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Effect of fly ash and slag on the performance of lightweight expanded clay aggregates concrete

ABSTRACT

Although structural lightweight expanded clay aggregate concrete (LECA concrete) has properties of low weight, there is a problem that appears when achieving the strength requirements due to the weak strength of LECA aggregate. To compensate for the weak strength of LECA aggregate, the amount of cementcould increase, thereby increasing in emissions of carbon dioxide by increasing the cement consume. On the other hand, the high absorption of LECA aggregate due to high porosity may be threaten the durability of this type of concrete. Therefore, the significance of this study comes in addressing these problems by changing the properties of the matrix and the LECA aggregate, also the amount of cement was reduced using a group of supplementary cementitious materials SCMs, most notably fly ash and slag, which have lower carbon emissions. The type of LECA was also changed by using two forms with different densities. The experimental programme included casting various specimens for evaluation of compressive strength, water absorption, chloride migration coefficient, and corrosion of reinforced LECA concrete. The findings of this study indicated that compressive strength was greatly affected by changing the type of LECA, whereas no significant effect when changing the properties of the matrix. Meanwhile, fly ash and slag contributed inreducing emissions and improving the durabilityof LECA concrete by reducingwater absorption and porosity, as well as reducing chloride migration coefficient and reducing crack width resulting from corrosion of steel reinforcement.

Keywords.*Durability, lightweight aggregate concrete, LECA, fly ash, slag, CO_2emission, impressed current, corrosion, chloride ingress.*

1. INTRIDUCTION

To produce lightweight concrete, there are three types of methods,using lightweight aggregate concrete LWAC, cellular or aerated concrete, and no-fines concrete [1]. LECA concreteis considered one of the types of LWAC.LWAC can be utilized for structural purposes, according to [2], the structural lightweight concrete should satisfy the compressive strength requirements, not less than 17 MPa at 28 days and equilibrium density not greater than 1842 kg/m^3.

The internal structural of lightweight aggregates, LWA is characterized by cellular or highly porosity. This cellular structureled to a reduction in the specific gravity of the LWA [3]. The dynamic modulus of elasticity (DME) of LWA particles range from 10–16 GPa, while, DMEvalue for normalweight aggregate range from 30–100 GPa therefore, the strength of LWA has a significant effect on the strength of concrete [3].

In LWAC, the term “strength ceiling” is increasingly used, which can be defined as the maximum strength that concrete can reach regardless of the extension of age [4]. Holm and Bremner (2000) showed that strength ceiling depends on the properties of the coarse aggregate and the quality of the interfacial transition zone (ITZ) [5]. Clark (1993) indicated that the strength ceiling of the concrete is determined by the type of aggregate [6].

On the other hand, the high porosity of LWA may allow for greater moisture movement in LWAC compared to normal weight concrete NWC [1], which makes the durability of LWAC in critical case because the absorbed water, along with the harmful substances it carries with it, such as chlorides. They will lead to a deterioration in the durability of reinforced LWAC that cause destructive passive protection layer of steel rebar inside the LWAC and activated the rust process even if the pH of the concrete surrounding the steel rebar is still high [7][1]. There are three mechanisms for the penetrate of chloride ions into hardened concrete [8], which are:diffusion,

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absorption, and permeation. From these three transport mechanisms, the most common way for chloride ions to transport is diffusion. The process of chloride ions penetration inside the concrete is slow and in order to evaluate the penetration, this process need to accelerate within a reasonable period of time.

Currently, SCMs have become widely used in the production of different concrete types, either as they are added during cement packaging, which is called blended cement, or separately while mixing concrete components in the mixer [1]. The use of these materials has become an essential option for reducing emissions through partial cement replacement, and the fact that the production of these materials comes secondary to other industries. Where, their production is in a way that does not require additional calcination operations, as happens in cement, so the emissions reduction is significant [9]. Cement hydration can produce various compounds, the most important of which are hydrates C-S-H, also called gels, and other compounds such as portlandite $Ca(OH)_2$ or CH, ettringite, AFT and AFM phases. The pozzolanic reaction occurs by mixing SCMs with cement, where both the alumina and silica in these SCMs can react with portlandite, which leads to the formation of additional hydrates C-S-H and C-A-H causing an increase in the strength and durability of the concrete [10]. This research deals with the useof two popular types of these SCMs: fly ash class-C and ground granulated blast furnace slag GGBS as partial substitutes for ordinary Portland cement OPC. By reviewing previous studies, certain proportions were determined for the use fly ash FA and slag GGBS. The pozzolanic reactivity of FA is lower, which leads to a decrease in compressive strength of lightweight aggregate concrete, especially at early ages [11]. Lo et al. (2004) indicated that the compressive strength of LECA concrete and containing 15-25% FA decreases at early ages (7 days), but at later ages it exceeds the strength of the control mix without FA [12].In terms of the effect of FA on the durability of LECA concrete, Realet al. (2015) found that the use of 20% FA increases the water absorption, porosity, and chloride diffusion coefficient of LECA concrete [13]. This was attributed to the short curing period, which specimens cured in water for 7 days, as well as low interaction of FA, while long curing period for 28 days show decrease in the permeability and porosity of LECA concrete [14]. From this it is clear thatthe hydration of FA requires a longer curing period to show improvements in properties of LECA concrete.

On the other hand, the use of GGBS in LECA concrete, also shows a behavior similar to that of FA, but with high effectiveness, especially at early ages[15]. In the same previous study, (0-50) % GGBS was used, and it was found that using 30 % GGBS gives the best results in improve compressive strength.In terms of the effect of GGBS on the durability of LECA concrete, Cui et al. (2010) noted that when using GGBS in contents of (0, 25, and 40) %, the permeability of the LECA concrete increases with the increase in the content of GGBS [16]. Kadhum et al. (2025) found that the optimal ratio for using GGBS to improve the mechanical properties of concrete is 40%, while increasing the replacement amount to 50% contributed to additional improvements in durability properties [17].

