**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL**

# EFFECT OF PARTICLE PACKING ON PROPERTIES OF HEAVYWEIGHT AND SELF-COMPACTING CONCRETE MORTAR

**M.Sc. THESIS**

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**OCTOBER 2021**

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**ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ**

# DOLDURMA YOĞUNLUĞUNUN KENDİLİĞİNDEN YERLEŞEN AĞIR BETON HARCI ÜZERİNE ETKİLERİ

**YÜKSEK LİSANS TEZİ**

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Alper Orhun ERÜZ, a M.Sc. student of İTU Graduate School student ID 50181005, successfully defended the thesis entitled "EFFECT OF PARTICLE PACKING ON PROPERTIES OF HEAVYWEIGHT AND SELF-COMPACTING CONCRETE MORTAR," which he prepared after fulfilling the requirements specified in the associated legislations before the jury whose signatures are below.

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## FOREWORD

In this thesis, the influence of packing density in heavy-weight self-compacting concrete mortar is investigated. The effect of silica fines and polymer admixtures is studied in the sense of packing density, unit weights in fresh and hardened states, mechanical and durability properties of concrete mortar are examined.

This study was conducted in the Structural Materials Laboratory of İTÜ Faculty of Civil Engineering. It is my responsibility to thank my advisor, Prof. Dr. M. Hulusi ÖZKUL, for his continuous support of immense experience and knowledge for guiding me through this study.

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October 2021 Alper Orhun ERÜZ

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**ABBREVIATIONS**

| | |
|---|---|
| **CPM** | **:** Compressible Packing Model |
| **ITZ** | **:** Interfacial Transition Zone |
| **LPDM** | **:** Linear Packing Density Model |
| **OPC** | **:** Ordinary Portland Cement |
| **PMC** | **:** Polymer Modified Concrete |
| **SCC** | **:** Self-Compacting Concrete |

**SYMBOLS**

| | |
|---|---|
| **ρ** | **:** Density |
| **C – S - H** | **:** Calcium silicate hydrate |
| **CH** | **:** Calcium hydroxide |
| **d** | **:** Particle Size |
| **dmax** | **:** Maximum Solid Particle Size in Mixture |
| **dmin** | **:** Minimum Solid Particle Size in Mixture |
| **f*** | **:** Packing Density of the Mixture |
| **fL** | **:** Packing Density of Large Particles in Binary Mixture |
| **fS** | **:** Packing Density of Small Particles in Binary Mixture |
| **k** | **:** Coefficient of Capillarity |
| **P(d)** | **:** Percentage of the Particles that Pass from d Size |
| **Q** | **:** Amount of Absorbed Water from a Unit Area |
| **q** | **:** Distrubution Factor of Packing Models |
| **t** | **:** Time |
| **W/B** | **:** Ratio of Water to Binders in Weight |
| **W/C** | **:** Ratio of Water to Cement in Weight |
| **XL** | **:** Fraction of the Large Particles in Binary Mixture |
| **XS** | **:** Fraction of the Small Particles in Binary Mixture |
| **ε** | **:** Void Ratio of Material |
| **π** | **:** Porosity |
| **Φ** | **:** Packing Density |

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## EFFECT OF PARTICLE PACKING ON PROPERTIES OF HEAVYWEIGHT AND SELF-COMPACTING CONCRETE MORTAR

## SUMMARY

Concrete is a composite material that is also the most produced material in the world due to its strength, durability, availability, and versatility. It consists of proper proportioning of ingredients such as water, cement, coarse and fine aggregates, along with the chemical and mineral admixtures if required, in order to fulfill the desired characteristics of concrete in the fresh and hardened states. Most of the mineral admixtures are commonly produced from other industrial processes and have a wide range of usage in concrete production. The effects of the products such as organic admixtures, mineral admixtures, such as pozzolans, as supplementary cementitious materials, fibers, polymers, etc., are not only limited to the final compressive strength but also rheological properties, early-age characteristics, properties according to the capacity of deformation and, durability aspects. Hence the aim of the mixture proportioning is to obtain a concrete that will have optimum workability and flowability together with the required unit weight, strength at a specified age, dimensional stability, and desired durability.

In this study, the effect of packing density on heavyweight and self-compacting mortar is investigated. The packing density is known as the solidity of material which is defined as the fraction of solid ingredients to the total volume of material. The increase in the packing density is a desired objective in order to reach greater properties in concrete. The increase in the properties happens both in the fresh and hardened state of concrete. A higher packing degree of aggregates leads to an increase of solid materials in the unit volume of concrete. The remaining void volume allows for the minimization of the amount of cement needed in the same volume to fill the gaps between particles. Therefore, the cost of producing concrete can be reduced with less usage of cement. To achieve these goals, the modified Andreassen packing model is used.

Another main topic of the investigation is heavyweight concrete. Heavyweight concretes are known for their exceptional unit weights, above 2600 $kg/m^3$, that stem from the high density of the aggregates. Heavyweight concrete is used in several means in modern society. In the beginning, the reason behind the development of such material was increasing the stability of constructions that inclined to overturn or applications including constant vibration such as heavy machinery. Later with the introduction of nuclear technology in the civilian field, the power plants of such kind required shielding for the radiation, and the heavyweight aggregate was found suitable for this application.

The SCC is developed in 1986 by Okamura in Japan as an underwater castable concrete. The high flowability is a direct result of the superplasticizer content. However, the very high amount of superplasticizer causes segregation in concrete, and to solve this problem, the fine materials are increased. Due to its high ratio of fine

particles, which include cement, mineral admixtures, and fine aggregates, the concrete obtains high viscosity.

For the experimental part, reference curves created via software EMMA and gradiation of the ingredients of the mortar is adjusted accordingly. The limitations were selected as 3 mm for upper and 1 micron for reference and micro silica groups. The lower boundary set 10 nm for nano silica groups. The q distribution factor is selected between 0.22 to 0.25 in order to achieve the fineness for SCC. Six sample groups are created with combinations of micro silica, nano silica, and polymer. There are reference groups, which contain no pozzolan, micro silica groups, and lastly, nano silica - micro silica combined groups. Each group also contains polymer added mixtures. Flow test, unit weight test, and packing density were determined in the fresh state. In the hardened state, compressive strength, flexural strength, water absorption, and unit weight tests were conducted.

According to test results, the packing density increases with the pozzolan and polymer addition due to their filling ability of the voids. Flow values diminished by polymer variations. Unit weight and compressive is found higher in pozzolanic groups than reference or polymer variations. Polymer addition decreases water absorption in general. It was also found that polymer addition decreases compressive strength but increases flexural strength. Further research is required for further clarifications.

# DOLDURMA YOĞUNLUĞUNUN KENDİLİĞİNDEN YERLEŞEN AĞIR BETON HARCI ÜZERİNE ETKİLERİ

## ÖZET

Beton, mukavemeti, dayanıklılığı, kolay bulunurluğu ve çok yönlülüğü nedeniyle dünyada en çok üretilen malzemesi kompozit malzemedir. Beton, taze ve sertleşmiş halde istenen özelliklerini yerine getirmek için su, çimento, iri ve ince agrega gibi bileşenlerden ve gerektiğinde kullanılan kimyasal ve mineral katkılardan oluşur. Beton katkılarının bir çoğu yaygın olarak diğer endüstriyel süreçlerin yan ürünü olarak üretilir ve beton üretiminde geniş bir kullanım alanına sahiptir. Kimyasal, bağlayıcı etkiye sahip puzolanlar gibi mineral veya lifler gibi katkıların etkileri sadece nihai basınç dayanımı ile sınırlı olmayıp aynı zamanda yaş betonun reolojik özelliklerini, erken yaş karakteristiklerini ve diğer özelliklerini de içerir. Bunlara ek olarak mekanik dayanımlardan olan deformasyon kapasitesi, eğilme, çekme ve eğilme dayanımları da katkılar ile isteğe bağlı olarak ayarlanabilir. Dolayısıyla karışımdaki malzemelerin oranlanmasının amacı isteğe bağlı olarak, maksimum birim ağırlığa, belirli bir yaşta dayanım ve dayanıklılığa, boyutsal kararlılığa ve bunlarla birlikte optimum işlenebilirlik ve akışkanlığa sahip ancak ayrışmayacak bir beton elde etmektir.

Bu çalışmada, kendiliğinden yerleşen ağır beton harcında doldurma yoğunluğunun, bir diğer adıyla paketleme yoğunluğunun etkisi araştırılmıştır. Paketleme yoğunluğu, birim hacimdeki katı bileşenlerin toplam hacme oranı olarak tanımlanır. Betondaki dayanıklılık ve dayanım gibi özelliklere ulaşmak adına dolgu yoğunluğunun artırılması arzu edilen bir yöntemdir. Özelliklerdeki artışlar, isteğe bağlı olarak betonun taze veya sertleşmiş halinde veyahut her iki halinde de etkisini gösterebilir. Agregaların beton içerisindeki oranının artışı diğer malzemeler için kalan boşluk hacmini azaltır. Bu azalan boşluk hacmi, agregaların arasındaki boşlukları doldurmak ve agregaları bağlamak için ihtiyaç duyulan çimento miktarının en aza indirilmesine izin verir. Bu durum sayesinde daha az çimento kullanımı ile beton üretim maliyeti düşürülebilir. Çimento miktarı düşürüldüğünde su miktarının değiştirilmemesi durumunda ise, serbest su, hamurun akışkanlığını artırmaktadır. Düşürülen çimento miktarı ile birlikte su/çimento oranı sabit tutulmak istediğinde ise, birim hacimde daha az su kullanılacağından ötürü boşlukların sayısında ve hacimlerinde azalma olur. Bu azalma betonun durabilitesini ve uzun vadede dayanıklılığını artırmaktadır.

Araştırmanın bir diğer ana konusu ise ağır betonlardır. Ağır betonlar, içerisinde kullanılan agregaların yüksek yoğunluğundan kaynaklanan yüksek birim ağırlıkları sebebiyle bu adı almışlardır. 2600 kg/m$^3$ üzerinde birim ağırlığa sahip olan betonlar ağır beton olarak adlandırılmaktadırlar. Bu birim ağırlığa sahip olmak için gereken yüksek yoğunluklu doğal agregalara örnek olarak barit, manyetit, hematit ve serpantin; yapaylara ise çelik bilyeler, kurşun içeren taneler verilebilir. Ağır betonlar çeşitli projelerde kendilerine yer bulmaktadırlar. Gelişiminin ilk aşamasında devrilmeye yatkın yapıların dengelerini sağlamak için üretilmişlerdir. Buna ek olarak sürekli titreşim altında bulunan makinelerin stabilitesini sağlamak ve uzun ömürlü beton elde

etmek adına kullanılmaktadırlar. Nükleer teknolojinin gelişimi ile radyasyon geçirimsizliğini sağlamadaki faydalarının fark edilmesi ile birlikte, ağır betonlar bu alandaki açığı kapatmaktadır. Sivil nükleer alanda, nükleer santrallerin yapımında, hastanelerin radyasyon yayan aletlerinin bulundağu odalarda ve çeşitli laboratuvarlarda geçirimsizlik önlemi olarak kullanılmaktadırlar.

Kendiliğinden yerleşen beton 1986 yılında Japonya'da Okamura tarafından sualtı betonu olarak geliştirilmiştir. Uygulamadaki zorluklardan ötürü taze hamurun akışkan ancak dağılmayan bir yapıda olması gerekmektedir. Bu durum ise süper akışkanlaştırıcıların kullanılmasını gerekli kılmaktadır. Ancak süperakışkanlaştırıcıların kullanımının sonuçlarından biri de hamuru ayrışmaya yatkın hale getirmesidir. Sorunu çözmek adına beton karışımındaki ince tanelerin yani çimento, mineral katkılar ve ince agregaların oranı arttırılmış ve akıcı ancak vizkozitesi yüksek, kendi ağırlığı altında yerleşen ve ayrışmayan bir beton elde edilmiştir.

Tez kapsamında üretiliecek harçların karışım hesabını elde etmede Elkem Yapı Kimyasalları'nın EMMA yazılımı ile oluşturulan referans eğrileri kullanılmıştır. Modifiye Andreassen modelini kullanan bu yazılım, içerisine aktarılan malzemelerin granülometrisini kullanarak, referans eğrisine olabildiğince yakın ve dolayısıyla optimum doldurma yoğunluğu elde etmeye yardımcı olmaktadır. Buna ek olarak bu modelin formülasyonunda bulunan, tanelerin boyut dağılımlarının alt ve üst limitleri ile, q üssel dağıtma katsayısının belirlenmesi gerekmektedir. Kullanılacak malzemelerin tane boyut dağılımlarına bakılarak, harcın boyut limitleri belirlenmiştir. Kullanılacak en büyük taneler 3 mm ile sınırlandırılmış olup bundan ötürü tüm tane grıplarındaki referans eğrinin üst limiti 3 mm olarak belirlenmiştir. Alt limit ise kullanılan mineral katkıya bağlı olarak değişkenlik göstermiştir. Tane boyut dağılımlarından ötürü referans ve mikrosilika grupları için alt sınır 1 mikron olarak seçilmiştir. Nanosilikaların boyut dağılımı incelendiğinde ise en küçük tane boyutu 10 nm olduğu görülmüştür. Nanosilikanın boyutlarından dolayı alt sınır, nanosilica ve grupları için 10 nm olarak belirlenmiştir. Kendiliğinden yerleşen betonlar için önerilen q dağılım katsayısı 0,22 ila 0,25 arasında seçilmiştir. Mikrosilika, nanosilika ve polimer kombinasyonları ile altı numune grubu oluşturulmuştur. Referans grupları pozzolan katkısı içermeyip karşılaştırma için temel oluşturmaktadır, diğer gruplar ise mikrosilika grupları ve son olarak nanosilika ve mikrosilikayı içeren kombine gruplardır. Her grubun ayrıca bir polimer katkı bulunduran varyasyonu üretilmiştir.

Deneysel çalışma iki aşamada gerçekleştirilmiştir. İlk olarak taze haldeki beton harcının yayılmasını istenilen düzeye getirmek ve su ihtiyacını belirlemek için yayılma testi yapılmıştır. Yayılma testi yapılan bu numuneler, sonrasında birim ağırlık testine tabii tutulmuşlardır. İçerisindeki su miktarı istenen seviyeye ulaşan numunelerin paketleme yoğunlukları yine bu esnada, birim hacimden su miktarının çıkarılması ile hesaplanmıştır. İkinci aşama ise sertleşmiş beton harcı üzerindeki testleri barındırmaktadır. Toplam altı numune grubundan üçer adet 4x4x16 cm boyutlarında prizmatik numuneler hazırlanmıştır 28 gün su içerisinde kürünü tamamlayan numuneler dış etkilere kapalı, oda sıcaklığındaki odada bir gün kurumaya bırakılmışlardır. Bir gün sonunda kuruyan numuneler üzerinde üç nokta eğilme deneyi ve elde edilen parçalar üzerinde basınç deneyi uygulanmıştır. Test edilen numunelerden grupların her birinden bir adet numune, fırın kuruluğuna ulaşması için 40 saat boyunda 70 derece sıcaklıkta kurutulmuşlardır. Bu süre sonunda numuneler fırından çıkarılıp soğutulmuş ve boyutları ve ağırlıkları ölçülmüştür. Ağırlıkları ölçülen numunelerin birim ağırlıkları hesaplanmıştır. Fırından çıkarılıp özellikleri

ölçülen numuneler daha sonra, kılcal geçirimlilik deneyi için alt yüzeyleri açıkta kalmak üzere, yan yüzeylerinden parafin ile kaplanmışlardır. Bu numunelerin ağırlıkları tekrar ölçülüp, sığ su dolu bir kap içerisine yerleştirilmişlerdir. Düzenli aralıklar ile su emme değerleri ölçülüp not edilmiştir. Bu değerler üzerinden kılcal geçirimlilik katsayısı hesaplanmıştır.

Bu testlerin sonuçları incelenerek şu değerlendirmeler yapılmıştır; puzolan ve polimer katkılarının doldurma özellikleri nedeniyle , boşlukların azalarak paketleme yoğunluğunun artırdığının söylenmesi mümkündür. Ayrıca deney gruplarının polimer katkı içeren varyasyonlarının sonuçlarına bakıldığında yayılma değerleri azaldığı gözlenmiştir. Sertleşmiş beton üzerinden yapılan testlerde elde edilen sonuçların incelenmesinde ise mineral katkı içeren grupların birim ağırlık ve basınç testi sonuçları, referans veya polimer içeren numunelerden daha yüksek olduğu görülmüştür. Polimer katkısı genel olarak kılcallık katsayısını azaltmıştır. Polimer katkısı içeren numunlerin, basınç dayanımının azaldığı, ancak eğilme dayanımının arttığı gözlemlenmiştir.

# 1. INTRODUCTION

Concrete is a composite material that is also the most produced material in the world due to its strength, durability, availability, and versatility. It consists of proper proportioning of ingredients such as water, cement, coarse and fine aggregates, along with the chemical and mineral admixtures if required, in order to fulfill the desired characteristics of concrete in the fresh and hardened states. Furthermore, the concrete mortar possesses almost the same constituents as that of conventional concrete except for coarse aggregate. The mineral admixtures of concrete are commonly produced from other industrial processes and have a wide range of usage in concrete production. The effects of the products such as organic admixtures, mineral admixtures, such as pozzolans, as supplementary cementitious materials, fibers, polymers, etc., are not only limited to the final compressive strength but also rheological properties, early-age characteristics, properties according to the capacity of deformation and, durability aspects. Hence the aim of the mixture proportioning is to obtain a concrete that will have optimum workability and flowability together with the required unit weight, strength at a specified age, dimensional stability, and desired durability.

Mentioned earlier, the composition of concrete is made of several ingredients. The ingredients of the simplest concrete can be basically named as cement, fine aggregate, coarse aggregate and water. In addition, several other admixtures may take part in the mixture. These materials can be divided into two classes: chemical and mineral admixtures. The purpose of admixtures is to change the properties of concrete in the fresh or hardened state in the desired direction.

The packing density is known as the solidity of material which is defined as the fraction of solid ingredients to the total volume of material. The increase in the packing density is a desired objective in order to reach greater properties in concrete.The increase in the properties happen both in the fresh and hardened state of concrete. A higher packing degree of aggregates leads to increase of solid materials in the unit volume of concrete. The remaining void volume allows to minimization of the amount of cement

needed in the same volume to fill the gaps between particles. Therefore, the cost of producing concrete can be reduced with less usage of cement. By reducing the cement, it is also possible to reduce water by keeping W/C constant. Lower the the W/C is beneficial for both mechanical and durability properties since the porosity decreases even further with less water. Other than economical and structural benefits of the reduced cement usage in the concrete, it also contribute to a more environment. As the cement used in concrete reduces, the $CO_2$ release during the productions diminishes,also decreases the use of natural resources. Five-to-eight percent of global man-made $CO_2$ emissions are produced by the cement industry.

