Jordan Journal of Civil Engineering, Volume **16**, No. **2, 2022**

Effect of Recycled Waste Glass Addition on the Resistance of High Performance Concrete to Freeze-Thaw Cycles

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ABSTRACT

Glass is considered among the most environmental recycled wastes. One of its important contributions is concrete production as an echo-friendly concrete. This research focuses on the effects of particle size and content of recycled glass powder on durability with respect to resistance to freezing and thawing of high-performance concrete. White waste glass bottles, finely crushed, are used as a partial replacement for fine aggregate with various proportions (15%, 20%, 25% and 30%) and two particle sizes of waste glass powder were selected for each replacement ratio including size ranges of 0–315µm (HPCGA) and 0.315–1.25mm (HPCGB). Specimens with silica fume have been made for comparison. This study aims to determine the level of waste glass powder replacement resulting in optimal resistance to freeze-thaw. Experimental tests deal with the exposure of specimens to periodic freezing and thawing. Sets have been tested focusing on the measurement of relative dynamic modulus, change in mass and compressive strength at 7, 28 and 90 days. Up to 30% waste glass content and particle size less than 300 µm seem fairly satisfactory compared with silica fume. The durability factor was 98%, indicating good freeze- thaw resistance.

KEYWORDS: Waste glass powder, Durability factor, Freeze-thaw, Silica fume, High-performance concrete, Relative dynamic modulus of elasticity.

INTRODUCTION

Growing need for urbanization in Algeria generated high consumption of materials, which clearly raises questions about the national availability of these materials. The excessive extraction of sand along the coastline is a serious source of threat causing various problems, in particular depletion of natural resources and groundwater pollution. It was therefore necessary to look for other resources of construction materials from recycled waste that have less impact on the environment. Glass is considered among the most environmental recycled wastes; its uses save much energy and one of its important contributions is concrete production as an echo-friendly concrete. The use of crushed glass is relatively recent; a review of earlier research shows that waste glass can be used in concrete as glass powder (GP) or as a replacement for fine aggregate (GSA).

Recent research has been carried out by considering optimal and rational use of recycled waste, showing that glass powder (GP) can be used as a pozzolanic material in similar concrete in amounts of by-product admixtures (25% and 50%), where it improves durability by reducing pore size and porosity (Soliman, 2016; Premalatha and Srinivasan, 2019), while previous research (Zainab et al., 2009; Serpa et al., 2013; Ramdani et al., 2018) has concluded that by up to 20% of incorporation of waste glass in cement mixtures with non-reactive aggregates, expansion can be reduced by 66%; on the other hand, several other studies have been conducted by using waste glass as a replacement for aggregate showing a strong reaction between reactive silica in glass and alkali in cement (Almesfer and Jason Ingham, 2014; Ibrahim, 2017; Kılıçoğlu and Çoruh,

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Received on 5/7/2021.
Accepted for Publication on 22/1/2022.

2017; Marcin et al., 2020). In order to fight efficiently, or at least reduce an Alkali Siliceous Reaction (ASR), Gagne and Pigeon (2003) suggested adding some supplementary cementitious materials properly dosed, as silica fume and fly ash, that are commonly used to reduce ASR expansions. The findings from Guojun et al. (2018) showed that waste glass with particle size less than 315 µm used as fine aggregate can be incorporated into concrete up to 30% partial replacement of sand; it would improve durability and eventually exhibit a certain mitigation effect on ASR expansion. In contrast, Maraghechi et al. (2014) and You et al. (2016) suggested that crushed glass with particle size more than 315 µm used as an aggregate is susceptible to ASR expansion in concrete, because the amorphous silica in glass is dissolved under alkali attack to form ASR gel.

As mentioned above, research has been carried out on considering optimal use of recycled waste concluding that waste glass could be used as a replacement for fine aggregate or, as glass powder, as a pozzolanic material in ordinary concrete (OC), but the utilization of waste glass powder in high-performance concrete (HPC) has not been completely explored yet. Very little information is available on the effect of recycled waste glass addition as a partial replacement for fine aggregate on the freeze-thaw resistance of high-performance concrete, although a few investigations on bulk density, flexural strength and compressive strength have been reported (Mariakováa et al., 2019).

This study focuses on the effect of finely crushed waste glass as partial replacement for sand on the freeze-thaw resistance of high-performance concrete with the aim to determine the level of waste glass powder replacement resulting in optimal resistance to freeze-thaw. Experimental tests were conducted on measuring the relative dynamic modulus of elasticity (RDME), the change in mass and compressive strength for high-performance concrete.

