Mechanical and durability performance of lightweight concrete (LWC) from colombian thermally expanded clay aggregates

Comportamiento mecánico y de durabilidad de concreto ligero (CL) con agregados de arcilla colombiana expandida térmicamente

Camilo Higuera-Flórez ; Jhon Cárdenas-Pulido ; A. Vargas-Aguilar

DOI: https://doi.org/10.22517/23447214.24726
Article of scientific and technological research

***Abstract*—Lightweight concrete (LWC) has become an outstanding material in the construction sector to conform non-structural and structural members into buildings. Expanded clay aggregate is a special type of lightweight aggregate formed by heating clay with little lime content, having low unit weight, high durability, and mechanical strength. Despite the massive use of the expanded clay lightweight aggregate worldwide, their use in the Colombian context is still limited. This research reports the characterization of the behavior of lightweight concrete from Colombian expanded clay aggregates. Experimental tests on fresh and hardened state (compressive strength, apparent density, and chloride migration) were carried out on lightweight concrete added Colombian expanded clay aggregate. It was found that the inclusion of up to 50% of the Colombian expanded clay aggregate causes a 15% workability decrease, 36% compressive strength decrease, 22% apparent density decrease as well as 34% decrease in the chloride migration coefficient of the lightweight concrete. In the same way, the lightweight concrete added with 50% of Colombian expanded clay aggregate meets the lightweight concrete requirements prescribed by the ACI 318 building code in terms of compressive strength, and unit weight. From the results, it is concluded that the use of Colombian expanded clay aggregate added up to 50% by weight of conventional aggregate is feasible to manufacture structural lightweight concrete.**

***Index Terms*—Chloride penetration resistance, Colombian thermally expanded clay, Compressive strength, Concrete, Durability, Lightweight concrete (LWC), Mechanical properties.**

***Resumen*—El concreto liviano (CL) se ha convertido en un material destacado en el sector de la construcción para conformar elementos estructurales y no estructurales en las edificaciones. El agregado de arcilla expandida es un tipo especial de agregado liviano formado al calentar arcilla con poco contenido de cal, exhibiendo un peso unitario bajo, alta durabilidad y resistencia mecánica. A pesar del uso masivo del agregado ligero en todo el mundo, su uso en el contexto colombiano aún es limitado. Este estudio reporta la caracterización del comportamiento del concreto liviano adicionado con agregados de arcilla expandida colombianos. Se llevaron a cabo ensayos de laboratorio en estado fresco y endurecido (resistencia a la compresión, densidad aparente y migración de cloruros) del concreto liviano adicionado agregado colombiano de arcilla expandida. Se encontró que la inclusión de hasta 50% del agregado colombiano de arcilla expandida causa en el concreto liviano reducción de 15% de la trabajabilidad, 36% de la resistencia a la compresión, 22% en la densidad aparente y 34% en el coeficiente de migración cloruros. Así mismo, el concreto liviano adicionado con agregado colombiano de arcilla expandida cumple los requisitos de concreto liviano prescritos en el reglamento de construcción ACI 318 en términos de resistencia a la compresión, y peso unitario. A partir de los resultados, se concluye que el uso del agregado de arcilla expandida de fuentes colombianas adicionado en hasta 50% por peso de agregado convencional es adecuado para la fabricación de concreto liviano estructural.**

***Palabras claves*—Arcilla Colombiana expandida térmicamente, Concreto, Concreto ligero (CL), Durabilidad, propiedades mecánicas, Resistencia a la compresión, Resistencia a la penetración de cloruros.**

I. Introduction

THE manufacture of lightweight aggregate concrete (LWC) using thermally expanded clays, has become a relevant alternative for building structures, due to its low density, good durability, and high strength [1]. Likewise, this kind of concrete has other advantages such as its high strength/weight ratio, lower coefficient of thermal expansion, and better tensile capacity [2]. However, in Colombian context the use of lightweight aggregate is limited, because its properties have not been studied enough. Furthermore, its cost is slightly higher than the commercial normal-weight aggregate (NWA) [1] [2]. For this reason, it is necessary to carry out research to characterize and describe the properties of Colombian thermally expanded clays for use as lightweight aggregate [3].

The applications of LWC have been mainly in high-rise buildings, shell structures, and long-span bridges; for this reason, its mechanical behavior has been widely studied [4]. However, the characterization of the durability behavior of LWC has been more difficult due to the multiple factors that

This manuscript was sent on June 06, 2021 and accepted on August 28, 2022.

influence it, which include the type of lightweight aggregate (LWA), the type of cement, the exposure conditions, and the water content [5].

Lightweight concrete is a special type of concrete with low density and advanced insulation, produced mainly with lightweight aggregates or cellular matrix. Lightweight concrete has been used in civil construction for over 2000 years with widespread use in the last 100 years [6]. The main advantage of using lightweight concrete in structures is the reduction of its weight. In building and bridge design, this means a reduction in gravity loading and, in the seismic inertia mass, resulting in reduced structural member sizes and gravitational forces to the foundation [7]. Moreover, lightweight concrete has additional advantages, including lower transportation cost, better sound absorption capacity, better thermal insulation, and greater resistance to fire and frost attack. However, it has some disadvantages in terms of mechanical properties and durability [8].

Currently, some studies have found advantages in the incorporation of lightweight expanded clay aggregate in construction. In the study by Sravan, Manoj, and Rao [9], it is reported the lightweight expanded clay aggregate, is a special type of aggregate which is formed by heating clay with little or no lime content. This clay is dried, heated, and burned in a rotary kiln at a temperature of 1200 ° C. This process generates a gas that is released inside the granules and is trapped in them during cooling; the organic compounds are burned forcing the granules to swell, producing ceramic granules with a porous structure. This porous structure provides the material with lightweight and high resistance to crushing, as well as thermal and acoustic insulation. The spherical geometry of the granules is produced due to the rotation of the furnace [9]. In the study by Zukri et al [10], it is reported that this type of aggregate is commonly used in the manufacture of lightweight concrete. The lightweight expanded clay aggregate is found in sizes from 0.1 mm to 25 mm and its apparent density from 250 kg/m^3 to 750 kg/m^3. This study explains that this type of aggregate has specific properties that can be applied as a suitable material in structural and geotechnical applications. Additionally, lightweight expanded clay aggregate is reported to have been used successfully to produce lightweight concrete structures [10]. The study by Sharma et al [11] highlights that the manufacture of expanded clay is non-toxic and ecological in contrast to other compounds used in concrete. Thus, the use of this type of aggregate in concrete structures also contributes to environmental sustainability.

The American Concrete Institute [12] establishes that the reference density for lightweight concretes should be between 1440 kg / m^3 and 1840 kg / m^3, in turn, it establishes that the maximum compressive strength of light-weight concrete that can be used in design calculations structural is limited to 35 MPa. It is also established that to calculate the tensile strength, compressive strength, and modulus of rupture of lightweight concrete, it is necessary to use the modification factor, which must be based on the composition of the lightweight aggregate in the concrete mix. When concrete with fine and coarse lightweight aggregates is used, the modification factor λ will be 0.75. When the concrete composition is light aggregate and fine mix, the modification factor λ, should be between 0.75 and 0.85. When the concrete composition is light sand, the modification factor λ will be 0.85. When the composition of the concrete is light sand and coarse mix, the modification factor λ, must be between 0.85 and 1.00. Finally, when the concrete is of normal-weight, the factor of modification λ will be 1.00 [12].

