geotextiles and Geomembranes*, 45(2), 98–102. https://doi.org/10.1016/j.geotexmem.2017.01.001

Correia, A., Oliveira, P. J., and Custódio, D. G. (2015). Effect of Polypropylene Fibres on the Compressive and Tensile Strength of a Soft Soil, Artificially Stabilised with Binders. *Geotextiles and Geomembranes*, 43(2), 97–106. https://doi.org/10.1016/j.geotexmem.2014.11.008

Das, B. M. (2019). *Advanced Soil Mechanics*. 5th edition. CRC Press eBooks. https://doi.org/10.1201/9781351215183

Edinçliler, A., and Cagatay, A. (2013). Weak Subgrade Improvement with Rubber Fibre Inclusions. *Geosynthetics International*, 20(1), 39–46. https://doi.org/10.1680/gein.12.00038

Edincliler, A., Baykal, G., and Dengili, K. (2004). Determination of Static and Dynamic Behavior of Recycled Materials for Highways. *Resources, Conservation and Recycling*, 42(3), 223–237. https://doi.org/10.1016/j.resconrec.2004.04.003

Edincliler, A., Baykal, G., and Saygili, A. (2010). Influence of Different Processing Techniques on the Mechanical Properties of Used Tires in Embankment Construction. *Waste Management*, 30(6), 1073–1080. https://doi.org/10.1016/j.wasman.2009.09.031

Edincliler, A., Cabalar, A. F., Cagatay, A., and Cevik, A. (2012). Triaxial Compression Behavior of Sand and Tire Wastes Using Neural Networks. *Neural Computing and Applications*, 21(3), 441–452. https://doi.org/10.1007/s00521-010-0430-4

Estabragh, A. R., Namdar, P., and Javadi, A. A. (2012). Behavior of Cement-Stabilized Clay Reinforced with Nylon Fiber. *Geosynthetics International*, 19(1), 85–92. https://doi.org/10.1680/gein.2012.19.1.85

Fan, H., and Kong, L. (2013). Empirical Equation for Evaluating the Dispersivity of Cohesive Soil. *Canadian Geotechnical Journal*, 50(9), 989–994. https://doi.org/10.1139/cgj-2012-0332

Fannin, J. (2008). Karl Terzaghi: From Theory to Practice in Geotechnical Filter Design. *Journal of Geotechnical and Geoenvironmental Engineering*, 134(3), 267–276. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:3(267)

Fernando, J. (2010). Effect of Water Quality on the Dispersive Characteristics of Soils Found in the Morwell Area, Victoria, Australia. *Geotechnical and Geological Engineering*, 28(6), 835–850. https://doi.org/10.1007/s10706-010-9345-1

Flores-Berrones, R., Ramírez-Reynaga, M., and Macari, E. J. (2011). Internal Erosion and Rehabilitation of an Earth-Rock Dam. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(2), 150–160. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000371

Goktepe, A. B., and Sezer, A. (2010). Effect of Particle Shape on Density and Permeability of Sands. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, 163(6), 307–320. https://doi.org/10.1680/geng.2010.163.6.307

Goodarzi, A. R., and Salimi, M. (2015). Stabilization Treatment of a Dispersive Clayey Soil Using Granulated Blast Furnace Slag and Basic Oxygen Furnace Slag. *Applied Clay Science*, 108, 61–69. https://doi.org/10.1016/j.clay.2015.02.024

Huang, Q., Zhan, M., Sheng, J., Luo, Y., and Su, B. (2014). Investigation of Fluid Flow-Induced Particle Migration in Granular Filters Using A DEM-CFD Method. *Journal of Hydrodynamics*, 26(3), 406–415. https://doi.org/10.1016/S1001-6058(14)60046-9

Indraratna, B., and Raut, A. K. (2006). Enhanced Criterion for Base Soil Retention in Embankment Dam Filters. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(12), 1621–1627. https://doi.org/10.1061/(ASCE)1090-0241(2006)132:12(1621)

Indraratna, B., Athukorala, R., and Vinod, J. (2013). Estimating the Rate of Erosion of a Silty Sand Treated with Lignosulfonate. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(5), 701–714. https://doi.org/10.1061/(asce)gt.1943-5606.0000766

Indraratna, B., Nguyen, V. H., and Rujikiatkamjorn, C. (2011). Assessing the Potential of Internal Erosion and Suffusion of Granular Soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(5), 550–554. https://doi.org/10.1061/(asce)gt.1943-5606.0000447

Indraratna, B., Nguyen, V. T., and Rujikiatkamjorn, C. (2012). Hydraulic Conductivity of Saturated Granular Soils Determined Using a Constriction-Based Technique. *Canadian Geotechnical Journal,* 49(5), 607–613. https://doi.org/10.1139/t2012-016.

