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Performance of Glass Concrete Subjected to Freeze-Thaw Cycling

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Abstract: This article reports the potential use of waste glass powder (GP) to improve the performance of concrete subjected to freeze-thaw (FT) cycling. Three GP contents were utilized in the study: 6%, 12%, and 18% by weight of cement. The other experimental parameters that were investigated in the study include: water to cement ratio (0.4 and 0.6) and aggregate type (limestone and tuff). Concrete prisms were exposed to accelerated FT cycles following ASTM Procedure B (rapid freezing in air and thawing in water). The FT damage of concrete prisms was evaluated using the relative dynamic modulus of elasticity and durability factor of concrete prisms.

The results of the study showed that the performance of GP concrete to FT damage was found higher than that of plain concrete. Additionally, the performance of concrete was increased with the increase of the GP level. The GP concrete with w/c ratio of 0.4 showed higher durability to FT damage than the GP concrete with w/c ratio of 0.6. The concrete containing tuff aggregate showed higher resistance to FT damage than the concrete containing limestone aggregate. The impact of w/c ratio and aggregate type on the durability of concrete to FT deterioration is more pronounced for GP concrete than for plain concrete.

Keywords: Durability factor, freeze-thaw damage, glass powder, relative dynamic modulus.

1. INTRODUCTION

The phenomenon of temperature fluctuating in concrete structures above and below freezing of water is called freeze-thaw (FT) cycles. Repeated cycles of FT are causing major damage of concrete structures such as columns, beams, slabs, etc in cold climates countries around the globe. One cycle of FT causes a local damage in the concrete internal structure. Nevertheless, another cycle of FT increases the damage from the first cycle. More cycles of FT increase substantially the damage of concrete internal structure [1].

The main causes of FT damage in concrete internal structure may be explained as follows: The capillary water in the cement paste matrix of concrete expands significantly (about 8%) upon freezing. Hydraulic pressure is generated in the capillary pores of concrete as a result to the expansion of the frozen water. Hence, the hydraulic pressure causes damage in the surrounding cement paste matrix [2]. Moreover, the ice may accumulate in the capillary pores during freezing of water. Since, water in the gel pores needs a very low temperature of about -75 ºC to freeze. At a temperature below 0 ºC, the gel water flow into the capillary pores to freeze there. The accumulation of ice in the capillary pores causes internal pressure on the cement paste matrix that leads to damage of concrete [3].

Saturated aggregate particles of concrete are subjected. also to internal hydraulic pressure upon freezing of water. Therefore, these aggregate must accommodate the expansion of freezing water by either expelling the excess water or by expanding. Very porous aggregates such as lightweight aggregates have a very high permeability so that water may escape during freezing without major aggregate damage. The transition zone between aggregates and the cement paste may be deteriorated when water under pressure is expelled from aggregate particles [4]. Many factors affect the performance of concrete to FT damage including w/c ratio, aggregate type, capillary pore structure characteristics and degree of saturation.

The utilization of by-product supplementary cementing materials and fillers in concrete mixtures such as silica fume, fly ash, tire rubber ash and blast-furnace slag had been observed a beneficial materials to improve the resistance of concrete to FT damage [5-9]. Ground glass powder (GP) is a new supplementary cementing material obtained by grinding waste glass into fine powder. Few research studies are reported in the literature concerning the effect of glass powder on different properties of concrete [10-12].

1.1. Novelty and Aims

A detailed literature survey revealed that there is no research works were conducted in the literature pertaining the influence of GP on the performance of concrete exposed to FT damage. This study aims to investigate the influence of GP on the performance of concrete to cycles of FT damage under different experimental parameters including: GP replacement level (0%, 6%, 12%, and 18%), w/c ratio (0.4 and 0.6) and aggregate type (limestone and tuff).

2. EXPERIMENTAL PROGRAM

The standards of the tests utilized in this study were as follows: ASTM C192-02 [13], ASTM C666-03 [14] and ASTM C215-08 [15].

