REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

# DURABILITY ASSESSMENT OF CONCRETE INCORPORATING LIMESTONE SAND WITH DIFFERENT FINES CONTENT

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MSc. THESIS
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PROGRAM OF STRUCTURAL ENGINEERING

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İSTANBUL, 2015

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A thesis submitted by Hakan ÖZKAN in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 13.11.2015 in Department of Civil Engineering, Structural Engineering Program.

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## ACKNOWLEDGEMENTS

This master study was carried out in Concrete Laboratory of Yıldız Technical University (YTU) under the supervision of Assistant Professor Ahmet GÖKÇE, Department of Civil Engineering. I am grateful to him for placing me in this research. This research was a great experience for me.

I am also deeply grateful to NOMAYG JV, Nurol-Ozaltin-Makyol-Astaldi-Yuksel-Gocay, and IHI Infrastructure Systems Co., Ltd., as a EPC Contractor for sharing Izmit Bay Crossing Suspension Bridge Project data and their permission for publication in this thesis.

I should also express my sincere gratitude to Tahir TURGUT and Tansu ŞAHİN from Oyak Beton who equipped me with concrete knowledge and for materials supply.

I also wishes to thank ITU-Marmaray Laboratory and YTU students for carrying out the experimental work as part of a final year undergraduate project in this research.

My special thanks are due to IHI Infrastructure Systems Co., Ltd., Design Engineer and my colleague in Yıldız Technical University, Çiğdem BEYAZ for her guidance and cooperation during this experimental study.

October, 2015

Hakan ÖZKAN

# TABLE OF CONTENTS

Page

## LIST OF ABBREVIATIONS

| | |
|---|---|
| AMF | Aggregate microfines |
| CA | Crushed aggregate |
| CFA | Crushed fine aggregate |
| CS | Crushed sand |
| H | High water/cement ratio |
| HRWR | High range water reducer |
| ICAR | International Center for Aggregates Research |
| L | Low water/cement ratio |
| LSF | Limestone fines |
| NDT | Non-destructive test |
| PSD | Particle size distribution |
| RCM | Rapid chloride migration |
| w/c | water/cement |

# LIST OF FIGURES

Page

# LIST OF TABLES

Page

# ABSTRACT

## DURABILITY ASSESSMENT OF CONCRETE INCORPORATING LIMESTONE SAND WITH DIFFERENT FINES CONTENT

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MSc. Thesis

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This study investigates the effect of fines content below 63 μm in crushed sand (CS) obtained from limestone quarry on mechanical and durability performance of concrete. Two different w/c ratios respectively 0,38 (L series) and 0,58 (H series) were used in concrete mix design. Slag cement content were kept constant as 380 kg/m$^3$ for L series and 280 kg/m$^3$ for H series. In order to determine the mechanical behavior of conrete compressive strength test was performed. Besides mechanical test to explain the fines content effect on durability performance of concrete, chloride ion permeability, water penetration depth and capillary water absorption tests were performed. The abrasion resistance of concretes was also investigated. Non-destructive tests (NDT) such as Wenner probe electrical resistivity and ultrasounic pulse of velocity were performed to support durability tests. The results show that for L series concretes, the increment of fines content from 0% to 15% did not have clear effect on compressive strength. On the other hand for the H series, compressive strength increased with the addition of limestone fines (LSF). No significant change was observed in abrasion resistance. Furthermore, the rapid chloride migration (RCM) resistance decreased by the increment of LSF. Similar results were observed for the water permeability and capillary water absorption tests. NDT tests also supported durability test results. It can be concluded that the durable concretes can be produced from CS with around 10% LSF.

**Keywords:** Fines content, crushed sand, limestone fines, durability performance, chloride-ion permeability

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# ÖZET

# FARKLI İNCE MALZEME ORANLARINDA KİREÇTAŞI KUMU İÇEREN BETONLARIN DURABİLİTE DEĞERLENDİRMESİ

Hakan ÖZKAN

İnşaat Mühendisliği Anabilim Dalı

Yüksek Lisans Tezi

Tez Danışmanı: Yrd. Doç. Dr. Ahmet Gökçe

Bu çalışma kireçtaşı ocağından elde edilen kırma kum içindeki ince malzeme miktarının (<63 µm) betonun mekanik ve durabilite özellilkerini etkisini içermektedir. Beton tasarımında sırasıyla 0,38 (L serisi) ve 0,58 (H serisi) olmak üzere iki farklı su/çimento oranı kullanılmıştır. Cüruf içerikli çimento miktarı L serisi beton karışımlarında 380 kg/m$^3$, H serisi beton karşımlarında 280 kg/m$^3$ değerinde sabit tutulmuştur. Betonun mekanik davranışının anlaşılması için basınç dayanımı testi yapılmıştır. İnce malzemenin betonun basınç dayanımına etkisinin yanı sıra durabilite performansına etkisini görebilmek için klor geçirimliliği, basınçlı su geçirimliliği ve kapilerite deneyleri yapılmıştır. Betonun aşınma direnci de bu çalışmada araştırılmıştır. Durabilite testlerini desteklemek için rezistivite ve ultrases deneyleri tahribatsız deneyler olarak yapılmıştır. Sonuçlara göre, ince malzeme miktarının artması L serisi betonların mukavemet değerlerinde herhangi bir etki yaratmamıştır. Öte yandan H serisi betonlarda ince malzeme miktarının artması basınç dayanımında artış sağlamıştır. Aşınma direncinde önemli bir değişim gözlemlenmemiştir. Klor geçirimliliği katsayısı ince malzeme miktarının artmasıyla azalmıştır. Bu sonuçlara benzer olarak basınçlı su geçirimliliği ve kapiler su emme değerlerinin de ince malzeme miktarının artması ile azaldığı gözlemlenmiştir. Aynı zamanda tahribatsız deney sonuçlarının da durabilite sonuçlarını desteklediği gözlemlenmiştir. Sonuç olarak %10 civarında ince malzeme kullanılarak durabilitesi yüksek betonların üretilebildiği tecrübe edilmiştir.

**Anahtar kelime:** İnce malzeme, kırma kum, kireçtaşı ince malzemesi, durabilite performansı, klor geçirimliliği

**YILDIZ TEKNİK ÜNİVERSİTESİ FEN BİLİMLERİ ENSTİTÜSÜ**

# CHAPTER 1

# INTRODUCTION

## 1.1 Literature Review

A literature review of fines content effect on concrete performance is presented in this chapter. Many researches and studies have been developed on the effect of fine aggregate on concrete. The topics of researches included their effect on fresh concrete properties and mechanical behavior of concrete. However, besides these properties durability performance of concrete was also researched in this study. This durability performance contains abrasion performance, chloride migration resistance, water permeability, water sorptivity and non-destructive tests (NDT).

### 1.1.1 Background of the Researches on Fines Content Effect on Concrete

Concrete is one of the main material in construction industry as a structural material. Moreover, it plays the key role to determine the service life of construction. A concrete mix consists of aggregate, water and cement. Besides these constituents high range water reducer admixture (HRWRA) is necessary for fresh state. Huge percent of the volume of concrete is occupied by the aggregates which means that aggregate properties have a big impact on concrete properties. Aggregates are divided into two as a coarse aggregate and fine aggregate in accordance with their size.

Generally natural sand, which is one of the constituents used in the production of conventional concrete as a fine aggregate, has become highly expensive and also scarce [1]. With the development of economic construction, the amount of natural sand has been unable to meet the growing demand of concrete [2]. To overcome these problems there is a need of cost effective alternative and innovative materials [3]. To overcome this problem, the application of replacing natural sand with crushed sand (CS) has become a trend in concrete industry.

According to Menadi [4], there is a growing interest in the use of crushed sand obtained from limestone quarries in some countries where river sand is not widely available. Crushed sand is very abundant in limestone quarries and its use could significantly decrease the materials cost of concrete, eliminate the dust disposal cost, reduces environmental pollutions and dilapidation of natural resources [4].

Limestones are sedimentary rocks primarily of calcium carbonate [5]. The use of crushed limestone as a fine aggregate in concrete has been and is a welcomed development in areas where limestones abound and where natural sands are scarce, expensive or unsuitable [6]. The use of limestone fines (LSF) as cement and sand replacement present interesting possibilities to reduce the cement cost production, $CO_2$ emission and the conservation of natural resources [7]. Some countries such as Spain, France, Algeria and Argentina experienced a big shortage in natural sand but crushed sand is abundant [4].

Crushed sand is produced by crushing a large parent mass of rock [8]. Thus, many aggregate properties depend on the properties of the parent rock (e.g., chemical and mineralogical composition, petrographic classification, specific gravity, hardness, strength, physical and chemical stability, pore structure and color) [8]. Donza [8] stated that these properties have an important influence on the quality of fresh and hardened concrete.

Natural sand, which may be weathered, differs from most crushed fine aggregates (CFA) in its grading, particle shape and surface texture [9]. CS are produced by crushing rock depositions to produce a fine aggregate which is generally more angular and has rougher surface texture than naturally weather sand particles [10].

The production of CS also generates high percentages of fines content, particles that pass the 75 µm sieve, ranging from 5% to 20% [10]. Menadi [4] introduced that CS does not have a significant demand due to its high fines content that exceeds the standard allowable limit of 5%. Fine aggregates play a very important role in controlling the properties of fresh concrete [11]. Among the fine and coarse aggregates, the fine aggregate has greater effects because the fine and coarse aggregates are generally blended such that the fine aggregate is more than enough to fill the voids within the coarse aggregate or in other words such that the fine aggregate is dominant [12].

Kwan [12] stated that the particle size distribution (PSD) of the aggregate in concrete has great effects on the performance of the concrete mix produced. The content of fines (particles smaller than 0.075 mm) in aggregates used for the production of concrete is generally limited by most standards worldwide [11]. ASTM C 33 [13] limits the amount of aggregate smaller than 75 µm No. 200 sieve to be used in concrete [14]. Historically, the reason for this limit is that most deleterious clay or silt that may be present in an aggregate will be removed along with this size fraction [14]. Before the 1980s, limestone was assumed as an inert filler [15]. However, in many crushed aggregates, the fines content portion does not contain clay or silt, and is only "dust of fracture [14]. Then, the use of CS to prepare concrete has become a trend [16].

Many previous researches on the effect of inclusion of LSF as either sand or cement replacements on fresh and hardened mortar and concrete have been developed [7]. It appears that the authors of the standards realize that, in the case of CS, it is difficult to produce sand with very low fines content, although its effect on concrete is critical [11]. Therefore, somewhat higher amounts of fines are allowed in CS, as long as it is free from clay and shale [11]. It has been established that 10–15% of LSF could be allowed in CS without harmful effects on the physical and mechanical properties of concrete [17]. Some of these benefits include good strength, low possibility of alkali-silica reaction and the decrease in drying shrinkage in concrete [18]. The effect of inclusion of LSF in CS on fresh and hardened concrete has been a major research topic for many years [17]. However, little work has been done so far on the effect of fines in CS on the durability of concrete [17]. If it is possible to use this crushed stone dust in making concrete by partial replacement of natural river sand, then this will not only save the cost of construction but at the same time it will solve the problem of disposal of this dust [3].

### 1.1.2 The Impact of Limestone Characteristics on Concrete Properties

Concrete can be constructed using a variety of aggregates and constructability and long-term performances are influenced by the characteristics and physical properties of the aggregates used [10]. Aggregate is a granular material such as sand, gravel, crushed stone, and blast furnace slag that usually occupies approximately 60 to 75% of the volume of concrete [19]. Aggregates have a significant influence on both rheological and mechanical properties of mortars and concrete [20]. The characteristics of the aggregate influence the water demand of the concrete [21]. Limestone, dolomite, granite, and traprock are crushed aggregates most commonly used in concrete and account for 94% of the crushed stone produced in the U.S in 1996 [22]. The current ASTM C 33 [13] specification limits the amount of aggregates smaller than the No. 200 sieve (75 µm) that can be included in concrete mixes to 3–7%. Stewart [14] stated that historically, the reason for this limit is that most deleterious clay or silt that may be present in an aggregate will be removed along with this size fraction. However, Li, Wang and Zhou [17] reported, CS differs from natural sands in its grading, particle shape, and texture; and typically has between 10% and 20% fines (the particles passing the 75 µm sieve).

In many crushed aggregates, the fines content portion does not contain clay or silt, and is only ‘‘dust of fracture’’ [14]. In CFA these fines are most likely smaller size fractions of the crushed aggregate, while in natural sands the fines can be clays or other deleterious particles that harm the concrete [23]. If no deleterious materials such as clay, shale, coal, lignite or other impurities are present, the dust should be considered clean and acceptable for use in concrete [24]. Kumar [25] stated the fine aggregate should be free from organic impurities, clay  and silt.

Kwan [12] et al. stated since the fine aggregate has smaller mean particle size and larger specific surface area, the specific surface area of the blended aggregate would also be determined mainly by the specific surface area of the fine aggregate. A number of studies have dealt with the influence of both grading and particle shape of the fine aggregate in mortars and concrete [20].

Norvell [26] et al, introduced the type and gradation of aggregates have significant effects on concrete properties and performance. The smallest particles often referred to as “fines” play an important role from workability to strength and durability. Historically fine aggregates have been viewed as undesirable for many reasons. Early experimental results showed that they are seen to reduce workability due to their high surface area, which necessitates an increase in the amount of water, which in turn reduces strength and durability.

The main reasons for the appropriate LSF improving strength and abrasion resistance of concretes are that: LSF act as nucleation sites for CH and C–S–H reaction products at early hydration ages and accelerate the hydration of clinker minerals and carboaluminates are formed by the reaction between limestone fines and $C_3A$, resulting in an improvement in early strength; meanwhile, the fines material also can improve fine-particle packing, thus increase the density of paste matrix and interfacial transition zone in hardened concrete, and improve the pore structure of abrasion area [10].

CFA differs from natural sands in gradation, particle shape and texture because of that each of these characteristics has some influence on concrete performance and influences cement requirements, water requirements, additive requirements, workability, and finishing characteristics of the concrete [24].

#### 1.1.2.1 Particle Shape

Some people think that higher content of powder in the aggregate increases the fineness and the total surface area of aggregate particles, thus increasing water content will adversely affect the quality of concrete [27]. As a composite material, the performance of concrete materials can be expected to depend on the properties of the interfaces between its two major components, aggregate and cement paste [28]. The shape and PSD of aggregate particles used in concrete (sand, gravel; 0,2 mm to 15 mm) can affect various properties in the fresh and hardened states, particularly rheological and mechanical properties [29]. Hu and Stroeven [28], explained shape is one of the most difficult features to define and, without definition, quantification is impossible since approximately 80 percent of the total volume of concrete mix consist of aggregate, their characteristics significantly affect the performance of fresh and hardened concrete and have an impact on the cost effectiveness of concrete [30]. Michel and Courard [31] reported limestone particles modify the grain size distribution. The shape of fine particles was reported as having a significant effect on water demand [31]. The workability, flow, yield, air content, water requirement, bleeding and finishability of concrete are all influenced by the particle shape of the fine aggregate in the mortar [24]. Poorly shaped (e.g. high angularity or elongated) sands in concrete have a much greater total effect on concrete quality and workability than do poorly shaped coarse aggregates because of the relationship between particle size and surface area to volume ratio [23]. When using irregularly shaped (non-spherical) CFA, it has also been shown that including very fine mineral fillers can reduce the water requirement in superplasticized concrete [23]. Kronlof [32] reported more irregular the fine particles below 63μm are shaped, the greater packing improvement this fines provide.