MATERIALS AND METHODS

Materials

In this experimentation, local materials have been carefully selected to make consistent high-performance concretes. An artificial Portland Cement CEM I 52 in accordance with European standard EN 197-1[EN 197-1, 2001] is used and two types of local gravel are used for adequate graduation of concrete mixtures, having a limestone content varying between 41 and 61%; namely, 3/8 and 8/15 granular class gravel with a bulk density respectively of 1.86t/m^3 and 2.07t/m^3. As fine aggregate, local natural 0/5 mm sand with a specific gravity of 2.72 is used. The mineral admixture used is an air-entraining agent (AE) MICROAIR 111 and a commercial superplasticizer (SP) (MEDA-PLAST-SP40) in accordance with European standard NF EN 934-2 [AFNOR NF EN 934-2, 2005] was also used. Silica fume had been used as mineral additive for concrete mixtures in accordance with European standard NF EN 934-2 [AFNOR NF EN 13263-1, 2005]. Concrete mixtures were made with tap water. White glass bottles were crushed by an electric mill for 40 minutes to generate waste glass powder. Then, the particles were selected in two size fractions including size range of 0-315µm (HPCGA) and 0.315–1.25mm (HPCGB). Fractions in excess of 1.25mm have been discarded in order to avoid excessive ASR.

Table 1 and Table 2 show chemical analysis and physical characteristics of materials used in this investigation. Size distribution of fine aggregate is presented on Table 3 and particle size distribution curve for fine and coarse aggregates is shown in Figure 1.

Table 1. Chemical analysis

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	CO_2
Cement	22.30	4.84	2.63	66.2	0.83	1.63	0.18	0.19	1.30
Glass Powder	72.8	1.53	0.42	11.03	2.38	0.13	0.49	12.89	/
Silica Fume	96.0	0.9	0.6	1.6	0.2	0.45	0.9	0.2	/

Table 2. Physical characteristics

Characteristics	Materials							
	CA		RS	SF	GP	AE	SP	Cement
Density	3/8	8/15	2.72	2.2	1.6	1.084	1.05	3.10
	1.86	2.07						

Table 3. Size distribution of sand and waste glass powder

Size Fractions	0.08 µm	0.16 µm	0.315 µm	0.63 µm	1.25 mm	2.5 mm	4 mm	5 mm	6.3mm
Sand	0	2.15	19.57	34.25	52.64	75.84	87.64	94.87	100
Glass Powder	1.6	15.3	21.2	45.2	54.2	100	100	100	100

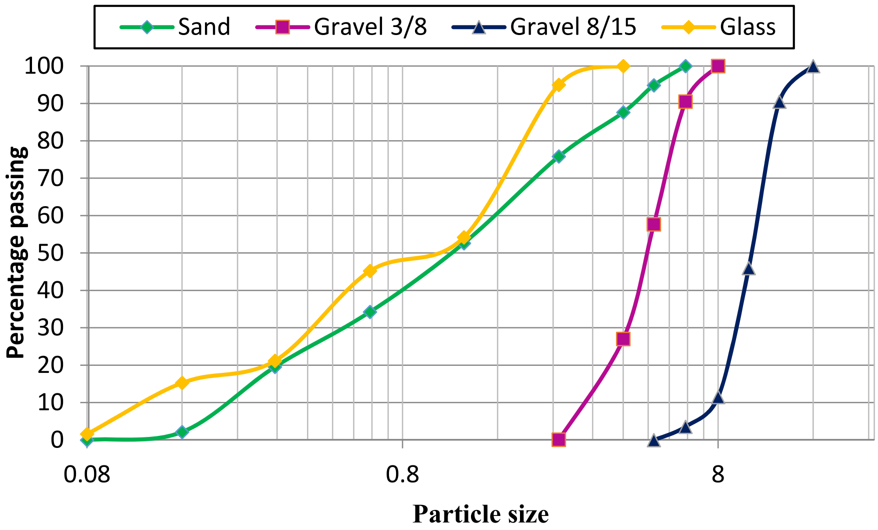

Figure (1): Particle size distribution curves for fine and coarse aggregates

Mix Design

A total of 10 sets of 10 x 10 x 40 cm prismatic specimens were used for the experimental analysis. Natural sand was partially replaced by waste glass powder at percentages of 15, 20, 25 and 30% and for each replacement ration, two particle sizes of WGP were adopted including size ranges of 0–315µm labeled [(HPCGA15), (HPCGA20), (HPCGA25) (HPCGA30)] and 0.315–1.25mm labeled [(HPCGB15), (HPCGB20), (HPCGB25) (HPCGB30)]. The control concrete mix (HPCC) includes cement (450kg/m^3), 3/8 granular class gravel, 8/15 granular, 0/5 natural sand as fine aggregate and water. Specimens with silica fume (HPCF) substitution of 10 % were also made for comparison.

A constant W/C = 0.30 had been used for all mixes; slump was adjusted by incorporating a superplasticizer and to obtain the appropriate air content, an air entraining agent was incorporated into all mixes; mixtures of concrete were prepared according to the grout formulation method.

The characteristics of fresh concrete using standard procedures; slump [NFEN 12350-2 1999], air content [NF P 18-353, 1985] and density [NF EN 12350-6 1999] were also measured. Table 4 shows mix proportions and properties of fresh HPC.

