ESCUELA DE CONSTRUCCIÓN CIVIL
FACULTAD DE INGENIERÍA

Revista de la Construcción
Journal of Construction

Research Article

Effect of aggregate size and polyethylene sheet curing on mechanical and microstructural properties of lightweight expanded clay aggregate concrete

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Received: 04.03.2021; **Accepted:** 11.03.2022; **Published:** 18.04.2022

Citation: Karakurt, C., Uğur, M. and Güneş, O. (2022). Effect of aggregate size and polyethylene sheet curing on mechanical and microstructural properties of lightweight expanded clay aggregate concrete. Revista de la Construcción. Journal of Construction, 21(1), 145-155. https://doi.org/10.7764/RDLC.21.1.145.

Abstract: This study assessed the effect of lightweight expanded clay aggregate (LECA) grain size and curing with polyethylene concrete curing film (PCCF) on microstructure, interfacial transition zone (ITZ), and compressive strength of structural lightweight aggregate concrete (LWAC) produced with two different D_{max} (16 or 22.4 mm). To this end, 2 series of normal weight aggregate concretes (NWAC) and 6 series of LWAC incorporating 40% by vol. unprewetted LECA having (0-3, 3-8, or 8-16 mm) grain sizes were evaluated by using unit weight, compressive strength tests at 1, 7, and 28 days and SEM-EDX observations. Preventing the moisture loss from fresh concrete through PCCF curing had positive effects on compressive strength up to 14 and 9% for 1 and 28 days respectively. Shell thickness of LECA considerably increased with the decrease in LECA grain size. Thus, the compressive strength of LECA and LWAC increased by the decrease in LECA grain size. LWAC containing 0-3 mm LECA, achieved up to 21% higher compressive strength to weight ratio compared with the NWAC with the aid of the pozzolanic reactivity of fine LECA particles.

Keywords: expanded clay, internal curing, lightweight concrete, polyethylene sheet.

1. Introduction

The own weight of concrete structures is higher when compared with the load that they can carry. In parallel with the construction industry's technological development, high-rise buildings, large-size, and long-span concrete structures are becoming popular. Lightweight aggregate concrete (LWAC) can be used to reduce the dead load of the building. This composite material has several advantages like; saving in dead-load of the structure, decreasing the seismic effects, superior heat and sound insulation characteristics, better fire resistance, and saving from construction labor and time (Kalpana and Tayu, 2020; Costa et al., 2018; Cho, 2019). It has also great environmental and economic benefits (Ramalingam, et al., 2020).

Lightweight expanded clay aggregate (LECA) is one of the strongest lightweight aggregates (LWA) conforming to the criteria of ASTM C330M-17a. LWAC with LECA has a 28-day compressive strength in the range of 23-60 MPa, with densities in the range of 1290–2044 kg/m^3 (ASTM C330M-17a, 2017; Ramalingam and Ramanagopal, 2018). The concrete strength behavior is affected commonly by LECA strength, and it can be developed significantly by reducing the maximum grain size of the LECA for most LWAC. According to ACI 213R-14 compressive strength of concrete containing 19 mm maximum size of a specific LWA, was 35 MPa while it was 42 and 52 MPa when the maximum size of the aggregate was reduced to 13 and 10 mm respectively, without changing the cement content. The unit weight of concrete increases for these series were just 48 and 80 kg/m^3 respectively (ACI 213R-14, 2014).

Inadequate external curing and hot weather conditions cause shrinkage cracks and voids due to self-drying, notedly at low water to binder ratio. Internal curing can evenly supply the extra curing water in the concrete and increase the hydration of the cementitious material, resulting in a reduction in self-drying, high internal relative humidity, dense microstructure, and higher concrete strength. Saturated LWA can desorb water when there is no water for hydration in the surrounding concrete layers. Thanks to this, ITZ between the aggregates and binding phase enhances due to proper hydration and denser micro-structure with increased CSH amount (Venkateswarlu et al., 2020; Kamal et al., 2018; Nie et al., 2018; Henkensiefken et al., 2009).

Water absorption of LWA during concrete mixing according to EN 206-1 corresponds to 1-hour absorption by pre-dried aggregates in water (EN 206-1, 2009). LWAC today is generally prepared with prewetted or dry LWA to more easily control the effective water in the mix. In literature (Bogas et al., 2012; Punkki and Gjorv, 1995) two types of LWA were mentioned to absorb approximately 7.0 % in water after 60 min, but only 3.5-4 % and 4.5-5.5 % in fresh concrete.