ACI Education Bulletin E1 standards [19] summarized particle shape as follows: sphericity and roundness. Sphericity is a measure of whether the particle is compact in shape and roundness refers to the relative sharpness or angularity of the particle edges and corners.

Sinecen [30] et al explained that the flaky and elongated particles will have less strength and durability when compared with cubical, angular or rounded particles of the same aggregate and these particles tend to produce harsh mixtures and affect finishability. An excess of poorly shaped particles could reduce the strength of concrete through the increase of mixing water.

Hu and Stroeven [28] conducted a research on differences between fluvial gravel and crushed rock. The results showed that the sphericity ratio for the fluvial gravel is slightly higher than that of the crushed rock, confirming that the latter aggregate type is more angular than the other.

A similar study was performed by Arasan et al [33]. The results showed that the crushed aggregate gives higher roundness value than the natural river aggregate and the fractal dimensions of natural river aggregate are also lower than crushed aggregate.

ACI Education Bulletin E1 standards [19] also explained surface texture refers to the degree of roughness or irregularity of the aggregate particle surface. Usually, terms such as rough, granular, crystalline, smooth, or glassy are used to describe surface texture rather than using any quantitative method. Smooth particles will require less mixing water and therefore less cementitious material at a fixed water to cementitious material ratio to produce concrete with a given workability, but will have less bonding area with the cement paste than rougher particles. With the increase of surface roughness of MS particles, the compressive and flexural strengths of concrete increase; while with the increase of crushing value of CS particles, the flexural strength of concrete decreases [10].

The shape and surface texture of the individual particles of sand, rock, gravel, slag, or lightweight aggregate making up an aggregate will have an important influence on the workability of freshly mixed concrete and the strength of hardened concrete.

Fine aggregate particle shape and texture affects concrete in one major way through its influence on the workability of fresh concrete [19]. Angular rough sands will require more mixing water in concrete than rounded smooth fine aggregates to obtain the same level of slump or workability, with other factors being equal. This, in turn, will affect the water-cementitious material ratio if the cementitious content is held constant; or it will require an adjustment in the cementitious content if a certain water-cementitious material ratio is needed [19]. The influence of fine aggregate shape and texture on the strength of hardened concrete is almost entirely related to its influence on the resulting water-cementitious material ratio of the concrete if the fine aggregate has a grading within the normally accepted limits and its grading is taken into account in selecting concrete proportions [19].

#### 1.1.2.2 Grading

Grading refers to the distribution of particle sizes present in an aggregate [19]. The grading and grading limits are usually expressed as the percentage of material passing each sieve [33].

Besides particle shape, crushing processes also influence grading of the CFA, and the proportion of microfines (minus 75 μm material), particularly when compared to natural fine aggregates [20]. The significance of the aggregate grading is that it directly influences many important properties of fresh concrete, such as consistency and segregation, and to a certain extent the properties of hardened concrete as well and generally, within the permitted standard limits, the gradation of fine aggregate has a greater influence on the properties of concrete than that of coarse aggregate [24].

Chen [34] et al. stated the addition of LSF to fill into the voids between aggregate particles can reduce the volume of voids.

The gradation of the aggregate, or distribution of particle sizes, should meet the specifications outlined in ASTM C33 [13], "Standard Specification for Concrete Aggregates." ASTM C33 [13] suggests that the gradation curve be smooth, with neither a deficiency nor excess of material of any one size. A smooth gradation curve decreases the voids between the aggregate particles in a homogeneous concrete mix, and, because the voids must be filled with a mixture of cement and water, it therefore decreases the amount of cement required [35].

#### 1.1.2.3 Deleterious Component Assessment

Particles finer than 75µm may be present in three different forms: clay, silt, or dust. [24]. These may be naturally occurring constituents in the aggregate or can be contaminants resulting from the transportation of aggregates in gondola cars, barges, and trucks that were previously used to haul coal or other harmful substances [19]. Organic impurities such as peat, humus, organic loam, and sugar delay setting and hardening of concrete and may lead to deterioration in some cases [19]. Concrete aggregates contained in the fine sand of the 0,063 mm sieve very thin materials (clay, silt and very fine stone flour) is of great importance in terms of content and quality of the concrete quality [36].

The methylene blue test is widely accepted in Europe as an effective method to quantify the clay content both in natural sand and CS [24]. As methylene blue dye is added to a fine aggregate and water slurry, the aggregate absorbs the blue dye until an endpoint is reached when the aggregate stops absorbing additional blue dye [37]. According to the EN 12620 [38] standard less than 3% of the content of very fine material contained in the fine aggregate means harmless. Clay and silt are known to increase water demand and decrease concrete durability [14]. This is due to their structure and cation exchange capacity [37]. ACI [19] stated excessive amounts of this material may unduly increase the water required to produce a given slump for the concrete, or, if the amount of fine material varies from batch to batch, may cause undesirable fluctuations in the slump and strength.

Özbebek [36] et al. explained the effect of clay and silt on concrete as follows,

- They weaken the bond between the coarse aggregate and cement paste.

- They increase the amount of specific surface. The amount of water required for the concrete mix in consequence increases. Therefore, durability and strength decreases.
- They prevent adherence by reacting with cement.

Fate [39] carried out a research on MS. According to the result if CS is free from chemical impurities such as sulphates and chlorides, the properties of concrete like strength and durability would be better.

In the interest of increasing allowable limits of microfine 75 mm aggregates in concrete, it is important to understand the effects of ultrafine particles on concrete performance, including those of clay and nonclay mineralogy [26]. Aggregate should be clean, hard, and durable, graded from coarse to fine materials to increase density by filling voids [40].

### 1.1.3 Crushed Sand as an Innovative Solution and Alternative Way

Concrete is probably the most extensively used construction material in the world [41]. It is obtained by mixing cementitious material, water & aggregates in required proportions [39].

Natural river sand is one of the key ingredients of concrete, is becoming expensive due to excessive cost of transportation from sources and also large scale depletion of sources creates environmental problems [3]. With the rapid development of infrastructure construction, the natural sand currently in use as fine aggregate in concrete does not meet the requirements for engineering construction [16]. As environmental transportation and other constraints make the availability and use of river sand less attractive, a substitute or replacement product for concrete industry needs to be found [1].

Manufacturers have had to opt for alternatives such as crushed aggregate and finer gravel [32]. Crushed sand is manufactured by crushing larger stones of quarry to particular size of sand. Its chemical & physical properties such as color, size & shape, surface texture up particles depend upon types of stone & its source [39]. If it is possible to use this crushed stone dust in making concrete by partial replacement of natural river sand, then this will not only save the cost of construction but at the same time it will solve the problem of disposal of this dust [3].

#### 1.1.3.1 Differences between Natural Sand and Crushed Sand

Aggregates have a significant influence on both rheological and mechanical properties of mortars and concrete [20]. Gonçalves [20] et al. stated that their specific gravity, PSD, shape and surface texture influence markedly the properties of mortars and concrete in the fresh state and the mineralogical composition, toughness, elastic modulus and degree of alteration of aggregates are generally found to affect the properties of mortars and concrete in the hardened state.

ACI [19] concluded that aggregates may be broadly classified as natural or artificial, both with respect to source and method of preparation. Natural sands and gravels are the product of weathering and the action of wind or water, while stone sands and crushed stone are produced by crushing natural stone. Coarse and fine aggregates are generally sieved separately. That portion of an aggregate passing the 4.75 mm (No. 4) sieve and predominantly retained on the 75 mm (No. 200) sieve is called fine aggregate or sand, and larger aggregate is called coarse aggregate.

Because of the crushing process, CS differs from natural sands in its grading, particle shape, and texture; and typically has between 10% and 20% fines (the particles passing the 75 μm sieve) [17].

Some natural aggregates have spherical particles while others contain angular, more cubical particles [42]. CS particles are generally more angular with a rougher surface texture than river sand particles [10]. Because of that the workability is reduced [39]. CS can also contain significant quantities of particles smaller than 75 µm called rock microfines [10]. In CS these fines usually are most likely smaller size fractions of crushed aggregate, while in natural sands the fines can be clays or other deleterious particles [17]. CS is free from chemical impurities such as sulphates and chlorides which improves the properties of concrete like strength and durability [39**].** The characteristics of the fine aggregate significantly influence water requirement, workability, finishability, bleeding, segregation, strength and durability properties of the concrete [42].

### 1.1.3.2 Crushing Process of Crushed Sand

The first commercial use of CFA was made in the early 1930's and current usage of CFA is over 100 times the amount utilized in 1930's and represents approximately 20% of total concrete fine aggregate requirements [24]. In terms of operating, increasing amount of fine material in the sand effects workability and pumping positively but crushed sand quality should be followed very well with increasing filler material [36]. Due to variations in the rock type and crushing process the physical characteristics of the CFA, such as gradation, shape, dust-of-fracture content and texture, can change significantly and influence the performance of concrete [24].

Impact crushers of various types have been employed in CFA production, in particular vertical shaft impactors and comminution in this type of crusher is the result of propelling particles with a rotor moving at high speeds, against an anvil or a curtain of falling particles [20]. The result is that particles with greater integrity and more isometric shapes are produced by this crushing process in comparison to other comminution machines, such as cone, jaw and roll crushers [20]. In the case of cone crushers, particle fracture depends on loading condition [20].

Particle shape is also influenced by crusher type and operation of crushing equipment. Impact crushers break rock by "hitting" the material, thereby giving the rock a sudden blow of high energy [42]. This causes the rock to break along natural zones of weakness along grain interfaces. Impac tcrushers generally produce particles having good cubical shape [42].

### 1.1.4 Influence of Limestone Fines Content on Fresh Concrete Properties

Since the early 20$^{th}$ century, the concrete industry has recognized the need to monitor concrete workability to ensure that concrete can be properly placed and can achieve adequate hardened strength [43]. Aggregate properties significantly affect the workability of plastic concrete [19].

Bederina [44] et al. stated that workability improves by increasing the amount of limestone filler in concrete. It is clear that, in the case of ‘‘w/c=constant’’, the workability slightly decreases when the fillers content increases. The main reason of this conclusion is water demand. Increasing filler content means more specific surface.

Altough the specific surface of aggregates was increased, the water content did not change. But when the evolution is studied with “W/(C+F)=constant”, we can see that the workability improves with increasing fillers content.

Beixing [17] et al observed that with the increment of LSF content in CS, the slump for low strength concrete is increased and the slump for high strength concrete is little influenced, It is suggested that when the fines content is, respectively, 10% to15% for series low strength concrete and 7% to 10% for series high strength concrete, the mixes achieved better workability.

A similar study was performed by Kapgate [3]. It is observed that the slump value increases with increase in percentage replacement of sand with quarry dust for the same w/c ratio.

Norvell [26] et al carried out a research to observe the influence of clays and clay-sized particles on concrete performance on workability, compressive strength. The results of this work demonstrate that nonclay ultrafine particles are not harmful to workability, compressive strength, and drying shrinkage.

One of the major differences in adding microfines to a concrete mix is the change in the water demand of the mix [23]. For the most part, concrete mixes with microfines need additional water to achieve the same workability as mixes with no microfines, but in some cases less water is needed. According to a study done by Teychenne [45], the majority of concrete mixes including 10 to 25 percent dust of fracture needed more water, although there were a few tests that had a decreased water demand.

Higher levels of water reducers are usually required for manufactured aggregate concretes to achieve the same slumps compared to natural sand concretes, but no adverse effects have been found [21].

### 1.1.5 Limestone Filler Impact on Hardened Concrete Properties

Some people think that higher content of microfines increases the total surface area of aggregate particles, thus increasing water content in concrete mixture, and high w/c ratio will adversly affect the concrete quality [27]. Generally the compressive strength, flexural strength, and abrasion resistance as well as freezing resistance tend to increase to a certain limit with increasing proportions of microfines [10]. After the limit is reached, the strength decreases because there is not enough paste to coat the aggregate; impermeability varies without law and shrinkage, while slightly higher, is still within acceptable ranges [10].

However much research has shown that aggregate micro fines (AMF) not only does not have a negative effect on concrete quality, but also may improve its performances if the optimal amount is used [27]. Therefore, there are arguments about the use of AMF. Some point out that AMF may increase water content [27] and accordingly there are bad effects on performances of concrete; but the others indicate that AMF acts as a filler and helps to reduce the total voids content in concrete [10].

#### 1.1.5.1 Effect on Physical and Mechanical Properties of Concrete

The influence of fines in crushed sand on physical and mechanical properties of concrete has been widely investigated [4]. The results proved that up to 15% of fines content in crushed sand could be used without adversely affecting concrete strength [4].

Kumar [25] stated recent studies have shown that this crushed stone sand can be used to produce concrete with higher compressive and flexural strengths. The compressive strength of concrete is the most common performance measure used by the engineer in designing buildings and other structures [46]. The compressive strength is measured by breaking cylindrical concrete specimens in a compression-testing machine [46].

Beixing [17] et al. carried out some tests to observe the effect of microfines on physical and mechanical properties of concrete. These tests performed both low strength concrete and high strength concrete. The increment of LSF improved the compressive strength for all series. For low strength concrete, there was a sligth increase of stregth. For series high strength was improved with the increment of LSF content.

A similar study was performed by Ünal [47]. In the case of the investigation of aggregate gradation, the results showed there was increase of compressive stregth when the fine content of aggregate increases. Increment of coarse aggregate content will increase void ratio with the placing problem. High void ratio in concrete is a structural defect. This structural defect means low strength.

Kenai [7] et al. stated that the influence of LSF on the compressive strength is stronger in the range of LSF as sand replacement of 5% to 10%. The decrease in strength at higher level of LSF may be due to the dilution effect.

The compressive strength of concrete containing higher contents of dust of fracture has been shown comparable to concrete conforming to ASTM C33 in many studies [24].

Dukatz and Marek [48] reported that concrete made with CFA containing up to 7 percent dust of fracture obtains compressive strength equal to or better than concrete made with natural sand with the same w/c.

Ahmed [49] reports that the concrete made with CFA was stronger at all ages than concrete made with blended natural sand.

Celik and Marar [50] reported that as the dust of fracture content was increased to 10 percent the 28-day flexural strength increased 10 percent as compared to the control specimens with no dust of fracture. As the dust of fracture content was increased to 30 percent, the 28-day flexural strength decreased 10 percent as compared to the control concrete mixture.

Bonavetti and Irassar [51] tested the flexural strength of mortars containing up to 20 percent dust of fracture. For all levels of replacement, the concrete showed increased flexural strength at all ages as compared to the control concrete.

The shrinkage of concrete typically increased with the percentage of the minus 75-μm-size fraction [24].

#### 1.1.5.2 Effect on Concrete Durability Performance

Many previous researches [1, 15] on the effect of inclusion of LSF as either sand or cement replacements on fresh and hardened mortar and concrete have been developed. They concluded that, the inclusion of 12 to 18% of fines could be allowed in sand without harmful effects on the physical and mechanical properties of mortar and concrete [7]. However, not much work is reported regarding the effect of LSF on the durability properties of crushed sand concrete [7].

