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Evolution of mechanical properties of concrete containing ground granulated blast furnace slag and effects on the scaling resistance test at 28 days

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Abstract

Compressive strength, ultrasonic pulse velocity (UPV), non-evaporable water content and the interplay between them were investigated at 1, 3, 7 and 28 days to determine the effects of using ground granulated blast furnace slag (GGBFS) as cement replacement. The variables considered include percentage of GGBFS as cement replacement (0–60%), total binder content (270–450 kg/m^3), water-to-binder ratio (0.31, 0.38) and curing period. The dilution effect was observed at day 3, at which point, increasing the amount of GGBFS as cement replacement yielded lower compressive strengths. The results show that the evolution of mechanical properties is affected by the amount of water, percent of GGBFS added and curing regime. By 28 days, the benefit of using GGBFS as cement replacement owing to its effect on the concrete's packing density and hydration processes was reflected in the compressive strength and UPV measurements when used up to 50% cement replacement. Compressive strength of concrete containing GGBFS is found to increase on average by 10% from 28 days to 120 days. Measurements of non-evaporable water content and mass loss due to scaling revealed that the scaling resistance test for concrete at 28 days is more favorable towards OPC concrete and discriminates against concrete containing high percentages of GGBFS as cement replacement.

Keywords: Compressive strength; Density; Freeze–thaw salt scaling test; GGBFS; Kinetics; Non-evaporable water content; UPV

1. Introduction

It is well known that the use of ground granulated blast furnace slag (GGBFS) as a cement replacement, in addition to the ecological and environmental benefits [1,2], has considerable advantages and some disadvantages when compared to the performance of conventional ordinary Portland cement (OPC) concrete [3–5]. When GGBFS is used as cement replacement, one improvement is the compressive strength due in part to the fineness of the GGBFS and to the chemical hydration [6–9]. GGBFS, which is latently hydraulic, undergoes hydration reactions in the presence of water and calcium hydroxide, $Ca(OH)_2$. This secondary pozzolanic reaction yields a denser microstructure because the $Ca(OH)_2$ is consumed and CSH paste is formed [1,10,11]. Another benefit of using mineral admixtures, which leads to an increase in strength development, is due to heterogeneous nucleation. This process enhances the chemical activation of the hydration of cement. Thus, increasing the amount of the mineral admixture and refining its particle size will promote heterogeneous nucleation due to the availability of sites [6,7].

Compressive strength gain of concrete has been attributed to the degree of hydration and porosity [12–14]. Although the hydration kinetics of concrete containing GGBFS is not yet fully understood, it has been shown that the rate of hydration of concrete containing GGBFS compared to OPC concrete is slower [1,15]. As a result, the recommended curing period for concrete containing GGBFS

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is generally 7 days in comparison to 3 days for OPC concrete [16]. However, what is not clear, are the implications of the hydration kinetics on the mechanical properties and other properties of concrete products at 28 days. Especially when published reports show that by 28 days, only 18–55% of the GGBFS used as cement replacement has reacted [1,2,15,17,18].

One reported disadvantage of concrete containing high percentages of GGBFS as cement replacement in comparison to OPC concrete is lower resistance to de-icer salt scaling when tested at 28 days [3,5,19–23]. This observation is based on laboratory de-icer salt scaling tests carried out in accordance with MTO LS-412 [24] or ASTM 672 [25]. The reasons for the poorer performance are not clear. However, some researchers have partially attributed it to the slow hydration and insufficient curing regime for concrete containing GGBFS [3,19]. This implies that the evaluation of the scaling resistance of GGBFS concrete at 28 days is partially influenced by the relatively slower rate of hydration and curing period. This postulation is evaluated in this study, where the interplay between the hydration kinetics of concrete containing varying percentages of GGBFS as cement replacement, the curing period, and the evolution of the mechanical properties, is first investigated. The impacts of these variables on the salt scaling durability of concrete containing varying percentages of GGBFS are then evaluated by comparing the compressive strength, density, ultrasonic pulse velocity (UPV) and non-evaporable water content measurements at 1, 3, 7 and 28 days.

