ESTIMATION OF LIGHTWEIGHT EXPANDED CLAY AGGREGATE CONCRETE'S COMPRESSIVE STRENGTH BY USING META-ANALYSIS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

İLBÜKE USLU

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

JANUARY 2023

Approval of the thesis:

ESTIMATION OF LIGHTWEIGHT EXPANDED CLAY AGGREGATE CONCRETE'S COMPRESSIVE STRENGTH BY USING META-ANALYSIS

submitted by **İLBÜKE USLU** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering, Middle East Technical University** by,

Prof. Dr. Halil KALIPÇILAR
Dean, Graduate School of Natural and Applied Sciences

Prof. Dr. Erdem CANBAY
Head of the Department, Civil Engineering

Prof. Dr. İsmail Özgür YAMAN
Supervisor, Civil Engineering, METU

Assoc. Prof. Dr. Can Baran AKTAŞ
Co-Supervisor, Civil Engineering, TED University

Examining Committee Members:

Prof. Dr. Sinan Turhan ERDOĞAN
Civil Engineering, METU

Prof. Dr. İsmail Özgür YAMAN
Civil Engineering, METU

Assoc. Prof. Dr. Çağla MERAL AKGÜL
Civil Engineering, METU

Assoc. Prof. Dr. Hande Işık ÖZTÜRK
Civil Engineering, METU

Assoc. Prof. Dr. Can Baran AKTAŞ
Co-Supervisor, Civil Engineering, TED University

Date: 27.01.2023

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

Name Last name : İlbüke Uslu

Signature :

ABSTRACT

ESTIMATION OF LIGHTWEIGHT EXPANDED CLAY CONCRETE'S COMPRESSIVE STRENGTH BY USING META-ANALYSIS

Uslu, İlbüke
Master of Science, Civil Engineering
Supervisor: Prof. Dr. İsmail Özgür Yaman
Co-Supervisor: Assoc. Prof. Dr. Can Baran Aktaş

January 2023, 70 pages

One of the most effective methods of reducing the density of concrete is the incorporation of lightweight aggregates. Lightweight expanded clay aggregate (LECA) is preferred in lightweight concrete production due to its high compressive strength when compared to other lightweight aggregates. The study aims to assess the compressive strength of LECA incorporated lightweight concrete through meta-analysis. Within the scope of the study, more than 140 data points are compiled through literature and analyzed to conduct the meta-analysis of LECA incorporated lightweight concrete properties. Detailed statistical analysis procedures such as ANOVA and regression analysis are used to investigate the relations between the amount of LECA, w/c ratio, amount and type of binder, and the compressive strength and density of lightweight concrete. An equation is derived to estimate the relationship between the 28-day compressive strength and the evaluated variables based on the regression analysis. It includes 15 different studies conducted independently, as the equation is derived by using the meta-analysis. It is statistically more robust than single studies conducted independently from each other due to the combined effect. Results indicate that the effect of LECA, water, and cement on the 28-day compressive strength is more than the amount of fly ash and silica fume.

Moreover, 13 different mixtures are prepared to evaluate the accuracy of the estimations according to the compressive strength test results. Estimations and compressive strength test results are compared to determine the accuracy of the derived equation.

Keywords: Lightweight Expanded Clay Aggregate, Lightweight Concrete, Meta-Analysis, Strength Estimation

ÖZ

GENLEŞTİRİLMİŞ KİL AGREGALI HAFİF BETONUN META-ANALİZ YÖNTEMİ İLE BASINÇ DAYANIMI TAHMİNİ

Uslu, İlbüke
Yüksek Lisans, İnşaat Mühendisliği
Tez Yöneticisi: Prof. Dr. İsmail Özgür Yaman
Ortak Tez Yöneticisi: Doç. Dr. Can Baran Aktaş

Ocak 2023, 70 sayfa

Beton yoğunluğunu azaltmanın etkili yöntemlerinden biri betonda hafif agregaların kullanılmasıdır.Genleştirilmiş kil agregası (GKA), diğer hafif agregalar ile karşılaştırıldığında basınç dayanımı yüksek olması sebebiyle tercih edilmektedir. Mevcut çalışma, meta-analiz yoluyla hafif GKA'lı betonun 28 günlük basınç dayanımını değerlendirmeyi amaçlamaktadır. Meta-analiz kapsamında literatürden 140'tan fazla veri noktası derlenmiş ve analiz edilmiştir. GKA miktarı, bağlayıcı miktarı, mineral katkı miktarı ve türü, 28 günlük basınç dayanımı gibi farklı parametreler arasındaki korelasyonların ayrıntılı istatistiksel analizi varyans analizi (ANOVA) ve regresyon analizi kullanılarak gösterilmiştir. Regresyon analizine dayalı olarak, 28 günlük basınç dayanımı ile değerlendirilen bağımsız değişkenler arasındaki ilişkiyi tahmin etmek için bir denklem türetilmiştir. Meta-analiz yöntemiyle türetildiği için birbirinden bağımsız yürütülen 15 farklı çalışmayı içermektedir. Bu bütünleşik etki sebebiyle elde edilen denklem, bireysel çalışmalara göre istatistiksel olarak daha güçlüdür. Analizlerin sonucunda GKA, su ve çimento miktarının basınç dayanımına olan etkisinin, silis dumanı ve uçucu kül miktarından daha çok olduğu sonucuna varılmıştır. Regresyon analizine bağlı olarak elde edilen

denklemden elde edilen tahminlerin, basınç dayanımı test sonuçlarına göre doğruluğunu değerlendirmek için 13 farklı karışım hazırlanmış ve test edilmiştir.

Anahtar Kelimeler: Genleştirilmiş Kil Agregası, Hafif Beton, Meta-Analiz
Dayanım Tahmini

To my beloved family,

ACKNOWLEDGMENTS

First and foremost, I would like to express my sincere gratitude to my supervisor Prof. Dr. İsmail Özgür Yaman for his continuous support, perfect guidance, and insight throughout the study.

I would like to express my deepest appreciation to my Co-Supervisor Assoc. Dr. Can Baran Aktaş, who entirely supported me since 2018. He has been always a mentor to me. I am grateful for all his support, encouragement, guidance, criticism and advice.

I could not have undertaken this journey without Orkun Uysal. I am thankful for his invaluable support in every step of the preparation of thesis. Above all, experimental procedure of the thesis was completed with him. Therefore, the same data set was used for both of us.

I would like to thank to Türkan Ekin Mısırlı for her great help and continuous motivation during my MSc study.

I am eternally grateful to my beloved fiancé Hasan Mert Yalçınkaya for his continuous support and endless patience throughout this study. I am so glad for always inspiring me in all aspects of my life.

Sincere thanks are extended to LECAT® for supplying Lightweight Expanded Clay Aggregate (LECA) that I used throughout my thesis study.

I am indebted to the Yüksel Proje for providing the opportunity to study and supporting me.

And last but not least, I would like to thank my family for their endless love, encouragement, and patience no matter what path I choose throughout my whole life.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

ACI	: American Concrete Institute
ANOVA	: Analysis of Variance
ASTM	: American Society for Testing Materials
LECA	: Lightweight Expanded Clay Aggregate

LIST OF SYMBOLS

SYMBOLS

df : Degree of freedom

f_c : Compressive strength

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

k : Number of independent groups

MS : Mean sum of squares

n : Number of observations

R^2 : Coefficient of determination

S : Standard error

SS : Sum of squares

MS : Mean sum of squares

σ : Standard deviation

x_i : Each value in the data set

$\bar{x}$: Mean

CHAPTER 1

INTRODUCTION

1.1 Background on Lightweight Concrete

Over 2000 years have passed since lightweight concrete was first used. In ancient times, Babylon was constructed by using volcanic materials during the Sumerian Civilization (Chandra & Berntson, 2002). The Port of Cosa, the Pantheon Dome, the Coliseum, and St.Sofia Cathedral or Hagia Sofia are the five remarkable lightweight concrete structures of the Roman Empire (Chandra & Berntson, 2002). Natural volcanic materials are used as a lightweight aggregate in the construction of The Port of Cosa. The foundations and walls of the Coliseum were constructed by using crushed volcanic lava and porous crushed brick aggregate, which makes the concrete as a lightweight material. Although the use of lightweight concrete was limited due to the fall of the Roman Empire, lightweight aggregates were started to be used extensively in the 20th century. Since there are a considerable amount of construction practices, concrete was chosen to be an alternative for reducing the weight of the several types of structures. As an example, reinforced lightweight concrete was used effectively in ship and barge construction around 1918 (ACI 213R-2, 2003). Many types of structures were started to be designed by using lightweight reinforced concrete during the 1950s (Thienel et al., 2000). Concrete that has a unit weight of about 1120 to 1920 kg/m^3 and has a 28-day corresponding compressive strength of more than 17 MPa, is considered as lightweight concrete (ACI 213R-2, 2003). The primary considerations for structural lightweight concrete are its unit weight and strength properties.

The main objective of using lightweight concrete is to produce concrete that does not fall below the minimum strength limits without exceeding the maximum unit weight limits.

The use of lightweight aggregates provides many advantages. Türkiye is located on many critical fault lines, and it is one of the world's most earthquake-prone regions. In earthquakes, applied loads on the structures are directly proportional to the weight of the structure. Therefore, reducing the structure's weight decreases the amount of inertial forces that may occur during an earthquake.

Also, a weight reduction may decrease foundation loads which means the cross-section of supporting elements is reduced, such as smaller footings, fewer piles, and steel reinforcement. Dimensions of all supporting members may be decreased, such as beams, columns, girders, etc. Besides buildings, there are significant economic benefits related to bridges. The spans of a bridge can be increased, which will result in fewer supporting elements. Weight reduction can decrease transportation cost because more elements can be carried over per load. Structures that are constructed with lightweight aggregates also require less scaffolding, which decreases the structure's construction cost.

It is essential to acquire the unit weight in desired range with the use of lightweight aggregate in the manufacturing of lightweight concrete. Lightweight aggregates that are used in lightweight concrete can be grouped into two as natural and artificial aggregates. The first naturally occurring aggregates have volcanic origins such as pumice, volcanic slag, tuff, and diatomite. The second type is an artificial one which is obtained as a result of heat-treated abrasion by natural materials or waste industries such as expanded clay, perlite, shale, vermiculate, and slate.

Lightweight expanded clay aggregate is produced in 20 different countries with different names and it is used as a structural lightweight aggregate because of its profound advantages. It is one of the aggregates with the highest strength compared to natural aggregates such as pumice, volcanic tuff, and slag (Aslam et al., 2017). LECA also has excellent thermal insulation, fire resistance, and soundproof properties and is durable against freeze/thaw. Also, there is only one factory that produces LECA in Turkey.

Söğüt Toprak Madencilik Sanayi A.Ş. founded the LECA factory in 2017 and they have started to produce LECA pebbles since 2019. The company branded the LECA as LECAT.

1.2 Objective and Scope

This study aims to examine the relationship between the use of Lightweight Expanded Clay Aggregate (LECA) and the 28-day strength of lightweight concrete, using a meta-analysis approach. Meta-analysis is a research method that systematically synthesizes and interconnects the results of multiple scientific studies using statistical methods, and is known to increase the statistical accuracy by combining the results of more than one study.

From the research gathered from the 15 different studies incorporating more than 140 data points, correlations between different parameters, like the amount of LECA, 28-day compressive strength, density, and water binder ratio is determined, and the relationship between the dependent and independent parameters is obtained using regression analysis. The dependent parameter is the 28-day compressive strength, and independent parameters are the cement, water, LECA, and amount and type of mineral admixtures. As a result of the statistical analysis, an equation is derived related with the 28-day strength of the LECA concrete.

In addition to the statistical analysis, an experimental study is conducted in order to examine the compressive strength of LECA incorporated concrete. 13 different mix proportions are prepared to compare the results of the compressive strength test by using the meta-analysis conducted earlier.

In this context, Chapter 1 includes general information about the study. Chapter 2 introduces the review of literature on LECA and meta-analysis. Chapter 3 presents the meta-analysis results which included analysis of variance (ANOVA), regression analysis, and sensitivity analysis.

Chapter 4 shows the experimental findings and includes the results and comparison of the meta-analysis and compressive strength tests of LECA. Finally, Chapter 5 presents the main conclusions that can be obtained from the whole study, and provides some recommendations that may shed some light on future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 LECA Definition and History

LECA is a type of artificial lightweight aggregate that can be used in structural concrete. Natural clay which has a trace amount of lime content is used in the production of LECA (Rashad, 2018). The first production of LECA and other lightweight aggregates started with the production of Haydite which is a type of lightweight aggregate, and it is produced by heating shale or slate. Around the 1900s, a ship (SS Selma) is constructed in Kansas City and Haydite is invented by Stephen J. Hayde to use in the construction of SS Selma. Hayde discovered the horizontal rotary kiln process in clays and shale while producing durable, low-density aggregate. (ACI 213R-2, 2003; Bragdon, 1996). Expanded clay or shale currently accounts for 2/3 of the annual production of lightweight construction aggregate, in the USA., around 8 to 9 million m^3 production was made between 2019-2020. In addition, large companies that are producing expanded clay around the world have established an organization called “Expanded, Shale Clay and Slate Institute” (ESCSI) together with Canadian, Belgian, Australian, Swiss, and Japanese organizations (Argex, 1994).

In Europe, the U.K., Germany, Holland, and Denmark were the first countries to use LECA. Beginning in the 1950s, lightweight concrete has been used in many small and simple open-sea floating platforms. (ACI 213R-2, 2003; Thienel et al., 2000). In Norway, LECA was produced from expanded clays in a normal kiln in 1954. At that time, less than 100.000 m^3 was produced per year. Today, the production amount has reached 1.000.000 m^3 by using rotary kilns (Chandra & Berntson, 2002). In Türkiye, LECA is being produced since 2000’s.

The number of expanding clay reserves is quite high in Turkey. MTA General Directorate started to make field surveys about expanding clay studies for the first time in the year of 2000. The expanding clay aggregate reserves are located in Ankara, İzmir, Aydın, Afyon, Konya, Sivas, Kastamonu, Karabük, Bartın, Bilecikand Bolu in Turkey. Today, expanded clay is produced in the Söğüt district of Bilecik province. (MTA, n.d.)