According to some studies, the shrinkage of concrete quickly increases in the first 5 h after the initial setting and reaches more than 50% of the 3-day shrinkage (Lai et al. 2014). The cement paste's early age physical and mechanical properties are detrimentally affected due to the decreased hydration in windy weather. Curing concrete with an impermeable coating such as a membrane or polymer sheeting is the most practical and efficient way to cure concrete considering water and labor costs, and unfavorable weather conditions (rain, wind, etc.). The required thickness of the impermeable curing sheet should be 0.01 mm as prescribed in ASTM C 171 (2016). Concrete curing with polyethylene concrete curing film (PCCF) i) improves the degree of hydration and elastic modulus of the cement paste, ii) reduces water loss and drying shrinkage at early ages (Zhang et al., 2020).

The porous structure of the hardened concrete is reduced with the increased PCCF curing time. The concrete becomes more homogeneous regarding the open surface and core porosity of concrete (Samouh et al., 2017). The grain size has strongly influenced the crack formation strength, internal curing capacity of LECA in parallel with LECA-cement paste interface, microstructure, and compressive strength of LWAC. The novelty of this study is not to apply prewetting of the LECA before mixing process. To prevent loss of consistency in fresh LWAC, the water that LECA can absorb during the mixing and placement of concrete was determined and added to the LWAC mixture as additional water. Furthermore, the effect of PCCF curing and LECA grain sizes on the physical, mechanical, and microstructural properties of LWAC were investigated.

2. Materials and methods

2.1. *Materials*

CEM I 42.5 R supplied from the CIMSA cement factory was used in all concrete series. The physical and mechanical properties of cement were given in Table 1. Polycarboxylic ether-based Sika superplasticizer (SP) and Kütahya tap water were used for concrete mixtures.

Table 1. Important properties of CEM I 42.5R cement.

Oxide	%	Physical and mechanical properties	
CaO	62.50	Blain fineness (cm^2/g)	3372
Al_2O_3	5.59	Specific gravity	3.05
Fe_2O_3	3.09	Initial setting (min.)	117
SiO_2	19.40	Final setting (min.)	178
MgO	1.74	Soundness (mm)	2
K_2O	0.64	Compressive strength, MPa	
Na_2O	0.20	2-day	30.8
SO_3	3.29	7-day	39.5
LOI*	3.15	28-day	56.0

Two types of aggregate were used for concrete mixtures. The normal weight aggregate (NWA) was supplied from the Kırdar crushed stone plant in sizes of 0-5 mm, 4-12 mm, and 12-22 mm. The LECA in grain sizes of 0-3 mm (small), 3-8 mm (medium), and 8-16 mm (big) provided by Söğüt Soil and Mining Incorporated Company were labeled as LECA-S, LECA-M, and LECA-B respectively. The particle density and water absorption of aggregates calculated following the EN 1097-6 (2013) were given in Table 2. The grain size distribution of aggregates was presented in Fig. 1.

Table 2. Physical properties of NWA and LECA.

Aggregate type	NWA			LECA		
Grain size	0-5	4-12	12-22	0-3	3-8	8-16
Particle density, g/cm^3	2.71	2.72	2.72	1.75	1.15	0.85
*Water absorption by weight, %	1.29	0.77	0.62	5.72	8.46	12.17
Fine particle % (< 63 µm)	0.8	0.3	0.1	11	1	0.5

* 1 day and 1-hour absorption in water for NWA and LECA respectively.

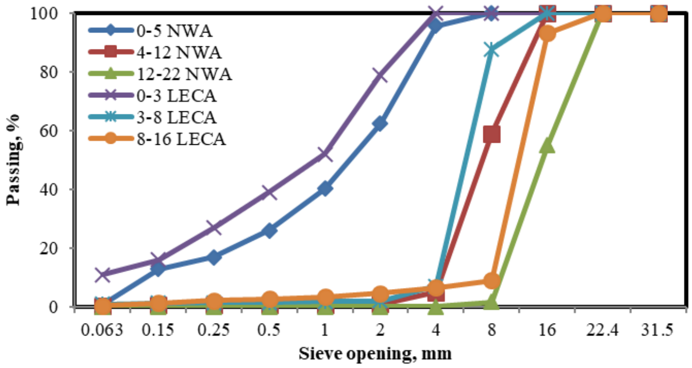

Figure 1. Sieve analyses of the aggregates.

