PHYSICAL AND MECHANICAL PROPERTIES OF LIGHTWEIGHT EXPANDED CLAY AGGREGATE CONCRETE

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ABSTRACT

PHYSICAL AND MECHANICAL PROPERTIES OF LIGHTWEIGHT EXPANDED CLAY AGGREGATE CONCRETE

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Expanded clay aggregate is an artificial type of aggregate manufactured from clay, and it has a porous nature, making it lighter than normal weight aggregates. When used in concrete, this porous nature is decisive in the physical and mechanical properties of concrete. A comprehensive experimental study was carried out on physical and mechanical properties like density, absorption capacity, porosity, compressive strength, splitting tensile strength, and modulus of elasticity. In this context, 13 different mixtures were designed, and 234 specimens were produced for the desired tests. The wet density of the mixtures varied between 1559 – 1980 kg/m^3. Specimens were much lighter than normal aggregate concrete but still met the structural needs. Unlike the vast majority of studies found in literature, this experimental study also investigated the effects of moisture state on the mechanical properties, thus the compressive strength and the modulus of elasticity tests were conducted for specimens in moist and oven-dry states. It was observed that moisture reduced the compressive strength of concrete but increased its modulus of elasticity. The dry compressive strengths of mixtures were found to be 9% higher than moist compressive strength on average. The reduction in static modulus of elasticities from moist to dry state was found to be 26% on average. The study also includes an evaluation of modulus of elasticity prediction models from widely accepted codes. Moreover, a new model was proposed in estimating the dry and moist modulus of elasticity of expanded lightweight aggregate concretes by using the dry and moist density and compressive strength. The proposed model's accuracy was also assessed using the data from experimental studies found in the literature conducted on relevant topics.

Keywords: Lightweight Expanded Clay Aggregate, Moisture State, Compressive Strength, Modulus of Elasticity

ÖZ

GENLEŞTİRİLMİŞ KİL AGREGALI HAFİF BETONUN FİZİKSEL VE MEKANİK ÖZELLİKLERİ

Uysal, Orkun
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Genleştirilmiş kil agregası, kilden üretilen yapay bir agrega türüdür ve normal ağırlıklı agregalardan daha hafif olmasını sağlayan gözenekli bir yapıya sahiptir. Betonda kullanıldığında bu gözenekli yapı, betonun fiziksel ve mekanik özelliklerinde belirleyicidir. Yoğunluk, su emme kapasitesi, gözeneklilik, basınç dayanımı, yarmada çekme dayanımı ve elastisite modülü gibi fiziksel ve mekanik özellikler üzerinde kapsamlı bir deneysel çalışma yapılmıştır. Bu kapsamda 13 farklı karışım tasarlanmış ve istenilen testler için 234 adet numune üretilmiştir. Karışımların nemli yoğunlukları 1559 – 1980 kg/m^3 arasında değişmiştir. Literatürde bulunan çalışmaların büyük çoğunluğunun aksine, bu deneysel çalışma, nem durumunun mekanik özellikler üzerindeki etkilerini de araştırmış, böylece nemli ve fırında kurutulmuş durumdaki numuneler için basınç dayanımı ve elastisite modülü testleri gerçekleştirilmiştir. Nemin betonun basınç dayanımını azalttığı fakat elastisite modülünü arttırdığı gözlenmiştir. Karışımların kuru basınç dayanımları ortalama olarak nemli basınç dayanımlarından %9 daha yüksek bulunmuştur. Nemli durumdan kuru duruma statik elastikiyet modülündeki azalma ortalama %26 olarak bulunmuştur. Çalışma ayrıca, yaygın olarak kabul görmüş bazı kodların, elastisite modülü tahmin modellerini değerlendirmektedir. Daha sonra, genleştirilmiş hafif agregalı betonların elastisite modülünün tahmininde kullanılabilecek yeni bir model önerilmiştir. Önerilen bu model, literatürde benzer parametleri çalışmış deneysel araştırmaların çıktıları ile test edilmiş ve tahmin sonuçları değerlendirilmiştir.

Anahtar Kelimeler: Hafif Genleştirilmiş Kil Agregası, Nem Durumu, Basınç Dayanımı, Elastisite Modülü

To my family

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ABBREVIATIONS

ACI	: American Concrete Institute
ASTM	: American Society for Testing Materials
EN	: European Norm
LECA	: Lightweight Expanded Clay Aggregate
LWAC	: Lightweight Aggregate Concrete
MoE	: Modulus of Elasticity
CoV	: Coefficient of Variation
w/c	: Water to Cement Ratio
w/b	: Water to Binder Ratio

LIST OF SYMBOLS

SYMBOLS

f_c : Compressive strength

$f_{c,28}$: 28-day compressive strength

E_{dry} : Dry Modulus of Elasticity

E_{moist} : Moist Modulus of Elasticity

f_t : Splitting Tensile Strength

r : Coefficient of Correlation

R^2 : Coefficient of determination

MSE : Mean Squared Error

CHAPTER 1

INTRODUCTION

1.1 General

The need for alternative construction materials is rising in recent years as structures are becoming more complex with growing cities and developing technology; therefore, the demand for advanced materials has been in the rise. Most of the studies focus on improving and modifying concrete, the most widely used construction material around the globe, rather than experimenting with whole new alternative materials for construction. Lightweight Aggregate Concrete (LWAC) is one of these modified materials, where normal weight aggregates in conventional concretes are replaced entirely or partially with lightweight aggregates. There are some different lightweight aggregate options in literature. However, this study examines LWAC made up of lightweight expanded clay aggregate (LECA). They are an artificial type of lightweight aggregate manufactured by heating clay up to 1300 ^{o}C degrees in rotary kilns. The concrete produced by using expanded clay aggregate is often called as LECA concrete (Rashad, 2018).

LECA concrete is lighter than conventional concrete produced with normal weight aggregate, which has a unit weight of around 2350 kg/m^3. On the contrary, lightweight concretes are classified as having a minimum compressive strength of 17 MPa and a dry unit weight between 1120 – 1920 kg/m^3 (ACI 213R-2, 2003). When compared with normal weight concretes, their strength parameters are lower, however they can still be used in structural applications, as sufficient compressive strengths can be obtained by right mixture proportions. Furthermore, lightweight characteristic is an advantageous issue when a lighter design is needed for structures. For example, in structures where the dead load is important such as bridges or high-rise buildings, LECA concrete significantly decreases total loading on the foundation of the building, thus reducing the necessary reinforcement, concrete, and overall materials amount that is needed (Vijayalakshmi & Ramanagopal, 2018).

Besides its natural advantage on weight, LECA concrete has great thermal properties. As demand for energy is exponentially rising due to increasing population and developing industrial productions, energy efficiency is becoming a more vital issue than ever. Studies show that using LECA concrete in buildings can yield up to 50 % savings on heating-cooling expenses of buildings (Vijayalakshmi & Ramanagopal, 2018). This feature makes the material popular in regions where thermal properties of the chosen material is important.

LECA concrete also has great advantages when earthquake loads are considered because earthquake loads on buildings are directly proportional to the weight of the structure. When it is used as a construction material with structural purposes, inertial forces during an earthquake decrease and the destructive effects of earthquakes will be weakened (MTA,n.d.).

LECA concrete is a material that has been used worldwide since early 1900s (Chandra & Berntson, 2002). Therefore, there are significant amount of studies on this material in literature.

As expanded clay aggregate is a porous material with high water absorption capacity, significant changes were expected between parameters measured in moist and dry states. Therefore, an experimental program is conducted to evaluate the effects of moisture state on the mechanical properties of LECA concrete. Within the scope of this study compressive strength and static modulus of elasticity of LECA concrete specimens were determined at both dry and moist states. Besides, modulus of elasticity results were also compared with some of the models commonly used in literature. According to variation between these models, a new model was proposed in line with the data obtained from this experimental study.

1.2 Objective and Scope

Existing academic literature has a number of studies that investigated various mechanical and durability parameters of lightweight expanded clay aggregate concrete. For example, although there were some studies on the mechanical and durability parameters of LECA concrete, only a few investigated modulus of elasticity, and none focused on the modulus of elasticity at different moisture states. Studies that are focusing on compressive strengths also did not mentioned this issue.

In line with this identified gap, this study aims to examine physical and mechanical properties of LECA concrete at different moisture states. Besides the physical properties like density and porosity, mechanical properties that were studied in this experimental study are; compressive strength, splitting tensile strength and modulus of elasticity. The compressive strength and modulus of elasticity were determined at moist and oven-dry states and the effects of moisture state of LECA concrete on its mechanical properties are studied. The study also covers the modulus of elasticity parameter by comparing different prediction models used in the literature. Moreover, a unique prediction model was also proposed using regression using the data obtained via the experimental program.

In this context, an experimental program was prepared to determine the specified parameters. 13 different mixture designs, 18 specimens for each design for a total of 234 specimens were produced to measure the desired properties. Results were analyzed by investigating relations between parameters. Outcomes obtained following the analysis prove and strengthen existing knowledge and fill the mentioned gap in the literature.

In this context Chapter 2 included the literature review with two sections; expanded clay aggregate as a material and the concrete produced using expanded clay as an aggregate. Chapter 3 presented the details of the experimental program, and tells about the processes, observations and scope of the experiments. In Chapter 4, test results were shown and these results were discussed in detailed way. This chapter includes tables, figures and graphs which clearly expresses the relations between certain parameters which are crucial in concrete design and its structural aspects. Lastly, Chapter 5 presented the main conclusions that can be drawn from the experimental program together with some recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Expanded Clay Aggregate

2.1.1 General

Lightweight expanded clay aggregate (LECA) is an artificial aggregate manufactured by using clay. It is a lightweight aggregate but still it can be used for producing structural concrete (Rashad, 2018). LECA is obtained by using clay as raw material and heating it in rotary kilns up to 1300 C^{o}. Properties of this final product after processing depends on the feed material, additives used during production, and production technology (Abdulmajeed et al., 2016).

LECA is not a new material, and it has been produced for many years since early 1900s. The idea of heating and expanding clay to produce aggregates originally came from the USA, where the first patent was granted in 1918 in Kansas City. The first commercial production of expanded clay made its way to Europe in 1935 (Chandra & Berntson, 2002).

LECA could be manufactured in a wide range of density, size and strength. This diversity allows designers to design concretes for various applications. LECA Concrete is a building material that has good thermal insulation properties. (Abdulmajeed et al., 2016).

The material was used for many years to produce lightweight structural concrete and has a wide range of applications especially in structures where the dead load of the building is important.

Turkey has rich reserves of expanded clay and there is a huge potential. Expanded Shale, Clay and Slate Institute (ESCSI) were founded in 1949 in United States of America. In Germany, the pumice institute has been operating for many years. A comparable initiative has yet to take place in Turkey. Properties and potential usage areas of the material should be investigated better for future applications (MTA,n.d.).

2.1.2 Mineral Composition and Production

LECA chemical composition mainly includes, SiO_2, Al_2O_3, Fe_2O_3, CaO and some alkalis such as Na_2O and K_2O. According to data from various studies, SiO_2 content varies between 53% to 70%, Al_2O_3 varies from 15% to 27%, Fe_2O_3 content varies between 1% to 14% and CaO fluctuated between 0.2 % to 4% (Rashad, 2018).

Expanded Clay Aggregate (ECA) is an artificial type of lightweight aggregate. ECA is produced by a thermal process using clay as a natural material. Similar to Portland cement production, rotary kilns are used for producing ECA. These kilns are generally thirty to sixty meters long. Raw materials are put into kilns from the higher end, and the fire is located at the lower end. Kilns have different heating zones and temperature increases as the material move towards the lower end, which cause gradual increase in temperature leading to expansion (Chandra & Berntson, 2002).

Rotary kilns are heated up to degrees around 1100 – 1300 °C. The clay that is placed from the higher end of the rotary kiln expands about 5-6 times with respective to their original size and takes the shape of pellets. During the heating process, gas is released inside of the expanding raw materials which is entrapped, forming a porous structure during cooling (Rashad, 2018).

There are several factors that can affect the quality and properties of LECA, including the type of clay used, the heating temperature and duration, and the cooling rate. The size and shape of the aggregates also varies depending on the process. Coarser grain size means lighter material as the structure is porous, density will increase as grain size decreases.

Heating process by rotary kilns cause expansion of aggregates. Having smaller clay particles before heating process leads to more expansion. Researchers have tried adding various substances to clay to improve the production process and properties of lightweight expanded clay aggregates (LWCA). Adding sodium carbonate (Na_2CO_3) caused the pellets to have low expansion, irregular shapes, and stick together. Adding silicon dioxide (SiO_2) had little effect on the properties being studied within the tested range. Iron had a significant impact on the properties of LECA. Adding iron oxide (Fe_2O_3) created larger pores in the center of the pellets, while adding metallic iron powder significantly increased expansion and reduced both the density and strength of the particles. Iron powder may be a useful additive to decrease the density of LWCA in situations where low density is more important than strength (Vijayalakshmi & Ramanagopal, 2018).

2.1.3 Properties and Characteristics

LECA is a porous and environmentally friendly construction material. Its' lightweight nature, good thermal insulation properties, high porosity and low density make that material suitable for a variety of construction applications. It has much lower density when compared with conventional aggregates used in concrete production. It has higher strength and is more resistant to external effects when compared with other lightweight aggregates (Hedayati, 2017).

Expanded clay aggregates are known for having a high compressive strength among other lightweight building materials. This makes them useful for the concrete industry. It is reported that using expanded clay aggregates in a building can potentially lead to a 20% reduction in the amount of reinforcing steel needed and a 50% reduction in heating and cooling expenses (Vijayalakshmi & Ramanagopal, 2018).

2.1.3.1 Density and Specific Gravity

The specific gravity of ECA can vary depending on the manufacturing process and the properties of specific type of clay used (Luo et al., 2007; Li et al., 2017).

Dry specific gravities of about 0.67 to 1.65 have been reported and these values indicate that LECA's specific gravity is 20 – 45% less than conventional or normal-weight aggregates (Vijayalakshmi & Ramanagopal, 2018).

Moreover, it is also reported that specific gravity of LECA decreases as the grain size of the aggregates are increased because pore amount will increase with grain size (Zhang et al., 2012).

According to European Standards, an aggregate made of minerals should not have an oven-dry specific gravity greater than 2.0 or a loose dry bulk density above 1200 kg/m^3. To produce structural concrete, an aggregate having a loose dry bulk density between 880 and 1120 kg/m^3 is acceptable according to ASTM C 330, depending on the size of the aggregates (Vijayalakshmi & Ramanagopal, 2018).

2.1.3.2 Shape and Texture

Shape and texture have a crucial impact on the concrete matrix in terms of particle packing and aggregate interlocking. In terms of shape, expanded clay aggregate is typically round or irregular in shape, with a rough and porous surface. The color is typically brown, and it has a black internal core (Vijayalakshmi & Ramanagopal, 2018).

In general, spherical aggregates have a lower "Shape Index" compared to angular aggregates. For aggregates having similar strength, those having a higher Shape Index may exhibit higher strength in concrete (Vijayalakshmi & Ramanagopal, 2018).

2.1.3.3 Water Absorption

Because of its porous nature, water absorption capacity is an important parameter when LECA is considered. Absorption values between 10% to 50% have been reported. This value changes with the production method, properties of raw material, surface texture and particle size. If surface texture is glassy, water absorption is reduced. With an increase in particle size and a reduction in density, water absorption capacity also increases (Vijayalakshmi & Ramanagopal, 2018; M. M. Al-Jabri and M. S. Al-Habsi, 2014; J. R. Stark and A. G. Kwaramba, 2010; M. A. Al-Ghamdi et al.,2013).

2.1.3.4 Mechanical Properties

When only aggregates are considered, mechanical properties were not typically reported. According to a review article which include various studies from literature, crushing value of the aggregates varied from 1.4 to 8.3 MPa. According to the same study, crushing strength depends on the porosity, mineralogical composition, melting temperature of binders, bloating of aggregate and internal deformations due to thermal processes (Vijayalakshmi & Ramanagopal, 2018).

2.2 Expanded Clay Aggregate Concrete

2.2.1 General

Expanded clay aggregate concrete is the type of concrete where the aggregate in the matrix is replaced partially or fully with LECA. It is a type of lightweight concrete, and its density is significantly lower than the conventional concrete. The mechanical and durability properties of that concrete highly depend on the type and properties of LECA. In this section, the studies on this subject in the literature are investigated and briefly explained.

2.2.2 Characteristics and Area of Usage

Throughout literature, the material is generally mentioned by its lightweight nature, thermal properties, fire resistance and its advantages on energy savings. Because of its porous nature, expanded clay is lighter than the commonly used aggregates of concrete, therefore the main characteristic of that concrete is its low density. This low density makes LECA concrete suitable for applications where the dead load of the structure is a concern, such as bridges, high rise buildings or roofing systems.

