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Dematerialization of Concrete: Meta-Analysis of Lightweight Expanded Clay Concrete for Compressive Strength

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Abstract: The construction industry is responsible for a significant share of global material consumption, including natural resources. Therefore, the United Nations Sustainable Development Goal 12.2 on sustainable management and efficient use of natural resources cannot be achieved without significant advances and contributions from the construction sector. Furthermore, various materials used by the construction industry contribute to the development and expansion of the LEED (Leadership in Energy and Environmental Design) system. LECA (Light Expanded Clay Aggregate) is one such material that enhances LEED performance through its key benefits, including lightness, thermal insulation, sound insulation, and fire resistance. One of the most effective methods for reducing the weight of concrete is the incorporation of lightweight aggregates, and the advantages of LECA include lessening loads and enabling reduced cross-sections, directly improving the sustainability of the built environment via reduced materials consumption. This study aims to develop a prediction model for the compressive strength of LECA-incorporated concrete through a meta-analysis. More than 140 data points were compiled through literature via 15 separate studies, and results were analyzed to conduct the meta-analysis. Moreover, an experimental program was carried out to verify the model and evaluate its accuracy in predicting compressive strength. Results from the developed model and the experimental program were in accordance with concrete having lower compressive strengths compared to those at high strength values. Likewise, more accurate results were obtained for concrete mixes that have w/b ratios of 0.5 or higher. Concrete mixes that have higher amounts of LECA by volume of concrete yielded more accurate results when using the prediction model. A sensitivity analysis was carried out to quantify the impact of several parameters on the compressive strength of LECA concrete.

Keywords: lightweight expanded clay aggregate; lightweight concrete; dematerialization; UN SDG 12; structural concrete minimization; compressive strength prediction

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1. Introduction

The construction industry is responsible for a significant share of global material consumption, including natural resources. Therefore, the United Nations Sustainable Development Goal 12.2 on sustainable management and efficient use of natural resources cannot be achieved without significant advancements and contributions from the construction sector. Dematerialization directly aims to reduce and minimize materials used, thereby contributing positively to the goal. In the construction sector, numerous materials support the growth and expansion of the LEED (Leadership in Energy and Environmental Design) system. There are several materials that enhance LEED performance. Home-produced concrete, fly/wood ash concrete, recycled aggregates, and light expanded class aggregates are such examples [1–3]. Lightweight Expanded Clay Aggregate (LECA) is one such material

that boosts LEED performance due to its primary advantages, such as lightness, thermal insulation, sound insulation, fire resistance, and low water absorption. LECA provides multiple advantages for structures, mainly by enabling the dematerialization of the structure. Reduced concrete weight translates into reduced dead loads, thereby lessening foundation loads and enabling reduced cross-sections for foundation design. Benefits extend to the superstructure as well, with economies in section dimensions of beams and columns and steel reinforcement used. For structures with extended spans and bridge design especially, these potential benefits cannot be underestimated [4]. Such benefits directly improve the environmental performance of the built environment via reduced material consumption. Economic savings extend onto the transportation of materials, where cost savings from transportation were determined to be seven times greater than the cost of lightweight aggregates [5].

Another benefit of lightening structures may also be felt in earthquake-prone regions of the world. In earthquakes, applied loads on the structures are directly proportional to the weight of the structure. Therefore, reducing the structure's weight decreases the number of inertial forces that may occur during an earthquake.

The primary considerations for structural lightweight concrete are its unit weight and strength properties. To that end, a unit weight between 1120 and 1920 kg/m^3 and a 28-day compressive strength of more than 17 MPa is required for lightweight concrete [5].

The most effective way to obtain lightweight concrete is to use lightweight aggregates in concrete making [6]. Lightweight aggregates that may be used for concrete making may be grouped into two natural or artificial aggregates. The first naturally occurring lightweight aggregates have volcanic origins, such as pumice, volcanic slag, tuff, and diatomite. Artificial lightweight aggregates are obtained as a result of the heat-treated abrasion of natural materials or waste derived from industry, such as expanded clay, perlite, shale, vermiculate, and slate. Among lightweight aggregates used for making lightweight concrete, LECA continues to receive much attention due to its availability and cost-effectiveness [7].

Lightweight Expanded Clay Aggregate (LECA) is produced in 20 different countries under different brand names and is being used as a structural lightweight aggregate. One of the reasons contributing to the preference of LECA over other natural aggregates, such as pumice, volcanic tuff, and slag, is its higher strength properties [8]. LECA also has a lower coefficient of thermal expansion, provides better thermal insulation compared to ordinary concrete, and improves fire resistance, which are all important for the structural design of buildings [9,10].

