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Experimental Evaluation of Workability Compressive Strength and Freeze-Thaw Durability of Concrete Containing Expanded Clay Aggregates

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Abstract – The development of the building materials industry in Algeria and worldwide has opened up new commercial opportunities for waste recovery. Using recycled materials and natural resources such as expanded clay aggregates are increasingly seen as a solution for the future to meet the gap between production, consumption, and environmental protection. The present study investigates the effect of expanded clay aggregate (ECA) on a concrete slump, porosity, softening coefficient, compressive strength, and Freeze-thaw durability. Tests were conducted according to Russian National State Standard (GOST) 10060-2012 of concrete mixtures with expanded clay aggregate (ECA). A total of 7 mixtures were prepared. One is considered a reference mixture based on limestone aggregates. The other six mixtures were prepared by replacing the limestone aggregates with expanded clay aggregates, using two substitution rates (15%, 30% by weight) and three aggregates sizes (Sand 0/4, Gravel 8/16, and 16/25) while maintaining the same w/b ratio. The results indicate that ECAs can be used for concrete production. Furthermore, concrete containing 30% ECA (0/4) has the best properties and is the most freeze-thaw resistant than the other mixtures with ECA.

Keywords: Expanded clay aggregates, softening coefficient, compressive strength, Freeze-thaw durability.

Introduction

Recycling and reusing materials are predominant concerns in all major industries. In the construction and engineering sectors, great importance is given to how waste, recovered materials, and natural resources can provide high-performance cementitious materials. One of the extremely promising natural resources for the future is expanded clay aggregates (ECA). ECAs are manufactured after shaping by pelletizing, heating, and firing the clay without or with some lime at 1100-1300°C in a rotary kiln. The clay expands (or swells) to about five to six times its original size and takes the shape of dark brown or reddish-brown pellets, which have different sizes (from 0.1 to 25 mm) (Rashad, 2018; Vijayalakshmi and Ramanagopal, 2018).

Currently, the ECA is used in various sectors such as agriculture and construction, which use ECA to produce lightweight brick and blocks or lightweight concrete. Several studies were carried out to understand the properties of fresh and hardened concrete containing ECA. Researchers (Rashad, 2018; Yew *et al.*, 2020; Ahmad *et al.*, 2019; Rumsys *et al.,* 2018; Bogas *et al.,* 2012) demonstrated that the use of ACE increases workability and the optimal substitution rate is 70% of ACE reported by Yew *et al.* (Yew et al., 2020). Other authors (Rashad, 2018; Yew *et al.,* 2020; Ahmad and Chen, 2019; Hubertova *and* Hela, 2013) reported that increasing the substitution rate of ECA decreases the compressive strength of concrete by up to 20%. It was also reported (Yew *et al.*, 2020; Bogas *et al.*, 2012; Chidighikaobi, 2019; Dabbaghi *et al.*, 2021; Dilli *et al.*, 2015; Nahhab and Ketab, 2020) that the use of ECA decreases flexural strength, splitting tensile strength and modulus of elasticity which generate more brittle behavior compared to conventional concrete. Research by Yew *et al.* (2020) and Nahhab and Ketab (2020) suggested that a clay aggregate substitution rate of 60-70% is considered optimal with a maximum size of 10 mm.

On the other hand, several studies (Rashad, 2018; Yew *et al.*, 2020; Everhart, *et al.*, 1958; Lee *et al.*,2019) showed that concrete with ECA has a lower density, which allows to have lighter and smaller structural elements with greater durability to seismic loads. Research by Rashad (2018), Ahmad *et al.* (2019) Bogas *et al.* (2012) Nahhab and Ketab (2020), Bogas *et al.* (2015), and Nepomuceno (2018) indicated that increasing the ECA content affects the sorption coefficient, porosity, and generates separation between aggregates and mortar compared to conventional concrete. The authors of Rashad (2018), Ismail and Halim (2020), Uglyanitsa *et al.* (2015) reported that open and closed pores of ECA have an advantage in the formation of bonds between aggregates and cement paste. The open and closed pores of ECA, also, contribute to improving the properties of concrete against chloride penetration and reinforcement corrosion. Other authors, i.e., Chidighikaobi (2019), Dabbaghi *et al.,* (2021), Ismail *and* Halim (2020), and Uglyanitsa *et al.,* (2015), demonstrated that mixtures with ECA have higher thermal insulation and less affected than ordinary concrete after exposure to high temperatures or after cooling, which is favorable to improving the energy consumption of buildings. Several studies (Nahhab *and* Ketab, 2020; Nepomuceno, 2018; Ismail and Halim, 2020; Muñoz *et al.,* 2018) found that the properties of mortars and concretes containing ECA depend on the size and shape of aggregate. The use of ECAs with different quantities and combinations in the production of concrete is possible and represents a potential alternative to conventional concrete (Rumsys *et al.,* 2018; Bogas *et al.,* 2012; Bogas *et al.,* 2012; Hubertova *and* Hela, 2013; Lee *et al.*,2019; Hammer *et al.,* 2000). However, few studies focused on the effect of expanded clay aggregate size on concretes and the resistance of this concrete to freeze-thaw cycles.

