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Physical and Mechanical Properties of Lightweight Expanded Clay Aggregate Concrete

Orkun Uysal [1], İlbüke Uslu [1], Can B. Aktaş [2,*], Byungik Chang [3] and İsmail Özgür Yaman [1]

[1] Department of Civil Engineering, Middle East Technical University, Ankara 06800, Turkey; orkunuysal1@gmail.com (O.U.); ilbukeuslu@gmail.com (İ.U.); ioyaman@metu.edu.tr (İ.Ö.Y.)
[2] Department of Civil Engineering, TED University, Ankara 06420, Turkey
[3] Department of Civil and Environmental Engineering, University of New Haven, West Haven, CT 06516, USA; bchang@newhaven.edu
* Correspondence: can.aktas@tedu.edu.tr

Abstract: The porous nature of lightweight expanded clay aggregate (LECA) is decisive in the physical and mechanical properties of concrete. A comprehensive experimental study consisting of 13 different mixtures and 234 specimens was carried out on density, absorption capacity, porosity, compressive strength, splitting tensile strength, modulus of elasticity, and the effect of moisture state of LECA concrete. Dry compressive strengths of mixtures were found to be between 18–38 MPa, and 9% higher on average than moist compressive strength. Modulus of elasticity values decreased significantly when specimens were oven-dried, where the decrease was 26% on average. The study also includes an evaluation of modulus of elasticity prediction models. All prediction models consistently overestimated dry modulus of elasticity, which is problematic for structural applications of LECA concrete. A unique model for modulus of elasticity prediction was developed as part of the study and verified using independent data from literature for its accuracy.

Keywords: lightweight expanded clay aggregate; lightweight concrete; modulus of elasticity; concrete moisture state

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1. Introduction

The need for alternative construction materials is rising as projects become more demanding with budgetary and temporal limitations. Focus remains on improving and modifying concrete, the most widely used construction material around the globe, rather than experimenting with entirely new alternative materials for construction. Lightweight Aggregate Concrete (LWAC) is one such approach, where normal-weight aggregates in conventional concretes are replaced entirely or partially with lightweight aggregates. This study examines LWAC made up of lightweight expanded clay aggregate (LECA). They are an artificial type of lightweight aggregate manufactured by heating clay up to 1300 °C in rotary kilns. Concrete produced by using expanded clay aggregate is often called LECA concrete [1].

Lightweight concretes are classified as having a minimum compressive strength of 17 MPa and a dry unit weight between 1120–1920 kg/m^3 [2]. When compared to normal weight concretes, their strength parameters are lower; however, they can still be used in structural applications as sufficient compressive strengths can be obtained by right mixture proportions [3]. Furthermore, lightweight characteristic is an advantageous issue when a lighter design is needed for structures [4]. In structures where the dead load is especially important such as bridges or high-rise buildings, LECA concrete significantly decreases total loading on the foundation of the building, thus reducing the necessary reinforcement, concrete, and overall materials amount that is needed [5]. The savings is reported to be up to 20% for steel reinforcement [6]. A decrease in structural weight may also provide advantages when earthquake loads are considered [7].

Incorporation of LECA in concrete improves the thermal properties of concrete. Thus, it also has many non-structural insulation applications [8]. The thermal conductivity of LECA is lower than normal weight aggregates, since LECA has a lower density and a more porous structure than normal-weight aggregates. This leads to less thermal conductivity and higher thermal insulation. Thus, LECA concrete may improve energy performance of buildings and positively contribute towards building energy efficiency [1,9]. A study found that households constructed with lightweight aggregate concrete can save more than 30% of the heating energy consumption during the heating season [10].

Even though LECA concrete is a material that has been used worldwide since early 1900s, the subject requires further analysis [11]. Expanded clay aggregate is a porous material with high water absorption capacity. Therefore, significant changes may be expected between parameters measured in moist and dry states. In this study, an experimental program was conducted to evaluate the effects of moisture state on the mechanical properties of LECA concrete. Within the scope of this study, compressive strength and static modulus of elasticity of LECA concrete specimens were determined at both dry and moist states. Furthermore, modulus of elasticity results were compared to models found in literature, and a new model was proposed that better explains the data obtained from this experimental study and data found in literature. Even though there were studies on mechanical and durability parameters of LECA concrete in literature, only a few investigated modulus of elasticity and none focused on the modulus of elasticity at different moisture states. Considering the porosity and properties of the material at hand, this was noted as an important shortcoming.

In line with this identified gap, this study aims to examine physical and mechanical properties of LECA concrete at different moisture states. In addition to physical properties such as density and porosity, mechanical properties that were studied in this experimental study are compressive strength, splitting tensile strength, and modulus of elasticity. The compressive strength and modulus of elasticity were determined at moist and oven-dry states and the effects of moisture state of LECA concrete on its mechanical properties are studied. A further detailed study on modulus of elasticity was carried out by comparing different prediction models available through literature and national codes. Moreover, a unique prediction model was proposed using regression on the data obtained via the experimental program.

1.1. Expanded Clay Aggregates

LECA is an artificial aggregate produced from clay. Properties of the final product depends on the feed material, additives used during production, and production technology [12]. LECA could be manufactured in a wide range of density, size and strength. This diversity allows designers to design concretes for various applications.

There are several factors that can affect the quality and properties of LECA, including the type of clay used, the heating temperature and duration, and the cooling rate. The clay that is used as raw feed expands about 5–6 times with respect to their original size and takes the shape of pellets. Entrapped gasses result in a porous structure during cooling. The size and shape of the aggregates also varies depending on the process. Coarser grain size means lighter material; as the structure is porous, density will increase as grain size decreases [1].

The specific gravity of ECA can vary depending on the manufacturing process and the properties of specific type of clay used. Dry specific gravities of about 0.67 to 1.65 have been reported and these values indicate that LECA's specific gravity is 20–45% less than normal-weight aggregates [1,6]. Because of its porous nature, water absorption capacity is an important parameter when LECA is considered. Absorption values between 10% to 50% have been reported [6,13].

While LECA chemical composition mainly includes, SiO_2, Al_2O_3, Fe_2O_3, CaO and some alkalis such as Na_2O and K_2O, it is nonetheless an engineered product and various substances may be added to clay to alter the properties of LECA. Adding sodium carbonate

(Na_2CO_3) causes the pellets to have low expansion, irregular shapes, and stick together. Adding iron oxide (Fe_2O_3) created larger pores in the center of the pellets, while adding metallic iron powder significantly increased expansion and reduced both the density and strength of the particles. Thus, iron powder may be a useful additive to decrease the density of LWCA in situations where low density is more important than strength [6].