Table 1
Chemical composition of OPC and GGBFS

Constituent	OPC (%)	GGBFS (%)
SiO_2	20.1	34.0
Al_2O_3	5.1	11.1
Fe_2O_3	2.3	0.5
CaO	63.6	36.6
MgO	2.5	11.6
SO_3	3.0	3.3

2. Experimental program

2.1. Material

Concrete samples for 13 mixtures were cast using type 10 OPC, GGBFS, crushed coarse aggregate with a maximum size of 13 mm, and fine aggregate consisting of natural rounded silica sand mixed with 12–18% crushed limestone stone (fineness modulus (FM) = 2.76). Table 1 provides the chemical composition of the OPC and GGBFS. A ratio of 60% fine to 40% coarse aggregate was adopted for the concrete mixes.

2.2. Concrete mix design

Table 2 provides the concrete mixture proportions. None of the mixtures contained air-entraining agent. Two different water reducing agents (WRA) were used; RheoMix 700FC was used for mixtures M2, M4, M6, M8, M9, M11, and M13, and RheoMix 750 for mixtures M1, M3, M5, M7, M10, and M12. The amount of OPC, GGBFS, total binder, and w/b ratio were the main variables considered in the proportioning of the concrete mixtures. The w/b ratio was either 0.31 or 0.38. The OPC content ranged from 180 to 360 kg/m^3 and the GGBFS content ranged from 0 to 270 kg/m^3, or from 0% to 60% cement replacement by weight. The total cementing material, OPC plus GGBFS, ranged from 270 to 450 kg/m^3.

The concrete was weighed, and mixed in an industrial pan mixer with the mixing time and mixing sequence kept the same for all batches. The aggregates and cementing materials were mixed for 2 min and then mixed for 75 s once the water was added. The WRA was then added and mixed for 75 s. The concrete mixtures were cast using

Table 2
Concrete mix design composition

Mix#	OPC:GGBFS	Total binder (kg/m^3)	OPC (kg/m^3)	GGBFS (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	w/b	w/c
M1	3:0	270	270	0	1328	883	0.31	0.31
M2	2:1	270	180	90	1310	879	0.38	0.57
M3	4:0	360	360	0	1253	835	0.31	0.31
M4	4:0	360	360	0	1275	847	0.38	0.38
M5	3:1	360	270	90	1249	833	0.31	0.41
M6	3:1	360	270	90	1257	843	0.38	0.51
M7	2:2	360	180	180	1246	831	0.31	0.62
M8	2:2	360	180	180	1257	843	0.38	0.76
M9	4:1	450	360	90	1204	808	0.38	0.48
M10	3:2	450	270	180	1156	771	0.31	0.52
M11	3:2	450	270	180	1204	808	0.38	0.63
M12	2:3	450	180	270	1152	768	0.31	0.78
M13	2:3	450	180	270	1204	808	0.38	0.95

Table 3
Paste mix design proportions by weight

Mix ID (OPC:GGBFS)	OPC (%)	GGBFS (%)	w/b ratio
4:0	100	0	0.31
4:0	100	0	0.40
3:1	75	25	0.31
3:1	75	25	0.40
2:2	50	50	0.31
2:2	50	50	0.40

standard cylinders (10 cm diameter × 20 cm height) and consolidated on a vibrating table.

2.3. Paste mixture proportioning

Six paste samples were prepared using the same OPC and GGBFS, proportioned as given in Table 3. The two main variables considered in the paste mixtures were the percent of GGBFS as cement replacement and the water content.

The paste materials were mixed in a Hobart mixer, according to the following mixing sequence:

(a) Mix dry cementing material (OPC and GGBFS) for 30 s manually.
(b) Add water and mix for 45 s on slow speed.
(c) Stop mixer to collect material from sides of mixer bowl and mix again for 45 s on slow speed.

The mixtures were cast into 51 mm × 51 mm × 51 mm molds.