2.2 *Method*

Material contents (kg) used in concrete series for 1 m^3 according to TS 802 (2016) concrete mix design code and fresh concrete unit weight (UW) of these series were given in Table 3. The concrete mixes were prepared in 2 groups according to the maximum aggregate size (D_{max}) of 16 mm and 22 mm respectively. Each group consisted of one NWAC and three LWAC series (Güneş, 2019).

Table 3. Material contents used in concrete series for 1 m^3 and fresh concrete unit weight of the concrete series.

Material	NWAC 16	NWAC 22	LWAC 16-S	LWAC 22-S	LWAC 16-M	LWAC 22-M	LWAC 16-B	LWAC 22-B
Cement	410	410	410	410	410	410	410	410
Water	172	164	172	164	172	164	172	164
Additional water	-	-	13.10	13.44	12.82	12,99	13.39	13.81
Superplasticizer	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15
NWA (0-5)	904	930	355	274	716	543	791	725
NWA (4-12)	363	187	357	274	-	-	-	-
NWA (10-22)	545	748	357	550	360	546	265	364
LWAC (0-3)	-	-	458	470	-	-	-	
LWAC (3-8)	-	-	-	-	303	307	-	-
LWAC (8-16)	-	-	-	-	-	-	220	227
UW (t/m^3)	2.40	2.44	2.11	2.15	1.97	1.98	1.86	1.89

LWAC series were constituted by replacing the 40% of NWA with LECA-S, LECA-M, and LECA-B by volume. Each concrete mixture was labeled due to aggregate properties (type, D_{max}, and grain size). For example, the mix LWAC16-S has a D_{max} of 16 mm and comprises 40% 0-3 mm LECA by vol. of total aggregate, while NWAC22 resembles the concrete mixtures produced with NWA having 22 mm D_{max}. The superplasticizer was added in the amount of 1.5 percent by weight of cement to achieve slump values of 10 ±1 and 5 ±1 cm for the NWAC and LWAC respectively. Since LECA was used without prewetting and effectively reduced the workability of LWAC by absorbing water during mixing and casting, many trials were done in the laboratory to determine the necessary additional water (AW) amount for the LWAC series.

Initially, a dry mix was obtained by mixing aggregates and cement for 60 sec. Then, the mixing continued for 60 seconds with 1/2 of the total mixing water. Lastly, the remaining water was included in the mixture with a superplasticizer, and the mixing continued for 60 sec. The prepared concrete was cast into 100×100×100 mm plastic molds. For water curing (WC); after leaving the concrete mixes for 24 hours in the molds, the samples were demolded and cured in lime saturated water at 20±2 °C until testing at 7 and 28 days as prescribed in EN 12390-2 (2019). The other curing was performed by using polyethylene concrete curing film (PCCF). The concrete-filled mold was completely covered with polyethylene film (0.2 mm thick) for 24 hours. Afterward, hardened concrete was demolded from the mold and recovered again with PCCF, and stored at 20±2 °C until the test date. PCCF curing helps to retain moisture in the concrete having positive effects on compressive strength. Thus, sustainable hydration of cement will help for the strength development and volume stability (shrinkage) of the concrete. Besides, PCCF can hinder the detrimental effect of rain, high temperature, wind, etc.

For all the 8 mix types, the fresh concrete slump value, fresh unit weight, and compressive strength were determined. The specimens were subjected to uniaxial compressive strength at 0.6 MPa/s loading rate and were performed as prescribed in EN 12390-4 (2019). All the reported results are the means of three tested specimens. The SEM-EDX analyses were carried out on the 28-day concrete series having a D_{max} of 22 mm. Since their mechanical properties of them were superior to the D_{max} 16 mm group.

3. Experimental results and analysis

3.1 Evaluation of physical and mechanical properties

Uniaxial compressive strength test results for water and PCCF cured concrete were presented in Fig. 2 and 3 respectively. In Fig. 2, the 28-day compressive strength of LWAC22-B was 27.57 MPa, while the strength increased by 38 and 93% for LWAC22-M and LWAC22-S, respectively. On the other hand, the fresh unit weight for LWAC22-B was 1.89 t/m^3. The UW was increased only by 5 and 14% for LWAC22-M and LWAC22-S respectively. It is obvious that as the LECA grain size decreases; the compressive strength of LWAC increases more than the increase in its unit weight. The porosity and water absorption of LECA reduce as its grain size decreases as illustrated in the literature (Castro et al., 2011; Castro et al., 2012). Compared to water curing, the 7/28 day compressive strength ratio of LWAC-B increased around 8-9% with PCCF curing while the increase in other series was 2-3% for both two D_{max}. Curing with PCCF was more effective for LWAC produced with coarse LECA.