This study aims to assess the impact of changes in the type of LWA (LECA) on the engineering properties ofstructural lightweight concrete, with a particular emphasis on the reduction of carbon emissions and protecting it from corrosion by using more sustainable alternatives (fly ash and slag).Unlike previous studies that commonly consider LECA as a single LECA aggregate type, this work examines the effect of density variation within LECA aggregates on LWAC properties.

By knowing the carbon emission values of each component used in concreteproduction, it is possible to determine the resulting CO_2 emission of the LECA concrete. Table 1 shows the CO_2 emission values of each LECA concrete component used in this study.

Table 1.The amount of CO_2 emitted from production LECA components

Concrete element constituent	CO_2/kg
Cement OPC	0.912[18]
Fly ash FA	0.029[19]
Slag GGBS	0.01[18]
Water	0.001[20]
Superplasticizer SP	0.01[21]
Sand	0.005[18]
LECA	0.5[22]

EXPERIMENTAL INVESTIGATION

2. MATERIALS

The basic binder wasordinary Portland cement (CEM I-R 42.5) of specific gravity(3.12) partially replaced with fly ash class-C(FA) of specific gravity (2.15) and ground granulated blast furnace slag (GGBS) of specific gravity (2.69).The chemical compositions of these materials are listed in Table 2. As for the aggregate used, it was divided into two sections: normal weight fine aggregate (sand) with particle size <4.75 mm and dry specific gravity (2.59).Two different types of (LECA) as coarse aggregate were employed, LECAlow density (LL) of dry specific gravity (0.9) and LECA high density (LH) of dry specific gravity (1.1) as shown in Fig.1.

Figure 1. Two different types of LECA from left (LL), and from right (LH)

The particle size of both types ranged from (4–10) mm. The physical properties of LECA are shown in Table 3. In addition, the w/c is set for all mixtures to (0.41). Superplasticizer (SP) was employed to enhance workability.

Table 2. Chemical oxide compositions of the matrix- forming materials

Property	CEM I	Fly ash class-C	Slag
SiO_2, %	20.6	38.4	38.8
Al_2O_3, %	5.4	18.7	11.6
CaO, %	60.8	24.6	34.0
MgO, %	2.6	5.1	6.4
SO_3, %	2.5	1.4	0.3
Na_2O, %	–	1.7	1.7
K_2O, %	–	0.6	1.5
Fe_2O_3, %	4.0	1.5	0.7
L.O.I, %	2.6	0.3	2.4

Table 3. Physical properties of LECA aggregates

LECA ID	Specific gravity		Density, kg/m^3		Absorption, %	Porosity, %	Color
	SSD	OD	Compacted	Un compacted			
LL	1.0	0.9	429	362	8.0	57	Brown
LH	1.23	1.1	547	520	8.3	55	Black

2.1. Mix Proportions, Mixing, Casting, and Curing of LECA Concrete Specimens

The absolute volume method according to (ACI 211.2.98) was used to determine the proportions of LECA concrete components [2]. The design of the LECA concrete mixture took into consideration the provision of an acceptable structural compressive strength exceeding 17 MPa and a density not exceeding1843 kg/m^3. The amount of cement used was 452 kg/m^3. The aggregates content and w/c were fixed for all mixtures to measure the change in properties of LECA concrete resulting from partial replacement of cement with fly ash and slag in volume ratios to maintain the volume of the mixtures depending on the specific gravity of fly ash and slag. The size and quantity of particles for all materials were measured by sieve analysis for aggregates, while for cementitious materials, a Bettersize 2000 laser particle size analyzer device was used, Fig.2 shows the particle size distribution of all LECA concrete components used in this study. To verify the particles packing of the mixtures, these sizes of particles and quantities were entered in the Elkem Materials- Mixture Analyzer *EMMA* programme to get the best particles packing which allows viewing the particles packing of the designed mixture and giving a representation of the best packing, this will reduce the consumption of additional paste if there is a shortage or loss in a certain particle size of the aggregate and will proved minimum volumetric chang due to drying shrinkage, also this will reflect positively on reducing CO_2 emission. Table 4 shows the mix proportions and some properties of the LECA concrete mixtures.

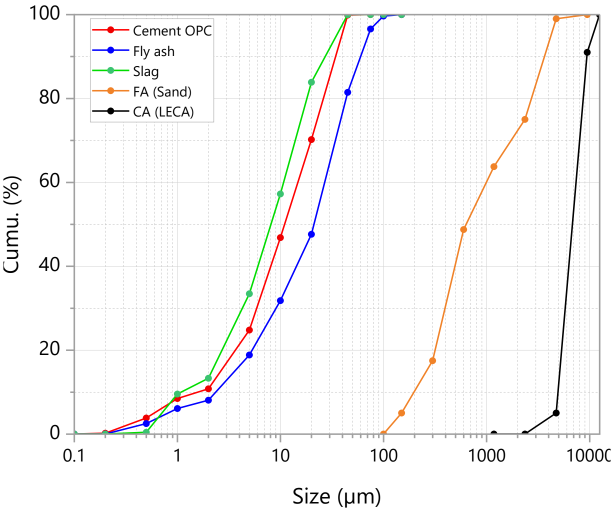


Figure 2. Particle size distribution of LECA concrete components.