The present study evaluates the impact of limestone aggregates partial substitution by expanded clay aggregates, using two substitution rates (15%, 30% by weight) and three aggregates sizes (Sand 0/4, Gravel 8/16 and 16/25), on a concrete slump, porosity, softening coefficient, compressive strength, and especially freeze-thaw durability.

Materials

Cement

In this study, a Portland cement CEM II/42.5 was used. The chemical and physical characteristics of cement are presented in Table 1. The cement potential mineralogical composition was calculated according to the empirical formula of Bogue (Bogue, 1955).

Water

This study used tap water that complied with the requirements of the NFP 18-404 standard. The chemical composition is presented in Table 2.

Table 1. Chemical and physical characteristics of Portland cement CEM II 42.5

Chemical composition						Bogue composition			
SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	C_3S	C_2S	C_3A	C_4AF
27.83	6.21	3.12	57.22	2.02	0.94	56.6	22.98	9.87	8.25

Insoluble residue = 2.28%
Loss on ignition = 2.41%
Fineness = 3891 cm^2/g
Specific density = 3100 kg/m^3

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Table 2. Chemical composition of water

concentration in water (mg/l)	
Insoluble residue	neglected
Dissolved salts	1469
Sulfates (SO_4^{-2})	411.68
chlorides (Cl^-)	299.01
pH	7.8
Calcium (Ca^{+2})	36
Magnesium (Mg^{+2})	60
Bicarbonates (HCO_3^{-})	26
Carbonates (CO_3^{-2})	3.4

Table 3. Chemical and physical properties of sand

Chemical composition								
SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	K_2O	TiO_2	Na_2O
0.05	0.03	0.02	56.03	0	0.19	0.03	0.008	0.06
Loss on ignition = 43%								
Specific density = 2530 kg/m^3								
Apparent density = 1780 kg/m^3								
Sand equivalent = 64.6%								
Fines content = 14%								
Fineness modulus = 2.8								

Crushed Sand

A 0/5 mm crushed sand was used. Its chemical and physical properties are presented in Table 3. The properties of crushed sand were measured according to NF P18-553, NF P18-555, NF P18-560, NF P18-597, and NF P18-598 standards. The sand grading curve is given in Figure 1.

Gravel

Two fractions of 8/16 mm and 16/25 mm with an apparent density of 1564 kg/m^3, a specific density of 2560 kg/m^{3,} and Los Angeles coefficient of 26.84% (hard) were used. The properties were measured using NF P18-560, NF P18-554, and NF P18-573 standards, respectively. The coarse aggregate grading curves are given in Figure 1.

Expanded clay aggregate

The used expanded-clay aggregate was obtained from the Bouinan factory of Blida – Algeria, by expanding natural clay in a rotating drum at a temperature of approximately 1200 C°. The chemical composition, physical properties, and grading curve of ECA are presented in Tables 4, 5, and Figure 2. The results show a high content of SiO2 and Al2O3, which exceeds 59% and 18%, respectively.