This study aims to establish the relationship between the use of LECA and the 28-day strength of lightweight concrete using a meta-analysis. A meta-analysis is a research method that systematically synthesizes and interconnects the results of multiple scientific studies using statistical methods. It is also known to increase statistical accuracy by combining the results of more than one study. A prediction model for the 28-day compressive strength of LECA concrete was developed based on the results of the meta-analysis, and an experimental program was carried out to verify the model.

2. Literature on Lightweight Expanded Clay Aggregates

LECA is produced by heating raw materials to between 1100 and 1300 °C, thereby resulting in a volume increase of 5–6 times its original state, resulting in a mass filled with sintered gas bubbles [11]. Such bubbles are entrapped during cooling, yielding a porous and lightweight material [12]. Organic compounds are ignited during the heating process, thereby resulting in a non-combustible end product. The ultimate properties of LECA depend on the chemical and mineralogical composition of raw materials, the grain size of clay, the size of LECA pellets, and the temperature of the kiln. Increased amounts of Fe_2O_3 cause larger pores in LECA pellets, thereby contributing to lightweightness. A decrease in the grain size of the clay also results in greater expansion of the LECA pellets [13]. The temperature in the kiln also has an effect on the ultimate properties of LECA, and ideal

conditions are essential to producing high quality LECA for engineering applications whose size varies between 0.1 and 2.5 mm [14]. The density of LECA available commercially varies between 250 and 710 kg/m^3. Other compounds, such as SiO_2, constitute a major component of the chemical composition of LECA, but other alkalis, such as Al_2O_3, Fe_2O_3, CaO and Na_2O, and K_2O, also exist in their composition [11]. LECA has a pH value of 9.5, contributing to resistance to chemicals and acid attack in hardened concrete [15].

Density is an essential parameter of structural lightweight concrete. Concrete design can be engineered to yield different density values by integrating different proportions and types of LECA. Most articles in the literature evaluate LECA as a coarse aggregate in concrete, while the evaluation of LECA as a fine aggregate is less common [12].

Compressive strength is a key parameter for lightweight structural concrete, and among lightweight aggregates, LECA has one of the highest compressive strengths. Generally, the compressive strength of concrete is decreased by the incorporation of the LECA. However, there are multiple factors that affect the compressive strength of concrete, such as the water/binder ratio, use of admixtures, grading and properties of aggregates, and appropriate design, which may yield satisfactory mixes [12]. According to design specifications, structural lightweight concrete should have a minimum compressive strength of 17 MPa. However, compressive strength values of 40 MPa or more have also been reported with lightweight aggregates [5].

Lightweight aggregates have more capacity to absorb water compared to normal-weight aggregates due to their cellular structure. Water absorption of coarse LECA to be used for structural applications was reported as 12.3% by Bogas et al. [16]. For medium-coarse LECA, water absorption capacity was reported as 17% by Yoon et al. [4].

3. Methods

3.1. Meta-Analysis and Used Statistical Measures

Meta-analysis is the process of combining the findings of several separate empirical research studies to explain a phenomenon realistically and holistically, thereby enabling generalizations that are more applicable in practice [17]. A meta-analysis study, therefore, helps bridge the gap between theory and practice [18]. Results obtained through meta-analysis are more statistically accurate than those that can be provided by a single study due to the inherent amount of variation and uncertainty that is captured. Results of multiple studies may also be compared to identify trends and discrepancies by using meta-analysis [19].

The following statistical parameters are used to carry out the analysis in this study:

- Correlation coefficient: Correlation is a statistical measure that expresses the linear relationship between two variables. The correlation coefficient (r), ranging from -1 to 1, shows the strength of the relationship between two variables, where a value of 1 indicates a strong positive correlation and a value of -1 indicates a strong negative correlation.
- Coefficient of determination: The coefficient of determination (R^2) is the square of the correlation coefficient and measures how strong the linear relationship between two variables is. Potential values are between 0 and 1. A value of 1 indicates that there is a predictable and strong relationship between these variables and that the data can fit perfectly on a regression line. A value of 0 indicates that there is no relationship between the variables. The coefficient of determination does not show the cause–effect relationship between two variables but rather the strength of the relationship between the two variables [20].
- Analysis of variance: Analysis of variance (ANOVA) is a statistical analysis tool that is used to determine the effect of the independent variables on the dependent variable. Application of statistical procedures was found to be lacking in studies involving LECA. In fact, no study using ANOVA related to LECA was encountered during the literature review.