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2.1. Materials

Locally available ordinary Portland cement (ASTM Type I) was used in the study. The physical properties and chemical composition of the cement are presented in Tables **1** and **2**, respectively. Two types of aggregate were used in the study: crushed limestone and volcanic tuff. The crushed limestone is widely used as coarse aggregate for concrete mixtures. The volcanic tuff was used in this work as porous aggregate to investigate the effect of aggregate type on the performance of GP concrete to FT deterioration. The physical properties of the aggregates used are shown in Table **3**.

Table 1. The Physical Properties of the Cement and GP Used in the Study

Property	Cement	GP
Specific gravity	3.14	2.35
Blaine fineness (m^2/kg)	340	410
Average particle size (μm)	13	10
Color	Gray	White

Table 2. The Chemical Composition of the Cement and GP Used in the Study

Compound (%)	Cement	GP
SiO_2	20.4	73.4
Al_2O_3	5.7	1.2
Fe_2O_3	3.7	0.53
MgO	2.2	5.2
CaO	64.4	8.3
Na_2O	0.15	10.5
K_2O	0.17	0.42
SO_3	2.0	0.1
Loss on ignition	0.7	0.05

The waste glass powder was obtained by grinding flat waste glass in a laboratory grinding machine. The resulting GP had a white color, specific gravity of 2.35, Blaine fineness of 410 m^2/kg, and contains 73% silica. The physical properties and chemical composition of the GP are presented in Tables **1** and **2**, respectively.

2.2. Mixtures Details

Eight concrete mixtures were prepared and used in this study to investigate the effect of GP on the performance of concrete to FT cycling. Details of the concrete mixtures are shown in Table **4**.

Concrete mixtures 1, 2, 3, and 4 were prepared using limestone aggregate, w/c ratio of 0.6 and the GP levels were 0%, 6%, 12%, and 18% by weight of cement, respectively. These concrete mixtures were used to investigate the effect of GP contents on the performance of concrete to FT damage.

Concrete mixtures 5 and 6 were prepared using tuff aggregate, w/c ratio of 0.6 and, 0% and 12% GP levels. These concrete mixtures were used to investigate the effect of aggregate type on the resistance of concrete to FT damage.

Concrete mixture 7 and 8 were prepared using limestone aggregate, w/c ratio of 0.4 and, 0% and 12% GP contents. These concrete mixtures were used to investigate the effect of w/c ratio on the resistance of concrete to FT damage.

Table 3. Physical Properties of the Aggregates used in the Study

Aggregate	D_{max} (mm)	BSG	Absorption (%)	FM (%)	Unit Weight (kg/m^3)
Limestone CA	12.5	2.56	2.1	---	1450
Limestone FA	4.75	2.58	2.8	2.7	---
Tuff CA	12.5	2.32	7.0	---	870
Tuff FA	4.75	2.22	8.3	2.5	---

FM = fineness modulus, D_{max} = maximum aggregate size, BSG = bulk specific gravity. CA = coarse aggregate, FA = fine aggregate.

2.3. Specimens Preparation

Prismatic specimens (7.5 × 7.5 × 45 cm) were used for the FT cycling tests. Casting of concrete specimens was conducted in two layers. Each layer was compacted on a vibrating table to ensure good compaction and to reduce the entrapped air voids. Fresh concrete was poured into oiled steel molds and covered with wet burlaps for 24 hours at 23 ± 2 °C. Concrete specimens were then de-molded, labeled as to the date of casting and mixture type, and submerged in a water bath for an initial moist curing period of 90 days. Three concrete specimens were prepared and tested for each test condition to obtain average values.

2.4. Test Procedures

The concrete mixtures were mixed and prepared according to the ASTM C192-02 procedure using a tilting drum mixer of 0.04 m^3 capacity. The FT exposure of the concrete specimens was performed following Procedure B (rapid freezing in air and thawing in water) according to ASTM C666-03. This kind of testing represents an accelerated testing type and the purpose of this test is to compare the performance of different concrete mixtures to FT damage.