Indraratna, B., Raut, A. K., and Khabbaz, H. (2007). Constriction-Based Retention Criterion for Granular Filter Design. *Journal of Geotechnical and Geoenvironmental Engineering*, 133(3), 266–276. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:3(266)

Indraratna, B., Trani, L. D., and Khabbaz, H. (2008). A Critical Review on Granular Dam Filter Behaviour - from Particle Sizes to Constriction-Based Design Criteria. *Geomechanics and Geoengineering*, 3(4), 279-290. https://doi.org/10.1080/17486020802406632

Ishaku, J., Gadzama, E., Kaigama, U. (2011). Evaluation of Empirical Formulae for the Determination of Hydraulic Conductivity Based on Grain-Size Analysis. *Journal of Geology and Mining Research,* 3(4), 105-113. http://www.academicjournals.org/jgmr

Ivanov, V., and Chu, J. (2008). Applications of Microorganisms to Geotechnical Engineering for Bioclogging and Biocementation of Soil in Situ. *Reviews in Environmental Science and Biotechnology* 7(2), 139-153. https://doi.org/10.1007/s11157-007-9126-3

Joga, J. R., and Varaprasad, B. (2019). Sustainable Improvement of Expansive Clays Using Xanthan Gum as a Biopolymer. *Civil Engineering Journal*, 5(9), 1893–1903. https://doi.org/10.28991/cej-2019-03091380

Joga, J. R., and Varaprasad, B. (2020). Effect of Xanthan Gum Biopolymer on Dispersive Properties of Soils. *World Journal of Engineering*, 17(4), 563–571. https://doi.org/10.1108/WJE-05-2020-0152

Kakuturu, S., and Reddi, L. N. (2006a). Evaluation of the Parameters Influencing Self-Healing in Earth Dams. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(7), 879–889. https://doi.org/10.1061/(ASCE)1090-0241(2006)132:7(879)

Kakuturu, S. P., and Reddi, L. N. (2006b). Mechanistic Model for Self-Healing of Core Cracks in Earth Dams. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(7), 890–901. https://doi.org/10.1061/(ASCE)1090-0241(2006)132:7(890)

Kandra, H. S., Deletic, A., and McCarthy, D. (2014). Assessment of Impact of Filter Design Variables on Clogging in Stormwater Filters. *Water Resources Management*, 28(7), 1873–1885. https://doi.org/10.1007/s11269-014-0573-7

Karabash, Z., and Cabalar, A. F. (2015). Effect of Tire Crumb and Cement Addition on Triaxial Shear Behavior of Sandy Soils. *Geomechanics and Engineering*, 8(1), 1–15. https://doi.org/10.12989/gae.2015.8.1.001

Khatami, H. R., and O'Kelly, B. C. (2013). Improving Mechanical Properties of Sand Using Biopolymers. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(8), 1402–1406. https://doi.org/10.1061/(asce)gt.1943-5606.0000861

Kiymik, I., Cabalar, A.F. (2023). Permeability of a Sand with Waste Tire, *Proceedings of the 3rd International Mediterranean Congress, Iksad Global- 2023*. 529-536.