Table 4. Chemical composition of Expanded clay aggregate (%)

SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Cl	Na_2O	H_2O	MgCo3 +CaCo3
59.37	18.44	7.98	0.74	0	0	0	0.02	4.21
Loss on ignition = 3.11 %								

Table 5. Physical properties of Expanded clay aggregate

	Water absorption (%)	Apparent density (kg/m^3)	Specific density (kg/m^3)
ECA (0/4)	8.78	1030	1922
ECA (8/16)	8.35	564	932
ECA (16/25)	7.30	489	812

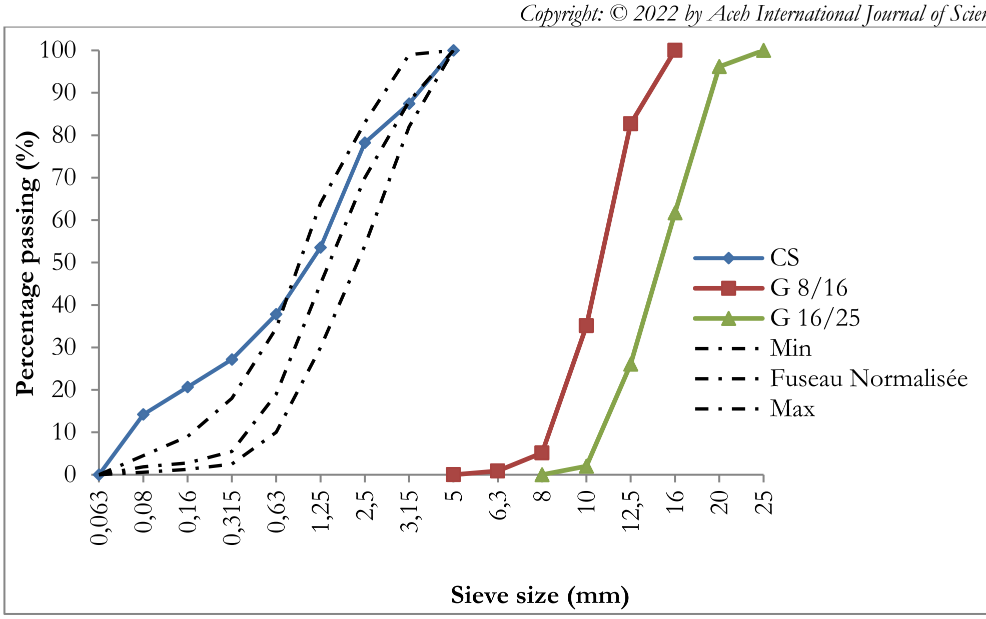

Figure 1. Grading curves of gravel and crushed sand compared with the normalized curve

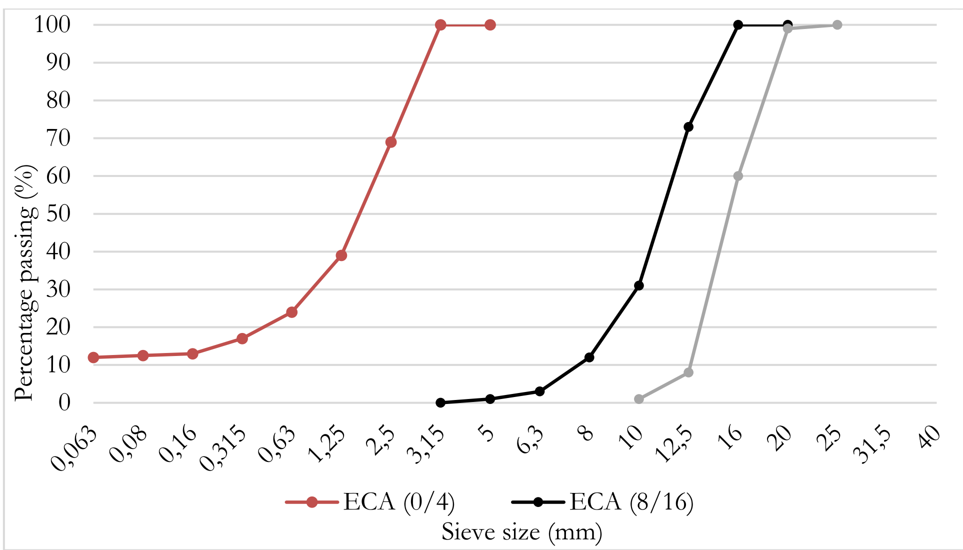

Figure 2. Grading curves of Expanded clay aggregates (0/4 mm, 8/16 mm, and 16/25 mm)

Mix proportions

The Dreux-Gorisse method (Dreux and Festa, 1998) was used. A total of 7 mixtures were prepared. One is considered as a reference mixture based on limestone aggregates, while the other six mixtures were prepared by replacing the limestone aggregates with expanded clay aggregates, using two substitution rates (15%, 30% by weight) and three aggregates sizes (Sand 0/4, Gravel 8/16 and 16/25), while maintaining the same w/b ratio. The details of concrete mixtures are given in Table 6.