Due to the exponentially increasing demand for current nonrenewable energy resources and their scarcity around the globe, recent studies are now focusing on using energy efficient materials. In China, 35% of total energy is consumed by the construction industry itself. As construction industry is rapidly expanding, environmental stability and energy efficiency of buildings increase their importance. Energy efficiency of buildings can be increased by improving thermal properties of construction materials (Ahmad et al., 2019).

In this context, a study found that households constructed with lightweight aggregate concrete can save more than 30% of the heating energy consumption during winter season, as LWAC has a lower thermal conductivity than a conventional one (Youm et al., 2016a). A different study indicates that buildings containing LECA concrete may save up to 50% of their heating-cooling expenses (Vijayalakshmi & Ramanagopal, 2018).

LECA improves the thermal properties of concrete, therefore thermal insulation properties of the concrete element increases as the amount of LECA in that concrete increases. The thermal conductivity of LECA is lower than normal weight aggregates, since LECA has a lower density and a more porous nature than normal weight aggregates. This leads to less thermal conductivity and higher thermal insulation. Interconnected pores in LECA reduces thermal conductivity as trapped air in these pores provide good insulation. Due to these advantageous thermal properties, LECA concrete can improve energy performance of buildings and positively contribute towards energy consumption reduction (Rashad, 2018).

LECA concrete also has good fire resistance properties. The porous nature of aggregates allows for high amount of water absorption, this absorbed water reduces the temperature of the material during fire. This advantage makes LECA concrete a great option to be used in critical buildings such as hospitals or even high-rise buildings (Şen, 2012).

The earthquake loads induced on buildings are directly proportional to the weight of the structure. Therefore, reducing the dead load of a structure will reduce the risk of damage in an earthquake. Some studies concluded that walls consisting of lightweight materials get damaged even though the structural system takes no damage, and concrete made up of lightweight materials has lower compressive strength which will cause some problems in stress transfer in the structure. However, when lightweight concrete was used in the load-bearing system of the structure, the moment of inertia at earthquakes and destructive effects of earthquakes will be lowered as lesser loads will act on the building's frame (MTA,n.d.).

Structural lightweight concrete is reported to improve the structural efficiency of buildings and leads to savings up to 20% of reinforcing steel. (Vijayalakshmi & Ramanagopal, 2018). Reduced dead load will result in reduced footing at foundation and lighter upper structure which may led to reduction in cement quantity and reinforcement. It has also have advantages for pre-cast elements, as lighter and smaller elements will decrease the handling and transportation cost (Subaşı, 2009).

Lightweight concrete is an alternative solution to the conventional normal weight concrete when lighter solutions are needed. LWC is often used in bridges and buildings since the middle of 20th century, it also has many non-structural insulation applications (Bogas et al., 2014). There are plenty of bridge examples designed and constructed with lightweight aggregate concrete in Norway, as the dead weight of the bridges can be reduced by using lightweight aggregates. These bridges were designed with high compressive strengths (Youm et al., 2016b).

2.2.3 Physical and Mechanical Properties

2.2.3.1 Density

The density is a very crucial parameter when identifying lightweight expanded clay aggregate concrete. Fresh density could be explained as fully compacted fresh concrete with minimum possible air content. Expanded clay aggregate incorporated full replacement can reduce fresh and oven-dry densities compared to any control mix (Vijayalakshmi & Ramanagopal, 2018).

The oven- dry density of LECA concrete is reported to vary between 25% to 34% lower than the conventional normal weight aggregate concrete. According to BS EN 206-1, lightweight concrete's oven-dry density should between 1320 – 2044 kg/m^3 (Vijayalakshmi & Ramanagopal, 2018).

Structural lightweight aggregate concrete should conform ASTM C 330 Standards. To be called as "structural lightweight aggregate concrete" it should has a dry density between 1120 – 1920 kg/m^3 and 28th day compressive strength of the concrete should exceed 17 MPa.

Density of the concrete depends on grading of aggregates, moisture content, mix proportions, cement content and w/c ratio. Besides the raw material and other factors, it is also affected by the method of compaction and curing conditions (Chandra & Berntson, 2002).

Although density values depend on many parameters, literature agrees that density decreases as LECA used in the concrete matrix increases. Writing down the measured density values of different studies throughout literature could be misleading because in order to make comments on these values, every effective parameter should be discussed, as density is highly dependent on the raw materials used and mix proportions.

2.2.3.2 Porosity

Porosity is another important parameter for LECA concrete, as expanded clay aggregates have a porous structure. Density of hardened concrete is highly related to porosity, as the density of concrete decreases with an increase in porosity increases. Pore amount also affects thermal properties, thermal conductivity of LECA concrete related to its air-void system. Thus, concrete with higher porosity will have lower thermal conductivity (Chandra & Berntson, 2002).

Porosity also significantly affects the strength of concrete. Compressive strength of concrete is inversely proportional to porosity and LECA concrete with low porosity has a high compressive strength values (Subaşı, 2009).

Mixtures with LECA replaced fully with aggregates resulted higher sorptivity level than 50 % replaced LECA mixtures. This was explained by the amount of aggregate with porous nature, which increases the porosity of concrete (Nahhab & Ketab, 2020).

2.2.3.3 Splitting Tensile Strength

Some crucial mechanical properties of reinforced structural concrete like; shear strength, bonding strength, and its resistance to cracking is affected by the tensile strength of the concrete (Chandra & Berntson, 2002). The splitting tensile strength of LECA concrete is an important property that determines its suitability for use in structural applications. Several studies have been conducted to investigate the splitting tensile strength of LECA concrete and the factors that influence it.

Splitting tensile strength of LECA concrete increased with an increase in the water-cement ratio (W/C) and the volume fraction of the LECA. The presence of steel fibers in the concrete improved the splitting tensile strength, while the use of high volumes of LECA resulted in a decrease in the strength (El-Sayed, 2011).

The splitting tensile strength of LECA concrete was influenced by the size and shape of the expanded clay pellets, with larger and more spherical pellets resulting in higher strength. Moreover, the strength is influenced by the curing conditions, with longer curing times resulting in higher strength (Scrivener, 2007).

The splitting tensile strength of LECA concrete is also influenced by the type of cement used, with the strength increasing as the cement content increased. El-Sayed, 2012 reported that the strength was influenced by the W/C ratio and the volume fraction of the LECA (El-Sayed, 2012).

2.2.3.4 Compressive Strength

Literature has many studies that focuses on the compressive strength of the LECA concrete. Compressive strength results highly depend on the design parameters and the materials used. In general, lightweight expanded clay incorporation decreases the ultimate compressive strength, however the results can still satisfy structural concerns. Making generalized comments could be misleading because compressive strength results depend on the mixture design parameters and properties of the raw materials like LECA.

Pukacki et. al. found out that LECA concrete has similar compressive strength to conventional normal weight concrete when expanded clay aggregate was used as a replacement for coarse aggregate up to 50 %. Same study measured LECA concrete's compressive strength as 31.9 MPa whereas the control specimen yielded 32.3 MPa (Pukacki et. al., 2016).

In another study, compressive strength results of LECA Concrete varied between 20 MPa to 70 MPa. Compressive strength increased with an increase in unit weight and a decrease in the water-to-cement ratio (Dilli et al., 2015).

In an experimental study, compressive strength values of 5 different mixtures varied between 41.3 MPa to 50.6 MPa for densities varying between 1850 – 1902 kg/m^3. In the same study normal weight concrete that was produced as a control specimen yielded 60.4 MPa compressive strength with a density of 2348 kg/m^3 (Malešev et al., 2014). Same study also indicates that, compressive strength highly depends on aggregate type, cement type and cement amount.

A review article stated that 28th day compressive strength of LECA concrete varied between 23 – 60 MPa, with a density range of 1290 – 2044 kg/m^3. Expanded clay aggregates have high compressive strength when compared with other lightweight aggregates. The porous nature of LECA causes the reduction in compressive strength of concrete. The aggregate not alone determines the strength characteristics, Interfacial Transition Zone has a crucial impact on compressive strength (Vijayalakshmi & Ramanagopal, 2018).

LECA Concrete has a consistent strength gain for mixes which includes higher amounts of cement. A higher compressive strength was obtained for normal weight concrete which produced with gravel and dolomite as aggregates. When LECA used as a replacement and used in mixture with other aggregates, it is found to be have higher compressive strength when compared to full LECA containing concretes. Partial replacement of LECA improved strength parameters for every cement content (Wegian, 2012).

2.2.3.5 Modulus of Elasticity

The modulus of elasticity of a material can be explained as, the material's resistance to axial deformation. The value can be measured by calculating the slope of the stress-strain curve in the elastic region. Concrete is a non-linear elastic material, that is why the modulus of elasticity is typically obtained within the assumed proportional limit in applied stress (Malešev et al., 2014).

The value of static modulus of elasticity depends on the density, compressive strength and type of aggregate used in the mixture. The modulus of elasticity of structural lightweight aggregate concrete varies between 10 to 24 GPa. An experimental study conducted by Malasev et.al. found out different static modulus of elasticity values between 21.52 to 22.36 GPa. Compressive strength results were varied between 41.3 to 50.6 MPa for the same study (Malešev et al., 2014). Another study conducted by Youm et.al. found out static modulus of elasticity value as 21 GPa on average of 3 specimens, which their compressive strengths varied between 46.1 to 47.9 MPa (Youm et al., 2016b). An experimental study conducted by Karamloo et.al. found out modulus of elasticity values ranging between 19.23 GPa to 25.12 GPa. 6 different mixtures were prepared in context and their compressive strength were varied between 27 MPa to 48.3 MPa (Karamloo et al., 2016). All mentioned studies stated that, static modulus of elasticity is smaller when compared to the normal weight conventional concrete.

CHAPTER 3

EXPERIMENTAL PROCEDURE

The experimental component of this study aims to determine the physical and mechanical properties of LECA Concrete listed below:

- Fresh and Oven-dry density
- Compressive Strength (7th day, 28th day – moist, 28th day – dry)
- Splitting Tensile Strength (28th day)
- Modulus of Elasticity (28th day – moist, 28th day - dry)
- Porosity.

This study's experimental procedure was completed with another master's degree graduate İlbüke Uslu. Therefore, the same data set was used for our calculations.

3.1 Experimental Program

13 different mixtures were designed, and a total of 234 specimens were produced during the study. LECA amount was kept constant in all mixtures at 0.27 and 0.36 by volume. In mixtures where the LECA amount was taken as 0.27 by volume, coarse and medium-coarse LECA were used in the same amount by volume. However, in mixtures where LECA volume was 0.36, coarse, medium-coarse and fine LECA was used with the same volume. Every mixture also contained crushed limestone as natural sand in calculated amounts except for the 13th mixture. In the 13th mixture cement dosage, fly ash replacement and w/c ratio were decided and only expanded clay aggregate was used. Cement dosage varies between 400 kg/m^3, 500 kg/m^3, and 600 kg/m^3 and different w/c ratios between 0.3 – 0.5 were chosen to create a parametric dataset. Only in three mixtures, fly ash was used as a cement replacement. While choosing fixed and independent parameters in mixture design, creating a logical and wide-ranging density distribution was considered. The

densities range from 1924 kg/m^3 to 1722 kg/m^3. 13th Mixture has 1578 kg/m^3 density because it contains only lightweight aggregates.

Specimen size was selected as 100 x 200 mm cylinders; 100 x 200 mm cylinder specimens are commonly used in literature and allowed by the widely used national codes.

In some mixtures, an adequate amount of superplasticizer was used to ensure adequate slump and workability. Especially in mixes where w/c ratios were low, superplasticizer was used. The amount of superplasticizer and other raw material amounts used in each mixture are presented in Table 3.1.

Table 3.1 LECA Concrete Mixture Design Table

Mixtures	M_{cem} (kg/m^3)	M_{flyash} (kg/m^3)	w/b	M_{water} (kg/m^3)	V_{leca} (m^3)	M_{SP} (kg/m^3)	$M_{c\ leca}$ (kg/m^3)	$M_{mc\ leca}$ (kg/m^3)	$M_{f\ leca}$ (kg/m^3)	$M_{nat.sand}$ (kg/m^3)
Mix 1	400	-	0.6	240	0.27	-	109	150	-	885
Mix 2	400	-	0.6	240	0.36	-	97	133	218	653
Mix 3	500	-	0.4	200	0.27	10.0	109	150	-	883
Mix 4	500	-	0.4	200	0.36	5.0	97	133	218	662
Mix 5	500	-	0.6	300	0.27	-	109	150	-	648
Mix 6	500	-	0.5	250	0.36	-	97	133	218	545
Mix 7	600	-	0.3	180	0.27	18.0	109	150	-	833
Mix 8	600	-	0.3	180	0.36	15.0	97	133	218	608
Mix 9	600	-	0.5	300	0.27	-	109	150	-	566
Mix 10	600	-	0.4	240	0.36	-	97	133	218	489
Mix 11	400	100	0.4	200	0.36	2.0	97	133	218	648
Mix 12	400	200	0.4	240	0.36	-	97	133	218	446
Mix 13	400	200	0.4	240	0.53	-	107	148	483	0

3.2 Material Properties

3.2.1 Lightweight Expanded Clay Aggregate

Lightweight expanded clay aggregates formed the main material under analysis in the study, as the aim of experiments was determining important physical and mechanical properties of expanded clay aggregate concrete. The material was obtained from a regional supplier located in Bilecik – Turkey, and the commercial name of the material is LECAT.

In this study, expanded clay aggregates were used together with natural sand. Only the 13th mixture consists entirely of expanded clay as an aggregate. The commercial company is marketing its products in 4 different particle size ranges. In this study their 0 - 3 mm aggregate was used as Fine, 3 - 8 mm aggregate was used as Medium – Coarse, and lastly 8 - 16 mm aggregate was used as Coarse aggregates in mixtures.

Fundamental material tests were conducted before mixture design according to related standards. For density and water absorption ASTM C127 -15 and ASTM C – 128, and for sieve analysis ASTM C136/136M were used. The results of the sieve analysis and the physical properties of aggregates are given in Tables 3.2-3.4 and Figure 3.2.

Table 3.2 Sieve Analysis Results of Fine LECA

	Sieve Size	**Mass Retained (g)**	**Mass Retained (%)**	**Cumulative Mass Retained(g)**	**Cumulative Retained (%)**	**Percent Passing (%)**
1/2	**12.50**	0	0.0	0	0	100.0
3/8	**9.50**	0	0.0	0	0	100.0
No.4	**4.75**	1.2	0.1	1.2	0.1	99.9
No.8	**2.36**	279	28.0	280.2	28.1	71.9
No.16	**1.18**	326.2	32.7	606.4	60.8	39.2
No.30	**0.60**	217.4	21.8	823.8	82.7	17.3
No.50	**0.30**	111.6	11.2	935.4	93.9	6.1
No.100	**0.15**	41.6	4.1	977.0	98.0	2.0
PAN	**PAN**	19.6	2.0	996.6	100.0	0.0

Table 3.3 Sieve Analysis Results of Medium Coarse LECA

	Sieve Size	**Mass Retained (g)**	**Mass Retained (%)**	**Cumulative Mass Retained(g)**	**Cumulative Retained (%)**	**Percent Passing (%)**
1/2	**12.50**	0	0.0	0	0	100.0
3/8	**9.50**	45.8	4.6	45.8	4.6	95.4
No.4	**4.75**	880.4	88.0	926.2	92.6	7.4
No.8	**2.36**	63.8	6.4	990	99.0	1.0
No.16	**1.18**	1.6	0.2	991.6	99.2	0.8
No.30	**0.60**	0.23	0.0	991.83	99.2	0.8
No.50	**0.30**	0.27	0.0	992.1	99.2	0.8
No.100	**0.15**	0.5	0.0	992.6	99.3	0.7
PAN	**PAN**	7.4	0.7	1000	100.0	0.0

Table 3.4 Sieve Analysis Results of Coarse LECA

Sieve Size	Mass Retained (g)	Mass Retained (%)	Cumulative Mass Retained(g)	Cumulative Retained (%)	Percent Passing (%)
25.40	0	0.0	0	0	100.0
19.10	0	0.0	0	0.0	100.0
12.70	410	13.8	410	13.8	86.2
9.50	975	32.9	1385	46.7	53.3
4.75	1497.8	50.5	2882.8	97.2	2.8
PAN	81.8	2.8	2964.6	100.0	0.0

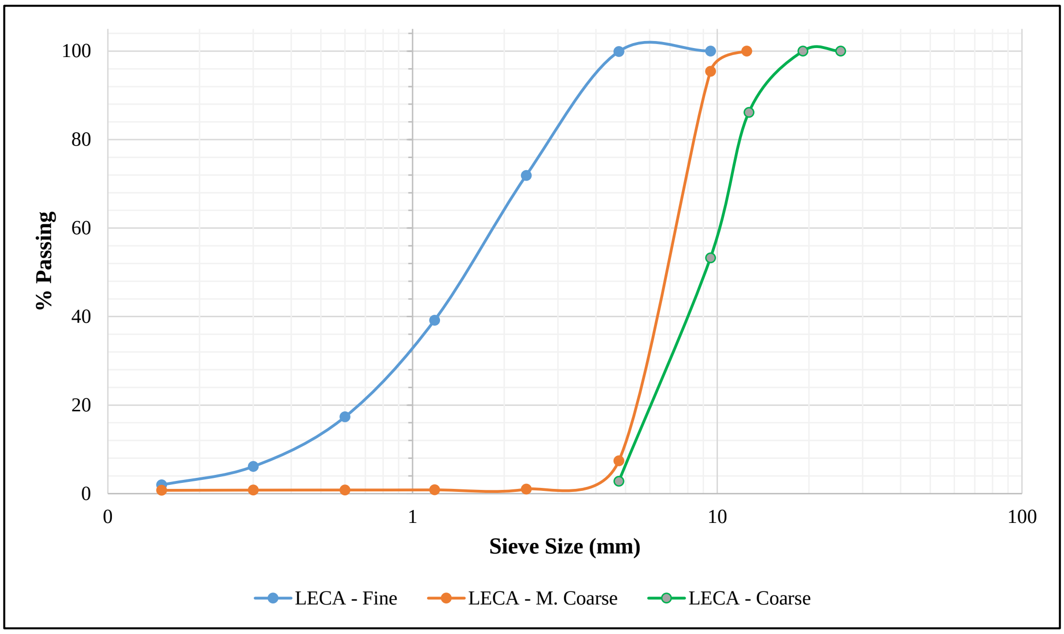


Figure 3.1 The Particle Size Distribution of LECA

Table 3.5 Physical Properties of LECA

Properties	Coarse LECA	M.Coarse LECA	Fine LECA
SSD Specific Gravity	0.805	1.109	1.814
Water Absorption (%)	20.5	19.6	10.0

3.2.2 Portland Cement

CEM I 42.5 R type Portland Cement produced by Baştaş Cement Company Inc. was used in the mixtures and the specimens produced. The chemical, physical, and mechanical properties of used cement are given in Table 3.6 and Table 3.7. Those data were obtained from Turkish Cement Manufacturers' Association.