- Parameter optimization: Parameter optimization is used to determine optimal settings for controllable parameters that are defined as independent variables. The optimal value is sought for each independent variable to achieve a specifically defined goal for the dependent variable. Parameter optimization was carried out using MATLAB software release 2022a in this study.
- Sensitivity analysis: Sensitivity analysis determines how the target variable (the dependent variable) is affected by changes in the independent variables. It is used to understand the magnitude of the effect the independent variables have on the dependent variable. Sensitivity analysis also reveals which independent variable has the greatest effect on the dependent variable [21,22]. Understanding which parameters have a greater impact may direct attention toward improving the process or product.

One of the objectives of this study was to examine the relationship between the use of LECA and the 28-day compressive strength of structural concrete using a meta-analysis approach. More than 140 data points from 15 different academic studies that were conducted in 8 different countries, such as Portugal, India, Poland, Korea, Serbia, Iran, Turkey, and Canada, were used in the meta-analysis. Data extracted from selected studies involving LECA include information on material contents, 28-day compressive strength, and concrete density values. Data used for the analysis are presented in Appendix A. The reported wet density of LECA concrete and its 28-day compressive strength were found to be in the range of 1200–2490 kg/m^3 and 10–88 MPa, respectively.

3.2. Nature of Concrete and Correlations between Various Parameters

Statistical analysis of results, especially those results from multiple studies carried out by different researchers across different countries, is a scientific necessity. However, working with concrete, a composite material with inherent variability, does pose challenges in that regard. For example, an R^2 value of 0.6 may be judged to be insufficient as proof of a relationship between two parameters in some fields of science with less material variation. However, even lower values were obtained for the relationship between well-established concrete parameters.

An initial analysis of the relation between the water/binder ratio and the 28-day compressive strength of LECA concrete yielded an R^2 value of 0.22, as presented in Figure 1. The reason for obtaining a lower-than-expected value is that variation in compressive strength depends on a number of parameters. For this reason, a strong correlation value cannot be obtained between the individual cement, binder, or water/binder ratio and compressive strength of LECA concrete.

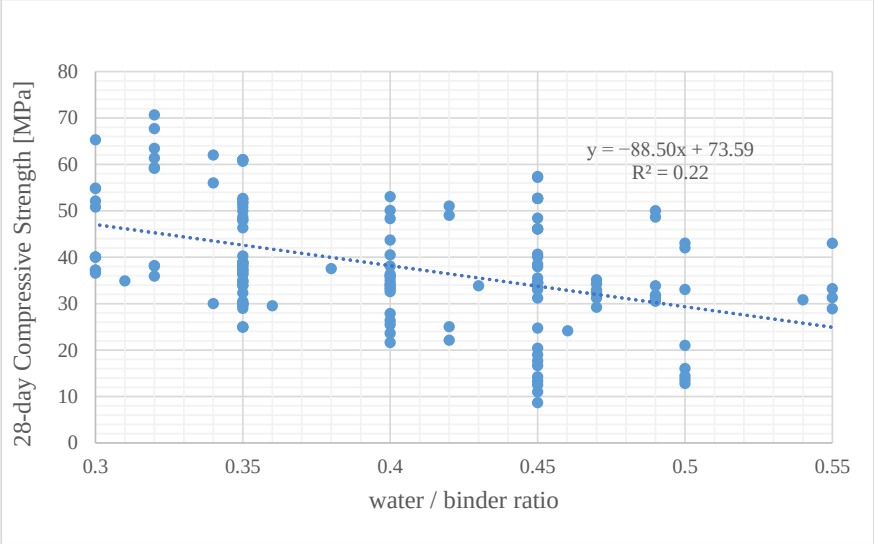


Figure 1. Correlation between water/binder ratio and 28-day compressive strength of concrete.

3.3. Materials

Common commercially available materials and standard testing procedures were used. CEM I 42.5 R type Portland cement was used in mixtures. Type F fly ash was used to enhance the cementitious matrix in some mixes to observe the effect of pozzolanic materials. MasterRheobuild 1000, a high-grade superplasticizer, was used as a chemical admixture in some mixtures.

Crushed limestone was used as fine aggregate in the mixtures. The sieve analysis was made according to ASTM C136-06 [23], and the aggregate batch was judged to be acceptable for use in the experimental program. Specific gravity and water absorption tests were conducted according to ASTM C127-15 [24], and the results are presented in Table 1.

Table 1. Physical properties of fine aggregate.