In this study, a concrete slump test was performed according to standard NF P 18-451, and the porosity test was carried out according to standard NF P 18-459. For each mixture, cylindrical specimens (10x20)cm^2 were used to determine the porosity, softening coefficient, compressive strength, and Freeze-thaw durability.

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After demolding, the specimens were kept in water until testing. At 28 days, the compressive strength test was performed according to NF P 18-406 standard. The freeze and thaw test was performed according to the Russian National State Standard (*GOST 10060*, 2012). After 28 days of curing, the specimens were subjected to 50 freeze and thaw cycles in a Controls Group 10-D1429/A climatic chamber where temperatures ranged from −15 °C to 15 °C with a constant speed and a number of 3 cycles per day for all mixtures. The compressive strength was recorded before and after the 50 cycles.

Table 6. Compositions of concretes in 1m^3

Compositions	Concrete abbreviation	W/C ratio	Cement (kg/m^3)	Water (l/m^3)	S 0/4 (kg/m^3)	G1 8/16 (kg/m^3)	G2 16/25 (kg/m^3)	ECA 1 8/16 (kg/m^3)	ECA 2 16/25 (kg/m^3)	ECA 3 0/4 (kg/m^3)
Concretes without ECA	B1	0.6	350	212.1	630	585.5	511.5	/	/	/
Concretes with 15 % ECA (8/16)	B2	0.6	350	212.1	630	497.7	511.5	87.8	/	/
Concretes with 30 % ECA (8/16)	B3	0.6	350	212.1	630	409.9	511.5	175.7	/	/
Concretes with 15 % ECA (16/25)	B4	0.6	350	212.1	630	585.5	434.8	/	76.7	/
Concretes with 30 % ECA (16/25)	B5	0.6	350	212.1	630	585.5	358.05	/	153.45	/
Concretes with 15 % ECA (0/4)	B6	0.6	350	212.1	535.5	585.5	511.5	/	/	94.5
Concretes with 30 % ECA (0/4)	B7	0.6	350	212.1	441	585.5	511.5	/	/	189

Results

Concrete slump

The obtained slump test results are shown in Figure 3. The results shown in Figure 3 indicate that the best concrete slump value was obtained with B7 mixture (70% S + 30% ECA 3 + 100% G1 + 100% G2). This is because the use of 30% ECA (0/4) in concrete results in an increase in workability (100%), which changes the concrete from firm to plastic concrete. Moreover, the substitution by 30% ECA (0/4, 8/16, 16/25) in the concretes increased the workability compared to 15% ECA (0/4, 8/16, 16/25). This increase is approximately 5% for mixtures B2 and B3, 20% for mixtures B4 and B5, and 5% for mixtures B6 and B7.

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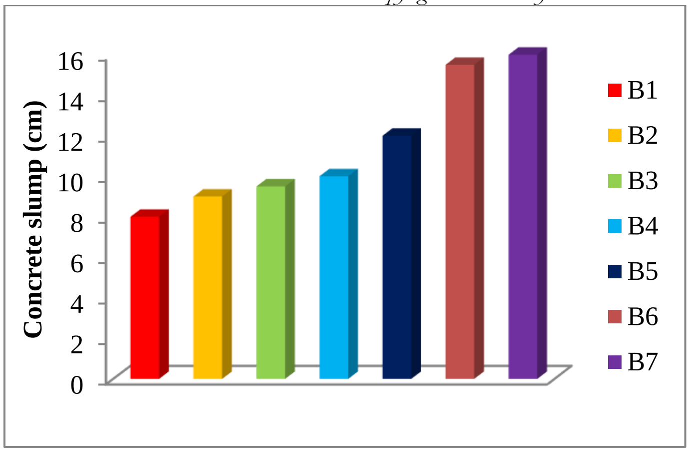