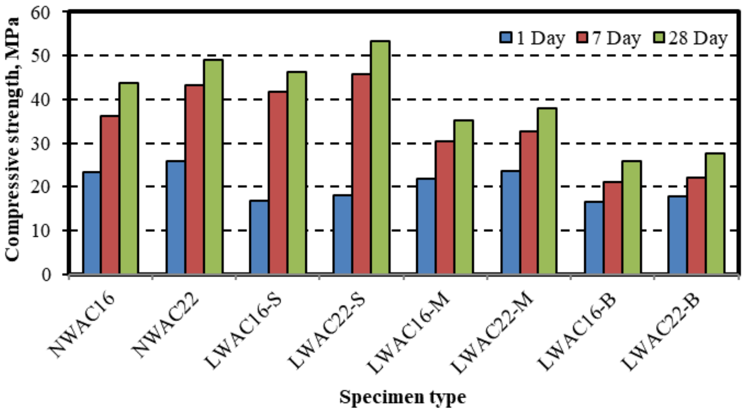

Figure 2. Compressive strength of water cured concrete series.

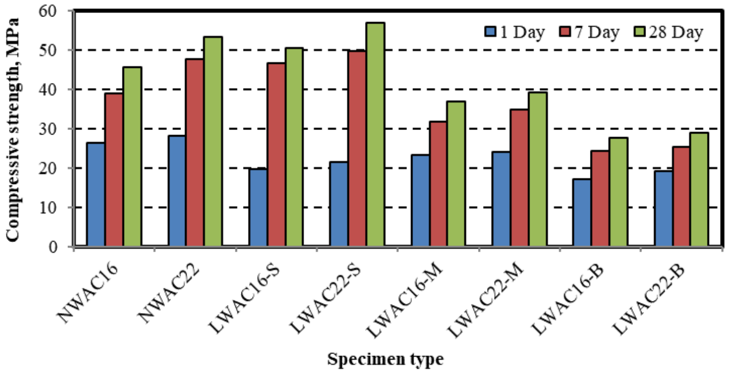

Figure 3. Compressive strength of PCCF cured concrete series.

The fresh unit weight and strength to weight ratio (CS/UW) of specimens are presented in Table 4. Compressive strength to weight ratio enhanced by 21% for LWAC22-S regarding NWAC22 for PCCF curing.

Table 4. Compressive strength to weight ratio (CS/UW) of concrete series.

Curing type	NWAC 16	NWAC 22	LWAC 16-S	LWAC 22-S	LWAC 16-M	LWAC 22-M	LWAC 16-B	LWAC 22-B
Water curing	18.26	20.14	21.94	24.8	17.84	19.17	13.90	14.58
PCCF curing	19.02	21.80	23.95	26.45	18.73	19.75	14.80	15.28

3.2 *Evaluation of surface texture*

The cross-section of the NWAC and 3 LWAC series was presented in Fig. 4. Compared with the LECA-B, the LECA-S was more homogeneously distributed in LWAC. More LECA-B grains were observed at the top of the concrete. This inhomogeneous distribution of LECA-B can also be a reason for the lower strength of LWAC produced with LECA-B.