The FT equipment functions at five cycles per day. Every FT cycle consists of lowering the temperature of the concrete specimens from +5 to –18 °C in 3.6 hour, and raising it from –18 to +5 °C in 1.2 hour. Every 25 cycle, the concrete specimens were taken out (in thawed condition) from the FT equipment, dried in air for 90 minutes, and the fundamental transverse resonant frequency measurements were performed. A maximum number of 300 FT cycles was selected to stand for a typical FT exposure on the concrete material throughout the structure life according to ASTM C 666-03.

Table 4. Proportions of Concrete Mixture (kg/m³) used in The Study

Mix	GP (%)	w/c	Cement (kg)	GP (kg)	Water (kg)	CA (kg)	FA (kg)	Aggregate
1	0	0.6	367	0	220	830	705	Limestone
2	6	0.6	345	22	220	830	705	Limestone
3	12	0.6	323	44	220	830	705	Limestone
4	18	0.6	301	66	220	830	705	Limestone
5	0	0.6	367	0	220	540	515	Tuff
6	12	0.6	323	44	220	540	515	Tuff
7	0	0.4	550	0	220	830	705	Limestone
8	12	0.4	484	66	220	830	705	Limestone

CA = coarse aggregate, FA = fine aggregate.

The amount of FT damage was evaluated by measuring the fundamental transverse frequency of concrete prisms every 25 cycles of FT exposure. The fundamental transverse frequency of simply supported concrete prisms was performed according to ASTM C215-08. The relative dynamic modulus of elasticity was calculated based on the fundamental transverse frequency measured using the following equation (ASTM C 215-08):

$$RD = \left(\frac{f_n^2}{f_0^2} \right) \times 100 \qquad (1)$$

Where *RD* = relative dynamic modulus of elasticity (%), f_n = fundamental transverse frequency after *n* cycles of FT exposure, and f_0 = initial fundamental transverse frequency at 0 FT cycles.

The durability factor was calculated using the following equation (ASTM C 666-03):

$$DF = RD\frac{N}{M} \qquad (2)$$

Where, *DF* = durability factor of GP concrete prism (%), *RD* = relative dynamic modulus of elasticity at c cycles of FT (%), *N* = number of FT cycles that RD reaches the specified value for stopping the test, *M* = specified number of FT cycles that the exposure is stopped.

3. RESULTS AND DISCUSSION

3.1. GP Content

This study investigated the influence of three GP contents (6%, 12%, and 18%) on the resistance of concrete to FT damage. The selection of the GP levels was based on previous research available in the literature to provide optimum performance of concrete mixtures containing GP [12]. Fig. (**1**) shows the influence of GP replacement on the variation of the relative dynamic modulus of elasticity with the number of FT cycles.

The performance of GP concrete to FT damage was found higher than that of plain concrete (without GP replacement). Additionally, the performance of concrete to FT damage increased with increasing the GP level from 6% to 18%. Plain concrete showed little resistance to FT damage and the relative dynamic modulus of elasticity approached 58% after 100 cycles of FT.

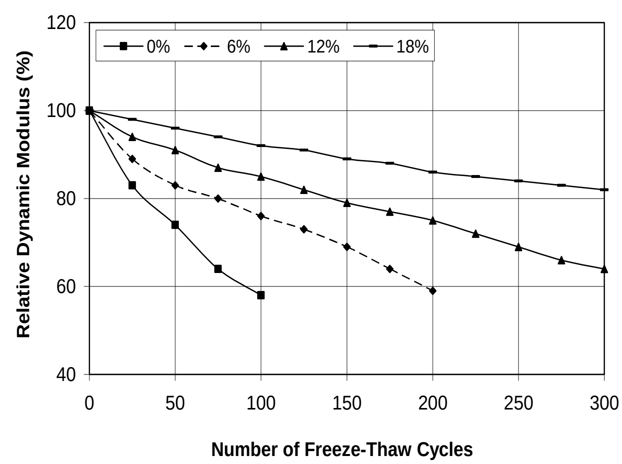

Fig. (1). Effect of GP content on the variations of the relative dynamic modulus of elasticity with number of FT cycles.