Table 3.6 Chemical Composition of Portland Cement Used in the Study

Oxide Composition (%)	
CaO	63.71
SiO_2	18.53
Al_2O_3	4.60
Fe_2O_3	3.1
MgO	1.6
SO_3	3.05
K_2O	0.90
Na_2O	0.45
Cl	0.021

Table 3.7 Physical and Mechanical Properties of Portland Cement Used in the Study

Property	Value
Specific Gravity	3.11
Blaine Fineness (cm^2/g)	3411
Initial Setting (min)	165
Final Setting (min)	215
Compressive Strength (MPa) - 2 days	26.4
Compressive Strength (MPa) - 7 days	37.5
Compressive Strength (MPa) - 28 days	48.3

3.2.3 Fly Ash

Fly ash was used in only three mixtures out of 13 as a cement replacement. It was added to mixtures to see its effects on workability and strength parameters. Fly ash is a by-product of coal-burning thermal power plants. In this study, fly ash was obtained from Sugözü Thermal Power Plant located in Adana – Turkey. The chemical composition of the used fly ash is given in Table 3.8. Those data were obtained from Turkish Cement Manufacturers' Association.

Table 3.8 Chemical Composition of Fly Ash Used in the Study

Chemical Composition (%)	
SiO_2	58.45
Al_2O_3	22.02
Fe_2O_3	6.41
CaO	3.13
MgO	2.15
SO_3	0.28
Na_2O	1.00
K_2O	1.39
TiO_2	0.92
Loss on Ignition	3.34

3.2.4 Crushed Limestone (Natural Sand)

Crushed limestone was used as natural sand in the mixtures. The sieve analysis was carried out according to ASTM C136-06. Specific gravity and water absorption tests were conducted according to ASTM C127-15. The gradation curve and physical properties measured in line with mentioned standards are shown in Figure 3.2 and Table 3.9.

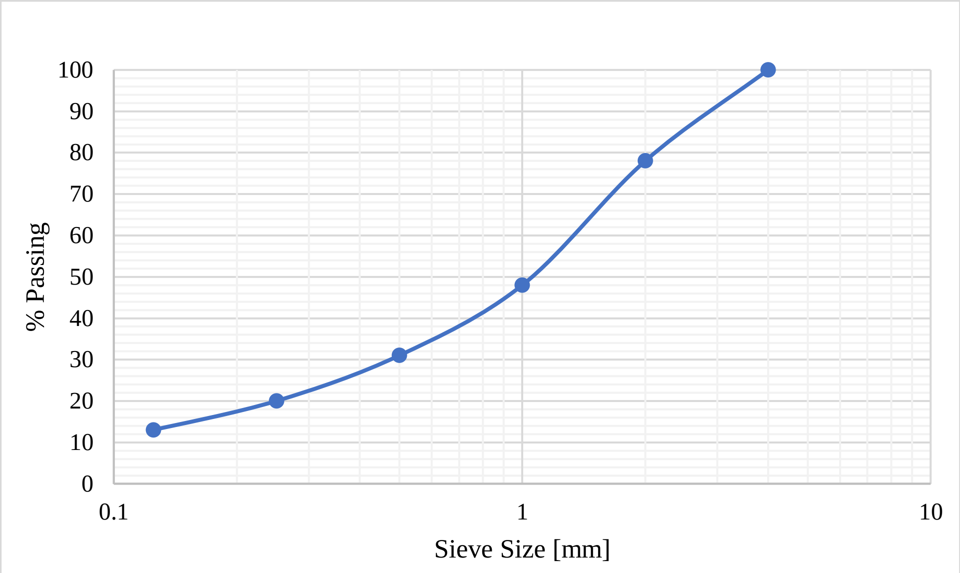


Figure 3.2 The Particle Size Distribution of Crushed Limestone

Table 3.9 Physical Properties of Natural Sand Used in the Study

Physical Properties	
Specific Gravity (Saturated Surface Dry)	2.64
Specific Gravity (Oven Dry)	2.58
Specific Gravity (Apparent)	2.70
Water Absorption (%)	2.32

3.2.5 Chemical Admixture – Superplasticizer

The commercial name of the used chemical was MasterRheobuild 1000. This product is used as high range water reducer and hardening accelerator. The admixture improves workability of concrete without the addition of additional water.

3.2.6 Water

The Middle East Technical University Civil Engineering Material Division Laboratory was used for the experimental program. During the production of specimens, METU tap water is used as mixing water.

3.3 Experimental Procedure

The experimental process starts with materials preparation. Cement and fly ash were directly used from their bags; therefore, their condition does not include anything particularly noteworthy.

Lightweight expanded clay aggregates are very porous and have high absorption capacities as mentioned earlier. Absorbed water amount inside lightweight aggregates increases over time as they are exposed to water. So, for this kind of material, dry or as-is condition usage yields non-homogeneous concrete production. Because uncontrolled water absorption can cause serious water loss, the water amount in the mixture is crucial for the hydration reaction of the cement. Therefore, using this material in SSD condition is the safest way to prevent uncontrolled water loss that is needed for hydration. In line with that characteristic of the material, expanded clay aggregates were immersed in water for at least 72 hours before batching as specified in ASTM C127-15 Standard Test Method for Relative Density and Absorption of Coarse Aggregate.

Before the batching process, cement, fly ash, sand, and mixing water were weighed in line with the calculations at mixture design. Coarse and medium-coarse expanded clay aggregates were dried with a towel to get them to the SSD state. For coarse and medium-coarse aggregates a towel was generally enough to ensure the SSD state, however, for fine expanded-clay aggregates, additional drying methods were applied besides wiping with a towel, with a drying machine. The drying machine was gently used while caring for the saturated condition, the machine used an adequate temperature with a constant angle focusing only on the surface of the material. After maintaining the SSD state of the expanded clay aggregates, they were also weighed in the needed amount.

Superplasticizer was also weighed in small cups containing 0.5% of the cement mass that was used in a mixture to be ready to use in increments. The chemical amounts were not pre-determined in the design, there were only guesses and some examples from the literature. The exact amount of chemical was determined in the batching process by visual inspections, considering workability and the slump results that were done instantly after mixing.

For batching, a Pan type of concrete mixer was used. The total volume of the mixer is 100L, however effective capacity is around 40-56 liters. The turning speed of the pan can be adjusted by the frequency controller. Mixer blades could be easily cleaned before proceeding to another batching and the capacity was enough for prepared mixtures. A photo of the mixer is presented in Figure 3.3.

Figure 3.3 Pan Type Concrete Mixer Used in the Study

First coarse, then medium coarse and fine aggregates were added to the pan - mixer. Then, SSD-state lightweight aggregates and natural sand are mixed for 3 minutes. Approximately 80% of the mixing water was added to the pan. After all dry components get wetted by water, cement was added to the mixture. The addition of cement was done step by step with a small cup because when all cement was added to the mixture, the mixing machine could not properly stir all the components to form a homogenous mix. Remaining mixing water was added either slowly while adding cement or added at the end of mixing all dry components with superplasticizer chemical. As mentioned earlier, superplasticizer amounts were not pre-determined, so with visual inspections, chemical admixture amounts were increased step by step until a workable and moldable mixture with adequate slump values are maintained. Superplasticizer was not used in every mixture, mixtures that have high water content did not require any chemical to adjust consistency. Figure 3.4 shows the mixture in the pan after batching and mixing process were over.

Figure 3.4 Sample Mixture as it Appeared in the Pan Mixer

After batching stage was over and a workable mixture was obtained, the mixture was poured into a plastic container for molding. 100 x 200 mm plastic cylinder molds were used. Form release agent was used inside of the molds with a wide brush before pouring concrete to ease the de-molding operation. Plastic molds were rodded for 25 times in two stages 50% and 100% full for better compaction. After the mold was filled, a mallet was used to remove entrapped air in the mixture. After this compaction process, the top of the mold was finished with a trowel to provide a smooth and flat surface. Plastic container and 100 x 200 mm plastic molds can be seen from Figure 3.5.

Figure 3.5 Plastic Container and Plastic Molds

Plastic molds were left still for hardening, but they were covered with a wet towel to prevent evaporation of water until de-molding. Specimens were placed and stored under a wet layer immediately after finishing to minimize moisture loss. Freshly placed molds and wet towels could be seen in Figure 3.6.

Figure 3.6 Freshly Filled Molds and Wet Towel Covering the Specimens

Specimens were removed from molds after at least 24 hours but not more than 30 hours. Regarding removal time, instructions from ASTM C192/C192M-18 were used. De-molding operation was carried out with an air compressor pump. Plastic molds have tiny holes at the bottom, allowing air to be pumped by preventing concrete from flowing out. Form release agent on the inner wall of the molds makes the process easier and safer.

Lastly, for curing, all the specimens were moist cured in a water tank with a constant temperature of 23.0 ± 2.0 C^{o}, and the entire surface area of specimens stayed under water until the moment of the planned test. For curing, instructions of ASTM C192/C192M-18 were used. The curing tank with some of the prepared specimens are shown in Figure 3.7.

Figure 3.7 Cylindrical Specimens Being Cured in the Curing Tank

3.4 Mechanical Test Performed

3.4.1 Compressive Strength

In this experimental study, compressive strength tests were conducted according to directives at ASTM C39/C39M after 7 and 28 days of curing. The 7^{th}-day, 28^{th}-day moist and 28^{th}-day dry compressive strengths were measured with tests conducted. Specimens were tested after saw cut from both ends after removal from moist storage, and for the time between testing and removal of specimens, permissible tolerance limits from mentioned standard were followed.

All specimens were saw-cut from both ends around 8 -10 mm thick and tested with a water gauge to check their perpendicularity. If specimens were perpendicular enough and meet the requirements written under Section 7 at ASTM C39, they were tested for compressive strength of a moist state.

For determination of 28th-day dry compressive strength, specimens that were previously saw-cut from the ends placed into the 50 C^o oven. That temperature was chosen to prevent potential formation of differential thermal cracks. Specimens were weighed every 24 hours until the change in mass was not more than 0.5 %, as stated in ASTM C567/C567M – 19. After making sure that the samples were dry, the samples were tested in a dry state. 3 specimens were tested for different strength parameters. A total of 9 specimens were used from each mixture to determine compressive strength parameters.

Loads were applied continuously without shock with a constant rate of 2.4 kN/s. After the failure of each specimen, ultimate strength data were noted. For most cases, fracture patterns and surface cracks were visually investigated, and some notes were taken for commentary. The picture of testing machine and testing setup was shown in Figure 3.8.

Figure 3.8 Compression Testing Machine and Experimental Setup

3.4.2 Splitting Tensile Strength

In this experimental study, splitting tensile strength tests were conducted according to directives at ASTM C496/C496M-17 after 28 days of curing. No additional process was applied to specimens before testing except wiping the excessive water on the specimens via towel.

Strength values were found by testing 3 specimens from each mixture and taking their averages. Loads were applied continuously without shock with a constant rate of 0.94 kN/s.

As shown in Figure 3.9, test were conducted with the same testing machine that was used for determining compressive strength, but special equipment was used for splitting tensile strength test. Special experiment set were shown in below. These metal casting parts were used to hold the sample properly and to direct the load at the middle as needed for determination of splitting tensile strength.

Figure 3.9 Splitting Tensile Strength Test Setup

3.4.3 Modulus of Elasticity

In this experimental study, static modulus of elasticity tests was conducted according to directives at ASTM C469/C469M – 22, after 28 days of curing. Same procedures in compression strength tests were followed for elasticity tests. 3 specimens for moist modulus of elasticity, 3 specimens for dry modulus of elasticity were used. Total of 6 specimens were used from each mixture for this test procedure.

Tests were conducted with a MTS Landmark 250 series of loading frame where the machine can load and unload the specimen up to specified units with constant loading without any shock. Specimens were loaded by 30 % of their ultimate compressive strength. Loading process comprise of 3 cycles with loading and unloading, then 3 different graphs were obtained for each loading-unloading cycle. 1^{st} cycle were excluded from calculations, within directives of ASTM C469.

Before loading the specimen, it was placed into compressometer, which is used for measuring the deformation that concrete cylinders undergo. The device includes two metal cast yokes connected with strong rod from one end, yokes have 3 screws on it, after placing the concrete specimen inside these metal circles, these screws were tightened to hold the specimen still. These circles are connected to each other with a rod at their one end, at the symmetrical end, there is a place for strain measurement device called LVDT. LVDT is an abbreviation of "linear variable differential transformer", this little measurement device is very sensitive and can measure 5 millionths the average deformation. LVDT device connected to the computer system, and transfers the displacement values to that system, displacement data were saved to create stress-strain graphs. Since screws were tightened to the concrete specimen, the compressometer that confines the concrete and the concrete itself acted as one structure. As the concrete started to deform under loading and displacement occurred in tiny amounts within the elastic range, LVDT started to measure some values since yokes were displaced, too, as they act as a single structure. Displacement cannot be detected by naked eye, however LVDT is a very sensitive measurement device as mentioned earlier. The schematic representation of the experimental set is as in Figure 3.10, the real picture of the setup where concrete specimen was placed inside shown in Figure 3.11.

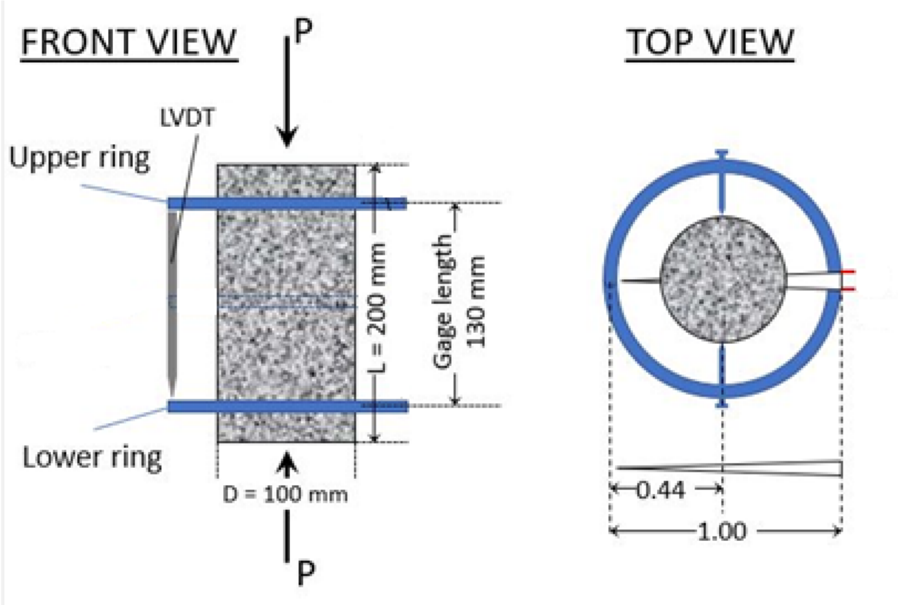


Figure 3.10 Schematic Representation of Compressometer Setup

Figure 3.11 Specimen that Placed in Compressometer in Experimental Setup

While loading and unloading cycles are occurring, the machine saves displacement values that measured with LVDT which is placed at compressometer. Obtained data which includes, time, displacement at certain time and force at certain time are then processed with a MATLAB code. After that process, load-time, LVDT displacement – time and stress-strain curves for each cycle were obtained. Load-time and displacement- time graphs are used for the conformation of the conducted test. Example graphs were shown in Figure 3.12 to explain the issue, shared graphs are from the measurement of one moist specimen of Mixture 8.