2.4. Curing regime

Immediately after casting, the concrete and paste specimens were covered with plastic sheeting for approximately 20–24 h, at which time they were demolded. After demolding, the samples were placed in lime-saturated water tanks for 13 days, where the temperature of the water was maintained at 23 ± 2 °C. The specimens were then cured for 14 days in a controlled environment with a temperature of 23 ± 2 °C and a relative humidity of 50 ± 5%. The adopted curing regime was consistent with MTO LS-412 [24] and ASTM C-672 [25] test procedures that are used to evaluate the de-icer salt scaling resistance of concrete.

3. Experimental procedures

3.1. Compressive strength and ultrasonic pulse velocity

Compressive strength and UPV measurements were taken at 1, 3, 7 and 28 days. Each test was conducted on three standard cylinders. ASTM C 39 [26] was the test procedure used to evaluate the compressive strength. UPV measurements are reported for three repeats per cylinder and conducted in accordance with ASTM C 567-97 [27].

3.2. Non-evaporable water content

The non-evaporable water content (w_n/b) was determined using an oven drying and a loss-on-ignition procedure [28]. Three samples per mixture were tested. The samples were first ground with a mortar and pestle to a maximum particle size of 2 mm and covered with acetone to halt the hydration reactions. Thereafter, approximately 10 g of the material was weighed in porcelain crucibles to a precision of 0.0001 g. After drying in an oven at 110 °C for 24 h and stabilizing to a constant weight, the material was ignited at a temperature of 1050 °C for 27 h. The sample weights after oven drying (m_{105}) and furnace ignition (m_{1050}) were measured to 0.0001 g. The non-evaporable water per unit mass of initial cementing material *(b)* was calculated as follows [29]:

$$\frac{w_n}{b} = \frac{m_{105}}{m_{1050}}\left[\frac{\text{OPC}}{\text{OPC}+\text{GGBFS}}(1-L_{\text{OPC}}) + \frac{\text{GGBFS}}{\text{OPC}+\text{GGBFS}}(1-L_{\text{GGBFS}})\right] - 1 \quad (1)$$

The loss on ignition of OPC, L_{OPC}, and GGBFS, L_{GGBFS}, were measured to be 2.3% and 0.8%, respectively.

4. Results and discussion

4.1. Influence of GGBFS on compressive strength

Figs. 1a–c show the development of mean concrete compressive strength plus and minus one standard deviation with age for mixtures with a constant total binder content of 270, 360, and 450 kg/m^3, respectively. The influence of GGBFS on the compressive strength is shown in Figs. 2a, b, and c for 3, 7, and 28 days, respectively.

Figs. 1a and b show the adverse effects of GGBFS on the concrete compressive strength after 1 day. The strength of mixes (3:0) and (4:0) is on average three times greater than those of mix (2:1), and mixes (3:1) and (2:2), respectively. This confirms the slower initial rate of hydration of concrete containing GGBFS as cement replacement in comparison to OPC concrete. However, between day 7 and 28, mixtures containing GGBFS gain more strength than OPC concrete.

From day 3 to 7, one observes that the rate of strength development is greater with increasing GGBFS content. At day 7, for concrete containing 360 kg/m^3 of cementing material, mixes (3:1) and (2:2) have achieved equal strengths to that of OPC concrete, mix (4:0). The influence of GGBFS in addition to the w/b ratio on the rate of strength development is more pronounced at earlier ages, between day 3 and 7 as compared to day 7 to 28. For example, from day 3 to 7, increasing the w/b ratio from 0.31 to 0.38 increases the rate of strength development from 0.3 to