Nevertheless, the GP concrete showed higher resistance to FT damage compared to the plain concrete. Moreover, the resistance of GP concrete to FT damage increased with increasing the GP content. The 6% GP concrete showed medium resistance to FT damage and the relative dynamic modulus of elasticity reached 59% after 200 cycles of FT. The 12% GP concrete showed higher resistance to FT damage than the 6% GP concrete and the relative dynamic modulus reached 64% after 300 cycles of FT. Additionally, the 18% GP concrete showed excellent durability to FT cycles compared to the 6% and 12% GP concrete and the relative dynamic modulus reached 82% after 300 cycles of FT.

Fig. (**2**) shows the influence of GP content on the durability factor of concrete. The durability factor of GP concrete is found higher compared to that of plain concrete. The durability factor of GP concrete increased with increasing the GP content from 19% for the plain concrete to 82% for the 18% GP concrete.

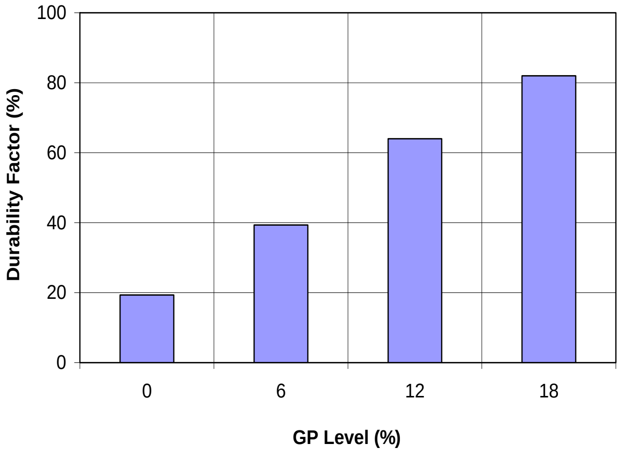

Fig. (2). Effect of GP content on the durability factor of concrete mixes.

The results of increasing the resistance of GP concrete to FT damage compared to that of plain concrete may be explained due to the pozzolanic reactivity of GP in concrete mixtures. The pozzolanic reaction produces additional C-S-H that fills the pores and decrease the porosity of the GP concrete. Therefore the water inside the small pores of the GP concrete needs very low temperature to freeze. Additionally, the amount of water present in the capillary pores of GP concrete will be less compared to that present in the pores on control concrete. Therefore, the amount of damage due to FT in GP concrete is less than that in plain concrete.

3.2. Aggregate Type

Aggregate type of concrete mixtures affects many properties of the concrete such as unit weight and compressive strength. The study investigated the effect of two aggregate types (limestone and tuff) on the resistance of GP concrete to FT damage.

Fig. (**3**) presents the influence of aggregate type on the variation of the relative dynamic modulus of elasticity with the number of FT cycles for plain and GP concrete. The concrete containing tuff aggregate showed higher performance to FT damage compared to the concrete containing limestone aggregate. The relative dynamic modulus of elasticity of GP concrete including limestone aggregate reached 64% after 300 cycles of FT. However, the relative dynamic modulus of elasticity of GP concrete including tuff aggregate reached 88% after 300 cycles of FT.

Fig. (**4**) shows the effect of aggregate type on the durability factor of plain and GP concrete. The concrete containing tuff aggregate showed higher durability factor compared to concrete containing limestone aggregate. The durability factor of plain concrete increased from 19% for concrete including limestone aggregate to 29% for concrete including tuff aggregate. Nevertheless, the durability factor of GP concrete increased from 64% for concrete including limestone aggregate to 88% for concrete including tuff aggregate. The effect of aggregate type on the performance of concrete to FT cycling is more pronounced in the presence of GP than for plain concrete.