Durability is a very important parameter to develop concrete technologies and construct reinforced concrete structures with long service life due to some economic and environmental reasons and durability is the resistance of concrete against chemical and physical attacks that lead deterioration of concrete during its service life [52]. The durability of concrete subjected to aggressive environments depends largely on transport properties, which are influenced by the pore system [53]. The addition of LSF to fill into the voids between aggregate particles can reduce the volume of voids [34].

Castro [53] et al. summarized the main mechanisms govern transport in cementitious systems: permeability, diffusion and absorption. Permeability is the measure of the flow of fluids under a pressure gradient, while diffusion is the movement of ions due to a concentration gradient. Absorption can be described as the ability to take in water by means of capillary suction.

Chloride binding is of great importance when service life predictions of marine structures are carried out [54]. Therefore, the resistance of chloride ion penetration into concrete is a crucial parameter affecting the durability of reinforced concrete structures [55].

Hobbs [56] assessed carbonation and water permeability data indicate that the aggregate could play an important role in influencing chloride ingress into concrete. His report showed that in the limestone concrete it appears that chlorides can be transported through the aggregate as well as through the surrounding cement paste.

Several models have been published to calculate service life of reinforced concrete based on considering diffusion as the main ingress mechanism [57]. However, these models have some limitations and involve destructive and time consuming testing [57]. Chloride ion diffusion coefficient in concrete is estimated very often by using electro migration tests, among which the Rapid Chloride Migration (RCM) test is becoming more and more popular [58].

Beixing [17] et al. reported that as the fines content increased, the chloride migration coefficient values for series L obviously decreased. Because of less cement amount and higher water/cement ratio, the low-strength concrete has a large number of pores after hardening, which causes low resistance to chlorine ion permeation. The decrease of permeability of series L mixes incorporating LSF is probably due to the filler effect of the fines, which blocks capillary passages formed during the hydration of the cement. In addition to the filler effect, there may be some contribution to the strength increase.

Menadi [4] et al. stated the resistance to chloride-ion penetration and gas permeability decreased for all concrete mixtures with the inclusion of 15% LSF as sand replacement. The presence of 15% LSF as partial replacement of fine aggregates causes an increase in chloride-ion penetration and gas permeability whereas reduces water permeability.

The higher chloride-ion penetration and gas permeability of crushed sand concrete with 15% of LSF means that its use in structures exposed to marine environment should be limited [4].

The concrete resistivity is a parameter that is related to the reinforcement corrosion and seems also very appropriate to represent concrete resistance against chloride ingress [57].

Water permeability is one of the durability properties of concrete. Permeability of concrete can be reduced by using CFA with high percentages of dust of fracture [24].

Menadi [4] performed some tests to explain water permeability performance of concrete incorporating fine content. The results evaluated according to the water penetration depth for all concrete mixtures with and without LSF at 90 days. There is reduction in the water penetration depth for all concretes with LSF. The incorporation of LSF up to 15% as replacement of crushed sand may improve pore structure in transition zone, and thereby reduces water permeability. The results of this research are in agreement with those obtained by Kenai et al. [4] who reported a reduction in the water depth penetration when 15% of LSF as cement replacement were used.

Bonavetti and Irassar [51] tested mortars with varying w/c and dust contents. As the w/c increased, the permeability increased, as would be expected. For every w/c, as the dust content increased the permeability of the mortar decreased as compared to the control mixture.

According to Celik and Marar [50] the absorption percentage of concrete containing up to 15 percent dust of fracture decreased. The decrease in absorption was attributed to the dust acting as filler in the concrete [24]. However, concrete containing more than 15 percent dust of fracture caused an increase in absorption, which they related to the observed decrease in compressive strength [24].

Chen [34] et al. carried out a research on concrete durability. The results of this research showed that at a constant W/C ratio, addition of LSF would significantly decrease water penetration depth and sorptivity coefficient. Furthermore the addition of LSF would also substantially reduce the permeable porosity of concrete. Both of them are linearly related $R^2$ values well above 0,9.

A similar study on durability performance of concrete was performed by Beixing [17]. Besides other properties, research also contains abrasion resistance. The result showed the abrasion resistance of CS concretes showed an improvement at 7% and 10% LSF, and more than 10% of LSF considerably increased the abrasion loss.

## 1.2 Objective of the Thesis

Natural sand is one of the most important consitituents of concrete for improving fresh and hardened properties of concrete. However, using natural sand causes some economic and ecological problems. The availability of natural sand for concrete production is facing challenges, while the so-called waste stockpiles at aggregate crushing areas are causing problems for producers. This means that the industry has a huge need to solve this challenge by finding suitable technology for usable crushed sand production.

Crushed sand is typically produced by mining a suitable rock deposit and breaking the removed rock down to the desired size using crushers. It is distinct from gravel which is produced by natural processes of weathering. After manufacturing process, crushed sand grading contains fines. Effects of these fines material on durability are big question. The aim of this study is to explain effects of crushed fine aggregate (CFA) on durability performance of concrete. This study also presents a case-study on durability assessment of the Izmit Bay Crossing Suspension Bridge project.

### 1.3 Hypothesis

It is hypothesised increases of fines (< 63 µm) content in crushed sand improve concrete properties. Durable structural concrete can be produced with high fines content.

# CHAPTER 2

# EXPERIMENTAL STUDY ON DURABILITY PERFORMANCE OF CONCRETE PRODUCED WITH VARIOUS FINES CONTENT

## 2.1 Introduction

Natural sand is an indispensable part of the concrete constituent due to its positive effect on concrete properties. However, recently natural sand has become a major problem in concrete and construction industry. With the rapid development of infrastructure construction, the natural sand currently in use as fine aggregate in concrete does not meet the requirements for engineering construction. Then, the use of crushed sand to prepare concrete has become a trend. It is difficult to supply natural sand and natural sand's area is far away from construction site that is why problem occurs. This problem tends to researchers to investigate new innovative components for concrete. Because of these reasons in recent years investigation on concrete with crushed sand is getting increased and with the new researches crushed sand has become one of the important component of concrete. The use of CFA instead of natural sand present interesting possibilities such as to reduce cost of production concrete. Using crushed aggregate such as crushed limestone sand also can automatically rescue natural sources. Even these advantages, effects of CFA on durability performance are still questionable. The standards are the biggest proof of this dubious glance. For example British standard 882 (BS 882) [59] allow up to 15% of fines in sand whereas the current ASTM C 33 [13] specification limits the amount of aggregates smaller than the 75 μm that can be included in concrete mixes to 3–7%.

Even though there are lots of researches on fines content effect on conrete, limited of them comprise durability performance. This research includes an experimental study on the effect of fine content obtained from limestone quarry on durability performance of concrete.

Experimental study was carried out focusing on the items as follows:

- Effect of various fine content on mechanical strength of concrete
- Influence of fine content on durability performance of concrete
- NDT to determine fine content effect

## 2.2 Materials

Blast furnace slag cement (type CEM III-B 32,5N) was used in concrete mix design. The properties of the cement are shown in Table 2.1. Two coarse aggregates and crushed limestone sand from same mineralogical sources were selected. The CS was made from pre-washed crushed limestone. Table 2.2 presents a summary of properties of the CS. The limestone fines (LF) below 63 μm were used as a fine material obtained by wet sieve analysis. Properties of coarse aggregates from the same quarry are summarized in Table 2.3. Figure 2.1 presents grading curves of each type of aggregate. One commercially available phosphonate polycaboxylate formaldehyde superplasticizer was used in all mixes. Properties of HRWR are given in Table 2.4. Water is an important ingredient of concrete as it initiates the chemical reaction with cement, and the mix water was completely free from chlorides and sulfates. Ordinary potable water was used throughout the investigation as well as for curing concrete specimens.

Table 2.1 Chemical composition and physical characteristics of the cement

| **Name Of Experiment** | **Unit** | **Measurement Results** |
|---|---|---|
| Corrected loss of ignition | % | 1,27 |
| $SiO_2$ | % | 32,59 |
| $Al_2O_3$ | % | 8,68 |

Table 2.1 Chemical composition and physical characteristics of the cement (Cont'd)

| | | |
|---|---|---|
| $Fe_2O_3$ | % | 1,97 |
| CaO | % | 48,18 |
| MgO | % | 3,58 |
| $SO_3$ | % | 1,76 |
| $Na_2O$ | % | 0,35 |
| $K_2O$ | % | 0,81 |
| $Na_2O$ equivalent total alkali | % | 0,88 |
| Cl - | % | 0,0209 |
| Insoluble residue | % | 0,37 |
| Total additives | % | 64,35 |
| 7 – Day heat of hydration | cal/g | 52 |
| 28 – Day heat of hydration | cal/g | 61,3 |
| Specific Gravity | $g/cm^3$ | 2,94 |
| Specific surface – Blaine | $cm^2/g$ | 5240 |
| 2 – Day compressive strength | MPa | 12,4 |
| 7 – Day compressive strength | MPa | 20,8 |
| 28 – Day compressive strength | MPa | 34,9 |
| Normal Consistency | % | 31,2 |
| Initial setting time | min | 170 |
| Final setting time | min. | 235 |
| Soundness | mm | 1 |

Table 2.2 Properties of limestone fines aggregates 0-4 mm

| **Property / Item** | **Unit** | **Test Result** |
|---|---|---|
| Water Absorption | % | 0,9 |
| Particle Density | $mg/m^3$ | 2,69 |
| Organic Impurities | - | Lighter |
| Water Soluble Chloride Content | % | < 0,001 |
| Water Soluble Alkali Content | % | < 0,01 |
| Potential Activity of Aggregate | % | 0,01 |
| Drying Shrinkage | % | 0,02 |
| Mica, Loam, Clay or Other Impurities | % | 0,3 |
| Methylene Blue Value | - | 0,25 |
| Fines Content | % | 9 |

Table 2.3 Properties of limestone coarse aggregates (4-12 mm and 12-22 mm)

| **Property / Item** | **Unit** | **Test Result (5-12)** | **Test Result (5-31,5)** |
|---|---|---|---|
| Water Absorption | % | 0,4 | 0,3 |
| Particle Density | $mg/m^3$ | 2,71 | 2,72 |
| Organic Impurities | - | Lighter | Lighter |
| Water Soluble Chloride Content | % | <0,001 | <0,001 |
| Water Soluble Alkali Content | % | <0,01 | <0,01 |
| Flakiness Index | % | 11 | 9 |
| Shape Index | % | 9 | 7 |
| Los Angeles Test | % | 29 | 29 |

Table 2.3 Properties of limestone coarse aggregates (4-12 mm and 12-22 mm) (Cont'd)

| | | | |
|---|---|---|---|
| Clay Lumps and Friable Particles | % | 0,1 | 0,05 |
| Drying Shrinkage | % | 0,02 | 0,02 |
| Fines Content | % | 1 | 0,4 |

Table 2.4 Properties of HWRWA

| **Properties** | **Test Result** |
|---|---|
| Appearance | Homogeneous |
| Colour | Yellow |
| Density | 1.060 |
| pH | 4,32 |
| Water soluble chloride | 0,026 |
| Solid content | 29,90 |
| Effective component | Acceptable |
| Alkali content | <%2 |

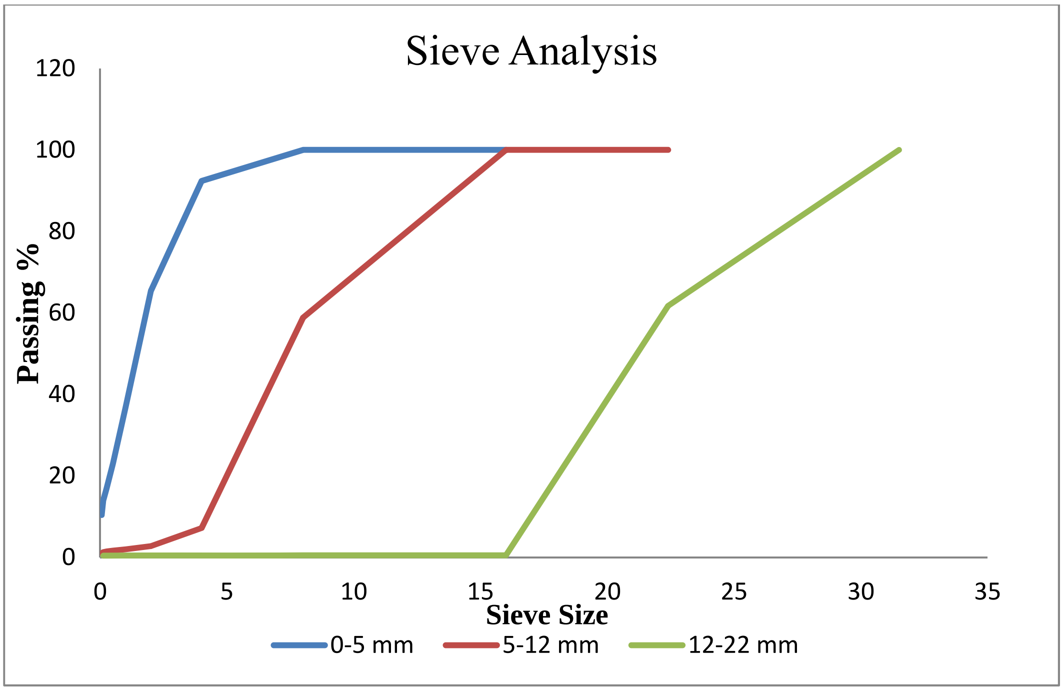



Figure 2.1 Grading curves of aggregates

Figure 2.2 Fine aggregate below 63 μm

Figure 2.3 Fine aggregate below 250 μm

Figure 2.4 Coarse aggregate

### 2.3 Concrete Mix Design

Two series of mixture proportions were, produced. Water/cement ratios were respectively 0.58 (Series H-high w/c ratio) and 0.38 (Series L-low w/c ratio). The limestone fines were used as fine material, the rate of fines is adjusted to 0%, 3%, 6%, 9%, 12% and 15%, by weight of fine aggregate. Table 2.5 shows the detailed data of mixtures. To arrange perfect fines content wet sieve analysis were performed for each sieve size and controlled gradations were obtained.

Two types of coarse aggregate, cement and crushed limestone sand with different fines content are introduced into a mixer and firstly mixed at dry state for 1 minute. Then water and HRWRA were added. Mixing operation until the proper homogenization of the materials continued around 2 minutes. After demoulding, 24 hours after casting, the specimens are kept in water at a temperature of 20 ± 5 ° C for 28 days.