2.2 Production and Characteristics

When LECA is manufactured and heated between 1100-1300 °C, it increases in volume 5-6 times of its original state and becomes a mass filled with sintered gas bubbles on its outer surface (Alexander et al., 1999). While the organic features burn off driving the particles to expand, forming ceramic particles with porous and lightweight material. After heating, gas is diffused from the inside particles and entrapped in them during cooling (Rashad, 2018). The quality of LECA depends on certain parameters which are chemical and mineralogical composition, the grain size of clay, the size of LECA pellets, and the heat of the kiln. First, it is known that iron significantly affects the light aggregate properties. The addition of Fe_2O_3 causes larger pores in the middle part of the LECA pellet which means that the addition of iron powder resulted in a massive increase in expansion. Both particle density and mechanical strength decrease. A decrease in the grain size of clay ends up with an increase in the expansion (Nepomuceno & Silva, 2014). However, an increase in the pellet size ends up with an increase in expansion. The temperature in the kiln is important because it affects the clay’s behaviour. When clay is heated, it expands to a certain level before it is started to melt which results in irregular and large pores. These creations affect the mechanical resistance of aggregate and increased temperatures cause economical problems in terms of production operations. Accurate temperature conditions are essential to produce LECA (Ozguven & Gunduz, 2012).

The colour of the LECA depends on the variation in the chemical composition and manufacture method/type. Generally, the color of LECA is dark brown or reddish brown. Infrequently, it can be gray, yellow, or black. It can be produced in different sizes such as 0.1 mm to 25 mm. The density of the LECA varies from 250-710 kg/m^3. (Hall, 2010). LECA is produced in more than twenty countries. SiO_2 constitutes a major part of the chemical composition of the LECA but also includes some alkalis such as Al_2O_3, Fe_2O_3, CaO and Na_2O, and K_2O (Alexander et al., 1999). In particular, Natural LECA includes 61.67% of SiO_2, 18.51% of Al_2O_3, 3.97% of MgO, 0.19 % of P_2O_5, 0.23% of SO_3, 3.28%K_2O, 3.5% of CaO, 0.65% TiO_2, 6.14% of Fe_2O_3, 0.13% SrO, 1.54% Na_2O (Sepehr et al., 2014).

Depending on the source and method of production, lightweight aggregates exhibit significant variations in particle shape and texture. Their shape can be cubic, round, angular, or irregular, while their structure can be fine or large-pored, smooth, or irregular. Lightweight aggregates are more capable of absorbing water than normal-weight aggregates due to their cellular structure. Based on the 24-hour absorption test, lightweight aggregates usually absorb water at a rate of 30% by weight depending on the porous structure of the aggregate. Saint Gobain Weber Ltd Laboratories conducted long-term tests on LECA. Tests were conducted for 13 years and results show that the LECA particles are continuously absorbing water according to BS EN 1097-6 "Testing for mechanical and physical characteristics of aggregates - Part 6: Determination of particle density and water absorption" test technique. Also, the behaviour of lightweight aggregates is similar to granular materials which have satisfactory drainage behaviour in terms of permeability properties. K value is between 1 to 100 cm/s for granular material and the k value of the LECA is determined as 2.53 cm/s according to the constant head test (ASTM D 2434). LECA particle has an advantage over granular material because it is lighter than gravel-like material. (Zukri et al., 2018).

LECA does not include any dangerous ingredients which means that it is a natural product. It is non-combustible, non-biodegradable, inert, and resistant to chemicals and frost. It also has a neutral pH value (9.5) which makes it inert (Zukri et al., 2018).

2.3 The Technical Properties and Areas of Usage of Lightweight Expanded Clay Concrete

Density is an essential parameter to define structural lightweight concrete and it is decreased with the increase in the volume of LECA in the mixture. Different density values can be reached by integrating different proportions of the LECA. Even though there are many articles related with the impact of LECA on the density of concrete, the majority of articles consider LECA as coarse aggregate, LECA can be used as fine aggregate less common. The least preferred situation is the replacement of both fine and coarse aggregate with LECA in terms of total publications (Rashad, 2018).

Compressive strength is a key parameter to use lightweight structural concrete and LECA is one of the light aggregates with the highest compressive strength. Generally, the compressive strength of concrete is decreased by the incorporation of the LECA. Compressive strength can be reduced by %0.15-70 with LECA incorporation. There is not only one factor to effect compressive strength which is the amount and type of the cementitious material, amount of water, w/c ratio, w/b ratio, amount and type of admixture, mechanical properties of LECA, size of LECA, etc. (Rashad, 2018)

According to the design specifications, the compressive strength of structural concrete is between 21 and 35 MPa range. Strength values of 48 MPa or above is rarely specified, and if so, those would likely be special applications. Although a few lightweight aggregates may produce extremely high strengths, it shouldn't be assumed that every lightweight aggregate labeled as "structural" would be able to produce concrete with higher strength values. (ACI 213R-2, 2003)

LECA usage has reduced crushing strength and increased air voids in comparison to normal-weight concrete. The fracture pattern follows the weak and porous sections in concrete which mostly consist of LECA. Its spherical shape causes weaker bond strength than angular ones (Bogas & Gomes, 2013).

LECA with coating cement strengthens the bond between the LECA particles and gives them a hard surface and it decreases the water absorption potential of LECA particles (Gao et al., 2021). Also, the bond between the cement and LECA particles can be enhanced and the compressive strength of LECA concrete can be increased by using a pozzolan such as silica fume and fly ash because they can fill the pores in LECA particles (Dabbaghi et al., 2021).

Water absorption capacities of LECA can be varied according to their production purposes. For instance, water absorption of coarse LECA which uses for structural purposes is 12.3% (Bogas et al., 2012). Also, water absorption of medium-coarse LECA is 17%. (Yoon et al., 2012).

LECA has a denser shell according to other types of lightweight aggregates; it has improved the interfacial transition zone (ITZ) which means that entry of water or any substance to the internal matrix is restricted. The degree of absorption close to LECA particles is considerably reduced because the LECA porous structure is rougher than the paste (Bogas et al., 2015). The surface roughness of LECA pebbles can ease the formation of hydration products and afterward it may enable the development of calcite crystals and CSH gel. It is the main basis of increased ITZ compactness (Koňáková et al., 2017).

In a particular manner, scanning electron microscope (SEM) observations demonstrate that ITZ may not be present between LECA and mortar which is related with the absorption capacity. LECA has a higher absorption capacity according to other lightweight aggregates. The surface of aggregates surrounded with cement paste those results in improved mechanical properties. Cement grains are identified by white patches in the shell of the pebbles. The periphery of the pebble reveals that the cement paste can surround the pores. However, the rest of the pebble’s interior preserves its initial microstructure (Ke et al., 2010).

LECA concrete has other advantages such as heat and sound insulation due to its internal cellular structure and thousands of air-filled spaces. It has a lower thermal conductivity which means that it has a lower coefficient of thermal expansion because it is heated to about 1100 °C during manufacturing (Lotfy et al., 2016).

It contributes to the increase of Leadership in Energy and Environmental Design (LEED) performance of buildings, along with basic advantages such as lightness and fire resistance. It has been created using strategies aimed at improving performances such as energy savings, water efficiency, reduction of CO_2 emissions, improved indoor environmental quality, and resource management and sensitivity to their impacts (Haselbach, n.d.). However, according to some researchers, air voids may negatively impact the resistance to higher temperatures. The interfacial transition zone (ITZ) which is the weakest zone of the concrete, creates a path for a thermal crack pattern to follow (Andiç-Çakir & Hizal, 2012).

LECA has a broad range of use and become a well-known material in construction. LECA may be used as a suitable material in geotechnical and structural applications due to certain characteristics (Zukri et al., 2018). For instance, LECA is used to construct lightweight concrete structures such as beams, columns, and foundations. Thus, the dead load is decreased which brings an advantage in terms of structural and economic. Cross sections, loads that affect to the foundation, and the amount of steel are decreased. These advantages result in cost savings (Yoon et al., 2015). Also, decreased dead loads create significant advantages on long-span bridges because fewer and smaller supporting members such as decks, piers, beams, and girders are needed. Lightweight aggregates require less trucking and minimize the industrial demands on finite resources of natural elements such as sand, gravel, etc. There are two studies carried out at U.S. precast plants about trucking costs. According to this research, the cost savings from transportation are seven times greater than the cost of lightweight aggregate (ACI 213R-2, 2003).

LECA can be used for the purpose of drainage and insulation in embankments of road infrastructures. Another implementation is to use it as a lightweight backfill for retaining walls and road infrastructures as well. The characteristics of LECA demonstrate that it may be utilized in many civil engineering projects in place of natural aggregates. Soft soils are stabilized, and possible collapses are prevented by filling the voids with LECA. It is used for reducing the pressure between the structure and the soil in retaining walls and backfilling bridges, basement walls, and foundations.

In addition to the structural purposes, lightweight expanded clay concretes are preferred for places that require high insulation properties such as insulating wall panels, blocks such as bricks, roofs, and screed concretes of factory constructions. It is an excellent filling material for heat, moisture, and sound insulation. It acts as a protective layer in case of possible fires with no additional insulation weight on the building.

2.4 Meta-Analysis Concepts

The gap between theory and practice in scientific studies is often criticized. The best evidence for linking the two different terms can be presented through meta-analysis, which includes a synthesis of previous studies in that specific area (Şen, 2019). Meta-analysis is the process of combining the findings of several separate empirical research studies. It is a research method that has been used for a long time. In 1976, Gene Glass first used the word meta-analysis in his presidential speech. He used it as the evaluation of the statistical analysis results to generalize (Hedges, 1992). Researchers can reach results through meta-analysis that are more precise and robust than those that can be provided in a single main study or in qualitative analysis. Differences and similarities can be easily seen among the results of several studies by using meta-analysis (Rosenthal & Dimatteo, 2000). Some steps should be followed by the researcher. First, the subject of the research should be determined, and relevant dependent and independent variables should be defined. Then, studies should be gathered systematically. Each study should be reviewed carefully to see how the independent and dependent variables are measured and statistical analyses should be chosen. Finally, details of the above-mentioned processes should be reported together with the meta-analysis results (Şen, 2019).

2.4.1 Correlations

Correlation is a statistical measure that expresses the linear relationship between two variables. The correlation coefficient shows the strength of the linear relationship between two variables which is shown in Equation 2.1. In the formula, the covariance of the two variables and standard deviations should be known to calculate the correlation. The standard deviation shows how far spreading out a series around the mean. Covariance measures the variability of the linear relationship between two variables.

$$Correlation\ Coefficient\ = \frac{Covariance\ (A, B)}{(Std.Deviation\ A\ *\ Std.Deviation\ B)} \tag{2.1}$$

The correlation coefficient (r) ranges from -1 and +1. The correlation coefficient (r) indicates to what extent the variation of one variable is determined by the other variable. The correlation coefficient of +1 indicates a strong positive correlation. In that case, as variable X increases, variable Y increases as well. The reverse is also true, where, as variable X decreases, variable Y decreases. The correlation coefficient of -1 indicates a strong negative correlation. As variable X increases, variable Y decreases, or as variable X decreases, variable Y increases. A coefficient close to 0 indicates that there is a weak correlation between the two variables (Bewick et al., 2003).

2.4.2 Coefficient of Determination (R^2)

The coefficient of determination (R^2) is the square of the correlation coefficient (r). It is the measure of the change in variables which is explained by each other. In other words, it is the amount of variance between one another. The remaining amount depends on other variables. It measures how strong the linear relationship between two variables is and takes a value between 0 and 1. The value of 1 indicates that the data can fit perfectly on a regression line. There is a reliable relationship between these variables. The value of 0 indicates that there is no relationship between the variables. Also, it means that the regression model cannot be able to predict the outcome accurately. The reliability of the value is directly proportional to the amount of data.

The coefficient of determination does not show the cause-effect relationship between two variables which is a common misinterpretation. It only shows the strength of the relationship between the two variables (Bewick et al., 2003)

2.4.3 Regression Analysis and ANOVA

Regression is a statistical method used to examine the relationship between a dependent variable and one or more independent variables. Correlation and linear regression are the two most often used methods to investigate the relationship between variables. Regression states the relationship as an equation, whereas correlation assesses the strength of the linear relationship. The most common is linear regression which assumes the linear relationship between independent variables (x) and dependent variables (y). The linear relationship between more than one independent variable and one dependent variable can be measured by multiple regression analysis (Chatterjee & Simonoff, 2013).

ANOVA stands for analysis of variance which is a statical analysis tool. It tests whether there is a significant difference between variables or not. In other words, it should be answered that is there a difference in the population between the different groups of the independent variable with respect to the dependent variable.

It is also used in testing hypotheses about the means of independent variables. The first one is the null hypothesis. It assumes that there are no differences in the population between the means of the individual groups. The second one is the alternative hypothesis H1 which assumes that at least one group means differ from the others in the population.

ANOVA test is used to determine the effect of the independent variables on the dependent variable. There is no study including ANOVA related with LECA but, there are studies in concrete consisting of other lightweight aggregates. For instance, lightweight concrete including fly ash is examined to assess the impact of high temperature on splitting tensile and compressive strength.

The amount of fly ash and heating degree are used as two control groups. ANOVA is used to examine the relative significance of these parameters for compressive and splitting tensile strength. The results of ANOVA show that the heating degree has the greatest impact on the compressive and splitting tensile strength. (Tanyildizi & Coskun, 2008). Another study is about artificial fly ash-based aggregates. ANOVA is used to determine the impact of lightweight aggregate and fly ash properties on the performance of lightweight concrete. The impact of lightweight aggregate type on the measured lightweight concrete parameters is validated by ANOVA.

The processing method, which is used to produce fly ash pellets, is the most effective parameter for determining the parameters of lightweight concrete which are modulus of elasticity, compressive strength, flexural strength, shrinkage, and porosity (Terzić et al., 2015).