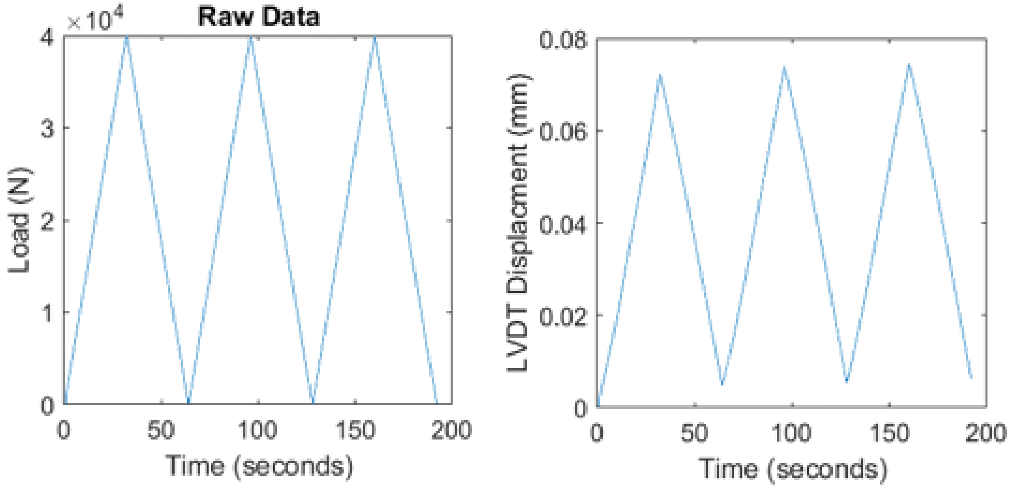


Figure 3.12 Typical Load-Time and Displacement-Time Data of a Specimen

The first graph verifies that each loading cycle finalized in same time interval and loading continued up to specified limit without any shock observed. The second graph shows the displacement over time. As we are loading the specimen in the specified elastic range, the tip of the wave should be aligned. This will verify that concrete specimen, deforms to a certain level and get back to its original form as we are loading the specimen in the elastic range. These two graphs were checked for every specimen, if any error were detected, tests were repeated, or new specimen of the same mixture were tested.

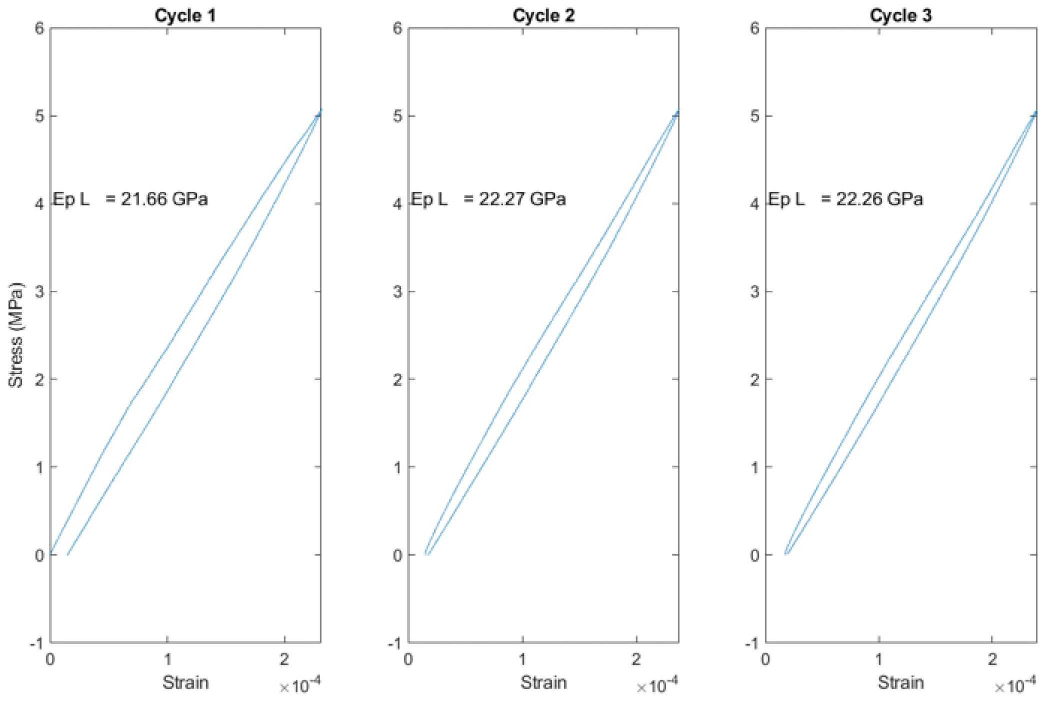


Figure 3.13 Typical Stress-Strain Plot of 3 Loading-Unloading Cycles

Stress-strain graphs were the other graphs that was obtained for each loading cycle. As mentioned before, the measurements of cycle 1 was excluded from calculations. Other two graphs were checked for any discontinuity or irrelevant trends or orientations. The line at graph should increase to certain level and come back to the starting point with a similar slope which verifies that we are at the elastic range and material shows elastic behavior. Just like other graphs, if any error were detected, test was repeated, or new specimen were tested. If the graphs are satisfying the sought criteria, calculated modulus of elasticity results were taken into account. Modulus of elasticity of each specimen is the average of values measured at the 2nd and 3rd loading cycle.

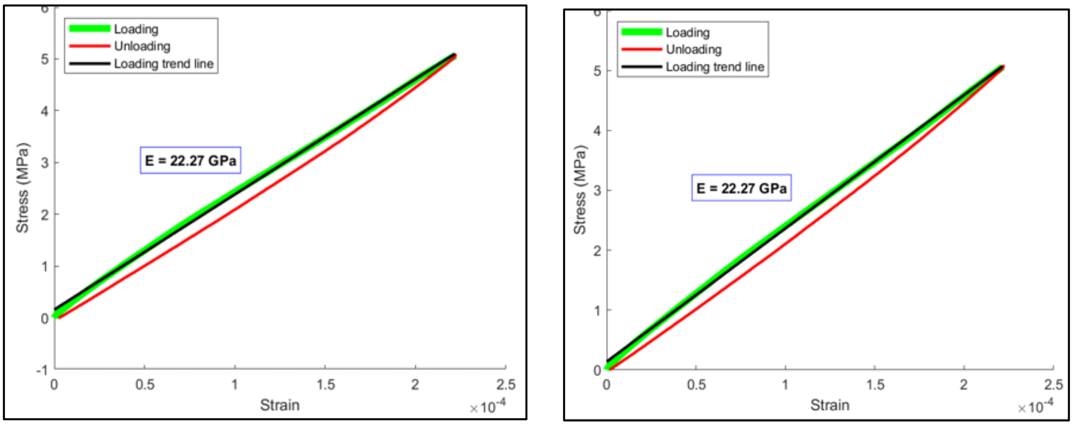


Figure 3.14 Detailed Stress- Strain Graphs of Cycle 2 and 3

These two graphs shown in Figure 3.14 are finalized graphs which shows the loading, unloading, and loading trend line. The average of those values is reported as static modulus of elasticity. The complete setup which shows compressometer, LVDT, concrete specimen placed in compressometer, and testing machine could be seen from the Figure 3.15.

Figure 3.15 Static Modulus of Elasticity Experimental Setup

CHAPTER 4

TEST RESULTS AND DISCUSSION

4.1 Density

Density is an essential physical parameter for concrete, especially when interpreting other concrete parameters. In this study, density results were also compared with all other parameters to check whether there were any relationships.

Fresh and oven-dry densities of the mixes were measured throughout the study. For each parameter, three specimens were measured from each mixture, and different values were obtained.

Density results are shown in Table 4.1 with mean values of 3 specimens, coefficient of variation and % change between wet and oven-dry density. The coefficient of variation (CoV) values was obtained by dividing the standard deviation of a selected sample by its mean and is a useful variable to understand the extent and the dispersion of the data used. The discrepancy is lower between specimens if CoV is closer to zero.

Density values were measured according to standard ASTM C567 and ASTM C138. Wet density of specimens were measured by weighing the specimens in surface dry condition, drying done by a towel. For the oven-dry density, specimens were placed in the oven and weighed periodically in every 24 hours; specimens were considered dry samples when the change in mass was measured less than 0.5%. Generally, 5 days were enough for an adequate drying process. However, specimens were kept for 7 days just in case and to ease the work schedule of the experiments. Fresh and oven-dry density results are shown below in Table 4.1.

Table 4.1 Mean Wet and Oven- Dry Density Test Results

Mixtures	**Fresh Density (kg/m³)**		**Oven – Dry Density (kg/m³)**		**Change (%)**
	Mean	CoV (%)	Mean	CoV (%)	
Mix #1	**1823**	3.5	**1713**	1.5	6.0
Mix #2	**1736**	0.6	**1611**	0.7	7.2
Mix #3	**1888**	6.2	**1806**	6.8	4.3
Mix #4	**1839**	0.7	**1758**	0.7	4.4
Mix #5	**1785**	2.6	**1630**	3.3	8.7
Mix #6	**1758**	1.5	**1606**	1.8	8.6
Mix #7	**1980**	0.3	**1908**	0.4	3.7
Mix #8	**1913**	1.3	**1840**	1.4	3.8
Mix #9	**1733**	1.2	**1613**	1.7	6.9
Mix #10	**1787**	2.2	**1697**	2.5	5.0
Mix #11	**1798**	1.5	**1727**	1.5	3.9
Mix #12	**1699**	1.4	**1619**	1.6	4.7
Mix #13	**1559**	2.2	**1457**	2.2	6.5

All density values appeared within reasonable and expected bounds and accommodate calculated values in the mixture design. CoV values are within acceptable limits, and the distinction is considered normal, as each specimen's molding procedure may differ because of the handmade process. From the table, only Mixture 3 and Mixture 5 seemed problematic as their variation coefficient were calculated significantly higher than other mixtures. These high values are because of segregation. Because when segregation occurs in the freshly mixed concrete, it was difficult to mold them properly, as creating homogenous specimens became almost impossible. Even in that case, too much attention has been paid, and the mixture was mixed by hand after filling each cylinder mold to ensure homogeneity.

In Mixture 3, 2% of superplasticizer was used; however, after the mixing process was over, it was understood that the used amount was redundant, especially when the water amount was reconsidered. That excessive amount of SP with high water amount also caused segregation in the mixture. Coarse LECA density is lower than water, which means that if unconfined, aggregates would float on water. Even some of the medium-coarse aggregates exhibit the same behavior. That situation eventually complicates the mixing process, if the designed mixtures' water amount and slump are high; that mixture tends to segregate more as aggregates inside the mixture tend to float. This case was observed very clearly in Mixture 3.

Segregation of Mixture 3 can be observed from Figure 4.1 below. This picture shows the saw-cut plates from both ends of the specimen; the left side was cut from the top of the specimen and the other one was from the bottom. This picture clearly shows how expanded clay aggregates floated in the mixture and were placed at the top side of the specimen. On the right side, mainly natural sand was observed with fine LECA that segregated from the mixture and sunk.

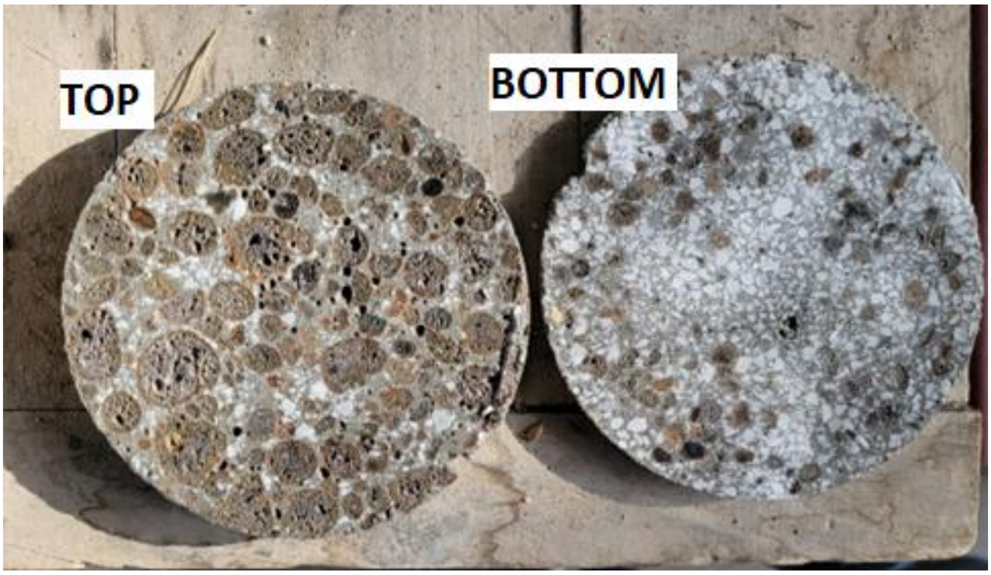


Figure 4.1 Cut Plates from Both Ends of Mixture 3

In Mixture 5, the problem was not the superplasticizer; it was the water itself. The mixture contained 300 kg of water: the highest value among all other mixes.

Segregation was also observed in this mixture, as water amount was high. The design of remaining mixtures was changed during the experiment phase upon this mixture to prevent further possible segregations. For example, w/c ratio of Mixture 6 was lowered from 0.6 to 0.5.

4.2 Porosity

Porosity is a crucial parameter for the mechanical properties and durability of concrete. Pores are directly affecting strength parameters and have a high impact on almost all durability parameters. When the scope of the study focused on the material expanded-clay aggregate, the porosity parameter has become even more crucial. Because LECA has a very porous structure, this characteristic of the material has a huge impact on some of the parameters. Porosity values were calculated by following formula;

$$Porosity = \frac{(M_{moist} - M_{dry})/\rho_w}{V_{concrete}} \times 100$$

Porosity values are calculated only by taking fresh and oven-dry masses of the specimens into consideration. No further tests were applied to calculate the porosity values. 3 specimens were used for calculations, and again their coefficient of variation were considered to verify the consistency. Porosity values are shown in Table 4.2.

Table 4.2 Porosity Values of Specimens for Each Mixture

Porosity Results (%)		
Mixtures	**Mean**	**CoV (%)**
Mix #1	10.98	4.5
Mix #2	12.49	0.2
Mix #3	8.13	7.5
Mix #4	8.13	1.3
Mix #5	15.55	5.2
Mix #6	15.20	2.8
Mix #7	7.27	2.3
Mix #8	7.31	0.6
Mix #9	12.00	6.7
Mix #10	9.01	4.8
Mix #11	7.09	1.9
Mix #12	7.99	2.8
Mix #13	10.18	3.7

As expected, fresh and oven-dry density values were decreased as the porosity of the mixture increased. Oven-dry density vs. porosity graph was shown in Figure 4.2 below.

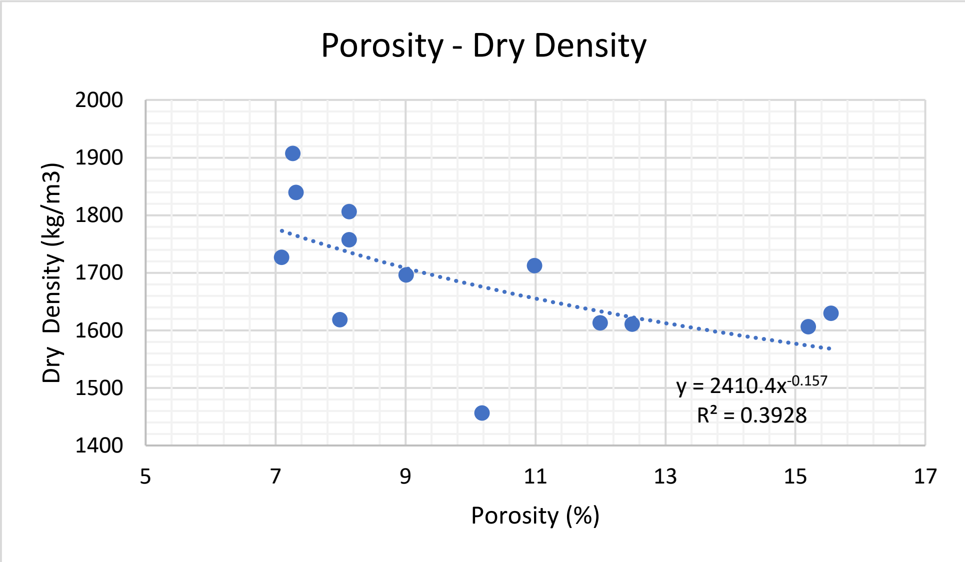


Figure 4.2 Relationship between Porosity and Dry Density

4.3 Compressive Strength

7-day, 28-day moist, and 28-day dry compressive strength tests were conducted. Test results were obtained using 3 specimens from each mixture. Their mean values were used for any comparison and calculation.