This modifying factor takes into account the reduced mechanical properties of lightweight concrete relative to normal - weight concretes of equal compressive strength. The inclusion of this factor λ for lightweight concrete reflects its lower tensile strength, as well as the greater dispersion of mechanical resistance and brittleness [12]. This standard does not specify limits of the maximum water to binder ratio (w/b) for lightweight concrete, because the amount of water in the mixture that is absorbed by the light aggregates makes the calculations of the water – binder uncertain.

On the other hand, the expanded clay aggregate is useful in the manufacture of foamed concrete, which can be described as a type of lightweight concrete, as indicated by Ahmad et al [13]. In that study, it is reported that foamed concrete consists primarily of Portland cement, a blowing agent, and aggregates. Among the foaming agents used to produce foamed concrete are detergents, resin soap, adhesive resins, saponin, and hydrolyzed proteins, such as keratin, and similar materials. The purpose of using a foaming agent is to introduce entrapped air into lightweight concrete. Within the civil works in which foaming concrete is used, there are load-bearing walls for low-rise buildings and partitions. Lightweight aggregate foamed concrete can also be used for thermal insulation, vibration attenuation, and dead load reduction. Lightweight aggregate foamed concretes have densities from 300 kg/m^3 to 1600 kg/m^3 and compressive strengths between 0.3 MPa and 30 MPa [13].

The main goal of this paper is to present the results of the preliminary characterization of the mechanical behavior and durability properties of lightweight aggregate concrete (LWC) from Colombian expanded clay. For this purpose, samples of normal-weight aggregate concrete (NWAC) and samples of lightweight aggregate concrete (LWAC) with different contents of expanded clay were manufactured. After that, some mechanical and durability properties of concrete samples were studied. Finally, some recommendations about use of lightweight aggregate from Colombian thermally expanded clay are provided.

II. Methodology

A. Raw materials

Commercial general Use (GU type) hydraulic cement with a density of 3.02 g/cm^3 according to standard ASTM C1157-20 was used to produce all the samples [14]. The chemical composition of hydraulic cement is shown in Table I.

Table I
Specifications Of Cement

Compound (%)	CaO	SiO_2	SO_3	Fe_2O_3	Al_2O_3	MgO	TiO_2	K_2O

GU Hydraulic Cement	68.16	16.29	5.46	3.55	3.38	1.98	0.43	0.36

Secondly, river aggregate was used as normal-weight aggregates (NWA). For the coarse aggregate, the specific gravity is 2.30 g/cm^3 and the maximum nominal size is 12.7 mm. In the case of fine aggregate, the sand has a specific gravity of 2.50 g/cm^3 and a modulus of fineness of 2.90. The particle size distribution of normal-weight aggregate (NWA) is shown in Fig. 1 according to standard ASTM C-136 [15].

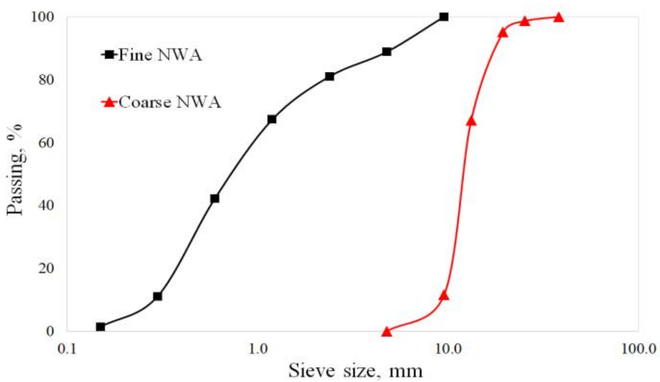

Fig. 1. Particle size distribution of normal-weight aggregates (NWA).

Likewise, commercial thermally expanded clays from Colombian sources were used as lightweight aggregates (LWA). The lightweight aggregate used is according to the standard ASTM C330 – 17 [16]. Fig. 2 shows the appearance of the Colombian expanded clay aggregates used in this research.

Fig. 2. Colombian expanded clay aggregates.

For lightweight aggregates (LWA), the coarse aggregate has a specific gravity of 1.50 g/cm^3 and a maximum nominal size of 12.7 mm. In the same way, the fine aggregate has a specific gravity of 1.60 g/cm^3 and a fineness modulus of 3.10. The particle size distribution of lightweight aggregate (LWA) is shown in Fig 3 shows according to standard ASTM C136-19 [15].

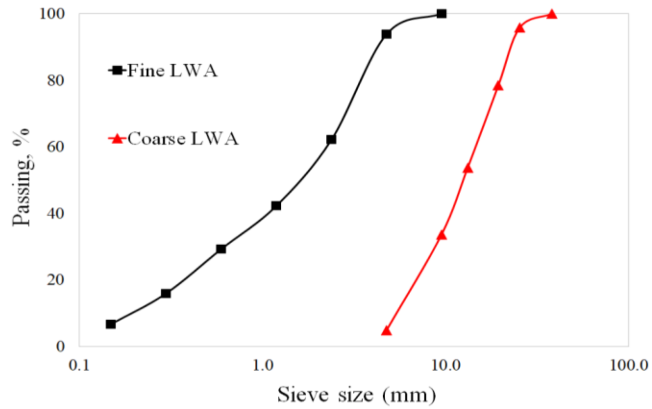

Fig. 3. Particle size distribution of the lightweight aggregates (LWA).

B. *Mixture proportions*

In this study, the mixture was designed according to guidelines of the standard ACI 211 [17] . First of all, the water to binder ratio (w/b) was 0.47 for all the mixes. Likewise, a constant binder to aggregate ratio of 1:2.75 was used. Finally, five different mixes were designed according to the lightweight aggregate volume replacements of 0.0%, 12.5%, 25.0%, 37.5%, and 50.0%. The mixture proportions of this research are presented in Table II.

TABLE II.
MIXTURE PROPORTIONS

Id.	Cement (kg/m^3)	Water (kg/m^3)	Normal-weight aggregate (kg/m^3)	Lightweight Aggregate (kg/m^3)
NWAC	536.5	260.2	1475.4	0.0
LWAC1	536.5	260.2	1290.9	119.1
LWAC2	536.5	260.2	1106.5	238.2
LWAC3	536.5	260.2	922.1	357.3
LWAC4	536.5	260.2	737.7	476.4

C. *Experimental methods*

First of all, the workability of fresh concrete was measured by the Abrams cone test according to ASTM C143 standard [18]. After that, compressive strength of concrete was measured in cylindrical molds with dimensions of ϕ100mm x 200mm according to the standard ASTM C39 [19]. The apparent density of concrete was measured on disk molds with dimensions of ϕ100mm x 50mm according to ASTM C642 [20]. Finally, the chloride non-steady state migration coefficient of concrete samples was evaluated on disk molds with dimensions of ϕ100mm x 50mm according to the NT BUILD 492 standard [21]. Three (3) samples were replicated for each mixture proportion, and all the samples were tested 28 days after casting and water curing.