2.4.3.1 Adjusted R^2

Adjusted R^2 is similar to the coefficient of determination (R^2) which is used only in multiple regression analysis because in these models, the value of R^2 increases by adding a new independent variable. To avoid the increase, the corrected R^2 value should be used which is shown in Equation 2.2 (Karch, 2020).

$$\bar{R}^2 = 1 - (1 - R^2)\,\frac{n-1}{n-k} \qquad (2.2)$$

where;

n is the number of observations (sample size) k is the number of independent groups

R^2 is the coefficient of determination

2.4.3.2 Coefficients

Regression coefficients are estimates of unknown population parameters and describe the relationship between an independent variable and a dependent variable. In a linear regression equation, the coefficients are multiplied by the independent variables. As seen in Equation 2.3, the value of ‘a’ is the regression coefficient, and ‘b’ is the intercept. Intercept is the point where the line obtained from linear regression, intersects with the y-axis.

$$y = ax + b \tag{2.3}$$

2.4.3.3 Standard Error

The standard error (S) of the regression analysis is a measure of the precision of the model. It is a measure that represents the mean absolute distance between the data and the regression line/best-fitted line. The formula is shown below in Equation 2.4. The smaller value means that the data is close to the best-fitted line. The standard error value of the regression can be used to evaluate the precision of the estimates, while R^2 represents the percentage of dependent variable variance explained by the model. Approximately 95% of the observations should be within ±2*S from the regression line. Standard deviation can be normalized by the standard error. The variation or distribution of the data around the mean is measured by the standard deviation. The standard error will decrease as the sample size increases, showing that the estimated sample mean value is closer to the population mean. (Altman et al., 2005)

$$S = \frac{\sigma}{\sqrt{n}} \tag{2.4}$$

where;

σ is the standard deviation

n is the number of observations (sample size)

2.4.3.4 P-value

The P-value is a key result of the ANOVA which is used to determine whether any difference between the means statically and to test the null hypothesis. The range of the p-value is 0 to 1. The evidence that the null hypothesis can be rejected, is stronger with the smaller p-value (Wasserstein & Lazar, 2017). Also, it can be explained as there is a strong and reliable relationship between variables. It is necessary to compare the p-value obtained from the ANOVA, with the significance level (alpha level). Generally, the significance level is accepted as 0.05. The level of significance indicates that there will be no difference between the means with a 5% risk. It corresponds to a 95 percent confidence interval.

2.4.3.5 T-Statistic

The T-test is one of several different types of tests used for the hypothesis. It is used to determine the relationship between the dependent variable and the different independent variables. It helps determine whether this relationship is statistically significant. The T statistic is obtained by dividing the variable by the standard error of the coefficient. The larger the T value, the greater the evidence against the null hypothesis. This means that there is a significant difference between the variances and the null hypothesis can be rejected. The closer the T value is to 0, it means that there is no significant difference between the variances, and the null hypothesis can be validated.

2.4.3.6 F-Test

F-test is used in regression and the aim is to compare variances between groups. F distribution is the basis of the ANOVA. Null hypothesis accepts that the variances are equal It uses the F-distribution to test a hypothesis. F-test uses the F statistic to compare variances by dividing them.

If the calculated F value is greater than the F critical value which can be obtained from the F-distribution table, the null hypothesis can be rejected. P-value should be considered to reject the null hypothesis as well (Shen & Faraway, 2004).

The SS value is the sum of the squares between or within groups which are shown in Equation 2.5. It measures the deviation from the mean statistically which can be named as a variation. A higher SS suggests higher variation, and a smaller SS suggests less variation between variables. Higher SS refers that there is difference between the populations from the mean.

$$SS = \sum_{i=1}^{n} (x_i - \bar{x})^2 \tag{2.5}$$

where;

x_i is the value of an individual data point

$\bar{x}$ is the sample mean

n is the number of observations (sample size).

The MS value is the basis of the F test, and it is the mean value found by dividing each sum of the square sum by its own degrees of freedom which is shown in Equation 2.6. It estimates the variance of the population. MS is used to decide the significance of the model in regression.

$$MS = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{2.6}$$

The calculated F value is shown in Equation 2.7.

$$F = \frac{\left(\frac{Sum\ of\ squares(SS)\ between\ the\ groups}{k-1}\right)}{\left(\frac{Sum\ of\ squares(SS)\ within\ the\ groups}{n-k}\right)} \tag{2.7}$$

where;

k is the number of independent groups

The critical F value is obtained from the F distribution table which is determined according to the specific significance levels. If the F value obtained from the above-mentioned Equation 2.7 is greater than the critical F value, the null hypothesis is rejected.

2.4.3.7 Confidence Intervals

The number indicates the probability of being wrong in the research calculation or forecast in statistics. It is usually expressed as a percentage, and it is shown as lower and upper limits. 90%, 95%, and 99% are the most commonly used confidence intervals. These ranges are found by subtracting the significance level (alpha) from 1 (Chatterjee & Simonoff, 2013). The 95% confidence interval indicates what range the estimated coefficient will be with 95% certainty, and there is a 5% chance to make a mistake in the conclusion of the analysis.

2.4.4 Parameter Optimization

Parameter optimization is used to determine optimal settings for controllable parameters which are the independent ones. The optimal value is sought for each independent variable to achieve a specifically defined goal. Parameter optimization is usually done before sensitivity analysis. It can be completed by using different software such as MATLAB, Minitab, etc.

2.4.5 Sensitivity Analysis

Sensitivity analysis determines how the target variable (the dependent variable) is affected due to changes in the independent variables known as input variables. It can be completed by using Excel.

It is used to understand the effect of independent variables on the dependent variable under certain conditions. It can be determined which independent variable has the greatest effect on the dependent variable with a sensitivity analysis (Valentine et al., 2009). It is necessary to reject the null hypothesis to do the analysis.

Sensitivity analysis provides a better comprehension of the relationship between the model's parameters and output. For example, the parameter, which is a less effective independent variable, can be adjusted without affecting the result of the model much. On the other hand, if the parameter is effective; any change in this parameter will dramatically change the outcome of the model, which is the dependent variable.

CHAPTER 3

META-ANALYSIS OF LECA

One of the objectives of this study is to examine the relationship between the use of LECA and the 28-day compressive strength of structural concrete, using a meta-analysis approach. Meta-analysis is a research method that systematically synthesizes or combines the results of multiple scientific studies using statistical methods. Determination of the overall trends by using several independent studies is the main goal of conducting a meta-analysis. Obtained results provide improved statistical accuracy when generalizing conclusions as compared to the results of a single study.

In the scope of the study, more than 140 data points are used in the meta-analysis from 15 different studies which are conducted in 8 different countries such as Portugal, India, Poland, Korea, Serbia, Iran, Turkey, and Canada. Data points include all information gathered from the studies i.e., all material contents, 28-day compressive strength, and density values. Data points which are shown in Appendix B, are used for completing the meta-analysis.

The distribution of the wet density and the 28-day compressive strength is in the range of 1200-2490 kg/m^3, and 10-88 MPa, respectively. All data points are obtained from the studies that investigate the effect of LECA and are compiled and analyzed within the scope of meta-analysis. Therefore, it should be stated that the statistical results of the present study are only valid for the LECA incorporated concrete specimens.

In this study, regression analysis and ANOVA are used to conduct the statistical analysis. The dependent variable is the 28-day compressive strength of concrete, and the independent variables are LECA, cement, water, silica fume and fly ash content.

3.1 Correlations between Various Parameters

This study includes more than 140 data points which are gathered from different studies, where the experiments are carried out by different researchers, and every researcher may have their own methods and materials. Therefore, the R^2 value of 0.65 should not be judged to be insufficient when compared to some other fields of science with less material variation, but on the contrary, should be regarded as the upper bound as to which other results should be compared.

R^2 value between the water/binder ratio and the 28-day compressive strength is 22% as seen in Figure 3.1. 22% of the variation in compressive strength can be explained by the w/b ratio. The reason for obtaining a lower than expected value is that variation in compressive strength depends on more than one variable, like cement content. For this reason, a strong correlation value cannot be obtained between the individual cement, binder, or water/binder ratio and compressive strength.

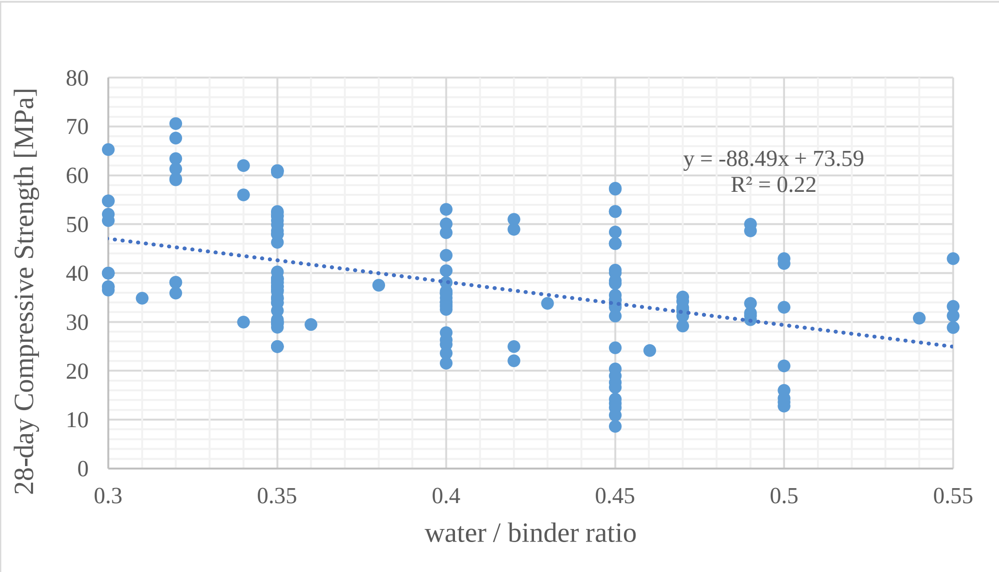

Figure 3.1 The Correlation between the Water/binder ratio and 28-day Compressive Strength of Concrete

In Figure 3.2, the R^2 between the amount of LECA and the compressive strength is 36%. Accordingly, 36% of the variation in compressive strength can be explained by the amount of LECA. This means that there is not a strong relationship between the amount of LECA and the compressive strength individually. While the first group shows the data of lightweight concrete with a LECA content of 0-100 kg/m^3, the second group shows data that contained more LECA than the first group in the range of 175-550 kg/m^3. The last group shows the data of lightweight concrete with a LECA content of 750-920 kg/m^3.

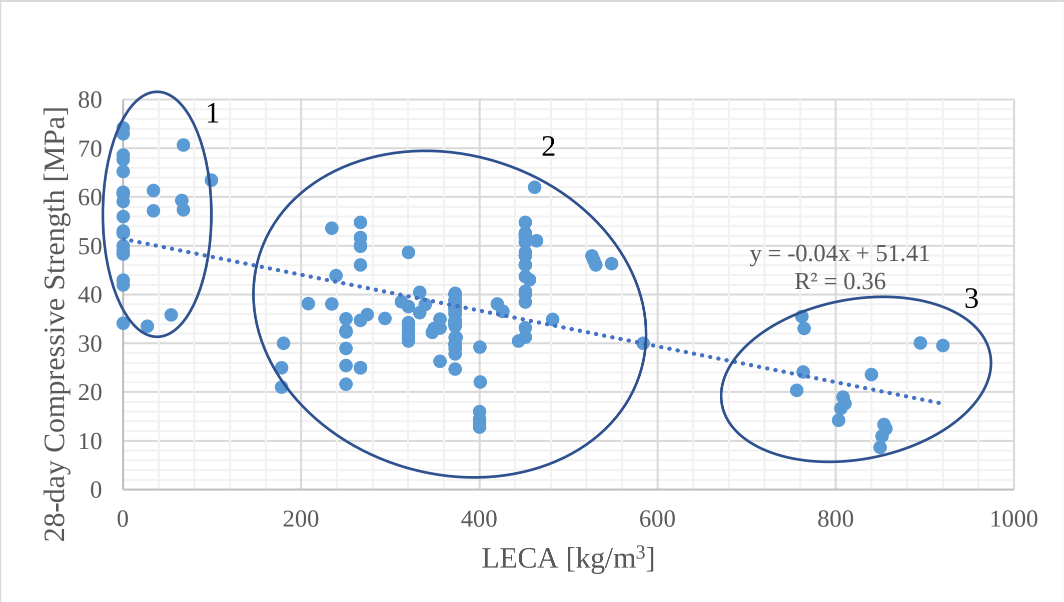

Figure 3.2 The Correlation between the LECA Content and 28-day Compressive Strength

3.2 ANOVA and Regression Analysis

In ANOVA and regression analysis, all data points are gathered from studies that investigate LECA incorporated lightweight concrete. All studies use LECA in different proportions and investigate the mechanical properties of LECA concrete Most of the data points for 28-day compressive strength values present in Figure 3.2

are LECA incorporated lightweight concrete. A small number of datapoints are the control parameters of LECA investigating studies which do not contain LECA. The results of the ANOVA and regression analysis in Table 3.1, Table 3.2 and Table 3.3 show how strong all independent variables which are LECA, cement, water, silica fume and fly ash content in predicting the dependent variable of 28-day compressive strength. The R^2 value is obtained from Table 3.1 is 0.59, and the adjusted R^2 value is 0.57. The adjusted value is considered in multiple regression analysis. This means that 57% of the variation in 28-day compressive strength is determined by all the above-mentioned independent variables. Considering the heterogenous nature of concrete at all scales, i.e., from the micro- to meso- and to macro-structure, the inability to obtain a very high R^2 value among relationships is noted in the literature and considering the presence of 5 different independent variables in concrete, this value is considered to be acceptable.

When the overall regression analysis is examined, the standard error value is 8.80. It is a measure that represented the mean absolute distance between the data and the regression line/best-fit line. This distance is 8.80 units wide. This number represents the average distance between the 28-day compressive strengths of more than 140 data points and the compressive strengths predicted by the model. The maximum divergence of compressive strengths from the predicted mean may be ±2*8.80=17.60 units away from the predicted compressive strength value.

Table 3.1 The Results of Regression Statistics

Parameter	*Value*
R	0.77
R^2	0.59
Adjusted R^2	0.57
Standard Error	8.80
Observations	147

Table 3.2 shows the ANOVA results and Table 3.3 is provided to enable statistical analysis for these independent variables separately. Regression analysis and ANOVA are used to examine for significance in all variables.