The absorption of LECA was calculated by immersing it in water for 1 hour, which is the effective period for the LECA to absorb the mixing water before setting occurs. Absorbent water was added to the LECA in dry state, and to prevent the evaporation of the absorbent water, the LECA was placed in a closed container. At first, all the components were mixed for a one minute (dry mix) to achieve homogeneity, then gradually add three-quarters of the mixing water and mixing continued for two minutes. After that, stop mixing and make sure that there are no dry clumps at the bottom of the mixer. Then the mixing process is resumed and the superplasticizer is mixed with the remaining amount of water and added gradually to increase the workability. This process continues for two minutes. The total mixing time takes approximately five minutes. When mixing process is finished, all the mixture is put in a large bowland their slump and temperature (T-mix) are measured, the molds are filled with fresh LECA concrete mixture in two layers for the cubic and prismatic molds. The compaction process is carried out using the compaction rod with the shake to ensure complete filling with concrete and empty the mold from air. The compaction by vibration should not be used when the slump value is higher than 75mm according to the (ASTM C 138-14) [23], because this causes segregation of the mixture components, especially in the LECA concrete, as it causes LECA particles to float on the surface. After casting and compaction, the specimens are wrapped in nylon to prevent evaporation of mixing water and reduce plastic shrinkage cracks. After 24 hours of casting, the specimens are removed from the molds and transferred directly to the curing tank with lime saturated water (1.7gm $Ca(OH)_2$: 1 liter water) at 23±2ºC and it remain there until the test age.

Table 4. Mix proportions (dry) for LECA concrete mixtures

Mix ID	Cementitious materials, kg/m^3		Aggregate, kg/m^3				w/cm	SP, lit/m^3	Slump, mm LL – LH	T-mix, ºC
			LL		LH					
	OPC	SCMs	Sand	LECA	Sand	LECA				
C	452	-	988	227	968	295	0.41	6.78	175– 170	30
FA 20 %	361.6	62.3	988	227	968	295	0.41	6.78	180– 175	30
FA 30 %	316.4	93.4	988	227	968	295	0.41	6.78	185– 180	29.5
GGBS 30 %	316.4	116.9	988	227	968	295	0.41	6.78	190– 185	29.5
GGBS 40 %	271.2	155.9	988	227	968	295	0.41	6.78	200– 190	29

2.2. Testing and Methodology

The shape and size of the specimens for measuring properties for LECA concrete vary from cubes with sides of 100 mm for measuring compressive strength according to the [24]. While to evaluate their durability, cubes 100 mm were used to measure absorption, cylindrical discs (100 mm diameter × 50 mm height) for examining non-steady-state migration coefficient of chloride ions. Two replacement ratios were used for both fly ash and slag to achieve the best results in compressive of LECA concrete. while for durability tests, the optimal replacement ratio was chosen for each fly ash and slag to conduct. As for the mechanical tests, they were carried out at the ages of 28, and 90 days and the curing period in lime water continues until the test reaches its lifespan.

The diffusion of chloride ions was calculated for non-steady state using the following simplified Eq. (1) presented within nordtest method [25]:

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left(X_d - 0.0238\sqrt{\frac{(273+T)L\,X_d}{U-2}}\right) \quad (1)$$

where: D_{nssm} is non-steady-state migration coefficient of chloride ions ($\times 10^{-12} m^2/s$), U= applied voltage (V), T= the primary and final temperature average of anolyte solution (°C), L= heigh of the specimen (mm), X_d= average penetration depth of chloride ions (mm), t= test period (hour). The migration coefficient is determined in non-steady state close to reality to give a measure of the resistance of LECA concrete materials to penetrate the chloride ions. This test was performed according to the (NT BUILD 492-99) [25]. The reason behind calling the diffusion coefficient by migration coefficient is that the movement of ions in this test is under the action of an external electrical field rather than a concentration gradient. The test duration ranging from (24 – 96) hours depending on the value of initial current resulting from applying (30 V). Appendix (2) of the (NT BUILD 492-99) mentions the required voltage and test duration. After the test is completed, the specimens are divided into two equal halves and sprayed with a solution of $AgNO_3$ (0.1M), where the depth of chloride ions penetration can be measured through the white color that appears from the precipitation of AgCl.

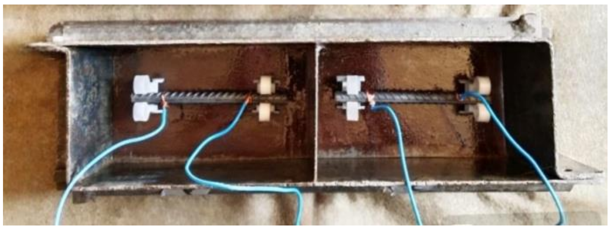


Figure 3. Molds and rebar for accelerated corrosion

Finally, accelerated corrosion was investigated by prisms reinforced LECA concrete with size of (100 × 100 × 200) mm reinforced with single bars with Ø 10 mm and length 150 mm was embedded at cover depthof 20 mm and connected to electrical wires as shown in Fig. 3.

Impressed current test is employed to measure the amount of corrosion in reinforced LECA concrete and exam the resistance of concrete against corrosion by applying an accelerating current in environmental conditions suitable for corrosion Fig.4 shows the diagram of this test.