Heavyweight concretes are known for their exceptional unit weights that stem from the high density of the aggregates. The heavyweight concrete finds several applications among projects due to not only its high unit weight but also the insulation against radiation. Such natural aggregates are barite, hematite, serpentine, magnetite, or industrial byproducts that contain ferrous or lead compounds. Heavyweight concrete is used in several means in modern society. In the beginning, the reason behind the development of such material was increasing the stability of constructions that inclined to overturn or applications including constant vibration such as heavy machinery. Later with the introduction of nuclear technology in the civilian field, the power plants of such kind required measurement for the radiation, and the heavyweight aggregate was suitable to fill the gap.

Another main issue of the study is self-compacting properties of the concrete mortar. The term is coined in 1986 by Okamura in Japan while developing a viscous and low segregation underwater concrete. The main distinction of the kind is leveling under its own weight without a need for vibration due to its high flowability and highly viscous form. The obtain high viscousity ratio of the fine materials, namely cement, mineral admixtures and fine aggregates, are higher in the SCC than traditional concrete. However, the W/B decreases as the binder rate increases. The reduction in the W/B rate decreases flowability, which is not desired in SCC. In order to obtain a high flowability, the usage of superplasticizers is crucial. The reduction diminished W/B ratio along with superplasticizer usage also affect durability since porosity reduces.

## 1.1 Purpose of Thesis

The main purpose of this study is to determine the affect of modified Andreassen particle packing method in self-compacting concrete mortar in the sense of flowability, compressive and flexural strengths, sorptivity and unit weight. In addition to the central purpose, effect of mineral and polymer admixture in the concrete mortar is investigated.

## 1.2 Methodology of the Study

In order to achieve this aim, several constants and parameters were chosen. The constants are the suggested range of q factor of modified Andreassen model to obtain SCC type mortar, and W/C ratio.

The parameters are chosen as samples with mineral and polymer admixture variations, lower limit of particle size distribution of the mixture depending on the pozzolan type, different amount of aggregate groups, and W/B ratio.

The modified Andreassen model and its q factor in suggested range to create a SCC type concrete mortar is used to create a model that leads to the highest packing density possible. By inputting the lower and upper size limits of the particles, the reference curve of the model is generated. The materials are picked according to their particle size distribution (PSD) to obtain a curve that converges reference model.

In the experimental part, three main and six subgroups of samples, in the shape of 4x4x16 cm prismatic specimens, are prepared with combinations of micro silica, nano silica and polymer admixtures. The maximum aggregate size limit is chosen as 3 mm, and lowest is 1 micron in non-nano silica containing, 10 nm in nano silica containing groups. A superplasticizer was used to keep the flowability above a certain threshold and unit weight in heavyweight concrete class.

Flow, unit weight and packing density tests were conducted in the fresh state. Compressive strenght test, flexural strength of three-point bending test, oven-dry unit weight and water absorption tests were carried out in hardened state of concrete mortars.

# 2. LITERATURE REVIEW

## 2.1 Concretes and Mortars

Since prehistoric times, cementitious reactions are known to some extent. In the earl 19th century, the modern hydraulic cement was produced. There are several types of Portland cement are in the market but the most common type is ordinary Portland cement (OPC). The name of stems from the similarity to the Portland stone which can be found in a quarry in Isle of Portland, England.

To this day, the extension of the use of concrete increased rapidly. Due to its modifiable properties, the concrete is the most used human-made materials in the construction industry. The material is commonly used in many installations from housing to harbors. But on the other hand, the concrete also accounts for the 6 to 8 percentage of global $CO_2$ emission globally.

In order to cope with the undesired properties and increase the existing ones, several approaches both in the theoretical and experimental phase have been developed. To reduce the $CO_2$ emissions and increase characteristics of the concrete, mineral admixtures and decrease in clinker factor is commonly used. Also approaches to decrease the cement ratio in concrete are often adopted in mixture design.

The advantages of the concrete that result in its favor than the other construction materials are its versataility and relatively cheapness with good mechanical and durability properties. However, the low tensile and flexural strength are among the disadvantages of the concrete. To deal with these problems, additives, or rebars are introduced to the construction industry.

### 2.1.1 The Ingredients of the Concrete

The concrete is a ceramic matrix type composite material with fine and coarse aggregates are dispersed in. The concrete consists of fine and coarse aggregates, cement, chemical and mineral admixtures and mixing water. With the existance of water

#### 2.1.1.1 Aggregates

Aggregates are the materials such as sand, gravel, crushed stone and etc that occupies most of the volume in the concrete or mortar. Usually it is not desired to have a reactive aggretages in concrete. Naturally, the aggregates affects the properties of concrete. Modulus of Elasticity, rigidity, toughness, hardness, thermal conductivity and volumetric stability are among the properties.

Aggregates can be classified as fine and coarse according to their sizes. The particles that can pass through 4 mm sieve are classified as fine aggregates, whereas retained is the coarse. Therefore the fine aggregates which have a diameter less than 4 mm and coarse aggregates are 4 mm or larger. the  There are several reference gradiation standards for concrete. In the case of mortar, there is the standart sand and guidelines to create similar sand mixture. With a well graded mixture, the concrete or mortar gains a better workability, high segregation resistance.

Self-compactibility can be define as the levelling of concrete without any external energy. In other words, the mortar or concrete does place and compact itself under self-weight homogeneously. Altough the materials used in conventional concrete and SCC concrete are similar, the usage of superplasticizers and several variables are the differences. The ratio of finer aggregates are higher which leads to high viscous property and to pass between rebars, the maximum size of coarse aggregate is limited. Usually the maximum size is not more than 16 mm in diameter for concretes.

#### 2.1.1.2 Cement

The most common cement type used in modern times is Ordinary Portland Cement (OPC). The name derives from the Portland Island where it was in the vicinity of the invention.

The following abbrevisions C, S, A and F are commonly used in cement industry. The chemical composition of OPC consists of 60-65% CaO(C), 17-25% $SiO_2$(S), 3-8% $Al_2O_3$ (A), 0,5-6% $Fe_2O_3$(F), 0.1-4% MgO, 1-3% $SO_3$ and other oxides. These oxides are the outputs of the reactions that happens in the rotary kiln and the inputs are the limestone, clay and iron. These inputs heat up in rotary kiln to 1450 degrees celcius to obtain clinker. Following the heating, the clinker is ground with gypsum to prevent flash set of concrete.

The reaction of hydration occurs with the presence of cement and water. Starts at the surface of the cement and advances to inside of the grain. 2.06 $cm^3$ cement gel takes shape from 1 $cm^3$ cement. The volumes that are not occupied by aggregates or cement gel are called capillar voids.

### 2.1.1.3 Pozzolans

Pozzolans are are materials that shows little to none binder property. Due to the silica or aluminum silicate content, finely ground pozzolans reacts with the calcium hydroxide (CH) with the presence of moist. The output product of $C_3S_2H_3$ (C-S-H) owns better binding features than calcium hydroxide. The reaction is shown in the Fig. 2.1.

$$2C_3S + 6H \xrightarrow{yields} C_3S_2H_3 + 3CH$$

$$2C_2S + 4H \xrightarrow{yields} C_3S_2H_3 + CH$$

$$Pozzolans + CH + H \xrightarrow{yields} C - S - H$$

**Figure 2.1 :** Pozzolanic Reaction.

The pace of pozzolanic reaction is slower than the hydratation of cement. The reactions starts with the presence of calcium hydroxide. Therefore, the influence on early days may not reach to the desired limits. W/C ratio, specific surface area, temperature and the curing conditions play significant role on pozzolanic reactions [1]. The main properties of pozzolans are their pozzolanic activity that depicted in Fig 2.1, and their filler effect in matrix since the particles are finely ground.

When the pozzolans is substituted for cement in concrete or mortar, several advantages can take place. Transformation of free lime to C-S-H inceases the strenght, decreases the permeability under required curing conditions. Also, due to the relatively low cost of pozzolans to cement, the overall price of concrete can reduced. In some cases, workability increases thanks to the sphrecial shape of puzzolans and due to the nature of the pozzolanic reaction, which follows hyration, the heat generated by reactions can be reduced. Since most of the pozzolans are byproducts of industrial processes, the usage of them aids to the preservation of nature.

There are two main types of pozzolans in the sense of origin: natural and artificial. Tuff, trass, volcanic ash are some examples of natural ones, whereas silica fume, fly ash, rice husk ash, and granulated blast furnace slag are the examples of artificial pozzolans.

**A. Micro silica**

The silica fumes are a byproduct of ferrosilicium alloy which is also known as silica fume. The researches started in Norway in 1950's and first usage in concrete as a mineral admixture is dated back 1969.

In order to have such material, firstly, the silica fume is collected at the chimneys of factories with filters. The chemical composition of the silica fumes depends on the industrial process. The main ingredient, $SiO_2$ is hightest when the fume is collected from the process of silicon metal.

The collected particles are sphreical shaped and usually around 1.5 microns in dimater. Due to its small size, the specific surface area of micro silica ranges between 15,000–30,000 $m^2/kg$.

As the micro silica has high specific surface area, it requires additional water for the same amount of slump compared to non-micro silica containing mixtures. Usually it is suggested to use plasticizers or superplasticizers along with silica fume to compensate to water demand [2]. Also due to their fineness, silica fumes are prefererred in particle packing models to produce a concrete with better properties. The spherical shape and high specific surface area leads to lower viscosity because of the lubricating effect. This also makes the way for workability since the energy requirement to work the concrete decreases This is also beneficial when aiming to produce SCC. The heat of hydratation is lower if micro silica replaces cement to keep binder amount same. The reason is the micro silica takes place in reactions after the formation of calcium hydroxide.

In the phase of hardening, micro silica reacts with calcium hydroxide, which is a product of hydration process of cement, and produces C-S-H. Therefore, the amount of binder increases, voids filled and permeability diminishes, and the gap (ITZ) between cement matrix and aggregates reduces. As a result, the compressive strenght of the concrete increases. However, the micro silica admixture makes concrete more brittle.

In Table 2.1, the analyses of the content of silica fume that collected from the ferro-silican alloy production is shown.

**Table 3.1 :** Analyses of Silica Fume from the Production of Silicon Metal and 75% Ferro-Silicon Alloy (%) [2].

| Compound | Si Metal | 75% FeSi |
|---|---|---|
| $SiO_2$ | 94-98 | 86-90 |
| C | 0.2-1.3 | 0.8-2.3 |
| $Fe_2O_3$ | 0.02-0.15 | 0.3-1.0 |
| $Al_2O_3$ | 0.1-0.4 | 0.2-0.6 |
| CaO | 0.08-0.3 | 0.2-0.6 |
| MgO | 0.3-0.9 | 1.0-3.5 |
| $Na_2O$ | 0.1-0.4 | 0.8-1.8 |
| $K_2O$ | 0.2-0.7 | 1.5-3.5 |
| S | 0.1-0.3 | 0.2-0.4 |
| LOI | 0.8-1.5 | 2.0-4.0 |

**B. Nano silica**

The nano silica is a silica containing mineral additive similar to the micro silica. The natural silica containing recources are not pure and not preferable for being admixture in concrete. In order to overcome this impurities, several methods have been developed to synthesis nano silica such as reverse microemulsion and flame synthesis, and widely utilized sol-gel [3]. The nano silica used in concrete is in colloidal form in which the particles are polorized to prevent agglomeration.

As the particles are smaller in size than micro silica, the reactivity increases. More of the silica atoms are located on the surface of the particles as the PSD is in nanometer levels. Such condition causes the growth of both specific surface area and reactivity.

The mechanism of nano silica is same as the micro silica and reacts with CH to form C-S-H. As the particles are smaller, same weight of nano silica reacts is faster than micro silica because the particles will be more in quantity. Therefore, the pozzolanic activity increases and CH amount reduces.

### 2.1.1.4 Chemical admixtures

The chemical admixtures are materials that used to alter the properties of concrete in fresh or hardened state to desired properties. The change occurs due a reaction that might happens in chemical or physical or in both ways. The amount of the chemical

admixtures should not exceed 5%. According to ASTM C494-19 [4], the chemical admixtures are divided into 8 types. These are:

- Type A—Water-reducing admixtures,
- Type B—Retarding admixtures,
- Type C—Accelerating admixtures,
- Type D—Water-reducing and retarding admixtures,
- Type E—Water-reducing and accelerating admixtures,
- Type F—Water-reducing, high range admixtures (superplasticizers),
- Type G—Water-reducing, high range, and retarding admixtures, and
- Type S—Specific performance admixtures.

These admixtures does improve the concrete only if the concrete is already good itself.

**A. Plasticizers**

The plasticizers are a chemical admixture that are used in concrete. A highly effective version of which is called superplasticizers and used especially in the SCC. There are several reasons to use plasticizers. These are; decrease in water demand, increased workability, increased mechanical properties, better durability, and restoration of the flowability of concretes[5].

These reasons can be explained in three points. First of which is the reduction of water due the lubrication effect of plasticizers. If desired, plasticizers allow as a result of lower water demand and therefore a lower water/cement ratio. A lower w/c leads to higher mechanical and durability properties. Secondly, in the same scenario where water amount is decreased, for the same water/cement ratio, the cement amount can be decreased to keep the ratio constant. This approach has both economical and environmental benefits as less cement usage reduces both the price and $CO_2$ emissions of the concrete for the unit volume. And lastly, the flowability of concreate can be increased for the mixture if the water amount kept same. The plasticizers decreases the internal frictions and therefore the internal stress and the flowability and workability of the fresh concrete increases without changing the proportioning.

The plasticizer admixture adsorbs on the surface of the cement particles and creates a layer which seperates the particles in different efficiencies depending on the type of

the admixture. According to the ASTM C494-19[4], there are five classes of water reducers: Type A, Type D, Type E, type F and Type G. Only the Type F can be classified as superplasticizer or high range water reducer among all.

The plasticizer has a common electrostatic effect that decreases the water need by adsorbing cement particles and charging them. The particles with same charge is inclined to stay apart, and consequently disperse in matrix.

### 2.1.2 Self-Compacting Concrete

Self-Compacting Concrete (SCC) or Self-Leveling Concrete is a special type of concrete that levels under its own weight evenly without a need for external compaction or vibration . A SCC must be viscous in order avoid segregation while having sufficient flowability and workability properties for the process of placing into mold. The main reason for its development can be traced back to the 1980's in Japan as a underwater concrete that does not dissolve in the water body. In 1988, the first first SCC was made of the materials which were already avaible [6]. Furthermore, further researches on this new type of concrete showed that due to its low porosity, the concrete has high durability properties along with its high workability. The increased workability porperty results in reduced high skilled worker need which is an issue in Japan.

The SCC does consist of cement, fine aggregate, coarse aggregate, chemical and mineral admixtures and water . Along with these materials, powders ,or fillers in other word, may be added to concrete. In order to achieve such consistency, the amount of coarse aggregates must be reduced whereas the fine material amount must increase. The usage of superplasticizer is crucial in SCC. As the amount of the fine particles increase, water demand also raises, and in order to meet the water demand, superplasticizer plays a crucial role in the concrete.

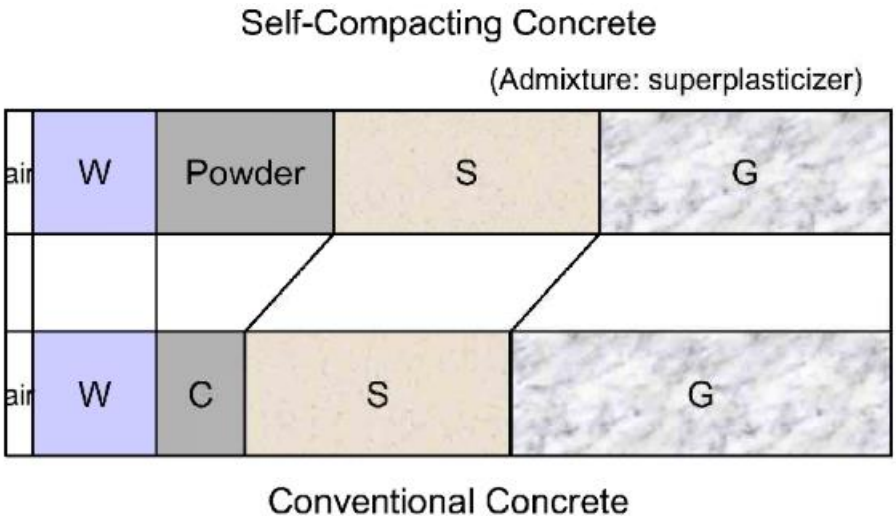


**Figure 2.2 :** Comparison of mix proportioning between Self- Compacting Concrete and conventional concrete. [6]

The mechanism for self compactibility accommodates two features. First of these is high deformability of the paste and the second is resistance to segregation. When the relative dinstance between particles reduces, the collisions occur more frequently. As a result of this, the internal stress increases as concrete deforms. The internal stress can be observed particularly around the obstacles. It is found in the research [6] that the flowability decreases espacially around the coarse aggregates due to the consumption of energy by internal stress. By limiting the coarse particles, the energy requirement for same amount of flowability would diminish greatly. Also this can be explain as: less amount of coarse aggregate in concrete allows flow with less energy.

As mentioned earlier, the SCC has the superplasticizer or high range water reducer content. The Type F of the ASTM 494-19 [4] is classified as a superplasticizer. Usually, the admixture is carboxylate based however, it is possible to find other chemical admixtures with similar properties.

There are two mechanism of superplasticizers that enhances the concrete properties. These are electrostatic and steric forces. The former can be found in any kind of superplasticizer however, the latter is introduced with the invention of hyper-plasticizer. The mechanism of superplasticizers occurs physically. The polymer chains adsorb on the surface of particles as a layer. The layer electrically charged with negative load. The loads place cement particles away from each other, increases the surface free to react with water and reduces the internal friction therefore the need of water to lubricate grains. This is a result of electrostatic effect. Also, the agglomeration

of cement particles is avoided by this effect and the water trapped within these agglomerates are freed and increases the flowability. The steric effect is caused by the long polymers that forces grains to stay further away from each other. As the hyper superplasticizers has both effects, it is superior to the other types of superplasticizers and favoured to use in SCC.