	Crushed Limestone	LECA		
Physical Property	**Fine Aggregate**	**Coarse Agg.**	**Medium—Coarse Agg.**	**Fine Agg.**
Specific Gravity (Saturated Surface Dry)	2.64	0.83	1.25	1.84
Specific Gravity (Oven Dry)	2.58	0.68	1.05	1.63
Specific Gravity (Apparent)	2.70	0.80	1.31	2.07
Water Absorption (%)	2.32	22.68	19.84	11.66

Three different particle-sized products were obtained for LECA: fine (0–3 mm), medium coarse (8–16 mm), and coarse (16–32 mm). The sieve analysis was carried out according to ASTM C136-06 [23], and the aggregate batch was judged to be acceptable for use in the experimental program. Specific gravity and water absorption tests were conducted according to ASTM C127-15 [24] and ASTM C128 [25], and results were presented in Table 1. Results indicate that water absorption of LECA may be up to an order of magnitude higher than that of crushed limestone used as fine aggregate in concrete-making. Following the procedure laid out in ASTM C330 [26], LECA was immersed in water for 72 $\pm$ 4 h to measure the specific gravity in the SSD state.

3.4. Concrete Mix Proportions

Mix proportions for concrete were determined according to ACI 211.2-9815 [27]. Table 2 provides the amount used for each constituent for mixes. The total amount of LECA used was categorized into two different dosages: 0.27 m^3 and 0.36 m^3, LECA/m^3 of concrete. The total volume of LECA was divided equally among fine, medium coarse, and coarse LECA. Mixes #1, #3, #5, #7, and #9 did not include fine LECA (0–3 mm). Therefore, the total volume of LECA was divided equally into medium coarse and coarse ones in those mixes. All mixtures included crushed limestone as fine aggregate, except mix #13, which contained LECA only. Fly ash was used as partial cement replacement in mixes #11–#13.

Table 2. Concrete mix proportions.

Mixture Label	Cement (kg/m^3)	Water (kg/m^3)	W/B Ratio	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)	Crushed Limestone (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

Table 2. *Cont.*

Mixture Label	Cement (kg/m^3)	Water (kg/m^3)	W/B Ratio	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)	Crushed Limestone (kg/m^3)
#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

3.5. Specimen Preparation and Segregation

ASTM C192 [28] was followed to prepare concrete specimens for testing. Standard 100 × 200 mm cylinder specimens were used for testing. Specimens were cured in a water storage tank after demolding. No issues were recorded during the production of the control specimens. However, certain mixes that contained a high amount of superplasticizer and coarse LECA posed challenges during placing and compacting concrete as a result of extensive segregation. This outcome necessitated extra effort during specimen preparation. Extra attention is necessary when working with LECA concrete having superplasticizers. Revising the superplasticizer amount may be necessary if segregation is observed.

One such example is mix #5, having a high W/B ratio. A trial specimen was cut horizontally into slices to observe the magnitude of segregation in the specimen, as shown in Figure 2. Results demonstrate the non-homogeneity of the mixture. Coarse LECA particles are observed at the top of the cylinder specimen, and fine particles, which are denser than the coarse ones, are observed towards the bottom of the specimen due to segregation.

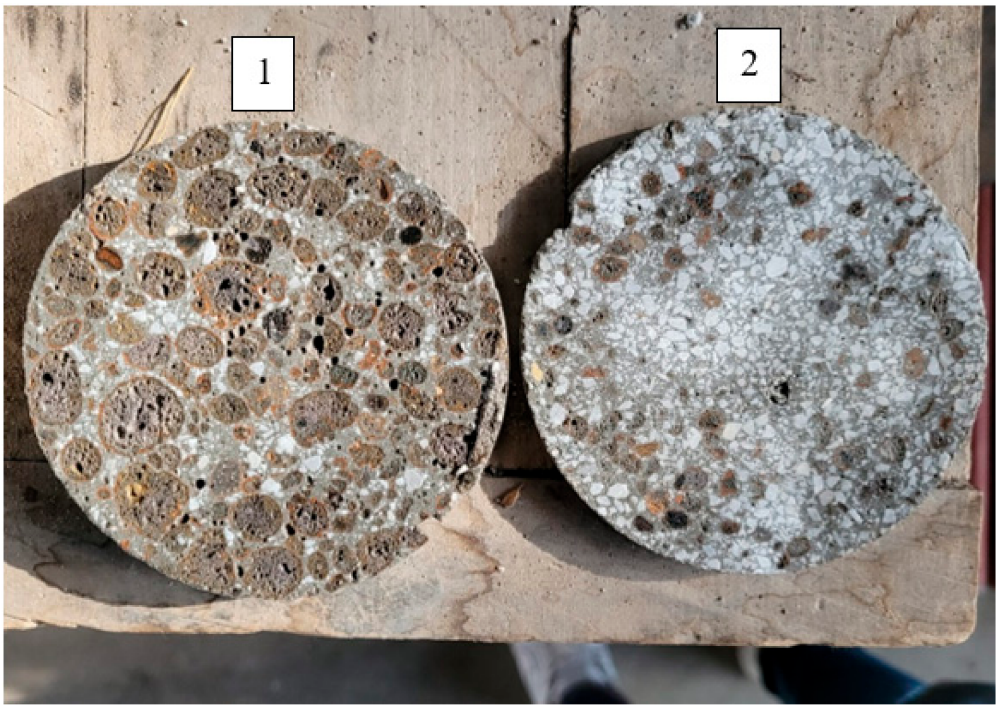


Figure 2. Cross-section of trial specimen from mix #5. The section view marked as 1 is from the top of the specimen, and the section view marked as 2 is from the bottom of the concrete specimen.

