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Research Article

Investigation of the Mechanical and Physical Properties of Structural Lightweight Concrete Produced with Expanded Clay Aggregate from Söğüt Region

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Abstract

The use of mild materials shows an increasing tendency in industrial areas. These materials are also preferred to reduce the unit weight of the building elements in the construction sector. Various light aggregates are used to produce light concrete with a lower density than normal concrete, and the properties of these light aggregates significantly affect the properties of the concrete. In this study, the use of expanded clay aggregate (ECA) produced in the Söğüt region in structural lightweight concrete was examined. Expanded clay, sand, and crushed stone aggregate were used as aggregates in concrete mixtures. The mixture granulometry was kept the same for each group. For this purpose, 60 samples were prepared for a total of 4 mixtures with different contents. Slump and unit volume weight tests were carried out on fresh concrete samples, and compressive, flexural, and splitting tensile strength tests were carried out on 7- and 28-day-hardened concrete samples. Some of the concrete mixture samples were subjected to tests after being kept in the curing pool for 7 days, and some for 28 days. As a result of the experiments, the unit weight and compressive strength values obtained from the samples produced with ECA as coarse and fine aggregate in order to achieve the highest strength target are 1413 kg/m³ and 30 MPa, respectively. The same values were found to be 1652 kg/m³ and 39 MPa in the samples produced with river sand as fine aggregate and ECA as coarse aggregate. In the samples produced using ECA as fine aggregate and crushed stone aggregate as coarse aggregate, these values were also found to be 1689 kg/m³ and 50 MPa.

1. Introduction

With the increase in the world population and the development of technology, the concrete industry has gained great importance. Concrete is the most preferred building material in the world in terms of providing long-term service, strength, durability, and being an economically very suitable material. However, in addition to its advantages, it has disadvantages such as low tensile strength, a high unit weight, and a high thermal conductivity coefficient. New research areas have emerged to eliminate the drawbacks of concrete and give it positive properties. One of these research areas is special kinds of concrete [1]. Some of these concrete kinds, which are specially produced according to their areas of use, are heavy concrete, structural lightweight concrete, self-compacting concrete, and concrete with insulating properties [2].

Lightweight concrete, one of the special types of concrete, is used instead of traditional concrete in many current civil engineering applications. These versatile materials offer technical, economic, environmentally remedial, and protective advantages [3, 4]. Structural lightweight concretes, which are one of the lightweight concretes, are defined as lightweight concretes with a 28-day compressive strength of more than 17 MPa and density values between 1400 and 2000 kg/m³, according to their compressive strength and density properties [5]. The use of structural lightweight concrete in the construction industry provides advantages such as a high strength/weight ratio, savings in dead load for structural design and foundation, reduced risk of structural damage in earthquakes, and a low coefficient of thermal expansion [6].

The best way to produce lightweight concrete is to use lightweight aggregates [7], because aggregates generally constitute 50%–80% of the concrete volume. Since their volume ratios are high, they have a significant effect on the properties of concrete [8]. Lightweight aggregates, due to their greater porosity, have less strength and are more deformable than regular aggregates. The weakest component of lightweight aggregate concrete is the aggregates, not the cement matrix or the interfacial transition zone (ITZ). Therefore, the mechanical performance of lightweight aggregate concrete depends not only on the quality of the cement matrix but also on the aggregate volume and aggregate properties of the concrete [9]. Therefore, the good mechanical properties of the aggregates to be used in concrete production will improve the mechanical properties of fresh and hardened concrete [10].

Among the lightweight aggregates, the aggregate with the highest compressive strength is expanded clay aggregates (ECA). ECA, which is used in many different fields, has great advantages compared to most industrial raw materials due to its technical and numerous properties [11]. The most important advantage of these aggregates is that they can be produced in different sizes to meet different consumption needs in the construction sector [12]. ECA is produced by expanding clay in size approximately four times by subjecting it to a high temperature of 1150 °C in rotary kilns [13].

In a study, load-bearing lightweight concrete with a unit weight of 1346 kg/m³, a compressive strength of 26.4 MPa, and a splitting tensile strength of 2.5 MPa was produced using 100% ECA. When limestone sand was used as fine aggregate and ECA was used as coarse aggregate in the study, a load-bearing lightweight concrete with a unit volume weight of 1813 kg/m³, a compressive strength of 36.5 MPa, and a splitting tensile strength of 2.6 MPa was obtained [13].