Table 4. Mix proportions and properties of fresh HPC

Specimen		**HPCC**	**HPCCF**	**HPCGA15**	**HPCGB15**	**HPCGA20**	**HPCGB20**	**HPCGA25**	**HPCGB25**	**HPCGA30**	**HPCGB30**
Cement		450	500	500	500	500	500	500	500	500	500
Coarce agregate (kg/m^3)		1186	1162	1165	1165	1178	1178	1186	1185	1175	1167
Sand (kg/m^3)		532	532	452	452	427	427	400	400	375	375
Power glass (kg/m^3)	15 (%)	/	/	80	80	/	/	/	/	/	/
	20 (%)	/	/	/	/	105	105	/	/	/	/
	25 (%)	/	/	/	/	/	/	133	133	/	/
	30 (%)	/	/	/	/	/	/	/	/	160	160
Silica Fume (kg/m^3)		/	22.4	/	/	/	/	/	/	/	/
W+AE (L/m^3)		145	145	148	147	144	143.6	145	144.6	145.7	147
Superplasticizer		8.25	10.25	9.85	9.82	8.96	8.95	8.5	8.5	8.4	8.6
W/C		0.32	0.29	0.29	0.3	0.31	0.3	0.32	0.3	0.3	0.3
Properties of fresh concrete	Density (kg/m^3)	2322	2372	2341	2354	2363	2363	2361	2361	2355	2346
	Air content (%)	2.3	2.2	2	2.1	2.1	2.3	2.3	2.4	2.3	2.5
	Slump (cm)	18	17	22	23	20	20	18	19	17	19

Testing Methods

Freeze-Thaw Test

At intervals of every 50 cycles up to 300, concrete mixes were exposed to periodic freezing and thawing in accordance with European standard [NF P 18-424]. Tests consisted of measuring change in mass and the Relative Dynamic Modulus of Elasticity (RDME) in accordance with European standard [NF P 18-414]. Before cycling (0 freeze-thaw cycles), specimens were immersed in water to cure for 28 days in accordance with European standard [NF P 18-424]. Also, dimensions, pulse velocity and mass of each specimen were recorded. Concrete specimens were subjected to freeze-thaw cycles at the same time and the temperature of the specimen had been alternately lowered from 9°C±3°C to -18°C ±2°C in 45 mins and raised from -18°C ±2°C to 9°C±3°C in 5 hrs and specimens were tested at 50- cycle intervals. At the same time, standard 100x 200mm cylindrical specimens were cast with each mix to determine compressive strength in accordance with European standard [NF EN 12390-3].

Relative Dynamic Modulus of Elasticity

Dynamic modulus of elasticity (E_{dyn}) is obtained by using the ultrasonic method. Ten sets of concrete 10 x10 x 40 cm prisms were prepared for measuring pulse velocity according to [NF P 18-418]. The dynamic modulus of elasticity (E_{dyn}) was calculated from the measured ultrasonic pulse velocity acros the 10-mm transverse dimension using the relationship between dynamic modulus of elasticity (E_{dyn}), pulse velocity (v), density (ρ_c) and Poisson's ratio (ν). For more precision in the results, an average value of three readings was obtained in the transverse direction.

The dynamic modulus of elasticity in defined as follows:

$$E_{dyn} = \rho\, V^2\, \frac{(1+\nu)(1-2\nu)}{1-\nu} \tag{1}$$

And the relative dynamic modulus of elasticity E_{rdy} (RDME) is defined as follows:

$$E_{rdy} = \frac{E_{dyn}}{E_{dyo}} \times 100 \tag{2}$$

(E_{rdy}) is the Relative Dynamic Modulus of Elasticity at n cycles of freeze-thaw expressed as percentage and computed as the average of three specimens.

(E_{dyn}) is the Dynamic Modulus of Elasticity at n cycles of freeze-thaw.

(E_{dy0}) is the Dynamic Modulus of Elasticity before freeze-thaw cycles.

Durability factor is defined as follows:

$$DF = E_{dyn} \times \frac{N}{M} \qquad (3)$$

E_{dyn}: is the Dynamic Modulus of Elasticity at n cycles of freeze-thaw.

N: is the maximum number of cycles specified by the standard if the material has not reached 60% of (E_{dyn}) before the end of the test.

M: is the maximum number of cycles specified by the standard (300 cycles).

Loss of Mass

The expansion of water due to freezing and thawing cycles can typically cause loss of mass. In this regard, loss of mass was measured in order to reveal the effect of particle size of (WGP) on resistance to freeze-thaw of HPC. The mass loss is defined as follows:

$$\Delta M_n = \frac{M_n - M_0}{M_0} \times 100 \qquad (4)$$

ΔM_n : is mass loss at n cycles of freeze-thaw, expressed as percentage, calculated as the average of three specimens.

M_0 : is mass before cycling.

M_n : is mass at n cycles of freeze-thaw.