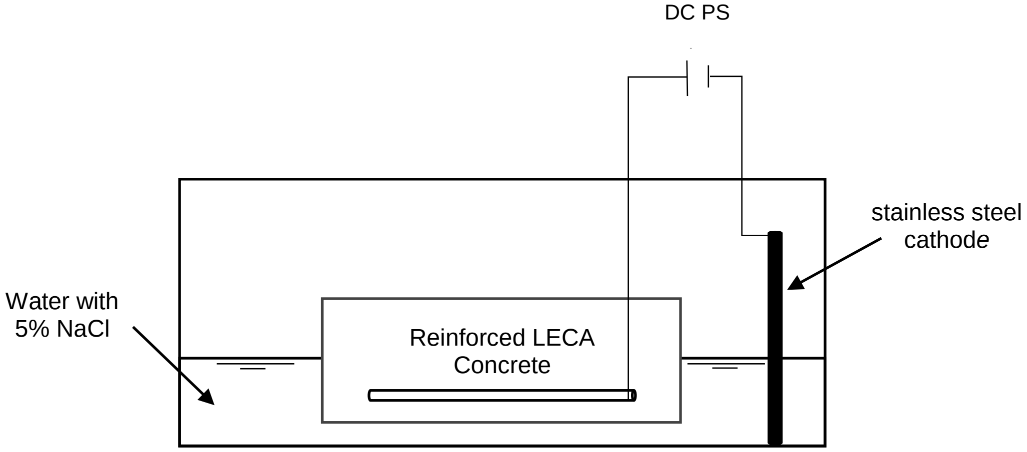


Figure 4. Impressed currentdiagram

The test duration was calculated from Faraday's law, assuming that a corrosion of (10 %) in the steel reinforcement is obtained as a result of apply corrosion current density (0.3 mA/cm^2) which is equal to (14.137 mA) according to the dimensions of the rebar. This current was applied for (25 day) to the reinforced LECA concrete specimens. After the test is finished, the corroded rebar is extracted and cleaned with sandblast and its mass is weighed to calculate the amount of mass loss due to corrosion using the following relationship Eq. (2):

$$Mass\ loss(\%) = \frac{W_i - W_f}{W_i} \times 100 \qquad (2)$$

where: W_i initial mass of rebar before test (gm), W_f final mass of rebar after complete test (gm). The annual corrosion rate can also be calculated through the following relationship Eq. (3) [26]:

$$Corrosion\ rate\ (\frac{mm}{year}) = \frac{k \times W}{D \times A \times T} \qquad (3)$$

where: k= conversion constant for unifying units (k=87.6×10^4), W= weight loss (gm), D= density of steel rebar = 7.45 (gm/cm^3), A= surface area of rebar (cm^2), T= exposure time (hr).

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Compressive Strength of LECA Concrete

The compressive strength for all mixtures used in this study is listed in Table 4. In addition,the influence of changes in cementitious content and LECA type on compressive strength are shown in Fig. 5 and Fig. 6. The results of compressive strength can be classified according to the main keys as below:

Effect of fly ash and slag

From Table 5 and Fig. 5, it may not appear that there is a significant effect of using fly ash and slag in improving the compressive of LECA concrete especially after 7 days. This is due to the effect of the weakening exerted by LECA on the strength of LECA concrete. In terms of using ground granulated blast furnace slag GGBS, increasing the replacement rate from 30% to 40% reduced the strength of LECA concrete at 7 and 28 days, while increasing it at 90 days, this is due to that GGBS needs a longer period to show improvement in strength because GGBS is an amorphous material that need hydroxyl ions $(OH)^-$ released from cement hydration to catalyze the decomposition of the glass structure of GGBS and initiate hydration [1]. As for fly ash FA class-C, it also takes a reactive form similar to GGBS, but with less effectiveness, especially at early ages, it may be due to a difference in mineral's composition of these SCMs. The volume of 20 % FA does not affect the strength of LECA concrete at 7 and 28 days, but by increasing the volume to 30 %, the strength decreases at these ages and increases at the age of 90 days. The particles size of the FA may be playing a vital role in the development of strength at early age, as it is noted from Fig. 2it has a coarser particles size than cement and GGBS, so this may delay the internal hydration of the FA.

Effect of LECA types

It is clearly noted from Fig.5 that the compressive strength was strongly affected when the type of LECA changed. The mixtures made of (LH) were characterized by higher compressive strength compared to the mixtures made of (LL). This is due to the higher specific gravity of (LH) compared to the specific gravity of (LL).

Table 5. Compressive strength and eCO₂of LECA concrete mixtures

Mix ID	f_{cu} for LECA concrete (LL),MPa			f_{cu} for LECA concrete (LH),MPa			eCO$_2$,kg/m^3
	7-day	28-day	90-day	7-day	28-day	90-day	
C	16.4	19.0	19.7	20.2	26.3	30.7	515
FA 20 %	18.8	20.4	20.6	20.8	26.7	31.5	436
FA 30 %	15.0	18.9	20.8	20.0	24.8	32.0	397
GGBS 30 %	17.5	20.0	21.5	20.7	26.5	31.4	395
GGBS 40 %	17.2	19.0	22.0	20.2	25.1	32.2	355

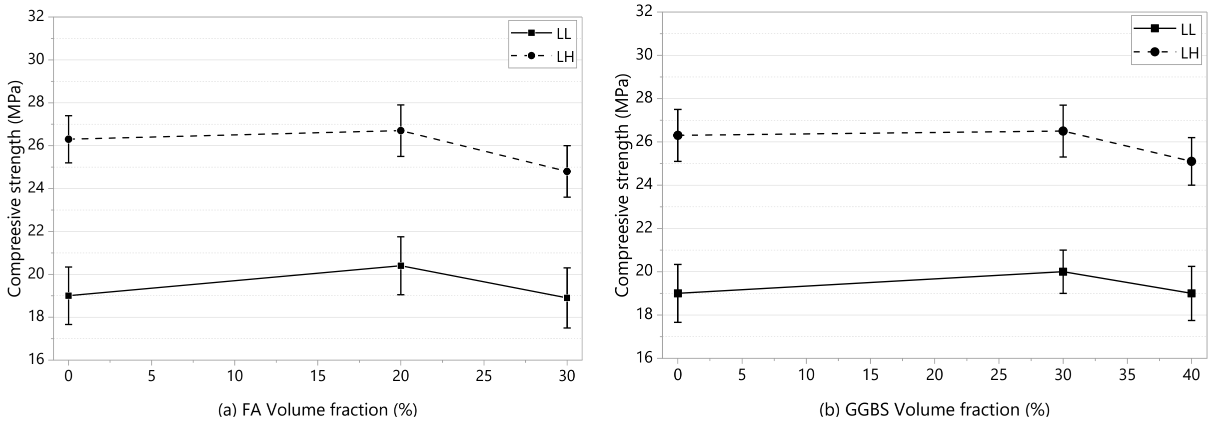


Figure 5. Effect offly ash FA andslag GGBS on 28-day compressive strength of LECA concrete made from different types of LECA aggregates