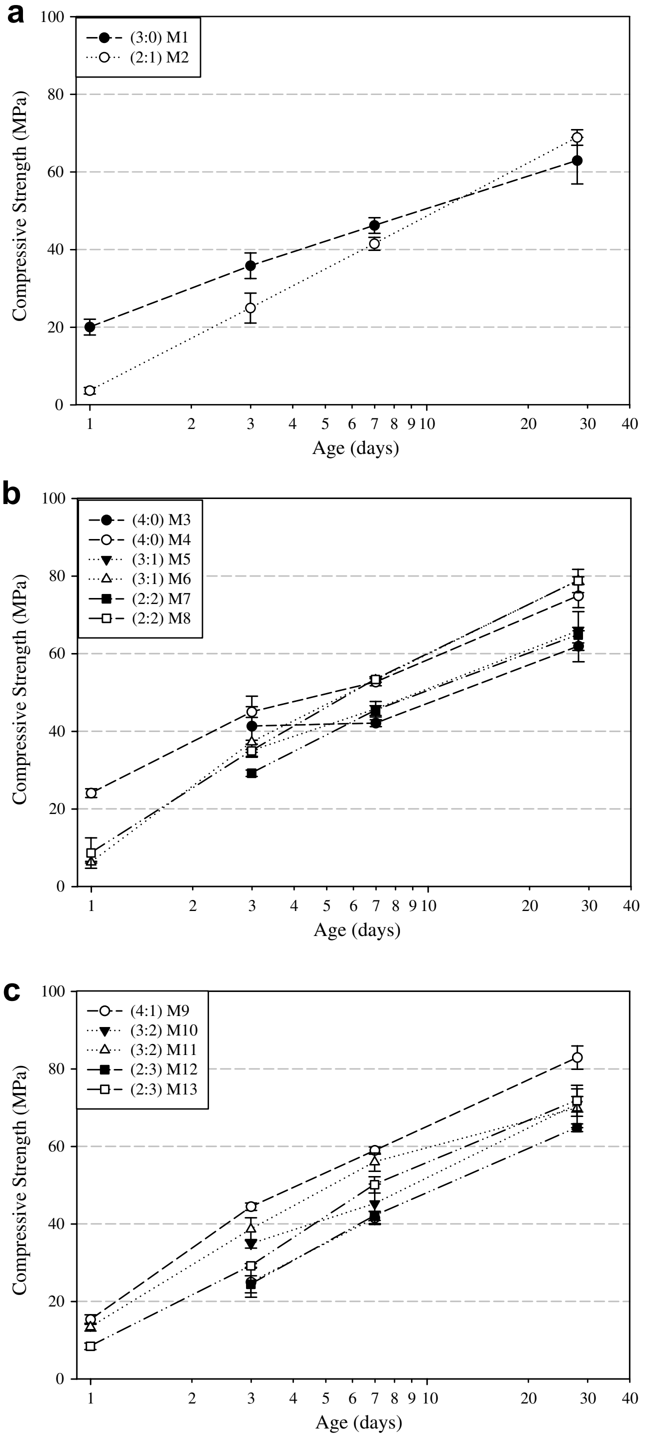

Fig. 1. Compressive strength development for concrete with a total cementing material content of (a) 270 kg/m^3, (b) 360 kg/m^3, and (c) 450 kg/m^3.