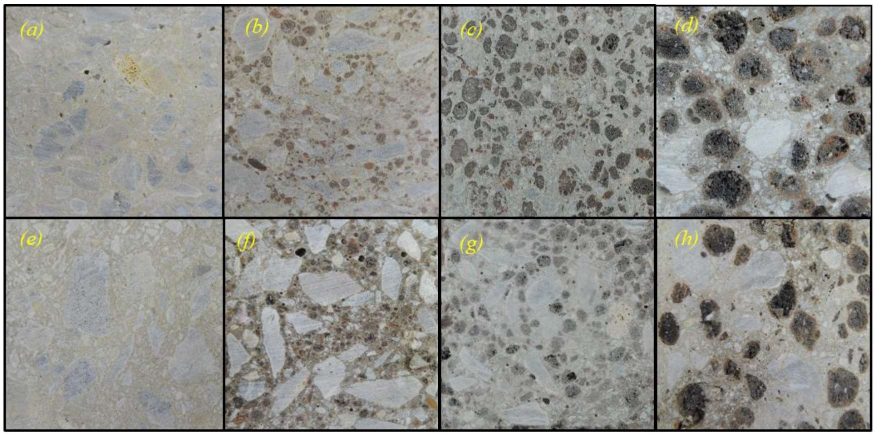

Figure 4. The cross-section of a) NWAC16, b) LWAC16-S, c) LWAC16-M, d) LWAC16-B e) NWAC22, f) LWAC22-S, g) LWAC22-M and, h) LWAC22-B.

3.3 *Microstructural investigation*

Properties of the binding phase and ITZ of water and PCCF cured NWAC22, LWAC22-S, LWAC22-M, and LWAC22-B were investigated by SEM and presented in Fig. 5-8 respectively. The chemical composition of the ITZ area was determined by using EDX detection as shown in Table 5. Excess calcium hydroxide (CH) crystals in ITZ (marked with circles in Fig. 5b) was attributed to the increase in the w-c ratio around the NWA. Due to the water film accumulated on the surface of NWA, the w-c ratio of the cement paste surrounding the NWA increases, thus enhancing the development of ettringite and CH, decreasing the interfacial strength as illustrated in the literature (Rangaraju et al., 2010; Huang et al., 2019).

The CSH is the main hydration product of cement which is responsible for the strength and shrinkage behavior of cementitious composites. The researchers have mentioned that the Ca/Si ratio of CSH in the hardened pastes varies between 1.4-2.0 and has an average of about 1.7 for the cementitious composites (Lam et al., 2000). However, CH can increase this ratio. EDX 117, 118, and 119 (Fig. 5d) have Ca/Si ratios of 6.36, 2.99, and 4.20 respectively. Extremely high Ca/Si ratios close to NWA favor the formation of high-volume CH. SEM observations demonstrate that microcracking is lower in the ITZ of LWAC compared with the ITZ of NWAC. Microcracking may be related to significant differences in the modulus of elasticity between NWA and the matrix (Ke et al., 2010).

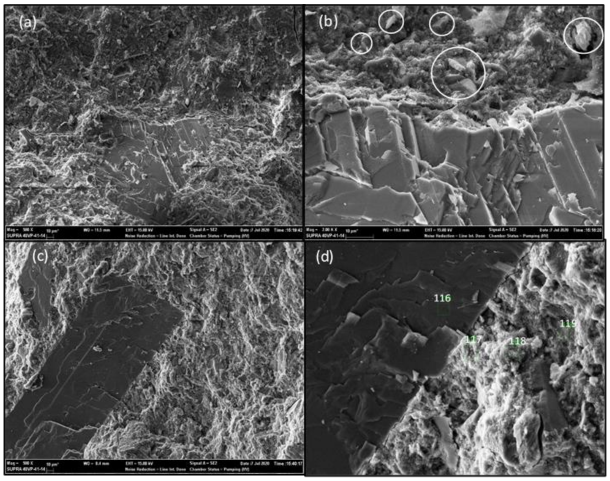

Figure 5. SEM-EDX of NWAC-22 for different curing types (a) WC 500x (b) WC 2000x (c) PCCF 500x and (d) PCCF 2000x.

Fig. 6b reveals a chemical interaction between the amorphous LECA-S surface and the binder phase (marked with a circle). A higher porosity matrix was observed in Fig. 6c due to the wall effect. This results in higher porosity in the contact zone compared to the cement paste as illustrated in the literature (Bentz and Garboczi, 1991; Nadesan and Dinakar, 2017). The addition of pozzolan to cement results in the formation of secondary CSH, which could possess a lower Ca/Si ratio (Sanchez and Sobolev, 2010). Kunther et al. (2017) found a significant increase in compressive strength by lowering the Ca/Si value of CSH paste. Compared to hardened cement paste; lower Ca/Si ratios of 0.84 (EDX 78) have been obtained at the ITZ of LWAC22-S. This was attributed to the pozzolanic reaction between CH and fine LECA particles in LWAC22-S. LECA is produced by heating clay to around 1200 °C in a rotary kiln. Since LECA was rapidly cooled to ambient temperature it gained a highly amorphous structure enhancing the pozzolanic reaction. The addition of nano-silica causes refinement of the microstructure and leads to the precipitation of small-sized CSH gel, probably having a higher stiffness and lower Ca/Si ratio (Quercia et al., 2014; Singh et al., 2016). Compared with EDX 79 having Ca/Si ratios of 2.27; it was remarked that CSH grain size reduced with the decrease in Ca/Si ratio. Despite the low strength of LECA-S versus NWA, the higher 28-day compressive strength of the LWAC22-S verified the formation of a stronger binder phase with the aid of pozzolanic reactions.