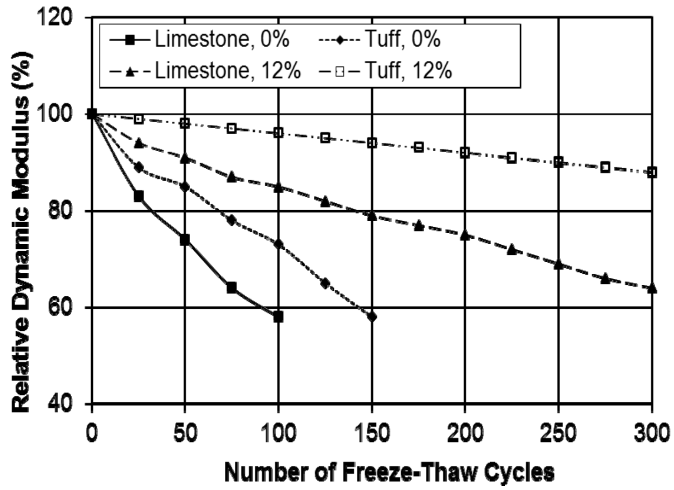

Fig. (3). Effect of aggregate type on the variations of the relative dynamic modulus of elasticity with number of FT cycles.

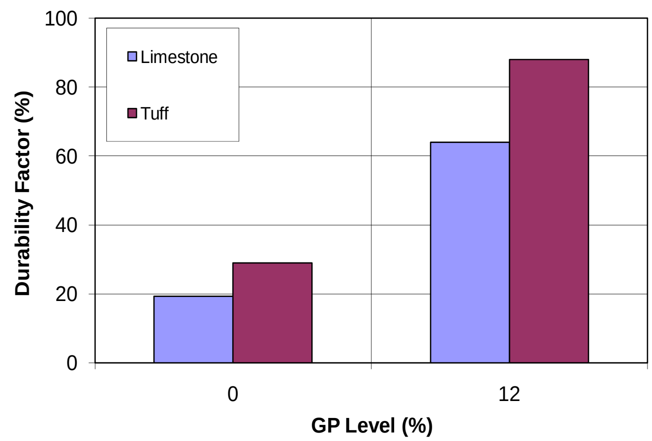

Fig. (4). Effect of aggregate type on the durability factor of plain and GP concrete.

The good resistance of GP concrete with tuff aggregate to FT damage compared to GP concrete with limestone aggregate maybe explained by the followings: The tuff aggregate type is lightweight aggregate that contains more capillary pores compared to the limestone aggregate type. Upon freezing, the water present in the concrete with tuff aggregate escapes to the pores of the tuff aggregate. Therefore, the pressure of frozen water in GP concrete containing tuff aggregate is reduced significantly.

3.3. Water to Cement Ratio

Water to cement ratio affects many properties of concrete such as pore refinement and mechanical properties. This study investigated the effect of two w/c ratios (0.4 and 0.6) on the resistance of GP concrete to FT damage. The use of w/c ratios of 0.4 and 0.6 in this study was chosen since these w/c ratios are generally used in the practice.

Fig. (**5**) presents the effect of w/c ratio on the variation of the relative dynamic modulus of elasticity with the number of FT cycles. The plain and GP concrete with w/c ratio of 0.4 showed higher durability to FT damage compared to the GP concrete with w/c ratio of 0.6. The relative dynamic modulus of elasticity of GP concrete with w/c ratio of 0.6 reached 64% after 300 cycles of FT. However, the relative dynamic modulus of elasticity of GP concrete with w/c ratio of 0.4 reached 86% after 300 cycles of FT.