As seen in Table 3.2, the MS values are used to find the F value. In order to reject the null hypothesis that all means are considered to be equal, the variation between groups should be greater than the variation within the group. This means that at least one of the groups means are different from the rest. According to the regression analysis results in Table 3.2, the F value is 39.93, which is sufficient to reject the null hypothesis. The critical F value is chosen as 2.21 from the F-distribution table which can be seen in Appendix A. The F value (39.93) obtained from Equation 2.7 is greater than the critical F value and this condition is satisfied as well to reject the null hypothesis.
Since the p-value value is 2.54E-30 which is much smaller than the alpha value of 0.05, the null hypothesis is easily rejected.

Table 3.2 The Results of ANOVA

Parameters	*Values*
SS between the groups	15465.04
SS within the groups	10921.11
df between the groups (n-1)	5
df within the groups (n-k)	141
MS between the groups	3093.01
MS within the groups	77.46
F	39.93
P-value	2.04E-25

As seen in Table 3.3, coefficients are used to derive the regression equation. The standard error of the independent variables reflects the variability of these numbers. In other words, when the regression model is used to estimate the coefficient of an independent variable, it shows how different the estimated coefficient can be. Accordingly, the standard error value is expected to be as small as possible.

For example, the standard error value of the LECA is the smallest among other independent variables, which means that the standard error of the coefficient of this variable is the smallest one according to other variables. T-statistical values of the independent variables in the Table 3.3. indicates that LECA has the highest value among the others. It is more reliable and meaningful in regression analysis because the larger the t-statistics value, the more reliable the coefficient will be. LECA and water are the more reliable ones according to others.

Also, it should be examined whether the p values of all independent variables are sufficient to reject the null hypothesis. According to Table 3.3, the p-value of LECA among the independent variables is greater than 0.05, which means that the null hypothesis cannot be rejected. Consequently, silica fume and fly ash which are the independent variables, are not significant in LECA included studies. In contrast, the p-value of LECA, water and cement is less than 0.05 which meant that the null hypothesis can be rejected. When the results of regression analysis are examined as a whole, silica fume and fly ash are not significant in predicting the 28-day compressive strength of LECA concrete because silica fume and fly increase the long-term strength of concrete. However, LECA, water and cement are significant values in estimating the 28-day compressive strength of LECA concrete.

The lower and upper boundaries for the 95% confidence interval are shown in Table 3.3. It means that there is a 95% probability that the actual value of those coefficients lies between the upper and lower boundaries.

Table 3.3 The Results of Regression Analysis

The Results of Regression Analysis	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	61.501	7.299	8.426	3.73E-14	47.071	75.930
LECA (kg/m^3)	-0.032	0.003	-9.199	4.38E-16	-0.039	-0.025
Water (kg/m^3)	-0.193	0.032	-6.058	1.19E-08	-0.257	-0.130
Cement (kg/m^3)	0.047	0.012	3.799	2.16E-04	0.023	0.072
Silica Fume (kg/m^3)	0.063	0.043	1.476	1.42E-01	-0.021	0.148
Fly Ash (kg/m^3)	0.005	0.013	0.405	6.86E-01	-0.021	0.032

Equation 3.1 which is created based on the coefficients and intercept value obtained from the regression analysis in Table 3.3 is presented below. The 28-day compressive strength of concrete can be estimated in MPa by entering LECA, cement, water, silica fume and fly ash in kg/m^3 into the equation. Since the equation is obtained by using more than 140 data points in the literature, it is more robust than the individual results based on a single data set and provides greater confidence to users.

$$f_{c,28} = 61.501 - 0.032*LECA + 0.047*Cement - 0.193*Water + 0.063*Silica\ Fume + 0.005*Fly\ Ash \tag{3.1}$$

Where,

LECA is the amount of LECA used in concrete making in kg/m^3

Cement is the amount of cement used in concrete making in kg/m^3

Silica fume is the amount of silica fume used in concrete making in kg/m^3

Fly ash is the amount of fly ash used in concrete making in kg/m^3

Water is the amount of water in concrete making in kg/m^3

3.3 Sensitivity Analysis

The mean values of all independent and dependent variables are used to complete the sensitivity analysis. The aim is to understand the effect of independent variables on dependent variable. The mean values of more than 140 data points are used. After that, the mean values of the independent variables, i.e., the LECA, cement, water, silica fume, fly ash, and water have been changed between plus and minus 0%, 10%, 20%, 30%, 40%, and 50%. Changed values are entered to the derived equation which is Eq. 3.1. The corresponding mean values of $f_{c,28}$ by varying independent variables are demonstrated in this graph. If the input (independent variable) had a big slope in the graph, the mean value of $f_{c,28}$ can be decreased/increased dramatically. These input parameters are LECA, cement and water. Inputs with a straight line that had a slope close to zero indicated that they have little or no effect on the mean value of $f_{c,28}$. These parameters are fly ash and silica fume.

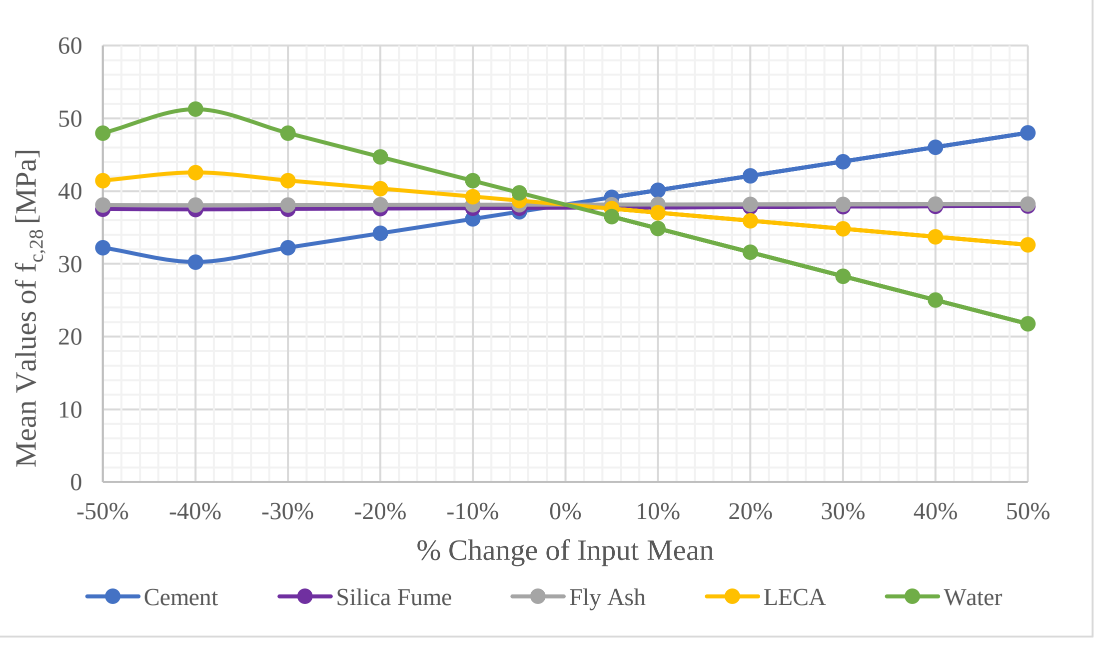

Figure 3.3 Results of Sensitivity Analysis of Concrete Constituents on $f_{c,28}$ Values

3.4 Parameter Optimization

MiniTab application is used for parameter optimization. The optimization goal in the example is to set the dependent variable $f_{c,28}$ as 30 MPa.

In this program, the minimum and maximum amounts for all independent variables are specified based on the more than 140 available data points. A more realistic design can be achieved by using the limitation of maximum and minimum values.

The maximum water amount is limited to 200 kg/m^3 to prevent too much increase in the w/c ratio.

The values presented in Table 3.4 where the water amount is limited to achieve a value of $f_{c,28}$ of 30 MPa. Different 28-day compressive strengths can be obtained by limiting different values by using parameter optimization. The w/b ratio of the first design is 0.43.

Table 3.4 The Results of First Design – Parameter Optimization

Independent Variables	*Total Amount (kg/m^3)*
LECA	410
Water	185
Cement	315
Silica Fume	35
Fly Ash	80

In the second design which is shown in Table 3.5, previous limitations are the same whereas the parameter optimization is completed for eliminating silica fume which means that only fly ash was used as an additive. The w/b ratio of the second design is 0.36.

Table 3.5 The Results of Second Design - Parameter Optimization

Independent Variables	*Total Amount (kg/m^3)*
Cement	400
LECA	300
Water	216
Silica Fume	0
Fly Ash	200

CHAPTER 4

EXPERIMENTAL PROGRAM AND ESTIMATION THROUGH META-ANALYSIS

4.1 General

The results of the meta-analysis are used to estimate the 28-day compressive strength of LECA concrete. The accuracy of the estimation should be investigated by testing the compressive strength of LECA concrete by preparing an experimental program. Therefore, 13 different mixtures were prepared and tested to compare the estimations and experiment results. Experimental procedure of the thesis was completed with master's degree graduate Orkun Uysal. Therefore, the same data set was used for both of us.

4.2 Materials

4.2.1 Cement

CEM I 42.5 R type Portland cement which was produced by Baştaş Cement Company Inc. was used in mixtures. In Table 4.1 and Table 4.2 analysis results which were provided by TURKCIMENTO are given. Only compressive strength test results were obtained by Baştaş Cement Company Inc.

Table 4.1 Chemical Analysis Results of Portland cement CEM I 42.5 R

Chemical 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
Loss on Ignition (LoI)	4.37
Insoluble Residue (IR)	0.76

Table 4.2 Physical and Mechanical Properties of Portland Cement CEM I 42.5 R

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
7 days	37.5
28 days	48.3

4.2.2 Sand

Crushed limestone was used as sand in the mixtures. The sieve analysis was made according to ASTM C136-06. Specific gravity and water absorption tests are conducted according to ASTM C127-15. The results of the sieve analysis and physical properties are shown in Figure 4.1 and Table 4.3.

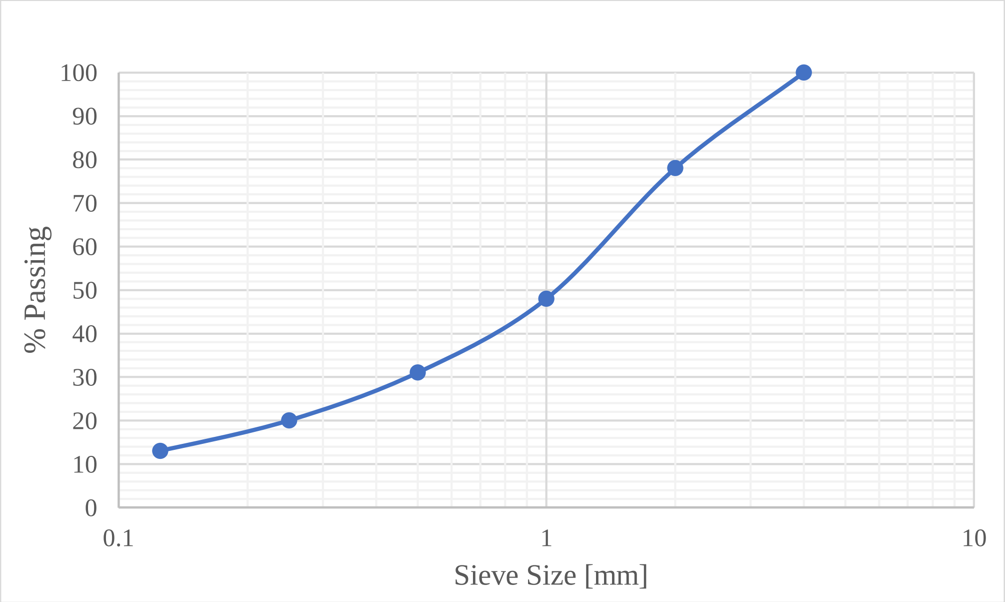

Figure 4.1 Gradation Curve for Sand

Table 4.3 Physical Properties of Sand

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

4.2.3 LECA

LECA which was produced by Söğüt Toprak Madencilik Sanayi Inc. was used in mixtures. Company branded aggregate as LECAT. Three different sizes were provided which are fine (0-3mm), medium coarse (8-16 mm), and coarse (16-32 mm). The sieve analysis was made according to ASTM C136-06. Specific gravity and water absorption tests are conducted according to ASTM C127-15 and ASTM C128. Gradation curves of all three sizes are given in Figure 4.2.

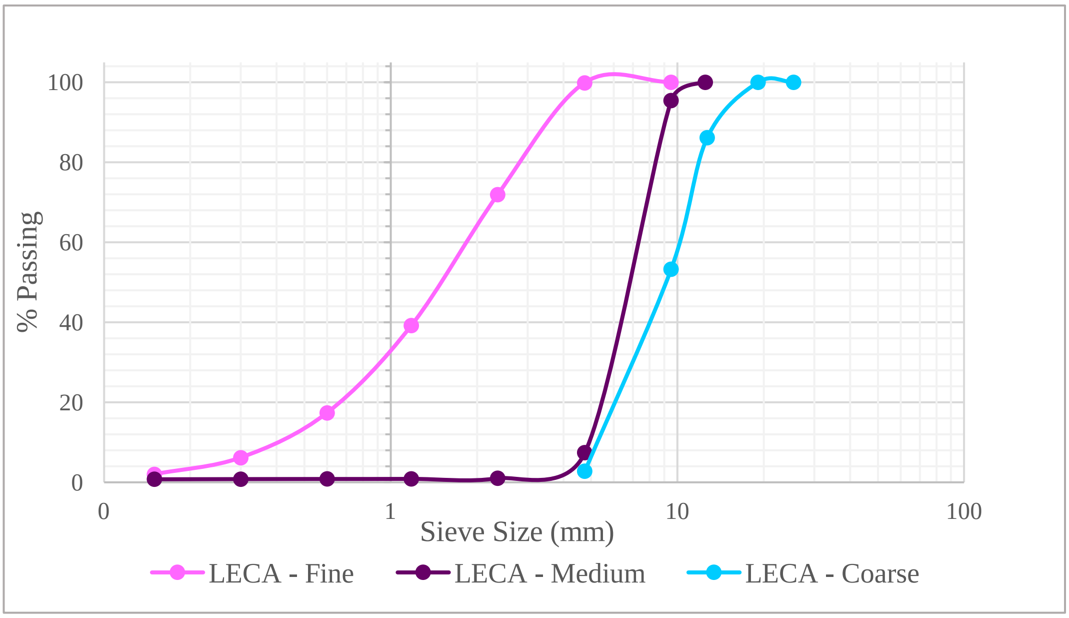

Figure 4.2 Gradation Curve for LECA

Table 4.4 Physical Properties of LECA

	Coarse Agg.	*Medium - Coarse Agg.*	*Fine Agg.*
Specific Gravity (Saturated Surface Dry)	0.83	1.251	1.839
Specific Gravity (Oven Dry)	0.677	1.052	1.625
Specific Gravity (Apparent)	0.799	1.314	2.069
Water Absorption (%)	22.68	19.84	11.66

According to the ASTM 330, LECA was immersed in water for 72 ± 4 hours to measure the specific gravity in the SSD state. As it could be seen in Table 4.4, the water absorption of LECA was too high which could cause the absorption of mixing water during production. Therefore, LECA was used in the mixture in the SSD state which was achieved after immersing 72h in water. This allowed us a more homogeneous and repeatable concrete production.