28^{th}-day compressive strength values are higher than 7^{th}-day results as expected. On the 7^{th} day, specimens reach approximately 70 – 80 % of their 28^{th}-day compressive strength for this study. The mean values of compressive strength test results are shown in Table 4.3.

Table 4.3 Compressive Strength Test Results (MPa)

Mixtures	7th Day Moist		28th Day Moist		28th Day Dry		Dry/Moist
	Mean	CoV	Mean	CoV	Mean	CoV	
Mix #1	15.7	0.2	18.6	4.4	21.1	4.1	1.14
Mix #2	16.0	6.9	19.2	3.1	20.5	5.6	1.07
Mix #3	17.6	2.7	25.8	1.9	28.5	12.8	1.10
Mix #4	23.9	4.1	26.8	0.6	28.5	7.6	1.06
Mix #5	13.6	1.3	15.5	1.8	18.2	7.8	1.17
Mix #6	14.6	7.7	20.7	7.0	21.7	2.7	1.05
Mix #7	26.5	6.2	29.9	6.3	31.2	3.4	1.04
Mix #8	24.4	4.3	35.6	5.0	37.9	1.7	1.07
Mix #9	13.2	4.1	20.9	8.9	22.2	9.9	1.06
Mix #10	16.6	3.4	27.0	8.9	28.9	6.2	1.07
Mix #11	20.1	0.7	24.6	7.9	27.0	4.8	1.10
Mix #12	15.5	3.2	22.1	5.3	27.0	2.2	1.22
Mix #13	14.2	4.3	21.1	3.2	21.6	2.7	1.03

Depending on the variables like water-to-cement ratio, cement dosage, and LECA volume; average 28 – day compressive strengths varied between 15 MPa and 36 MPa, and 28-day dry compressive strengths varied between 18 MPa to 38 MPa and as observed from Figure 4.4 both dry and moist compressive strength increased with increasing density. This situation is in line with other research found in literature (Wegian, 2012; Dilli et al., 2015). It should be mentioned that all of this data was obtained from compressive strength determined on moist state. However, this experimental study also includes 28-day compressive strength in an oven-dry state. As LECA is a porous material with high water absorption capacity, significant differences between moist and dry compressive strength were expected.

Higher compressive strength values were obtained after the drying process. This was explained by the pore pressure caused upon loading the concrete in compression. Free water in pores creates additional pressure to the walls of the capillary pores besides loading stress, that situation eventually accelerates the crack formation reduces the ultimate compressive load resulting in failures.

Because of this phenomenon, oven dried specimens showed an increase in compressive strength between 3 % to 22 % over moist state specimens as shown in Figure 4.3. Dry state compressive strength showed an increase of 9 % in average over moist state compressive strength.

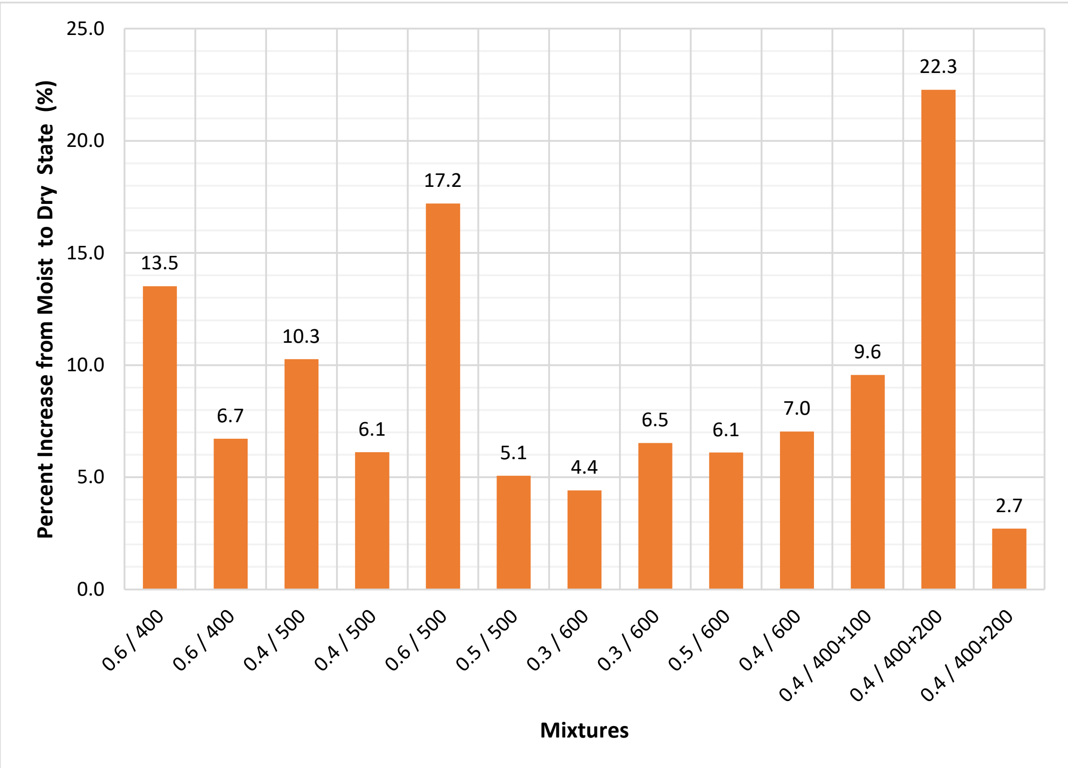


Figure 4.3 Percent Increase in Compressive Strength from Moist to Dry State

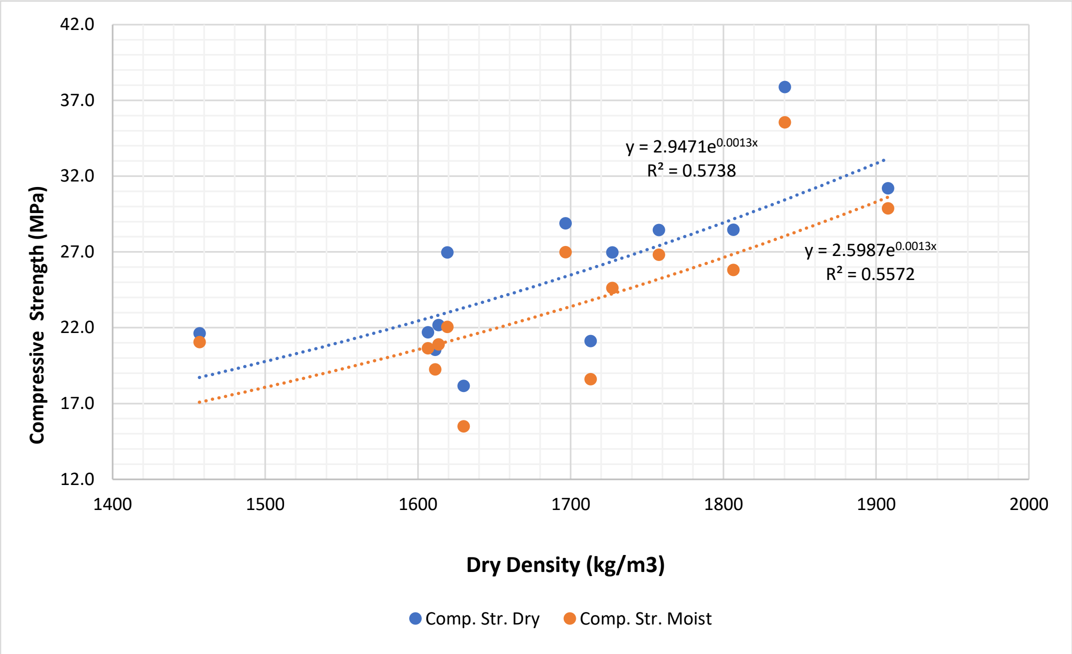


Figure 4.4 Change in Compressive Strengths with Dry Density

Porosity is also an important parameter while evaluating compressive strength because pores inside the concrete directly affects the strength. As capillary porosity increases, compressive strength decreases. Same thing observed in this study; as seen in Figure 4.5, compressive strength values decreased as porosity increased independent from its state or test day. Also, compressive strength increase can be seen from 7-day to 28-day and 28-day moist to 28-day dry.

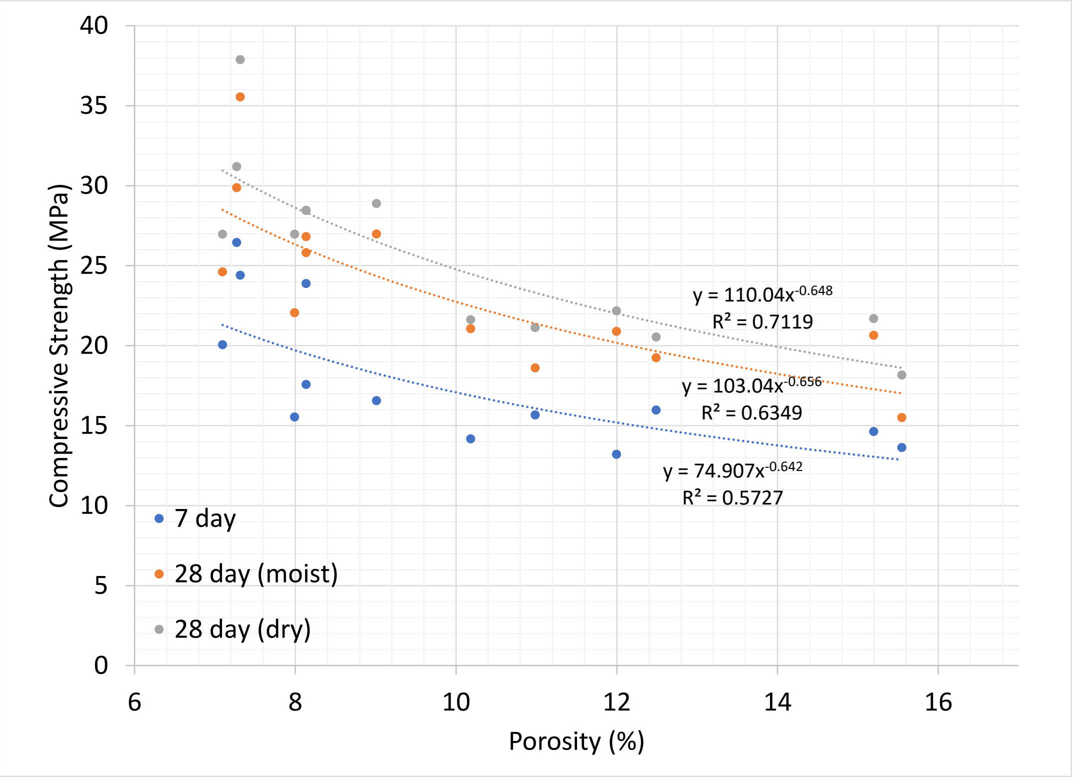


Figure 4.5 Effect of Porosity on the Compression Strength

Another crucial parameter that effects compressive strength is the water to cement ratio. When w/c ratio increases, the mixing water amount increases. In most cases, there can be more water than needed for cement hydration. That excessive water is important to ensure workability of concrete, cement could be full hydrated with less water, however in that case a workable concrete could not be obtained.

High water amount causes more evaporable water leading to pore formation. This situation can be seen from the Figure 4.6 below that showing the increase in porosity with the increase of water amount in the mixtures.

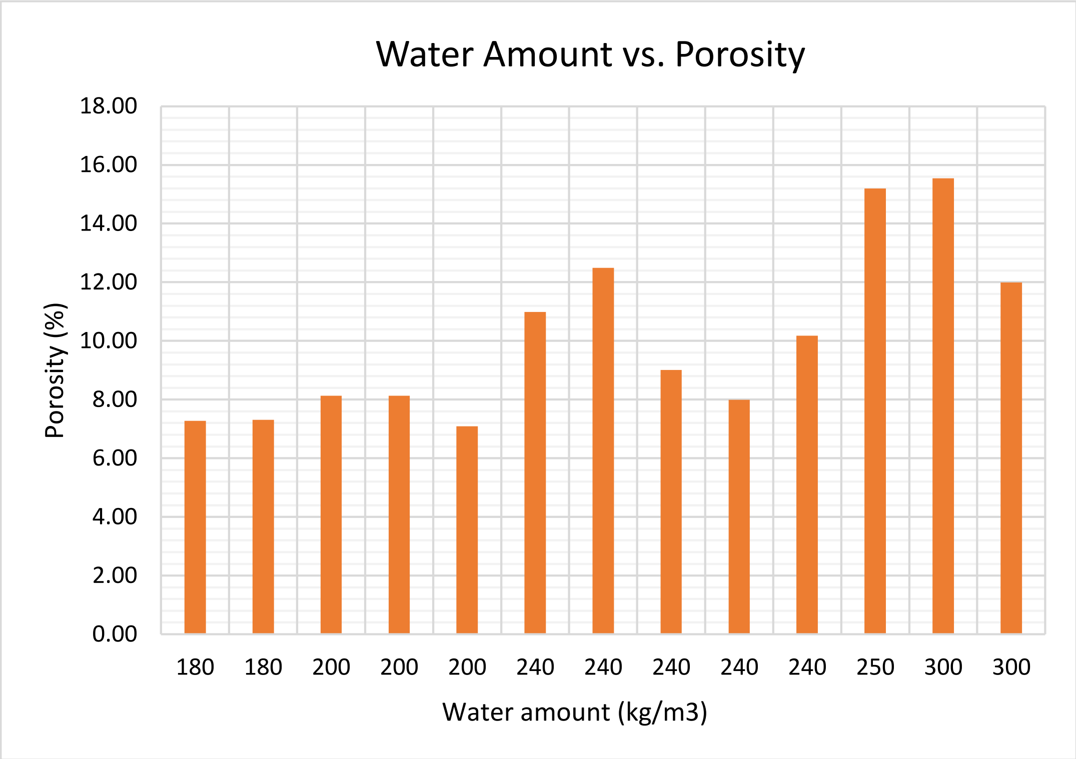


Figure 4.6 Water Amount vs. Porosity Graph

In this study w/c ratios varied between 0.3 to 0.6, the majority of mixtures designed with a w/c ratio of 0.4. As mentioned, while explaining relation between water amount and porosity, the compressive strength will decrease with the increase of w/c ratio.

4.4 Splitting Tensile Strength

Splitting tensile strength is also another parameter that can be used in the design of structural lightweight concrete. Tensile strength typically assumed to be as 1 / 10 of the compressive strength of concrete.

Splitting tensile strength of each mixture were shown in Table 4.4 below. The values are mean values which obtained from average of 3 specimens. CoV values were also shown in the same table below.

Table 4.4 Splitting Tensile Strength Test Results

	28th day Moist Strength				**Splitting Tensile to Compressive Strength Ratio**
	Splitting Tensile		**Compressive Str.**		
Mixtures	**Mean**	**CoV (%)**	**Mean**	**CoV (%)**	
Mix #1	2.12	6.9	18.6	4.4	0.114
Mix #2	2.06	0.4	19.2	3.1	0.107
Mix #3	2.06	7.5	25.8	1.9	0.080
Mix #4	2.20	8.6	26.8	0.6	0.082
Mix #5	1.85	8.1	15.5	1.8	0.119
Mix #6	1.95	4.5	20.7	7.0	0.095
Mix #7	2.09	0.5	29.9	6.3	0.070
Mix #8	2.06	5.8	35.6	5.0	0.058
Mix #9	1.70	4.1	20.9	8.9	0.081
Mix #10	1.64	1.3	27.0	8.9	0.061
Mix #11	1.82	6.6	24.6	7.9	0.074
Mix #12	1.42	8.5	22.1	5.3	0.064
Mix #13	1.02	5.2	21.1	3.2	0.049

The concrete structure has 3 main zones: cement paste, aggregates, and interfacial transition zone (ITZ). ITZ is a transition zone between aggregates and cement paste, it is a thin layer that formed around aggregates in the concrete structure. In conventional concrete, aggregate used in concrete mixture is the strongest zone, followed by cement paste, and ITZ is the weakest zone under any stress. For expanded clay lightweight aggregate concrete, the situation is not the same, LECA aggregate zone is weakest zone in the concrete matrix, as expanded clay aggregates are not strong as traditional gravel that is used in concrete.