1.2. Physical and Mechanical Properties of LECA Concrete

Density is a crucial parameter when identifying LECA concrete. To be classified as structural lightweight aggregate concrete, concrete should conform to the ASTM C 330 standard [14] and should have a dry density between 1120–1920 kg/m^3 and 28th-day compressive strength should exceed 17 MPa.

There are several studies in literature that focus on the compressive strength of LECA concrete. In general, LECA incorporation decreases the ultimate compressive strength. However, compressive strength results highly depend on the design parameters and the materials used and results indicate that LECA concrete can still satisfy structural concerns. Making generalized conclusions could be misleading as compressive strength results depend on mixture design parameters and properties of raw materials. The compressive strength of LECA concrete was reported to vary between 20–70 MPa in a study by Dilli et al. [15]. Malešev et al. [16] studied five different mixtures, and compressive strength results varied between 41.3–50.6 MPa, while densities varied between 1850–1902 kg/m^3. The control specimen yielded 60.4 MPa for compressive strength and a density of 2348 kg/m^3 in the same study.

The value of static modulus of elasticity depends on the density, compressive strength, and type of aggregate used in the mixture. The modulus of elasticity of structural lightweight aggregate concrete varies between 10–24 GPa. An experimental study conducted by Malešev et al. [16] reported static modulus of elasticity values between 21.52–22.36 GPa. Another study conducted by Youm et al. [17] reported a static modulus of elasticity value of 21 GPa on average. An experimental study conducted by Karamloo et al. [18] reported modulus of elasticity values ranging between 19.23–25.12 GPa. All aforementioned studies indicated that the static modulus of elasticity was smaller when compared to normal-weight conventional concrete.

2. Methods

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

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

To determine these properties for LECA concrete, 13 different mixtures were designed with a total of 234 specimens produced during the study. Two different LECA amounts by volume, 0.27 and 0.36, were used in the mixtures. In mixtures where the LECA amount was taken as 0.27 by volume, coarse and medium-coarse LECA were used in equal amounts by volume. However, in mixtures where LECA volume was 0.36, coarse, medium-coarse, and fine LECA were used in equal volume. All mixtures contained crushed limestone as fine aggregate in calculated amounts except for the 13th mixture. Cement dosage varied between 400 kg/m^3, 500 kg/m^3, and 600 kg/m^3 and different water/binder ratios between 0.3–0.6 were chosen to enable a parametric analysis. Fly ash was used as a cement replacement in three mixtures. A range of densities was sought during mix design. Superplasticizer was used in some mixes to design for slump and workability. Cylinders with dimensions 100 × 200 mm were used for the specimens, which is common in literature and enables better comparison of results with those reported elsewhere. Detailed material amounts for each mix are presented in Table 1. This study's experimental program was

carried out together with another graduate student, hence data on mix design is shared with Uslu [19].

Table 1. LECA Concrete Mixture Design Table.

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

M_{cem}: mass of cement; W/B: water to binder ratio; V_{leca}: LECA volume; M_{sp}: mass of superplasticizer; $M_{c\ leca}$: mass of coarse LECA; $M_{mc\ leca}$: mass of medium-coarse LECA; $M_{f\ leca}$: mass of fine LECA; M_{fa}: mass of fine aggregate.

2.1. Material Properties

2.1.1. Lightweight Expanded Clay Aggregate

LECA formed the main material under analysis in the study, which was obtained from a regional supplier located in Bilecik, Türkiye. Obtained material came in 3 different particle size ranges. In this study, 0–3 mm aggregate was used as fine, 3–8 mm aggregate was used as medium-coarse, and 8–16 mm aggregate was used as coarse aggregates in mixtures.

Fundamental material tests were conducted before concrete mixture design by adhering to related standards. ASTM C127-15 [20] and ASTM C128-15 [21] were used for density and water absorption tests, respectively, and ASTM C136/136M [22] was used for sieve analysis. Both specific gravity and water absorption properties differed greatly based on the type of LECA. Whereas coarse LECA was observed to have an SSD-specific gravity of 0.81 and a water absorption of 20.5%, fine LECA was observed to have more than double the SSD-specific gravity with 1.81 and half of water absorption capacity at 10.0%. Medium-coarse LECA had an SSD-specific gravity of 1.11 and a water absorption capacity of 19.6%. Thus, properties of LECA are closely linked to the size of the aggregates. The results for sieve analysis are provided in Figure 1.

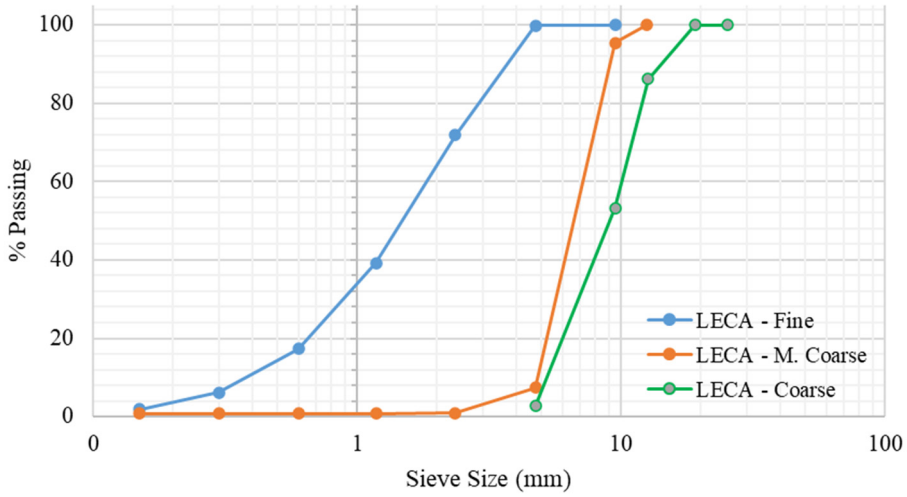


Figure 1. Particle size distribution of fine, medium-coarse, and coarse LECA used in the study.