In Fig. 2.3, both electrostatic and steric effects are illustrated.

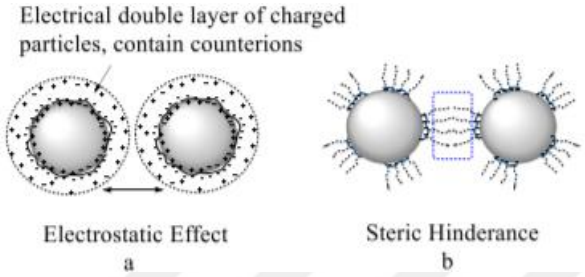


**Figure 2.3 :** A schematic representation of electrostatic repulsion (a) and steric hindrance (b), which are generated from the adsorbed superplasticizers on cement surface [7].

When the concentration of superplasticizer reaches to a treshold, the effect can be seen. This specific point is called critical dosage. Any dosage less than the critical dosage does not make a significant difference in flowability. Another meaningful limit, saturation dosage is where the dispersing ability of superplasticizer reaches its peak and does not influence the flowability further on [8]. This effect is shown in the Fig. 2.4.

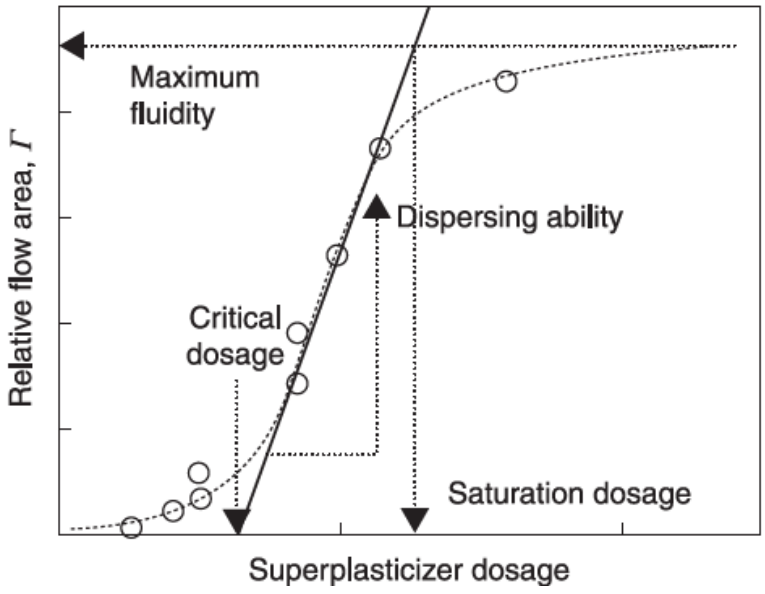


**Figure 2.4 :** Critical and Saturation Dosages with respect to the dispersing ability [8].

The segregation in concrete takes place when the gap between particles are high and what is more, the situation may stem from the gradiation of aggregates. In a space that coarse grains are dominant in such 4 to 1 ratio to fine ones, the fine grains sink to the bottom in the conventional concrete [9]. Since the SCC limits the coarse aggregate in favour of fine particles, this phenomenon will occur less likely. Also, if the particles are located in such optimum order with almost none gap between, the segregation does not happen due to the fractions between the grains.

### 2.2 Heavyweight Concretes and Mortars

The concrete is the most extensively used materials in radiation shelding due to its high efficiency, low cost and sufficient mechanic and durability properties. Heavyweight concrete can be defined as a type of concrete with the unit weight above 2600 kg/m$^3$ in the dry state. The high unit weight of the concrete derives from the aggregates used in. In order to achieve the mentioned high unit weight, the concrete or mortar is required to contain high amount of heavy particles. The aggregates used in the mixture must be above 3000 kg/m$^3$ density according to the TS EN 206 [10]. Such high density is required in order to reach the prementioned heavyweight concrete unit weight. Such heavy particles can be chosen from not only natural aggregates but also from products of industrial processes. As a heavyweight syntetic aggregate, iron, steel, ferrophosphorus and boron frit or other boron compounds or the natural aggregates such as barite, hematite, serpentine, ilmenite or magnetite can be used [11]. The aggregates are formed by heavy element compunds which also have high atomic numbers. It is crucial for the concrete that heavweight aggregates are inactive to alkalis which may create issues on bonding of the cement paste to the aggregate particles or affect cement hydration which are undesired situations.

The main function of the aggregates in the concrete is radiation shielding and being the core material that occupies the most of the volume in a concrete. With an accurate approach, the concrete can be produced at maximum density and with required structural strength. Also the model can allow the prediction of physical, chemical, thermal properties of the material. In specific situations, usage of barium sulphate in clinker production ,in which $Ca^{+2}$ is partically replaced by $Ba^{+2}$, is effective for the enhance in unit weight and radiation shielding further. [12]

The initial design of this types of concretes were developed for the safety purposes. The heavhweight concrete was used to increase the protection of specific buildings which were inclined to sliding and had no safety precautions against overturning. With the advent of nuclear energy created a need for a material which should be cheaper safeguard material than lead or steel with favorable mechanic properties. The need for protection from fatal neutron and γ rays, each of which is capable of penetrating objects, heavyweight concrete began to be used as a radiation shield. Naturally, these heavyweight concretes are used in structures such as nuclear power plants, nuclear shelters [13]. What is more, for the medical units and laboratories, transportation and preservation of nuclear wastes, heavy concrete is extensively used. The development of nuclear energy created a field that soon to be filled with largely heavyweight concrete.

The researches show that the increase of ratio of the barite in mortar replacing the natural aggregate contribute to enhance in unit weight greatly [14]. Usage of finer particles are also important due to the high weight of the aggregates. The segregation is a potential risk to occur due the impulse of sinking of grains. As a mesurement, duration of mixing of the concrete should be completed in short time to prevent downward movement of particles and, finer aggregates should be used to increase the viscosity of matrix material and friction that prevents the sinking.

The replacement of normal aggregate with heavyweight aggregate contributes to the decrease in water absorption in concrete. In other words, the amount of barite replacement has an inverse affect on water absorption. Another test that carried out on heavyweight concretes shows that the thermal conductivity shows almost negligible difference. The most significant difference is seen in the radiation permeability. Increase of barite content creates a shield against radiation. However, the concrete shows poorer compressive strenght with increased barite aggregate ratio [14].

### 2.3 Packing Density

Since 1907, with the study of Fuller and Thompson [15] on optimization of the properties of concrete by determining the role of the size distribution of the aggregates, particle packing models (PPM) have been a field that attractive to numerous researchers. In 1929, Furnas designed the first particle model that predicts voids ratio

of binary mixtures. Initial models were sufficient to determine the theoretical packing density of a given combination based on particle size of each aggregate distribution. Those models were lacking of broad range of factors, such as interparticle forces, shape factor, water demand and strength.

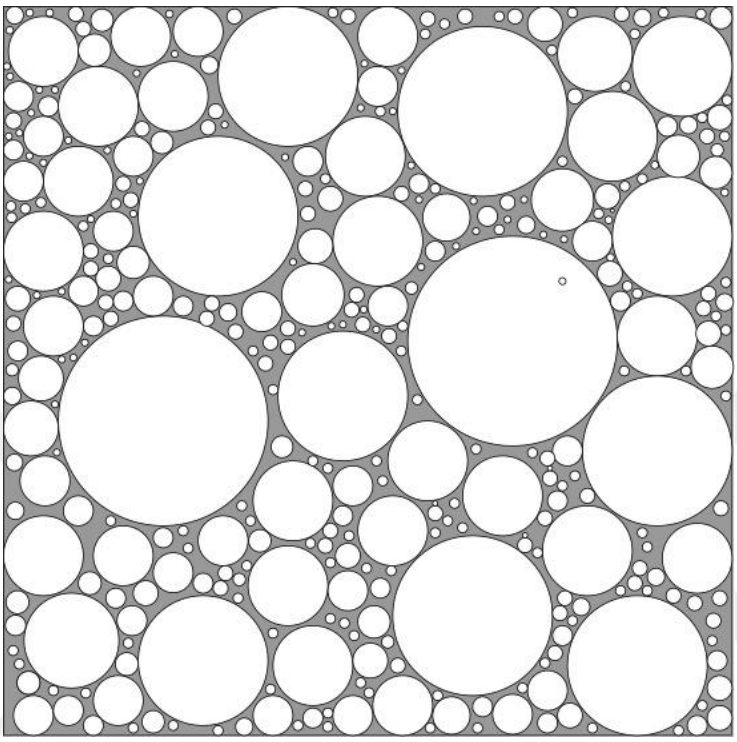

**Figure 2.5 :** Theoretical illustration of packing density of spherical particles.

In Fig 2.5 illustrates that a packing density of particles with different diameters in a matrix. In order to reach the highest possible solid ratio, the variety and proportioning of the particles are crucial. Therefore, as it is shown in Fig 2.6, it is required to provide aggregates of different sizes to fill the gaps between bigger particles and increase packing density.

The packing density is defined as the solid volume in a unit total volume of a mixture. In other words, the packing density may be described by the porosity:

$$\pi = 1 - \Phi \tag{2.1}$$

or by the void ratio:

$$\Phi = 1 - \varepsilon \tag{2.2}$$

Where $\pi$ represents porosity, $\Phi$ packing density and $\boldsymbol{\varepsilon}$ void ratio.

Proportioning of the concrete and mortar mixture is mainly based on experiments. A purely trial and empirically optimization design could not provide optimum proportion due to some of the parameters involved as input and output as mentioned earlier. Nevertheless, the technology of concrete has been developing for over a century, and during this period many researches conducted. The trial error method of earlier days provided precious data for the later researches. The mix proportioning methods built with the consideration of the results of previous tests. Concrete proportioning is first of all a packing issue. In order to cope with the problem, two distict approaches in the sense of determination of the particle distribution of a mixture has been developed [16]. These models can be categorised as continuous models, which are also known as optimization curves, and discrete element models.

### 2.3.1 Continuous models

Following the statement of Féret in 1892 that the grading of aggregates influences the strength of concrete [Féret, 1892], a pursue to reach an ideal optimization curve had initiated by many researchers. One of the pioneer and leading researcher of this area is Fuller with his eminent Fuller curve [15]. This curve is still in use for the mix design calculations. The Fuller curve is shown by Equation 2.3 with q=0.5 [17]

$$\boldsymbol{P(d)} = \left(\frac{\boldsymbol{d}}{\boldsymbol{d_{max}}}\right)^{\boldsymbol{q}} \tag{2.3}$$

In this equation, d represents particle diameter that considered in mm, P(d) size cumulative distribution function of considered d diameter, dmax maximum particle diameter in the mixture in mm and the q as a distribution factor, ranges between 0.33 to 0.5, which adjusts the curve's lean to opt for finer or coarser.

In 1930, Andreasen and Andreasen propesed using exponent q in a range of values between 0.33 to 0.5. This range was set to allow users to determine the value experimantally which particles' characteristics plays a role. Also Fig. 2.6 shows differences of various ideal packing curves. The curve is designed to represent the grading of particles with the highest possible density in dry state. This approaches may not be the case when combined with additional dry particles or mixed with water due to the hydration reaction and ability of which to fill the voids.

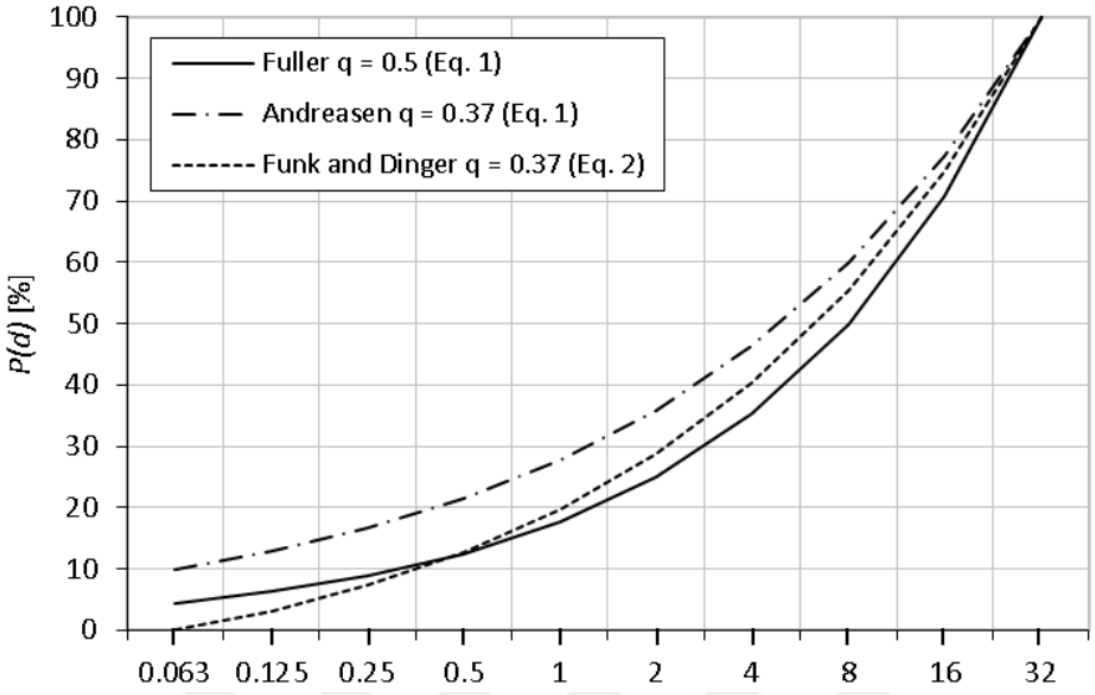


**Figure 2.6 :** Ideal packing curves according to Fuller, Andreasen and Funk and Dinger for a maximum particle diameter of 32 mm and a minimum particle diameter of 63 μm [18].

In 1980, recognisation of lack of lower size limit, Funk and Dinger modified the equation to meet the requirements [19]. Hence, the modified Andreassen method not only pays attention to coarsest particle but also to the finest particle. The equation 2.4 describes it.

$$\boldsymbol{P(d) = \frac{d^q - {d_{min}}^q}{{d_{max}}^q - {d_{min}}^q}} \qquad (2.4)$$

Where d represents particle diameter that considered in mm, P(d) size cumulative distribution function of considered d diameter, dmax coarsest particle diameter in the mixture in mm, dmin finest particle in the mixture in mm and the q as a factor.

A concrete or mortar mixture that constituted of combination of optimal amounts of different size classes particles fits one of the mentioned curves (Equations 2.3 and 2.4), should show the highest packing density possible. Since the packing density is described as the ratio of solid volume of particles in a unit volume also known as solidity, or as 1 - ε (1 - the porosity). As stated, optimization curves takes into account of broader range of the particle size distribution that leads to an improved packing density, regardless of the particle shape. However, mentioned approaches do not

include the influence of particle shape theoretically. Since the particle shape greatly affects the packing density, especially, in the case of the using different size classes of particles and, with varying particle characteristics [20].

The value of the exponent q also determines the workability and flowability of the concrete. Adjustment of a composition of a determined optimization curve is partially easy as the input parameters are limited. When the q factor is set, the optimization of particle size distributions is the final step to optimize the mixture. To achieve this goal in this study, both Emma [21] and excel cross used to eliminate any error to occur.

As mentioned before, particle characteristics such as packing density or shape of grains are not taken into account in this approach. In order to avoid these problems, the flowability and mixture density were measured in wet state. In the reaseach of Li and Kwan [22], it is suggested that to measure packing density in fresh state rather than dry packing. This case can be justified by the increased packing density in fresh state than dry state due the the lubrication effect of water and superplasticizers.

Materials mixtures reveal more accurate and higher packing density in this state thanks to the involvement of cement paste. The main role of cement paste in concrete is filling the voids between aggregates and binding the particles. With a higher packing density, the requirement for cement paste to fill the voids is diminished. However, the excess paste in same volume will lead to enhanced workability properties. The act of cement paste in this state can be explained by the reduction in friction by lubricating the solid grains. Also, for the same workability, the amount of not only water but also the amount of cement in a fixed volume can be lessen. The decrease of water will be beneficial in the sense of reduced water to cement ratio, increase in strenght without a decrease in the flowability. When the reduction in water is combined with the lower cement amount without compromising the workability, carbon foodprint and the unit cost of production can be lessen. Also in the same scenerio, the lower cement paste will contribute to dimentional stability. Therefore, for measuring the packing density of the samples prepared, the fresh state will be preferred in this study.

For this study, modified Andreassen method has been used with the assist of commercial software Emma of Elkem along with the Microsoft Excel to determine the proportions of the particle class sizes.

### 2.3.2 Discrete element model

Binary, ternary and multimodal mixture models are the classes of discrete models.These discrete models are based on the assumption that the each particle class will be occupying the maximum volume. Also the models generates a virtual packing denstiy by incorporating given particle size distribution. The main extension of this models to the continious models are consideration of the boundary conditions. The boundary conditions are wall effect and loosening effect. As calculating the packing density in discrete model, these boundary conditions are taken into account in order to achieve the highest density possible with the hightest precision.

#### 2.3.2.1 Binary

Binary model can be explain as situation where two distict classes of particles presented in a mix. Mathematical equations are used to determine how particles of different sizes interact geometrically. In order to achieve the optimum packing, fraction of each class should be calculated indivually prior to model calculations. Fig. 2.7 illustrates that the zenith of the packing can be achieved by an optimal proportioning of fine and coarse particles collectively.