For this experimental study, tensile strengths varied between 5 % to 12 % of compressive strengths of the same mixture. On average, the splitting tensile strength was 8.1 % of compressive strength for this study. Moreover, splitting tensile strength also increased as density of concrete increased, as observed in Figure 4.7.

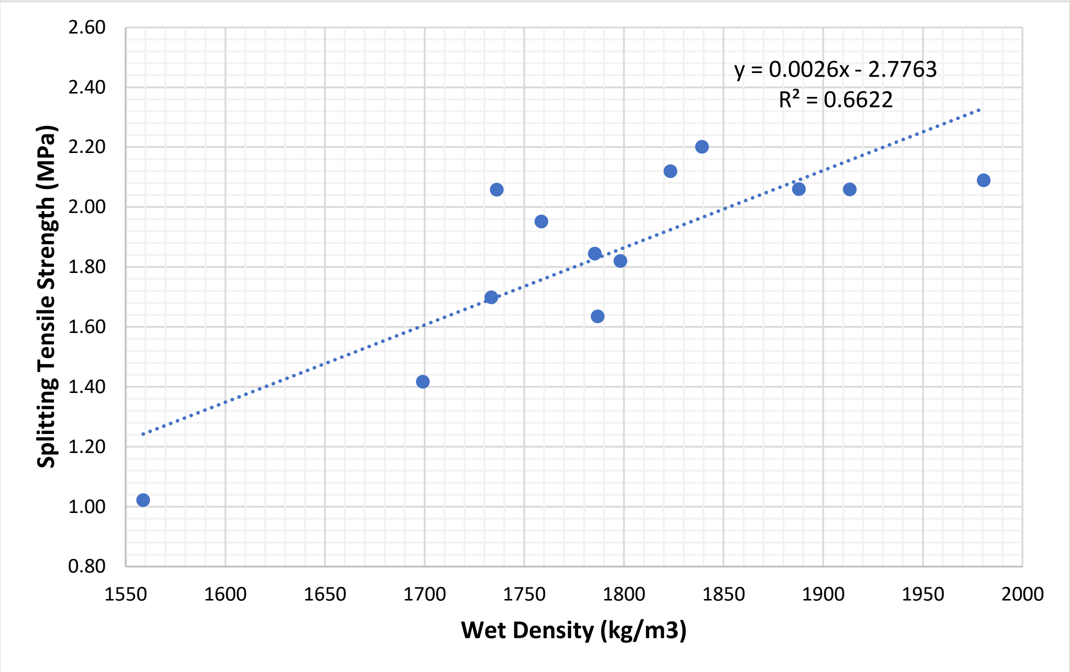


Figure 4.7 Splitting Tensile Strength vs. Density Graph

4.5 Modulus of Elasticity

The modulus of elasticity (MoE) is resistance of material to deformation within the elastic range. This parameter measured by loading the specimen between elastic range, where loading was not causing any permanent deformation on specimen. By loading the specimen within the elastic range, a stress-strain curve obtained, and the slope of that diagram yields the static modulus of elasticity value.

Table 4.5 shows the results of each mixture's moist and dry state modulus of elasticities. 3 specimens were tested from each mixture then their average was used in calculations while considering their variation.

Table 4.5 28^{th} Day Static Modulus of Elasticity (MoE) Results

Mixtures	Moist MoE (GPa)	CoV (%)	Dry MoE (GPa)	CoV (%)
Mix #1	17.1	11.3	14.9	6.0
Mix #2	16.4	0.4	12.8	1.7
Mix #3	18.7	0.9	11.8	1.8
Mix #4	24.5	6.3	12.9	14.9
Mix #5	17.6	1.8	10.8	14.7
Mix #6	15.4	12.3	12.6	9.2
Mix #7	20.8	16.1	19.6	4.0
Mix #8	22.4	0.9	16.3	2.4
Mix #9	13.9	3.4	11.8	12.1
Mix #10	15.5	2.5	13.0	8.4
Mix #11	18.5	1.6	12.4	7.1
Mix #12	17.1	4.3	10.8	7.7
Mix #13	12.3	8.7	8.8	13.8

As observed from the table, MoE values of specimens in the dry state are smaller than those obtained from the moist state. This was expected as the water inside the pores in the concrete matrix increases the elastic behavior of the concrete. The water inside creates an extra pressure inside, which increases the resistance of the material to deformation, it seems that extra pressure did not cause any problem in the elastic range when elasticity was considered. Because the case was different for the strength side, that additional pressure causes failure of concrete at lower uniaxial loads.(Yaman et al., 2002)

As presented in Figure 4.8, the decrease in MoE from the moist state to the dry state varied between 6 % to 47.6 %. The reduction between moist to dry state was found 26 % on average.

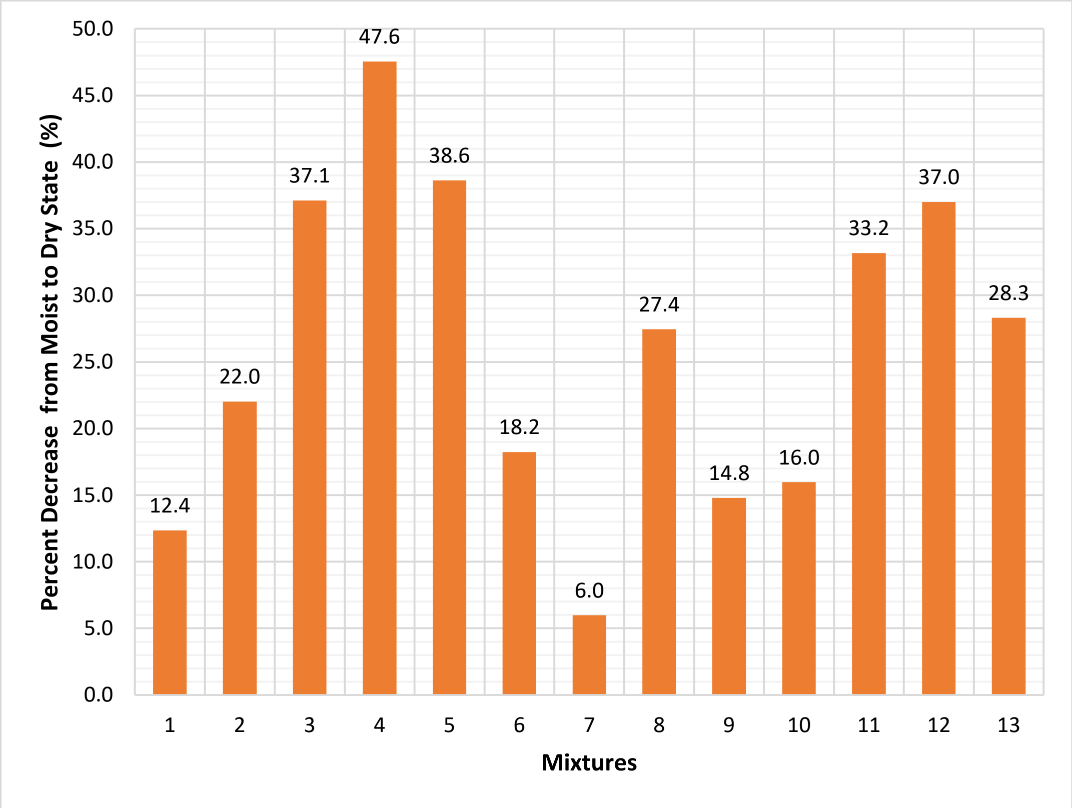


Figure 4.8 Percent Decrease in MoE from Moist to Dry State

MoE values were decreased as porosity increased as it can be seen from Figure 4.9 below. Porosity of concrete is one of the crucial parameters while discussing strength and durability of concrete. As porosity is observed as very effective parameter on compressive strength, it is also having a decisive role on the MoE of the concrete.

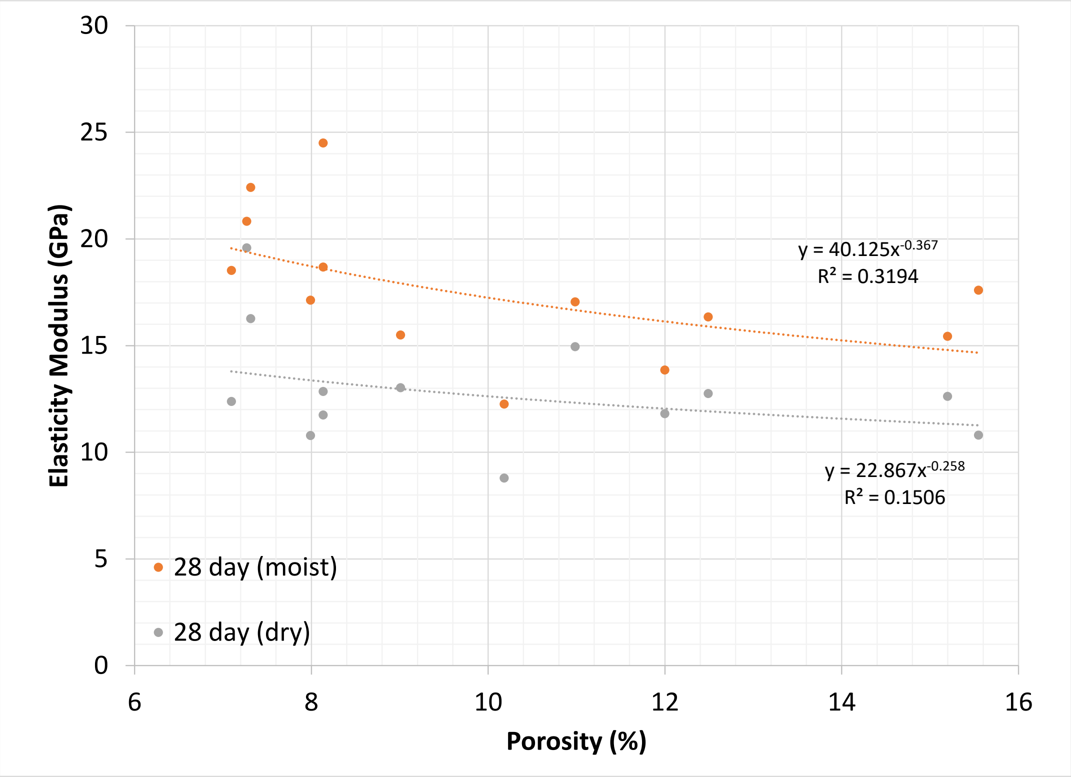


Figure 4.9 Effect of Porosity and Moisture State on the MoE

4.5.1 Comparison of MoE with Prediction Models

Measured MoE values were compared with some prediction models which are commonly used in literature. The used models are listed at below in Table 4.6.

Table 4.6 Static Modulus of Elasticity Prediction Models

Prediction Models	Equation	Parameters
ACI 318	$Ec = 0.043 \times w_c^{1.5}\sqrt{f_c'}$	w_c = Wet Unit Weight of Concrete f_c' = Compressive Strength of Concrete
ACI 363	$Ec = (3320\sqrt{f_c'} + 6900)(\frac{w_c}{2320})^{1.5}$	w_c =Wet Unit Weight of Concrete f_c' = Compressive Strength of Concrete
CEB - FIB	$Ec = 21500 \propto \times (\frac{f_c'}{10})^{1/3}$	f_c' = Compressive Strength of Concrete $\propto$= Coefficient for Aggregate Type
TS 500	$Ec = 3250\sqrt{f_c'} + 14000$	f_c' = Compressive Strength of Concrete
Dilli et. al. 2015	$Ec = 3000\sqrt{f_c'} * (\frac{w_c}{2300})^{3,7} + 12500$	w_c = Dry Unit Weight of Concrete f_c' = Compressive Strength of Concrete

The first four prediction models in Table 4.6 are suggestions from different national codes. The last one was proposed in a study by Dilli et al. (2015). Authors of that study also compared their study results with the prediction models listed here as well and proposed a model that matched their results more accurately. Their study includes MoE values of expanded clay aggregate concrete.

Table 4.7 Experimental MoE Values and Estimated Moist MoE by Models

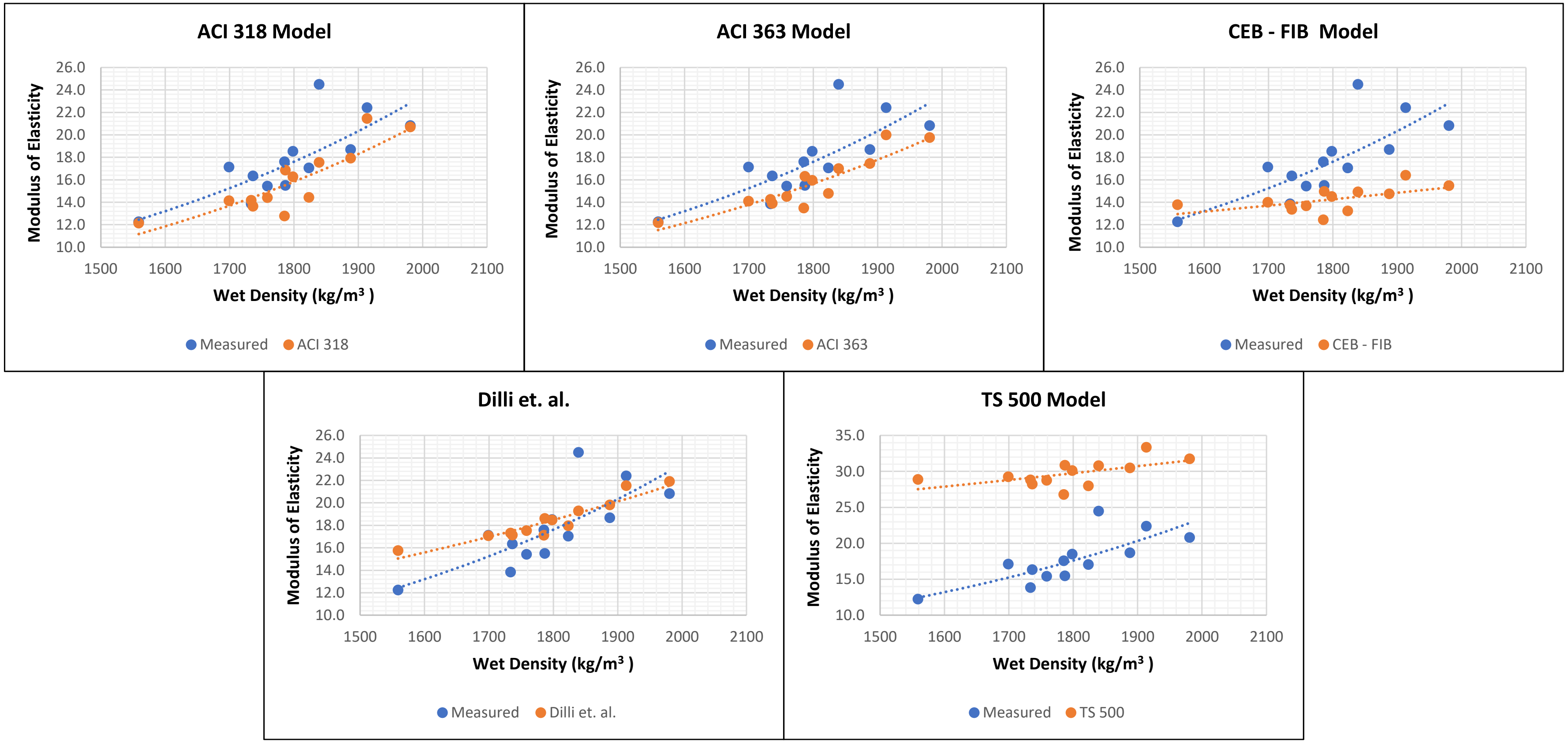
Mixtures	**E_{moist} (Experimental)**	**ACI 318**	**ACI 363**	**CEB-FIB**	**TS500**	**Dilli et.al.**
Mix #1	17.1	14.4	14.8	13.2	28.0	18.0
Mix #2	16.4	13.6	13.9	13.4	28.3	17.1
Mix #3	18.7	17.9	17.4	14.7	30.5	19.8
Mix #4	24.5	17.6	17.0	14.9	30.8	19.3
Mix #5	17.6	12.8	13.5	12.4	26.8	17.1
Mix #6	15.4	14.4	14.5	13.7	28.8	17.5
Mix #7	20.8	20.7	19.8	15.5	31.8	21.9
Mix #8	22.4	21.5	20.0	16.4	33.4	21.6
Mix #9	13.9	14.2	14.3	13.7	28.9	17.3
Mix #10	15.5	16.9	16.3	15.0	30.9	18.6
Mix #11	18.5	16.3	15.9	14.5	30.1	18.5
Mix #12	17.1	14.1	14.1	14.0	29.3	17.1
Mix #13	12.3	12.1	12.2	13.8	28.9	15.8

Table 4.7 includes, measured values of moist modulus of elasticity in this study, and calculated MoE values by using different prediction models. These values were compared by showing measured and calculated values on the same density – MoE graphs.