Figure 4.3 Immersing LECA into the Water

4.2.4 Fly Ash

Fly ash, which was type F, was used to enhance the cementitious matrix. It improves the workability, strength, and durability properties. It was a by-product of Sugözü Thermal Power Plant. The properties which are given in Table 4.5 are obtained from the TURKCIMENTO.

Table 4.5 Chemical Analysis Results of Fly Ash (Type F)

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 (LoI)	3.34

4.2.5 Chemical Admixture

MasterRheobuild 1000 was used as a chemical admixture in mixtures. It was a high-range water-reducing and hardening accelerator. It enhanced the strength properties and improved the workability of concrete because less amount of water could be used to reach the desired workability while less amount of water also improved the strength properties of concrete. Properties of MasterRheobuild 1000 were obtained from the supplier company and presented in Table 4.6.

Table 4.6 Properties of MasterRheobuild 1000

Structure of the Material	Naphthalene Sulphonate Based
Appearance	Brown
Specific gravity @ 20°C	1.17 - 1.22 kg/lt
pH-value	6-8
Alkali content (%)	≤ 10.00 (by mass)
Chloride content (%)	≤ 0.10 (by mass)

4.3 Mix Proportions

Mix proportions were determined according to ACI 211.2-9815. Table 4.7 provides the LECA proportions and Table 4.8 provides the mixture design. As seen from those tables, the total amount of LECA used was categorized into two different dosages, which are 0.27 m^3 and 0.36 m^3 LECA/m^3 of concrete. The total volume of LECA was divided equally into fine, medium coarse, and coarse LECA. Mixes #1, #3, #5, #7, and #9 did not include fine LECA (0-3mm) which means that the total volume of LECA was divided equally into medium coarse and coarse ones. All mixtures included sand as a fine aggregate except mix #13 shown in Table 4.7 which contained only LECA. Fly ash was used as a mineral admixture by replacing cement in mix #11, mix #12, and #13.

Table 4.7 Different Dosages of LECA

Mixture Label	*Total* V_{LECA} *(m^3)*	*Coarse* V_{LECA} *(m^3)*	*Medium Coarse* V_{LECA} *(m^3)*	*Fine* V_{LECA} *(m^3)*
#1	0.270	0.135	0.135	0.000
#2	0.360	0.120	0.120	0.120
#3	0.270	0.135	0.135	0.000
#4	0.360	0.120	0.120	0.120
#5	0.270	0.135	0.135	0.000
#6	0.360	0.120	0.120	0.120
#7	0.270	0.135	0.135	0.000
#8	0.360	0.120	0.120	0.120
#9	0.270	0.135	0.135	0.000
#10	0.360	0.120	0.120	0.120
#11	0.360	0.120	0.120	0.120
#12	0.360	0.120	0.120	0.120
#13	0.530	0.130	0.130	0.270

Table 4.8 Mix Design Proportions

Mixture Label	*Cement* *(kg/m^3)*	*Water* *(kg/m^3)*	*w/b*	*Fly Ash* *(kg/m^3)*	*Water* *(kg/m^3)*	*SP (%)*	*Coarse LECA* *(kg/m^3)*	*Medium Coarse LECA* *(kg/m^3)*	*Fine LECA* *(kg/m^3)*	*Sand* *(kg/m^3)*
#1	400	240	0.6	0	240	0	108.7	149.7	0.0	885.0
#2	400	240	0.6	0	240	0	96.6	133.1	217.7	652.8
#3	500	200	0.4	0	200	2	108.7	149.7	0.0	882.6
#4	500	200	0.4	0	200	1	96.6	133.1	217.7	662.2
#5	500	300	0.6	0	300	0	108.7	149.7	0.0	648.3
#6	500	250	0.5	0	250	0	96.6	133.1	217.7	545.1
#7	600	180	0.3	0	180	3	108.7	149.7	0.0	833.4
#8	600	180	0.3	0	180	2.5	96.6	133.1	217.7	608.3
#9	600	300	0.5	0	300	0	108.7	149.7	0.0	566.4
#10	600	240	0.4	0	240	0	96.6	133.1	217.7	489.0
#11	400	200	0.4	100	200	0.5	96.6	133.1	217.7	648.0
#12	400	240	0.4	200	240	0	96.6	133.1	217.7	446.4
#13	400	240	0.4	200	240	0	107.3	147.8	483.4	0.0

4.4 Specimen Preparation

All materials explained above, were mixed in a rotary mixer to obtain the appropriate concrete according to the different mix proportions. After that, the mixed concrete was poured into a bowl to be molded in Figure 4.5.

Figure 4.4 Rotary Mixer

Standard 100x200 mm cylinder specimens were used for testing. Plastic molds were used to place fresh concrete, which was compacted and laid to rest for 24 hours before removing the molds according to ASTM C192. Figure 4.6 demonstrated fresh concrete as they are being molded.

Figure 4.5 Concrete Mix in the Plastic Basin

Figure 4.6 Molded Specimens

After demolding all specimens were placed in a water storage tank for curing process according to ASTM C192. Showed the curing process of specimens.

Figure 4.7 Curing Specimens in the Water Storage Tank

Trial specimens (mix #1 and mix #10) were vertically cut into two parts to observe the distribution of LECA pebbles in concrete. As is shown in Figure 4.8 all particles, and especially coarse particles which were lighter than other ones, were evenly distributed in the concrete specimen.

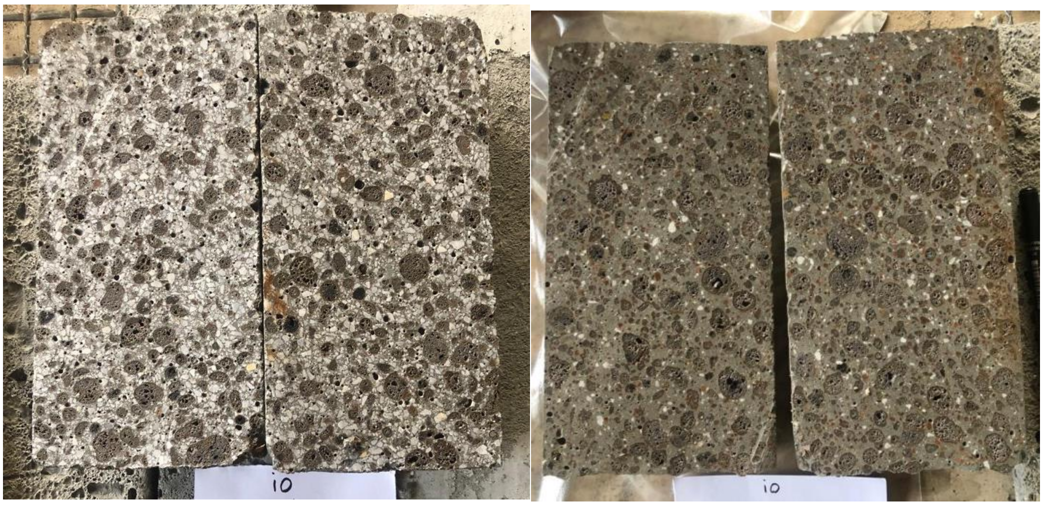

Figure 4.8 Longitudinal Cross-section of Mix #1 and #10

Cross-sections that are gathered along the height of the specimen show the non-homogeneity of the mixture in Figure 4.9. First cross-section is gathered from the surface of specimen and second cross section is gathered from the bottom of specimen. Coarse particles are observed in the first one and fine particles which are heavier than the coarse ones, are observed in the bottom part due to segregation.

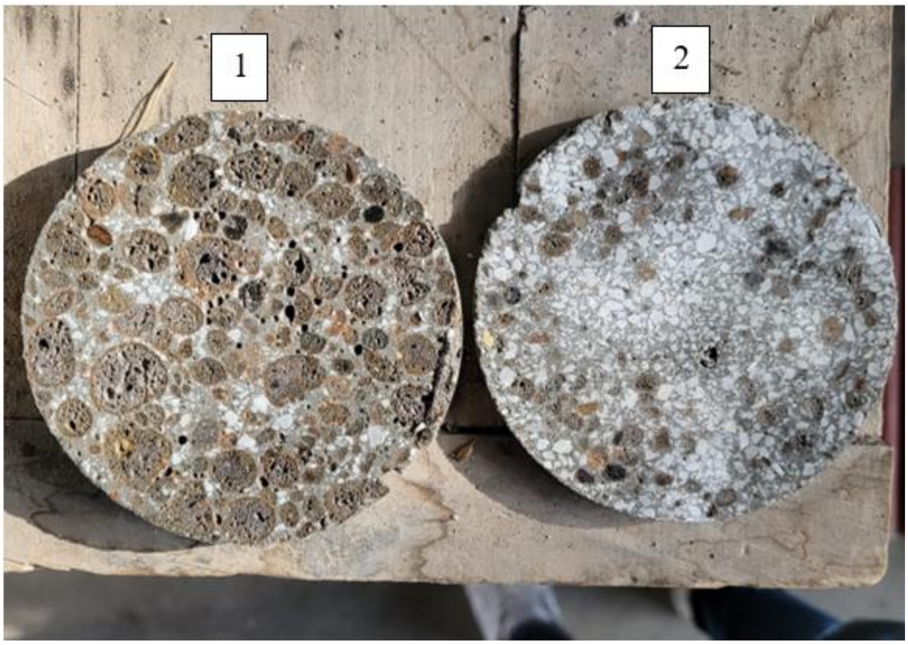

Figure 4.9 Cross Section of Mix #5

4.5 Compressive Strength Test and Results

After 28 days of curing, a force controlled compressive strength test with a loading rate of 2.40 kN/s was conducted on moist 100x200mm cylinder samples according to ASTM C39/C39M. A universal test machine (UTEST UTCM-6420) was used to determine the ultimate compressive strength of different samples. The testing setup is presented in Figure 4.10.

Figure 4.10 Testing Specimen in the UTS Machine

Density values were measured according to ASTM C567 and ASTM C138. Three specimens were measured and tested for each mix design, consequently, a total of 39 results were obtained for each mixture. For wet density and 28-day compressive strength values, mean and CoV(%) values are given in Table 4.9.

Coefficient of variation (CoV%) was the ratio of the standard deviation to the mean and it showed the extent and discrepancy of the data. A smaller CoV(%) shows that the dispersion of the data is lower. Higher CoV(%) values were obtained in Mixes #3 and #5 mainly due to segregation. An excessive amount of using SP caused the segregation in Mix #3 and highest water content among the other mixtures caused the segregation in Mix #5. These mixes were not homogeneous due to the segregation which is shown in Figure 4.11.

Figure 4.11 Segregation in Mix #3

For 28-day compressive strength values, CoV(%) was used to eliminate outlier data.. Outlier values were eliminated and presented in Table 4.9

Table 4.9 Compressive Strength Test Results for 13 Different Mixtures

Mixture Label	*Wet Density* *(kg/m^3)*	*CoV* *(%)*	$f_{c,28}$ *(MPa)*	*CoV* *(%)*
#1	1823	3.5	18.6	4.4
#2	1736	0.6	19.2	3.1
#3*	1888	6.2	25.8	1.9
#4*	1839	0.7	26.8	0.6
#5*	1785	2.6	15.5	1.8
#6	1758	1.5	20.7	7.0
#7*	1980	0.3	29.9	6.3
#8*	1913	1.3	35.6	5.0
#9*	1733	1.2	20.9	8.9
#10	1787	2.2	27.0	8.9
#11	1798	1.5	24.6	7.9
#12	1699	1.4	22.1	5.3
#13	1559	2.2	21.1	3.2

*Denotes the presence of eliminated values

While a general positive relationship between wet density and compressive strength can be seen in Figure 4.12, a strong relationship is not observed between wet density and compressive strength as the determination coefficient is calculated as 0.37, which meant that 37% of variation in the $f_{c,28}$ can be explained by the amount of density. The result may be expected when considering a number of different factors that determine strength such as w/c ratio and distribution of LECA particles in the specimens.

The best results are obtained by using higher cement content, lower water content, and lower w/b ratio as normal concrete mix design. In addition to that, using the fine LECA in the mixture increases the $f_{c,28}$ because it has the lowest absorption capacity. Increasing the coarse and medium coarse LECA content in the mixture affects the $f_{c,28}$ adversely because of their higher water absorption capacities. For instance, the highest $f_{c,28}$ is achieved in Mix #8 by using the highest cement content and lowest w/b ratio according to other mixtures. Mix #7 has the same amount of cement content and w/c ratio as Mix 8 but Mix 8 includes fine LECA which increases the $f_{c,28}$. Also, $f_{c,28}$ of Mix #4 is higher than the Mix #3 because it includes less coarse LECA and more fine LECA content even though they have the same cement content, water content and w/b ratio.