Table 2.5 Concrete mix design

| Mixture | | Fines Content (%) | Water Cement Ratio | Materials (kg/m$^3$) | | | | | | Slump Value (cm) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Water | Cement | Aggregates | | | HRWRA | |
| No | Code | | | | | 0-4 | 4-12 | 12-22 | | |
| **1** | LS-H-00 | 0 | 0,58 | 160 | 280 | 915 | 519 | 517 | 2,61 | 19 |
| **2** | LS-H-03 | 3 | 0,58 | 161 | 280 | 915 | 519 | 517 | 2,61 | 19 |
| **3** | LS-H-06 | 6 | 0,58 | 161 | 280 | 915 | 519 | 517 | 2,61 | 20 |
| **4** | LS-H-09 | 9 | 0,58 | 161 | 280 | 915 | 519 | 517 | 2,61 | 20 |
| **5** | LS-H-12 | 12 | 0,58 | 161 | 280 | 915 | 519 | 517 | 2,61 | 19 |
| **6** | LS-H-15 | 15 | 0,58 | 161 | 280 | 915 | 519 | 517 | 2,8 | 18 |
| **7** | LS-L-00 | 0 | 0,38 | 142 | 380 | 915 | 495 | 492 | 3,57 | 18 |
| **8** | LS-L-03 | 3 | 0,38 | 142 | 380 | 915 | 495 | 492 | 3,57 | 19 |
| **9** | LS-L-06 | 6 | 0,38 | 142 | 380 | 915 | 495 | 492 | 3,57 | 19 |
| **10** | LS-L-09 | 9 | 0,38 | 142 | 380 | 915 | 495 | 492 | 3,57 | 15 |
| **11** | LS-L-12 | 12 | 0,38 | 141 | 380 | 915 | 495 | 492 | 5,32 | 20 |
| **12** | LS-L-15 | 15 | 0,38 | 141 | 380 | 915 | 495 | 492 | 5,32 | 20 |

Table 2.6 Controlled gradations of crushed sand

| **Sieve Size (mm)** | **Controlled gradations adjusted according to target fines contents (percent <0.063 mm)** | | | | | | **Crushed sand (percent passing)** |
|---|---|---|---|---|---|---|---|
| | **0%** | **3%** | **6%** | **9%** | **12%** | **15%** | |
| 4 | 100 | 100 | 100 | 100 | 100 | 100 | 98 |
| 2 | 60 | 60 | 60 | 60 | 60 | 60 | 61 |
| 1 | 29 | 29 | 29 | 29 | 29 | 29 | 28 |
| 0,5 | 21 | 21 | 21 | 21 | 21 | 21 | 23 |

Table 2.6 Controlled gradations of crushed sand (Cont'd)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0,25 | 6 | 6 | 6 | 6 | 6 | 6 | 14 |
| 0,125 | 1 | 1 | 1 | 1 | 1 | 1 | 11 |
| 0,063 | 0 | 3 | 6 | 9 | 12 | 15 | 9 |

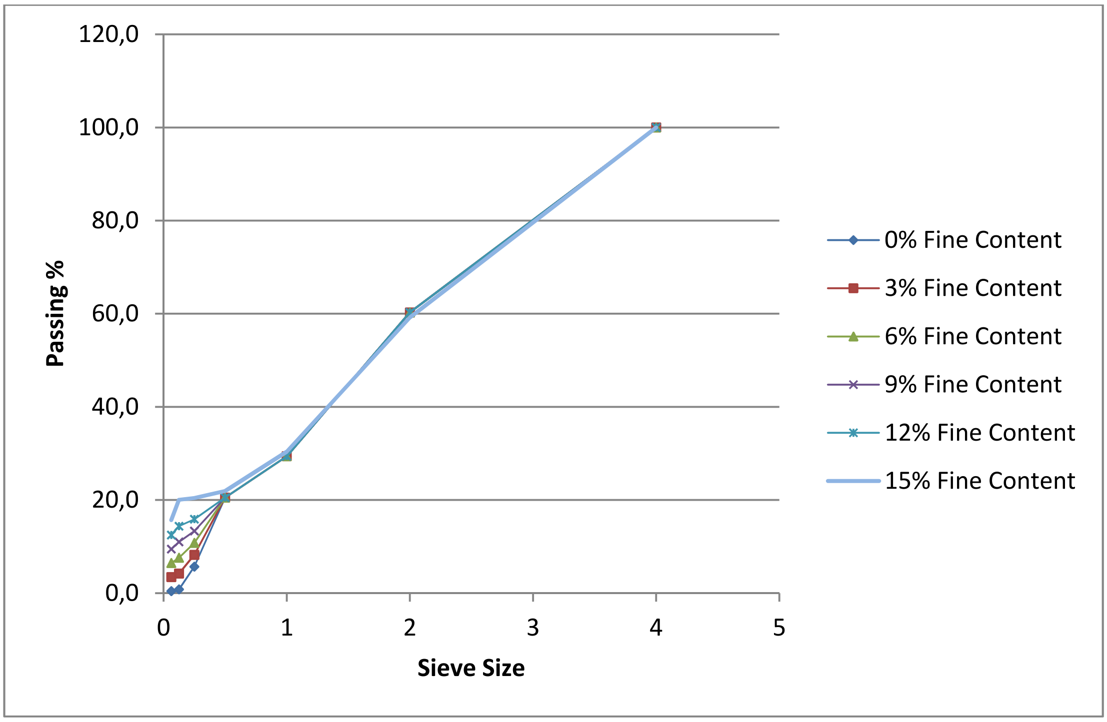



Figure 2.5 Sieve analysis graphs for each fine content design

Figure 2.6 Concrete mixing

## 2.4 Procedures of Hardened Concrete Tests

### 2.4.1 Compressive Strength and Basic Performance Parameter

Test for compressive strength were performed according to EN 12390-3[60], Compressive Strength of Test Specimens. This standard specifies a method for the determination of the compressive strength of the test specimens of hardened concrete. Tests were performed at 28 days on three 150x150x150 mm cubes. Moulds removed 1 day after casting and the samples were cured in a curing room until the testing day in laboratory conditions 20±2 C$^o$.

Vacuum-saturated weight in air and in water and oven-dry weight of the specimen were used in the calculation of volume of permeable pores (%) and water absorption (%).

Figure 2.7 Compression test

### 2.4.2 Capillary Water Absorption

Capillarity water absorption test was performed for cylinder specimen according to the ASTM C 1585 [61], Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. This test method is used to determine the rate of absorption (sorptivity) of water by hydraulic cement concrete by measuring the increase in the mass of a specimen resulting from absorption of water as a function of time when only one surface of the specimen is exposed to water. The sorptivity was measured on 100x200 mm concrete cylinder specimens, which were dried in a 50 $C^{o}$ oven for 3 days. After mass stabilization, the specimens were cut at specified dimensions and coated with epoxy on their lateral surfaces only, in order to ensure uniaxial water absorption. The specimen was rested on rods to allow free access of water to the surface and the tap water level was kept no more than 5 mm above the base of the specimen. The masses of the specimens were measured after various time of absorption. The change in mass of the specimen over time is used to calculate the initial and secondary rates of absorption of the concrete. From the increase in mass of the specimen due to water absorption (denoted by $m_t$), the absorbed volume of water per unit area of inflow surface (denoted by $I$) can be calculated using the following equal, where $a$ is the area of the inflow surface and q is the density of water.

$$I = \frac{m_t}{a \cdot q}$$

In general, the absorbed volume of water per unit area of inflow surface would increase with the time as a square root function of the time $t$ after the start of the sorptivity test, as given by the following equal where $k$ is the sorptivity coefficient of the concrete specimen.

$$I = k \cdot \sqrt{t}$$

To determine the sorptivity coefficient $k$, $I$ was plotted against the square root of $t$, the best-fit straight line was obtained by regression analysis, and then $k$ was calculated as the slope of the best-fit straight line.

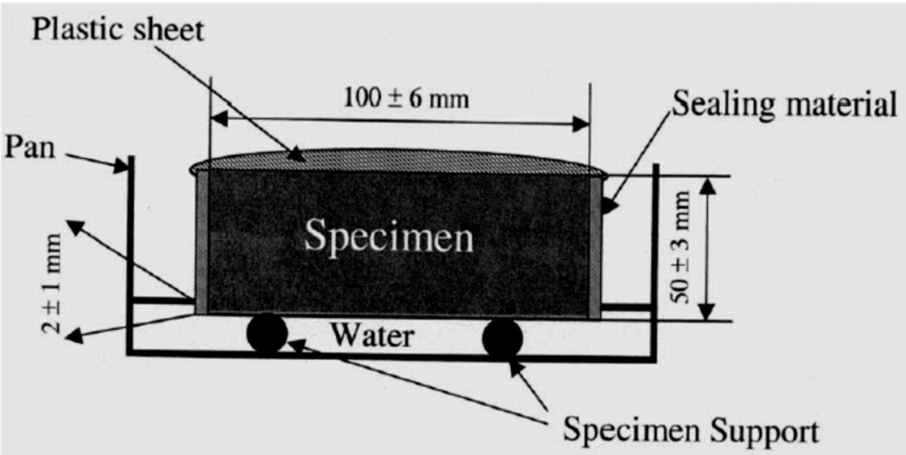



Figure 2.8 Schematic of the test procedure (ASTM C 1585)


Figure 2.9 Capillary water absorption test specimens

### 2.4.3 Bohme Abrasion

Cubic samples with a 70 mm side were prepared for surface abrasion test in accordance with BS-EN 1338 [62]. In compliance with EN 1338 [62], the abrasion system had an erect principal axis, a horizontal steel disc, which could apply 294 N on the specimens. In the test procedure, the specimens were fixed in the holding device of the abrasion machine, the load was applied to the specimen and the disc was rotated for 22 revolutions. After that, the surfaces of the disc and the sample were cleaned. The above-mentioned procedure repeated for 22 revolutions for each specimen. The abrasion test was carried out at 28 days ages. The abrasive wear after 16 cycles was calculated as the mean loss in specimen volume V, from the equation:

$$V = \frac{m}{R}$$

$V$ is the loss in volume after 16 cycles in cubic millimeters;

$m$ is the loss in mass after 16 cycles in grams;

$R$ is the density of the specimen or, in the case of multi-layer specimens, the density of the wearing layer in grams per cubic millimeter.

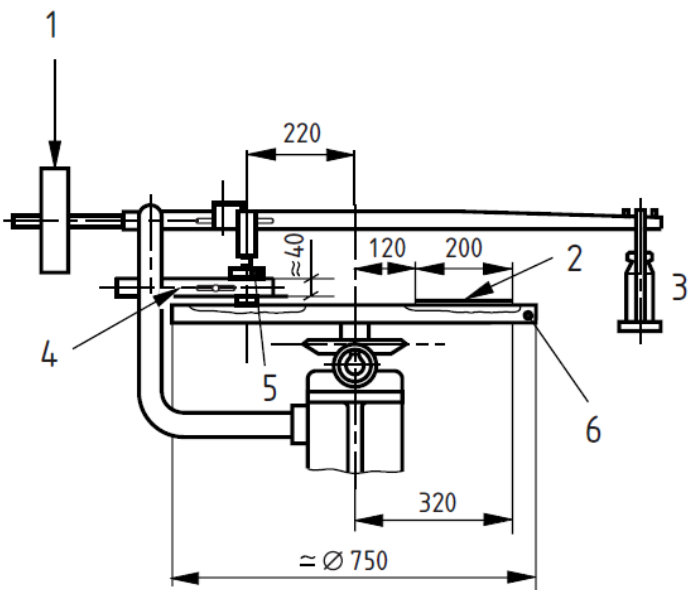



Figure 2.10 Bohme abrasion test mechanism

Parts of device which shown on Figure 2.10 with numbers, are called as follows;

| | |
|---|---|
| 1 counterweight | 4 specimen holder |
| 2 Test track | 5 specimen |
| 3 loading weight | 6 rotating disc |

Figure 2.11 Bohme abrasion devices

Figure 2.12 Measurement after cycling

### 2.4.4 Ultrasound

Ultrasound test was performed on cube specimens. Propagation time of mechanical impulse from the transmitter to the receiver probe was measured. Both transducers were sprinkled with an organic gel which plugged into a control panel. Transducer with gel was put on the specimen and time of transition speed was read from the device.

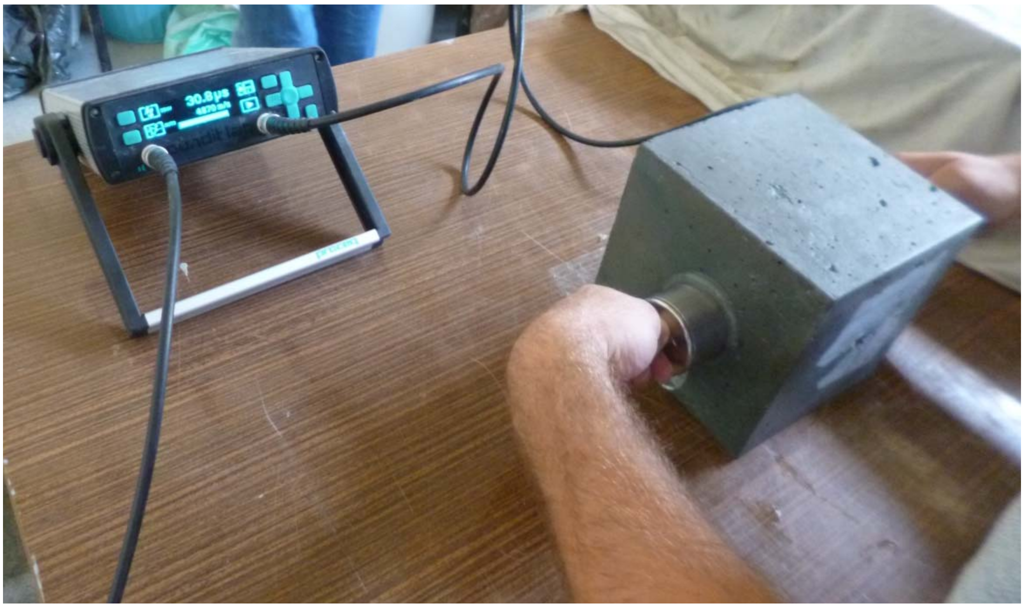


Figure 2.13 Device and test of cube specimen

Figure 2.14 Ultrasound test for cylinder specimen

### 2.4.5 Resistivity

The electrical resistivity meter was used to measure the surface resistivity at the age of 28 days. Saturated cylinders (100x200 mm) were used at each test age. The electrical resistivity test for concrete was carried out by the four-point Wenner array probe technique. The probe array spacing used was 40 mm. The resistivity measurements were taken at four quaternary longitudinal locations of the specimen.

Figure 2.15 Resistivity test

### 2.4.6 Chloride Migration

Rapid chloride-ion migration test used in this investigation was performed at 28 days as per recommended by NT Build 492 [63]. This procedure is for determination of the chloride migration coefficient in concrete, mortar or cement-based repair materials from non-steady-state migration experiments.