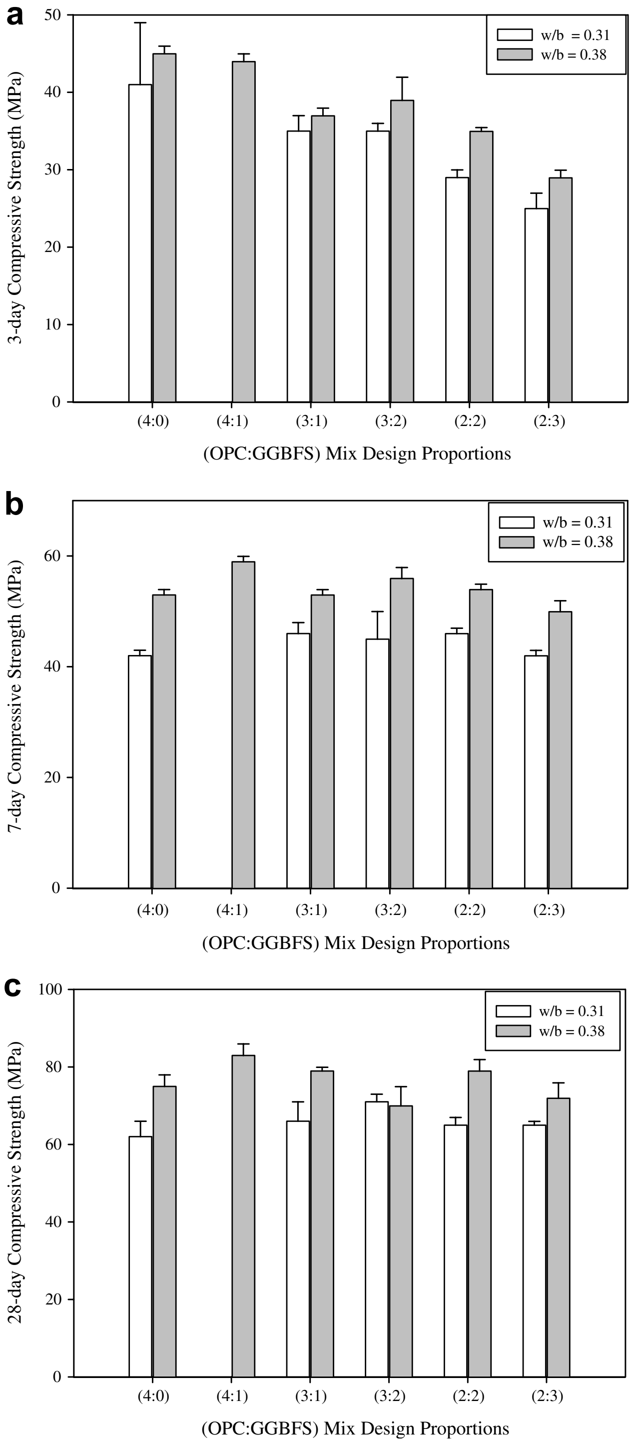

Fig. 2. Influence of GGBFS and w/b ratio on compressive strength (a) 3 days, (b) 7 days, and (c) 28 days.

2.0 MPa/day for mix (4:0), from 2.8 to 4.0 MPa/day for mix (3:1), and 4.3 to 4.8 MPa/day for mix (2:2). Between days 7 and 28, for concrete with a w/b ratio of 0.31, the rate of strength development, irrespective of the mix proportions, is approximately 0.9 MPa/day. Increasing the w/b ratio to 0.38, yields a rate of strength gain, which is approximately 1.1 MPa/day for the (4:0)-M4 mix and 1.2 MPa/day for the (3:1)-M6 and (2:2)-M8 concrete. These results show that at early ages, there are marked differences in the rates of strength development between the mixes. However, by 28 days, concrete of the same w/b ratio exhibits similar compressive strengths irrespective of the GGBFS content, as shown in Fig. 2c.

For concrete containing 450 kg/m^3, the rate of the concrete's strength development from day 3 to 7 is not clearly influenced by the OPC or GGBFS content. By 28 days, the presence of 40% and 60% GGBFS as cement replacement in concrete has a lower compressive strength as compared to concrete containing 20% cement replacement as shown in Fig. 2c. This finding is not the result of a limited supply of mix water available for hydration reactions or the hydration by-product required for pozzolanic reactions. Because if one examines mixes (4:0)-M4, (3:1)-M6 and (2:2)-M8, shown in Fig. 1b, which have the same w/b ratio as (3:2)-M11 mix and less total cementing material content, one can deduce that the strength at 28 days for a total cementing content of 450 kg/m^3 is mostly influenced by the limited space available for hydration processes. This consequently would result in a high percentage of unhydrated particles in mixtures with a binder content of 450 kg/m^3, M9 to M13. This observation is further explored by carrying a statistical analysis of the measurements.

Fig. 2a and b show greater compressive strengths with higher mix water content for all mixes at day 3 and 7. This is attributed to the availability of more pore water for the hydration reactions. The observation that increasing the w/b ratio increases the compressive strength is supported by the t-test and is statistically significant to a 95% confidence level. This finding is also true for the 28-day results with the exception of mix (3:2), shown in Fig. 2c. Examination of the compressive strength of mixes (3:2) and (2:3), given that both mixes have the same total cementing content, reveals that the mean compressive strength for w/b ratio of 0.38 is similar. The difference between the mean strengths is found statistically insignificant to a 95% confidence level. These results further demonstrate that the strength development for concrete containing 450 kg/m^3 of cementing material is likely impeded by the availability of pore space for hydration reactions to proceed. Reducing the w/b ratio to 0.31, results show mix (3:2)-M10 with a greater compressive strength as compared to (2:3)-M12. The response is most likely due to a combination of an insufficient supply of water and availability of physical space required for hydration and pozzolanic reactions.