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Since ECA is not a common building material in our country, there is less information about it than other aggregates. Generally, ECA was employed as a coarse aggregate in other studies. In this study, the use of ECA in concrete as both coarse and fine aggregate was investigated. Thus, it was aimed at increasing the knowledge in the literature by evaluating the mechanical properties of the produced concrete. For this purpose, ECAs with a maximum grain size (Dmax) of 16 mm, obtained from Söğüt/Bilecik region, and concrete produced with crushed stone aggregate and sand with similar grain sizes were comparatively examined. In the study, three different lightweight concrete types were produced using sand and crushed stone aggregate, and their mechanical properties were compared with normal concrete. In these structural lightweight concrete samples:

- coarse and fine aggregate consist of ECA,
- coarse aggregate consists of ECA, fine aggregate consists of normal crushed stone aggregate,
- fine aggregate consists of normal fine sand, and coarse aggregate consists of ECA.

2. Material and Method

2.1. Material

In the study, crushed stone aggregate, river sand, and ECA obtained from Söğüt region, a kind of mineral additive and water-reducing additive, CEM I 42.5R type cement, and Erzurum city water were used.

2.1.1. Cement

The physical and chemical properties of CEM I 42.5R cement used in concrete mixtures are given in Table 1.

Table 1. The physical and chemical properties of CEM I 42.5R cement

Chemical Properties(%)		Physical Properties(%)	
SiO2	19.58	Residue from 32-micron sieve (%)	7.47
Al2O3	4.70	Specific Weight(g/cm3)	3.12
Fe2O3	3.36	Specific Surface(cm2/g)	3.503
		Other Properties	
CaO	62.59	Socket head (Hr-mn)	2Hr-36mn
MgO	2.53	Socket end (Hr-mn)	3Hr-33mn
SO3	2.84	Expansion Volume (mm)	1.0
Na2O	0.32	Compressive Strength(MPa)	
K2O	0.71	2.day	26.7
CI-	0.01		
Loss of glow	2.82	28.day	55.1
Insoluble Residue	0.82		

2.1.2. Water

In this study, Erzurum city tap water was used for mixing water and Concrete curing.

2.1.3. Superplasticizer

In this study, a new-generation chemical additive based on modified polycarboxylate polymer with high water reduction properties in accordance with TS EN 934-2+A1 [14] standards were used as a superplasticizer. Polisan Kimya SAN. A.Ş. and its physical and chemical properties are given in Table 2.

Table 2. Chemical and physical properties of the superplasticizer

Properties(%)	Superplasticizer
Structure of Material	19.58
Appearance	Brown Liquid
Specific Weight(in'20°C) (g/cm³)	1.035 – 1.075
pH Value	3.0-7.0
Alkali Content (%)	≤ 3 (By mass)
Chlorine ion Content(%)	≤ 0.10 (By mass)

2.1.4. Fly ash

In this study, fly ash obtained from Adana/Yumurtalık İskenderun Enerji Tüketim ve Ticaret A.Ş. was used. The chemical and physical properties of the fly ash used are given in Table 3.

Table 3. Chemical and physical properties of fly ash

Physical and Chemical Properties	
Chemical Formula	NaCI
Color	White
Physical State	Crystal
Resolution (g/l)	358
Density (g/cm3)	2.17
Bulk Density (kg/m3)	1140
pH	4.5-7.0
Molecular Weight(g/mol)	58.44

2.1.5. Aggregates

ECA used in this study was produced by Söğüt Toprak Madencilik Sanayi A.Ş. in Söğüt district of Bilecik Province. ECA with a grain diameter of 0-4.4-8.8–16 mm, sand with a grain diameter of 0–4 mm, and crushed stone aggregate with a grain diameter of 4–8 and 8–16 mm were used in the study. The physical properties of the aggregates determined according to the TS EN 1097-6 [15] standard are given in Table 4, and the gradation curves of the aggregates among the TS 802 [16] standard curves are given in Figure 1.