In this test, a 50 mm thick specimen is cut from 100 mm (diameter) x 200 mm cylindrical concrete sample. Specimen side is covered by plastic band. After that, it is introduced in a vacuum chamber for 3 hours. The specimen was vacuumed water-saturated for 1 hour and immersed in water for 18 hours. Then the specimen was placed in the test device and subjected to a 30 V applied direct current voltage. The total charge passed was determined for each concrete mixture. The results were the average of three samples. An external electrical potential was applied axially across the specimen and forces the chloride ions outside to migrate into the specimen. After a certain test duration, the specimen was axially splitted and a silver nitrate solution is sprayed on to one of the freshly split sections. The chloride penetration depth can be measured from the visible white silver chloride precipitation. The chloride migration coefficient can be calculated from the penetration depth as follow equations:

$$D_{nssm} = \frac{RT}{zFE} \cdot \frac{x_d - \alpha\sqrt{x_d}}{t}$$

where:

$$E = \frac{U - 2}{L}$$

$$\alpha = 2\sqrt{\frac{RT}{zFE}} \cdot erf^{-1}\left(1 - \frac{2c_d}{c_0}\right)$$

$D_{nssm}$: non-steady-state migration coefficient, $m^2/s$;

z: absolute value of ion valence, for chloride, z = 1;

F: Faraday constant, F = 9.648 ×104 J/(V·mol);

U: absolute value of the applied voltage, V;

R: gas constant, R = 8.314 J/(K·mol);

T: average value of the initial and final temperatures in the anolyte solution, K;

L: thickness of the specimen, m;

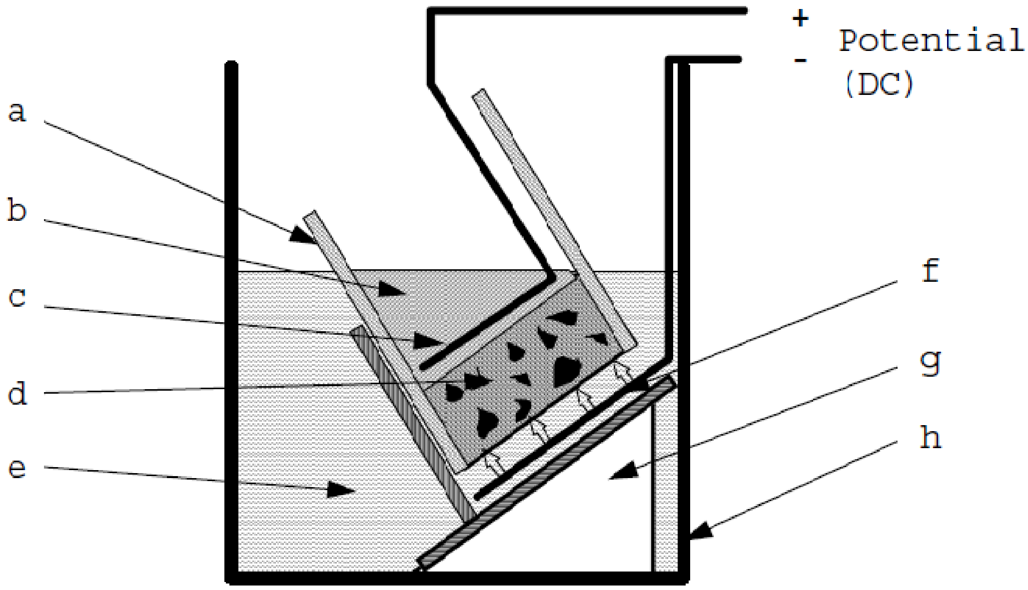
$x_d$: average value of the penetration depths, m;

t: test duration, seconds;

$erf^{-1}$: inverse of error function;

$c_d$: chloride concentration at which the color changes, cd ≈ 0.07 N for OPC concrete;

$c_0$: chloride concentration in the catholyte solution, $c_0 \approx 2$ N.




a. Rubber sleeve
b. Anolyte
c. Anode
d. Specimen
e. Catholyte
f. Cathode
g. Plastic Support
h. Plastic box

Figure 2.16 One arrangement of the migration set-up [63]

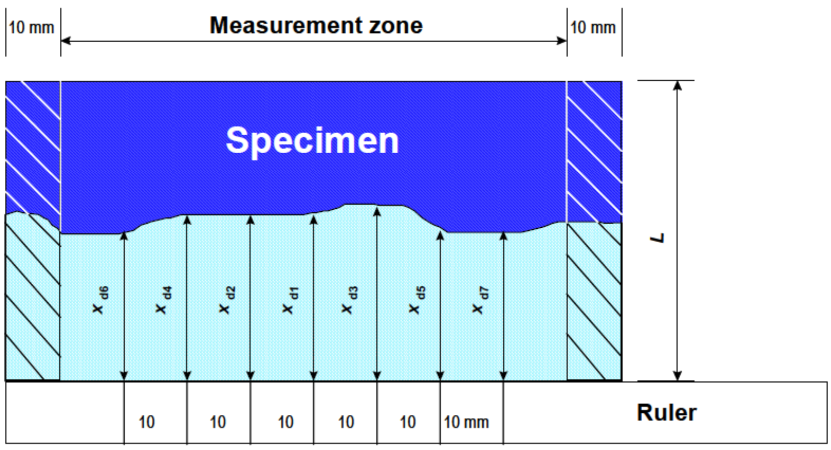



Figure 2.17 Illustration of measurement for chloride penetration depths [63]

Figure 2.18 Cutting slice from specimen after 28 days curing

Figure 2.19 Preparations before the test

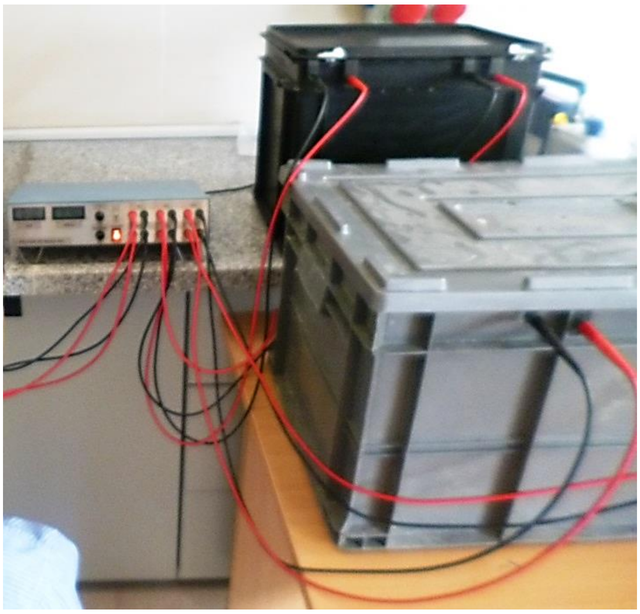


Figure 2.20 Test devices


Figure 2.21 Measuring the depth of chloride-ion penetration from a half slice of specimen

### 2.4.7 Water Penetration Depth

Each concrete mix was tested for its water permeability in terms of water penetration depth. Three 150x150x150 mm cube specimens were cast from each concrete mix for testing. The cube specimens were demoulded 1 day after casting and then water cured at a temperature of 20 ± 2 C° until the age of 28 days. The testing procedure for measuring the water penetration depth was carried out in accordance with EN 12390-8 [64].

During the test, a water pressure of 500 ± 50 kPa was applied to the one face of each cube specimen. After 72 h, the specimens were removed from the apparatus and then each specimen was split into two halves to measure the water penetration depth. The water penetration depth result is taken as the average water penetration depth of the three cube specimens cast from the same batch of concrete and tested at the same time.


Figure 2.22 Water penetration depth test device

Figure 2.23 Placing of specimen

## 2.5 Results and Discussion

### 2.5.1 Effect of Various Fines Content on Mechanical Strength of Concrete

The variation of compressive strength with w/c ratio, porosity, volume of permeable pores percentage and density values are shown in Table 2.7. Experimental results of the effect of fines content as a sand replacement on the compressive strength development of crushed sand at the age of 28 days of water curing are illustrated in Figure 2.24. Figure 2.25 plots the relationship between pores content-absorption and compressive strength of concrete with various amounts of fines content.

The strength values are the average of three test samples. Concrete mixtures contain two different w/c ratio high w/c ratio (H) and low water/cement ratio (L) series. All mixtures consist of various fines content from 0% to 15%.

Compressive strength of H series varied between 34 MPa and 46 MPa. Concrete with 15% of fines showed an increase in strength. It is obvious that after 28 days, the compressive strength reaches its maximum value at a rate of about 15% of fillers. This increase in strength is comparable to the decrease in pores percentage and absorption value. In addition to this Beixing [17] explained that the limestone fines grains act as nucleation sites for CH and CSH reaction products at early hydration ages, and accelerate the hydration of clinker minerals, especially $C_3S$, and carbo aluminates are formed by the reaction between limestone fines and $C_3A$, resulting in an improvement in strength.

In general for the L series, the influence of fines content on the compressive strength is stronger in the range of limestone fines as sand replacement of 0% to 15%. However, the inclusion of fines in concretes beyond level content of 15% lead to an upper compressive strength compared to other fines content. By comparing the different compressive strength results from Figure 2.24, it can be concluded that the use of crushed limestone fines in the range of 0% to 15% could be used without adversely affecting the compressive strength. In addition to this, findings of some previously published studies [3, 7, 11 and 17] showed that increment of fine content for L series did not affect strength properties of concrete.

Table 2.7 Compressive strength results discussion with other basic concrete properties

| Mix Design | | W/C Ratio (%) | Compressive Strength (N/mm$^2$) | Volume of Permeable Voids (%) | Water Absorption (%) | Oven Dry Density (kg/m$^3$) | Slump Value (cm) |
|---|---|---|---|---|---|---|---|
| No | Code | | | | | | |
| **1** | LS-H-00 | 0,58 | 34,00 | 8,997 | 3,20 | 2328 | 21 |
| **2** | LS-H-03 | 0,58 | 39,27 | 10,972 | 3,72 | 2364 | 19 |
| **3** | LS-H-06 | 0,58 | 40,27 | 10,970 | 3,55 | 2367 | 19 |
| **4** | LS-H-09 | 0,58 | 42,53 | 9,520 | 2,72 | 2354 | 18 |
| **5** | LS-H-12 | 0,58 | 41,63 | 10,143 | 3,03 | 2316 | 19 |
| **6** | LS-H-15 | 0,58 | **46,07** | **9,123** | **2,22** | **2334** | **18** |
| **7** | LS-L-00 | 0,38 | 72,15 | 7,220 | 1,75 | 2430 | 19 |
| **8** | LS-L-03 | 0,38 | 73,70 | 7,610 | 2,20 | 2424 | 18 |
| **9** | LS-L-06 | 0,38 | 65,37 | 7,599 | 1,91 | 2366 | 18 |
| **10** | LS-L-09 | 0,38 | 71,07 | 8,164 | 1,95 | 2315 | 18 |
| **11** | LS-L-12 | 0,38 | 67,85 | 5,928 | 1,97 | 2390 | 18 |
| **12** | LS-L-15 | 0,38 | **74,72** | **5,111** | **0,73** | **2389** | **18** |

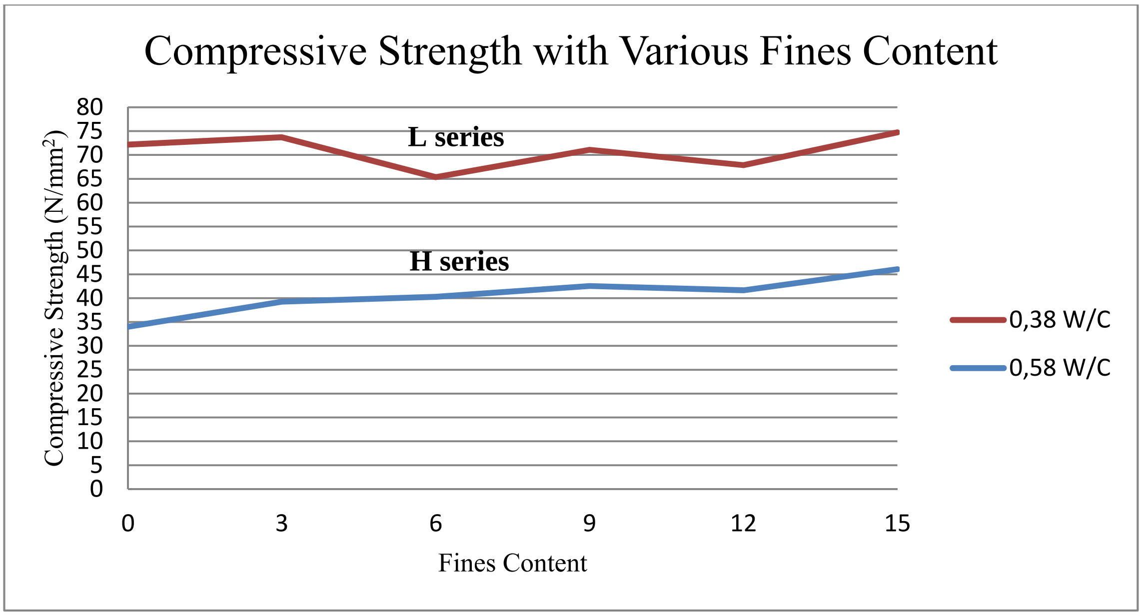



Figure 2.24 Compressive strength results for L & H series

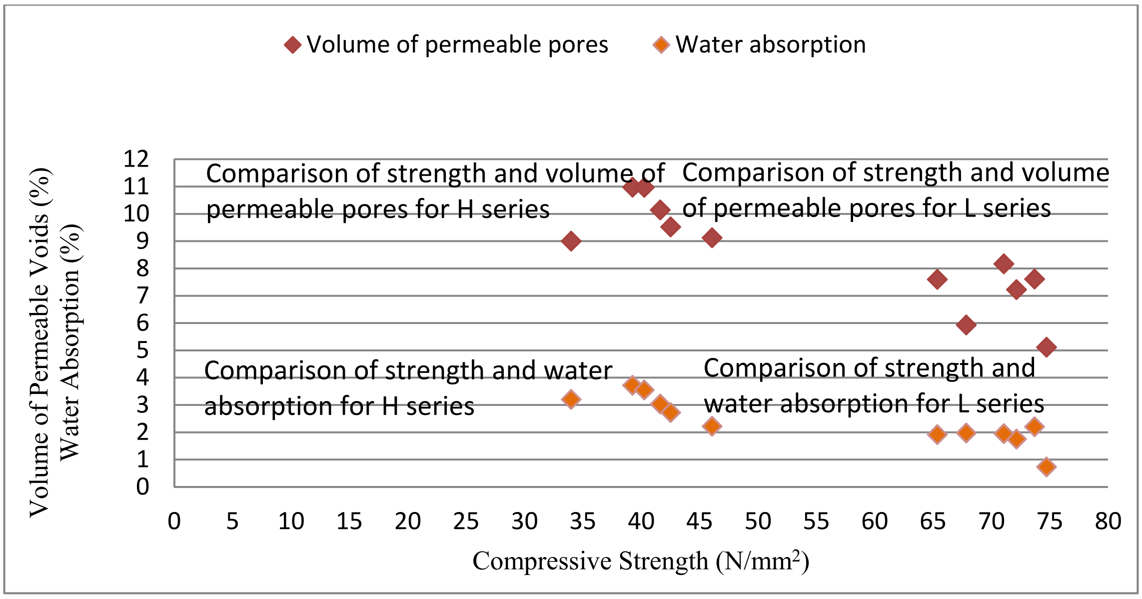



Figure 2.25 Comparison of compressive strength results between pores content and water absorption values of concrete

### 2.5.2 Influence of Fines Content on Durability Performance of Concrete

The durability properties include water permeability, chloride-ion permeability, capillarity water absorption and Bohme abrasion resistance.

Figure 2.26 shows the effect of limestone fines on the chloride-ion penetration of crushed sand concrete at 28 days of curing based on NT 492 [63]. It can be seen from this figure that the total charge passed through the specimen decreases with increasing amount of LSF for both series. The values of the chloride migration coefficient for L series were 2.29, 2.17, 1.69, 1.57, 1.58 and 1.27 for 0, 3, 6, 9, 12 and 15% of LSF respectively. For series L, the increment in the fines content had a meaningful effect on the chloride migration coefficient. The main reason is that high-strength concrete has higher cement content and lower water/cement ratio. This means there are fewer interconnected capillary pores, so fines can not obviously influence the hardened structure body of dense high-strength concrete, or modify the resistance to chloride ion permeation.