Figure 3. Slump test results of concrete without and with expanded clay aggregates. B1 (100% S+100%G1+100%G2); B2 (100%S+ 85%G1+15% ECA 1+ 100%G2); B3 (100%S+ 70%G1+30% ECA 1+100%G2); B4 (100%S+ 100%G1 + 85%G2+15% ECA 2); B5 (100%S+ 100%G1 +70%G2+30% ECA 2); B6 (85%S+ 15% ECA 3 + 100%G1 + 100%G2); B7 (70%S+ 30% ECA 3 + 100%G1 + 100%G2)

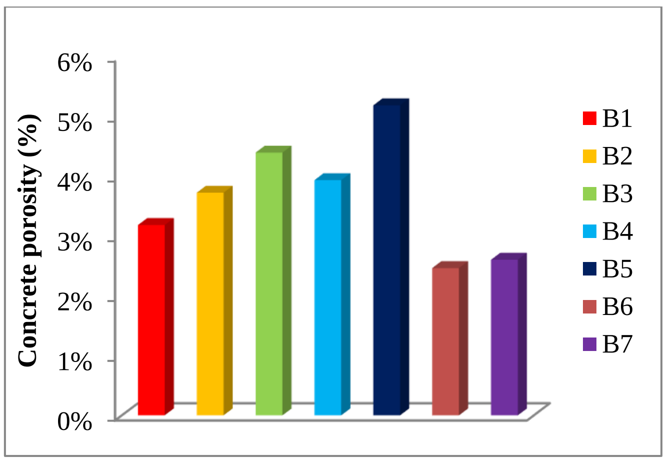

Figure 4. Concrete porosity of mixtures without and with expanded clay aggregates. B1 (100% S+100%G1+100%G2); B2 (100%S+ 85%G1+15% ECA 1+ 100%G2); B3 (100%S+ 70%G1+30% ECA 1+100%G2); B4 (100%S+ 100%G1 + 85%G2+15% ECA 2); B5 (100%S+ 100%G1 +70%G2+30% ECA 2); B6 (85%S+ 15% ECA 3 + 100%G1 + 100%G2); B7 (70%S+ 30% ECA 3 + 100%G1 + 100%G2)

Concrete porosity

The obtained results are shown in Figure 4. The results illustrated in Figure 4 indicate that the use of ECA increases the porosity rate in B2, B3, B4, and B5 mixtures. This increase was about 62 % for concrete with 30 % ECA 8/16 and 16/25 (B3 , B5). On the other hand, B6 and B7 concrete with 15% and 30% ECA (0/4), respectively, have a better performance than the other concretes. The decrease of the porosity rate for B6 concrete with 15 % ECA (0/4) was 22%, and 19% for B7 concrete with 30 % ECA (0/4).

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Softening coefficient

The softening coefficient is the ratio between the compressive strength of saturated material and the compressive strength of dry material. The obtained results are shown in Figure 5. The results given in Figure 5 indicate that the softening coefficient decreases with an increasing ECA substitution rate. This decrease is greater for concretes B3 and B5 (29,83 % for B3 and 19,35 % for B5). On the other hand, there was a slight increase in Softening coefficient (up to 4%) for B6 and B7 concrete (15% and 30 % of ECA 0/4).

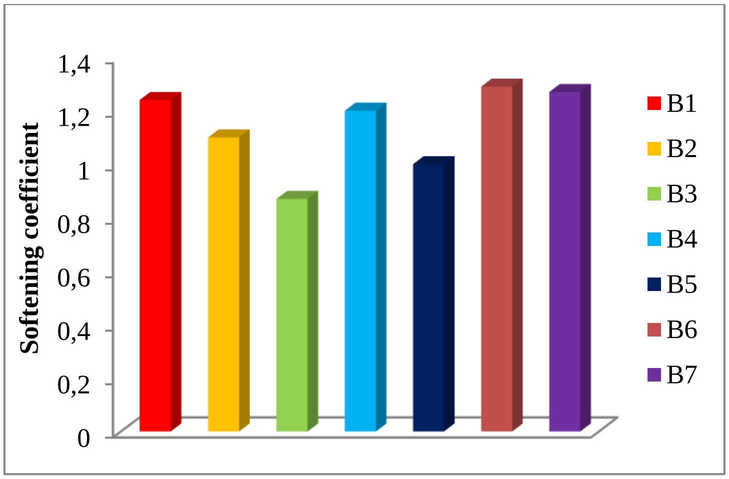

Figure 5. Softening coefficient of mixtures without and with expanded clay aggregates. B1 (100% S+100%G1+100%G2); B2 (100%S+ 85%G1+15% ECA 1+ 100%G2); B3 (100%S+ 70%G1+30% ECA 1+100%G2); B4 (100%S+ 100%G1 + 85%G2+15% ECA 2); B5 (100%S+ 100%G1 +70%G2+30% ECA 2); B6 (85%S+ 15% ECA 3 + 100%G1 + 100%G2); B7 (70%S+ 30% ECA 3 + 100%G1 + 100%G2)