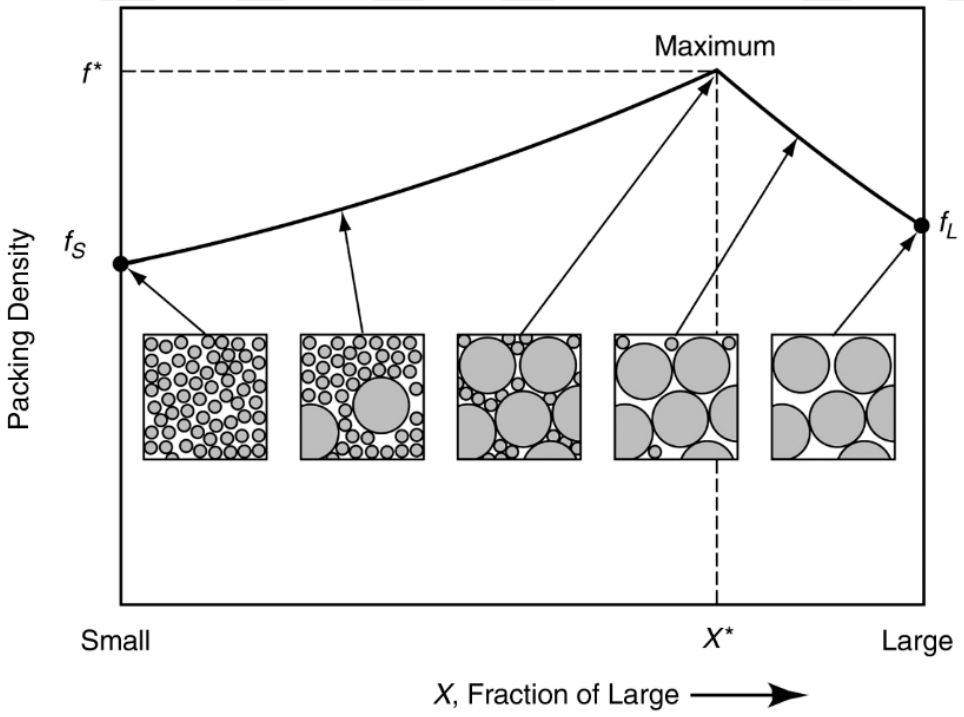


**Figure 2.7 :** Bimodal powder packing and the variation of large–small powder density with composition, showing the maximum fractional density and the composition of the maximum density [23].

The equations 2.5 and 2.6 assume that every particle available is spherical and each class is homogeneous.

$$f^* = \frac{f_S}{1-X_L} = \frac{f_S}{X_s} \text{ large particles are dominant} \quad (2.5)$$

$$f^* = \frac{1}{X_S+(\frac{X_L}{f_L})} \text{ small particles are dominant} \quad (2.6)$$

In the equations, the f*, fS and fL are the packing density of mixture, small particles, and large particles respectively, whereas XS, and XL are the fractions of mixture, small and large particles. For clarification, XS+XL=1

The boundary effects occur with the presence of the at least two distinct size classes. The first of effect, the wall effect which can be seen in Fig. 2.8, occurs in the case of domination of fine particles with a few coarse particles immersed this matrix.

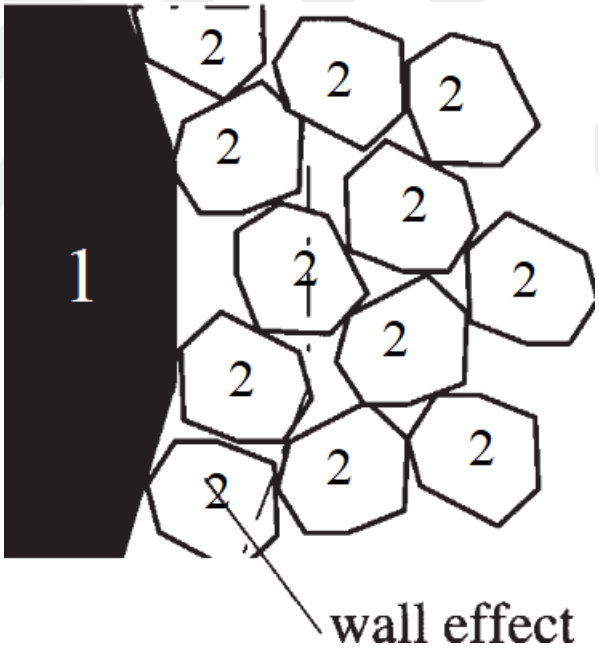


**Figure 2.8 :** Wall effect exerted by a coarse grain on a fine grain packing [24].

In Fig 2.8, the particle that given number 1 is coarse aggregate ,and particles with number 2 are fine aggregates.

The latter effect, loosening effect can be seen in Fig. 2.9, happens when a fine grain is entrapped among coarse grains where the void is not sufficient for fine particle to fit in. Both effects have an influence on the packing density since the voids between particles are affected.

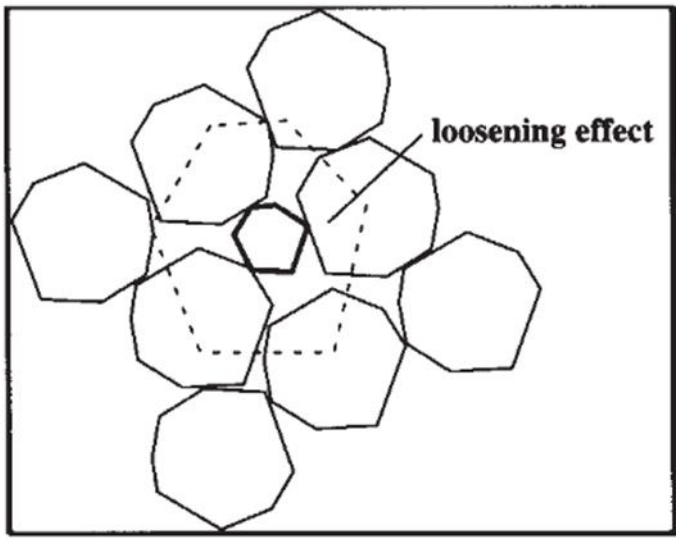


**Figure 2.9 :** Loosening effect exerted by a fine grain in a coarse grain packing [24].

### 2.3.2.2 Ternary

The difference of ternary model to binary is the presence of three distinct size classes in the volume. This change was made by Toufar et al [25] due to the consideration of the filler ability of small particles. In Toufar model, if the small particles are larger than one fifth of the large particles, there would be voids need to be filled. In order to solve this issue, they proposed the extension to binary model. This proposed model included an insertion of a third and median particle size class to the mixture. However, by adding a third class also means incorporating both boundary effects. But the interactions between disrorderly area are neglected in the model. This boundary effects can be seen in Fig. 2.10.

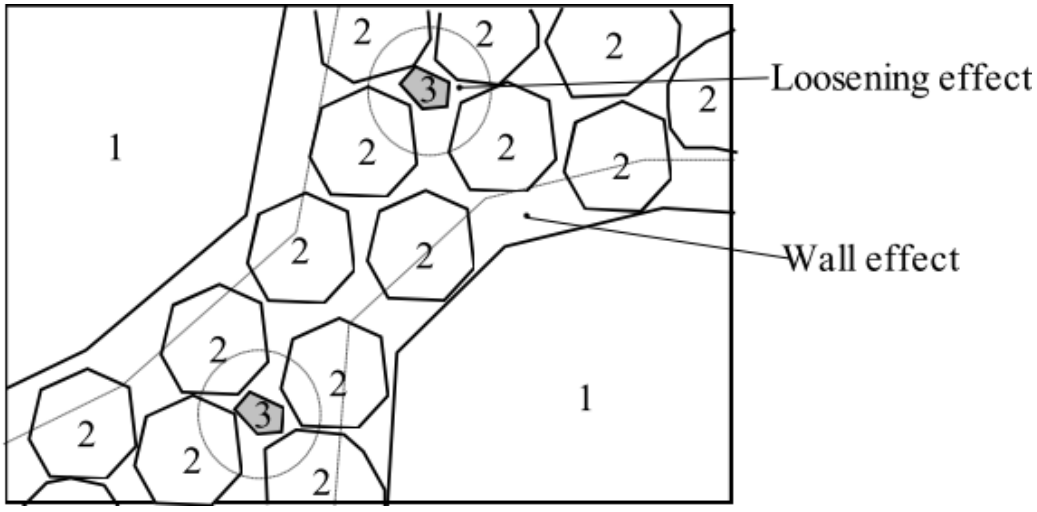


**Figure 2.10 :** Ternary packing of particles, where the intermediate class is dominant. [24].

In Fig. 2.10, Grain numbered as 1 represents coarse size particles, 2 intermediate size particles, and 3 fine size particles.

#### 2.3.2.3 Multimodal

The multimodal discrete models are mainly based on the studies of De Larrard [24][26] and often named after him. There are two main sub-models which are linear packing density model (LPDM) and compressible packing model (CPM). The linear packing density model is considered favorable when working with cementitious materials. The main innovation of this model is its differentiation of actual packing density then virtual one. In the compressible packing model, the consideration of virtual packing density and its definition are preserved. However, the empirical equations to calculate the values of the wall effect coefficient and loosening effect coefficient have been modified.

## 2.4 Polymer Modified Concretes

Polymer Modified Concrete (PMC) or Polymer Cement Concrete is a concrete type that contains polymer along with cementitious particles. A PMC sets within hours or days depending on the type of the polymer used and the increase in strength can continue for several years due to the curing still continues. The PMC is known for its high flexural and compressive strength, great durability properties, among other characteristics around the globe. Nevertheless, PMC also has some setbacks. The most prominent one is the price of polymer which is higher than the cement. Also, low tensile strength, susceptibility to sulphate and acid attacks can be considered as the negative sides. To solve these problems, several methods are implemented. For example: fibre reinforcements, employment of special cements against external chemicals attacks and coating. Even though it is added to the cement mixture in slight amounts due partially economic reasons, the properties are enhanced to the desired level [27]. The polymers can store as solution in water or in powder form that can be redispersed later.

The mechanical properties and durability are affected by the polymer especially. The latex polymer greatly increases the flexural strength of the cement concrete by creating polymer bonds between the aggregate and cement matrix and reducing the interfacial transition zone (ITZ). Furthermore, the polymer and cement create the organic-

inorganic bounds that results a composite matrix. These polymer-concrete bounds can be understand by various analytical methods, such as infrared spectroscopy, Nuclear Magnetic Resonance microscopy, and etc. [28].

The effect of polymer admixture can be noticed in mechanical properties of concrete and mortar. The flexural streght is the main benefactor of polymer admixture. The researches show that flexural strenght increases with the polymer content. However, the increase is not unlimited as the flexural strenght decreases after an optimum point. In some cases the compressive strength is increased along with raise in flexural strength [29]. In contrast, it is shown that the compressive strenght of mortar decreases if water curing is applied [30]. The study chemical reaction between polymer particles does not take part in water cuuring and prevent the formation of polymer layer. As a result, compressive strength of PMC is linked to the curing method. The toughness of concrete increases according to the researches, which shows boost in tensile strain with addition of polymer [31].

On the durability side, the result of the research on the effects of latex modification shows the performance of light weight concrete exposed to hostile environments was better than unmodified one [32]. The polymer also can reduce the internal stress that caused by the shrinkage and crack control because of its crack bridging [31]. The latex addition reduces the capillary voids and void sizes. The reduction in the voids leads to the less water absorption with increase in the polymer and therefore less chemical transportation into the matrix [32].

The workability, and therefore the flowability, of fresh concrete is another important factor for production and placement. In the case of polymer admixture, there is a controversy due to the type of the poylmer used in. In some types, an increase in flowability noticed, however, on the other a reduction is noticed. The research indicates that the reason behind the increase of flowability is water absorption of polymer which is less than its corresponded material in the paste, cement [29]. Other studies show similar increase in flowability with polymer content in fresh concrete[33][34]. In contrast, some studies found decrease in flowability with the polymer content [33][35]. To sum up, the type of polymer that used in the mixture affects the flowability and therefore the workability. [33].

# 3. EXPERIMENTAL STUDIES

**Properties of Materials**

Cement, barite and magnetite aggregates, micro and nano scale silica fumes, hyper superplasticizer, and polymer admixtures used in the scope of the thesis.

## 3.1 Binding Materials

### 3.1.1 Cement

In this study, fine ground CEM II 42.5 R white cement used. The cement has 379,8 $m^2/kg$ specific surface area and 3,14 kg/m3 density. The coarsest particle has 40 µm in diameter. The half of the cement particles were able under 11 µm in diameter, ten percentage 2.06 µm, and ninety percentage under 26 µm. In Table 3.1 and Fig. 3.1 the particle size distribution of cement particles and frequency of each size class and cumulative volume of particles smaller than shown size of CEM II 42.5 R white cement are given.

**Table 3.2 :** PSD of Cement.

| Particle Size (µ) | Volume Under (%) |
|---|---|
| 1 | 1 |
| 2 | 6.57 |
| 3 | 13.25 |
| 4 | 19.54 |
| 5 | 24.94 |
| 6 | 29.59 |
| 7 | 33.84 |
| 8 | 37.90 |
| 9 | 41.90 |
| 10 | 45.90 |
| 20 | 82.51 |
| 30 | 98.13 |
| 40 | 100 |

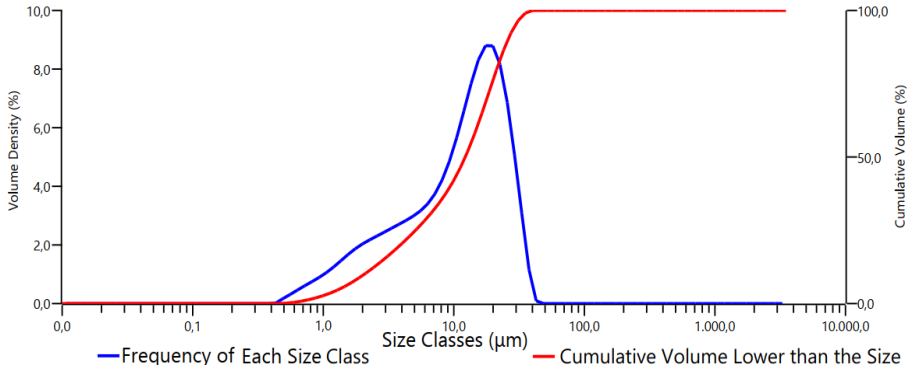


**Figure 3.1 :** Frequency of Each Classes and Cumulative Volumes Under Given Size of Cement.

### 3.1.2 Micro silica

The micro silica is a type of pozzolan used in the study with a density of 2,21 gr/cm$^3$. To simulate the effect of mechanical movement on the particle in mixing process, the micro silica particles are exposed to the vibration in duration of 15 seconds. 90% of the particles are under 20 microns accoridng to the given PSD of the material in Fig. 3.2.

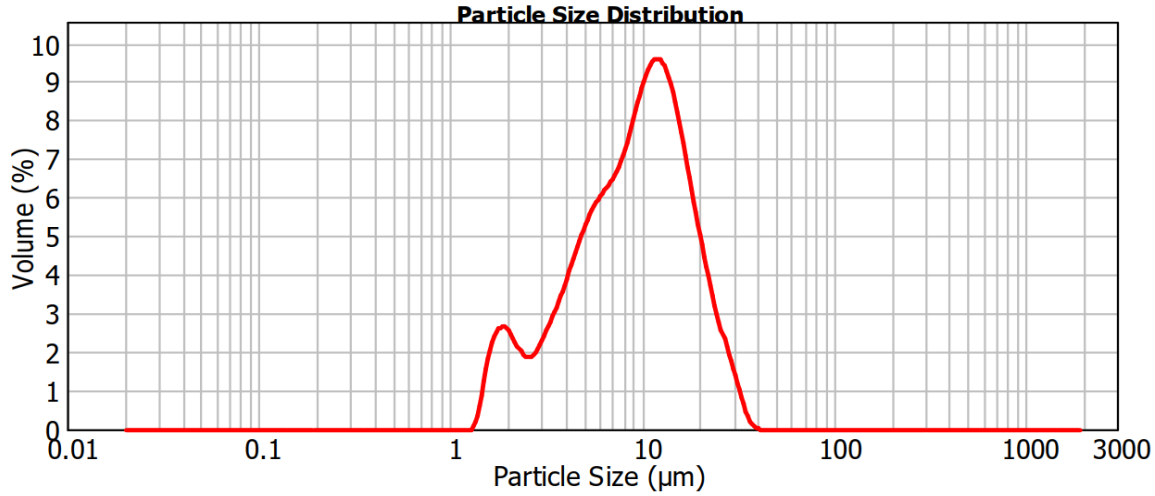


**Figure 3.2 :** PSD of Micro Silica.

### 3.1.3 Nano silica

The nano silica is a pozzolans that has particles in nano scale as its name suggests. It is the finest particle in the mixtures it was used. Due to its diluted form in water, it has only 1.3 gr/cm$^3$ density. Similar to the micro silica, nano silica particles were subjected

to vibration prior to the measurement. The PSD, cumulative distribution and frequency of each size class of the nano silica is given in Fig. 3.3.

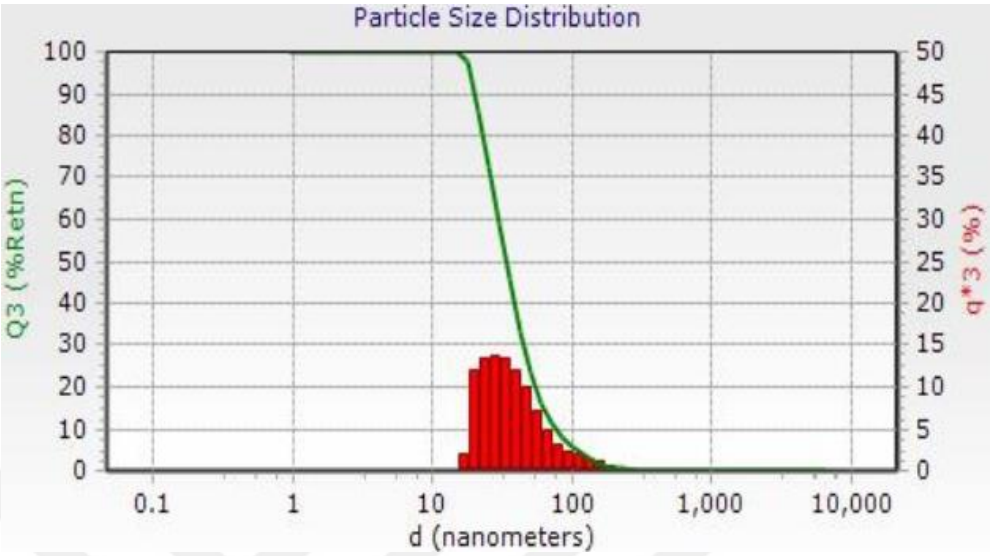


**Figure 3.3 :** PSD, Cumulative Distribution and Frequency of Each Class of Nano Silica Particles.

### 3.1.4 Aggregates

#### 3.1.4.1 Barite

Eight different size classes of barite have been used in the mixtures with different proportions. The particle distribution within each class is considered in a uniform distrubiton in size. The particle sizes and density of each class are given in the Table 3.2. In Fig. 3.4, the cumulative volume of each particle in given size is shown.