The values of the chloride migration coefficient for H series were 4.70, 4.13, 3.09, 3.25, 3.34 and 2.95 for 0, 3, 6, 9, 12 and 15% of LSF respectively. As the fines content increased, the chloride migration coefficient for series H obviously decreased. The decrease of permeability of both series mixes incorporating limestone fines is probably due to the filler effect of the fines, which blocks capillary passages formed during the hydration of the cement.

The decrease of the w/c ratio from 0,58 to 0,38 and significantly reduces the rapid chloride ion permeability.

All these results are in agreement with those obtained by Beixing et al. [17], who reported an increase of chloride-ion penetration for water cured concretes containing 15% limestone filler as replacement of cement.

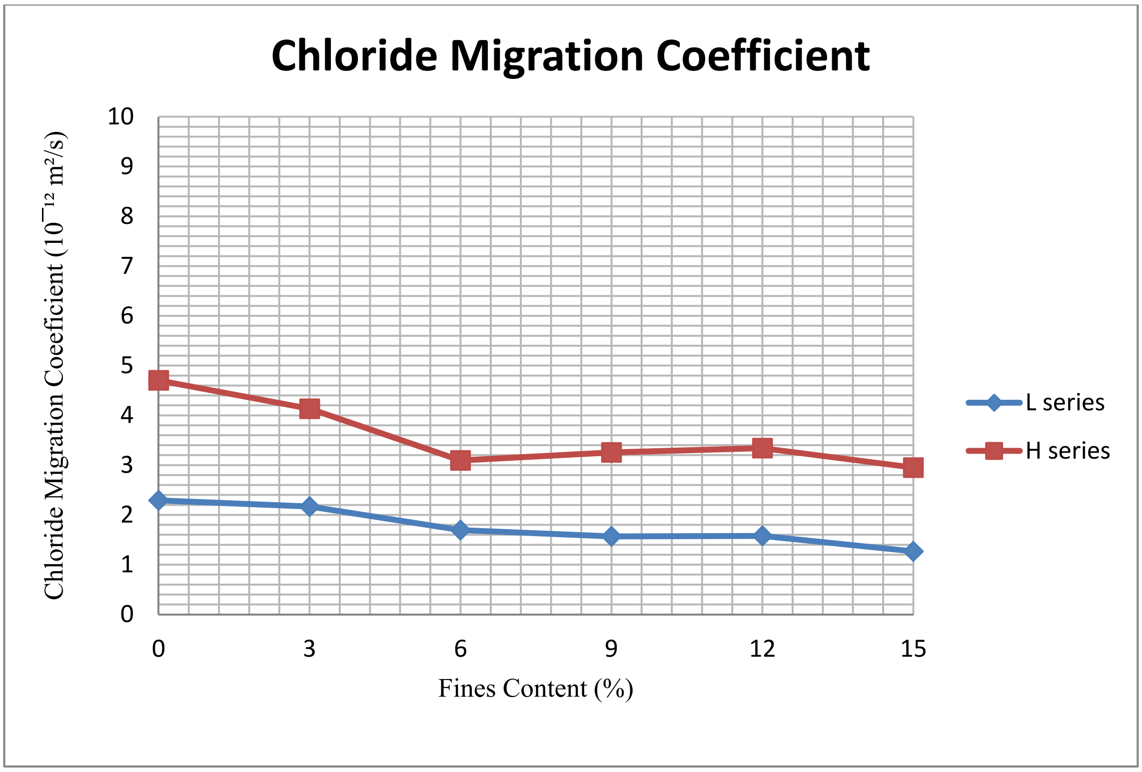



Figure 2.26 Chloride Migration Coefficient with a Range Fines Content

Figure 2.27 shows the water penetration depth for all concrete mixtures with and without LSF at 28 days. There is reduction in the water penetration depth for all concretes with LSF. The higher penetration depth was observed in concrete mixtures containing 0% fines content while the lowest water penetration depth is observed in concrete mixture containing 15% fines content. However, even observing a general decline for the L series, it is not easily said there is a significant reduces on permeability. The incorporation of LSF up to 15% as replacement of crushed sand may improve pore structure in transition zone, and thereby reduces water permeability. The results of this research are in agreement with those obtained by Menadi et al. [4] who reported a reduction in the water penetration depth when 15% of LSF as cement replacement were used. Moreover ICAR [23] stated that microfines have been hypothesized to reduce permeability by blocking the pores in the concrete, reducing the flow of water.

It can be concluded that the use of crushed LSF in the range of 0% to 15% could be used without adversely affecting the water permeability for L series.

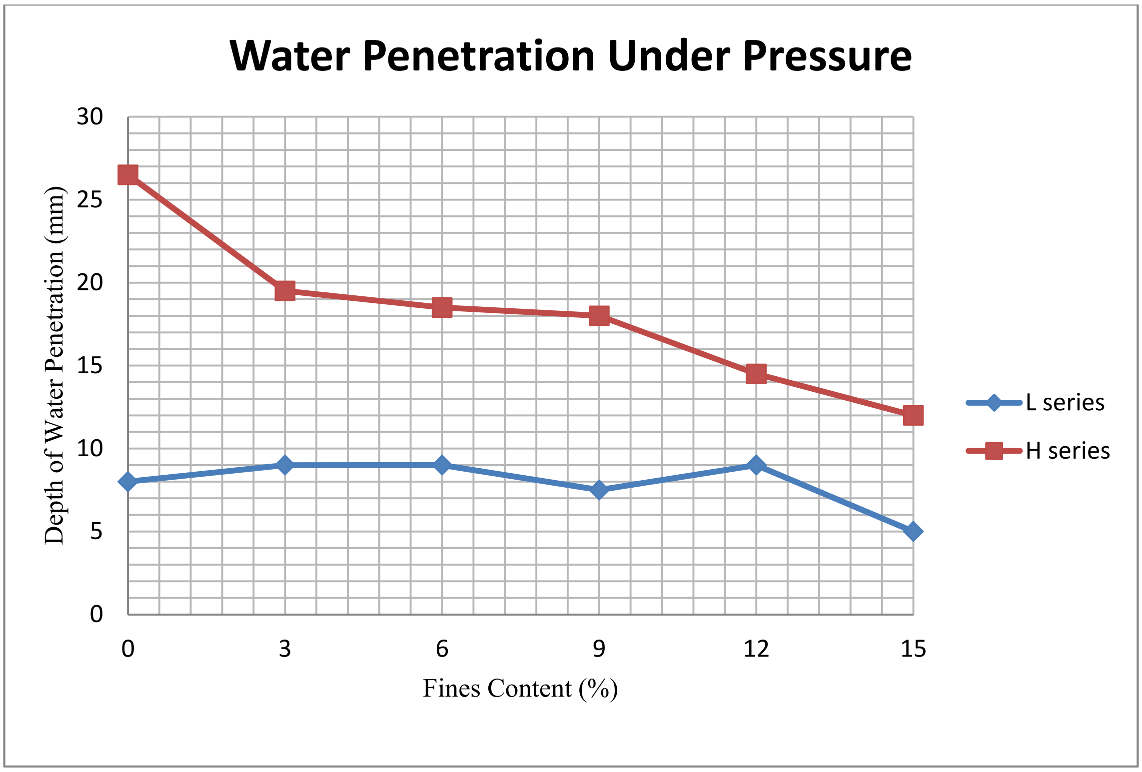



Figure 2.27 Depth of Water Penetration

Figure 2.28 shows the relationship between the amounts of water absorbed per unit area for concrete mixtures for various amounts of quarry LSF. From this figure it can be seen, that water absorption by capillary decreases with addition of LSF for all concrete mixtures. The 6 hours water absorption in concrete mixtures decreases with increasing the quantity of the LSF content beyond a level fines content of 15%. The increase of the absorption characteristics of concrete mixtures with higher amount of quarry LSF may be attributed to the lower porosity of these concretes. The absorption plotted against square root of time is presented in Figure 2.29.

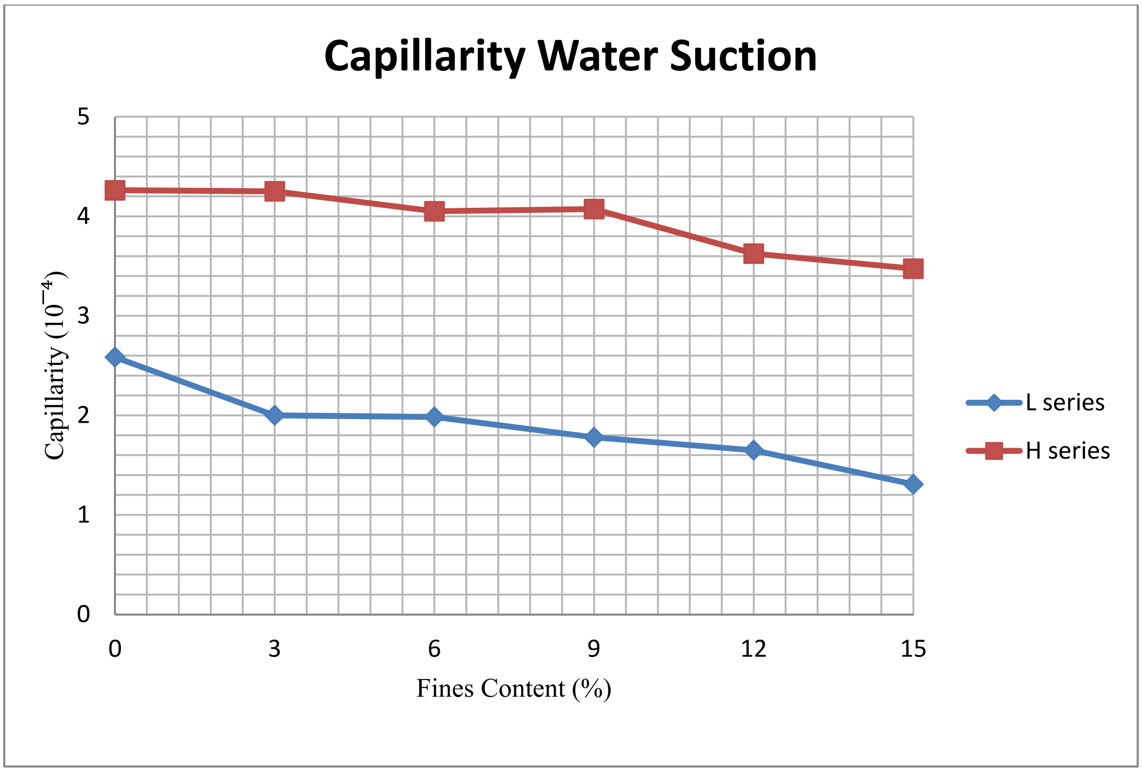
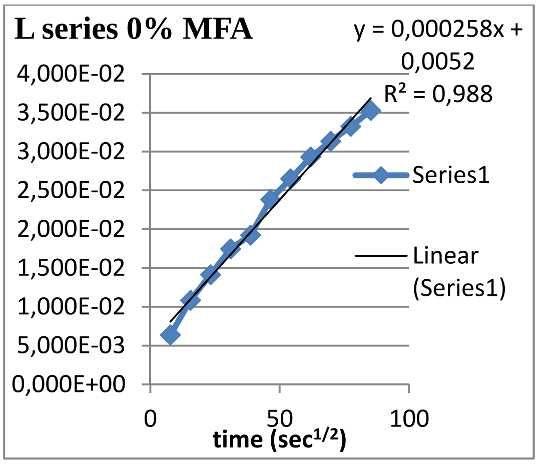



Figure 2.28 Capillariy water uptake



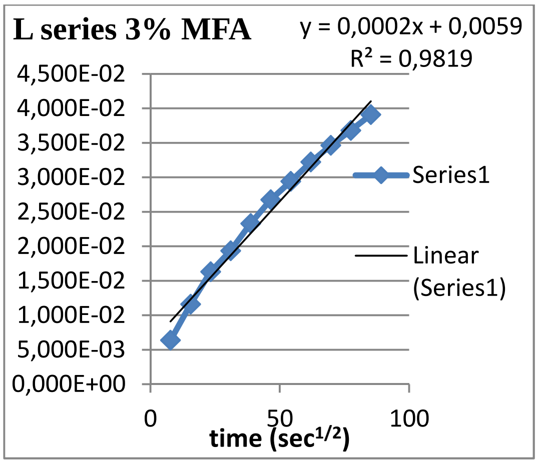




Figure 2.29 Depth of water penetration per unit area for time square root and correlation

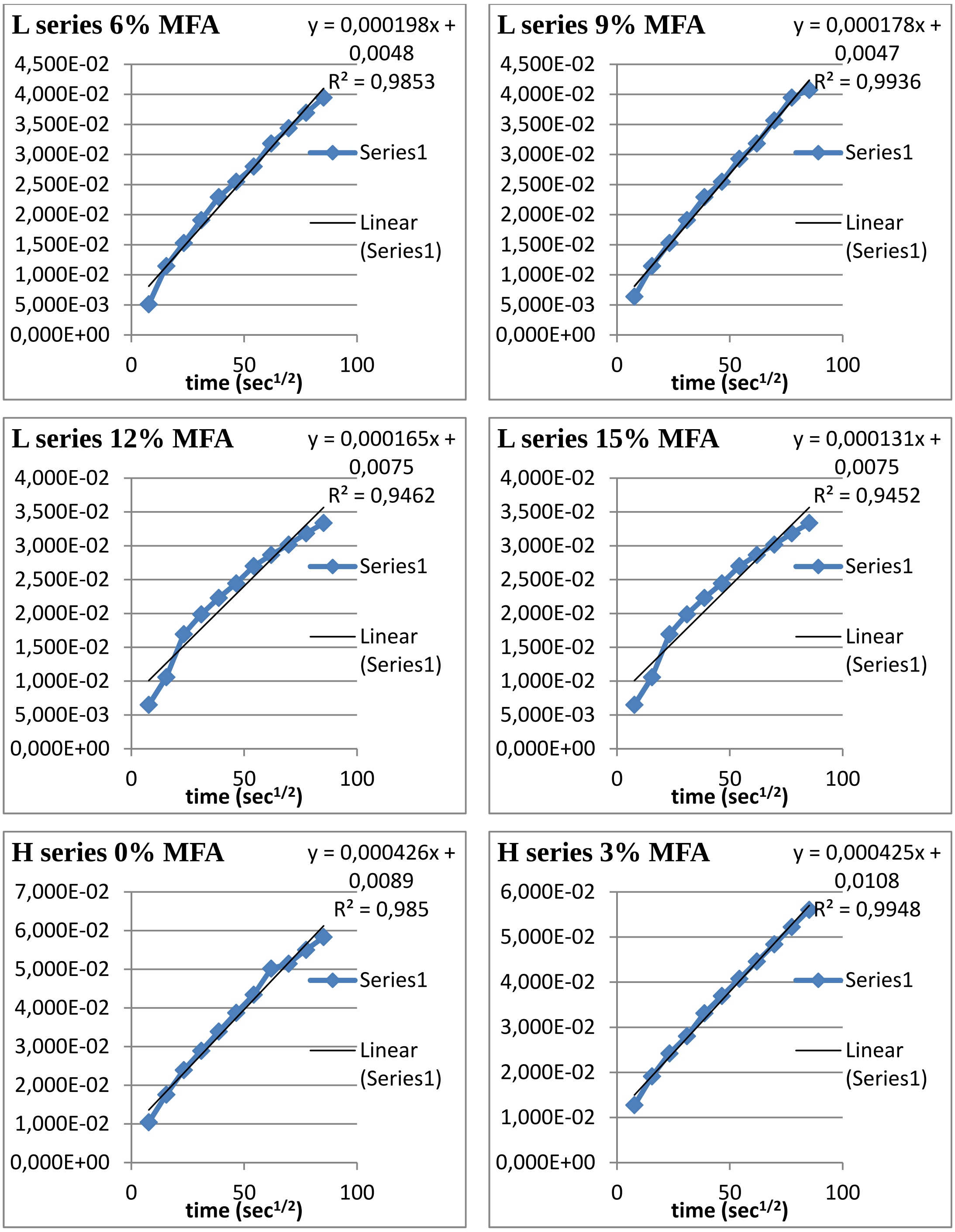



Figure 2.29 Depth of water penetration per unit area for time square root and correlation (Cont'd)