2.1.2. Binder

In terms of binder material, CEM I 42.5 R type Portland cement produced in accordance with EN197-1 standard [23] was used in the study. The chemical composition of cement used in the study is provided in Table 2. Fly ash was also used in three mixtures as a cement replacement, the main motive being able to observe its effects on workability and strength parameters. Fly ash used in the study was obtained from Sugözü Thermal Power Plant located in Adana, Türkiye.

Table 2. Chemical Composition of Portland Cement Used in the Study.

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

2.1.3. Fine Aggregate

Crushed limestone was used as fine aggregate in the mixtures. Sieve analysis was carried out according to ASTM C136-06 [22]. Specific gravity and water absorption tests were conducted according to ASTM C127-15 [20]. The SSD, oven dry, and apparent specific gravity of fine aggregates were 2.64, 2.58, and 2.70, respectively. Water absorption capacity was found to be 2.32%.

2.1.4. Chemical Admixture

The commercial name of the superplasticizer used was MasterRheobuild 1000. This product was used as a high range water reducer and hardening accelerator chemicaladmixture.

2.2. Processing Sequence

Lightweight expanded clay aggregates are very porous and have high absorption capacities as mentioned earlier. Dry or as-is condition usage of LECA yields non-homogeneous concrete production. Therefore, using this material in SSD condition is a necessity. Expanded clay aggregates were immersed in water for at least 72 h before concrete batching as specified in ASTM C127-15 [20]. Coarse and medium-coarse expanded clay aggregates were surface dried, and fine aggregates were dried with a blow-dryer to achieve SSD state.

A pan type of concrete mixer having a maximum volume of 100 L was used for batching. First coarse, then medium-coarse, and fine aggregates were added to the mixer which are mixed for 3 min. Approximately 80% of the mixing water was added to the pan at this time. Cement was later added to the mixture in small dosages to facilitate a homogenous mix. The remaining mixing water was added slowly. Superplasticizer amounts were not pre-determined, so with visual inspections, chemical admixture amounts were increased step by step until a workable and moldable mixture with adequate slump values were achieved. Superplasticizer was not used in every mixture; mixtures that have high water content did not require any chemical admixtures to adjust consistency. Figure 2 shows the mixture in the pan after batching and mixing process were over.

Specimens were removed from molds after at least 24 h but not more than 30 h. All specimens were moist-cured in a water tank with a constant temperature of 23.0 ± 2.0 °C. ASTM C192/C192M-18 [24] was adhered to during these steps.



Figure 2. Sample mixture as it appeared in the pan mixer.

2.3. Mechanical Tests Performed

Compressive Strength: Compressive strength tests were conducted according to directives in ASTM C39/C39M [25] after 7 and 28 days of curing. The 7th-day, 28th-day moist, and 28th-day dry compressive strengths were measured. For determination of 28th-day dry compressive strength, specimens were placed into the 50 °C oven. Specimens were weighed every 24 h until the change in mass was not more than 0.5%, as stated in ASTM C567/C567M-19 [26]. After making sure that the samples were dry, the samples were tested in a dry state. Three specimens were tested for each of the strength parameters. Compressive loads were applied continuously at a constant rate of 2.4 kN/s.

Splitting Tensile Strength: Splitting tensile strength tests were conducted according to directives in ASTM C496/C496M-17 [27] after 28 days of curing. Strength values were determined by testing 3 specimens from each mixture and calculating their averages. Loads were applied continuously without shock at a constant rate of 0.94 kN/s.

Modulus of Elasticity: Static modulus of elasticity tests were conducted according to directives in ASTM C469/C469M-22 [28] after 28 days of curing. The same procedures in compression strength tests were followed for elasticity tests. Three specimens each for moist and dry modulus of elasticity were used. An MTS Landmark 250 series loading frame [29] was used for testing. Specimens were loaded up to 30% of their ultimate compressive strength. The loading process comprised 3 cycles of loading and unloading. Results of the first cycle were excluded from calculations, as indicated by ASTM C469 [28].

Example graphs showing the 3 loading–unloading cycles for a specimen are shown in Figure 3. The concrete specimens deform to a certain extent but return to their original form as the loading is in the elastic range. Such graphs were carefully analyzed for errors, and tests were repeated or new specimens from the same mixture were tested if errors were detected. The modulus of elasticity of each specimen is the average of values measured during the 2nd and 3rd loading cycles.

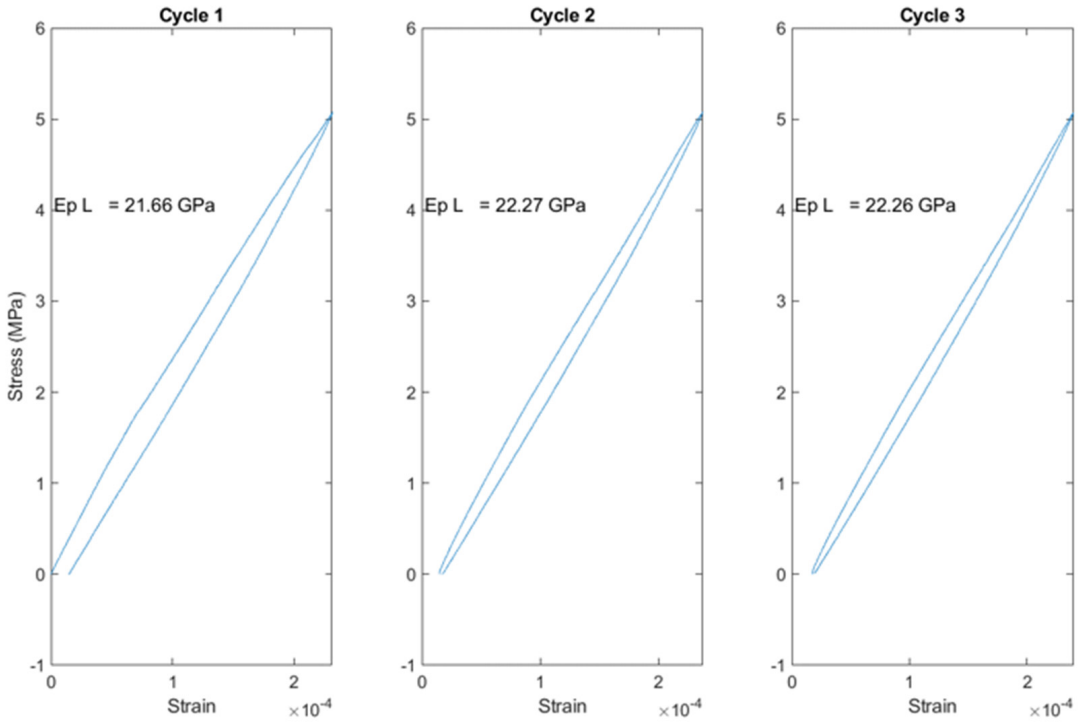


Figure 3. An example stress–strain plot of 3 loading–unloading cycles on the same specimen. Ep L represents the modulus of elasticity value calculated from the obtained loading–unloading cycle.