RESULTS AND DISCUSSION

Relative Dynamic Modulus of Elasticity

Figures 2 and 3 respectively show the relative dynamic modulus of elasticity *versus* the number of freeze-thaw cycles. Each reading represents the average value of three specimens. As mentioned in Figure 2 and Figure 3, during the first 200 freeze-thaw cycles, the RDME decreased slowly. In subsequent cycles of freeze-thaw, the RDME of concrete specimens containing WGP with particle size greater than 315 µm showed considerable loss, while concrete specimens with finer waste glass showed a slightly smaller loss. After 100, 200 and 300 cycles, the average values of (RDME) from ultrasonic pulse velocity were 96.5, 88.5 and 84.25% for the concrete specimens with particle size less than 315 µm of WGP and 91.12, 77.25 and 71.75% for the concrete specimens with particle size of WGP greater than 315 µm, respectively.

The above results illustrate a higher loss of RDME in (HPCGB) with a higher content of WGP without any favorable effect on durability; in contrast, in (HPCGA) with a higher content of WGP, results show lower loss of (RDME) with more favorable effect on durability. It can be noticed that at different cycles, loss of (RDME) of all concrete specimens decreases as the particle size of (WGP) becomes finer with more favorable effect on durability. On the contrary, the (RDME) decreases as the particle size of (WGP) increases.

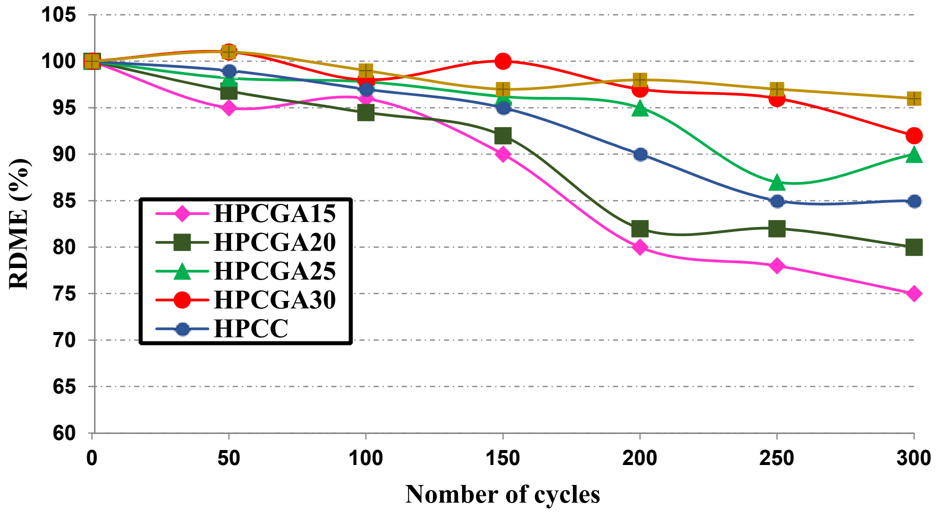

Figure (2): Relative dynamic modulus of elasticity *versus* number of cycles (HPCGA)

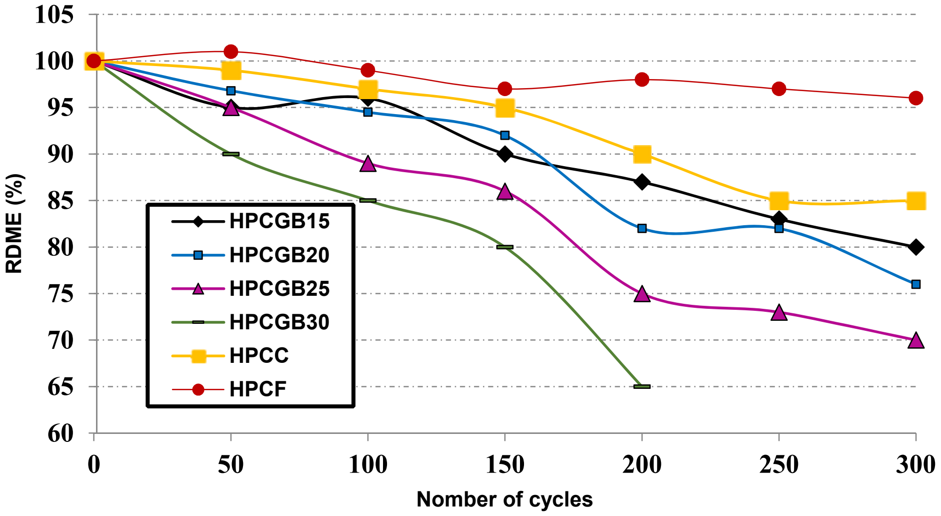

Figure (3): Relative dynamic modulus of elasticity *versus* number of cycles (HPCGB)

It can be concluded that (WGP) with particle size less than 315 μm used as fine aggregate might be incorporated into concrete up to 30 percent of partial replacement of sand. Guojun et al. (2018) suggested that finer (WGP) would improve durability and eventually exhibit certain mitigation effect on ASR expansion, due to the reaction between (WGP) and (CH) and the production of CSH gels. Pigeon (1996) reported that finer substitution provides empty space within the paste to which the excess capillary water can escape and freeze without causing damage. In contrast, (WGP) with particle size more than 315 μm is susceptible to ASR expansion in concrete, where the alkaline attack dissolves the amorphous silica in glass and forms ASR gel (Maraghechi et al., 2014; You et al., 2016).