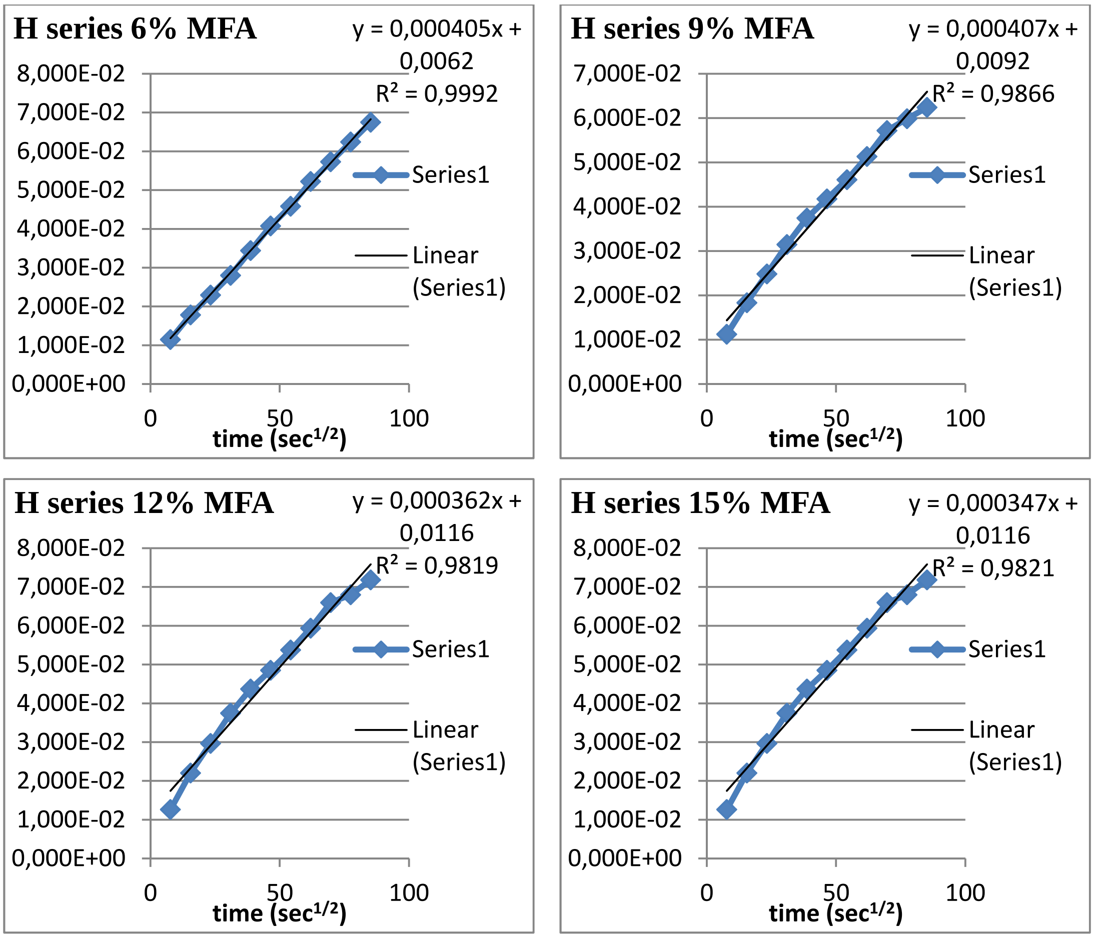



Figure 2.29 Depth of water penetration per unit area for time square root and correlation (Cont'd)

Due to the inclusion of high amounts of LSF, it is often a concern that abrasion resistance is lowered due to the increased percentage of finer particles near the surface. The test results for abrasion resistance of series L and H specimens are shown in Figure 2.30. For the L series the abrasion loss in mass for concrete containing up to 12% LSF decreased. However, the concrete containing more than 12% LSF caused an increase in abrasion loss. The decrease in abrasion loss was attributed to the fines improved strength of the concrete, but abrasion resistance did not increase with increasing compressive strength as would normally be expected, and also related to the paste volume of the concrete, the more paste volume, the lower abrasion resistance. The greatest compressive strength was observed with the concrete containing between 15% fines while the greatest abrasion resistance was observed at 12% fines content. Same information and results can be given for H series. The greatest compressive strength was observed with the concrete containing between 15% fines while the greatest abrasion resistance was observed at 6% fines content. Experimentally it is found that the abrasion loss was not apparently dependent on fines content of CS. In general, slightly higher resistance to wear was displayed by the concrete series of low water-cement ratio. Beixing [17] has an agreement with similar results.

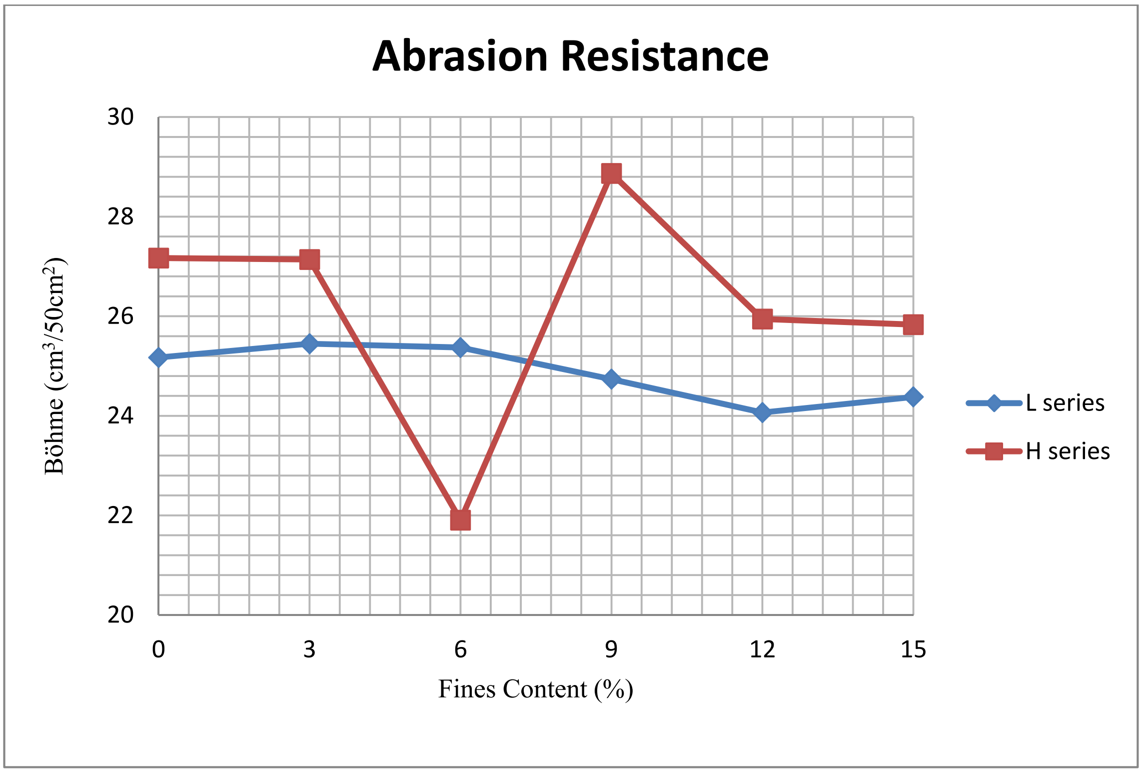



Figure 2.30 Volume loss due to abrasion

### 2.5.3 Non-destructive Tests in Evaluation Fines Content Effect

NDT includes Wenner-Probe resistivity and ultrasound tests. Results obtained from electrical resistivity tests Figure 2.31 indicate that the electrical resistivity decreases with increasing the w/c ratio and fines content. For the L series it can be seen a decrease with 3% LSF and H series 12% LSF. However generally Wenner-Probe resistivity increased with LSF. The electrical resistivity decreased in the B and C series with increasing limestone replacement. The highest value of electrical resistivity is 1170 Ohm.m and 820 Ohm.m for the L and H series.

Ultrasound velocity results are given in Figure 2.32. It can be easily seen that the velocity results increase with the increment of LSF. However, slightly reductions are observed for L series with 12% LSF and H series with 6% LSF.

Both resistivity results and ultrasound results are in agreement with chloride migration test results. The comparison of chloride migration and resistivity results are given in Figure 2.33. Electrical resistivity value which increase in contrast with chloride permeability coefficient value reduction is also supported all these results.