4. Results and Discussion

The results of the meta-analysis were used to develop a prediction model to estimate the 28-day compressive strength of LECA concrete. The accuracy of the developed model was investigated as part of the study by designing LECA concrete and testing for compressive strength as part of an experimental program. A total of 13 different concrete mixtures were prepared and tested to verify the model and ascertain its accuracy.

4.1. An Equation to Predict 28-Day Compressive Strength of LECA Concrete

Results of a regression analysis on the effect of LECA, cement, water, silica fume, and fly ash content in predicting the 28-day compressive strength of LECA concrete yielded an R^2 value of 0.59, with an adjusted R^2 value of 0.57. The adjusted R^2 value is considered for multiple regression analysis. Considering the heterogeneous nature of concrete at all scales, i.e., from the micro- to meso- and to macro-structure, the inability to obtain high R^2 values among relationships is noted in the literature, and considering the presence of five different independent variables in concrete, this value is considered to be acceptable.

The equation to estimate the 28-day compressive strength of LECA concrete presented below was developed based on the coefficients and intercept value obtained from regression analysis. The compressive strength of LECA concrete may be estimated in units of MPa by entering LECA, cement, water, silica fume, and fly ash content 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 disparate individual results of studies that are based on a single dataset. Thus, the equation provides greater reliability in predicting 28-day compressive strength.

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

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.

4.2. Sensitivity Analysis and Parameter Optimization

The mean values of all independent and dependent variables are used to carry out a sensitivity analysis. The aim is to understand the relative effect of independent variables on the dependent variable of compressive strength. The mean values of independent variables, i.e., LECA, cement, water, silica fume, fly ash, and water, were modified by assuming ±0%, 10%, 20%, 30%, 40%, and 50% material content. Modified values were entered into the derived equation to predict 28-day compressive strength. The corresponding mean values of $f_{c,28}$ by varying independent variables are demonstrated in Figure 3. If the input (independent variable) resulted in a large slope relative to other variables in the figure, this indicates that the mean value of $f_{c,28}$ can be decreased/increased dramatically by minor changes in the independent variable. Based on the results, the parameters that have the most effect are determined to be LECA, cement, and water amounts. Inputs that appear to be represented with a straight line had a slope close to zero, which indicates that they have little effect on the mean value of $f_{c,28}$. These parameters are fly ash and silica fume.

Having a mathematical model to predict compressive strength enables the application of parameter optimization to fine-tune a concrete design. An application was used in MiniTab version 20, a computer software, for parameter optimization. The optimization goal, for example, may be set as 30 MPa for dependent variable $f_{c,28}$. Minimum and maximum amounts for all independent variables were specified based on the ranges determined from the dataset produced within the study. It was noticed that more realistic concrete designs may be achieved by imposing limitations for maximum and minimum values on variables, such as for water.