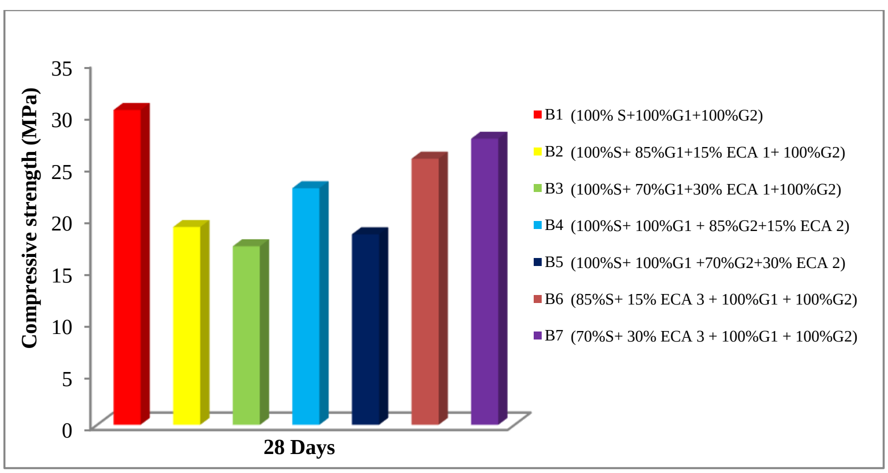

Figure 6. Compressive strength of concretes without and with expanded clay aggregates. B1 (100% S+100%G1+100%G2); B2 (100%S+ 85%G1+15% ECA 1+ 100%G2); B3 (100%S+ 70%G1+30% ECA 1+100%G2); B4 (100%S+ 100%G1 + 85%G2+15% ECA 2); B5 (100%S+ 100%G1 +70%G2+30% ECA 2); B6 (85%S+ 15% ECA 3 + 100%G1 + 100%G2); B7 (70%S+ 30% ECA 3 + 100%G1 + 100%G2)

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Compressive strength

The obtained results are illustrated in Figure 6. The experimental results in Figure 6 indicate that at 28 days, the use of ECA decreases the compressive strength of all concretes. This decrease is approximately 9.11% for B7, 43.28% for B3, and 39.47% for B5. Thus, for a substitution rate of 30% of ECA, there is a greater reduction in compressive strength for concretes containing clay aggregates of size (8/16) and (16/25) compared to that of clay sand (0/4).

Compressive Strength after Freeze-Thaw Cycling

The obtained results are illustrated in Figure 7. The results in Figure 7 clearly demonstrate an increase in the compressive strength of the concretes after exposure to 50 cycles of freezing and thawing. The increase is higher for B3 compared to B7 by a percentage of 27.6% and 6.76, respectively. This increase in the compressive strength of concrete was 11.5% for B1, 9.94% for B2, 27.6% for B3, 9.40% for B4, 5.05% for B6, and 6.76% for B7. This increase was particularly strong with B3 (100%S+ 70%G1+30% ECA 1+100%G2).