Durability Factor (DF)

The durability factor represents the mechanical deterioration of material. The minimum acceptance criteria for the test are set at 60% for RDME; when after 300 cycles, the (RME) is less than 60%, it is considered that the concrete does not withstand freeze-thaw cycles in according with European standard [NF P 18-424] requirements. After 300 cycles, the durability factor is specified for prisms of each mixture studied. The values were 92, 90, 82 and 77 % for the concrete specimens (HPCGA) and 80, 76, 70 and 61% for the concrete specimens (HCPGB), respectively. The above results illustrate that all mixes of high-performance concrete have successfully passed the test.

Change in Mass

Cyclic freeze-thaw in concrete is a major durability problem of cementitious materials. It is among the external agents that can cause several physico-chemical mechanisms of degradation (thermal expansion, hydraulic pressure, osmotic pressure). Consequences are surface scaling and internal cracking (Carles-Gibergues and Pigeon, 1992; Lessard et al., 1995). Expansion of water due to freezing and thawing causes a general loss of surface mortar on a concrete surface, thus causing a loss of mass (Pigeon, 1996). The changes in mass of concrete specimens were evaluated *versus* the number of freeze-thaw cycles, as shown in Figure 4 and Figure 5, respectively.

After 300 freeze-thaw cycles, the concrete prisms of (HPCGB) showed a considerable loss of mass, while concrete prisms containing finer waste glass powder showed a small loss of mass, as shown in Figures 4 and 5. The change in masse of concrete specimens with finer WGP was less than 1 percent compared with 2 percent for concrete specimens with size greater than 315 μm; for instance, all the losses of mass are less than 1% at up to 300 cycles, except for the specimen (HPCGB30) with a mass loss of 1.8% when the replacement ratio is 30%.

At 300 cycles, the loss of mass of high-performance concrete specimens (HPCGA15), (HPCGA20), (HPCGA25) and (HPCGA30) are 0.7, 0.61, 0.58 and 0.43%, respectively, which are all greater than 1% and

0.6, 1.2, 1.6 and 1.8% for the concrete specimens (HPCGB15), (HPCGB20), (HPCGB25) and (HPCGB30), respectively.

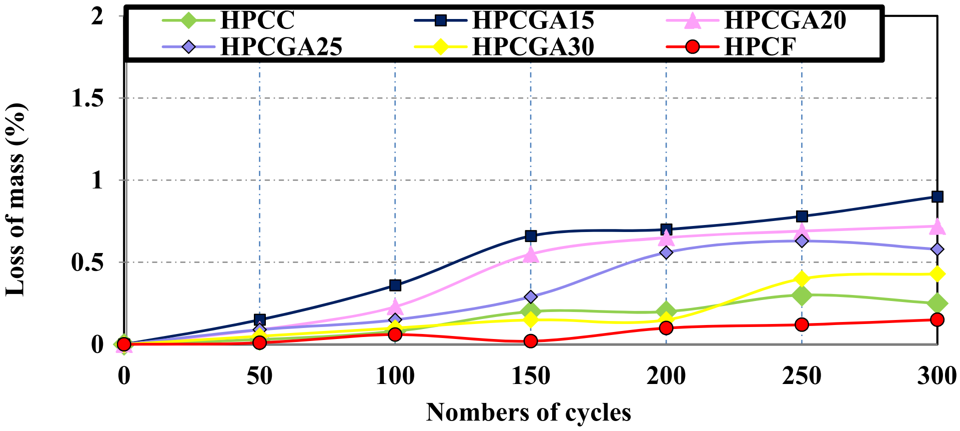

Figure (4): Loss of mass *versus* number of cycles for mixtures including size ranges of 0-315 µm of waste glass

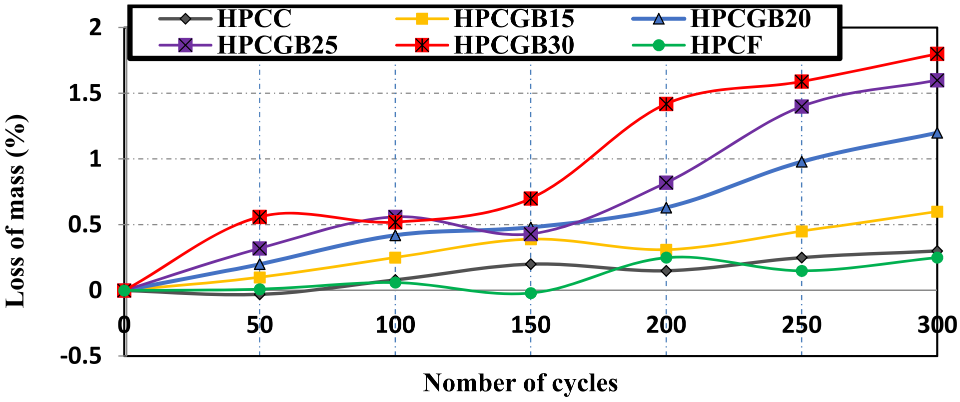

Figure (5): Loss of mass *versus* number of cycles for mixtures including size ranges of 315-1.25mm of waste glass