Table 4. Physical Properties of Aggregates

Aggregates	Specific Weight (gr/cm³)	Water Absorption (%)	Moisture Content (%)
ECA(0-4mm)	1.89	7.4	5.12
ECA(4-8mm)	1.25	13	14
ECA(8-16mm)	0.80	17	9
Sand(0-4mm)	2.5	1.14	1.16
Crushed Stone(4-8mm)	2.6	1.7	1.6
Crushed Stone(8-16mm)	2.7	1.7	1.6

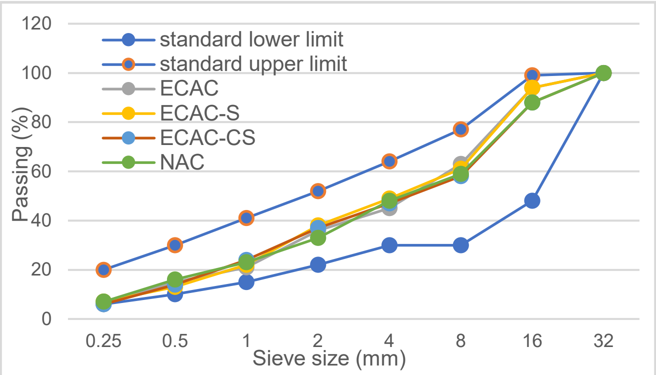

Figure 1. Gradation curve of aggregates and TS 802 standard limits

2.2. Method

The tests and relevant standards applied to the concrete mixtures produced within the scope of the study are given in Table 5. The specifications presented in the article are the average of the results obtained on three samples.

Table 5. Applied tests and relevant standards

Experiments Conducted on Concrete Samples	Sample Age (Day)	Relevant Standard
Collapse test	Fresh Concrete	TS EN 12350-2 [17]
Unit volume weight experiment	Fresh Concrete	TS EN 12350-6 [18]
Compressive Strength	7,28	TS EN 12390-3 [19]
Flexural Strength	7,28	TS EN 12390-5 [20]
Splitting Tensile Strength	28	TS EN 12390-6 [21]

Different aggregate combinations were created by substituting crushed stone aggregate and river sand into ECA and were compared with normal concrete produced with reference crushed stone and sand. For this purpose, a total of 4 mixtures with different contents were prepared. Concrete mixtures are named according to aggregate type and concrete age. According to aggregate type; ECAC: produced using only ECA, ECAC-S: produced with ECA and sand, ECAC-CS: structural lightweight concrete produced with expanded clay and crushed stone aggregate, NAC: normal concrete produced with sand and crushed stone aggregate. The age of concrete samples was indicated with a trailing age suffix: 7 and 28. For example, ECAC-CS-7 denotes a 7-day load-bearing lightweight concrete mix containing expanded clay and crushed stone aggregate. The slump of concrete designs is targeted to be at least 14 ± 1 cm. The superplasticizer usage rate was kept constant at 1.5% for 400 kg/m³, based on the total amount of binder material, and the binder dosage for all mixtures was kept constant as 400 kg/m³. Since CEM I 42.5 R cement was used in the design of concrete mixtures using fly ash, the k coefficient was determined to be 0.4. The equivalent binder amount was found with the formula (cement amount + k x mineral additive amount). The samples prepared according to the TS EN 12390-2 [22] standard were kept in the mold in the laboratory environment for 24 hours and then taken to the curing pool and wet cured. The temperature of the curing pools containing lime-saturated water is 20±1 °C. Some of the samples were subjected to experiments after being cured for 7 days, and some for 28 days. The mixing ratios of concrete are given in Table 6.

Table 6. Mixing ratios of concrete (kg/m³)

Component Name	ECAC	ECAC-S	ECAC-CS	NAC
Cement	350	350	350	350
Fly Ash	125	125	125	125
Water (%)	200	193.6	186.3	181
SA Ratio (%1.5)	6	6	6	6
0-4 (River Sand) (%40)	-	332.2	-	644.4
4-8(Crushed Stone) (%35)	-	-	-	563
8-16 (Crushed Stone) (%25)	-	-	266.6	402
0-4 (ECA) (%40)	303	-	417.3	-
4-8 (ECA) (%35)	274	293.5	377.4	-
8-16(ECA) (%25)	178	191	-	-

3. Results and Evaluatıon

3.1. Fresh concrete experiments

3.1.1. Collapse test results and evaluation

Consistency classes of concrete mixtures determined according to TS EN 206 + A2 [23] are given in Table 7.