It is noted from Fig. 6 that the development of compressive strength slows down significantly after 7-day for LECA concrete, especially for thetype (LL). For example, for the mixture made of (LL) and contain cement only C, the compressive strength at 7-day is about 85% of the corresponding at 28-days, in line with previous studies by (Fujji et al. 1998, Omar and Mohamed 2002, CEB/FIP 1977) which reported that the compressive strength of lightweight concrete LWC at 7- day is about 80%–95% of its 28-day compressive strength [27,28,29]. From Fig. 6 It can be said that the strength ceiling has been reached at 28-day for the LECA concrete made from (LL), while the LECA concrete made of (LH) has not reached their strength ceiling. Shafigh et al. (2018) indicated that the strength ceiling of LECA concrete (specific gravity of LECA 0.66) reaches at the age of 7-day [4].

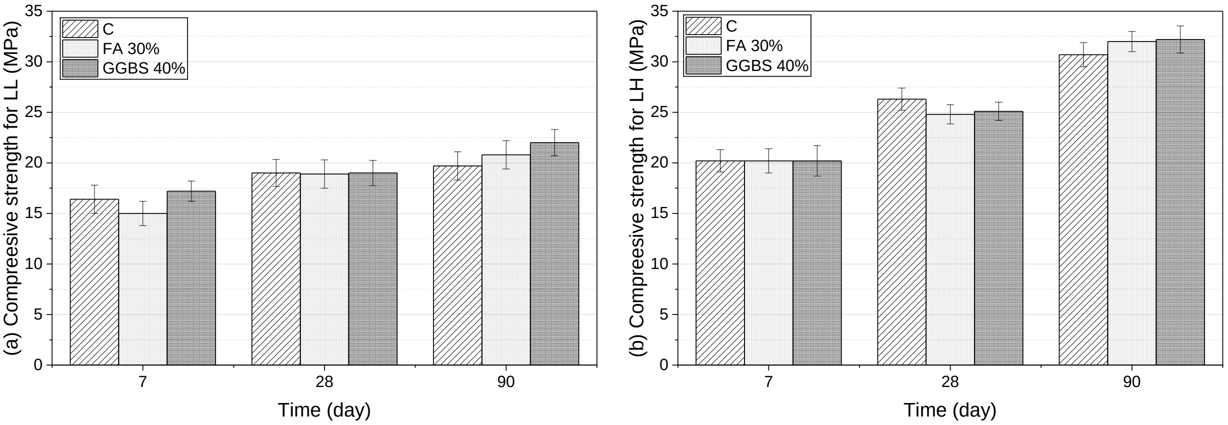


Figure 6. Development of compressive strength of LECA concrete made of (a) LL and (b) LH

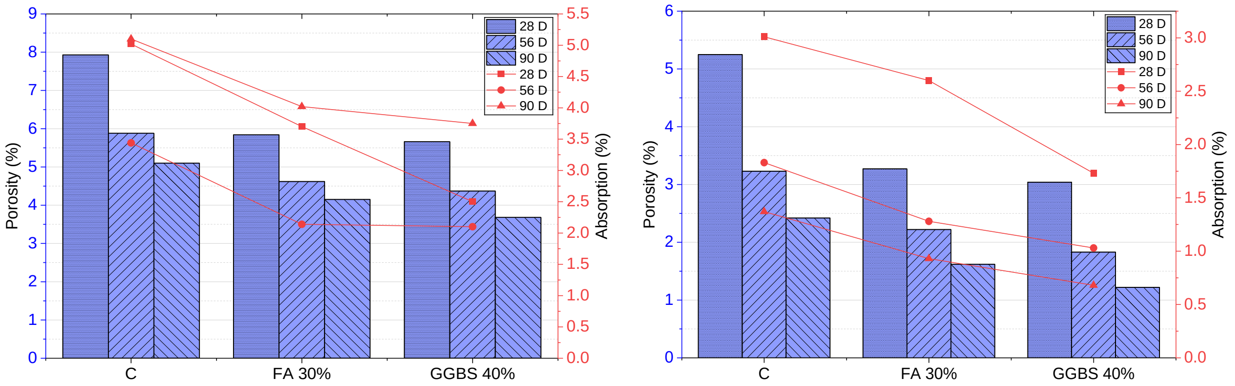
Therefore, the strength of LECA concrete will not increase significantly when the quantity of cementitious materials increases [30].From here, we conclude that there is no need to increase the quantity of binder materials for LECA concrete made from (LL), and it must be reduced for economic and environmental reasons to the extent that allows for reaching the strength ceiling.

3.2. Environmental Effect

Knowing the carbon emission values resulting from the manufacturing of each material used in LWAC production contributes to understanding its environmental impact. *EMMA* program was used to determine the emission of CO_2(eCO_2). As shown in Table 5, the SCMs contribute to a reduction eCO_2 by (14-21) % and (22-21) % when using (20-30) % FA and (30-40) % GGBS respectively. This improvement in eCO_2 reduction was achieved without compromising strength of LWAC, which indicate the significant advantage of these SCMs when incorporated into concrete production. In LWAC,eCO_2 can also be reduced once reached ceiling strength, where there is no need to increased cement. For mixtures made from LECA (LL), achieving the samestrength with less than 452 kg/m^3 of cementis possible. This indicate that increasing the quantity of cementitiousmaterials does not always guarantee increasedstrength. With this particular type of LECA, it is possible to reduce economic costs and environmental impacts producing LWAC meet the minimum limitof structural requirements.