It can be found that at different cycles, all the losses of mass are lower than the loss of mass of control concrete and the loss of mass of concrete specimens containing (WGP) with particle sizes less of 315 µm less decreasing with the increase in the content of (WGP). Soliman (2016) and Premalatha and Srinivasan (2019) reported that the porous network of the powder glass offers additional space for water movement caused by freezing. The constraints are thus reduced leading to enhanced durability. It is necessary to mention that the tests were carried out in accordance with European standard [NF P 18-424]. The latter does not specify a maximum limit for loss of mass. According to the different literature consulted, there are several limits and the main interest of these tests lies in the comparison of the behavior of conventional concrete and high-performance concrete including waste glass, more than in the strict quantitative assessment of the results.

Compressive Strength

Compressive strength testing had been conducted on 100×200 mm standard cylindrical specimens in accordance with European standard [NF EN 12390-3 2003] at ages of 7, 28 and 90 days. The compressive strength test results are given in Figure 6 and Figure 7, respectively.

Compared with control concrete, Figure 6 and Figure 7 show clearly that the compressive strengths of all mixes are lower at 7 days. Zidol et al. (2017) reported that the decrease of compressive strength can be explained by a diluting effect due to substituting a more reactive powder by a less reactive powder as cement and (WGP). At 90 days, the average values of compressive strength were about 73.2, 71, 61.8 and 51.1MPa, respectively for concrete specimens (HPCGA30), (HPCGA25), (HPCGA20) and (HPCGA15). Compared with control concrete, specimens (HPCGA) recorded the strongest resistance; for 15% (WGP) substitution of sand, it increased by 8% and by 18% for 30% (WGP) substitution of sand. These improvements have been attributed mainly to the fineness of waste glass. Guojun et al. (2018) found that the finer (WGP) contributes higher pozzolanic activity; CH crystals produced from cement hydration reaction are constantly consumed by the further hydration with waste glass powder. Because of the intense hydration reactions, the CH crystals are consumed quickly. Silica fume increases resistance to freeze-thaw compared to control concrete, which has been confirmed by Bosc et al. (1996).

On the other hand, concrete specimens (HPCGB15), (HPCGB20), (HPCGB25) and (HPCGB30) recorded the lowest resistance; the corresponding values were 48.2, 42.1, 41.8 and 39.1MPa, respectively. It can be observed that the compressive strength decreases when the replacement quantity of waste glass increases. Topçu et al. (2004) stated that decrease in compressive strength can be attributed to the incomplete adhesion between cement paste and (WGP) because of the high brittleness of glass, while the reduction of its specific gravity leads to heterogeneous distribution of aggregates.

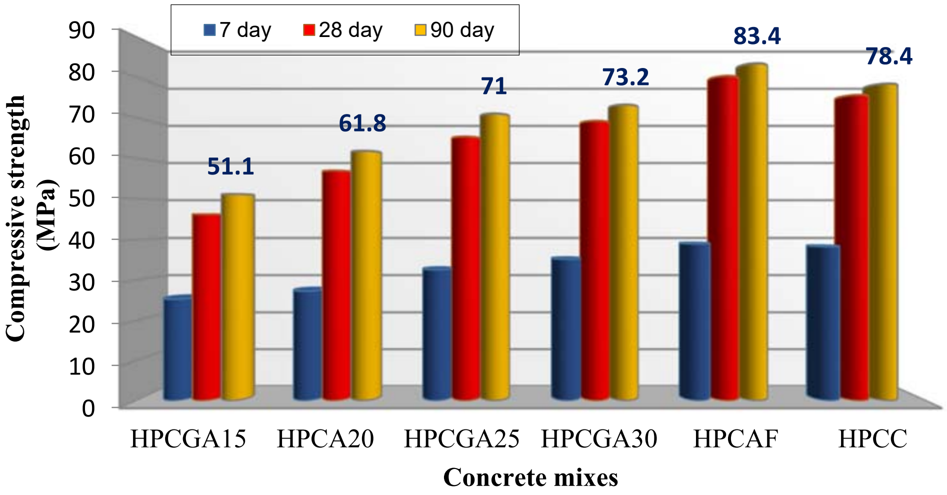

Figure (6): Compressive strength of different mixes including size ranges of 0-300µm of waste glass