2.4. Modulus of Elasticity Prediction Models

The modulus of elasticity of LECA concrete was measured in both dry and moist states as part of the experimental program. Results were compared with prediction models that are commonly used in literature. Models used for comparison are listed in Table 3 below. The first four prediction models in Table 3 are from different national codes. The last model listed was proposed by Dilli et al. [15] that also analyzed LECA concrete.

Table 3. Static Modulus of Elasticity Prediction Models.

Prediction Models	Equation	Parameters
ACI 318 [30]	$Ec = 0.043 \times w_c^{1.5}\sqrt{f'_c}$	w_c = Wet unit weight of concrete f'_c = Compressive strength of concrete
ACI 363 [31]	$Ec = \left(3320\sqrt{f'_c} + 6900\right)\left(\frac{w_c}{2320}\right)^{1.5}$	w_c = Wet unit weight of concrete f'_c = Compressive strength of concrete
CEB–FIB [32]	$Ec = 21,500 \propto \times \left(\frac{f'_c}{10}\right)^{1/3}$	f'_c = Compressive strength of concrete $\propto$= Coefficient for aggregate type
TS 500 [33]	$Ec = 3250\sqrt{f'_c} + 14,000$	f'_c = Compressive strength of concrete
Dilli et al. [15]	$Ec = 3000\sqrt{f'_c} * \left(\frac{w_c}{2300}\right)^{3.7} + 12,500$	w_c = Dry unit weight of concrete f'_c = Compressive strength of concrete

3. Results and Discussions

3.1. Density

Wet and oven-dry density results are presented in Table 4. Presented values are the mean results of three specimens, the coefficient of variation (CoV) among data, and % change between wet and oven-dry density values. The CoV represents the extent of dispersion in the data, with lower values indicating less variation among samples.

Table 4. Mean wet and oven-dry density test results.

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

Obtained density results were within reasonable and expected bounds and accommodate calculated values during mixture design. The average wet density was calculated as 1792 kg/m^3, and the average dry density as 1691 kg/m^3, indicating considerable water absorption capacity. The overall percent change in density between these two states was calculated as 5.67%. Average CoV values were 1.94% for wet density and 2.01% for dry density indicating successful sampling.

The amount of variation, measured via CoV, was noted to be high in Mixes 3 and 5. Segregation was encountered in those same mixes, which may explain the high variation observed among the three specimens. In Mixture 3 specifically, 2% superplasticizer was added. The excessive amount of superplasticizer with a high water amount contributed to segregation in the mixture. Coarse LECA density is less than water, which means that if unconfined, aggregates would float on water. This behavior was clearly observed during mixing in Mix #3. Further proof of segregation was observed, where a specimen was saw-cut from both ends, clearly revealing coarse LECA floating towards the surface and non-LECA fine aggregates sinking towards the bottom. The problem with Mixture 5 was excessive water. The mixture contained the highest amount of water among all other mixes, and segregation was also observed in this mixture.

3.2. Porosity

Porosity is an important parameter affecting mechanical properties and durability of concrete. Due to the porous structure of LECA, overall porosity of concrete requires careful consideration for LECA concrete. Porosity values were calculated by analyzing wet and oven-dry mass of specimens. Overall porosity of all specimens was calculated as 10.1%, with a CoV of 3.4%. Results ranged between 7.1–15.6%.

3.3. Compressive Strength

Compressive strength tests were carried out on the 7th and 28th days in the moist state, and again on the 28th day in dry state. Three specimens each were used for each mix during these tests. The mean values and CoV in test results are presented in Table 5. In line with expectations, 7th-day compressive strength values reached 70–80% of 28th-day compressive strength, which varied between 16–36 MPa. Dry 28th-day compressive strength values were higher, and ranged between 18–38 Mpa.

Due to the porous nature of LECA with high water absorption capacity, differences between moist and dry compressive strength were expected. Internal stresses caused by water in pores creates additional pressure in addition to the uni-directional loading stress, which accelerates crack formation and reduces compressive strength of concrete. Oven-dried specimens lacking such additional internal stresses showed an increase in

compressive strength between 2–22% over moist-state specimens. On average, dry-state compressive strength values were 9% higher than moist-state compressive strength values.

Table 5. Compressive strength test results.

Mixtures	7th Day–Moist		28th Day–Moist		28th Day–Dry		28-Day Dry/Moist Ratio
	Mean (MPa)	CoV (%)	Mean (MPa)	CoV (%)	Mean (MPa)	CoV (%)	
Mix #1	15.7	0.2	18.6	4.4	21.1	4.1	1.13
Mix #2	16.0	6.9	19.2	3.1	20.5	5.6	1.07
Mix #3	17.6	2.7	25.8	1.9	28.5	12.8	1.10
Mix #4	23.9	4.1	26.8	0.6	28.5	7.6	1.06
Mix #5	13.6	1.3	15.5	1.8	18.2	7.8	1.17
Mix #6	14.6	7.7	20.7	7.0	21.7	2.7	1.05
Mix #7	26.5	6.2	29.9	6.3	31.2	3.4	1.04
Mix #8	24.4	4.3	35.6	5.0	37.9	1.7	1.06
Mix #9	13.2	4.1	20.9	8.9	22.2	9.9	1.06
Mix #10	16.6	3.4	27.0	8.9	28.9	6.2	1.07
Mix #11	20.1	0.7	24.6	7.9	27.0	4.8	1.10
Mix #12	15.5	3.2	22.1	5.3	27.0	2.2	1.22
Mix #13	14.2	4.3	21.1	3.2	21.6	2.7	1.02

3.4. Splitting Tensile Strength

Splitting tensile strength was tested for each mixture. Mean values obtained through averaging three specimens ranged between 1–2 MPa, with CoV between 0–9%. As such, tensile strengths varied between 5–12% of compressive strengths of the same mixture, with an overall average of 8%. In conventional concrete, the interfacial transition zone (ITZ) is typically weakest when compared to cement paste and aggregates. In LECA concrete, the aggregate zone may be the weakest zone in the matrix, and visual observations of failed specimens indicate that LECA together with ITZ may have played a role in specimen failure.