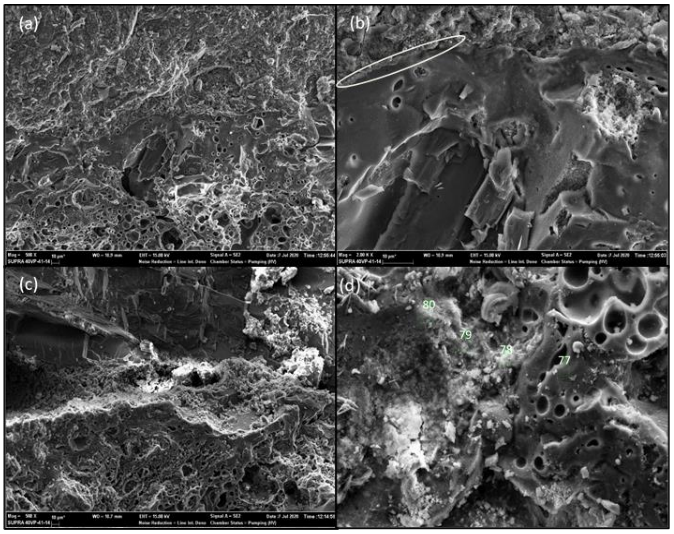

Figure 6. SEM-EDX of LWAC22-S for different curing types (a) WC 500x, (b) WC 2000x, (c) PCCF 500x, and (d) PCCF 2000x.

The shell of the LECA-M was thinner than the small LECA's shell but considerably thicker than the LECA-B shell. Smaller CH crystals in the ITZ of the LECA-M were observed in Fig. 7d. EDX numbered 87, 88, and 89 (Fig. 7d) have Ca/Si ratios of 7.62, 4.70, and 5.92 respectively.

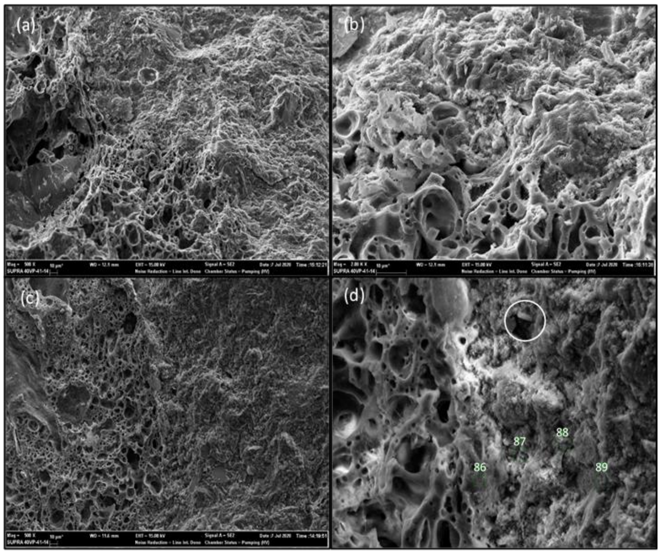

Figure 7. SEM-EDX of LWAC22-M for different curing types (a) WC 500x, (b) WC 2000x, (c) PCCF 500x, and (d) PCCF 2000x.

Considerably high Ca/Si ratio supports the high volume of CH formation around LECA-M. Greater 1/28-day compressive strength (62-65%) of LWAC22-M and LWAC22-B series compared to NWAC22 (52 %) were attributed to improved cement matrix and enhanced adherence allowing effective stress transferring between the aggregate and binding phase. The shell of LECA-B is very thin, which may lead to broken LECA particles (marked with a circle) in Fig. 8b. A mixture of the CSH phase with CH of nanometre sizes was found in hardened cement pastes with a very low w/c ratio (Groves and Richardson, 1994; Slamečka and Škvára, 2002). With the help of internal curing, visible CH plates were not observed in the binder phase around LECA-B (Fig. 8).