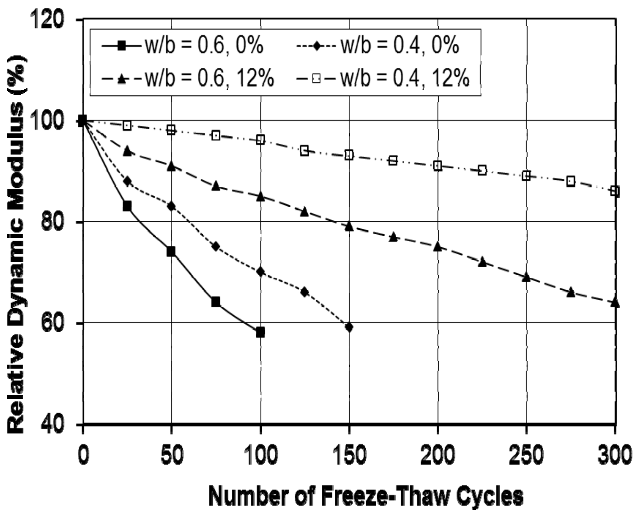

Fig. (5). Effect of w/c ratio on the variations of relative dynamic modulus of elasticity with number of FT cycles.

Fig. (**6**) shows the influence of w/c ratio on the durability factor of plain and GP concrete. The concrete with w/c ratio of 0.4 showed higher durability factor compared to concrete with w/c ratio of 0.6. The durability factor of plain concrete increased from 19% for plain concrete with w/c ratio of 0.6 to 30% for plain concrete with w/c of 0.4. Moreover, the durability factor of GP concrete increased from 64% for GP concrete with w/c ratio of 0.6 to 86% for GP concrete with w/c of 0.4.

The increase in the resistance of GP concrete to FT damage with decreasing the w/c ratio from 0.6 to 0.4 may be explained by the followings. The size of the capillary pores of the GP concrete with w/c ratio of 0.6 is larger than that of the GP concrete with w/c ratio of 0.4 [16]. Hence, GP concrete with w/c ratio of 0.6 is exposed to more hydraulic pressure upon freezing of water compared to GP concrete with w/c ratio of 0.4. Therefore, the hydraulic and internal pressure induced upon freezing of capillary water in GP concrete with w/c ratio of 0.6 is much higher compared to that of GP concrete with w/c ratio of 0.4.

3.4. Comparison with Other Data in Literature

The test results obtained from this study compares well with other results conducted using other supplementary cementing materials such as fly ash, silica fumes and slag. Yazıcı reported that the addition of high-volume fly ash and silica fume to self-compacted concrete mixtures produced good freeze–thaw and chloride penetration resistance [9]. Fu *et al* concluded that alkali activated slag has excellent freeze-thaw durability [3].

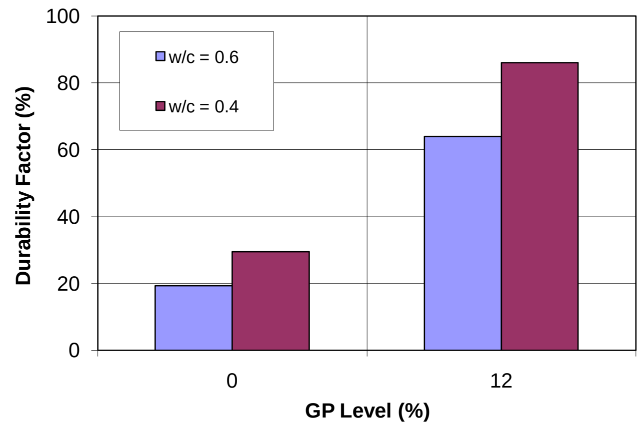

Fig. (6). Effect of w/c ratio on the durability factor of plain and GP concrete.

4. CONCLUSIONS

This study presents the results for the effect of GP on the resistance of concrete to FT damage. Based on the results obtained from this study, the following conclusions may be warranted:

1. The performance of GP concrete to FT cycling was observed higher compared to that of plain concrete. The resistance of GP concrete to FT damage increased with increasing the GP replacement level from 6% to 18%.
2. The GP concrete containing tuff aggregate showed higher resistance to FT damage compared to GP concrete containing limestone aggregate. The effect of aggregate type on the durability of concrete to FT cycling is more pronounced for GP concrete than for plain concrete.
3. The resistance of GP concrete with w/c ratio of 0.4 to FT damage was observed higher than that of GP concrete with w/c ratio of 0.6. The influence of w/c ratio on the performance of concrete to FT damage is more effective for GP concrete than for plain concrete.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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Declared none.

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