ACI 318 and ACI 363 prediction model slightly underestimates the measured modulus of elasticity results. There were some results that perfectly predict measured values, this can be seen from Figure 4.10, intersected points were the most accurate results. CEB – FIB prediction model's accuracy was low compared to the previous models. The slope of the predicted values trend was very different from the measured values. CEB-FIB prediction model worked better at lower densities; it can be clearly seen from Figure 4.10, model's predictions were closer in density value below approximately 1750 kg/m^3. After that point difference between predicted and measured values were significantly increased. TS 500 prediction model was significantly overestimating modulus of elasticity values, none of the values are close to each other, accuracy was very low in this model, when this experimental study's results were considered. When the graph was investigated, it can be observed that, predicted values are very high than measured ones, even the slope of the trends were not matching each other. ACI models were predicted results more accurately than CEB-FIB and TS 500 model, this situation can be explained by investigating the models. ACI models include 28^{th} day compressive strength and weight of concrete at the same time, however other two models only include 28^{th} day compressive strength of concrete. Including more parameter to the model increases the accuracy of the prediction.

Lastly, set of figures also includes the predicted results obtained from the model proposed by Dilli,2015. The model was modified for expanded clay aggregate concrete. As can be observed from the graph, the Dilli's model more accurately predicts the measured values when compared with other prediction models, especially after the density value of 1700 kg/m3, the model worked better in estimating.

Figure 4.10 Experimental Moist MoE values vs. Predicted Results via Models



CEB-FIB model also involves a special coefficient which varies with the type of the aggregate used in the concrete, because aggregate type is a crucial factor that affects the modulus of elasticity. However, the code has ∝ values for commonly used aggregates like basalt, limestone, quartzite, limestone, and sandstone aggregates, however it does not specify a value for lightweight expanded clay aggregate. Figure 4.11 showing the values when ∝ taken as 0.5, this value was taken from the literature, following the suggestions of Dilli, 2015 for expanded clay aggregate. This suggested 0.5 value were compared values obtained by α = 0.6 and α = 0.7, to see whether these values may give more accurate results than α = 0.5.

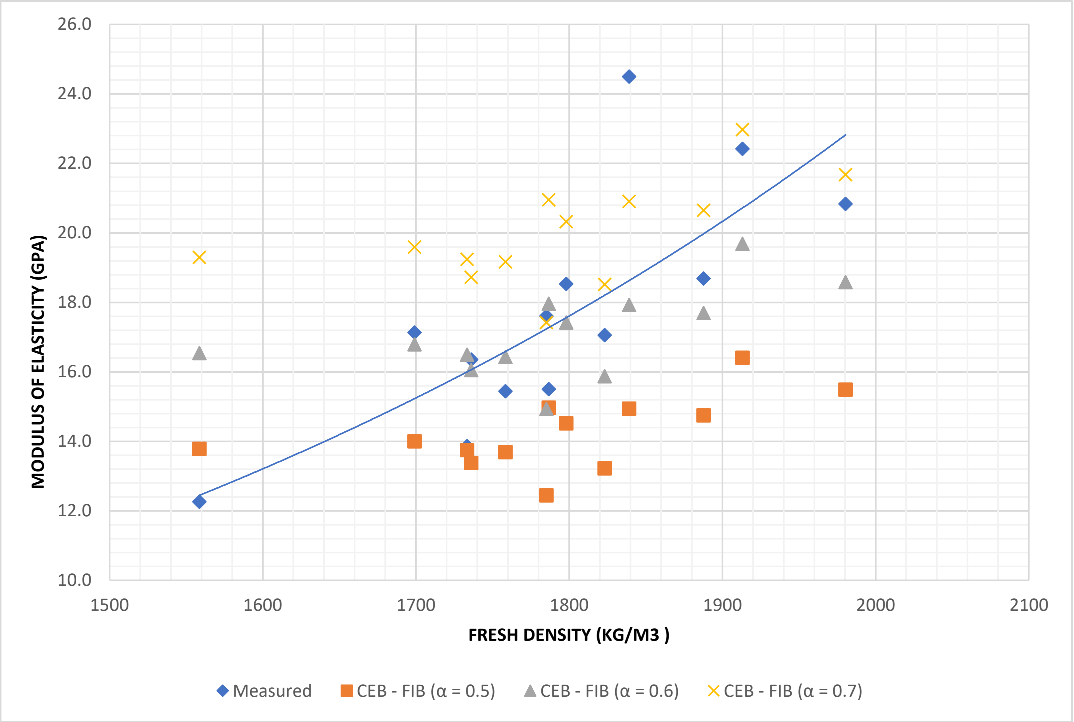


Figure 4.11 Measured Moist MoEs vs. CEB – FIB Model with Different ∝ Values

In Figure 4.11, different values of α were compared, and the modulus of elasticity values was predicted by taking α as 0.5, 0.6 and 0.7. Higher and lower values for α were not included in the figure as these values yield significantly low or significantly higher values than the measured ones. When α = 0.6, more accurate predictions were observed, even if the slope of the trend did not change and still differs from measured ones, model worked better in estimation of values especially in between densities 1700 – 1900 kg/m^3. Therefore, from the comparison of these different values from the figure, this experimental study suggests taking "α "as 0.6 when expanded clay aggregates were considered. Although, 0.6 value yielded better prediction results with this study's experimental results, more investigation should be made to certainly decide on this coefficient.

The accuracy of these different models can also be observed from Figure 4.12 below. TS 500 significantly overestimates the measured values, and clearly worked worse than other models when expanded clay aggregate concrete was considered. The other models were compared in the figure, the x-axis is for measured and the y-axis is for predicted MoE values.

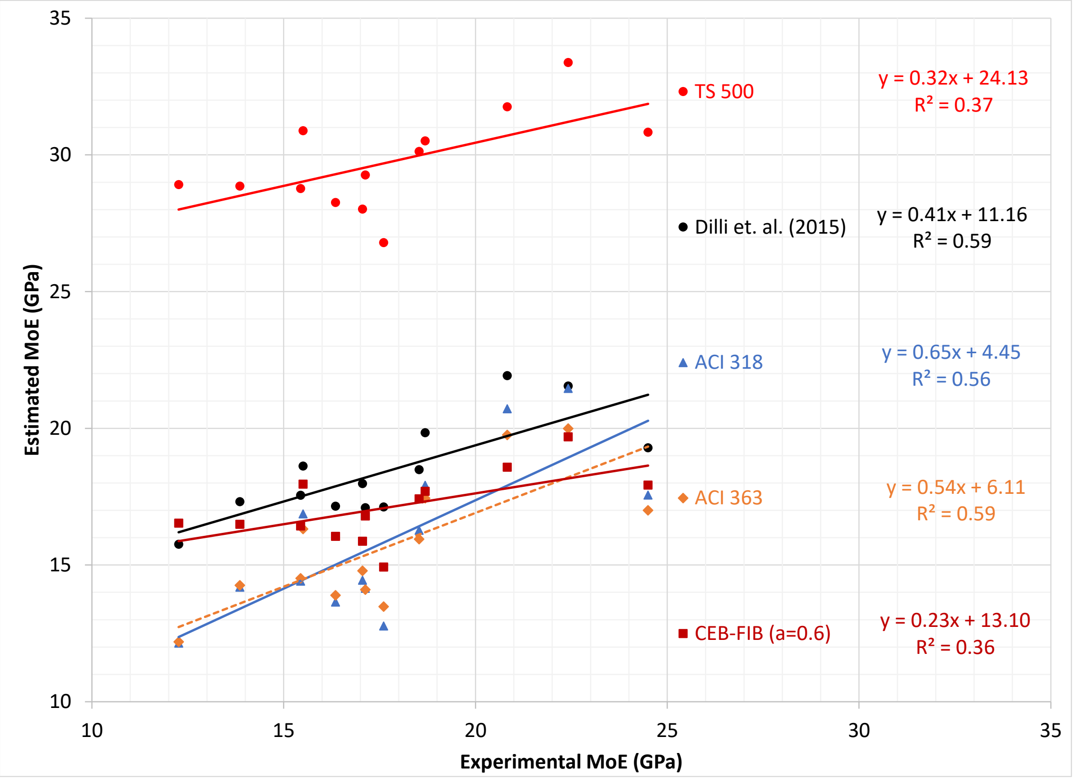


Figure 4.12 Measured Moist MoEs vs. Predicted Values for Different Models

The accuracy of models can be visually investigated via Figure above; however some numeric coefficients were calculated to express the difference between them. First, correlation coefficient and coefficient of determination were calculated for each prediction model. The results can be seen from Table 4.8, correlation coefficients are used to determine the strength of the correlation between two variables. The result will indicate a better correlation if it is closer to the 1. From the results, highest values were obtained for Dilli's model as expected. Which means correlation in that model was highest, then it followed by ACI models and least correlation were observed in other two prediction models.

Table 4.8 Correlation Coef. and Coefficient of Determination of Models

Prediction Models	**Correlation Coef. (r)**	**Coefficient of Determination (R^2)**
ACI 318	0.75	0.56
ACI 363	0.77	0.59
CEB - FIB	0.60	0.36
TS 500	0.61	0.37
Dilli et. al. (2015)	0.77	0.59

However, in most cases, the correlation coefficient and coefficient of determination are misleading when the accuracy is considered. Although they show the correlation between two different variables, they do not include the differences between calculated and predicted values, thus errors in the model. For this reason, Mean Squared Error was calculated to show and compare the accuracy of these different prediction models. MSE tells about the amount of error in statistical models. It assesses the average squared difference between the measured and predicted values. When a model perfectly predicts all values, MSE equals zero. As the MSE value increases, the error of the model increases, and the accuracy of the model decrease.

The formula of the MSE was shown below, y_i corresponding measured value, y_i' corresponds predicted value and n is the number of observations.

$$MSE = \frac{\sum(y_i - y_i')^2}{n}$$

MSE values for prediction models was shown in below Table 4.9.

Table 4.9 Mean Squared Error Values of Prediction Models

Prediction Models	**MSE Values**
ACI 318	8.02
ACI 363	8.50
CEB - FIB	7.62
TS 500	151.13
Dilli et.al. (2015)	5.43

According to these values, ACI and CEB-FIB model's accuracy was observed very close to each other. Among those there, CEB – FIB was better with a MSE value of 7.62. The TS500's error rate was significantly high as expected. The smallest value was obtained as 5.43 for the Dilli et.al. Model, which means it has the highest accuracy and precision among other prediction models. These MSE values are proving visual investigations and comments on accuracy which are held in the previous section.

Same prediction models were also used for calculating dry modulus of elasticity values by using dry densities and dry compressive strengths, to see whether these prediction models are working well with parameters at dry state. Measured values and predicted results are shown in

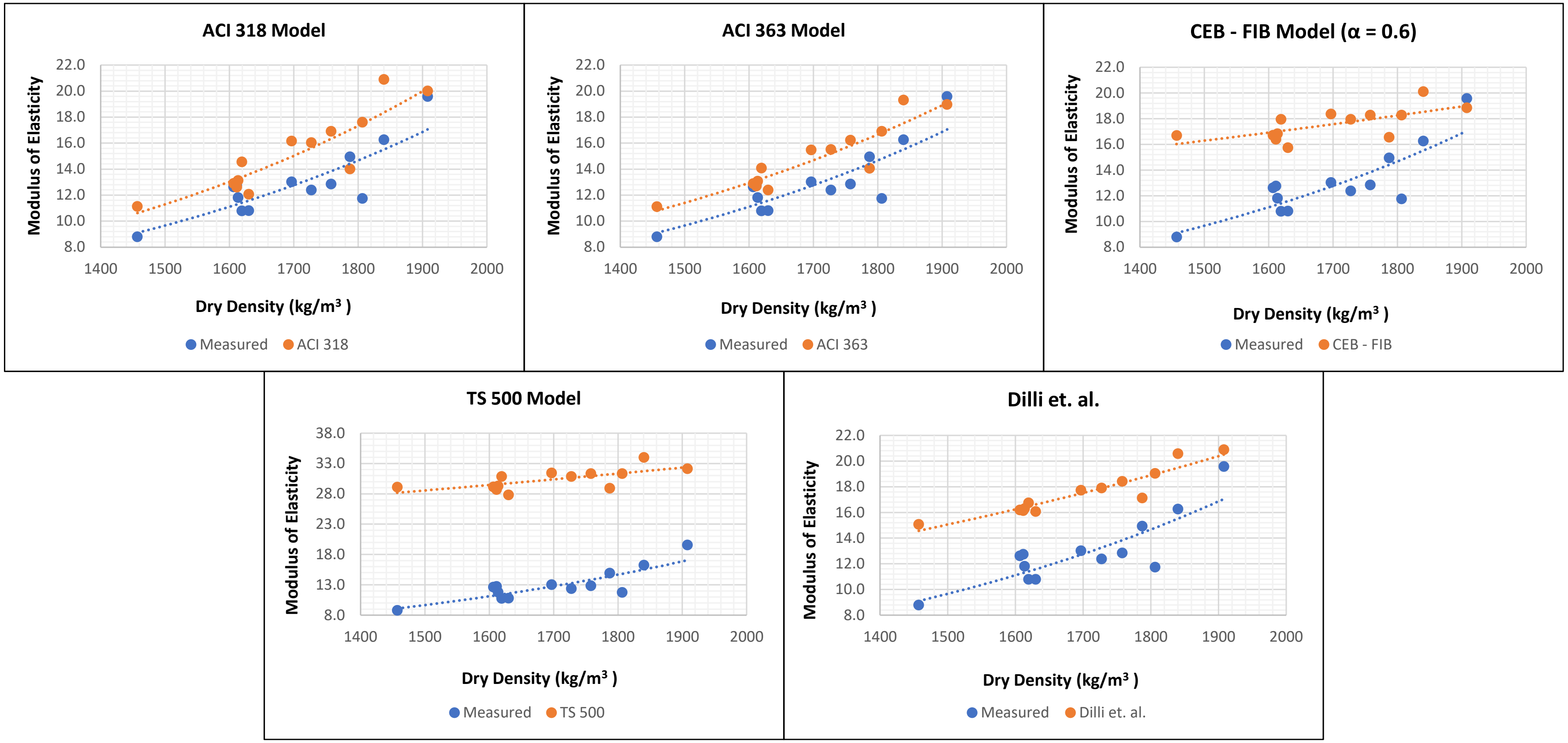
Table 4.10.

Table 4.10 Results of Dry MoEs Prediction Models

Prediction Models for Moe – Dry State						
Mixtures	**Measured Values**	**ACI 318**	**ACI 363**	**CEB-FIB**	**TS500**	**Dilli et. al.**
Mix #1	14.9	14.9	15.0	13.8	28.9	17.9
Mix #2	12.8	12.6	12.7	13.7	28.7	16.1
Mix #3	11.8	17.6	16.9	15.2	31.3	19.0
Mix #4	12.9	16.9	16.2	15.2	31.3	18.4
Mix #5	10.8	12.1	12.4	13.1	27.9	16.1
Mix #6	12.6	12.9	12.9	13.9	29.1	16.2
Mix #7	19.6	20.0	19.0	15.7	32.2	20.9
Mix #8	16.3	20.9	19.3	16.8	34.0	20.6
Mix #9	11.8	13.1	13.1	14.0	29.3	16.3
Mix #10	13.0	16.1	15.5	15.3	31.5	17.7
Mix #11	12.4	16.0	15.5	15.0	30.9	17.9
Mix #12	10.8	14.6	14.1	15.0	30.9	16.8
Mix #13	8.8	11.1	11.1	13.9	29.1	15.1

Same graphs were prepared to assess the accuracy of prediction models, figures below show predicted and measured values by related dry densities.

Figure 4.13 Experimental Dry MoE values vs. Predicted Results via Models



When, Figure 4.13 was investigated, ACI 318 and ACI 363 Models slightly overestimates the measured values and the slope of their trendlines were observed similarly. CEB – FIB model yielded less accurate results than fresh MoE prediction when α taken as 0.6. Therefore, α = 0.5 were tried and more accurate predictions were obtained. It can be clearly observed from Figure 4.14 that α = 0.5 resulted more accurate predictions. So, it would better to use α = 0.5 when Dry Modulus of Elasticities were considered within CEB – FIB Model.