3.3. Water Absorption, Porosity, and Density of LECA Concrete

Based on the results of mechanical tests at age of 90 days. The following LECA concrete mixtures were chosen: C,FA 30%, and GGBS 40%.It is evident from the results of the water absorption and porosity as shown in Fig.7 that the mixtures containing fly ash and slag are superior in reducing water absorption and porosity compared to the control mixture C containing cementonly. Also, LECA concrete made of GGBS was characterized by lowest water absorption and porosity at all age.For a certain age, the reduced porosity of LECA concrete containing SCMs resulted from the increased filling of pores with additional hydration products, which led toreduction in pore size [31].



(a) LL mixtures (b) LH mixtures

Figure 7. Effect of fly ash(FA) and slag(GGBS)on water absorption and porosity of LECA concrete made from (a) LECA(LL) and (b) LECA(LH)

In terms of impact the type of LWA, it is noted from Fig.7 that mixtures made of LECA (LL) have higher water absorption and porosity than type (LH), this is due to the high porosity of this LECA type.As for the effect of introducing fly ash FA and slag GGBS on reducing the water absorption and porosity ofLECA concrete, Fig.8 describes the area between the LECA particles and the matrix, which is called the interfacial transition zone ITZ, for three mixtures (a. cement only, b.30% FA, and c. 40% GGBS).The SEM images were taken from specimens that had been cured in water for a short period of seven days.The C mixture show that the ITZ appears with a thickness range from (4–6) µm and has high porosity, while the 30% FA mixture show low density of ITZ and its thickness range from (15–24) µm. This may be due to the effect of dilution, as the FA hydration process is delayed, and also to the short curing period, as seen in Fig. 8-b, where the FA particle appears in its spherical shape with incomplete surface reaction. However, with the continues of curing process for 28 days, the solid hydration products can increase, also FA particles can play a role in reducing water permeability through the filler effect, similar to fine aggregate, thus contributing to a reduction in water absorption which is reflected in a reduction in porosity.

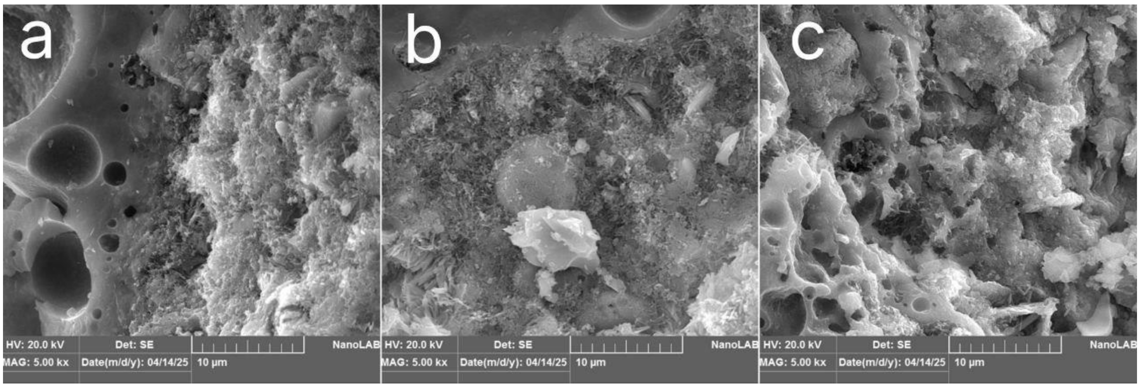


Figure 8. (ITZ) of LECA concrete made from (a) C, (b) 30% FA and (C) 40% GGBS

As for the 40% GGBS mixture, which exhibited the best results in reducing absorption and porosity, this can be attributed to the high reactivity of the GGBS particles and also to high fineness as shown in Fig.2. It is observed that the ITZ in Fig. 8-c has a high density and a thickness ranging from (0–8) µm. It is also noted in Fig. 8-c that there is a high degree of bonding between the matrix and the LECA surface by the presence of hydration products within certain areas of the outer layer of the LECA. This may be due to the ability of the LECA to absorb GGBS particles as a result of their high fineness.

In terms of the change in the density of LECAconcrete, it is noted in Fig. 9 that there is a slight effect of using fly ash and slag due to the difference in the specific gravity of these materials when replacing them with cement. While the variation types of LECA aggregates significantly affect the density of the LECA concrete, since coarse aggregate constitutes the largest part of the total volume of the concrete, so any change in its type or properties leads to a noticeable change in the density of the concrete. According to ACI 211-2:98, one of the requirements for considering concrete as a structural lightweight aggregate concrete is to achieve an equilibrium density (Eq.D.) not exceeding 1842 kg/m³ [2]. According to ASTM C567-05a, the equilibrium density for most structural lightweight concretes is typically reached after about 90 days, whereas for high-strength lightweight concretes generally after 180 days. Extensive experimental results indicate that, the equilibrium density is usually about 50 kg/m³ higher than the oven-dry density [32]. By observing the equilibrium density in Fig.9, it can be said that all mixes made from LECA (LL) and (LH) can be considered lightweight concrete.

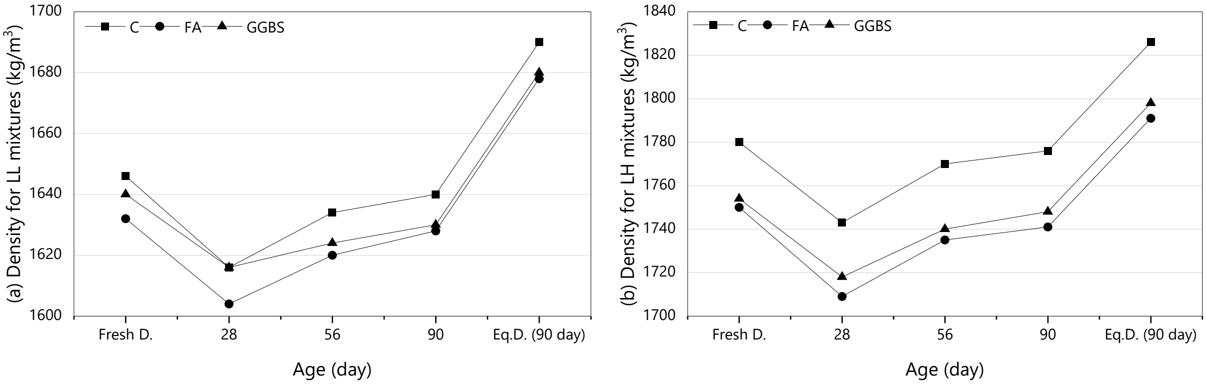


Figure 9. Effect of fly ash(FA) and slag(GGBS) on density of LECA concrete(a) LL and (b) LH