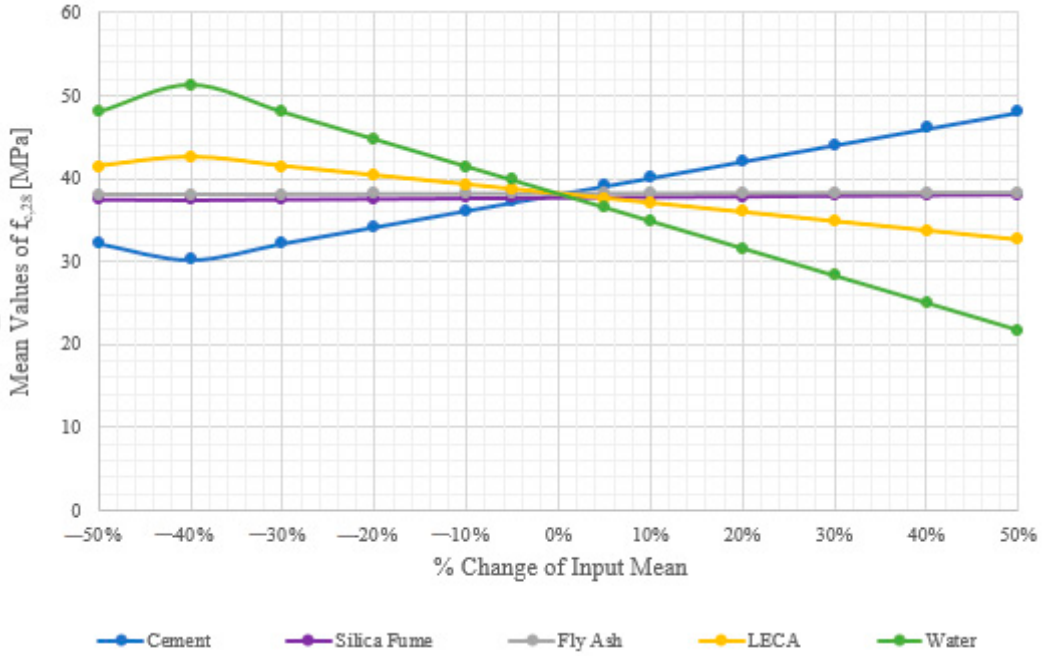


Figure 3. Results of sensitivity analysis of concrete constituents on $f_{c,28}$ values.

4.3. Compressive Strength Test 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 100 × 200 mm cylinder samples according to ASTM C39/C39M [29]. Density values were measured according to ASTM C567 [30] and ASTM C138 [31]. Three specimens were measured and tested for each mix design. Mean values for wet density and 28-day compressive strength values are given in Table 3. Quantities of concrete constituents for each mix were entered into the prediction model formula provided previously. The estimated 28-day compressive strength results are also provided in Table 3.

Table 3. Wet density, compressive strength test results, and predicted compressive strength values for the 13 concrete mixes.

Mixture Label	Wet Density (kg/m^3)	Experimental $f_{c,28}$ (MPa)	Prediction Model Estimation (MPa)	Ratio of Estimated/ Experimental Result
#1	1823	18.6	25.5	1.38
#2	1736	19.2	21.5	1.03
#3	1888	25.8	36.1	1.48
#4	1839	26.8	32.4	1.20
#5	1785	15.5	18	1.21
#6	1758	20.7	23.3	1.08
#7	1980	29.9	43.1	1.56
#8	1913	35.6	39.3	1.14
#9	1733	20.9	21.7	1.12
#10	1787	27.0	28.9	1.08
#11	1798	24.6	29.6	1.13
#12	1699	22.1	23	0.94
#13	1559	21.1	14.9	0.54

Using fine LECA in the mixture increases the $f_{c,28}$, whereas increasing the coarse and medium-coarse LECA content in the mixture affects the $f_{c,28}$ adversely. For instance, the highest $f_{c,28}$ is achieved in mix #8 by using the highest cement content and the lowest w/b ratio compared to other mixtures. Mix #7 has the same amount of cement content and w/b 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 mix #3 as it includes less coarse LECA and more fine LECA content, even though they have the same binder and water contents and thus w/b ratio.

A general positive relationship between wet density and compressive strength can be observed in Figure 4. However, results also indicate that the compressive strength of samples that contained 0.36 m^3 LECA/m^3 concrete or more is higher than samples that contained 0.27 m^3 LECA/m^3 concrete for a given density value. Another way to evaluate this result would be that higher LECA-containing concrete has lower densities while satisfying a given compressive strength value. Therefore, the amount of LECA does not appear to be a problem in terms of the compressive strength of concrete; rather, particle size appears to be an important factor that must be considered during design.