Table 7. Collapse Class

Class	Slump (mm)
S1	10-40
S2	50-90
S3	100-150
S4	160-210
S5	≥220

Regardless of the cement dosage and w/c ratio in all concrete mixtures, the slump value was determined to be approximately 14±1 cm, and concrete corresponding to S3 consistency was produced. In this study, it was observed that the consistency of the load-bearing lightweight concrete mixtures produced with ECA was better than the concrete produced with normal aggregate, and as the ECA content increased, the workability increased. The workability of concrete mixtures depends on the composition of the mixture and the type of aggregate. The roundness of the ECA surface positively affects the workability of lightweight concrete [24].

3.1.2. Unit weight test results and evaluation

The unit weight test results performed on concrete mixture samples are given in Table 8.

Table 8. Unit weights of concrete mixtures

Mixtures	Individual Results (kg/m³)	Average (kg/m³)	Mixtures	İndividual Results (kg/m³)	Average (kg/m³)
ECAC-1	1410	1413	ECAC-CS-1	1688	1689
ECAC-2	1414		ECAC-CS-2	1690	
ECAC-3	1415		ECAC-CS-3	1689	
ECAC-S-1	1650	1652	NAC-1	2385	2389
ECAC-S-2	1654		NAC-2	2390	
ECAC-S-3	1652		NAC-3	2393	

It is seen that all concrete samples produced with ECA meet the predicted structural lightweight concrete boundary conditions. Among the structural lightweight concrete, the highest unit volume weight was observed in ECAC-CS, and the lowest unit volume weight was observed in ECAC. This is due to the fact that the specific gravity of crushed stone aggregate is higher than the specific gravity of ECA and sand. The decrease in density with the addition of lightweight aggregates can be attributed to the lower specific gravity of lightweight aggregates compared to normal aggregates. Lightweight aggregates also reduce concrete density by creating a porous structure in the matrix [24 ,25]. It was determined that the densities of structural lightweight concrete samples were 40.9%, 30.8%, and 29.3% lower than NAC, ECAC, ECAC-S, ECAC-CS, respectively.

3.2. Hardened concrete test results and evaluation

3.2.1. Compressive strength test results and evaluation

The compressive strength test results performed on concrete mixture samples are given in Table 9. The graphs drawn based on the values given in Table 9 are given in Figure 2.

Table 9. 7- and 28-day compressive strengths of concrete (MPa)

Mixtures	7-day Compressive Strength (MPa)	7-day Average (MPa)	28-day Compressive Strength (MPa)	28-day Average (MPa)	7/28-day increase ratio (%)
ECAC-1	19		30		
ECAC-2	24	23	28	30	30,4
ECAC-3	25		32		
ECAC S-1	27		39		
ECAC S-2	29	28	37	39	39,3
ECAC S-3	29		41		
ECAC CS-1	35		48		
ECAC CS-2	32	35	52	50	42,9
ECAC CS-3	38		50		
NAC-1	44		60		
NAC-2	42	44	65	64	45.5
NAC-3	46		67		

In the study, the highest compressive strength values among all concrete mixtures were achieved in samples subjected to 28-day standard water curing, and all structural lightweight concretes performed above the 28-day minimum compressive strength boundary condition. Considering the compressive strength of the samples, the lowest strength level for each age was obtained in ECAC, and the strength values closest to NAC were obtained in ECAC-CS. It has been observed that when aggregates with high elastic modulus are used in structural lightweight concrete, as the unit weight of the concrete increases, their compressive strength increases. The relationship between elasticity and compressive strength changes in direct proportion. The elasticity modulus of lightweight aggregates is lower than that of normal aggregates, and the elasticity modulus of lightweight aggregates decreases as the aggregate size increases. In normal aggregate concrete, the elasticity modulus increases as the aggregate size increases [25, 26]. In this study, it was determined that the aggregates used in concrete mixtures at 7/28-day rates had an effect. It is seen that the 28-day average compressive strengths of ECAC, ECAC-S, ECAC-CS are 30.4%, 39.3% and 42.9% higher, respectively, compared to the 7-day average compressive strengths. Regression equations relating compressive strength to concrete mixtures are shown in Figure 2.