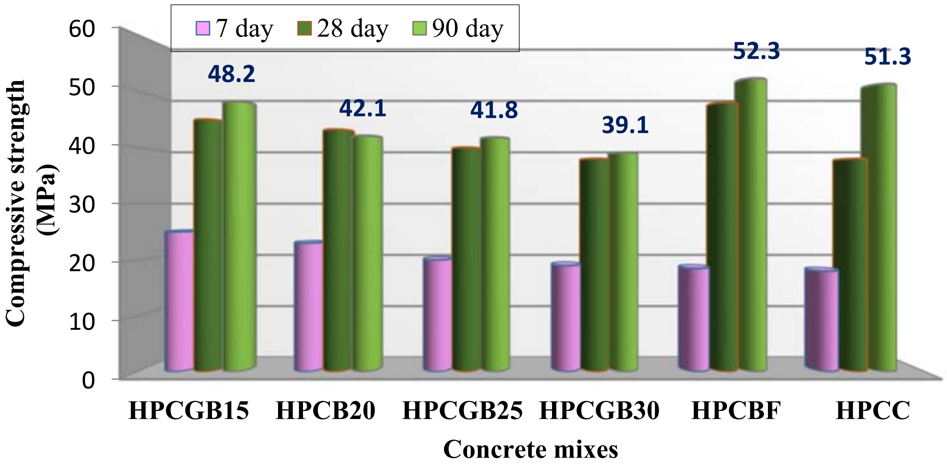

Figure (7): Compressive strength of different mixes including size ranges of 315-1.25mm of waste glass

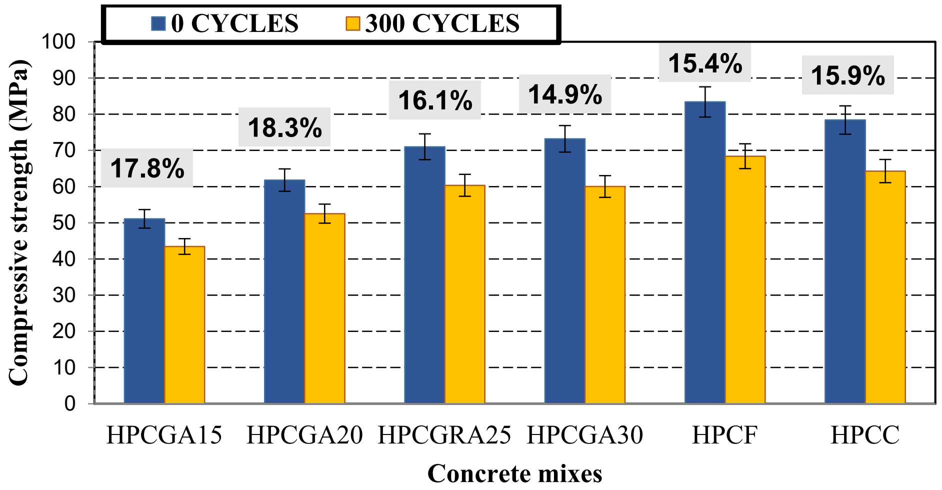

Figure (8): Compressive strength of (HPCGA) before and after 300 cycles of freeze-thaw

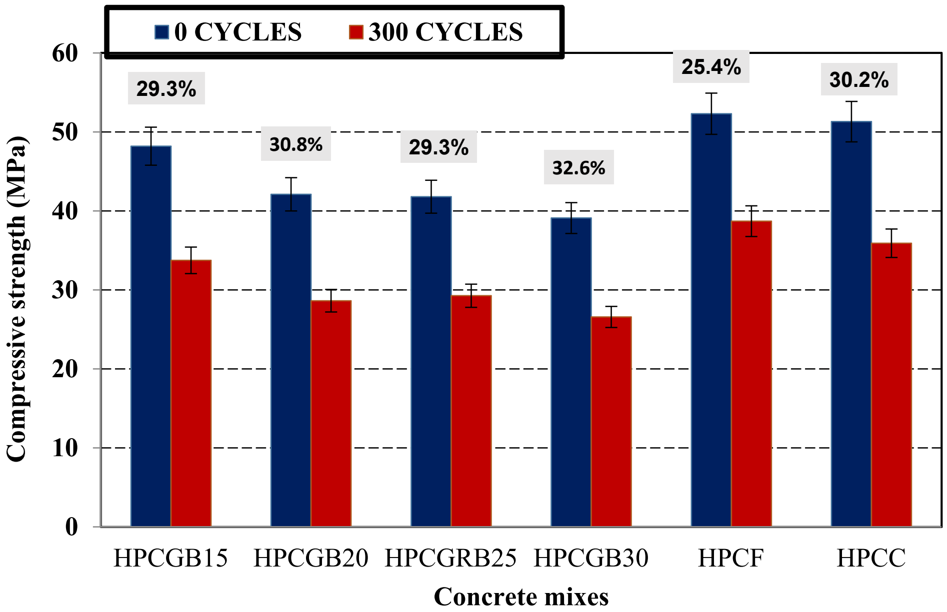

Figure (9): Compressive strength of (HPCGB) before and after 300 cycles of freeze-thaw