**Table 3.3 :** PSD and Density of Each Class.

| Class ID | PSD (micron) | Density, ρ ($g/cm^3$) |
|---|---|---|
| Barite 1 | 1-250 | 4,2 |
| Barite 2 | 1-355 | 4,2 |
| Barite 3 | 355-500 | 4,2 |
| Barite 4 | 500-710 | 4,2 |
| Barite 5 | 710-1000 | 4,2 |
| Barite 6 | 1000-1400 | 4,2 |
| Barite 7 | 1400-2000 | 4,2 |
| Barite 8 | 2000-3000 | 4,2 |

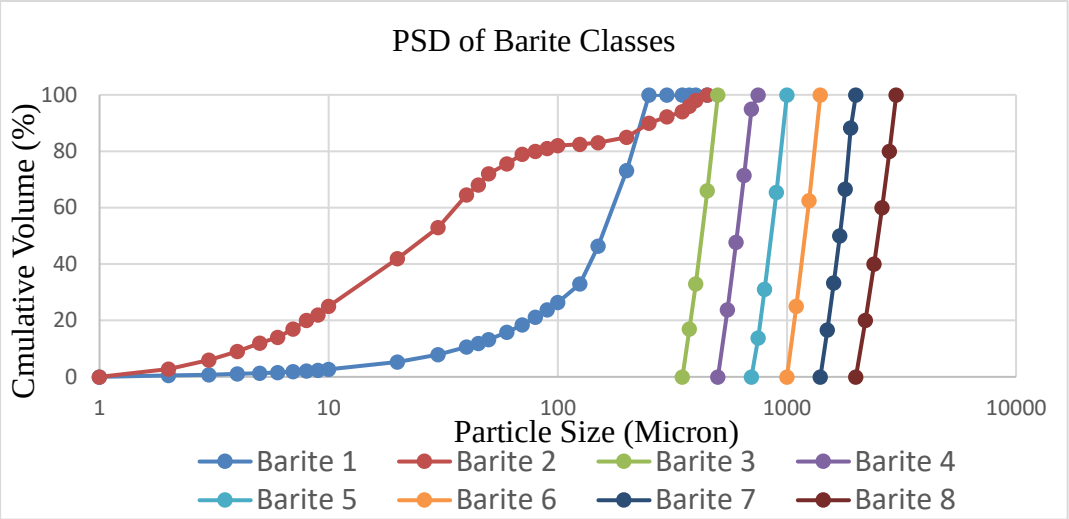


**Figure 3.4 :** PSD of Each Barite Class

### 3.1.4.2 Magnetite

Finely ground magnetite had used to increase the overall unit weight of concrete with its prominent 4.9 gr/cm3 density. The PSD and the frequency of each reflected size is given in Fig. 3.5.

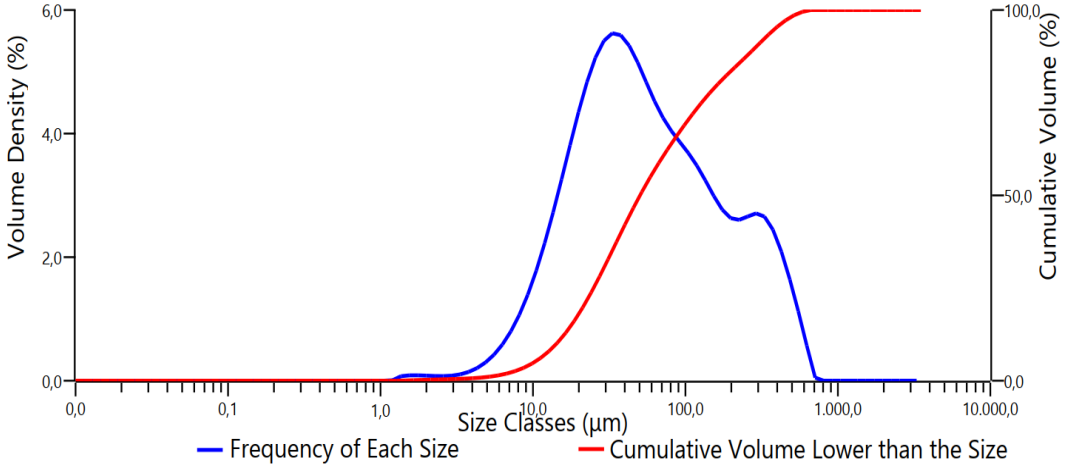


**Figure 3.5 :** Frequency of Each Classes and Cumulative Volumes Under Given Size of Magnetite.

### 3.1.5 Superplasticizer

In the study, a third-generation, hyper plasticizer admixture, HR50 [36] was used to increase the flowability and to reduce water demand. The admixture has 1.10 specific gravity with a 50% content of water.

### 3.1.6 Polymer

The bettolatex polymer [37] is a admixture with 1.05 density and its main purpose of usages are; lower permeability, increase in inter-bounding and increase of workability.

### 3.1.7 Mixing Water

Locally available potable water was used as mixing water in the study. In order to keep w/c ratio constant in polymer incorporated and polymer-free groups, the amount of water that polymer contains is required to reduce from the mixing water. Thus this amount of water in polymer admixture is calculated and same amount is removed from the mixing water.

## 3.2 Determination of Mixing Proportions of Mortars by Software

The PSD of each material was imported to the software EMMA [21]. Having been imported into the program, the materials are selected for the mortar recipe. Also, a spreadsheet was created in excel to compare the results. As mentioned earlier, the modified Andreassen method was applied to the mixture according to the PSD of each material. The mixture was adapted to the reference curve in order to reach the optimum packing. In Table 3.3, the materials that used in mixtures, size classes, and their densities are illustrated. Also in Table 3.4, the table of volumetric usage percentages in different mixtures can be seen.

**Table 3.4 :** Materials, Size Classes, and Densities.

| **Material ID** | **Size Class (micron)** | **Density, ρ ($g/cm^3$)** |
|---|---|---|
| Magnetite | 1-600 | 4.9 |
| Barite | 1-3000 (8 distinct size groups) | 4.2 |
| Micro silica | 1-30 | 2.21 |
| Nano silica | 0.02-0.24 | 1.3 |
| Cement | 1-40 | 3.14 |
| Mixing Water | - | 1 |

**Table 3.5 :** Volumetric Percentage of Usage of Materials in Each Group.

| Material | PS | PP | MS | MP | NS | NP |
|---|---|---|---|---|---|---|
| Cement | 17.99 | 17.88 | 18.20 | 18.08 | 17.95 | 17.84 |
| Magnetite | 7.33 | 7.29 | 7.42 | 7.37 | 5.23 | 5.20 |
| Barite | 49.51 | 49.22 | 48.24 | 47.92 | 50.62 | 50.32 |
| Mixing Water | 22.45 | 21.48 | 22.26 | 21.20 | 20.42 | 19.50 |
| Micro silica | - | - | 1.18 | 1.17 | 1.16 | 1.15 |
| Nano silica | - | - | - | - | 1.97 | 1.96 |
| Superplasticizer | 2.72 | 2.71 | 2.70 | 2.68 | 2.66 | 2.65 |
| Polymer | - | 1.42 | - | 1.58 | - | 1.39 |

It can be seen in Table 3.5, the volumetric percentage of cement particles are relatively fixed approximately to 18%.

**Table 3.6 :** Weight Percentage of Usage of Materials in Each Group.

| Material | PS | PP | MS | MP | NS | NP |
|---|---|---|---|---|---|---|
| Cement | 17.34 | 17.30 | 17.64 | 17.60 | 17.44 | 17.41 |
| Magnetite | 11.03 | 11.01 | 11.23 | 11.20 | 7.93 | 7.91 |
| Barite | 63.82 | 63.70 | 62.54 | 62.40 | 65.81 | 65.68 |
| Mixing Water | 6.89 | 6.62 | 6.87 | 6.57 | 6.32 | 6.05 |
| Micro silica | - | - | 0.80 | 0.80 | 0.79 | 0.79 |
| Nano silica | - | - | - | - | 0.79 | 0.79 |
| Superplasticizer | 0.92 | 0.92 | 0.92 | 0.91 | 0.91 | 0.90 |
| Polymer | - | 0.46 | - | 0.51 | - | 0.45 |

In Table 3.6, the weight of each material group is given by its percentage.

In Fig. 3.6 and Fig 3.7, the optimization curves and PSD of mixture are shown together.

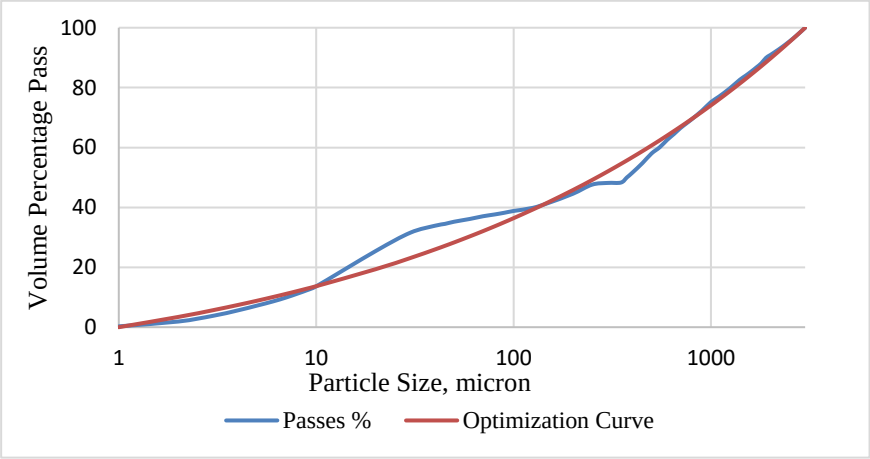


**Figure 3.6 :** Optimization Curve for PS, PP, MS, and MP q=0.22 with 1 micron minimum and 3000 microns maximum.

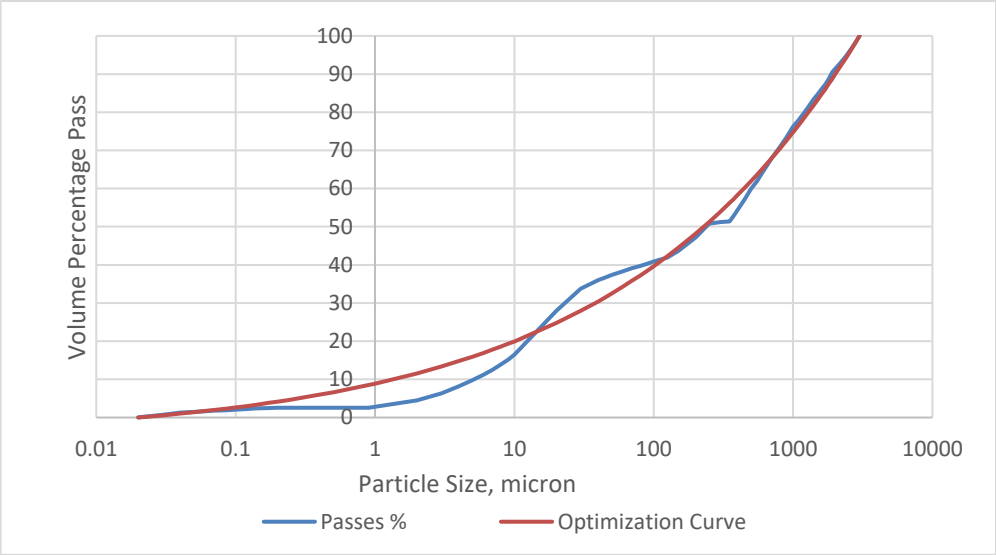


**Figure 3.7 :** Optimization curve for NS and NP q=0.25 with 0,01 micron minimum and 3000 microns maximum.

### 3.3 Production and Casting of Mortar Sample Groups

The required mortars were produced in mortar mixers in the laboratory of construction materials of ITU. The mortar was mixed according to the TS-EN 196-1 [38]. Six different sample groups were determined and produced. Each group was made of three samples. The sizes of samples were 4x4x16 cm3 with a shape of a rectangular prism. The apparatus of the mould is shown in Fig. 3.8. The codes and definition of the codes are given in Table 3.6.

**Table 3.7 :** Group Codings and Definements.

| Group Code | Code Definement |
|---|---|
| PS | Pozzolan Free with Superplasticizer Admixture |
| PP | Pozzolan Free with Superplasticizer Admixtures, and Polymer |
| MS | Micro silica and Superplasticizer Admixtures |
| MP | Micro silica, Superplasticizer Admixtures, and Polymer |
| NS | Micro silica, Nano silica and Superplasticizer Admixtures |
| NP | Micro silica, Nano silica, Superplasticizer Admixtures and Polymer |


**Figure 3.8 :** Mortar Specimens in Mold

## 3.4 Testing Procedures

### 3.4.1 Fresh Concrete Tests

The fresh concrete tests are conducted while the concrete was still unset. Since the aim was to produce self-compacting mortar, unit weight and spread of mortar were tested in the fresh state.

#### 3.4.1.1 Slump Flow Test

The slump flow test is appropriate for the SCC rather than the slump test. The reason can be explained as the effectiveness of superplasticizers on the concrete or mortar to have high flowability. The flow tests were conducted according to the guidance of the TS EN 1170-1 [39]. Numerous pieces of equipment are required for the test. The most crucial is a tube that has specific requirements for the measurements and materials. The tube should have a smooth surface and made of a metal or plastic material. The dimensions must have 55 mm height and 57 mm inner diameter with an external diameter no less than 65 mm. For measurement of the samples, a smooth plate with larger than 300x300 mm length and wide used. In Fig 3.9, the photo of tube that used for flow test is shown.

For the procedure, the plate was placed to create a plain space the sample can spread evenly without any obstruction. The tube and the plate are cleaned prior to the test with a wet towel to moisturize the surfaces. Then the tube was placed on the centre of the plate. A volume of concrete that was sufficient to fill the tube was filled in with mortar and the excess amount was taken. After waiting a span of a couple of seconds for the release of entrapped air in the sample, the top surface was flattened. Following these, the tube was lifted slowly to allow mortar to spread. After thirty seconds of wait, the spread was measured. In this study, the spread value of the mortar was aimed to be more than 175 mm in diameter.

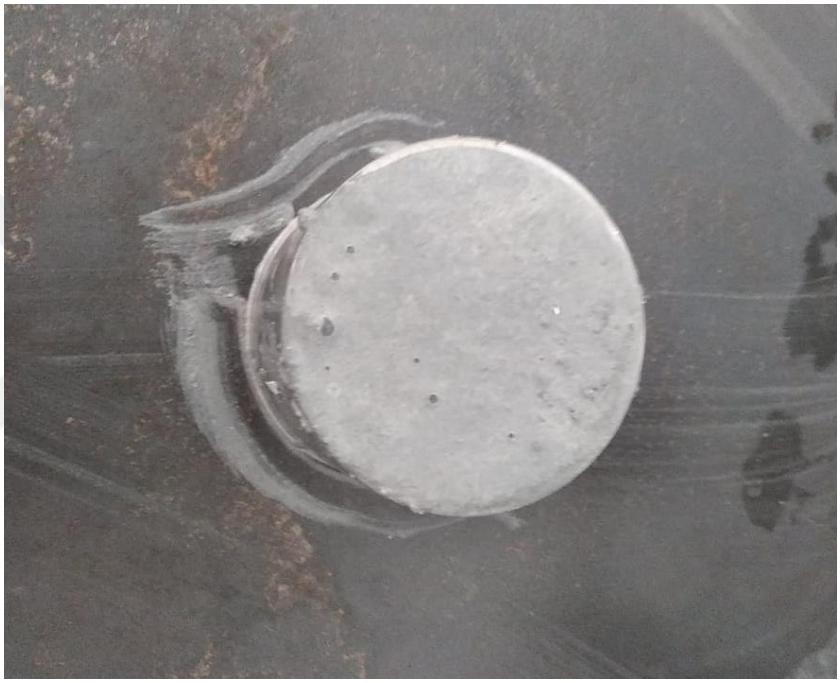

**Figure 3.9 :** Test Apparatus with Mortar to be Tested

### 3.4.1.2 Trials for highest unit weight in fresh state

For this test, a container with premeasured volume of 393 $cm^3$ and weight of 61 gr was filled with mortar. Then the weight of the container was measured with a 0.01 gram error. To calculate the unit weight, the net weight of mortar was divided by the premeasured volume of the container. To increase the precision, the container should be filled with mortar till the top and the surface should be flat.

In order to reach heavyweight mortar objective, the unit weight must be higher than minimum limitation as the water evaporetes and leaves the matrix with voids.

### 3.4.1.3 Calculation of packing density

The packing density is the volume ratio of solid particles to total volume. The method that was used to calculate the packing density named wet packing which was developed by Wong and Kwan [40]. The mixtures were made according to Modified Andreassen method outputs. Following the mixing process, the mixtures were measured for their unit weights. Then with the addition of water and therefore with a higher water to cement ratio, the measurements continued to notice the highest unit weight possible. In order to calculate the packing density, the measured water amount, and other liquid content, the total volume of liquid were computed [41]. Since the extraction of liquid volume from total volume leads to the solid volume, the division of this volume to total volume yielded the packing density.

### 3.4.2 Hardened State Experiments

Hardened state tests were conducted after 28 days of the production of the mortar. During these 28 days, the samples were cured in the air till set. Following the set, samples were transferred to the water pools till the end of 28 days. After drying one day at a stable room temperature to reach surface dry conditions, the tests were carried out.

### 3.4.2.1 Three-point flexural test

The three-point flexural test is a method which can be used for the determination of the tensile strength of the concrete in an indirect approach. For the procedure, the sample places on the machine which can be seen in Fig. 3.10.

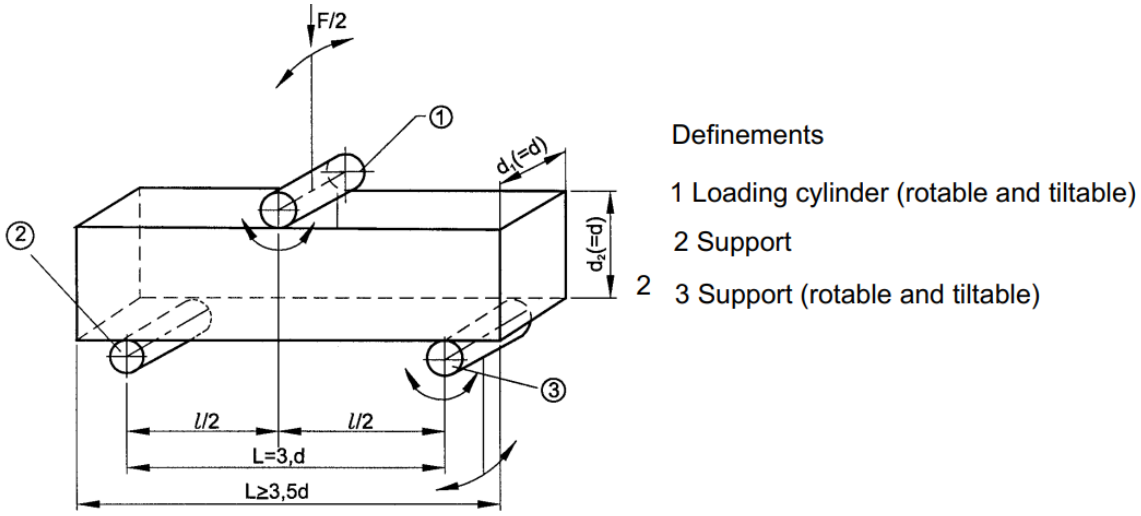


**Figure 3.10 :** Test sample loading device [42].

The symbols of Fig. 3.10 are $d_1$, $d_2$ for the width and height of the sample in mm, F/2 is the half value of the load in N, and L is the distance between supports in mm.