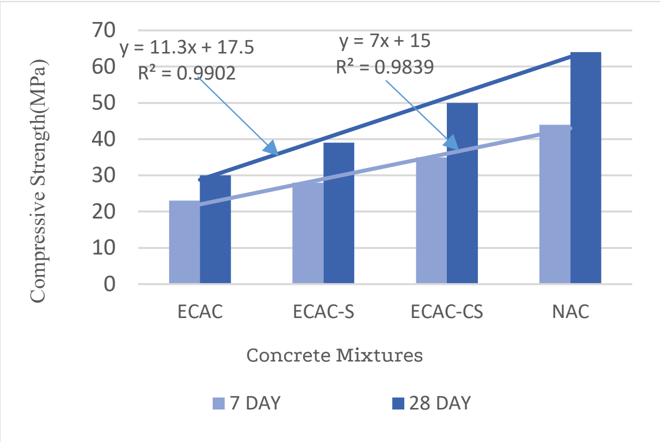

Figure 2. Relationship between 7 and 28-day compressive strength of concrete

3.2.2. Flexural strength test results and evaluation

The flexural strength test results performed on concrete mixture samples are given in Table 10. The graphs drawn based on the values given in Table 10 are given in Figure 3.

Table 10. 7- and 28-day flexural strengths of concrete (MPa)

Mixtures	7-day Flexural Strengths (MPa)	7-day Average (MPa)	28-day Flexural Strengths (MPa)	28-day Average (MPa)	7/28-day increase ratio (%)
ECAC-1	2.80		3.56		
ECAC-2	3.20	3.00	3.66	3.61	20.3
ECAC-3	3.00		3.60		
ECAC S-1	3.70		4.20		
ECAC S-2	3.50	3.50	4.60	4.43	26.6
ECAC S-3	3.30		4.50		
ECAC CS-1	4.80		5.20		
ECAC CS-2	4.00	4.30	5.80	5.50	27.9
ECAC CS-3	4.10		5.50		
NAC-1	7.10		8.60		
NAC-1	7.00	7.00	9.40	9.00	28.5
NAC-1	6.90		9.00		

In structural lightweight concrete, the lowest flexural strength level for all ages was obtained in ECAC, and the highest flexural strength level was obtained in ECAC-CS. When the flexural strengths obtained after 7 days were evaluated, ECAC-S and ECAC-CS gave higher results by 16.6% and 43.3%, respectively, compared to ECAC. When looking at the 28-day flexural strengths, these rates are 22.7% and 22.7%, respectively. It was observed that it was 52.3. It has been observed that when aggregates with high elastic modulus are used in structural lightweight concrete, as the unit weight of the concrete increases, their flexural strength increases. It is seen that the 28-day average flexural strengths of ECAC, ECAC-S, ECAC-CS are 20.3%, 26.6%, and 27.9% higher, respectively, compared to the 7-day average flexural strengths. Regression equations relating flexural strength to concrete mixtures are shown in Figure 3.

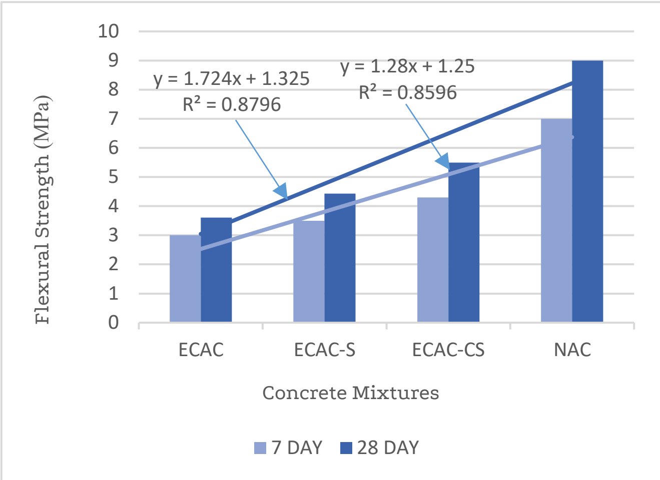

Figure 3. Relationship between 7 and 28-day flexural strength of concrete

3.2.3. Splitting tensile strength test results and evaluation

The splitting tensile strength test results performed on concrete mixture samples are given in table 12. The graphs drawn based on the values given in Table 12 are given in Figure 4.