3.5. Modulus of Elasticity

Modulus of elasticity (MoE) values were determined for each specimen. Table 6 presents results for each mixture's moist and dry state MoE. Dry MoE values were lower than moist state MoE for every mix, as was expected [34]. On average, the dry to moist MoE ratio was calculated as 0.74, indicating a 26% reduction.

Table 6. The 28th-day static modulus of elasticity test results.

Mixtures	Moist MoE		Dry MoE		Dry/Moist MoE Ratio
	Mean (GPa)	CoV (%)	Mean (GPa)	CoV (%)	
Mix #1	17.1	11.3	14.9	6.0	0.87
Mix #2	16.4	0.4	12.8	1.7	0.78
Mix #3	18.7	0.9	11.8	1.8	0.63
Mix #4	24.5	6.3	12.9	14.9	0.53
Mix #5	17.6	1.8	10.8	14.7	0.61
Mix #6	15.4	12.3	12.6	9.2	0.82
Mix #7	20.8	16.1	19.6	4.0	0.94
Mix #8	22.4	0.9	16.3	2.4	0.73
Mix #9	13.9	3.4	11.8	12.1	0.85
Mix #10	15.5	2.5	13.0	8.4	0.84
Mix #11	18.5	1.6	12.4	7.1	0.67
Mix #12	17.1	4.3	10.8	7.7	0.63
Mix #13	12.3	8.7	8.8	13.8	0.72

4. Comparison of Modulus of Elasticity Results with Prediction Models

Modulus of elasticity values obtained as part of the study were compared to prediction models commonly used in literature. Comparative results for moist MoE values are presented in Figures 4 and 5. Overall, ACI 318 [30] and ACI 363 [31] prediction models

underestimated the modulus of elasticity results obtained experimentally. CEB–FIB prediction model's [32] accuracy was low compared to the two preceding models, with clear divergence towards samples with higher densities. On the other end of the spectrum, TS 500 [33] prediction model significantly overestimated modulus of elasticity values, with no overlap with experimental results. Among the available national codes, ACI models [30,31] predicted results more accurately than CEB-FIB [32] and TS 500 [33] models, albeit consistently underestimating moist modulus of elasticity values. The last prediction model proposed by Dilli et al. [15] specifically included LECA concrete. That may be a factor contributing to the good fit between the predicted values and observed results, especially after density values of 1700 kg/m^3.

CEB-FIB model involves a coefficient which varies with the type of the aggregate used in concrete. However, the code has α values for commonly used aggregates like basalt, limestone, quartzite, limestone, and sandstone aggregates, but does not specify a value for lightweight expanded clay aggregates. Even though an $\propto$ value of 0.5 was proposed by Dilli et al. [15] for expanded clay aggregates, analysis indicate that α = 0.6 yields more accurate predictions and hence is recommended for LECA concrete in moist state.

A similar analysis on modulus of elasticity values yielded by prediction models was carried out for dry state LECA concrete as well. Results are presented in Figures 6 and 7. All models consistently overestimated dry modulus of elasticity. Even though the slope of the trendlines were reasonable, there was significant deviation from the experimentally obtained values. This result is dangerous from an engineering design point of view, as consistent overestimating dry modulus of elasticity may pose problems in structural applications of LECA concrete such as in bridges or high-rise buildings.

Unlike prediction results for moist MoE, Dilli et al.'s model seemed as the least accurate model for dry MoE excluding TS500. ACI318 and ACI363 models performed better in predicting dry MoE compared to moist MoE.

The CEB–FIB model, requiring a coefficient for the type of aggregate used, yielded less accurate results than moist MoE prediction when α was taken as 0.6. An α of 0.5 yielded more accurate results, and hence is recommended for use in predicting dry modulus of elasticity using the CEB–FIB model. This finding is interesting as the moisture state of LECA may require different coefficients be used for more accurate results, unlike more common types of aggregates in conventional concrete. Relatively high porosity of LECA and the presence or lack thereof of water in pores yields two different behaviors, making it difficult to classify LECA to a single coefficient.