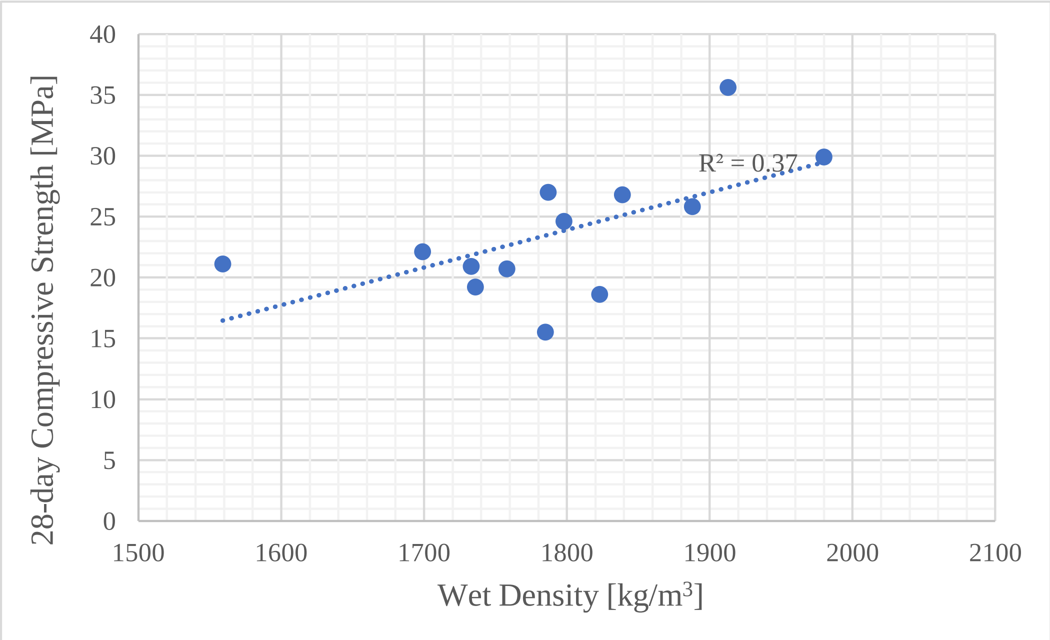

Figure 4.12 Relationship between the Wet Density and 28-day Compressive Strength

It can be observed in Figure 4.13 that the compressive strength of samples that contained more than 0.36 m^3 LECA/m^3 concrete is higher than samples that contained 0.27 m^3 LECA/m^3 concrete. the R^2 between the amount of wet density and the compressive strength for containing 0.27 LECA/m^3 concrete is 69%. Accordingly, 69% of the variation in compressive strength can be explained by the amount of 0.27 LECA/m^3. the R^2 between the amount of wet density and the compressive strength for containing more than 0.36 LECA/m^3 concrete is 57%. Accordingly, 57% of the variation in compressive strength can be explained by the amount of more than 0.36 LECA/m^3.

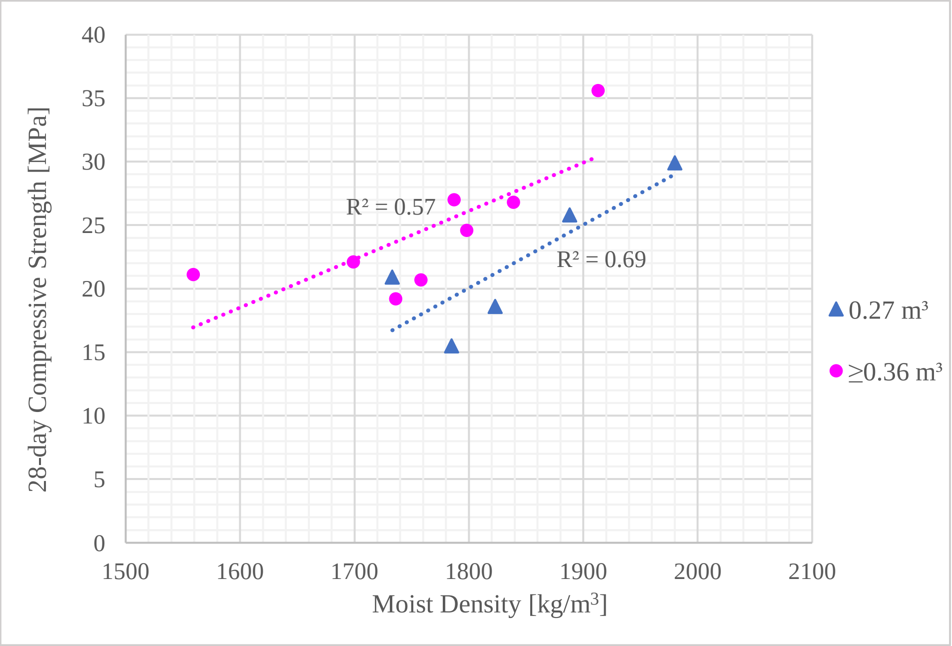

Figure 4.13 Relationship between the Wet Density and 28-day Compressive Strength with Comparison of LECA Contents

Analysis results presented in Figure 4.14 indicate that 28-day compressive strength decreases as w/b ratio increases. In fact, a strong correlation is observed between these variables, as is expected and is supported by literature. 74% of the variation in the $f_{c,28}$ can be explained by the w/b ratio. Datapoints indicated with different colors show different cement contents such as 400, 500, and 600 kg/m^3. It is observed that 28-day compressive strength increases by increasing binder content even for the same w/b ratios.

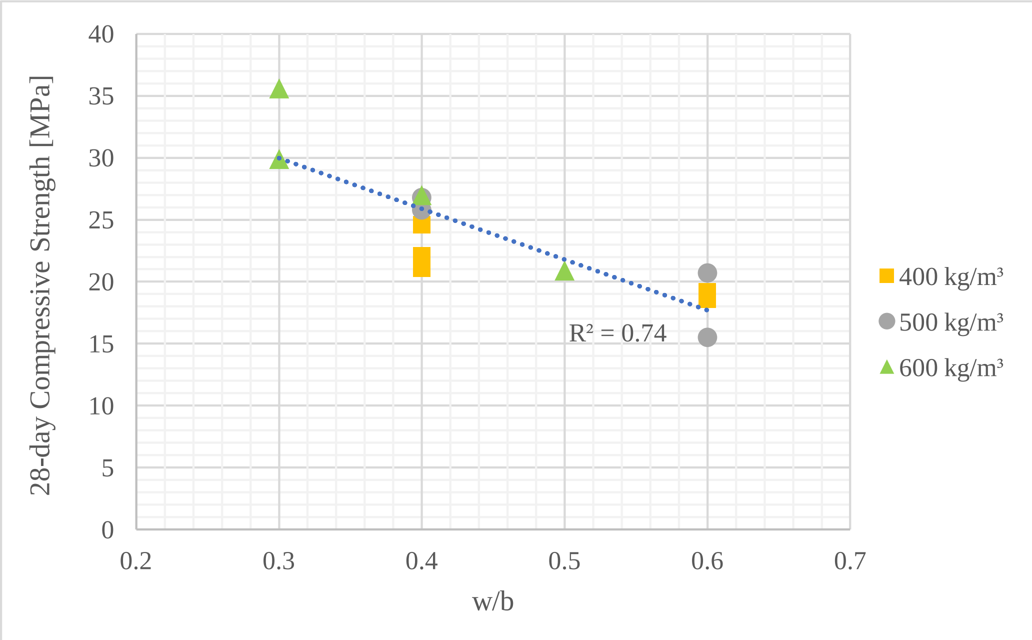

Figure 4.14 Relationship between the w/b Ratio and 28-day Compressive Strength with Binder Contents

4.6 Estimation of the Results by META-Analysis

All independent variables of the prepared mixtures are entered into the formula which is shown in Equation 3.1. 28-day compressive strength test results are estimated. Estimated values for different mixtures are shown in Table 4.10.

Table 4.10 Estimations of $f_{c,28}$ for 13 Different Mixtures

Mixture Label	*Total LECA (kg/m³)*	*Cement (kg/m³)*	*Fly Ash (kg/m³)*	*Sand (kg/m³)*	*Water (kg/m³)*	*Estimation (MPa)*
#1	258.4	400	0	885.0	240	25.5
#2	447.4	400	0	652.8	240	21.5
#3	258.4	500	0	882.6	200	36.1
#4	447.4	500	0	662.2	200	32.4
#5	258.4	500	0	648.3	300	18
#6	447.4	500	0	545.1	250	23.3
#7	258.4	600	0	833.4	180	43.1
#8	447.4	600	0	608.3	180	39.3
#9	258.4	600	0	566.4	300	21.7
#10	447.4	600	0	489.0	240	28.9
#11	447.4	400	100	648.0	200	29.6
#12	447.4	400	200	446.4	240	23
#13	738.5	400	200	0.0	240	14.9

4.7 Comparison of the Estimations and Results of Experimental Program

There are differences between the estimations and test results as presented in Table 4.11. Equation 3.1, which is a result of the meta-analysis carried out in this study, overestimated the $f_{c,28}$ of all mixes except mix #13. The reason for that is the effect of LECA is considered less in the equation.

The overall average of the ratio of estimated to experimental results is calculated to be 1.15, which indicates that compressive strength values estimated by using the proposed equation presented in this study overestimate compressive strength by 15%.

The reason for the 15% difference between the estimated and experimental results is that LECA used in the experiments is produced mainly for agricultural purposes. structural LECA is used in the estimations which are gathered from the 15 particular studies. Improved technical properties of structural LECA can be different than the agricultural LECA which can affect the estimations.

Table 4.11 Estimations and Test Results of $f_{c,28}$ for 13 Different Mixtures

Mixture Label	*Estimation (MPa)*	*Experimental Result (MPa)*	*Ratio of Estimated/Experimental Result*
#1	25.7	18.6	1.38
#2	19.7	19.2	1.03
#3	38.1	25.8	1.48
#4	32.1	26.8	1.20
#5	18.8	15.5	1.21
#6	22.4	20.7	1.08
#7	46.7	29.9	1.56
#8	40.6	35.6	1.14
#9	23.5	20.9	1.12
#10	29.1	27.0	1.08
#11	27.9	24.6	1.13
#12	20.7	22.1	0.94
#13	11.3	21.1	0.54

In Figure 4.15, the relationship between wet density compressive strength test results is shown based on the results of estimations and experiments.

There should be a positive and strong correlation between the wet density and $f_{c,28}$ because they are related parameters. In estimations, a stronger relationship is obtained between wet density compressive strength test results because the determination coefficient is found as 88% which means that 88% of the variation in compressive strength can be related to the wet density. However, 37% of the variation in compressive strength can be related to the wet density which is a quite low value. The reason for that, in the experiments, other real-life factors can be taken into consideration such as the distribution of the LECA pebbles in the specimen, the amount of SP, and human errors.

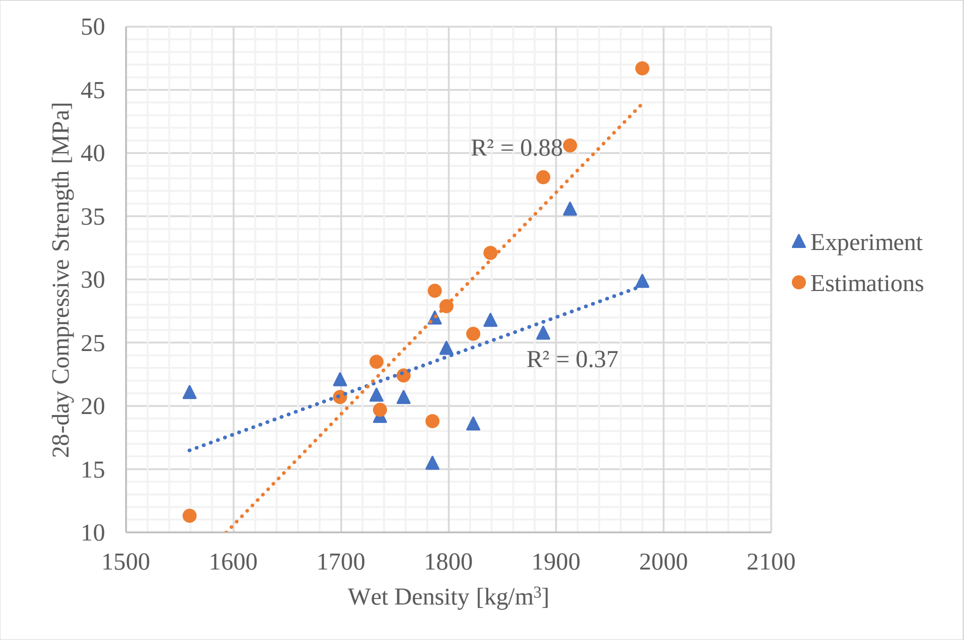

Figure 4.15 Comparison of Wet Density and Compressive Strength based on Experiment and Estimations

A strong relationship is obtained between the estimations and compressive strength test results in Figure 4.16 as indicated by the determination coefficient of 65%. All data fall above the line of equality except mix #13, supporting the overestimation conclusion described previously. Experiment results and estimations are compared according to their w/b ratios. There is relatively small difference between the regression line or line of best fit and the majority of the data which have a w/b ratio of 0.4. Also, data that has a w/b ratio of 0.5 is matched with the regression line.

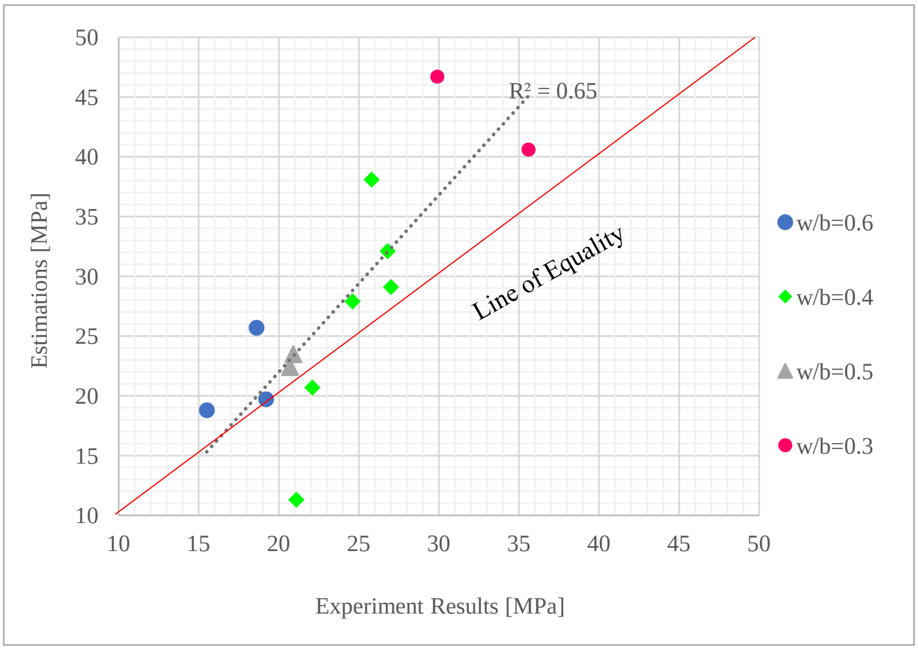

Figure 4.16 Comparison of Experiment Result and Estimations by Showing w/b

Experiment results and estimations are compared according to LECA amounts and results are presented in Figure 4.17. Data including more than 0.36 m^3 LECA/m^3 are closer to the regression line than the data including 0.27 m^3 LECA/m^3. This result indicates that the equation from the regression analysis provides more reliable estimates for mixes that contain more LECA.