III. Results And Discussion

A. Slump

The results of slump test for each fresh concrete mix are shown in Fig. 4. In this case, the increase in the amount of lightweight expanded clay aggregate up to 50% in the concrete produces a 15% decrease in fresh concrete slump compared to concrete with normal-weight aggregate. This decrease is because the absorption of the lightweight expanded clay aggregate (LWA) is higher than that for the normal-weight aggregate (NWA), which reduces the slump of the fresh mix. According to the results showed in Fig. 4, it is evidenced that concretes with different percentages of lightweight expanded clay aggregate, LWAC1 (12.5%), LWAC2 (25%), LWAC3 (37.5%), and LWAC4 (50%), show a reduction of 2%, 10%, 16%, and 18%, respectively, in the degree of slump compared to normal-weight aggregate concrete NWAC.

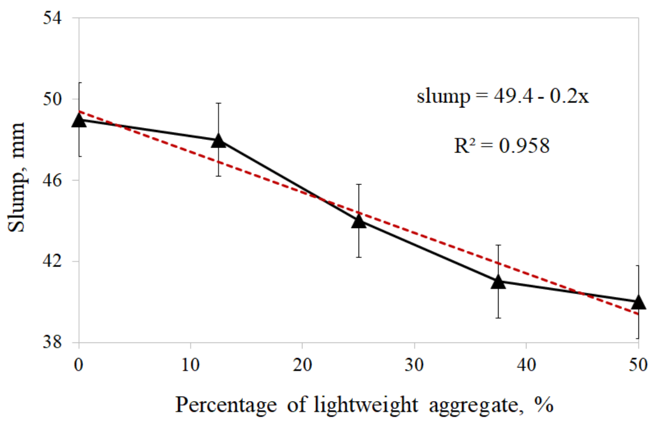

Fig. 4. Slump tests results for fresh concrete mixes.

Fig. 4 shows as the percentage of lightweight expanded clay aggregate increases in the concrete, there is a reduction in its slump. This reduction is due to the water absorption capacity of lightweight expanded clay aggregates through their porous structure. This absorption causes less workability in concrete, as explained by the study carried out by Lee, Shafigh, and Bahri [22]. In that research, it is stated that the surface of the lightweight expanded clay aggregates is porous absorbs part of the water from the cement paste, reducing the workability of the concrete.

Similarly, the study carried out by Wang [23] confirms that the decrease in the slump is related to the great water absorption capacity that the lightweight expanded clay aggregates have on the concrete mix. This phenomenon explains the reason why the workability of concretes with a lightweight expanded clay aggregate is reduced. Therefore, the author affirms that it is necessary to adopt a higher water content or the addition of a superplasticizer to maintain good workability. In turn, the study by Nahhab, and Ketab [24] confirms the high water absorption capacity of the lightweight expanded clay aggregate leads to the loss due to the slump of the fresh mixes. Further, the study by Vijayalakshmi, and Ramanagopal [25], supports the previous theories, stating that the value in the slump is affected by the porous structure of the lightweight expanded clay aggregates and their round shape. Finally, the study carried out by Ketab, and Nahhab [26] confirms that the decrease in the slump of concretes with lightweight aggregate may be related to the spherical shape of the expanded clay aggregate.

Another possible cause of the reduction of workability may be due to the size classification of the aggregates. According to the study by Chung, Elrahman, and Stephan [27], the size of the lightweight aggregates particles is a very important factor that affects the workability of concrete. The theory is confirmed by Chen, and Wu [28], who described the influence of the size of the lightweight aggregate influences on the slump of the fresh concrete mix; that study showed a 70% increase in workability when a particle size of 16 mm was used instead of particle size of 7 mm.

In the present study, a slump value of 48 mm was measured when a normal-weight aggregate was used; after that, when the lightweight expanded clay aggregate with smaller particle size was included, the slump of fresh concrete mix decreased. This behavior is in accordance with the results obtained by Chia [29], because the inclusion of lightweight expanded clay aggregates in the concrete produces a small impact on the slump of fresh concrete. Additionally, in the study carried out by Heiza et al [30], a reduction of approximately 40% in the concrete slump was found, when the content of lightweight expanded clay aggregate was increased from 390 kg to 410 kg per m^3 of concrete. Likewise, in the study by Abdeen, and Hodhod [31] a reduction in workability of 85% was found when fine and coarse aggregate was replaced with lightweight expanded clay aggregate with a particle size of 25 mm in the concrete. Finally, in the present study, it was found that the addition of up to 50% of lightweight expanded clay aggregate with a particle size of 12.7 mm generates a reduction in the slump of 18%. The trends of reduction of concrete workability due to the increase of the content of lightweight expanded clay.

B. Compressive strength

In the case of compressive strength for each concrete mix at 28 days, the increase in the amount of lightweight expanded clay aggregate up to 50% in the concrete produces a reduction in compressive strength up to 36% compared to normal-weight aggregate concrete (NWAC), as shown in Fig. 5. This reduction occurs because the strength of the normal-weight aggregate (NWA) is higher than the strength of the lightweight aggregate (LWA).

According to Fig.5, the LWAC1, LWAC2, LWAC3, and LWAC4 samples, showed a decrease in their compressive strength of 13%, 29%, 26%, and 36%, respectively, compared to the normal-weight concrete. It is evident that as the content of lightweight aggregate in concrete increases, there is a progressive reduction in compressive strength. It is well known that the characteristics of the aggregate influence the compressive strength of concrete. The decrease that occurs in the strength of concrete with higher percentages of lightweight aggregate may be due to the low density of the lightweight expanded clay aggregate concerning the aggregate of normal-weight.

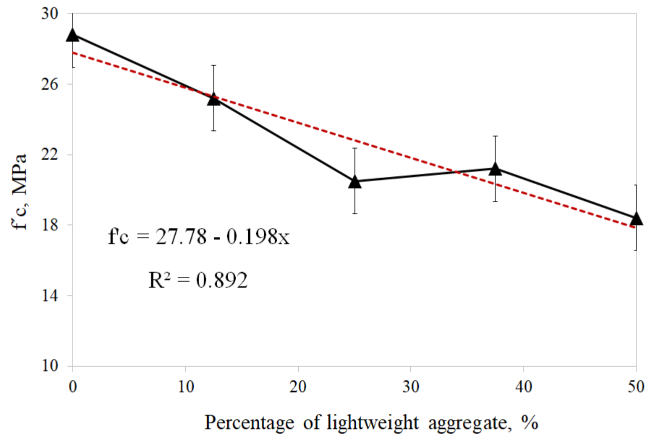

Fig. 5. Compressive strength tests results for hardened concrete.

According to Kumar and Pannem [32], the reduction in compressive strength can be explained according to Griffith's theory, which indicates that voids are decisive in the mechanical strength of concrete, because those voids are the source of stress concentration, so reducing voids could improve the packing density of particles. Single-size (spherical) particles tend to produce more voids, so the cement paste needed to fill these voids and the additional cement paste needed to produce fluency will be greater.