Table 11. 28-day splitting tensile strength of concrete (MPa)

Mixtures	28 Days	
	Splitting Tensile Strength (MPa)	Average (MPa)
ECAC-1	2.5	2.5
ECAC-2	2.4	
ECAC-3	2.6	
ECAC-S-1	3.0	3.1
ECAC-S-2	3.1	
ECAC-S-3	3.2	
ECAC-CS-1	3.7	3.5
ECAC-CS-2	3.5	
ECAC-CS-3	3.8	
NAC-1	8	7.3
NAC-1	7	
NAC-1	7	

In order for structural lightweight concrete to be used in structural section elements, it must have a minimum splitting tensile strength of 2 MPa [27]. It is seen that all structural lightweight concrete mixtures produced with ECA perform above the tensile strength boundary condition at the anticipated 28-day minimum cure. In structural lightweight concrete, the lowest splitting tensile strength was obtained in ECAC, and the highest splitting tensile strength was obtained in ECAC-CS. Compared to ECAC, ECAC-S and ECAC-CS gave 24% and 40% higher splitting tensile strength results, respectively. The reason for the difference in tensile strength in splitting is coarse aggregates. The modulus of elasticity has a stronger bond with the aggregate skeleton than the cement paste. While normal coarse aggregates increase the elasticity modulus of concrete mixtures, light coarse aggregates decrease the elasticity modulus of the mixtures [28]. Regression equations relating split tensile strength to concrete mixtures are shown in Figure 4.

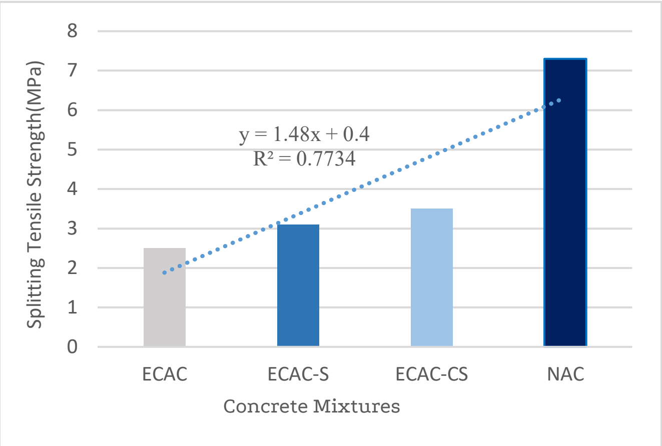

Figure 4. Relationship between 28-day splitting tensile strength of concrete

4. Conclusions

The following conclusions were reached from the materials used in the study and the experiments performed:

- Incorporating more ECA into the structural lightweight concrete mixtures has increased the workability of the concrete due to its rounded surface.
- The increase in the use of ECA has led to an increase in gap rates in light concrete samples and a decrease in unit weight. If the ECA is used as a large aggregate, the unit weight decreases by approximately 30.8%, while its use as a fine aggregate decreases the same by 29.3% and 40.9% if used as both fine and coarse aggregates.
- The mechanical behavior of light concrete is largely dependent on the aggregate type and mixture composition. The inclusion of ECA in concrete has reduced mechanical strengths. If the ECA is used as a coarse aggregate, the decrease in 28 day pressure strength was approximately 39%, 21.9% when used as a fine aggregate, and 53% when used as both fine and coarse aggregates. It has been observed that the resistance of the lightweight concrete produced with ECA used as fine aggregate and crushed stone as coarse aggregate had the highest strength. Therefore, the avoidance of using coarse aggregate in lieu of fine aggregate in load bearing light concrete will give better results in terms of strength.
- When the 28-day compressive strengths were examined, the compressive strengths of ECAC, ECAC-S, ECAC-CS were found to be 30 MPa, 39 MPa, 50 MPa, respectively. Within the scope of TS EN 206-1-A_2 standard concrete strength classes, it has been determined that concretes are in LC30/33, LC40/44, LC50/55 strength classes, respectively.
- Considering that the unit volume weights of all series obtained are lower than approximately 1800 kg/m³ and the lowest 28-day strength is above 30 Mpa, it can be accepted that all series produced are in the structural lightweight concrete class.
- It is thought that the use of lightweight structural concrete, which is the subject of this study, will increase day by day. The obtained values and results will shed light on academic studies on load-bearing lightweight concrete.

Nomenclature

ECA: Expanded clay aggregate
ECAC: structural lightweight concrete produced using only expanded clay aggregate
ECAC-S: structural lightweight concrete produced with expanded clay aggregate and sand,
ECAC-CS: structural lightweight concrete produced with expanded clay and crushed stone aggregate,
NAC: normal concrete produced with sand and crushed stone aggregate.

Declaration of Conflict of Interests

They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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