3.4. Chloride Migration Coefficient (D_{nssm}) of LECA Concrete

The performance of LECA concrete to chloride attack was evaluated by chloride migration coefficient. Fig. 10 shows the variation in the depths of chloride penetration for LECA concrete mixtures. These depths may give an indication of the D_{nssm}, but applied voltage, test period, temperature, and thickness of the specimen still affect them.

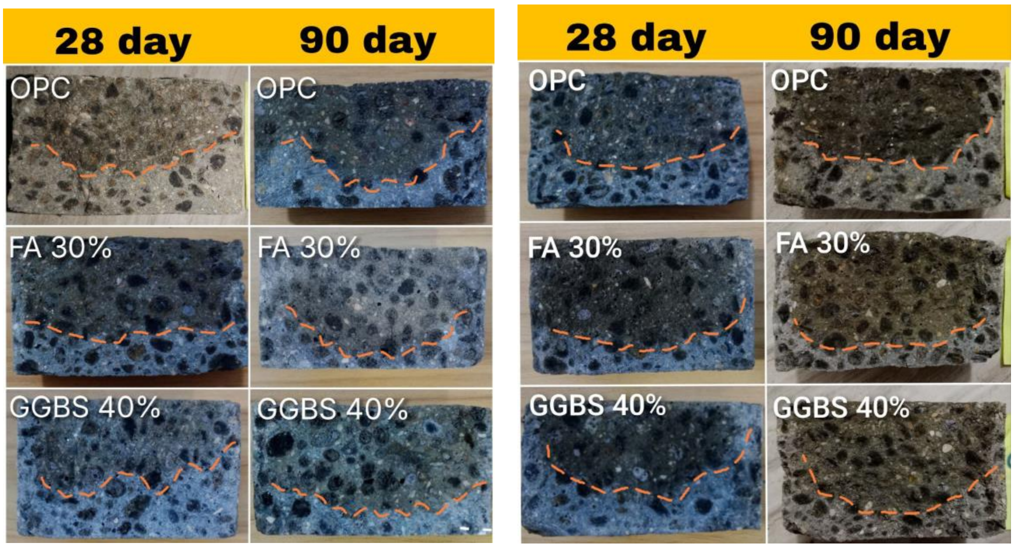
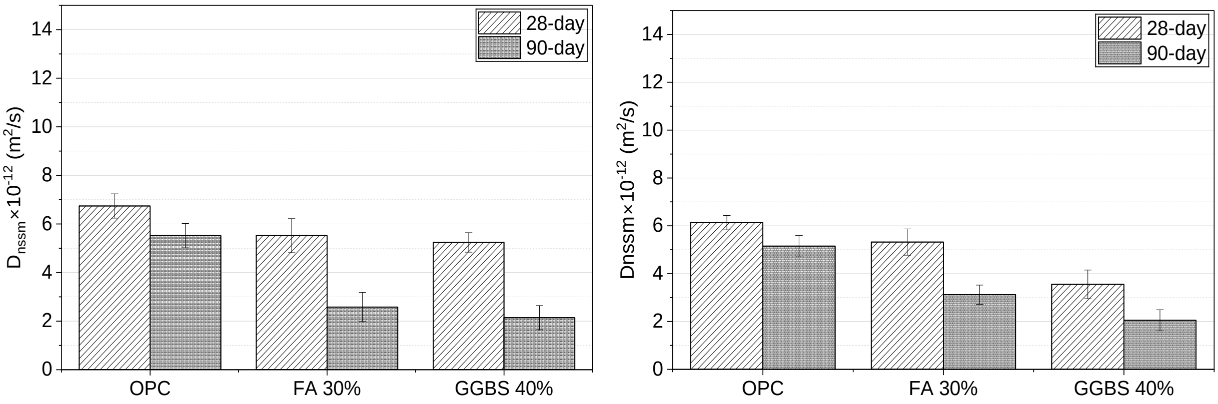


Figure 10. Penetration of chloride ions in LECA concrete from left (LL) and from right (LH).



(a) LL mixtures (b) LH mixtures

Figure 11. Chloride migration coefficient of LECA concrete

From the results of the D_{nssm} as shown in Fig. 11, it is noted that, All LECA concrete mixtures showed a decrease in the values of the D_{nssm} with the increase in age. This is due to the continued decrease in porosity as a result of the continued reaction, which refine the pore structure as the additional hydration products fill the pores, which narrows the passage of the chloride ions and reduces the D_{nssm}.

Mixture with 30% FA and 40% GGBSled to a clear improvement in decreasing the D_{nssm} of LECA concrete. At first glance, it might appear from that the penetration depth that the mixture with FA 30% has a higher resistance to chloride penetration, but asmentioned previously, D_{nssm} values also affect by the applied voltage, duration period, and other. For example, the mixtures containing OPC and FA 30% required 50V/24hr to complete the test, while the mixture containing GGBS 40% required 60V/48hr. At 90 days, clearly show the effect of FA and GGBS in decreasing D_{nssm}, this indicates the extent to which the voids are filled with additional hydration products, as the porosity decreased significantly, which made the penetration of chloride ions difficult.