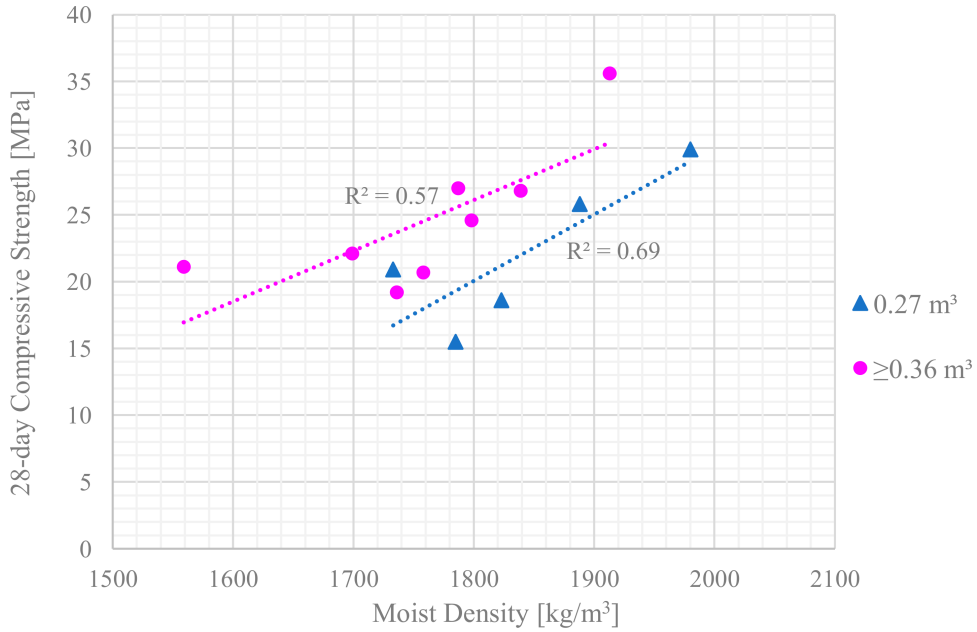


Figure 4. Relationship between wet density and 28-day compressive strength with comparison of LECA contents.

5. Comparison of the Estimations and Results of Experimental Program

The main aim of this study was to develop a prediction model for the compressive strength of LECA concrete by using data derived from meta-analysis, thereby building on and combining the works of seemingly disparate and geographically distant studies. The experimental program was carried out to verify the results and to ascertain the accuracy of the prediction model. To that end, both results are presented in Table 3.

Overall, it may be concluded that the expected results from the prediction model typically overestimate the $f_{c,28}$ of concrete mixes. This holds for the majority of mixes produced during the experimental program. The overall average for 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%.

A potential reason for the 15% difference between the estimated and experimental results is that LECA used in the experiments was produced mainly for agricultural applications, which may not have strength as a top priority. Structural LECA was reported to be used in some studies, thereby affecting the prediction model.

Predicted and experimental results are plotted in comparison in Figure 5 together with the line of equality. Some conclusions may be derived from this result. Predicted results for concrete having lower compressive strengths appear to be on or near the line of equality compared to those at high strength values, thereby indicating better accuracy. When results are further categorized based on w/b ratios, the best fit appears to be for concrete mixes that have w/b ratios of 0.5 or higher.

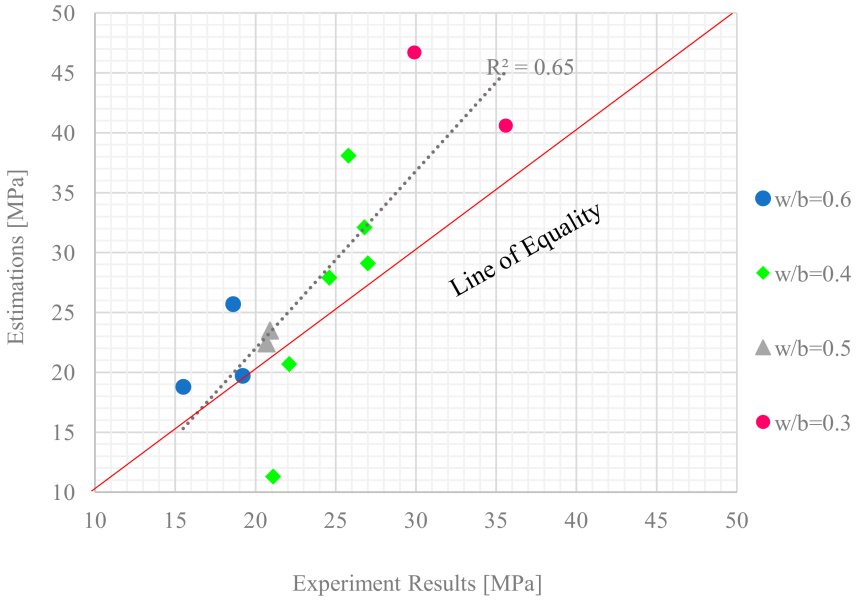


Figure 5. Comparison of experimental results with estimations from the prediction model. Results are categorized based on w/b ratios.

A further step was to investigate whether the total amount of LECA by volume of concrete influenced the accuracy of the model. Results presented in Figure 6 indicate that a stronger relationship, indicated by proximity to the line of equality, is obtained for mixes that have higher amounts of LECA, indicated by 0.36 m^3 LECA/m^3 concrete or higher in the figure.