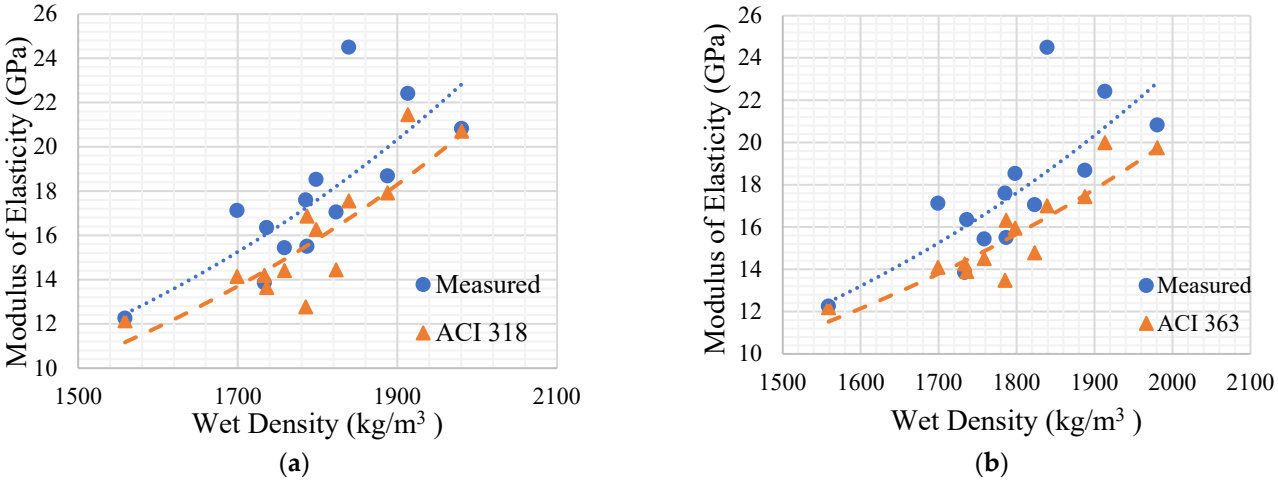


Figure 4. *Cont.*

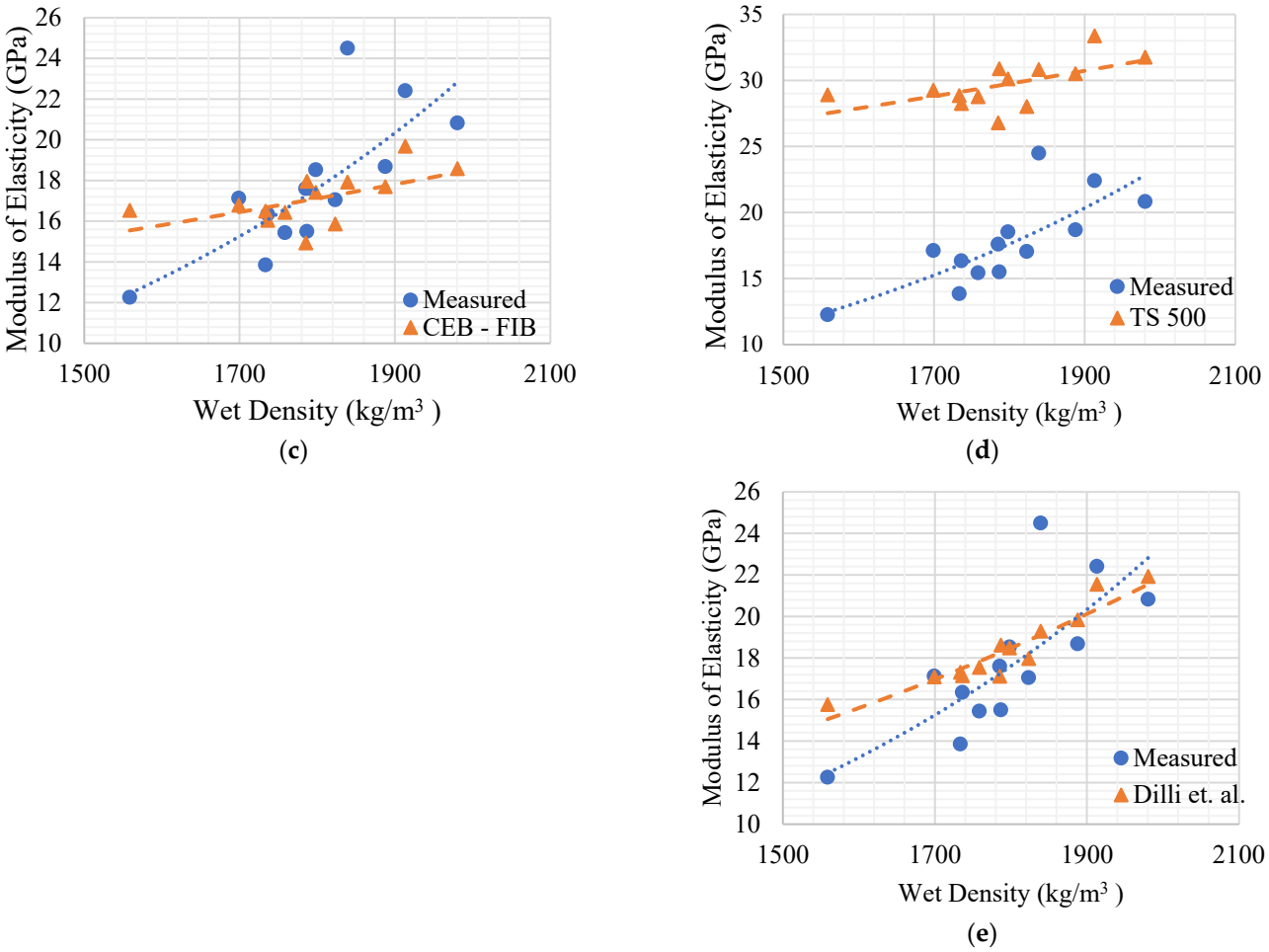


Figure 4. Experimental moist modulus of elasticity results versus predicted values via models. (**a**) ACI 318 [30] (**b**) ACI 363 [31] (**c**) CEB–FIB [32] (**d**) TS 500 [33] (**e**) Dilli et al. [15].

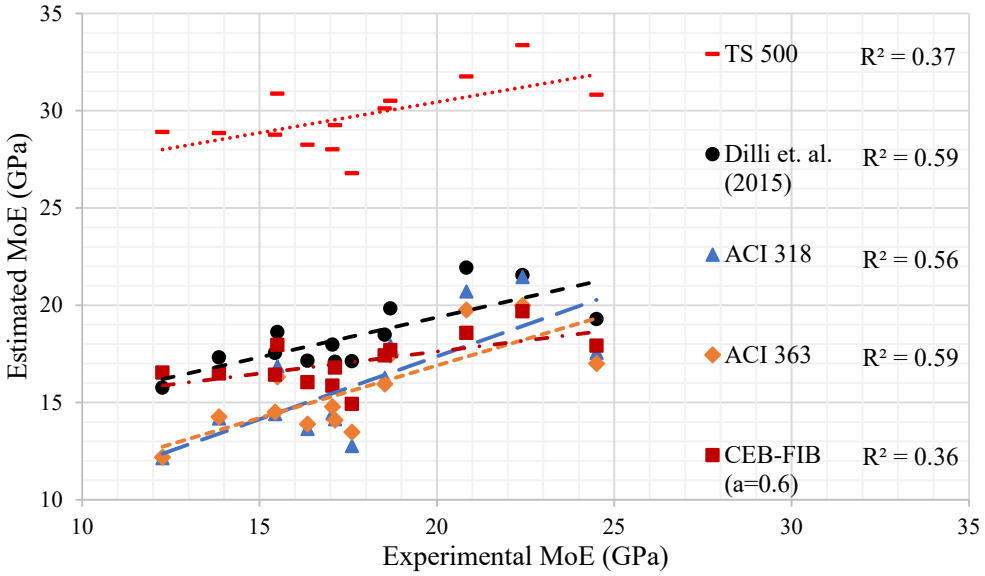


Figure 5. Measured moist modulus of elasticity (x-axis) versus predicted values by different models (y-axis) [15,30–33].