For the test, after being surface dried, the samples are smoothened on the surface to obtain correct results. Then the 40x40x160 mm samples are placed on the test mechanism one at a time. Later the sample was tested according to the ASTM C78 [43] standard, the test speed was chosen 0.2 mm/min to keep the stress between the boundaries. All of the samples were loaded until the failure of the material and results were noted. In Fig 3.11, the device with a sample is illustrated.


**Figure 3.11 :** Three-point flexural test.

### 3.4.2.2 Compression test

The compression test is a method to evaluate the limitations of the material. The materials for this test should be in the shape of a cube, cylinder, or drilling core. The samples are placed in the hydraulic compression machine and bear the load to its limits. By dividing the peak load by the area under the load, the stress that the material can handle calculated. In the research, after the flexural test, the broken samples were subjected to the compression test. The tests were conducted in accordance with the instructions of TS EN 12390-3 [44]. Test device is shown in the Fig. 3.12.


**Figure 3.12 :** Compression Test.

### 3.4.2.3 Unit weight test for dry samples

The unit weight test in dry state is the method to decide the weight class of the concrete or mortar. Since the aim was creating a heavyweight mortar, the samples have to be tested after evaporation of free water in pores of the mortar. To gather the data, one failed sample each group, 12 pieces of 6 samples in total, of the flexural test was placed in the oven to reach oven-dry samples. After waiting 40 hours in 70 degrees celcius oven, the samples were taken out to cool down to the room temperature. Having been cooled down, samples are named and taken to weighting machine with relative error of 0.1 gr. Each part of the samples are weighed seperately and collectively and dimensions are measured. Dividing the weight by the volume, unit weight in the oven-dry state was calculated.

### 3.4.2.4 Capillarity test

The test of capillarity is a method that is used to determine the capillary voids of concrete or mortar. The materials that are placed in water would absorb the water in these voids. As a consequence, the weight of the material will increase over time. The amount of absorbed water indicates the existence and volume of the capillary voids. To measure the weight change, samples are weighed in predetermined periods. Therefore the sorptivity, also known as capillarity coefficient, can be calculated.

In experiments, previously oven-dried and weighed twelve sample pieces are sealed with paraffin film on sides to avoid water contact except for the base 40x40 $mm^2$ area. Then the pieces measured for their weight for the initial mass. The procedure carried out conforming to TS EN 480-5 [45], and ASTM C1585-20 [46]. After the measurement, each piece located in the shallow water no more than 50 mm one by one with a time span between them. Each specimen measured at 5, 10, 15, 20, 25, 30, 45, 60, 120, 180, 240, and 1440 minutes. The data collected for each piece and transferred to excel.

In the calculation part, the following equation is used.

$$\boldsymbol{Q = k\sqrt{t}} \tag{2.3}$$

Where the Q is the amount of the water that absorbed in from a unit area, t is the time in seconds, and k is the coefficient of the capillarity.

The transferred data has placed in to the spreadsheet. Then the mass change of each sample is calculated and divided by the area that absobs water. The result gives the water absorption by unit area. Following these calculations, also the square root of the time is computed. Afterwards, a graphic with square root of time on the X axis and absorbed water on the Y axis is created based on the spreadsheet and a trendline generated from the data. The slope of the trendline gives the k, the coefficient of capillarity.

# 4. RESULTS and DISCUSSION

In this section, the results of the tests that applied on the sample groups, which can be seen in Table 4.1, is given.

**Table 4.1 :** Group Codings and Definements.

| Group Code | Code Definement |
|---|---|
| PS | Pozzolan Free with Superplasticizer Admixture |
| PP | Pozzolan Free with Superplasticizer Admixtures, and Polymer |
| MS | Micro silica and Superplasticizer Admixtures |
| MP | Micro silica, Superplasticizer Admixtures, and Polymer |
| NS | Micro silica, Nano silica and Superplasticizer Admixtures |
| NP | Micro silica, Nano silica, Superplasticizer Admixtures and Polymer |

## 4.1 The Results of Fresh Mortar Tests

### 4.1.1 Flow Test

In the flow test the expected results are, as mentioned earlier, 175 mm or higher after 30 seconds of the release of mortar from the container tube. The results of each group are illustrated in Table 4.2 and Fig. 4.1.

**Table 4.2 :** Flow Values of Fresh Mortar of Each Groups.

| Group Code | Slump Flow Values (mm) |
|---|---|
| PS | 192.5 |
| PP | 185 |
| MS | 195 |
| MP | 172.5 |
| NS | 190 |
| NP | 172.5 |

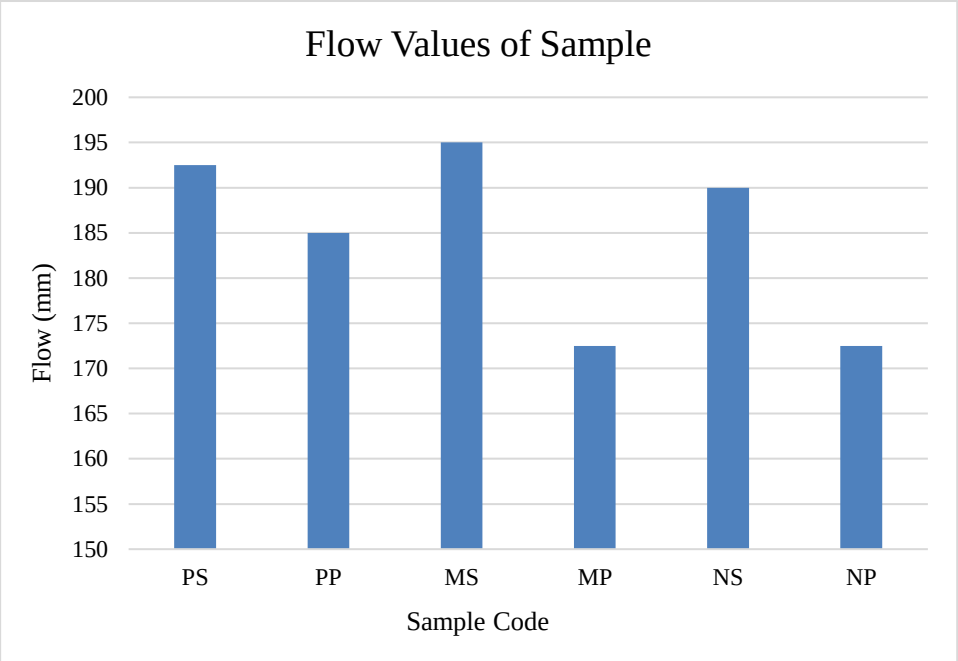


**Figure 4.1 :** Slump Flow Values of Samples.

When the test results are examined, the outcomes show that two-third of the sample groups obtained the expected or higher flowability. The mixtures had an identical superplasticizer to cement ratio of 0.05 in all sample groups. The highest flowability observed in the MS group and lowest in MP and NP groups.

The groups of MP and NP that did not attain the desired 175 mm, their spread had 172.5 mm. The value of 172.5 mm is reasonably high, even though still under the aim value.

As the polymer admixture is diluted with water, it contains water that cannot be ignored. This water in the polymer admixture is excess and increases the amount of water in mixture, therefore raises w/c ratio. In order to keep the water ratio constant in the mixture and to keep the w/c ratio consistent with the polymer free variations, the amount of water should be reduced. Thus, this amount of water in polymer admixture is calculated and same amount is removed from the mixing water. By doing so, the w/c ratio kept uniform in variations. As the solid ratio increases due to the solid particles of polymer and mixing water amount decreases, the reason behind the reduction in flowability can be due to this reason.

In the case of pozzolan admixtures, no significant differences observed between the samples.

### 4.1.2 Unit Weight Test

The unit weight of the fresh mortar was measured in a pre-weighed container prior to the placement of mortar into the molds. The results of the test are demonstrated in Table 4.3 and Fig. 4.2.

**Table 4.3 :** Unit Weights of Each Group in Fresh State.

| Group Code | Unit Weight (g/cm$^3$) |
|---|---|
| PS | 3.15 |
| PP | 2.98 |
| MS | 3.15 |
| MP | 2.94 |
| NS | 3.08 |
| NP | 2.93 |

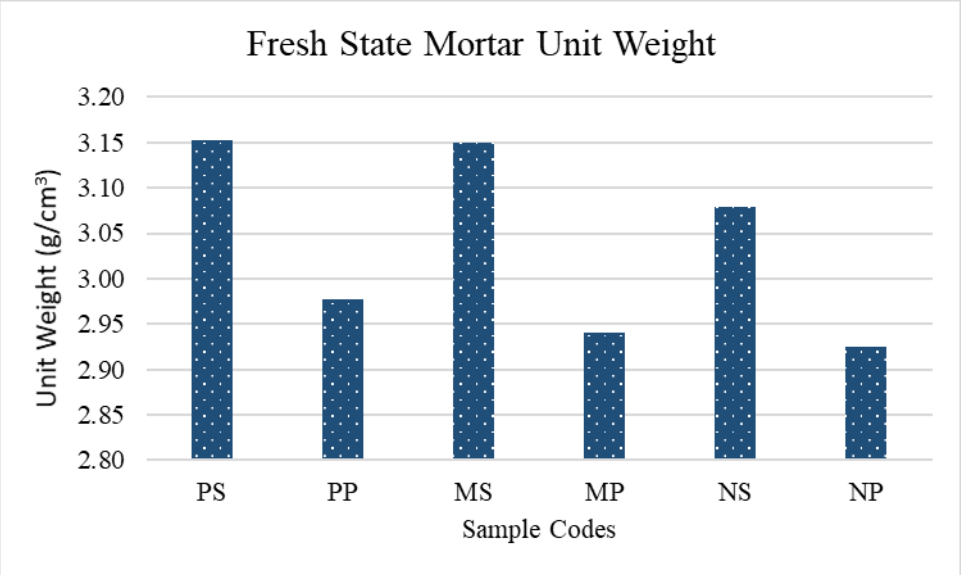


**Figure 4.2 :** Frest Mortar Unit Weight's of Samples.

The results of the unit weight test in the fresh state showed that the polymer admixture decreases the unit weight in general. This phenomenon is occurred due to the low density of the material. As the non-polymer added mixture content is the same except polymer containing one, the polymer particles replace the materials in mortar. This results in a lower unit weight of mortar.

On the pozzolana side, the pozzolan-free and micro silica added sample had the highest unit weights among all. The nano silica and micro silica containing NS group showed slightly lower unit weight which could be the result of the volume that low density of micro silica and nano silica, 2.21 and 1.3, respectively, occupied.

### 4.1.3 Packing Density

The packing densities were calculated by dividing the solid volume by total volume in the fresh state of mortar. Table 4.4 and Fig. 4.3 show the results.

**Table 4.4 :** Packing Densities of Sample Groups.

| Group Code | Packing Density |
|---|---|
| PS | 0.748 |
| PP | 0.750 |
| MS | 0.750 |
| MP | 0.752 |
| NS | 0.754 |
| NP | 0.755 |

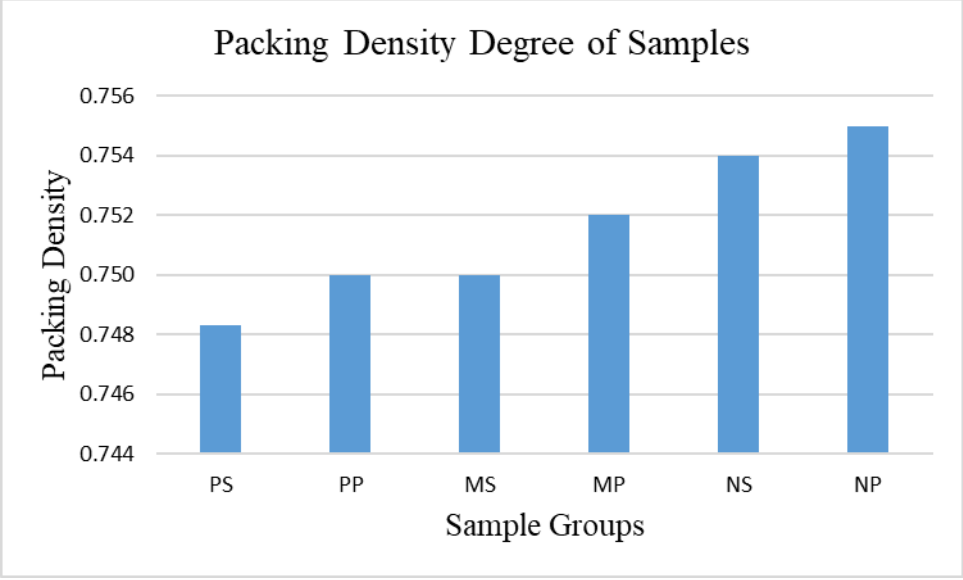


**Figure 4.3 :** Packing Density of Sample Groups.

The calculated packing densities were slightly higher in the polymer containing mixtures. The results can be linked to the particles of polymer that occupies the volume which were otherwise filled with liquids. Moreover, the degree of packing density

increases with the pozzolanic admixtures. Having been smaller in particle size, the silica fumes functioned as fillers and expanded the volume of solid particles in total volume. The best result was observed in the NP groups which contains not only silica fine admixtures but also the polymer.

## 4.2 The Results of the Hardened Mortar Tests

### 4.2.1 Three-Point Flexural Strength Test

3 specimen of each sample was subjected to flexural testing. The average values of the results are given below in Table 4.5 and Fig. 4.4.

**Table 4.5 :** Average Flexural Strenght of Sample.

| Group Code | Average Flexural Strenght (MPa) |
|---|---|
| PS | 3.47 |
| PP | 3.66 |
| MS | 3.55 |
| MP | 4.99 |
| NS | 3.41 |
| NP | 4.74 |

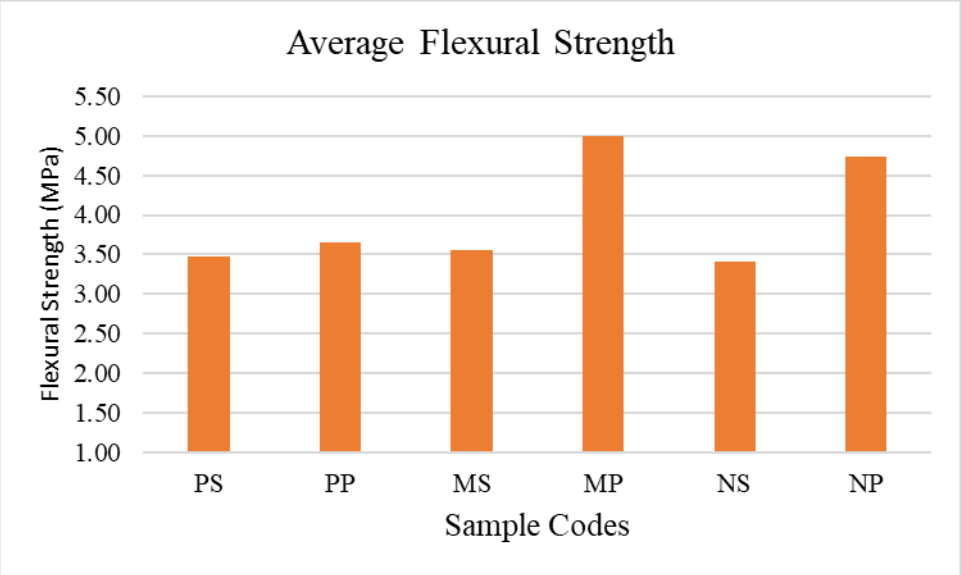


**Figure 4.4 :** Average Flexural Strength of Samples with Test Speed 0.2 mm/min.

The test results showed that the PP, MP, and NP had better flexural strength than their counterparts, PS, MS, and NS, respectively. As it was observed in the results, the admixture of polymer increased the flexural strength in general. This trend in polymer addition is noticeable in M and N series than the in the P groups. This enhancement in flexural strength is also recognized by researchers [19], [37]. The reason behind it can be the result of the even distribution of polymer particles in the matrix in the fresh state that later caused the creation of a continuous chemical bond between polymer particles [32]. Moreover, a slight increase in the MS group is noticed which can be linked to the effect of micro silica.

### 4.2.2 Compressive Strength Test

Two of the three specimens in each sample, totally 12 pieces, which were tested till material failure, taken to compressive test. The outcomes are shown in table 4.6 and Fig. 4.5.

**Table 4.6 :** Average Compressive Strenght of Samples.

| Group Code | Average Compressive Strenght (MPa) |
|---|---|
| PS | 56.28 |
| PP | 43.55 |
| MS | 65.68 |
| MP | 50.18 |
| NS | 60.33 |
| NP | 50.53 |

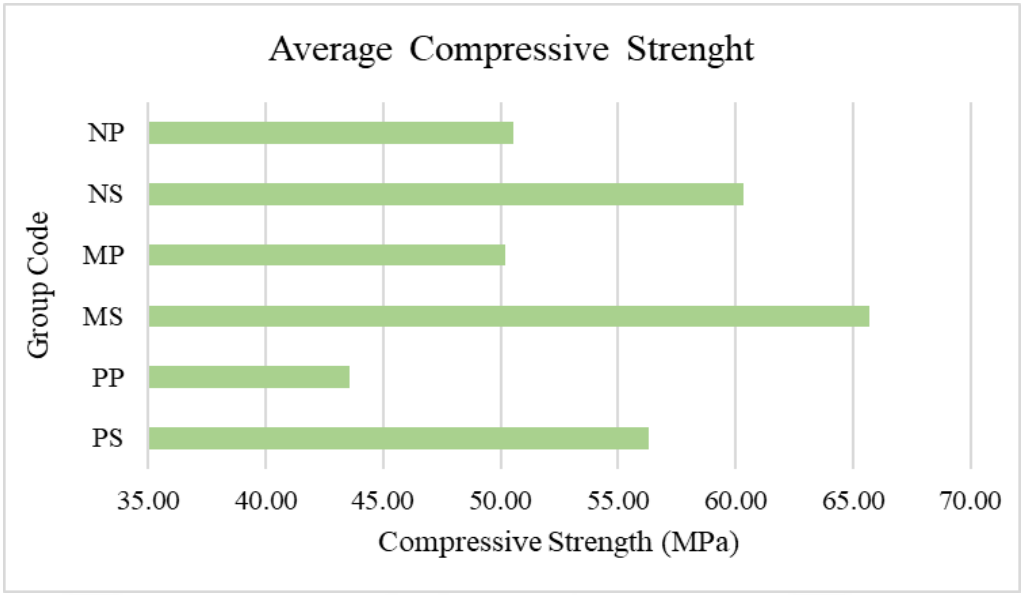


**Figure 4.5 :** Average Compressive Strength of Samples

When the test results are analysed, the two following outcomes can be made.