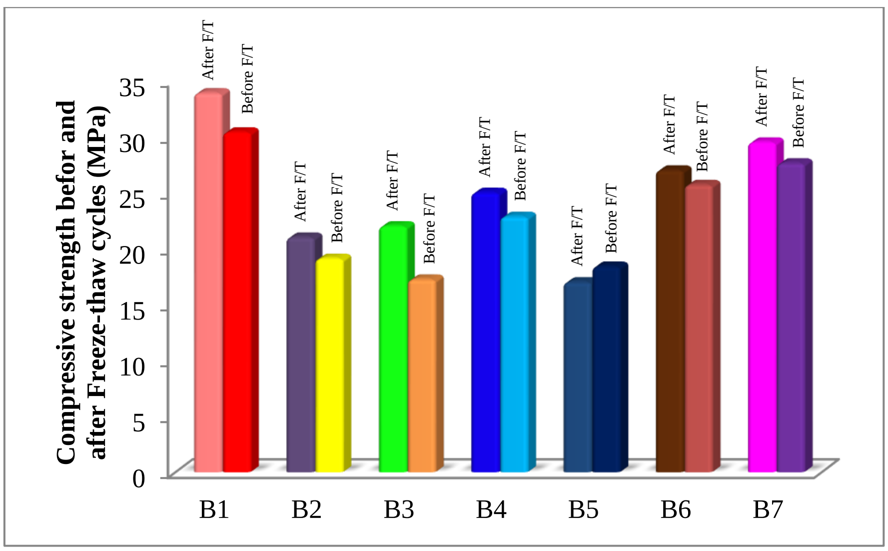

Figure 7. Compressive strength of concrete mixtures without and with ECA before and after freeze-thaw cycles. B1 (100% S+100%G1+100%G2); B2 (100%S+ 85%G1+15% ECA 1+ 100%G2); B3 (100%S+ 70%G1+30% ECA 1+100%G2); B4 (100%S+ 100%G1 + 85%G2+15% ECA 2); B5 (100%S+ 100%G1 +70%G2+30% ECA 2); B6 (85%S+ 15% ECA 3 + 100%G1 + 100%G2); B7 (70%S+ 30% ECA 3 + 100%G1 + 100%G2)

Discussion

As shown in Figure 3, the concrete slump is affected by the grain size (0/4, 8/16, 16/25) and the expanded clay aggregates substitution rate. On the other hand, the concrete porosity results (Figure 4) confirm the findings of Everhart *et al.* (1958) concerning the fact that concrete can be porous without altering its porosity because the pores are not connected to each other and do not constitute a threat to the porosity of concrete. Furthermore, the replacement of limestone aggregates by ECA aggregates increases the porosity especially when the replacement rate and size are increased, while the replacement of limestone sand with ECA sand reduces the porosity. Indeed, these results were confirmed with the softening coefficient (Figure 5) results because concretes with a substitution rate of 30% ECA and a grain size of (8/16) or (16/25) are less resistant to water than other concretes.

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Regarding the experimental results of the compressive strength in Figure 6, it can be seen that concretes with clay aggregates size (8/16) and (16/25) are less resistant and more porous than concretes containing clay sand (0/4) which confirms the results of porosity and softening coefficient. Finally, the results of compressive strength after freeze-thaw cycling (Figure 7) demonstrate that the high porosity of the concretes, based on 8/16 and 16/25, could explain the increase in compressive strength of concrete. During freezing cycles, the ice formation does not create an internal pressure on concrete, which ensures good durability to freeze-thaw cycles. This confirms the results of (Everhart *et al.,* 1958) concerning concrete porosity. The ECA can be porous without altering the concrete porosity because the pores of the materials are not connected to each other and do not pose a threat to concrete porosity. On the other hand, the pore size ECA (0/4) mm, being smaller than ECA (8/16) and ECA (16/25), freezes after the larger pores, so the stress expansion appears later (Muñoz *et al.,*2018).

Conclusions

The use of ECA improves concrete workability. The improvement depends on the substitution rate and size of ECAs. The best performance was obtained with B7 concrete with 30% ECA 0/4 mm and a W/C ratio = 0.6. The concrete porosity is affected by ECA's substitution rate and size. Concretes B6 and B7 with 15 % and 30% ECA (0/4) mm have better performance because when the substitution rate and size of ECA increase, the rate of concrete porosity increases as well. The Softening coefficient of concrete is affected by the substitution rate and size of ECA and confirms the results of porosity and concrete slump. The best performances were always obtained with B6, and B7 concretes. The use of ECA decreases the compressive strength and concrete with 30 % ECA (0/4) mm had a minor decrease of 9% compared to other concretes. The freeze-thaw resistance of concrete with ECA is affected by ECA's substitution rate and size. Concrete with 30 % ECA (0/4) mm had a slight decrease of 13.5% in comparison to control concrete. Therefore, it is possible to use ECA in concrete. The recommended combination uses expanded clay aggregates of size 0/4 mm with a substitution rate of 30%.

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