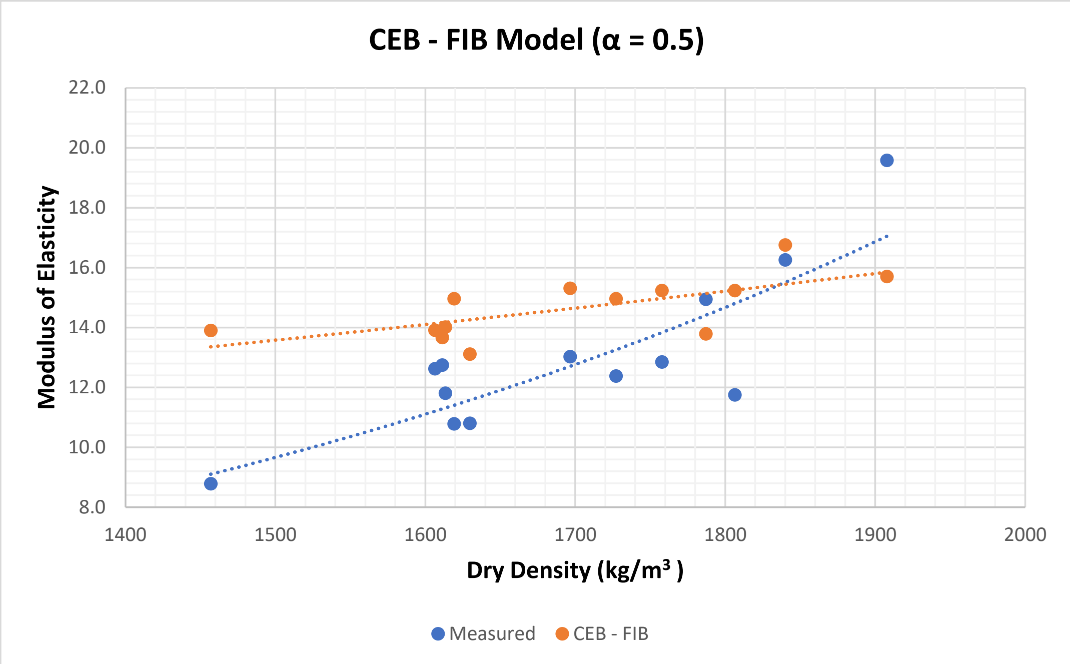


Figure 4.14 Measured Dry MoEs vs. CEB – FIB Model (α = 0.5)

TS 500 Prediction Model again highly overestimated the measured results, and the reasons are in line with the problems that mentioned in the prediction of moist state MoE results.

Model by Dilli et.al. predicted less accurate results than moist MoE and significantly overestimated the measured values.

Figure 4.15 is showing, predictions of different models. Unlike the prediction results in moist MoE, Dilli's model seemed as the least precise model for Dry MoE when TS500 was not considered. ACI318 and ACI363 Models observed more accurate in predicting Dry MoEs than moist ones. Correlation coefficients and MSE values were investigated again for Dry MoEs to see certain results about the accuracy of the prediction models.

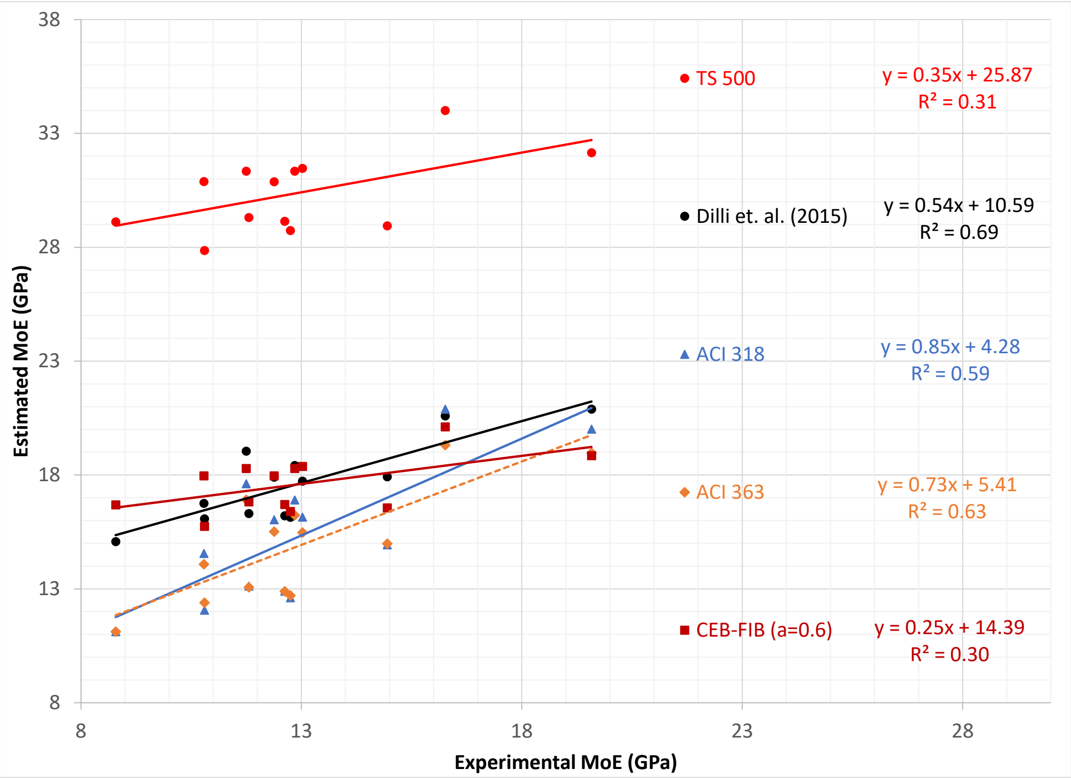


Figure 4.15 Measured Dry MoEs vs. Predicted Values for Different Models

Table 4.11 Correlation Coefficients and Coefficient of Determination of Models

	DRY MoE		MOIST MoE	
Prediction	Correlation	Coefficient of	Correlation	Coefficient of
ACI 318	0.77	0.59	0.75	0.56
ACI 363	0.79	0.63	0.77	0.59
CEB - FIB	0.55	0.30	0.60	0.36
TS 500	0.55	0.31	0.61	0.37
Dilli et.al.	0.83	0.69	0.77	0.59

This time correlation coefficients and coefficient of determination values for both dry and moist state predictions were shown in the Table 4.11. It can be clearly understood from here that these coefficients are not showing the accuracy of the prediction model. Correlation coefficient calculated as 0.83 which is higher than the calculated value for Moist MoE, 0.77. It is closer to the 1 which means, stronger correlation was observed. However, it can be clearly observed from previous figures, Model by Dilli et.al. is less accurate in prediction of Dry Modulus of Elasticities. Therefore, Mean Square Error is a more reliable parameter when the accuracy of a prediction model is considered. MSE values for results of models were shared for both dry and moist states in below Table 4.12.

Table 4.12 Mean Squared Error Values of Prediction Models for Dry and Moist State

	DRY MoE	MOIST MoE
Prediction Models	MSE Values	MSE Values
ACI 318	9.11	8.02
ACI 363	6.45	8.50
CEB - FIB	7.89	7.62
TS 500	309.06	151.13
Dilli et.al.	24.12	5.43

For prediction of Dry Modulus of Elasticities, most precise and accurate prediction were done by ACI 363 Model. Accuracy significantly improved from moist state when dry values were considered. Good performance followed by CEB – FIB and

ACI 318 Models, both decreased their accuracy when compared to moist state, but the difference was not significant as observed in ACI 363. TS500 Model's accuracy was found to be even worse than moist state prediction. A similar observation can be made in the Model by Dilli et al. While this model was the best performer when Moist state MoEs were considered, for Dry state MoEs, it can be counted as least accurate when TS500 Model results are excluded from the context.

4.5.2 Creating a Unique Model for MoE Prediction

This study also proposed a unique Modulus of Elasticity Prediction Models for both moist and dry state, these models were obtained by using regression analysis method on measured parameters of this experimental study. As national codes and models in literature includes compressive strength and unit weight of concrete as variables, this unique model is also comprised of two independent variables; compressive strength and unit weight of concrete to predict modulus of elasticity of concrete.

Proposed unique model for predicting Moist Modulus of Elasticity was shown below.

- $E_{moist} = 0.0204\, w_c + 0.14\, f_c' - 22$

Proposed unique model for predicting Dry Modulus of Elasticity was shown below.

- $E_{dry} = 0.0271\, w_c + (f_c')^{0.275} - 30.5$

These models were prepared using the regression method in Excel. In the following, the accuracy and precision of the proposed model were investigated and compared with other prediction models assessed throughout this study. From this point, the model will be referred to as the Proposed Model by Uysal. Prediction results were shown in Table 4.13.

Table 4.13 Measured and Predicted Moist MoE of Proposed Model by Uysal

Mixtures	Moist MoE Values		Dry MoE Values	
	Measured	**Predicted**	**Measured**	**Predicted**
Mix #1	17.1	17.8	14.9	15.6
Mix #2	16.4	16.1	12.8	10.9
Mix #3	18.7	20.1	11.8	15.9
Mix #4	24.5	19.3	12.9	14.6
Mix #5	17.6	16.6	10.8	11.4
Mix #6	15.4	16.8	12.6	10.7
Mix #7	20.8	22.6	19.6	18.6
Mix #8	22.4	22.0	16.3	16.6
Mix #9	13.9	16.3	11.8	10.9
Mix #10	15.5	18.2	13.0	13.0
Mix #11	18.5	18.1	12.4	13.8
Mix #12	17.1	15.7	10.8	10.9
Mix #13	12.3	12.7	8.8	6.7

Newly proposed model predicts the measured values for this study better when compared to other prediction models mentioned. The situation can clearly be seen from calculated statistical values. Correlation coefficients, coefficient of determination and Mean Square Error values were showed in Table 4.14 and Table 4.15.

Table 4.14 Correlation Coefficient and Coefficient of Determination of Models including Uysal's Model for Both Moisture States

Prediction Models	**Moist State MoE**		**Dry State MoE**	
	r	**R^2**	**r**	**R^2**
ACI 318	0.75	0.56	0.77	0.59
ACI 363	0.77	0.59	0.79	0.63
CEB - FIB	0.60	0.36	0.55	0.30
TS 500	0.61	0.37	0.55	0.31
Dilli et.al.	0.77	0.59	0.83	0.69
Proposed Model	**0.79**	**0.63**	**0.84**	**0.70**

Table 4.15 Mean Squared Error Values of Prediction Models

Prediction Models	**MSE Values for Moist MoE**	**MSE Values for Dry MoE**
ACI 318	8.02	9.11
ACI 363	8.50	6.45
CEB - FIB	7.62	7.89
TS 500	151.13	309.06
Dilli et.al.	5.43	24.12
Proposed Model	**3.97**	**2.88**

It can be seen from Table 4.14 and Table 4.15, that the new proposed model is so far the best performer when this study's measured values were considered. The model showed a strong correlation between measured values and predicted ones. At the same time, the model predicted the measured values more accurately when compared with other prediction models, this situation was proven by obtaining the smallest MSE value among other models. The situation was expected as this model were created by using this study's measured values.

4.5.3 Checking the Reliability of Unique Model for MoE Prediction

The proposed unique model yields good results with this study's measured values as they are created using them. However, further evaluations should be made to check this model's reliability. In this manner, five different experimental studies from literature focusing on the expanded clay aggregate concrete and the Modulus of Elasticity were investigated. Using their measured density and compressive strength values, corresponding MoE values were predicted by the proposed model and compared with their measured MoE values. Predicted results and measured values with the used parameters are shown in Table 4.16.

The proposed model for moist state MoE was used for the prediction, and the wet density values and the 28th-day compressive strength results of studies were used. In the first four studies in the table, MSE values are significantly low, especially when previously obtained MSE values were considered for this study's measured results. Only in the last experimental study's parameters, Youm et al. yielded significantly higher values than measured ones with a MSE value of 25.91. In the first three studies, better MSE values were obtained than the best-performed prediction models investigated in this study. The fourth study yielded a MSE value of 5.53 which is still very close to the value of the best performer of the moist state prediction. These four studies from the literature increase the model's reliability in accurately predicting MoE values. On the other hand, the last study presented in the table by Youm et al. may hint that the model may not be optimal for higher density values. This is somewhat expected as the mathematical model is based on lightweight aggregates, hence lightweight concrete.

Table 4.16 Measured Results of Experimental Studies, Predicted MoE values and MSE Results

	Wet Density	Comp. Str.	Measured MoE	Predicted MoE	Squared Errors	MSE
Malesev et.al. (2014)	1854	38.1	22.4	21.2	1.46	**0.62**
	1902	40.5	23.2	22.5	0.55	
	1877	36.3	21.5	21.4	0.02	
	1850	33.0	21.4	20.4	1.01	
	1890	37.9	22.1	21.9	0.07	
Bogas et.al. (2012)	1797	31.8	19.1	19.1	0.00	**0**
Karamloo et. al. (2016)	1939	35.0	25.1	22.5	7.07	**2.75**
	1891	32.6	23.1	21.1	4.02	
	1929	32.3	23.3	21.9	2.06	
	1890	25.4	20.3	20.1	0.03	
	1929	29.0	23.2	21.4	3.22	
	1889	21.6	19.2	19.6	0.11	
Dilli et.al. (2015)	1799	30	22	18.9	9.61	**5.53**
	1749	25	20	17.2	7.95	
	1710	21	15	15.8	0.68	
	2101	62	29	29.5	0.29	
	2075	51	25	27.5	6.10	
	2005	43	22	24.9	8.54	
Youm et.al. (2016)	2053	46.1	20.89	26.34	29.65	**25.91**
	2038	47	21.02	26.16	26.37	
	2006	47.9	20.97	25.63	21.70	

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, mechanical properties of lightweight expanded clay aggregate concrete were examined. In line with the detected gap in the literature, this experimental study focuses mainly on moist and dry state values of the mechanical properties. In this context, this experimental study covered the determination of fresh and oven-dry densities, porosity, moist and dry state compressive strength, moist and dry state modulus of elasticities of the prepared mixtures. Mixing proportions were designed to obtain reasonable distribution of density values within the acceptable limits of creating structural lightweight concrete. Parameters such binder amount, mineral additives, water to binder ratio and LECA volume chosen meticulously to create a parametric study which shows relations between parameters adequately. Within this scope, 13 different mixture design were prepared. These parameters were analyzed and relations between them were investigated. The following conclusions can be drawn:

- LECA has a low density and a porous structure. Coarse and medium-coarse aggregates were observed to float in water. Due to such behavior of aggregates, extra attention is needed to prevent segregation during mixing. Superplasticizer should be utilized meticulously in order to prevent segregation especially in mixtures where water content is high.
- Porosity is parameter that has an important impact on the mechanical properties of concrete. In LECA concrete it has an even more determining role as LECA has a porous nature. In this experimental study, porosity was found to be also related with water to cement ratio as in conventional concrete. When the water amount in the mixture increases, capillarity also

increases and that causes the formation of unwanted pores which adversely affect the concrete's strength. Within the result of this study, porosity increased as the water-to-binder ratio increased.

- 28th day moist compressive strength values varied between 15 MPa to 36 MPa and 28th day dry compressive strengths varied between 18 MPa to 38 MPa. Compressive strength values were increased after the drying process because the water inside the concrete in moist state causes extra stress towards the surrounding matrix under loading, this extra stress accelerates the crack formation thus fracture. Dry compressive strength values are 9.0 % higher in average than moist compressive strength values. Increment was measured 3 % in minimum and 22 % at maximum.
- Increased porosity decreased the compressive strength values.
- Modulus of Elasticity values in the moist state varied between 12.3 – 24.5 GPa, for the dry state they varied between 8.8 to 20.8 GPa. The modulus of elasticity values was decreased significantly when specimens were oven-dried, the decrement amount varied between 6 % to 47.6 % with an average of 26 %. That decrease was explained by free water inside the pores inside the specimen that caused extra stress which increases the resistance of the specimen.
- Modulus of Elasticity in both dry and moist states decreased as the porosity of concrete increased.
- Proposed Model by Uysal developed as part of this study for the determination of moist and dry state Modulus of Elasticities of concrete outstands any other prediction model that considered throughout this study. The model yielded the best MSE values among other models and showed better fits on distribution graphs. However, that prediction model was created by conducting regression analysis on measured data from this study. Therefore, this model also evaluated by different results in the literature to state its reliability, and promising results were obtained. To increase the model’s reliability, more data should be evaluated from literature.

5.2 Recommendations

Mixing water amount and superplasticizer dosage should be carefully adjusted to prevent segregation because prepared mixtures tend to segregate more than conventional concrete mixtures because of the lightweight nature of expanded clay aggregate. Further evaluations should be made on the proposed model to increase its reliability. Comparing more predicted and measured data from literature would drive a path for developing the proposed model. Different parameters could be added to the model to develop its' accuracy. The perpendicularity of the concrete specimens should be specifically cared before measuring MoE results. Before testing, all specimens should be tested by water gauges and different apparatus, because even the smallest disorders on the testing surface can yield problematic results.

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