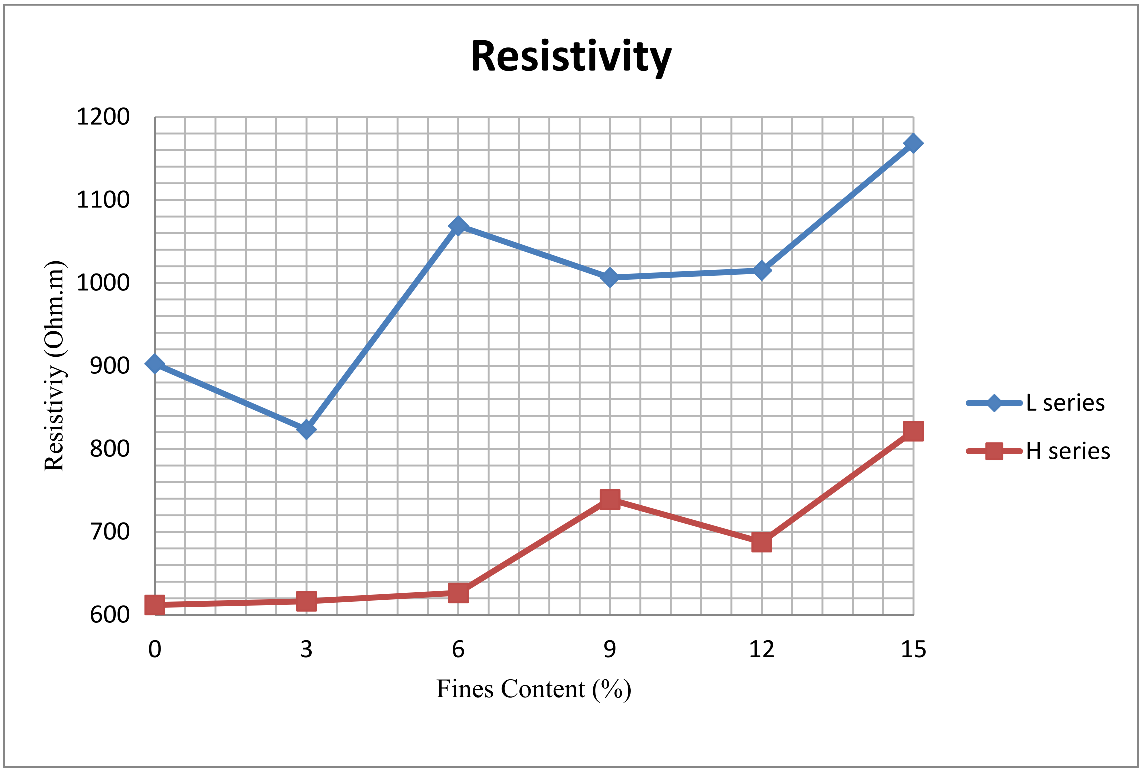



Figure 2.31 Resistivity

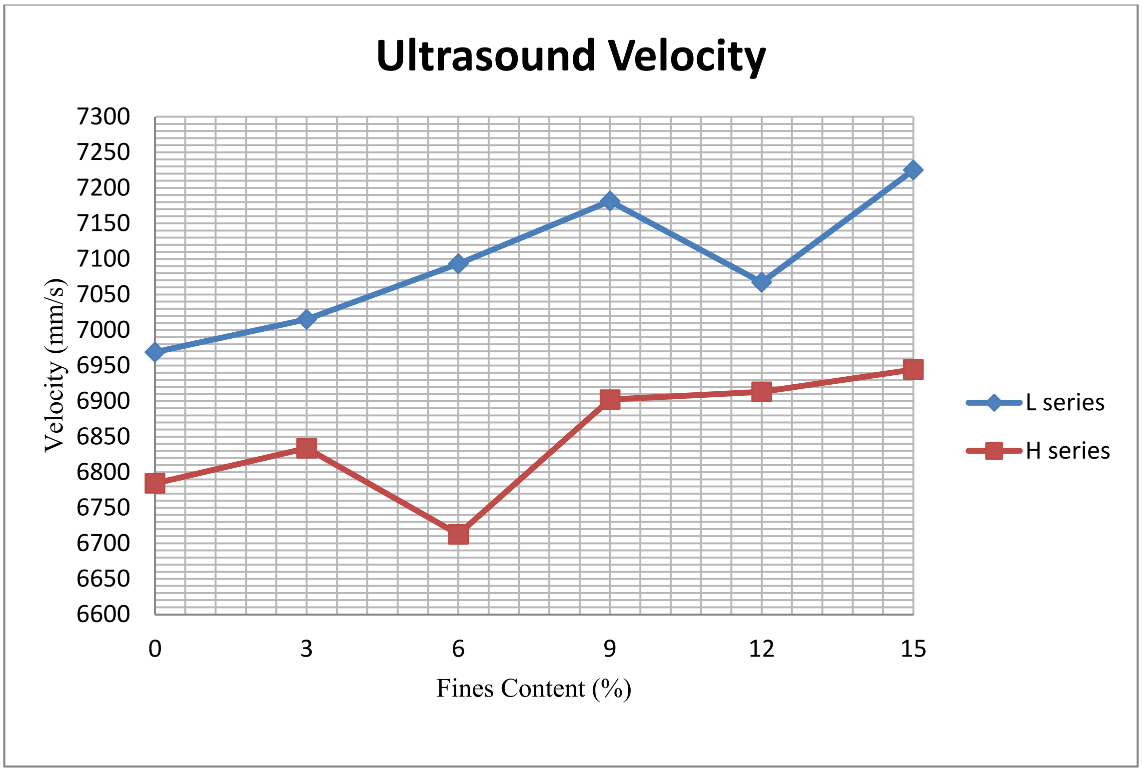



Figure 2.32 Ultrasonic pulse of velocity

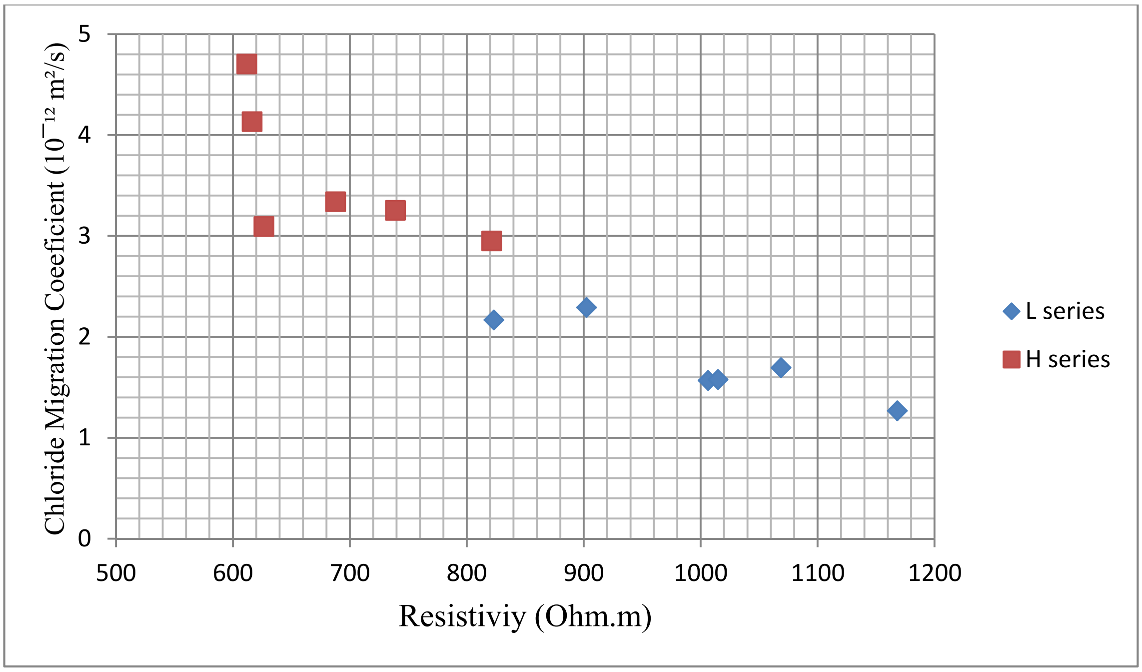



Figure 2.33 Comparison chloride-ion resistance with resistivity

## CHAPTER 3

# CASE STUDY: IZMIT BAY BRIDGE STRUCTURAL CONCRETE INCORPORATING MICROFINE RICH LIMESTONE FINE AGGREGATE WITH SLAG CEMENT

This chapter contains an assessment in order to present the performance of concrete mixtures in use of high fines content in crushed sand from ongoing experience belonging to Izmit Bay Crossing Suspension Bridge Project. Izmit Bay Crossing Suspension Bridge will be a 2,682 m long structure located at the eastern end of Marmara Sea with the main span of 1550 m making it the world's fourth longest suspension bridge at the completion of 2016 [65].

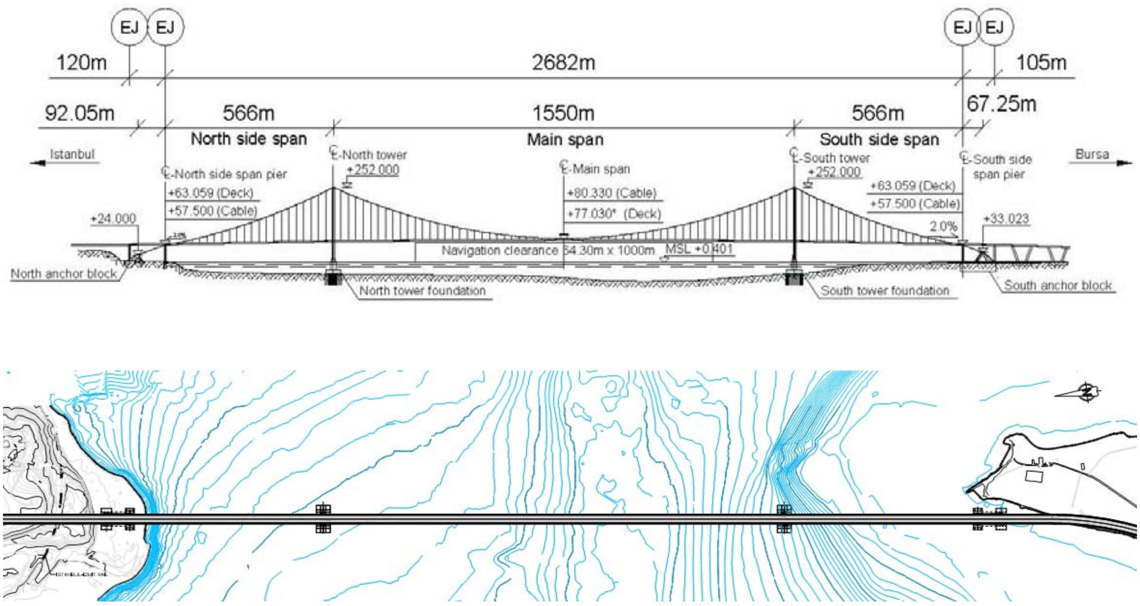



Figure 3.1 Izmit Bay Crossing Suspension Bridge

The design of concrete structure is of upmost importance to achieve the durability for the service time of 100 years, and chloride-induced reinforcement corrosion is identified as deterioration risk for traditional carbon steel reinforced concrete structures. The primary approach to achieve the durability is based on two protective measures. Dense concrete with lowest permeability hence low chloride diffusivity and sufficient concrete cover thickness. Concrete mix was carefully developed so that the requirement of chloride migration coefficient is fulfilled and full-scale trial casting was performed to confirm constructability. During the execution of the Izmit Bay Crossing Suspension Bridge project construction it has been studied to develop a concrete mix design. Concrete and different mixes have been studied in Oyak Beton Kurtköy Research and Development Laboratory.

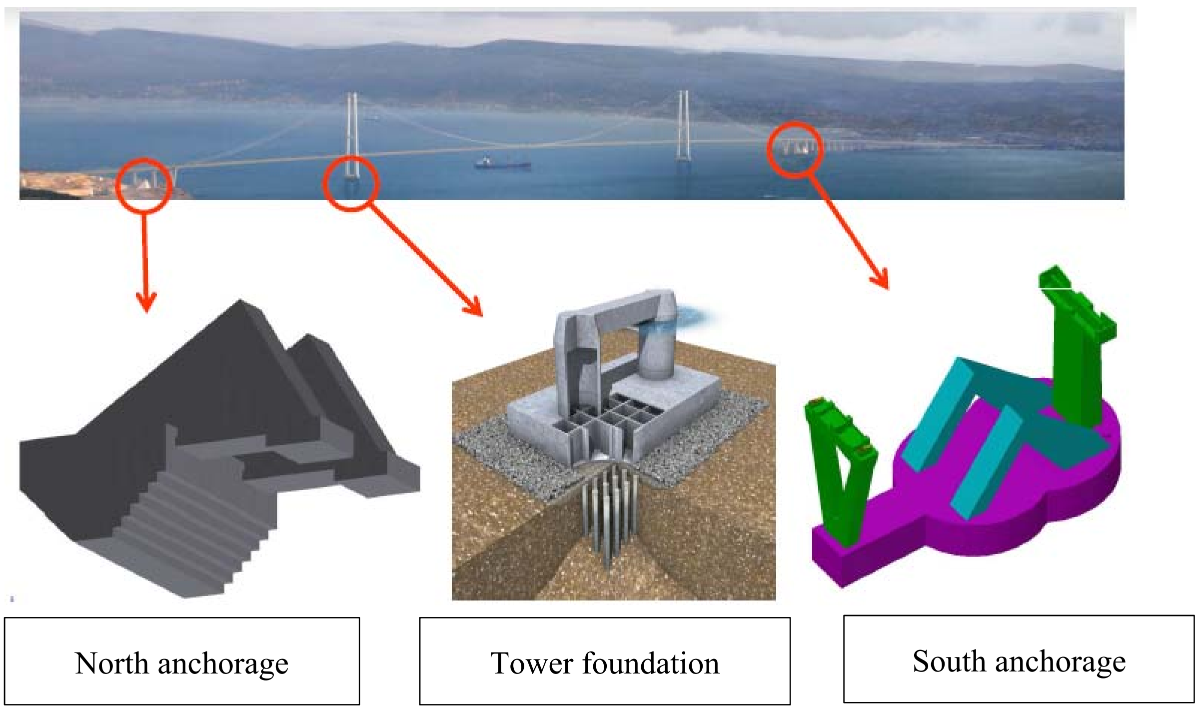



Figure 3.2 Layout of concrete foundation structures of the bridge

Chloride migration coefficient was determined to be lower than 3.0 (x $10^{-12} m^2/s$). In addition to this minimum 3 hours slump protection was necessary. The scope of this study is limited to the north transition pier, north side span pier and north anchorage block of Izmit Bay Crossing Suspension Bridge. The reason for this restriction is about aggregate source. These structural concrete was casted with the same quarry used in experimental part mentioned in Chapter 2. The constituent materials shown in Table 3.1 have been tested on the ITU laboratory and found to be proper to use in this mix. Combined fine aggregate properties are given below in Table 3.2 and the combination ratio has been calculated as 48%+52%, by calculation from the existing each fraction separate test results. Among the alternative binder systems, CEM III/B slag cement was chosen as the best binder in achieving the lowest chloride migration coefficient, highest density and low porosity in structural concretes of the project. Concrete mixture was designed with water-cement ratio of 0.38 and unit binder content of 380 kg/m$^3$.

After the preparation works it could be easily observed that concrete meet the project requirement. Figure 3.3 presents the chloride migration coefficient values in chronological order. The results showed that chloride migration coefficients are better than the project requirements. According to these results, durability performance of concrete is over the requirements and service time of structure will be more than 100 years. This mega-scale field application demonstrated that properly selected and good quality manufactured sand with high fines content would significantly contribute the performance of engineered concretes.

Table 3.1 Constituents definitions & sources

| Material | Type | Supplier | Source & Location |
|---|---|---|---|
| **Cement** | CEM III/B 32,5N | Bolu Cement Inc. | Bolu |
| **Natural Sand** | 0-1 mm | Umer | Kemerburgaz |
| **Crushed Sand** | 0-5 mm | Çerkeşli | Çerkeşli-Dilovası |
| **Coarse aggregate** | 5 – 12 mm<br>12 - 22 mm | Çerkeşli<br>Çerkeşli | Çerkeşli-Dilovası |
| **Water** | - | Local | Kurtköy |

Table 3.2 Fine aggregate grain size distribution

| Sieve Size (mm) | 31,5 | 22 | 16 | 8 | 4 | 2 | 1 | 0,5 | 0,25 | 0,125 | 0,063 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Natural Sand** | 100 | 100 | 100 | 100 | 100 | 99 | 99 | 97 | 15 | 1 | 0,9 |
| **Crushed Sand** | 100 | 100 | 100 | 100 | 100 | 84 | 54 | 38 | 22 | 15 | 10,4 |
| **Blended Sand** | 100 | 100 | 100 | 100 | 100 | 91 | 76 | 66 | 18 | 8 | 5,8 |

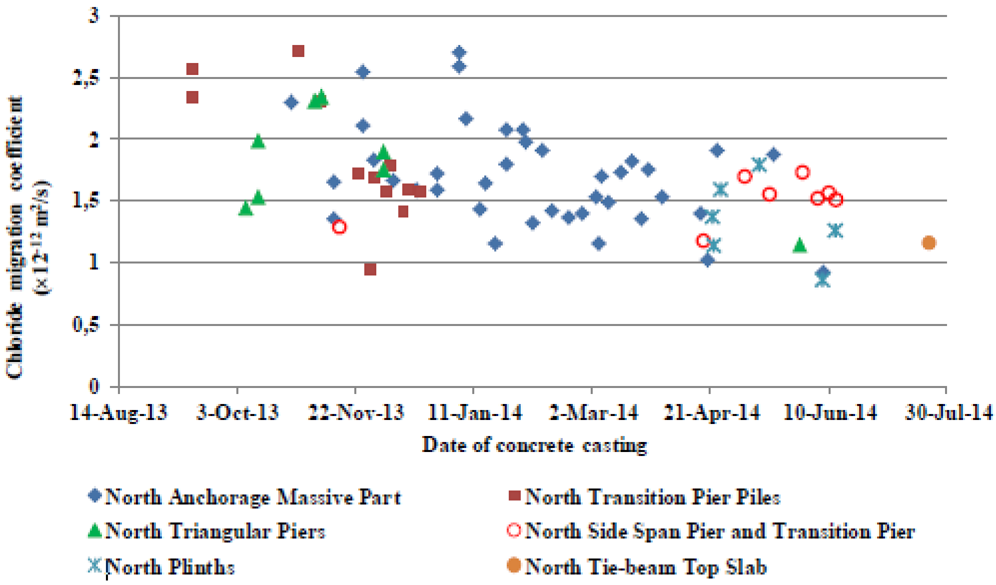



Figure 3.3 Chloride migration co-efficient from each structure

Figure 3.4 Concrete casting in caissons

# CHAPTER 4

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## CONCLUSION OF EXPERIMENTAL STUDY

The effect of crushed limestone fines up to 15% percentage of concrete strength and durability properties were investigated. The main conclusions to be drawn from the present study are as follows:

- The inclusion of fines content below 63 µm in crushed sand up to 15% does not appear to affect compressive strength of concrete for low w/c ratio. By contrast, higher fine content increases the strength for high w/c. For low w/c ratio fine content effect may not be observed because of characterization of slag cement.
- Increment of fines to the both series mixtures decreased chloride-ion permeability. A significant decline was observed up to 6% LSF. After 6% LSF minor decreases were observed. The reduction rate was greater for the H series.
- Similar behavior observed for water penetration under pressure. It can be concluded that the use of crushed limestone fines in the range of 0% to 15% could be used without adversely affecting the water permeability for L series. For H series water permeability absolutely decreases with increment of fine content.
- The water absorption by capillary decreases with addition of LSF for all concrete mixtures. The increase of the absorption characteristics of concrete mixtures with higher amount of quarry limestone fines as sand replacement may be attributed to the lower porosity of these concretes.
- A noticeable change was not observed in electrical resistivity values for L series. However, an increasing trend might be observed after 3% LSF. Similar observation can be reported for H series. More than 6% LSF addition resistivity values tends to increase.

- Ultrasound velocity tests results have a meaningful of pore structure of concrete. With the LSF addition all gaps in concrete were fulfilled. This means velocity values increased with the addition of LSF. However, slightly reduction observed 3% LSF for L series and 6% LSF for H series.
- Experimentally it is found that the abrasion loss of slag cement concrete was not apparently dependent on fines content of MS.

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# APPENDIX-A

PERMISSION TO USE FIELD DATA AND GENERAL INFORMATION

Chapter 3 ''Case Study: Izmit Bay Bridge Structural Concrete Incorporating Microfine Rich Limestone Fine Aggregate With Slag Cement'' presents some field data and evaluation of Izmit Bay Crossing Suspension Bridge Project. All the informations shared in this chapter was used under permission of main contractor, IHI Infrastructure Systems Co. Ltd,.

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# CURRICULUM VITAE

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