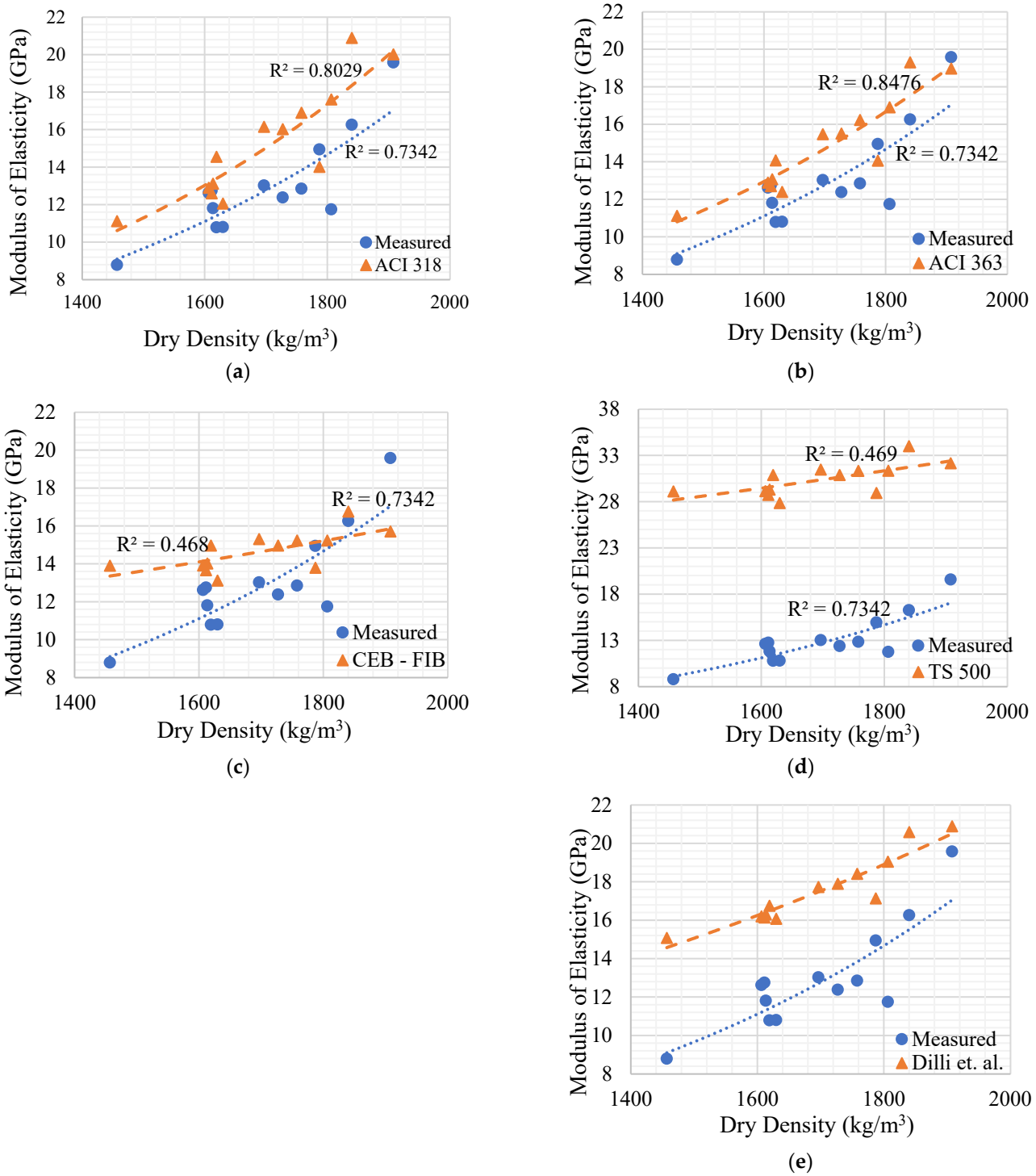


Figure 6. Experimental dry modulus of elasticity results versus predicted values via models. (**a**) ACI 318 [30] (**b**) ACI 363 [31] (**c**) CEB–FIB [32] (**d**) TS 500 [33] (**e**) Dilli et al. [15].

Statistical parameters were calculated to better evaluate results of prediction models. Correlation coefficients indicate the strength of the correlation between two variables: in this case, the measured and predicted modulus of elasticity values. A value closer to one indicate better correlation. Mean squared error is a measure related to the amount of error in statistical models. It assesses the average squared difference between the measured and predicted values. When a model perfectly predicts all values, MSE equals zero. As the MSE value increases, the error of the model increases, and the accuracy of the model decrease.

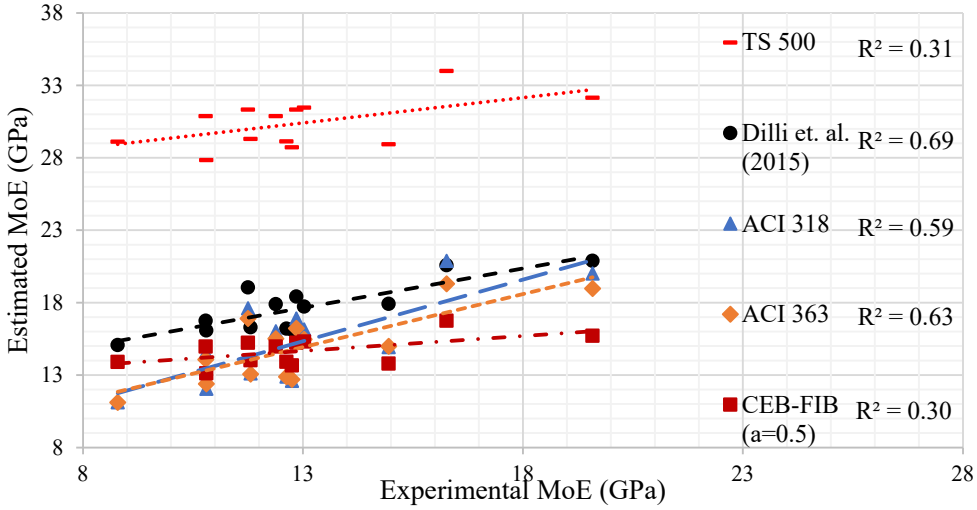


Figure 7. Measured dry modulus of elasticity (x-axis) versus predicted values by different models (y-axis) [15,30–33].

Correlation coefficient and mean squared error values were calculated for each model, and results are presented in Table 7. Overall, statistical parameters of ACI models and the CEB–FIB model were comparable. TS 500 was the worst performer among the models. The model proposed by Dilli et al. [15] was the best performer for moist MoE but lagged behind national codes for dry MoE.