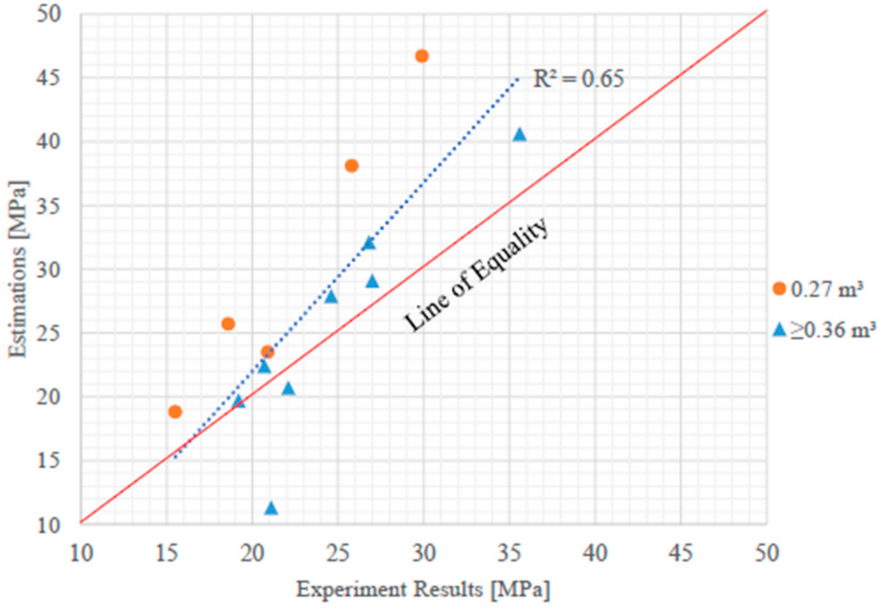


Figure 6. Comparison of experimental results with estimations from the prediction model. Results are categorized by LECA content.

6. Conclusions

The relationship between LECA content and the 28-day compressive strength of concrete is examined through a meta-analysis approach in this study. A prediction model to estimate the 28-day compressive strength of LECA concrete was derived as part of the study. A sensitivity analysis was carried out to determine the magnitude of the effect the variables have on compressive strength. An experimental program was carried out to verify the results and to ascertain the accuracy of the prediction model. A total of 13 different mix proportions were tested.

The underlying calculation for the model is based on a compilation of 140 data points on LECA concrete. Thus, results may be deemed to be more reliable than results proposed by an individual study or its results. Still, results from the prediction model and the experimental results did not always match. Generally, the model overestimated the 28-day compressive strength values. The coefficient of the estimated/experimental result value is found to be 1.15 on average. This means that the estimated values are 15% higher than the experimental ones. The equation may be adjusted by using such a coefficient, but further analysis is necessary. The accuracy of the model may be improved with more quantitative results, which would help further diminish the effects of inter-study variations.

When predicted and experimental results are plotted in comparison, predicted results for concrete having lower compressive strengths appear to be on or near the line of equality compared to those at high strength values, thereby indicating better accuracy. When results are further categorized based on w/b ratios, the best fit appears to be for concrete mixes that have w/b ratios of 0.5 or higher. Mixes that have higher amounts of LECA by volume of concrete yielded more accurate results when using the prediction model.

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Appendix A

Table A1. Data on LECA from published journal articles used for meta-analysis.

No	Article	Range of Mixing Parameters (kg/m^3)					Specimen Geometry	$f_{c,28}$ (MPa)	Density (kg/m^3)
		Cement	Silica Fume	Fly Ash	LECA	Water			
1	Jozwiak-Niedzwiedzka, D. (2005) [32]	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) [33]	450	-	-	0–54	180	Cubic	41.9–44.8	-
3	Bogas, J. A., & Nogueira, R (2014) [34]	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) [4]	559	-	-	401	235	Cylinder	22.1	1600
5	Malešev, M., Radonjanin, V., Lukić, I., & Bulatović, V. (2014) [35]	350–450	-	-	0–420	180–195.6	Cubic	41.3–60.4	1850–2348
6	Bogas, J. A., & Gomes, A. (2015) [36]	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) [37]	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) [38]	366.2–400	0–33.8	-	400	200	Cubic	16.0–20.0	1691–1757
9	Sajedi, F., & Shafigh, P. (2012) [39]	450–540	45–60	-	207.9–482	153.4–200	Cubic	32.9–67.0	1622–1984
10	Subaşı, S. (2009) [40]	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) [41]	362–458	-	80–100	0–464	188–228	Cylinder	21–62	1710–2407

Table A1. *Cont.*

No	Article	Range of Mixing Parameters (kg/m^3)					Specimen Geometry	$f_{c,28}$ (MPa)	Density (kg/m^3)
		Cement	Silica Fume	Fly Ash	LECA	Water			
12	Bogas, J. A., Gomes, A., & Pereira, M. F. C. (2012) [16]	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) [42]	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) [43]	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) [44]	400–450	-	-	250	157.5–160	Cubic	27–43.8	1889–1939

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