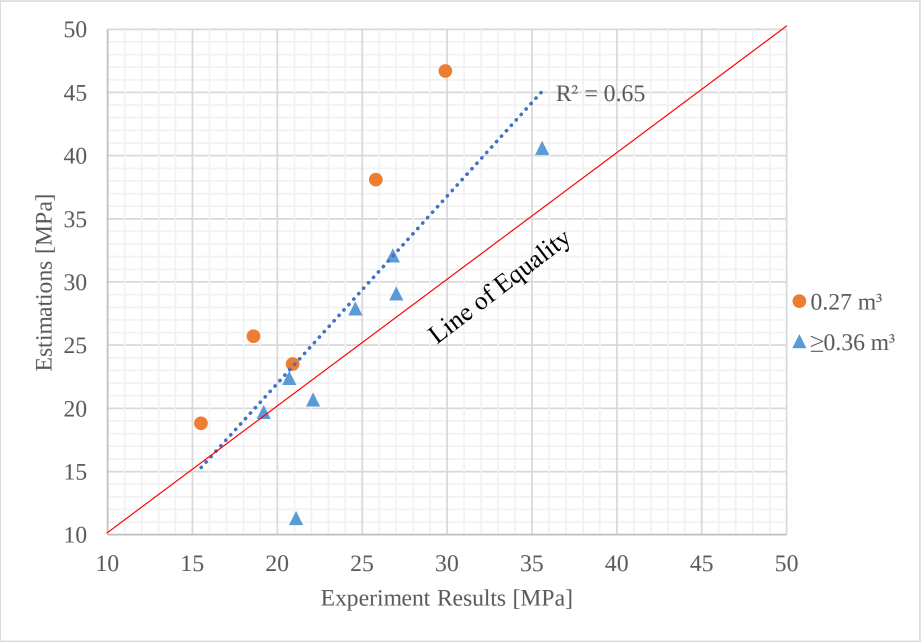

Figure 4.17 Comparison of Experiment Result and Estimations by LECA Content

When the relationship between the estimated and experiment results is examined separately, a stronger relationship is obtained for the data including 0.27 and 0.36 m^3 LECA/m^3 in Figure 4.18.

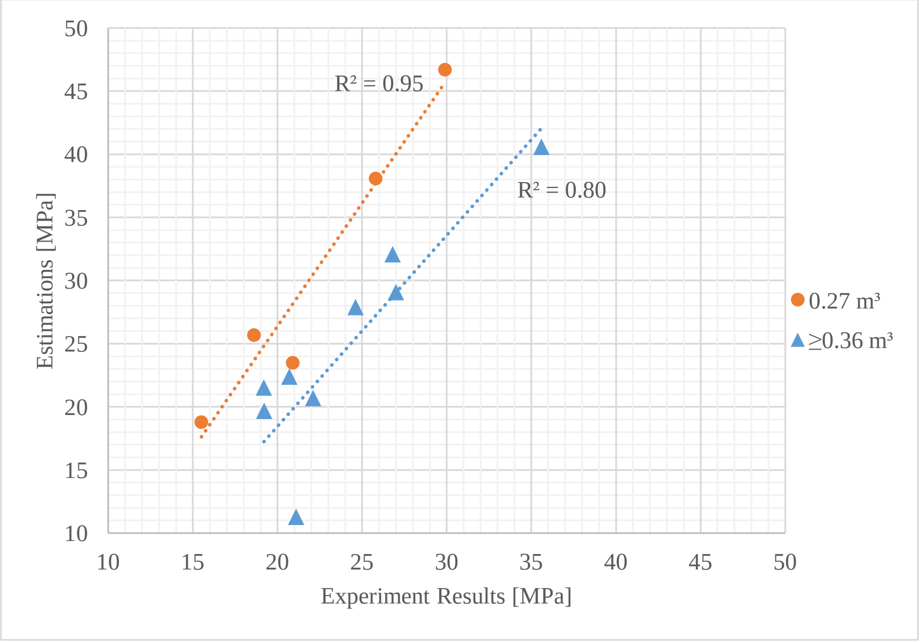

Figure 4.18 Comparison of Experiment Results and Estimations by LECA Content, with Individual Trend Lines

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, the relationship between the use of LECA and the 28-day strength of concrete is examined through a meta-analysis approach. Detailed statistical analysis and correlations between different parameters such as the amount of Lightweight Expanded Clay Aggregate (LECA), w/c ratio, 28-day compressive strength, and density are shown. An equation is shown to determine the 28-day compressive strength by using independent variables such as LECA, cement, water, and mineral additives by using more than 140 data points which are gathered from the 15 different studies in 8 different countries. All data points that are used to complete the meta-analysis is shown in Appendix B. Furthermore, the results of meta-analysis are compared with an experimental study to investigate the 28-day compressive strength of LECA concrete. 13 different mix proportions are prepared to test the compressive strength.

- It is important to note that the statistical analysis is conducted for the LECA included mixtures.
- Correlations between the water/binder ratio, LECA, and 28-day compressive strength of concrete are shown. The reason why obtaining the small R^2 values is low is the uniqueness and variability of the material. Furthermore, more than 140 data points are compiled and analyzed which results in variability.
- According to ANOVA and regression analysis results, the p-value of the whole statistical model is found as 2.04E-25 which means that the null hypothesis could be rejected.
- When the p-values of all independent variables are examined, the p-value of LECA is found as 4.38E-16 which is quite less than the alpha value (0.05).

The null hypothesis can be rejected. Also, the p-values of cement and water are less than the alpha value (0.05). Therefore, LECA, water, and cement as independent variables are significant in determining the 28-day compressive strength according to data points gathered from the LECA included studies.

- The p-values of silica fume and fly ash are greater than 0.05 which means that null hypothesis cannot be rejected, and these parameters are considered insignificant because 28-day compressive strength of concrete is investigated.
- Equation is generated according to regression analysis:

  $f_{c,28}$ = 61.501 - 0.032*LECA+ 0.047*Cement – 0.193 *Water + 0.063*Silica Fume + 0.005*Fly Ash

  The 28-day compressive strength of concrete can be estimated in MPa by entering LECA, cement, silica fume, fly ash, and water in kg/m^3 into the equation which provides great convenience to the user. Since more than 140 data points are compiled and analyzed to create the equation, it is more strong and more accurate than the individual results.
- Sensitivity analysis and regression analysis results are compatible because LECA, cement, and water have the greatest effect because they influence the mean value of $f_{c,28}$ dramatically. However, fly ash and silica fume can be considered as less effective parameters because they have little or no effect on the mean value of $f_{c,28}$.
- 28-day compressive strength tests are conducted for different 13 mixtures to compare the meta-analysis and experiment results. Generally, the equation obtained from the regression analysis overestimates the 28-day compressive strength values. The coefficient of the estimated/experimental result value is found as 1.15 on average. It means that the estimated values are 1.15 times higher than the experimental ones and the coefficient can be used to estimate the 28-day compressive strength of LECA concrete.
- A strong relationship is obtained between the estimations and compressive strength test results because R^2 is 0.65. Values with a w/b ratio of 0.4 are

closer to the regression line/best-fit line. Values with a w/b ratio of 0.5 are almost matched with the regression line/best-fit line. Also, specimens that consist of more than 0.36 m^3 LECA are closer to the regression line than the specimens that consisted of 0.27 m^3 LECA. This result indicates that the equation from the regression analysis provides more reliable estimates for mixes that contain more LECA.

- The reason for the production of LECA is an important factor that may have contributed to the difference in experimental results with estimations. LECA used in the experiments was produced mainly for agricultural purposes. Underlying data used for the estimations on the other hand used LECA produced as a structural lightweight aggregate. They may have different technical properties that contributed to the increase in estimations of compressive strength.

5.2 Recommendations

The study included two distinct comprehensive sections: meta-analysis and statistical analysis that followed; and experimental testing. There is a slight discrepancy between estimated 28-day compressive strength values and those obtained from experiments. That may be due to the type of LECA used. A recommendation for future study may be to repeat the set of experiments by using LECA produced specifically for structural applications.

REFERENCES

ACI Committee. (2004). *Standard Practice for Selecting Proportions for Structural Lightweight Concrete* (ACI 211.2-98) Farmington Hills, Michigan: American Concrete Institue.

ACI Committee. (2003). *Guide for Structural Aggregate* (ACI 213R-2) Farmington Hills, Michigan. American Concrete Institue

Alexander, M. G. (Ed.). (1999). *Engineering and transport properties of the interfacial transition zone in cementitious composites* (Vol. 20). Rilem Publications.

Alexandre Bogas, J., Gomes, M. G., & Real, S. (2015). Capillary absorption of structural lightweight aggregate concrete. Materials and Structures/Materiaux et Constructions, 48(9), 2869–2883.

Altman, D. G., & Bland, J. M. (2005). Standard deviations and standard errors. Bmj, 331(7521), 903.

Andiç-Çakir, Ö., & Hizal, S. (2012). Influence of elevated temperatures on the mechanical properties and microstructure of self consolidating lightweight aggregate concrete. *Construction and Building Materials*, *34*, 575–583.

Aslam, M., Shafigh, P., Alizadeh Nomeli, M., & Zamin Jumaat, M. (2017). Manufacturing of high-strength lightweight aggregate concrete using blended coarse lightweight aggregates. *Journal of Building Engineering*, *13*, 53–62.

ASTM C330/C330M-14. (2017). *Standard Specification for Lightweight Aggregates for Structural Concrete*. West Conshohocken, Pennsylvania, United States of America: ASTM International. doi: 10.1520/C0330_C0330M-14

ASTM C127-15. (2016). *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*. West Conshohocken, Pennsylvania, United States of America: ASTM International. doi: 10.1520/C0127-15

ASTM C128-15. (2023). *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate*. West Conshohocken, Pennsylvania, United States of America: ASTM International. doi: 10.1520/C0128-15

ASTM C136-06. (2015). *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. West Conshohocken, Pennsylvania, United States of America: ASTM International. doi: 10.1520/C0136-06

ASTM C192. (2015). *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*. West Conshohocken, Pennsylvania, United States of America: ASTM International. doi: 10.1520/C0192_C0192M-14

ASTM C39/39M-21. (2021). *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. West Conshohocken, Pennsylvania, United States of America: ASTM International. doi: 10.1520/C0039_C0039M-21

ASTM C567/567M-19. (2020). *Standard Test Method for Determining Density of Structural Lightweight Concrete*. West Conshohocken, Pennsylvania, United States of America: ASTM International. doi: 10.1520/C0567_C0567M-19

Bewick, V., Cheek, L., & Ball, J. (2003). Statistics review 7: Correlation and regression. In *Critical Care* (Vol. 7, Issue 6, pp. 451–459).

Bogas, J. A., & Gomes, A. (2013). Compressive behavior and failure modes of structural lightweight aggregate concrete - Characterization and strength prediction. *Materials and Design, 46*, 832–841.

Bogas, J. A., Gomes, A., & Pereira, M. F. C. (2012). Self-compacting lightweight concrete produced with expanded clay aggregate. *Construction and Building Materials, 35*, 1013–1022.

Bogas, J. A., Nogueira, R., & Almeida, N. G. (2014). Influence of mineral additions and different compositional parameters on the shrinkage of structural expanded clay lightweight concrete. *Materials and Design, 56*, 1039–1048.

Bogas, J. A., & Gomes, A. (2015). Non-steady-state accelerated chloride penetration resistance of structural lightweight aggregate concrete. *Cement and Concrete Composites*, *60*, 111–122.

Bogas, J. A., & Nogueira, R. (2014). Tensile strength of structural expanded clay lightweight concrete subjected to different curing conditions. *KSCE Journal of Civil Engineering*, *18*(6), 1780–1791. https://doi.org/10.1007/s12205-014-0061-x

Chatterjee, Samprit., & Simonoff, J. S. (2013). *Handbook of Regression Analysis*. Wiley.

Chandra, S., & Berntsson, L. (2002). *Lightweight aggregate concrete*. Noyes publications-Wiliam Andrew Publishing, Norwich, New York

Dabbaghi, F., Dehestani, M., Yousefpour, H., Rasekh, H., & Navaratnam, S. (2021). Residual compressive stress–strain relationship of lightweight aggregate concrete after exposure to elevated temperatures. *Construction and Building Materials, 298*.

Dilli, M. E., Atahan, H. N., & Şengül, C. (2015). A comparison of strength and elastic properties between conventional and lightweight structural concretes designed with expanded clay aggregates. *Construction and Building Materials*, *101*, 260–267.

Gao, H., Xia, S., Chen, F., Stuedlein, A. W., Li, X., Wang, Z., Shen, Z., & Chen, X. (2021). Dynamic shear modulus and damping of cemented and uncemented lightweight expanded clay aggregate (LECA) at low strains. *Soil Dynamics and Earthquake Engineering*, *142*.

Genleştirilmiş Kil. MTA Genel Müdürlüğü. (n.d.). Retrieved January 3, 2023, from https://www.mta.gov.tr/v3.0/bilgi-merkezi/genlestirilmis-kil

Haselbach, L. (n.d.). The Engineering Guide to LEED-New Construction: Sustainable Construction for Engineers, Second Edition.

Hedges, L. v. (1992). Meta-Analysis. In *Journal of Educational Statistics Winter* (Vol. 17, Issue 4).