As can be seen in Fig. 2, the Colombian expanded clay aggregates present a predominant spherical shape. This geometry in the aggregate could cause the presence of more voids in the concrete, obtaining a lower packing density. The study by Nahhab, and Ketab [24] supports this theory to assert that the reduction in compressive strength using lightweight expanded clay aggregate is related to the low volumetric density of this type of aggregate. In turn, the study by Sohel et al [6] maintains that the decrease in density of concrete with lightweight expanded clay aggregates influences the decrease in compressive strength. Similarly, the study by Vijayalakshmi, and Ramanagopal [25] explains the shape of the aggregate influences the packing density, the binding of the lightweight aggregate within the matrix, and the mechanical properties of concrete. The authors indicate the lightweight expanded clay aggregate has a lower shape index compared to the shape index of the angular shape aggregate, so concrete with high shape index aggregates has higher compressive strengths.

Another possible cause of the reduction in compressive strength can be attributed to the heat treatment process of the aggregates; in its internal structure, a gas is formed as a result of various decompositions during the combustion process, which causes the structure of the lightweight expanded clay aggregate to become porous. Therefore, the volume of water absorbed by the pores of the aggregate is greater. This porosity may be directly related to the decrease in compressive strength of concrete with lightweight expanded clay aggregate [33]. According to Wu et al [34], the larger exposed pores on the surface of the expanded clay aggregate absorb more water from the mortar matrix during the mixing procedure. For that reason, the porosity characteristics and the shape of the particles of the lightweight expanded clay aggregate are influencing factors to determine the compressive strength of lightweight concrete. In the same way, Bogas, Carriço, and Pontes [35] indicate the porosity of the lightweight expanded clay aggregate and the decrease in the water to binder ratio influence the reduction of the compressive strength. Additionally, the decrease in the compressive strength of the concrete is attributed to the physical properties of the lightweight expanded clay aggregates, since they are less rigid than the surrounding cement paste. When these aggregates are subjected to the load test, cracks start around the particles, which accelerate failure in the matrix. On the other hand, normal-weight concrete fails in the interfacial transition zone between the cement paste and the aggregate [36]. For that reason, normal-weight aggregates are stiffer than cement paste and generate stress concentrations that initiate cracks at the interfaces of the aggregate and cement paste.

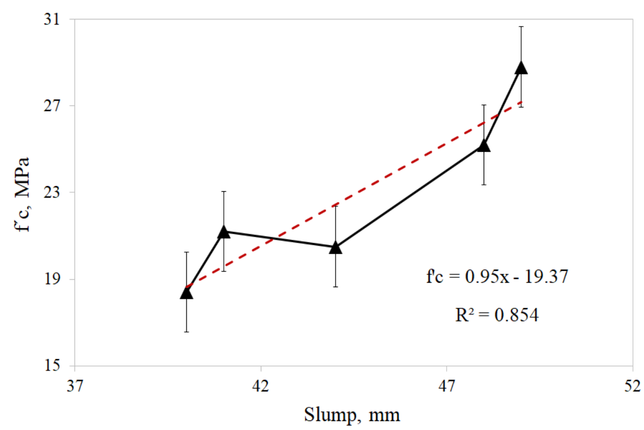

Fig. 6. Relationship between slump and compressive strength

On the other hand, the decrease in compressive strength could be explained through the slump. Fig. 6 shows that the reduction in compressive strength is proportional to the reduction in the slump of fresh concrete because a reduction in slump causes a higher percentage of voids in the hardened concrete.

Additionally, the maximum size of 12.7 mm of the lightweight expanded clay aggregate particles could be related to the decrease in compressive strength. Nahhab and Ketab [24] found that concrete with lightweight expanded clay aggregate with a maximum size of 10 mm, presented a better performance in its compressive strength compared to concrete with lightweight expanded clay aggregate of maximum sizes of 14 mm and 20 mm. In the same way, Chen and Wu [28] found that lightweight expanded clay aggregate with a size of 11 mm has higher compressive strengths compared to concretes made with normal-weight aggregate.

The trends in compressive strength of lightweight concretes in the present study are consistent with the findings of previous research from Ahmadet al [13], Ketab and A. Nahhab [26], Dilli et al [37], Sonia and Subashini [38], Paul and Lopez [39], Kulkarni and Muthadhi [40], Sindhuja et al [41], Bhogayata et al [42], and Priyanga et al [43]. Therefore, it can be concluded that the characteristics of density, unit weight, porosity, water absorption, size, and shape of the lightweight expanded clay aggregate, are influencing factors on the mechanical properties of the lightweight concrete of Colombian expanded clay.

C. Apparent density

Fig.7 shows the Apparent density ($\rho_{apparent}$) test results for each hardened concrete at 28 days. The trend indicates that the increase of lightweight expanded clay aggregate generates a reduction up to 22% in the apparent density of the samples, because the density of the lightweight aggregate (LWA) is less than the normal-weight aggregate (NWA) density. Another possible explanation for the reduction in apparent density of lightweight concrete of Colombian expanded clay aggregate may be due to the highly porous structure of this type of lightweight aggregate [42].

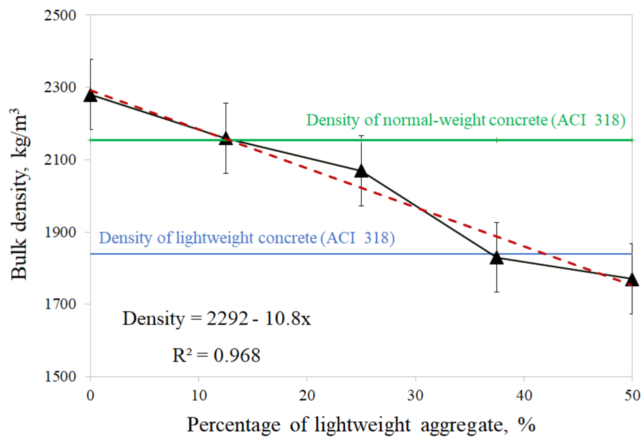

Fig. 7. Apparent density test results for hardened concrete.

Fig. 7 shows that as the dosages of lightweight expanded clay aggregate increase, greater porosity is generated in hardened concrete, causing a lower apparent density. This reduction is important because the use of these concretes allows to reduce the mass of the structures; It is known that lightweight concrete is generally used to reduce the dead load of the structures and the risk of earthquake damage, since the seismic forces that influence structures and buildings are proportional to the mass of these. Therefore, using this type of aggregate allows reducing the mass of the structure or building in reinforced concrete. Ünal et al [44] and Devecioglu, and Biçer [45] explain that reduced weight in the building allows a reduction in the cross-sectional areas of concrete elements and amounts of reinforcing steel. According to Ibrahim et al [46], the incorporation of lightweight expanded clay aggregate in concrete shows a better behavior under seismic load, compared to normal-weight concrete, since this kind of aggregate is flexible and has a reduced unit weight. Likewise, Monahan [47] reports the use of lightweight expanded clay aggregate in the design of pavements that are built on soft soils, allows obtaining a reduction of load generated to the soft soil layer.