First of which is the effect of silica fumes on the mortar. In both M and N groups have higher strength than the P groups. The impact was the result of the pozzolanic reaction in the mortar that bonds free calcium and forms C-S-H crystals. Therefore, the increase in the strength is a direct result of the pozzolan admixtures [38].

On the other hand, the polymer introduced groups showed lower strength than polymer-free groups. In the research of A. Parghi and M. Shahri Alam [23] similar results were reported for water cured specimens for 28 days. They argued that the reason of the decrease in the compressive strength results are due to the presence of water curing applied. For instance, the cement continues its hydration in wet curing, conversely, the same ambient of wet curing prevents polymer particles to create a chemical bond and therefore a film in the matrix.

### 4.2.3 Unit Weight Test

The specimen that did not involve the compression test after the flexural test were taken to the oven to stay 40 hours at 70 degrees to reach oven-dry weight. Afterward, the samples were weighed separately and collectively with their partners, respectively. The results are illustrated in Table 4.7 and Fig. 4.6 below.

**Table 4.7 :** Unit Weights of Oven-dry Specimen.

| Group Code | Oven-dry Unit Weight (g/cm$^3$) |
|---|---|
| PS | 3.02 |
| PP | 2.87 |
| MS | 3.11 |
| MP | 2.95 |
| NS | 3.13 |
| NP | 2.85 |

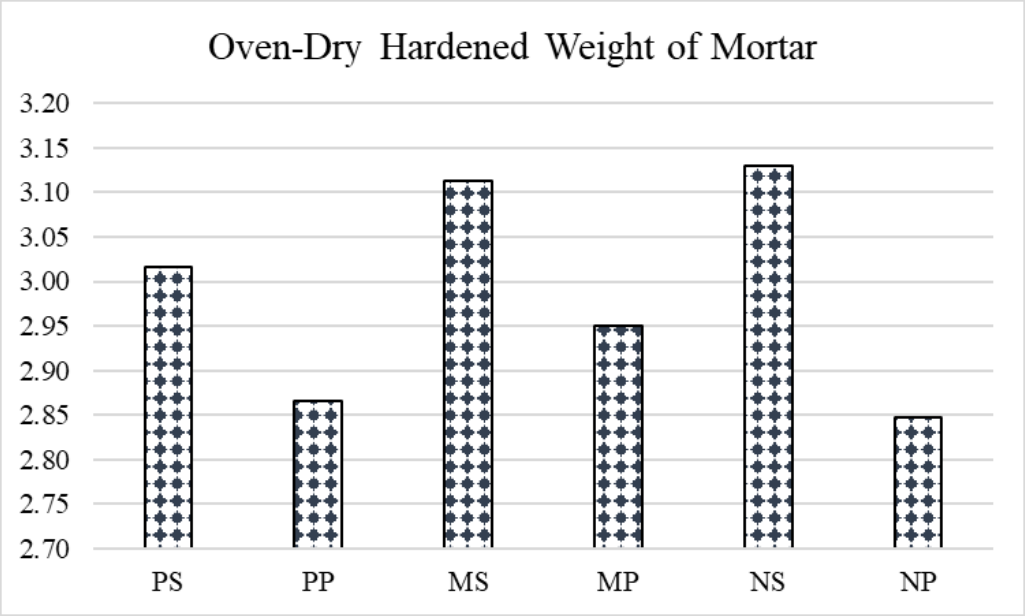


**Figure 4.6 :** Oven-dry Unit Weights of Samples.

Two considerable differences among groups were observed. Firstly, the polymer admixture used groups show lower unit weight than polymer-free groups, the direct result of the low density of polymer admixture.

Secondly, the groups with mineral admixtures showed higher unit weight. The reason behind this is the higher packing density of these groups and therefore increased solid volume. As micro and nano silicas are smaller to fill the voids, the solid ratio is higher in these groups. Therefore, the porosity is expected to be lower in M and N groups.

### 4.2.4 Water Absorption

2 oven-dried specimen pieces of each group were placed in shallow water. The average test results are given in Table 4.8 and Fig. 4.7.

**Table 4.8 :** Average Capillarity Coefficient of Sample.

| Group Code | k (mm/min$^{0.5}$)*10$^{5}$ |
|---|---|
| PS | 2,98570 |
| PP | 3,69700 |
| MS | 2,19040 |
| MP | 0,70620 |
| NS | 0,74920 |
| NP | 0,80342 |

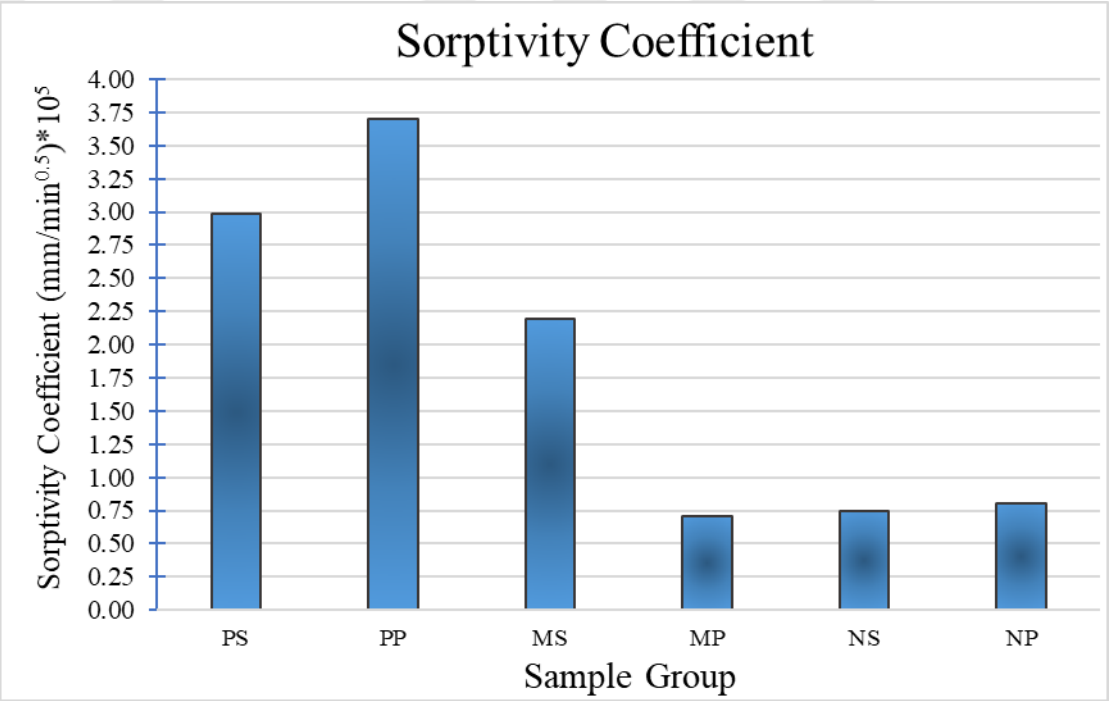


**Figure 4.7 :** Average Sorptivity (Capillarity) Coefficient of Sample Groups.

The aim water absorption test is to have an understanding of the capillary voids of the material. The capillary voids are generally within the range of 0.1 microns to 2.5 mm in size. Such voids affect the durability and strength of the mortar. The capillarity coefficient is an approach to calculate the volumes of the capillary voids. The higher the coefficient is, the higher the numbers and volume of voids are. [47]

The results show that the increase of mineral admixture reduces the water absporbtion, and therefore, the capillary voids in mortar regardless of polymer availability. In this situation, the finer particles of micro silica and later nano silica reduced the voids by

their reactions. The pozzolans worked as binders in this case and filled the gaps with hydration products. Therefore a reduction in the coefficient of capillarity with pozzolan presence was observed.

On the other hand, polymer admixture showed differences regarding to groups. For example, in pozzolan free groups, a slight deteriotion is observed between PS and PP. Although the change in coefficient is not significant between these groups. In the case of micro silica groups of MS and MP, the development is significant. Capillarity coefficient is fairly lower in polymer containing MP than MS. Separately from micro silica containing groups, the nano silica groups showed comparable results to pozzolan-free MS and MP regarding the reduction in the coefficient.

## 5. CONCLUSIONS

In the scope of this study, the effect of the packing density method of modified Andreassen on self-compacting heavyweight mortars is investigated. To this extend, three main sample groups, each containing two sub-groups, were designed to observe the impact of such the method. The sample groups were designed in accordance with the guidelines of Emma software [21]. The exponential q of the model was selected between 0.22-0.25 to obtain a self-compacting mortar. The size limitations were set according to the PSD of materials.

The results showed an increase in the packing density with the increase of both silica fume and nano silica addition. This can be explained by the fine size distribution of such materials. As micro silica's PSD is finer than cement's PSD and nano silica's PSD is incomparable smaller than cement, the particles fill the voids in the matrix and increase the solid ratio in equal volume. Also, the polymer addition increases the packing density thanks to its small-scale particles.

The flowabilities of the polymer-free PS, MS, and NS groups were over 190 mm. In contrast to this, the polymer-containing samples showed lower flowability. However, the results were immediate proximity to the designated 175 mm. Overall, the flowabilities of groups were sufficient. The reason behind the inferior flowability can be caused by the polymer. The type of the polymer affect the flowability properties of the mixture that used in.  water as the water in polymer and nano silica were deducted from it.

In the case of unit weight, which is crucial to reach heavyweight standards, the fresh state and oven-dry state results show parallelism. The existence of silica fumes affects the unit weight especially in oven-dry specimen than the fresh state. The highest unit weight is identified in PS and MS groups, whereas MS and NS were observed as the highest in the oven-dry specimen. The polymer including groups showed lesser unit weights in both fresh and oven-dry states.

Compressive stregth was found higher in pozzolan including specimen than non-pozzolanic PS and PP. The reason behind the increase can be the pozzolanic reactions.

Moreover, the samples containing polymer admixture showed lesser compression strength than their non-polymer designs. As mentioned before, the water curing does prevent or decelerate the formation of the polymer layer by polymer particles which would have enhance the compressive strength than current state.

Coefficient of capillarity is on the other hand, a method to determine the capillary voids of the matrix. The results suggest that the polymer presence in mortar decreases the coefficient in micro silica groups but increase in pozzolan free and nano silica containing groups. The of the polymer admixture in the heavyweight mortar shows contradictory results. It appears that the capillarity decreases in the micro silica containing groups with the polymer addition, however, with same addition, the capillarity increases in pozzolan-free and nano silica groups.

The controversy could be caused by the difference in the polymer layer's formation in case of micro silica containing designs, however, there is no significant change in the nano silica group regardless of polymer addition. Also, in pozzolan free groups, the variation with the polymer addition showed higher capillarity coefficient than poylmer free one.

In general, the overall sorpivity decreased with the pozzolan admixtures. The pozzolanic reactions could be behind the reason of the diminished sorpivity. The output of the reactions decrease the voids and therefore the capillarity coefficient. In overall, the mineral admixtures diminished the porosity and therefore the capillary voids. For clearification on the effect of both polymer and mineral admixtures, more research and data will be beneficial in future studies.

In order to sum up, it can be expressed that the sample groups of PP, MP, and NP showed better properties regarding the packing density, and flexural strength. The property regarding the water absorption illustrated unstable change in capillarity coefficient between polymer-free and poylmer containing groups. The lowest coefficient observed in the MP while highest in the PP groups. In general, water absorption decreased in the micro silica and nano silica groups. On the other hand, PS, MS, and NS showed higher unit weight in both fresh and hardened states, greater flow value, and compressive strength.