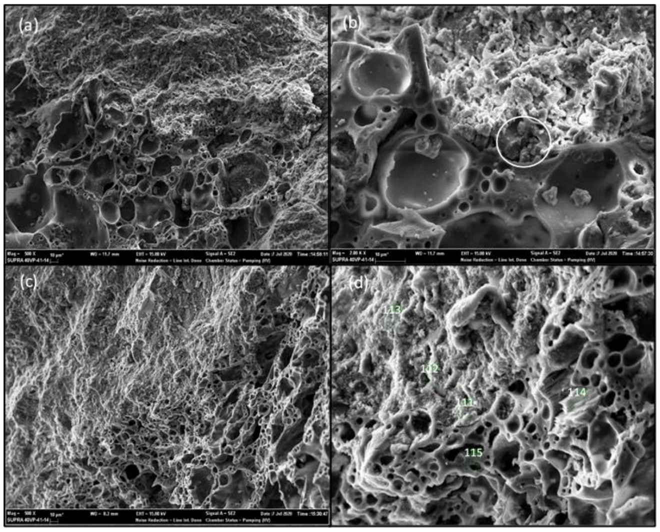

Figure 8. SEM-EDX of LWAC22-B for different curing types (a) WC 500x, (b) WC 2000x, (c) PCCF 500x, and (d) PCCF 2000x.

Similar Ca/Si ratios of EDX 111, 112, and 113 proved that CH distributed uniformly at the ITZ. During the mixing of fresh concrete, some part of the water is absorbed by LECA, which leads to a reduction of the w-c ratio in the ITZ as cited in (Sidorova et al., 2014). Hydration products were observed at pores of LECA-B In Fig. 8d. These are reported to act as multiple "hooks" binding the aggregate and the binder phase together (Lo et al., 2016; Zhang and Gjørv, 1990; Lo and Cui, 2004).

Table 5. The Ca/Si ratio of the ITZ.

EDX No	78	79	80	87	88	89	111	112	113	117	118	119
Ca/Si	0.84	2.27	9.67	7.62	4.70	5.92	3.58	3.41	3.93	6.36	2.99	4.20

4. Conclusions and comments

Based on this experimental study the following conclusions can be drawn out:

1. The compressive strength of LWAC22-B and LWAC22-S were 27.57 and 53.32 MPa respectively. On the other hand, the UW of these were 1.89 and 2.15 t/m3. It is obvious that as the LECA grain size decreases; the compressive strength of LWAC increases more than the increase in its UW.
2. According to SEM images the shell thickness of LECA considerably increased with the decrease in LECA grain size. Thus, the compressive strength of LWAC is significantly increased.
3. The internal curing with PCCF has beneficial effects on the rigid ITZ formation due to the water supply around the LECA grains. Compared with water curing, PCCF curing was superior considering higher compressive strengths up to 14 and 9% for 1 and 28-day. It can be concluded that the internal curing effect of LECA enhances the hydration of the binder phase.
4. Compared with NWAC, a considerably higher 28-day strength to weight ratio was obtained at LWAC produced with LECA-S. This was attributed to the stronger binder phase with the aid of pozzolanic reactions of fine LECA particles. This phenomenon was supported by the lower Ca/Si ratios (0.84) obtained at the binder phase of LECA-S with EDX detection.
5. With the help of enhanced internal curing around LECA-B, the w-c ratio of the binder phase around LECA-B was thought to be reduced. SEM-EDX results have revealed that CH crystals were not accumulated around the LECA-B. Mechanical interlocking was observed with the penetration of hydration products into pores of LECA-B.

Author contributions: The responsibility of the authors for this study can be declared as follows. Conceptualization, C.K. and M.U.T.; methodology, M.U.T.; validation, C.K. and M.U.T.; formal analysis, C.K. and O.G.; investigation, C.K, M.U.T. and O.G; resources, M.U.T. and O.G; data curation, C.K.; writing-original draft preparation, C.K. and M.U.T; writing-review and editing, C.K. and M.U.T.; visualization, C.K. and M.U.T.; supervision, C.K. and M.U.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no funding.

Acknowledgments: The authors, gratefully, acknowledge Söğüt Soil and Mining Incorporated Company for their help in lightweight expanded clay aggregate supply and Central Research Laboratories (Dumlupinar University, Bilecik Seyh Edebali University Turkey) for their help in some measurements and analysis.

Conflicts of interest: The authors declare no conflict of interest.

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