Another possible explanation for the decrease in apparent density of lightweight concrete of Colombian expanded clay aggregate may be due to the high temperatures used in the rotary kiln for the formation of expanded clay. According to Abdelfattah et al [48], when using temperatures above the pyroplasticity range, which are between 1050°C and 1100°C, in the clay sintering process, there is an increase in the density and pore size of the particles of expanded clay.

In the same way, another possible cause of the reduction in apparent density is the spherical shape that predominates in the Colombian expanded clay aggregates and the sizes of similar diameter due to the closed gradation; these factors influence the presence of voids in the hardened concrete, causing a lower packing density and lower apparent density, according to Zukri et al [10]. Ming et al [49], found a 7% reduction in apparent density was obtained through the inclusion of lightweight expanded clay aggregate. Similarly, the research by Devecioglu and Biçer [45] found that the densities of concretes with dosages of 10% and 20% of lightweight expanded clay aggregate decreased 13.2% and 23.8%, respectively. Additionally, Salem et al [33] found that the apparent density of the concrete with lightweight expanded clay aggregate decreased from 2375 kg/m^3 to 1978 kg/m^3.

For its part, the study by Ahmad et al [13] showed that the increase in the volume of lightweight expanded clay aggregate from 20.1% to 49.4% reduced the apparent density of concrete from 1352 kg/m^3 to 788 kg/m^3. Pradeep et al [50] observed that the density of the lightweight expanded clay aggregate is approximately 70% lower compared to the aggregate of crushed stone. The authors affirm that, by partially substituting the volume of coarse aggregate for lightweight expanded clay aggregate, it is possible to obtain a considerable reduction in the dead weight of concrete. Likewise, Sindhuja et al [41] used dosages of 30%, 50%, and 100% of lightweight expanded clay aggregate in concrete mix and found that apparent density of the concrete presented reductions of 6.3%, 24.1%, and 24.4 %, respectively. In the same way, Daria Jóźwiak-Niedźwiedzka [51] found reductions of 12.4% and 6.2% at the age of 28 days in apparent density for concretes with dosages of 33% and 50% of lightweight expanded clay aggregate. Similarly, Vosoughi [52] described that the use of a dosage of 40% of lightweight expanded clay aggregate produces a decrease in apparent density of approximately 10%.

Finally, in the present research, a apparent density of 2280 kg/m^3 was obtained for normal-weight concrete. After that, a dosage of 50% of Colombian lightweight expanded clay aggregate produced a apparent density of 1770 kg/m^3. In this case, the reduction in apparent density was approximately 22%. Therefore, the trends of reduction of apparent density with increasing content of lightweight expanded clay aggregate in concrete found in the present research are similar to the results obtained by Ming et al [49], Pradeep et al [50], Muñoz-Ruiperez [53], and Jóźwiak-Niedźwiedzka [51].

D. Chloride migration

Fig. 8 shows the results of the non-steady state migration coefficient (D_{nssm}) for each concrete mix at 28 days. In this case, the results indicate that the increase of lightweight expanded clay aggregate produces a reduction in the non-steady state migration coefficient up to 33.8%. This reduction may be because the inclusion of lightweight expanded clay aggregate generates an important reduction in the porosity of the material, which reduces the penetration of chlorides in concrete. In the same way, as the percentage of lightweight expanded clay aggregate in the concrete increases, there is a progressive reduction in the non-steady state migration coefficient (D_{nssm}).

According to Fig. 7, it is observed that concrete samples LWAC1 (12.5%), LWAC2 (25%), LWAC3 (37.5%), and LWAC4 (50%) present reductions of 22%, 21%, 32%, and 34% respectively, compared to NWAC.

Fig. 8 shows that the non-steady state migration coefficient (D_{nssm}) decreased from 12.1x10^{-12} m^2/s to 8x10^{-12} m^2/s when a dosage of 50% of lightweight expanded clay aggregate in concrete. An explanation for the decrease in the non-steady state migration coefficient (D_{nssm}) is the porous structure of the lightweight expanded clay aggregates acts as a barrier against migration to the rest of the concrete matrix, absorbing chlorides ions [54]. Likewise, Liu, Du, and Zhang [55] explained that the migration of chlorides in lightweight concretes is affected by the pore structure of the aggregate and the chemistry of the pore solution, because the presence of ions (such as hydroxide $(OH)^+$ and sodium $(Na)^+$) influences the total electric charge passed [56] [57].

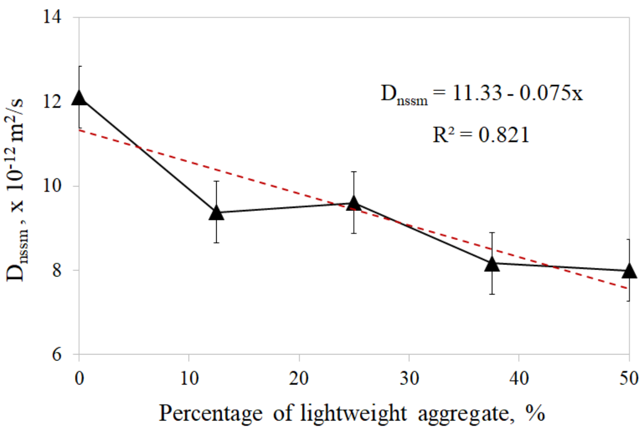

Fig. 8. Chloride migration tests results.

Another explanation for this behavior is that chloride penetration in concrete may decrease when pore connectivity is low [58]. Previous studies indicate that concrete with lightweight aggregates presents better quality in the bond of the cement paste and the aggregate (known as the interfacial transition zone - ITZ), which obstructs the penetration of chloride ions into the concrete. This process occurs because there are more cement hydration products deposited on the porous surface of the lightweight expanded clay aggregates which generate an increase in the densification and resistance of the interfacial transition zone (ITZ). In turn, Bentz [59] explains the densification of the interfacial transition zone (ITZ) provides greater resistance to ionic and fluid transport in the concrete matrix.

Another explanation for the decrease in the non-steady state migration coefficient (D_{nssm}) in the concrete of Colombian expanded clay aggregate is that lightweight aggregate increases the electrical resistivity of concrete compared to normal-weight aggregate. An increase in electrical resistivity decreases chloride ion migration in lightweight concrete, considering that chloride ion migration is a phenomenon that takes into account electrical and transport properties in concrete [28].

Fig. 9. Chloride penetration profile of lightweight aggregate concrete.