Jozwiak-Niedzwiedzka, D. (2005). Scaling resistance of high performance concretes containing a small portion of pre-wetted lightweight fine aggregate. *Cement and Concrete Composites*, *27*(6), 709–715.

Karch, J. (2020). Improving on adjusted R-squared. *Collabra: Psychology*, *6*(1).

Ke, Y., Ortola, S., Beaucour, A. L., & Dumontet, H. (2010). Identification of microstructural characteristics in lightweight aggregate concretes by micromechanical modelling including the interfacial transition zone (ITZ). *Cement and Concrete Research*, *40*(11), 1590–1600.

Koňáková, D., Čáchová, M., Vejmelková, E., Keppert, M., Jerman, M., Bayer, P., Rovnaníková, P., & Černý, R. (2017). Lime-based plasters with combined expanded clay-silica aggregate: Microstructure, texture and engineering properties. *Cement and Concrete Composites*, *83*, 374–383.

Karamloo, M., Mazloom, M., & Payganeh, G. (2016). Effects of maximum aggregate size on fracture behaviors of self-compacting lightweight concrete. *Construction and Building Materials*, *123*, 508–515.

Lotfy, A., Hossain, K. M. A., & Lachemi, M. (2016). Durability properties of lightweight self-consolidating concrete developed with three types of aggregates. *Construction and Building Materials*, *106*, 43–54.

Malešev, M., Radonjanin, V., Lukić, I., & Bulatović, V. (2014). The Effect of Aggregate, Type and Quantity of Cement on Modulus of Elasticity of Lightweight Aggregate Concrete. *Arabian Journal for Science and Engineering*, *39*(2), 705–711.

Mohammadi, Y., Mousavi, S., Rostami, F., & Danesh, A. (2015). The effect of silica fume on the properties of self-compacted lightweight concrete. *Current World Environment*, *10*(Special-Issue1), 381–388.

Nepomuceno, M. C. S., & Silva, P. D. (2014). Experimental evaluation of cement mortars with phase change material incorporated via lightweight expanded clay aggregate. *Construction and Building Materials*, *63*, 89–96.

Ozguven, A., & Gunduz, L. (2012). Examination of effective parameters for the production of expanded clay aggregate. *Cement and Concrete Composites*, *34*(6), 781–787.

Rampradheep, G. S., & Sivaraja, M. (2016). Experimental investigation on self-compacting self-curing concrete incorporated with the light weight aggregates. *Brazilian Archives of Biology and Technology*, *59*(Specialissue2).

Rashad, A. M. (2018). Lightweight expanded clay aggregate as a building material – An overview. In *Construction and Building Materials* (Vol. 170, pp. 757–775). Elsevier Ltd.

Rosenthal, R., & Dimatteo, M. R. (2000). *META-ANALYSIS: Recent Developments in Quantitative Methods for Literature Reviews*.

Sajedi, F., & Shafigh, P. (2012). High-Strength Lightweight Concrete Using Leca, Silica Fume, and Limestone. *Arabian Journal for Science and Engineering*, *37*(7), 1885–1893.

Sepehr, M. N., Kazemian, H., Ghahramani, E., Amrane, A., Sivasankar, V., & Zarrabi, M. (2014). Defluoridation of water via Light Weight Expanded Clay Aggregate (LECA): Adsorbent characterization, competing ions, chemical regeneration, equilibrium and kinetic modeling. *Journal of the Taiwan Institute of Chemical Engineers*, *45*(4), 1821–1834.

Shen, Q., & Faraway, J. (2004). An F test for linear models with functional responses. Statistica Sinica, .(Vol. 14, Issue 4). 1239-1257

Subaşı, S. (2009). The effects of using fly ash on high strength lightweight concrete produced with expanded clay aggregate. *Scientific Research and Essay*, *4*(4), 275–288.

Sykes, A. O. (1993). An introduction to regression analysis. *Chicago Lectures in Law and Economics*. Foundation Press

Şen, S. (2019). How to Do Meta-Analysis with SPSS? *Harran Education Journal*, *4*(1), 21–49.

Tanyildizi, H., & Coskun, A. (2008). The effect of high temperature on compressive strength and splitting tensile strength of structural lightweight concrete containing fly ash. *Construction and Building Materials*, *22*(11), 2269–2275.

Terzić, A., Pezo, L., Mitić, V., & Radojević, Z. (2015). Artificial fly ash based aggregates properties influence on lightweight concrete performances. *Ceramics International*, *41*(2), 2714–2726.

Thienel, KC., Sveindottir, E.L., Maage, M., Poot, S., Hansen, E.A., Bennenk, H.W., Helland, S., Norden, G., Kwint, E., Milencovic, A., Smeplass, S., Tarquis, F., Holand, I., Price, B., van Breugel, K., (2000). LWAC Material Properties-State-of-the-Art. *BriteEuram Proj. EuroLightcon*, 111.

Valentine, J. C., Hedges, L. v., & Cooper, H. M. (2009). *The handbook of research synthesis and meta-analysis*. Russell Sage Foundation.

Yoon, J. Y., Kim, J. H., Hwang, Y. Y., & Shin, D. K. (2015). Lightweight concrete produced using a two-stage casting process. *Materials*, *8*(4), 1384–1397.

Youm, K. S., Moon, J., Cho, J. Y., & Kim, J. J. (2016). Experimental study on strength and durability of lightweight aggregate concrete containing silica fume. *Construction and Building Materials*, *114*, 517–527.

Zukri, A., Nazir, R., Said, K. N. M., & Moayedi, H. (2018). Physical and mechanical properties of lightweight expanded clay aggregate (LECA). *MATEC Web of Conferences*, *250*.

Wasserstein, R. L., & Lazar, N. A. (2020). ASA statement on statistical significance and P-values. In *The theory of statistics in psychology* (pp. 1-10). Springer, Cham.

APPENDICES

A. F-Table for α=0.5

	F-table of Critical Values of α = 0.05 for F(df1, df2)																		
	DF1=1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**15**	**20**	**24**	**30**	**40**	**60**	**120**	**∞**
DF2=1	161.45	199.50	215.71	224.58	230.16	233.99	236.77	238.88	240.54	241.88	243.91	245.95	248.01	249.05	250.10	251.14	252.20	253.25	254.31
2	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38	19.40	19.41	19.43	19.45	19.45	19.46	19.47	19.48	19.49	19.50
3	10.13	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81	8.79	8.74	8.70	8.66	8.64	8.62	8.59	8.57	8.55	8.53
4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96	5.91	5.86	5.80	5.77	5.75	5.72	5.69	5.66	5.63
5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74	4.68	4.62	4.56	4.53	4.50	4.46	4.43	4.40	4.37
6	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10	4.06	4.00	3.94	3.87	3.84	3.81	3.77	3.74	3.70	3.67
7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68	3.64	3.57	3.51	3.44	3.41	3.38	3.34	3.30	3.27	3.23
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.35	3.28	3.22	3.15	3.12	3.08	3.04	3.01	2.97	2.93
9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.14	3.07	3.01	2.94	2.90	2.86	2.83	2.79	2.75	2.71
10	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02	2.98	2.91	2.85	2.77	2.74	2.70	2.66	2.62	2.58	2.54
11	4.84	3.98	3.59	3.36	3.20	3.09	3.01	2.95	2.90	2.85	2.79	2.72	2.65	2.61	2.57	2.53	2.49	2.45	2.40
12	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80	2.75	2.69	2.62	2.54	2.51	2.47	2.43	2.38	2.34	2.30
13	4.67	3.81	3.41	3.18	3.03	2.92	2.83	2.77	2.71	2.67	2.60	2.53	2.46	2.42	2.38	2.34	2.30	2.25	2.21
14	4.60	3.74	3.34	3.11	2.96	2.85	2.76	2.70	2.65	2.60	2.53	2.46	2.39	2.35	2.31	2.27	2.22	2.18	2.13
15	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59	2.54	2.48	2.40	2.33	2.29	2.25	2.20	2.16	2.11	2.07
16	4.49	3.63	3.24	3.01	2.85	2.74	2.66	2.59	2.54	2.49	2.42	2.35	2.28	2.24	2.19	2.15	2.11	2.06	2.01
17	4.45	3.59	3.20	2.96	2.81	2.70	2.61	2.55	2.49	2.45	2.38	2.31	2.23	2.19	2.15	2.10	2.06	2.01	1.96
18	4.41	3.55	3.16	2.93	2.77	2.66	2.58	2.51	2.46	2.41	2.34	2.27	2.19	2.15	2.11	2.06	2.02	1.97	1.92
19	4.38	3.52	3.13	2.90	2.74	2.63	2.54	2.48	2.42	2.38	2.31	2.23	2.16	2.11	2.07	2.03	1.98	1.93	1.88
20	4.35	3.49	3.10	2.87	2.71	2.60	2.51	2.45	2.39	2.35	2.28	2.20	2.12	2.08	2.04	1.99	1.95	1.90	1.84
21	4.32	3.47	3.07	2.84	2.68	2.57	2.49	2.42	2.37	2.32	2.25	2.18	2.10	2.05	2.01	1.96	1.92	1.87	1.81
22	4.30	3.44	3.05	2.82	2.66	2.55	2.46	2.40	2.34	2.30	2.23	2.15	2.07	2.03	1.98	1.94	1.89	1.84	1.78
23	4.28	3.42	3.03	2.80	2.64	2.53	2.44	2.37	2.32	2.27	2.20	2.13	2.05	2.01	1.96	1.91	1.86	1.81	1.76
24	4.26	3.40	3.01	2.78	2.62	2.51	2.42	2.36	2.30	2.25	2.18	2.11	2.03	1.98	1.94	1.89	1.84	1.79	1.73
25	4.24	3.39	2.99	2.76	2.60	2.49	2.40	2.34	2.28	2.24	2.16	2.09	2.01	1.96	1.92	1.87	1.82	1.77	1.71
26	4.23	3.37	2.98	2.74	2.59	2.47	2.39	2.32	2.27	2.22	2.15	2.07	1.99	1.95	1.90	1.85	1.80	1.75	1.69
27	4.21	3.35	2.96	2.73	2.57	2.46	2.37	2.31	2.25	2.20	2.13	2.06	1.97	1.93	1.88	1.84	1.79	1.73	1.67
28	4.20	3.34	2.95	2.71	2.56	2.45	2.36	2.29	2.24	2.19	2.12	2.04	1.96	1.91	1.87	1.82	1.77	1.71	1.65
29	4.18	3.33	2.93	2.70	2.55	2.43	2.35	2.28	2.22	2.18	2.10	2.03	1.94	1.90	1.85	1.81	1.75	1.70	1.64
30	4.17	3.32	2.92	2.69	2.53	2.42	2.33	2.27	2.21	2.16	2.09	2.01	1.93	1.89	1.84	1.79	1.74	1.68	1.62
40	4.08	3.23	2.84	2.61	2.45	2.34	2.25	2.18	2.12	2.08	2.00	1.92	1.84	1.79	1.74	1.69	1.64	1.58	1.51
60	4.00	3.15	2.76	2.53	2.37	2.25	2.17	2.10	2.04	1.99	1.92	1.84	1.75	1.70	1.65	1.59	1.53	1.47	1.39
120	3.92	3.07	2.68	2.45	2.29	2.18	2.09	2.02	1.96	1.91	1.83	1.75	1.66	1.61	1.55	1.50	1.43	1.35	1.25
∞	3.84	3.00	2.60	2.37	2.21	2.10	2.01	1.94	1.88	1.83	1.75	1.67	1.57	1.52	1.46	1.39	1.32	1.22	1.00

B. Data Points for Meta-Analysis

No	*Article*	*Range of Mixing Parameters (kg/m^3)*					*Type of Specimen*	$f_{c,28}$ *(MPa)*	*Density (kg/m^3)*
		Cement	*Silica Fume*	*Fly Ash*	*LECA*	*Water*			
1	Jozwiak-Niedzwiedzka, D. (2005)	340-400	0-40	-	33.9-99	96.8-138.2	Cubic	71.5-88.3	2372-2487
2	Rampradheep, G. S., & Sivaraja, M (2016)	450	-	-	0-54	180	Cubic	41.9-44.8	-
3	Bogas, J. A., & Nogueira, R (2014)	350-559	-	-	0-372.8	158	Cubic	31.2-81.6	1620-2430
4	Yoon, J. Y., Kim, J. H., Hwang, Y. Y., & Shin, D. K (2015)	559	-	-	401	235	Cylinder	22.1	1600

5	Malešev, M., Radonjanin, V., Lukić, I., & Bulatović, V. (2014)	350-450	-	-	0-420	180-195.6	Cubic	41.3-60.4	1850-2348
6	Bogas, J. A., & Gomes, A. (2015)	270-525	0-36	0-180	0-451.5	158-217	Cubic	30.9-76.2	1483-2411
7	Bogas, J. A., Nogueira, R., & Almeida, N. G. (2014)	270-525	0-36	0-180	0-548.3	135-247.5	Cubic	31.2-76.2	1540-2299
8	Mohammadi, Y., Mousavi, S., Rostami, F., & Danesh, A. (2015)	366.2-400	0-33.8	-	400	200	Cubic	16.0-20.0	1691-1757
9	Sajedi, F., & Shafigh, P. (2012)	450-540	45-60	-	207.9-482	153.4-200	Cubic	32.9-67.0	1622-1984
10	Subaşı, S. (2009)	245-450	-	0-135	756.2-856.4	157.5-202.5	Cubic	10.8-44.4	1200-1710

11	Dilli, M. E., Atahan, H. N., & Şengül, C. (2015)	362-458	-	80-100	0-464	188-228	Cylinder	21-62	1710-2407
12	Bogas, J. A., Gomes, A., & Pereira, M. F. C. (2012)	325-399	-	164-201	0-400.5	151-196	Cubic	36.5-62.5	1724-2277
13	Youm, K. S., Moon, J., Cho, J. Y., & Kim, J. J. (2016)	539.4-600	0-44.8	-	0-530.7	155-163	Cylinder	46.1-74.2	2006-2448
14	Lotfy, A., Hossain, K. M. A., & Lachemi, M. (2016)	395-430	37-40	62-67	840-920	178-215	Cubic	29.5-37.6	1608-1622
15	Karamloo, M., Mazloom, M., & Payganeh, G. (2016)	400-450	-	-	250	157.5-160	Cubic	27-43.8	1889-1939