3.5. Corrosion of Reinforced LECA Concrete

It is noted from the corrosion results for all reinforced LECA concrete mixtures in Table 6 that the amount of corrosion calculated practically is close to the theoretically imposed value of (10%). The reason behind this may be that the amount of corrosion current density is constant for all LECA concrete mixtures, making the current constant may be end the effect of the change in properties of the matrix. For example, during the test durationand to obtain current value (14.13 mA) constant for all specimens, the C specimen required (23.5–3.5) V, while for the FA 30%

specimen (26.5–4)V, and for GGBS 40% specimen (50–6)V. This variation in potential difference indicates a change in the electric resistance properties of each mixture. This means that the mixture containing GGBS 40% has a higher resistance to corrosion than the mixture containing FA 30%, and finally, cement alone has the lowest resistance. However, because the current was kept constant, the change in corrosion values (mass loss) was not clearly visible. To obtain corrosion values that reflect the mixture's properties, it is recommended to keep the current constant for all specimens. Increasing the voltage to obtain the same current overcomes the permeabilityof LECA concrete and makes the passage of ions (diffusion) at the rebar region almost equal. However, the variation in the voltage between specimens to obtain a constant corrosion current indicates a difference in properties of the matrix and thus there is also a difference in the corrosion values in the nature state.It is also noted in Table 6 that there is a difference in the crack width resulting from the corrosion, this indicates that the crack width is related to the properties of the matrix. In addition, when a crack occurs, the corrosion products precipitate, so there is no additional pressure to expand the crack.

Table 6. Corrosion of reinforced LECA concrete mixtures

Mix ID	Impressed Current for Corrosion at age of 90-days		
	Mass loss, %	Corrosion rate, mm/y	Crack width, mm
C	9.91	3.66	2.03
FA 30%	9.85	3.64	0.9
GGBS 40%	9.82	3.62	0.85

4. CONCLUSION

This study has contributed to provide a clear vision of the effect of LECA aggregate typeson the compressive strength and durability properties of lightweight concrete made from different cement it ious materials. Based on the results and interpretations presented above, the following conclusions can be summarized as follows:

The compressive strength of LECA concrete is largely governed by the properties of LECA, while the effect of cementitious matrix is relatively limited due to the effect of the weakening exerted by LECA on the strength of LECA concrete.

- The observed of improvements in the compressive strength of LECA concrete as a result of the incorporation of SCMs is associated with an increase in the density of LECA.
- Increasing the amount of cementitious materials in LECA concrete once it reaches its ceiling strength may be pointless if the goal is to improve compressive strength.
- Using 20% FA can improve the compressive strength of LECA concrete in early age, while increasing to 30% has a negative effect on early strength. The opposite occurs at later age (90 day), where the compressive strength can exceed the strength of a mixture containing cement only.
- Using (30–40) % GGBS can improve the compressive strength of LECA concrete in early age, and this improvement increases in later age for 40% GGBS.
- Although the use of fly ash and slag into LECA concrete resulted in slight improvements in compressive strength, however significant improvements in durability were observed through reduced water absorption and porosity, this is due to the fact that the durability properties is more closely related to the properties of the cementitious matrix.
- The use of slag and fly ash in LECA concrete reduced the chloride migration coefficient.
- In the reinforced-LECA concrete exposed to impressed current in a saline environment, the amount of corrosion is related to the amount of the current applied to the rebar.
- The use of slag and fly ash in the reinforced-LECA concrete helped to reduce the crack width caused by the corrosion of the rebar.
- Fly ash and slag contributed to increased slump values and decreased density and heat of LECA concrete mixture.
- Fly ash and slag contributed to reducing CO_2 emission, and achieving ceiling strength when using LECA (LL) can reduce the need for cement increment.
- Although changing the type of LECA affects the compressive strength, the durability properties are not significantly affected.

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IZVOD

UTICAJ LETEĆEG PEPELA I ZGURE NA PERFORMANSE BETONA OD LAKOG EKSPANDIRANOG GLINENOG AGREGATA

Iako strukturni lagani beton od ekspandiranog glinenog agregata (LECAbeton) ima svojstva male težine, postoji problem koji se javlja pri postizanju zahteva za čvrstoćom zbog slabe čvrstoće LECA agregata. Da bi se kompenzovala slaba čvrstoća LECA agregata, količina cementa može se povećati, čime se povećava emisija ugljen-dioksida povećanjem potrošnje cementa. S druge strane, visoka apsorpcija LECA agregata zbog velike poroznosti može ugroziti trajnost ove vrste betona. Stoga, značaj ove studije leži u rešavanju ovih problema promenom svojstava matrice i LECA agregata, takođe je količina cementa smanjena korišćenjem grupe dodatnih cementnih materijala SCM, posebno letećeg pepela i zgure, koji imaju niže emisije ugljenika. Vrsta LECA je takođe promenjena korišćenjem dva oblika sa različitim gustinama. Eksperimentalni program je uključivao livenje različitih uzoraka za procenu čvrstoće na pritisak, apsorpcije vode, koeficijenta migracije hlorida i korozije armiranog LECA betona. Rezultati ove studije ukazuju da je čvrstoća na pritisak u velikoj meri bila pod uticajem promene tipa LECA betona, dok nije bilo značajnog efekta pri promeni svojstava matrice. U međuvremenu, leteći pepeo i zgura doprineli su smanjenju emisija i poboljšanju trajnosti LECA betona smanjenjem apsorpcije vode i poroznosti, kao i smanjenjem koeficijenta migracije hlorida i smanjenjem širine pukotina koje nastaju usled korozije čelične armature.

Ključne reči: *Trajnost, beton sa lakim agregatom, LECA, leteći pepeo, zgura, emisija CO_2 usled udarne struje, korozija, prodor hlorida.*

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