The chloride penetration trends of lightweight concrete in the present study (see Fig. 9) are similar to the results presented by Arabani et al [60], in which concrete with lightweight expanded clay aggregate provided the lowest chloride migration coefficient for 28 and 90 days compared to the other lightweight aggregates (slag and pumice). In the same way, Liu et al [61] found that the non-steady state migration coefficient (D_{nssm}) was reduced from 8.8x10^{-12} m^2/s to 6.5x10^{-12} m^2/s when a 50% dosage of lightweight expanded clay aggregate was used in concrete. Additionally, Liu et al [62] found that lightweight concrete presented a chloride migration coefficient of 2.3x10^{-12} m^2/s, while normal-weight concrete presented a chloride migration coefficient non-steady of 1.5x10^{-11} m^2/s. Finally, in the present study, there were decreases of 22%, 21%, 32%, and 34% in the chloride migration coefficient when dosages of lightweight expanded clay aggregate of 12.5%, 25%, 37.5%, and 50% were used.

IV. Conclusions

In this work, the slump, density, compressive strength, and resistance to chloride penetration of concrete of thermally expanded Colombian clay aggregates were evaluated. The results led to the following conclusions:

- The inclusion of thermally expanded Colombian clay aggregate in the concrete mix decreases the slump of fresh concrete. This behavior is because the water absorption of the Colombian lightweight aggregate is higher than the absorption of the normal-weight aggregate.

- In the case of mechanical properties, increasing the amount of thermally expanded Colombian clay aggregate decreases the compressive strength of the concrete, because the strength of lightweight aggregates is less than the strength of normal-weight aggregates. According to the American Concrete Institute, concrete with dosages up to 50% of lightweight expanded clay aggregate achieve the compressive strength limit of 17 MPa to be applied in general-purpose structures. However, only concrete with dosages below 20% of Colombian lightweight aggregate achieved with the limit of 21 MPa to be used in moment-resistant frames and special structural walls.

- The inclusion of Colombian thermally expanded clay aggregate reduces the apparent density of hardened concrete, this could be a very important advantage in the reduction of seismic forces in seismic-resistant structures and for the settlement on soft soils. In this study, concrete with dosages higher than 37.5% of Colombian lightweight expanded clay aggregate, present apparent density below 1840 kg/m^3; following the provisions of the ACI 318S-19 standard, this concrete of Colombian expanded clay are lightweight concretes which could be used in structural applications such as high-rise buildings and bridges with large spans. These are the preliminary results of this work, for that reason It is recommended future research on this topic.

- In the case of resistance to chloride penetration, the inclusion of thermally expanded Colombian clay aggregate up to 50% reduces the chloride migration coefficient (D_{nssm}) by 33.8%, because this kind of lightweight aggregate produces a reduction in the porosity of hardened concrete. Therefore, the use of Colombian lightweight aggregate might generate an improvement in the useful life of concrete structures.

- Lightweight aggregate (LWA) concrete is an alternative used worldwide, which has allowed an improvement in the design and construction of concrete structures. However, in the Colombian case, this kind of aggregates has not been widely used. For that reason, in this research, the mechanical and durability properties of concrete of thermally expanded Colombian clay aggregate were studied. According to the results, it is concluded that Colombian lightweight expanded clay aggregate could be used in partial replacements for up to 50% of manufacturing of structural concrete, since the workability, apparent density, and resistance to chloride penetration of the concrete are improved, with allowable mechanical strength.

- Lightweight concrete from expanded clay aggregates is an innovative material widely used in industrialized countries, which allows to build resistant lightweight structures. However, expanded clay aggregates to manufacture lightweight concrete have not been widely used in the Colombian context. For this reason, it is advised future research to deepen on the mechanical and durability properties of the lightweight concrete added with Colombian expanded clay aggregate with the aim of boost the results reported in this work.

- Finally, because of the reduction in the compressive strength of concrete with expanded clay aggregate dosages greater than 20%, it is recommended to investigate the implementation of this type of concrete in non-structural elements such as partitions, ceilings, thermal insulation, heat attenuators, vibrations, dead load reductions and coating systems.

ACKNOWLEDGMENT

The authors gratefully thank to Instituto de Extensión e Investigación de la Escuela Militar de Cadetes General José María Córdova, and to Centro de Investigaciones de la Facultad de Ingeniería (CIFI) de la Universidad Católica de Colombia, for their support to this work derivative from the activities carried out in the research project "Evaluación de las propiedades de durabilidad de estructuras de concreto utilizando residuos de construcción y demolición (RCD'S)".

REFERENCES

[1] J. Cardenas-Pulido, D. Niampira, N. Lugo, S. Salgado y C. Higuera, "Preliminary characterization of the mechanical and durability properties of lightweight concrete from Colombian expanded clay aggregates", 2020 Congreso Internacional de Innovación y Tendencias en Ingeniería (CONIITI), Bogotá D.C., 2020. DOI: 10.1109/CONIITI51147.2020.9240348

[2] M. Zaichenko, S. Lakhtaryna and A. Korsun, "The influence of extra mixing water on the properties of structural lightweight aggregate concrete," *Procedia Engineering*, vol. 117, pp. 1036-1042, 2015. DOI: 10.1016/j.proeng.2015.08.228

[3] J. Cáceres, J. Rojas and J. Sánchez, "A review about the use of industrial by-products in the lightweight aggregates production of expanded clay," *Journal of Physics: Conference Series*, vol. 1388, pp. 1-7, 2019. DOI:10.1088/1742-6596/1388/1/012011

[4] S. Real and J. Bogas, "A review on the carbonation and chloride penetration resistance of structural lightweight aggregate concrete," *Materials*, vol. 12, pp. 1-32, 2019. DOI: 10.3390/ma12203456

[5] S. Real and J. Bogas, "Chloride ingress into structural lightweight aggregate concrete in real marine environment," *Marine Structures*, vol. 61, pp. 170-187, 2018. DOI: 10.1016/j.marstruc.2018.05.008

[6] K. Sohel, K. Al-Jabri, M. Zhang and J. Richard Liew, "Flexural fatigue behavior of ultra-lightweight cement composite and high strength lightweight aggregate concrete," *Construction and Building Materials*, vol. 173, pp. 90-100, 10 june 2018. DOI: 10.1016/j.conbuildmat.2018.03.276

[7] M. Kowalsky and H. Dwairi, "Review of parameters influencing the seismic design of lightweight concrete structures," *ACI Special Publications: Symposium Paper*, vol. 218, pp. 29-50, 2004.

[8] A. Banawair, G. Qaidb, Z. Adi and N. Nasir, "The strength of lightweight aggregate in concrete – A Review," *Sustainable Civil and Construction Engineering Conference*, vol. 357, pp. 1-6, 2017. DOI: 10.1088/1755-1315/357/1/012017

[9] V. Sravan, T. Manoj and M. Rao, "Effect of mineral admixture, w/b ratio and elevated temperature on strength of lightweight expanded clay aggregate concrete," *Journal of science and technology*, vol. 18, pp. 1-7, june 2020. DOI: 10.32377/cvrjst1801

[10] A. Zukri, R. Nazir, K. Said and H. Moayedi, "Physical and mechanical properties of lightweight expanded clay aggregate," *The 12th International Civil Engineering Post Graduate Conference (SEPKA) – The 3rd International Symposium on Expertise of Engineering Design (ISEED)*, vol. 250, pp. 1-18, 2018. DOI: 10.1051/matecconf/201825001016

[11] S. Sharma, S. Thakur and S. Onkar, "Reuse of natural material for making light weight concrete," *International Journal for Research in Applied Science & Engineering Technology*, vol. 8, pp. 1-7, 2020. DOI: 10.22214/ijraset.2020.5266

[12] American Concrete Institute, ACI 318S-19: Building Code Requirements for Structural Concrete and Commentary, Michigan, 2019.