Latifi, N., Horpibulsuk, S., Meehan, C. L., Majid, M. Z., Tahir, M. M., and Mohamad, E. T. (2017). Improvement of Problematic Soils with Biopolymer—An Environmentally Friendly Soil Stabilizer. *Journal of Materials in Civil Engineering*, 29(2). https://doi.org/10.1061/(ASCE)mt.1943-5533.0001706

Li, M., and Fannin, R. (2008). Comparison of Two Criteria for Internal Stability of Granular Soil. *Canadian Geotechnical Journal*, 45(9), 1303–1309. https://doi.org/10.1139/T08-046

Liu, L., Cai, G., Zhang, J., Liu, X., and Liu, K. (2020). Evaluation of Engineering Properties and Environmental Effect of Recycled Waste Tire-Sand/Soil in Geotechnical Engineering: A Compressive Review. *Renewable and Sustainable Energy Reviews*, 126, 109831. https://doi.org/https://doi.org/10.1016/j.rser.2020.109831

Lone, M. A., Hussain, B., and Asawa, G. L. (2005). Filter Design Criteria for Graded Cohesionless Bases. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(2), 251–259. https://doi.org/10.1061/(asce)1090-0241(2005)131:2(251)

Masoumi, E., Forooshani, S. M., and Nian, F. (2013). Problematic Soft Soil Improvement with Both Polypropylene Fiber and Polyvinyl Acetate Resin. *Geotechnical and Geological Engineering*, 31(1), 143–149. https://doi.org/10.1007/s10706-012-9575-5

Mínguez, R., Delgado, F., Escuder, I., and de Membrillera, M. G. (2006). Reliability Assessment of Granular Filters in Embankment Dams. *International Journal for Numerical and Analytical Methods in Geomechanics*, 30(10), 1019–1037. https://doi.org/10.1002/nag.511

Moo-Young, H. K., Sellasie, K., Zeroka, D., and Sabnis, G. (2003). Physical and Chemical Properties of Recycled Tire Shreds for Use in Construction. *Journal of Environmental Engineering,* 129(10), 921–929. https://doi.org/10.1061/(ASCE)0733-9372(2003)129:10(921)

Muszynski, M. R., and Vitton, S. J. (2012). Particle Shape Estimates of Uniform Sands: Visual and Automated Methods Comparison. *Journal of Materials in Civil Engineering*, 24(2), 194–206. https://doi.org/10.1061/(ASCE)mt.1943-5533.0000351

Odong, J. (2007). Evaluation of Empirical Formulae for Determination of Hydraulic Conductivity Based on Grain-Size Analysis. *The Journal of American Science,* 4(1), 1-6. https://www.engineerspress.com/pdf/IJAE/2013-01/a1%20_IJAE-133101_.pdf

Ouhadi, V. R., and Goodarzi, A. R. (2006). Assessment of the Stability of a Dispersive Soil Treated by Alum. *Engineering Geology*, 85(1–2), 91–101. https://doi.org/10.1016/j.enggeo.2005.09.042

Parameswaran, T. G., and Sivapullaiah, P. V. (2017). Influence of Sodium and Lithium Monovalent Cations on Dispersivity of Clay Soil. *Journal of Materials in Civil Engineering,* 29(7). https://doi.org/10.1061/(ASCE)mt.1943-5533.0001877

Park, S. S. (2009). Effect of Fiber Reinforcement and Distribution on Unconfined Compressive Strength of Fiber-Reinforced Cemented Sand. *Geotextiles and Geomembranes*, 27(2), 162–166. https://doi.org/10.1016/j.geotexmem.2008.09.001

Park, S. S. (2011). Unconfined Compressive Strength and Ductility of Fiber-Reinforced Cemented Sand. *Construction and Building Materials*, 25(2), 1134–1138. https://doi.org/10.1016/j.conbuildmat.2010.07.017

Premkumar, S., Piratheepan, J., Arulrajah, A., Disfani, M. M., and Rajeev, P. (2016). Experimental Study on Contact Erosion Failure in Pavement Embankment with Dispersive Clay. *Journal of Materials in Civil Engineering*, 28(4). https://doi.org/10.1061/(ASCE)mt.1943-5533.0001452

Rather, N. A., Lone, M. A., Dar, A. Q., and Mir, B. H. (2021). Laboratory Investigations for Development of Design Criteria for Varying Shapes of Protective Filters. *International Journal of Geotechnical Engineering*, 15(6), 774–781. https://doi.org/10.1080/19386362.2018.1475320

Raut, A. K., and Indraratna, B. (2008). Further Advancement in Filtration Criteria through Constriction-Based Techniques. *Journal of Geotechnical and Geoenvironmental Engineering*, 134(6), 883–887. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:6(883)