Table 7. Correlation coefficients and mean squared error values of prediction models for modulus of elasticity in moist and dry state of concrete.

Prediction Models	Moist MoE		Dry MoE	
	Correlation Coefficient (r)	MSE Values	Correlation Coefficient (r)	MSE Values
ACI 318 [30]	0.75	8.02	0.77	9.11
ACI 363 [31]	0.77	8.50	0.79	6.45
CEB–FIB [32]	0.60	7.62	0.55	7.89
TS 500 [33]	0.61	151.13	0.55	309.06
Dilli et al. (2015) [15]	0.77	5.43	0.83	24.12

5. Proposing a Unique Model for MoE Prediction

A unique modulus of elasticity prediction model was developed as part of the study for both moist and dry states using regression analysis method. The developed model also comprised two independent variables to predict modulus of elasticity of concrete; compressive strength (f_c), and unit weight of concrete (w_c). The proposed models for moist and dry modulus of elasticity are presented in Equations (1) and (2), respectively, and are as follows:

$$E_{moist} = 0.0204\ w_c + 0.14\ f_c - 22 \quad (1)$$

$$E_{dry} = 0.0271\ w_c + (f_c)^{0.275} - 30.5 \quad (2)$$

The equations were developed using regression analysis. The accuracy of the proposed model was investigated by comparing to other prediction models assessed throughout this study. Prediction results better matched experimental results from this study. Correlation coefficients were calculated as 0.79 and 0.84 for moist and dry state MoE, respectively. These values represent the highest coefficients among the prediction models. Mean squared errors were calculated as 3.97 and 2.88 for moist and dry state MoE, respectively. These values are the lowest coefficients among the prediction models. Therefore, it can be concluded that the proposed unique model performed better than existing prediction models when

this study's results were considered. However, this result may be expected as the proposed model was developed using the current study's experimental results. Hence, verification of the proposed model was necessary to ascertain this conclusion.

6. Verification of the Proposed Model for Modulus of Elasticity Prediction

Five different experimental studies from literature focusing on expanded clay aggregate concrete and involving data on modulus of elasticity were investigated. Using their reported density and compressive strength values, corresponding MoE values were predicted by the developed proposed model and compared with their measured MoE values. Measured and predicted results together with the used parameters are presented in Table 8. The proposed model for moist state MoE was used for the analysis. MSE values are significantly low for the first four studies, especially when compared to previously obtained MSE values in this study. Only the predicted results of Youm et al. [10] yielded higher values than measured ones.

Table 8. Verification of the proposed model through published articles. Reported MoE, predicted MoE, and mean squared error values are presented.

	Wet Density (kg/m^3)	Compressive Strength (MPa)	Measured MoE (GPa)	Predicted MoE (GPa)	Squared Errors	MSE
Malesev et al. (2014) [16]	1854	38.1	22.4	21.2	1.46	
	1902	40.5	23.2	22.5	0.55	
	1877	36.3	21.5	21.4	0.02	
	1850	33.0	21.4	20.4	1.01	
	1890	37.9	22.1	21.9	0.07	
Bogas et al. (2014) [8]	1797	31.8	19.1	19.1	0.00	0
Karamloo et al. (2016) [18]	1939	35.0	25.1	22.5	7.07	
	1891	32.6	23.1	21.1	4.02	
	1929	32.3	23.3	21.9	2.06	
	1890	25.4	20.3	20.1	0.03	
	1929	29.0	23.2	21.4	3.22	
	1889	21.6	19.2	19.6	0.11	
Dilli et al. (2015) [15]	1799	30	22	18.9	9.61	
	1749	25	20	17.2	7.95	
	1710	21	15	15.8	0.68	
	2101	62	29	29.5	0.29	
	2075	51	25	27.5	6.10	
	2005	43	22	24.9	8.54	
Youm et al. (2016) [10]	2053	46.1	20.89	26.34	29.65	
	2038	47	21.02	26.16	26.37	
	2006	47.9	20.97	25.63	21.70	

Verification of the proposed model through data from independent studies lends credence to conclusions and indicate its reliability in accurately predicting MoE values. Still, the results of the study by Youm et al. [10] may hint that the model may not be optimal for higher density concrete applications. This is expected, however, as the mathematical model is based on lightweight aggregates, hence lightweight concrete.

7. Conclusions

To resolve a detected gap in literature, physical and mechanical properties of LECA concrete at different moisture states were examined in this study. In this context, the experimental study covered the determination of wet and oven-dry densities, porosity, moist and dry-state compressive strength, and moist and dry-state modulus of elasticities of the 13 mixtures prepared. Mixing proportions were designed to obtain reasonable distribution of density values within the acceptable limits of creating structural lightweight concrete. Parameters such as binder amount, mineral additives, water to binder ratio and

LECA volume were chosen meticulously to create a parametric study that shows relations between parameters adequately.

Segregation in fresh concrete needs to be carefully monitored in LECA concrete as expanded clay particles tend to have lower densities than water, thus easily floating to the surface, creating an uneven distribution and a heterogeneous concrete mix. Thus, superplasticizer should be prevented or utilized meticulously in order to prevent segregation, especially in mixtures where water content is high.

Samples produced during the experimental program had porosity values between 7–16% due to the nature of LECA particles. Porosity is known to affect mechanical properties of concrete, and increased porosity was observed to decrease compressive strength of specimens. Similarly, modulus of elasticity in both dry and moist states decreased as the porosity of concrete increased.

28^{th}-day moist compressive strength values varied between 15–36 MPa, and 28^{th}-day-dry compressive strengths varied between 18–38 MPa. Dry compressive strength values were 9% higher on average than moist compressive strength values.

Modulus of elasticity values in moist state concrete varied between 12.3–24.5 GPa, and for the dry state they varied between 8.8–20.8 GPa. The modulus of elasticity values decreased significantly when specimens were oven-dried, where the decrease varied between 6–48% with an average of 26%.

All prediction models consistently overestimated dry modulus of elasticity. Even though the slope of the trendlines were reasonable, there was significant deviation from the experimentally obtained values. This result is dangerous from an engineering design point of view, as consistent overestimating dry modulus of elasticity may pose problems in structural applications of LECA concrete such as in bridges or high-rise buildings.

A unique model for modulus of elasticity prediction was developed using experimental results from this study. The developed model was verified using independent data from literature. From an accuracy perspective, the proposed model outstands all other models analyzed in this study.

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