[13] M. Ahmad, B. Chen and S. Shah, "Investigate the influence of expanded clay aggregate and silica fume on the properties of lightweight concrete," *Construction and Building Materials*, vol. 220, pp. 253-266, 2019. DOI: 10.1016/j.conbuildmat.2019.05.171

[14] ASTM International, ASTM C1157/ C1157M-20: Standard performance and specification for hydraulic cement, West Conshohocken, PA, 2020.

[15] ASTM International, ASTM C136/ C136M-19: Standard test Method for Sieve Analysis of Fine and Coarse Aggregates, West Conshohocken, PA, 2019.

[16] ASTM International, ASTM C330/C330M-17: Standard Specification for Lightweight Aggregates for Structural Concrete, West Conshohocken, PA, 2017.

[17] American Concrete Institute, ACI 211.1-91: Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete, Michigan, 2002.

[18] ASTM International, ASTM C143 / C143M-15: Standard Test Method for Slump of Hydraulic - Cement Concrete, West Conshohocken, PA, 2015.

[19] ASTM International, ASTM C39 / C39M-20: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, West Conshohocken, PA, 2020.

[20] ASTM International, ASTM C642-13: Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, West Conshohocken, PA, 2013.

[21] Nordtest Method, NT BUILD 492: Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments., Espoo, 1999.

[22] J. Chai-Lee, P. Shafigh and S. Bahri, "Comparative study of mechanical properties for substitution of normal weight coarse aggregate with oil-palm-boiler clinker and lightweight expanded clay aggregate concretes," *Journal of Design and Built Environment*, vol. 19, no. 3, pp. 1-17, 2019. DOI: 10.22452/jdbe.vol19no3.7

[23] R. Wang, M. Ren, X. Gao and L. Qin, "Preparation and properties of fatty acids based thermal energy storage aggregate concrete," *Construction and Building Materials*, vol. 165, pp. 1-10, 20 March 2018. DOI: 0.1016/j.conbuildmat.2018.01.034

[24] A. Nahhab and A. Ketab, "Influence of content and maximum size of light expanded clay aggregate on the fresh, strength, and durability properties of self-compacting lightweight concrete reinforced with micro steel fibers," *Construction and Building Materials*, vol. 233, pp. 1-14, 2020. DOI: 10.1016/j.conbuildmat.2019.117922

[25] R. Vijayalakshmi and S. Ramanagopal, "Structural concrete using expanded clay aggregate: A review," *Indian Journal of Science and Technology*, vol. 11, pp. 1-12, April 2018. DOI: 10.17485/ijst/2018/v11i16/121888

[26] A. Ketab and A. Nahhab, "The performance of self-consolidating concretes with lightweight aggregates," *TEST Engineering & Management*, vol. 83, p. 14920–14932, 2020.

[27] S. Chung, M. Elrahman and D. Stephan, "Effect of Different Gradings of Lightweight Aggregates on the Properties of Concrete," *Applied Sciences*, vol. 7, pp. 1-15, 2017. DOI: 10.3390/app7060585

[28] H. Chen and C. Wu, "Influence of aggregate gradation on the engineering properties of lightweight aggregate concrete," Applied Sciences, vol. 8, pp. 1-11, 2018. DOI: 10.3390/app8081324

[29] K. Chia, "Workability and stability of Lightweight Aggregate concrete from rheology perspective (Thesis)," *National University of Singapore*, pp. 1-190, 2006.

[30] K. Heiza, F. Eid and T. Masoud, "Flexure behavior of light weight self compacting reinforced concrete slabs with light expanded clay aggregate (leca) exposed to high temperatures.," *Ninth Conference of Sustainable Environmental Development*, pp. 1-15, 2017.

[31] M. Abdeen and H. Hodhod, "Experimental investigation and development of artificial neural network model for the properties of locally produced light weight aggregate concrete," *Scientific Research*, vol. 2, pp. 408-419, 2010. DOI: 10.4236/eng.2010.26054

[32] P. Kumar and R. Pannem, "Packing density of self compacting concrete using normal and lightweight aggregates," *International Journal of Civil Engineering and Technology*, vol. 8, p. 1156–1166, 2017.

[33] S. Nawel, L. Mounir and H. Hedi, "Characterisation of lightweight concrete of Tunisian expanded clay: mechanical and durability study," *European Journal of Environmental and Civil Engineering*, vol. 21, pp. 670-695, 2016. DOI: 10.1080/19648189.2016.1150893

[34] T. Wu, H. Wei, X. Liu and G. Xing, "Factors influencing the mechanical properties of lightweight aggregate concrete," *Indian Journal of Engineering & Materials Sciences*, vol. 23, pp. 301-311, 2016.

[35] J.A. Bogas, A. Carriço and J. Pontes, "Influence of cracking on the capillary absorption and carbonation of structural lightweight aggregate concrete," *Cement and Concrete Composites*, vol. 104, pp. 1-11, 2019. DOI: 10.1016/j.cemconcomp.2019.103382

[36] X. Cong, S. Gong, D. Darwin and S. McCabe, "Role of silica fume in compressive strength of cement paste, mortar, and concrete.," *The University of Kansas Structural engineering and Materials laboratory*, Lawrence, 1990.

[37] M. Dilli, H. Atahan and C. Sengül, "A comparison of strength and elastic properties between conventional and lightweight structural concretes designed with expanded clay aggregates," *Construction and Building Materials*, vol. 101, pp. 260-267, 2015. DOI: 10.1016/j.conbuildmat.2015.10.080

[38] T. Sonia and R. Subashini, "Experimental investigation on mechanical properties of light weight concrete using leca.," *International Journal of Science and Research*, vol. 5, pp. 1511-1514, 2016.

[39] A. Paul and M. Lopez, "Assessing lightweight aggregate efficiency for maximizing internal curing performance.," *ACI Materials Journal*, vol. 108, no. 4, pp. 385-393, 2011.

[40] P. Kulkarni and A. Muthadhi, "Improving thermal and mechanical property of lightweight concrete using N-butyl stearate/expanded clay aggregate with alccofine1203," *International Journal of Engineering*, vol. 33, no. 10, pp. 1842-1851, 2020. DOI: 10.5829/IJE.2020.33.10A.03

[41] S. Sindhuja, K. Raman and P. Bhuvaneshwari, "A review on strength characteristics of GGBS based fiber-reinforced lightweight aggregate concrete," *Materials Science and Engineering*, vol. 872, pp. 1-9, 2020. DOI: 10.1088/1757-899X/872/1/012135

[42] A. Bhogayata, S. Dave and N. Arora, "Utilization of expanded clay aggregates in sustainable lightweight geopolymer concrete," *Journal of Material Cycles and Waste Management*, vol. 22, p. 1780–1792, 2020. DOI: 10.1007/s10163-020-01066-7

[43] R. Priyanga, L. Rajeshwari and V. Baskars, "Experimental investigation on mechanical properties of lightweight concrete using leca and steel scraps," *SSRG International Journal of Civil Engineering*, No. Special Issue, pp. 594-598, 2017.