Reddy, J. J., and Varaprasad, B. (2021). Long-term and Durability Properties of Xanthan Gum Treated Dispersive Soils - An Eco-Friendly Material. *Materials Today: Proceedings*, 44, 309–314. https://doi.org/10.1016/j.matpr.2020.09.472

Richards, K. S., and Reddy, K. R. (2007). Critical Appraisal of Piping Phenomena in Earth Dams. *Bulletin of Engineering Geology and the Environment*, 66(4), 381–402. https://doi.org/10.1007/s10064-007-0095-0

Salarashayeri, A.F., and Siosemarde, M. (2012). Prediction of Soil Hydraulic Conductivity from Particle-Size Distribution. *World Academy of Science, Engineering and Technology, International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering*, 6(1), 16-20. https://doi.org/10.5281/zenodo.1055779

Savas, H. (2016). Consolidation and Swell Characteristics of Dispersive Soils Stabilized with Lime and Natural Zeolite. *Science and Engineering of Composite Materials*, 23(6), 589–598. https://doi.org/10.1515/secm-2014-0202

Seblany, F., Vincens, E., and Picault, C. (2021). Determination of the Opening Size of Granular Filters. *International Journal for Numerical and Analytical Methods in Geomechanics*, 45(9), 1195–1211. https://doi.org/10.1002/nag.3198

Sharif, Y. A., Elkholy, M., Chaudhry, M., and Imran, J. (2015). Experimental Study on the Piping Erosion Process in Earthen Embankments. *Journal of Hydraulic Engineering*, 141(7). https://doi.org/10.1061/(asce)hy.1943-7900.0001019

Sivakumar Babu, G. L., and Srivastava, A. (2007). A Procedure for the Design of Protective Filters. *Canadian Geotechnical Journal*, 44(4), 490–495. https://doi.org/10.1139/T07-005

Sujatha, E. R., and Saisree, S. (2019). Geotechnical Behaviour of Guar Gum-Treated Soil. *Soils and Foundations*, 59(6), 2155–2166. https://doi.org/10.1016/j.sandf.2019.11.012

Talukdar, P., and Dey, A. (2019). Hydraulic Failures of Earthen Dams and Embankments. *Innovative Infrastructure Solutions*, 4(1). https://doi.org/10.1007/s41062-019-0229-9

Ta'negonbadi, B., and Noorzad, R. (2017). Stabilization of Clayey Soil Using Lignosulfonate. *Transportation Geotechnics*, 12, 45–55. https://doi.org/10.1016/j.trgeo.2017.08.004

Tang, C., Shi, B., Gao, W., Chen, F., and Cai, Y. (2007). Strength and Mechanical Behavior of Short Polypropylene Fiber Reinforced and Cement Stabilized Clayey Soil. *Geotextiles and Geomembranes*, 25(3), 194–202. https://doi.org/10.1016/j.geotexmem.2006.11.002

Tsang, H. (2008). Seismic Isolation by Rubber-Soil Mixtures for Developing Countries. *Earthquake Engineering and Structural Dynamics*, 37(2), 283–303. https://doi.org/10.1002/eqe.756

Turkoz, M., and Vural, P. (2013). The Effects of Cement and Natural Zeolite Additives on Problematic Clay Soils. *Science and Engineering of Composite Materials*, 20(4), 395–405. https://doi.org/10.1515/secm-2012-0104

Turkoz, M., Savas, H., Acaz, A., and Tosun, H. (2014). The Effect of Magnesium Chloride Solution on the Engineering Properties of Clay Soil with Expansive and Dispersive Characteristics. *Applied Clay Science*, 101, 1–9. https://doi.org/10.1016/j.clay.2014.08.007

Vakili, A. H., and Selamat, M. R. (2014). An Assessment of Veracity of Filter Criteria for Earth Dams. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, 167(6), 574–584. https://doi.org/10.1680/geng.13.00119

Vakili, A. H., Ghasemi, J., Selamat, M. R., Salimi, M., and Farhadi, M. S. (2018a). Internal Erosional Behaviour of Dispersive Clay Stabilized with Lignosulfonate and Reinforced with Polypropylene Fiber. *Construction and Building Materials*, 193, 405–415. https://doi.org/10.1016/j.conbuildmat.2018.10.213