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## APPENDICES

**APPENDIX A:** Capillary Water Absorption Test

## APPENDIX A

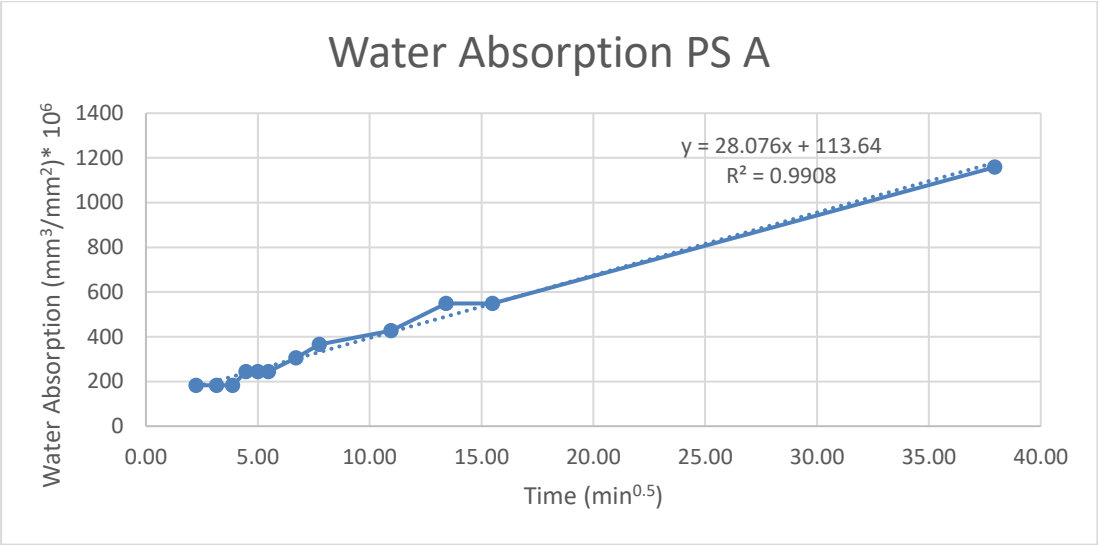


**Figure A.1 :** Graphic and Equation of the Capillarity Coefficient of PS A

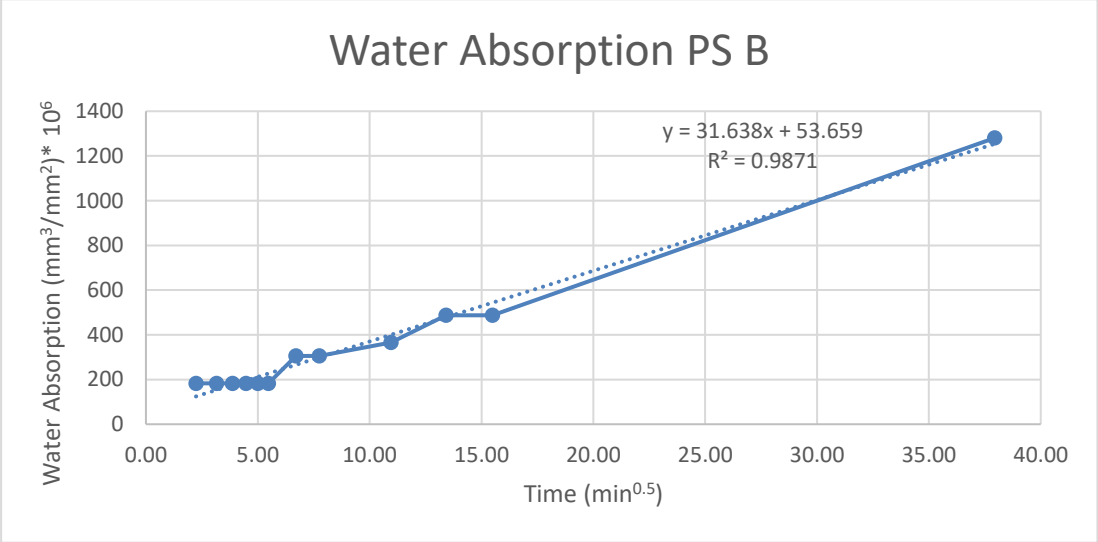


**Figure A.2 :** Graphic and Equation of the Capillarity Coefficient of PS B

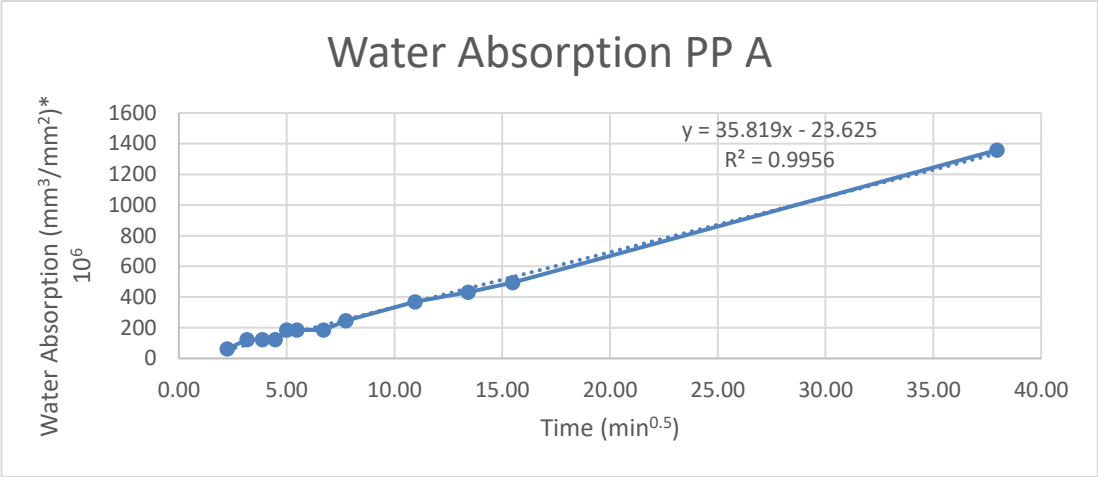


**Figure A.3 :** Graphic and Equation of the Capillarity Coefficient of PP A

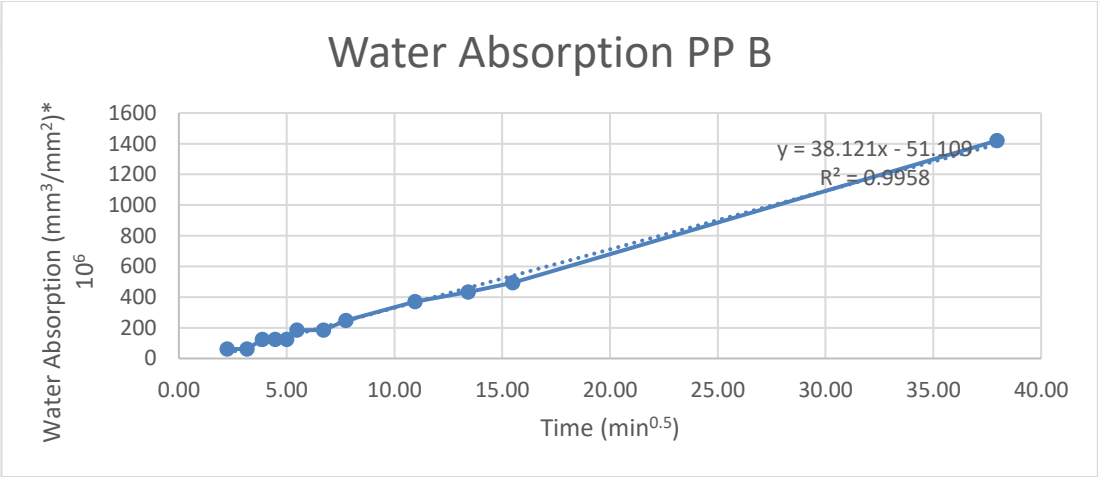


**Figure A.4 :** Graphic and Equation of the Capillarity Coefficient of PP B

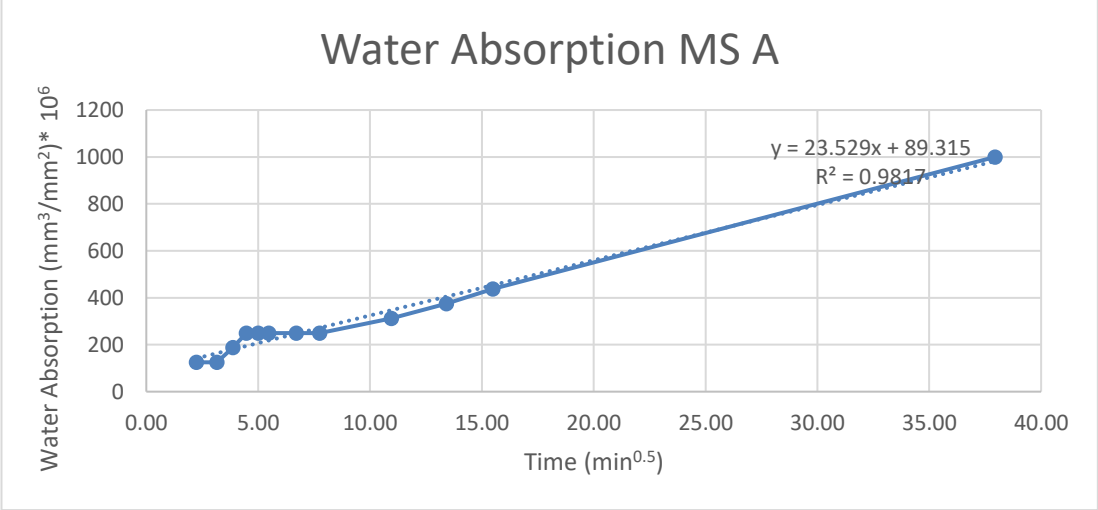


**Figure A.5 :** Graphic and Equation of the Capillarity Coefficient of MS A

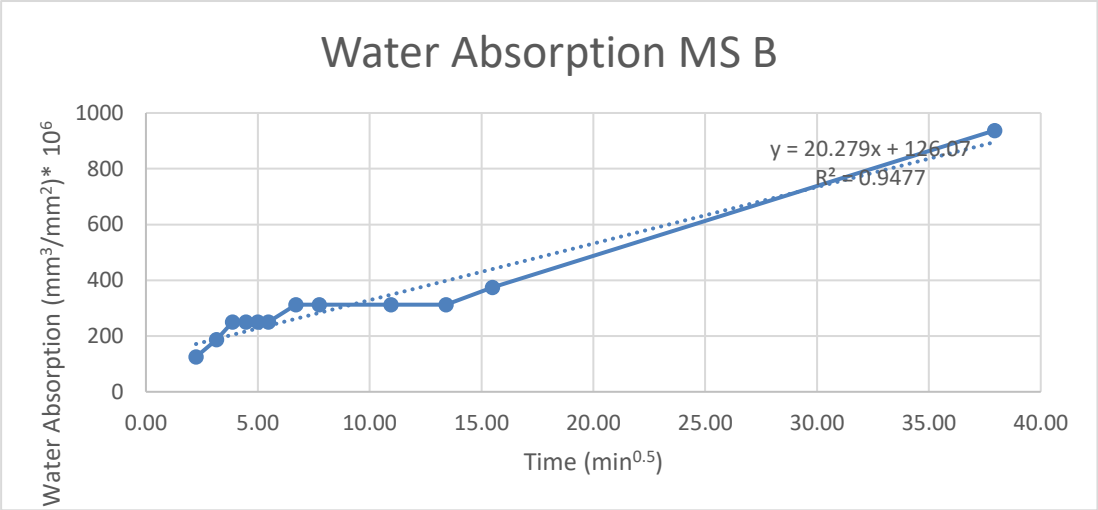


**Figure A.6 :** Graphic and Equation of the Capillarity Coefficient of MS B

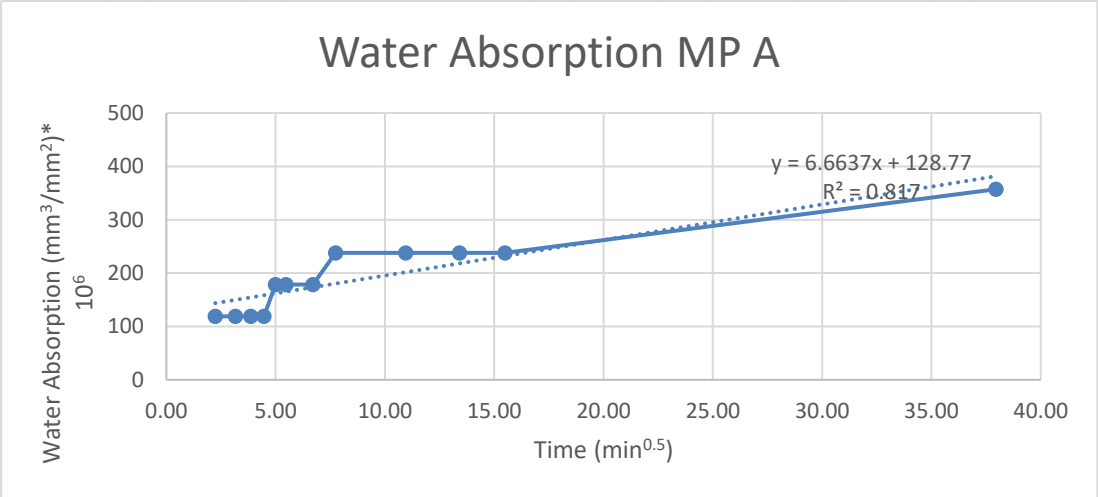


**Figure A.7 :** Graphic and Equation of the Capillarity Coefficient of MP A

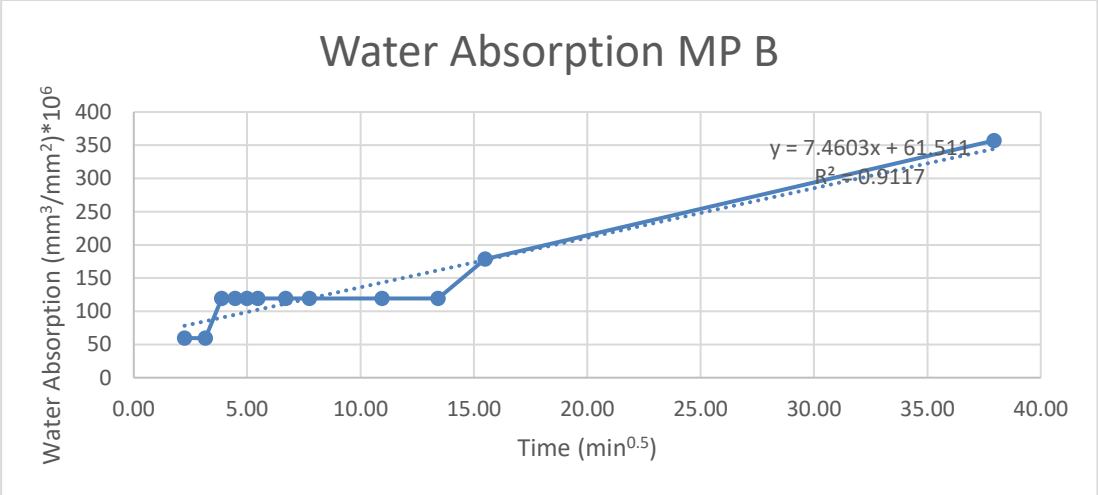


**Figure A.8 :** Graphic and Equation of the Capillarity Coefficient of MP B

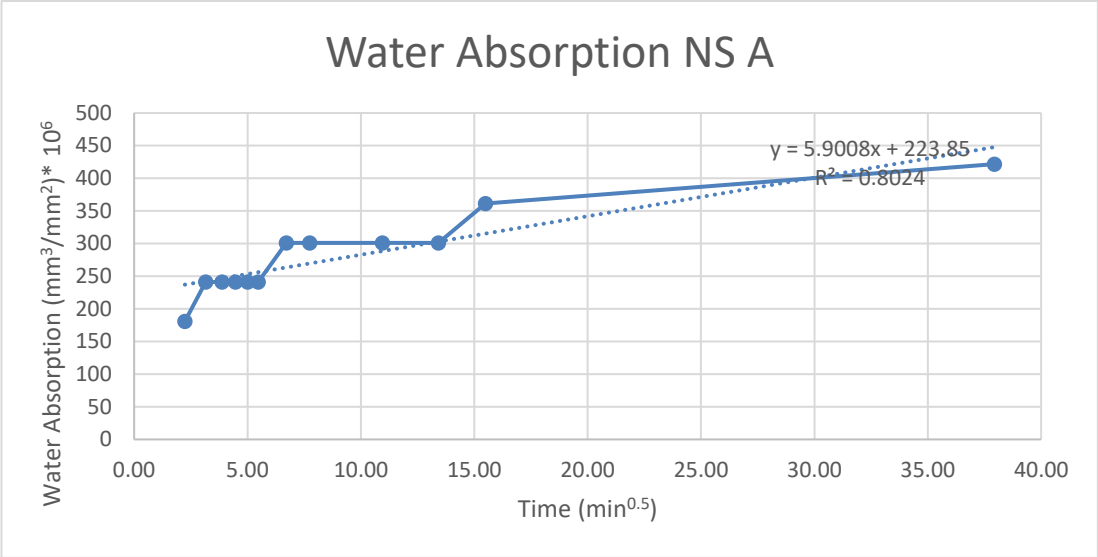


**Figure A.9 :** Graphic and Equation of the Capillarity Coefficient of NS A

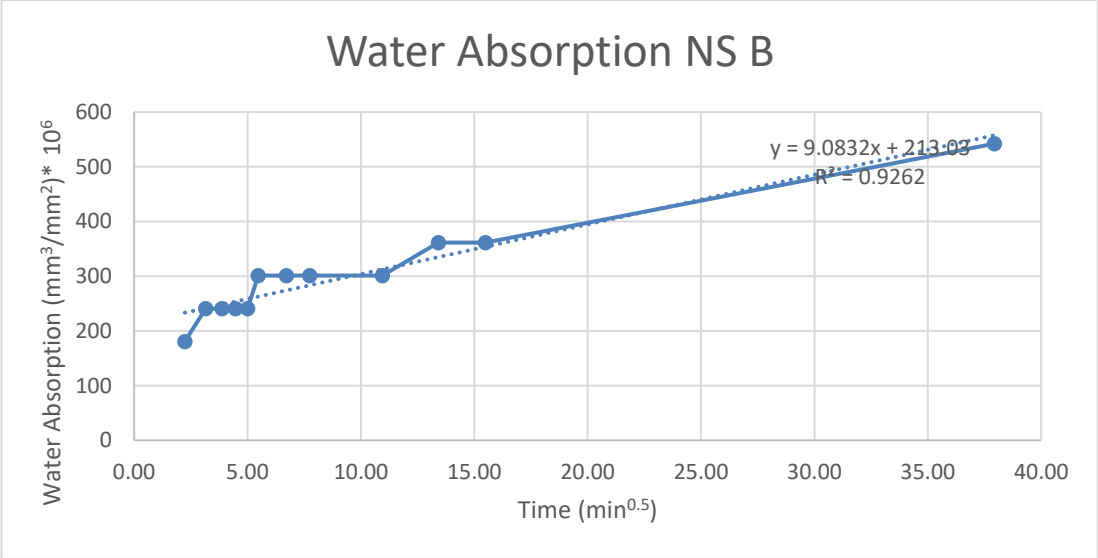


**Figure A.10 :** Graphic and Equation of the Capillarity Coefficient of NS B

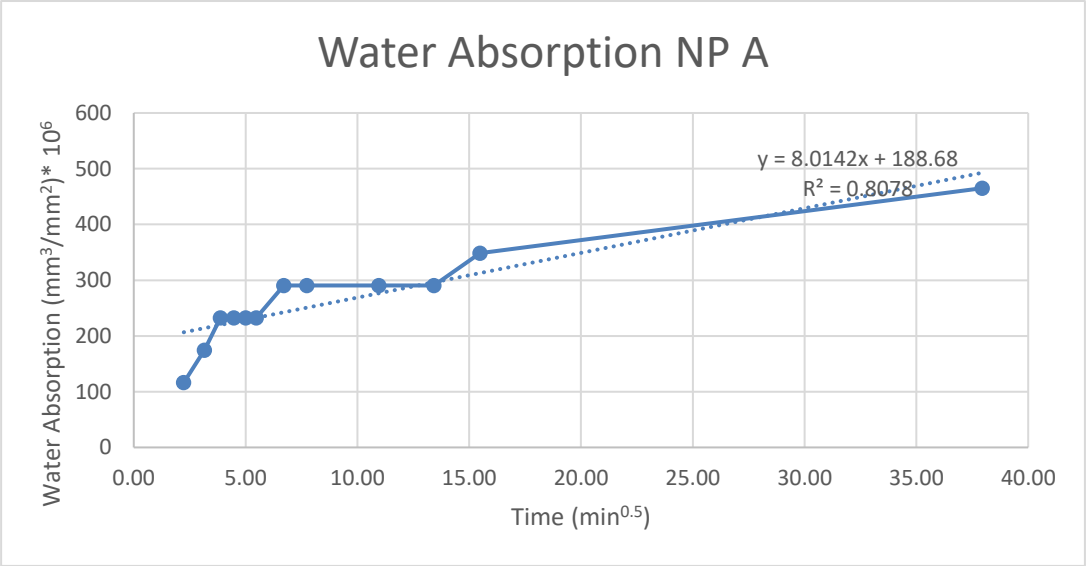


**Figure A.11 :** Graphic and Equation of the Capillarity Coefficient of NP A

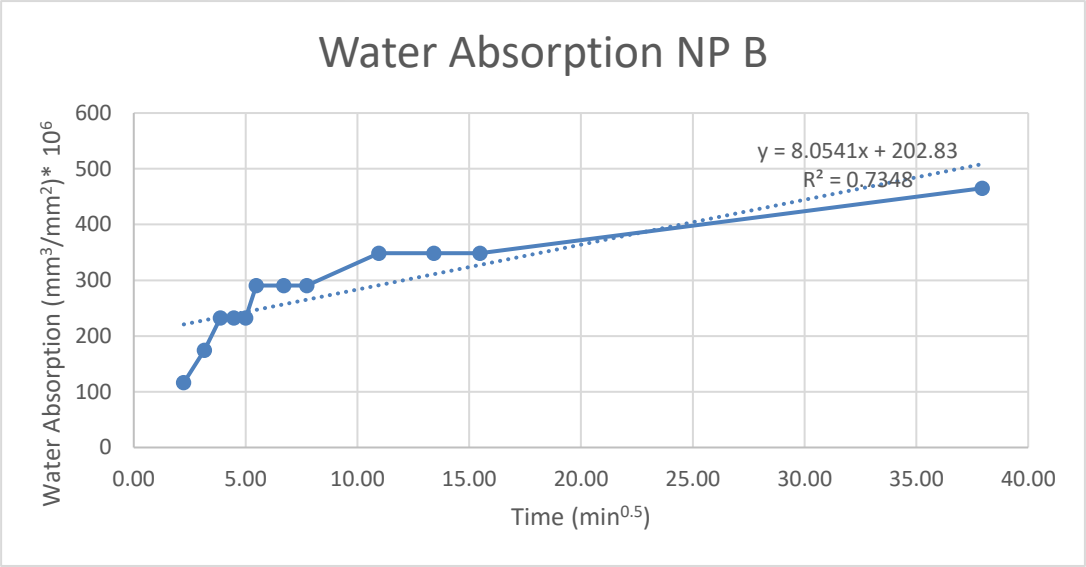


**Figure A.12 :** Graphic and Equation of the Capillarity Coefficient of NP B

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**PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:**

- A. O. Erüz, M. H. Özkul, Ö. Akalın, and M. Maraşlı, The Effects of The Modified Andreassen Particle Model for Increase of Packing Density in Heavy Mortar, ACE 2020-2021, 14th International Congress on Advances in Civil Engineering 2020-2021, vol. 1, pp. 97-104, September 6-8, 2021, Istanbul, Turkey

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R. Vasiljevs, D. Serdjuks, J. Gerasimova, K. Buka-Vaivade, and A. O. Erüz, "Behaviour of Timber-Concrete Joints in Hybrid Members Subjected to Flexure," IOP Conference Series: Materials Science and Engineering, vol. 660, no. 1, pp. 0–8, 2019, DOI: 10.1088/1757-899X/660/1/012050.