[44] O. Ünal, T. Uygunoğlu and A. Yildiz, "Investigation of properties of low-strength lightweight concrete for thermal insulation," Building and Environment, vol. 42, no. 2, pp. 584-590, 2007. DOI: 10.1016/j.buildenv.2005.09.024

[45] A. Devecioglu and Y. Biçer, "The effects of tragacanth addition on the thermal and mechanical properties of lightweight concretes mixed with expanded clay," Periodica Polytechnica Civil Engineering, vol. 60, no. 1, pp. 45-50, 2016. DOI: 10.3311/PPci.7984

[46] M. Ibrahim, A. Ahmad, M. Barry, L. Alhems and A. Suhoothi, "Durability of structural lightweight concrete containing expanded perlite aggregate," *International Journal of Concrete Structures and Materials*, vol. 14, no. 50, pp. 1-15, 2020. DOI: 10.1186/s40069-020-00425-w

[47] E. Monahan, "Weight-credit foundation construction using artificial fills (with discussion and closure)," *Transportation Research Record*, no. 1422, pp. 1-6, 1993.

[48] M. Abdelfattah, I. Kocserha and R. Géber, "Effect of firing on mineral phases and properties of lightweight expanded clay aggregates," *MultiScience - XXXIII. microCAD International Multidisciplinary Scientific Conference*, pp. 1-9, 2019. DOI: 10.26649/musci.2019.080

[49] L. Ming, A. Sandu, H. Yong, Y. Tajunnisa, S. Azzahran, R. Bayuji, M. Abdullah, P. Vizureanu, K. Hussin, T. Jin and F. Loong, "Compressive strength and thermal conductivity of fly ash geopolymer concrete incorporated with lightweight aggregate,expanded clay aggregate and foaming agent," *Revista de Chimie*, vol. 70, no. 11, pp. 4021- 4028, 2019. DOI: 10.37358/RC.70.19.11.7695

[50] P. Pradeep, Beenamol and H. Nair, "Effect of pre-soaked light expanded clay aggregate on strength, durability and flexural behaviour of high-performance concrete," *Journal of Engineering Science and Technology*, vol. 14, no. 5, pp. 2629-2642, 2019.

[51] D. Jóźwiak-Niedźwiedzka, "Scaling resistance of high performance concretes containing a small portion of pre-wetted lightweight fine aggregate," *Cement and Concrete Composites*, vol. 27, no. 6, pp. 709-715, 2005. DOI: 10.1016/j.cemconcomp.2004.11.001

[52] P. Vosoughi, Improving engineering properties of cement-based materials by internal curing (thesis), *Ames: Iowa State University*, 2019, pp. 1-119.

[53] C. Muñoz-Ruiperez, A. Rodríguez, S. Gutiérrez-González and V. Calderón, "Lightweight masonry mortars made with expanded clay and recycled aggregates," *Construction and Building Materials*, vol. 118, pp. 139-145, 2016. DOI: 10.1016/j.conbuildmat.2016.05.065

[54] O. Kayali and B. Zhu, "Chloride induced reinforcement corrosion in lightweight aggregate high-strength fly ash concrete," *Construction and*

Building Materials, vol. 19, no. 4, pp. 327-336, 2005. DOI: 10.1016/j.conbuildmat.2004.07.003

[55] X. Liu, H. Du and M. Zhang, "A model to estimate the durability performance of both normal and lightweight concrete," Construction and Building Materials, vol. 80, pp. 255-261, 2015. DOI: 10.1016/j.conbuildmat.2014.11.033

[56] X. Liu and M. Zhang, "Permeability of high-performance concrete incorporating presoaked lightweight aggregates for internal curing," *Magazine of Concrete Research*, vol. 62, no. 2, pp. 79-89, 2015. DOI: 10.1680/macr.2008.62.2.79

[57] B. Masood, A. Elahi, S. Barbhuiya and B. Ali, "Mechanical and durability performance of recycled aggregate concrete incorporating low calcium bentonite," *Construction and Building Materials*, vol. 237, p. 117760, 2020. DOI: 10.1016/j.conbuildmat.2019.117760

[58] K. Chia and M. Zhang, "Water permeability and chloride penetrability of high-strength lightweight aggregate concrete," *Cement and concrete research*, vol. 32, no. 4, pp. 639-645, 2002. DOI: 10.1016/S0008-8846(01)00738-4

[59] D. Bentz, "Influence of internal curing using lightweight aggregates on interfacial transition zone percolation and chloride ingress in mortars," *Cement & Concrete Composites*, vol. 31, no. 5, pp. 285-289, 2009.

[60] H. Arabani, A. Sadrmomtazi, M. Mirgozar Langaroudi, R. Kohani Khoshkbijari and M. Amooie, "Durability of self-compacting lightweight aggregate concretes (LWSCC) as repair overlays," *Journal of Rehabilitation in Civil Engineering*, vol. 5, no. 2, pp. 101-113, 2017. DOI: 10.22075/JRCE.2017.11415.1187

[61] X. Liu, K. Chia and M. Zhang, "Water absorption, permeability, and resistance to chloride-ion penetration of lightweight aggregate concrete," *Construction and Building Materials*, vol. 25, no. 1, pp. 335-343, 2011. DOI: 10.1016/j.conbuildmat.2010.06.020

[62] X. Liu, K. Chia, M. Zhang and R. Liew, "Water and chloride ion penetration resistance of high-strength ultra lightweight cement composite," *Proceedings of the 1st International Congress on Durability of Concrete*, pp. 1-9, 2012.

Camilo Higuera-Flórez received the degree of Civil Engineering in 2012 from Universidad Nacional de Colombia, Bogotá, and Master in Structural Engineering in 2017 from Universidad Nacional de Colombia, Bogotá. He is currently professor and researcher in the Faculty of Engineering at Universidad Catolica de Colombia.
ORCID: https://orcid.org/0000-0002-1952-7983

Jhon Cárdenas-Pulido received the degree of Civil Engineering in 2013 from the Universidad Militar Nueva Granada, UMNG, Colombia, and Master in Civil Engineering (area of structures and earthquakes) in 2017 from Universidad de los Andes, Colombia. He is currently professor and researcher in the Faculty of Engineering at Universidad Catolica de Colombia.
ORCID: https://orcid.org/0000-0003-4698-4896

CPT Adriana Vargas Aguilar is officer of the Administrative Corp of the National Army, in the rank of captain, Civil Engineer from Universidad Santo Tomas, and Specialist in Civil Engineering with emphasis on Structural Engineering from Escuela Colombiana de Ingeniería Julio Garavito. She has extensive experience in tasks related to the planning, design, execution, and management of infrastructure projects, and is empowered to carry out research work based on the formulation of hypotheses and the elaboration of analytical frameworks and application of models.
ORCID: https://orcid.org/0000-0002-7404-6875