As shown in Figure 8 and Figure 9, both of (HPCGA) and (HPCB) showed compressive strength loss after 300 cycles of freezing and thawing; the compressive strength decreases only by an average of 17% for (HPCGA) and an average of 30% for (HPCGB) which can be attributed to the finer substitution of concrete specimens (HPCGA). The higher content of (WGP) with smaller particle size in high-performance concrete (HPCGA30) generates a reaction between CH and (WGP) and produces a large amount of C-S-H gels, which obviously contributes to the denser microstructure and increase in compressive strength, so glass powder can be incorporated from 20% to 30% as partial replacement of fine aggregate in concrete without affecting its compressive strength in medium or long terms.

The correlation between loss of mass and compressive strength of both (HPCGA) and (HPCGB) specimens is given in Figure 10; the Figure shows that the loss in mass of high-performance concrete decreases with increasing compressive strength. High compressive strength improves frost resistance and our results confirm this observation often reported in the literature (Gagné et al., 1996; Lafhaj, 2006).

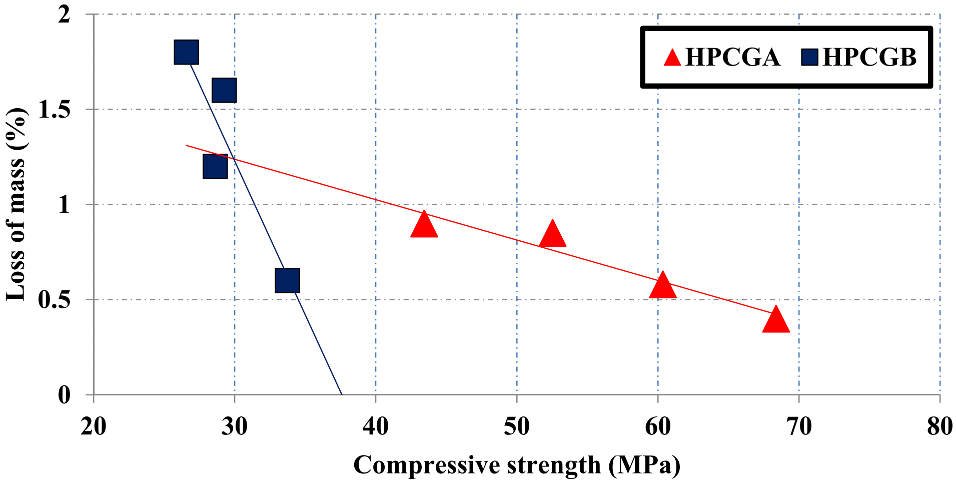

Figure (10): Correlation between compressive strength and loss of mass of (HPCGA) and (HPCGB)

CONCLUSIONS

This study focuses on the freeze-thaw effect on high-performances concrete properties containing waste glass finely crushed, with the aim to determine the level of waste glass powder replacement resulting in optimal resistance to freeze-thaw. Experimental tests were conducted on measuring the relative dynamic modulus of elasticity (RDME) from ultrasonic pulse velocity, the change in mass and compressive strength. A high-performance concrete including silica fume was made for comparison. The results of this study can be summarized as follows:

1. After 100, 200 and 300 cycles, the average values of the relative dynamic modulus of elasticity (RDME) were 96.5, 88.5 and 84.25% for concrete specimens (HPCGA) with particle size of (WGP) less than 315 µm and 91.12, 77.25 and 71.75% for concrete specimens (HPCGB) with particle size of (WGP) greater than 315 µm, respectively.
2. The finer waste glass powder decreases the loss of (RDME) and presents more favorable effect on the freeze-thaw durability. However, with smaller content and larger particle size, the RDME gradually increases.
3. After 300 cycles, the durability factor (DF) was found to be 92, 90, 82 and 77 % for the concrete specimens (HPCGA) and 80, 76, 70 and 61% for the concrete specimens (HPCGB), respectively; we might therefore conclude that the freeze-thaw durability of (HPCGA) is much higher than that of (HPCGB).
4. The compressive strength of high-performance concrete cylinders used in this research had an average value of 70.75 MPa for (HPCGA) and an average value of 42 MPa for (HPCGB). After 300 cycles, compressive strength decreases only by an average of 17% for (HPCGA) and by an average of 30% for (HPCGB).
5. In comparison with the control concrete (HPCC) and concrete containing silica fume (HPCF); concrete incorporating glass powder has a fairly satisfactory strength.
6. Glass powder can be incorporated from 20% to 30% as partial replacement of fine aggregate in concrete without affecting its compressive strength in medium or long terms.

Acknowledgment

The authors would like to express their deep gratitude to Mr. REMKI Mustapha, Phd, Senior Researcher at the National Center of Applied Research in Earthquake Engineering (CGS), Algiers, Algeria for his invaluable help and his support.

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