Vakili, A. H., Selamat, M. R., Aziz, H. (2015). Filtration of Broadly Graded Cohesive Dispersive Base Soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 141(5). https://doi.org/10.1061/(ASCE)gt.1943-5606.0001280

Vakili, A. H., Selamat, M. R., Aziz, H., Mojiri, A., Ahmad, Z., and Safarzadeh, M. (2017). Treatment of Dispersive Clay Soil by ZELIAC. *Geoderma*, 285, 270–279. https://doi.org/10.1016/j.geoderma.2016.10.009

Vakili, A. H., Selamat, M. R., Mohajeri, P., and Moayedi, H. (2018b). A Critical Review on Filter Design Criteria for Dispersive Base Soils. *Geotechnical and Geological Engineering*, 36(4), 1933–1951. https://doi.org/10.1007/s10706-018-0453-7

Viswanadham, B. V. S., Phanikumar, B. R., and Mukherjee, R. V. (2009). Swelling Behaviour of a Geofiber-Reinforced Expansive Soil. *Geotextiles and Geomembranes*, 27(1), 73–76. https://doi.org/10.1016/j.geotexmem.2008.06.002

Wiszniewski, M., and Cabalar, A. F. (2014). Hydraulic Conductivity of a Biopolymer Treated Sand. *New Frontiers in Geotechnical Engineering,* 19–27. https://doi.org/10.1061/9780784413456.003

Wiszniewski, M., and Cabalar, A. F. (2016). Applications of Permeability, Oedometer and Direct Shear Tests to the Sand Mixed with Waste Tire Crumb. *Acta Sci. Pol. Architectura*, 15(1), 69–82. http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.agro-eaf6690a-19aa-4f7e-bf9e-767ec530ecba

Wiszniewski, M., Skutnik, Z., and Cabalar, A. F. (2016). Laboratory Assessment of Permeability of Sand and Biopolymer Mixtures. *Annals of Warsaw University of Life Sciences, Land Reclamation*, 45(2), 217–226. https://doi.org/10.2478/sggw-2013-0018

Wiszniewski, M., Skutnik, Z., Biliniak, M., and Cabalar, A. F. (2017). Some Geomechanical Properties of a Biopolymer Treated Medium Sand. *Annals of Warsaw University of Life Sciences, Land Reclamation*, 49(3), 201–212. https://doi.org/10.1515/sggw-2017-0016

Yilmaz, Y. (2015). Compaction and Strength Characteristics of Fly Ash and Fiber Amended Clayey Soil. *Engineering Geology*, 188, 168–177. https://doi.org/10.1016/j.enggeo.2015.01.018

Yousif, O. S. Q., Karakouzian, M., Rahim, N. O. A., and Rashed, K. A. (2017). Physical Clogging of Uniformly Graded Porous Media Under Constant Flow Rates. *Transport in Porous Media*, 120(3), 643–659. https://doi.org/10.1007/s11242-017-0946-5

Zorluer, I., Icaga, Y., Yurtcu, S., and Tosun, H. (2010). Application of a Fuzzy Rule-Based Method for the Determination of Clay Dispersibility. *Geoderma*, 160(2), 189–196. https://doi.org/10.1016/j.geoderma.2010.09.017

Zornberg, J. G., Cabral, A. R., and Viratjandr, C. (2004). Behaviour of Tire Shred - Sand Mixtures. *Canadian Geotechnical Journal*, 41(2), 227–241. https://doi.org/10.1139/t03-086

CURRICULUM VITAE

Personal Information

İlker Kıymık

Education

Cracow University of Technology / Poland – 2019

BSc. – Civil Engineering – Gaziantep University / Türkiye – 2021

MSc. – Geotechnics / Civil Engineering – Gaziantep University/ Türkiye – 2023

Active Researches

AFAD - UDAP Projesi / Gaziantep Zemin Davranışlarının Deprem Zararlarının Azaltılmasındaki Rolü: Gaziantep-Kahramanmaraş İlleri - UDAP-Ç-21-16

Master Student Researcher – 2021

Languages

English: Advanced

Deutch, Polish: Beginner

Skills

MS Office

Autocad