4.2. *Influence of the water content and non-evaporable water content on compressive strength*

Fig. 3 shows the measured non-evaporable water content for pastes containing varying percentages of GGBFS as cement replacement with w/b ratios of 0.31 and 0.40. For all mix proportions, pastes with a w/b ratio of 0.31 have less chemically combined water compared to pastes with a w/b ratio of 0.40. This is partially attributed to the fact that the greater the w/b ratio, the more pore space available for the dissolution of reactants and the precipitation of hydration products [10,30]. As such, pastes with a low w/b ratio (0.31) can limit the GGBFS hydration reactions relative to a higher w/b ratio (0.40).

Fig. 4 shows the influence of GGBFS on the non-evaporable water content for variations of both the internal and external water supply. The pastes have been exposed to a moist curing period of 28 days compared to 14 days of moist curing followed by 14 days of air curing. Increasing the internal water supply from 0.31 to 0.40 increases the amount of hydrated particles more effectively than prolonging the external moist curing for an additional 14 days, irrespective of the amount of GGBFS. The results also show that at 28 days, the amount of chemically bound water decreases as the amount of GGBFS increases which is an indication of the amount of unhydrated particles. Recognizing that GGBFS is latently hydraulic, the amount of unhydrated GGBFS grains could be partially attributed to an insufficient supply of $Ca(OH)_2$.

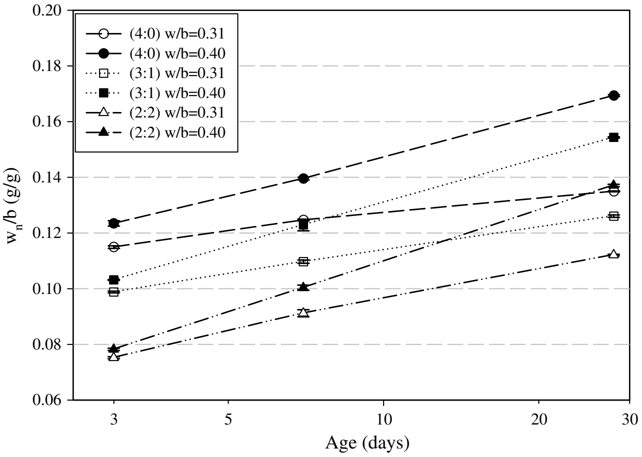

Fig. 3. Non-Evaporable water content of pastes.

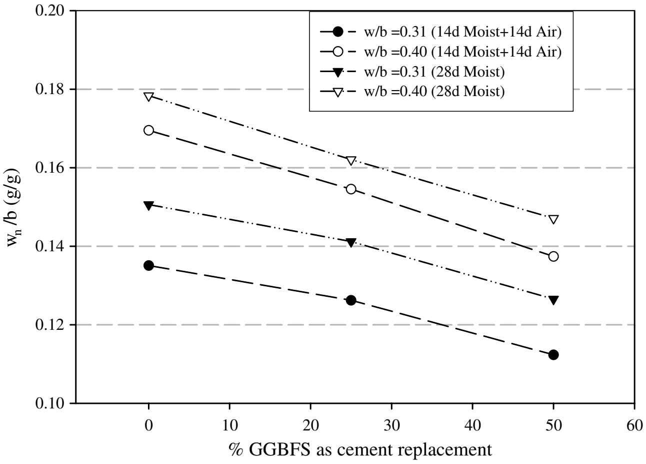

Fig. 4. Influence of extended moist curing on non-evaporable water content at 28 days.

The relative values of the non-evaporable water content, Fig. 3, correspond to the relative 3 day compressive strength measurements for mixes (4:0), (3:1) and (2:2) shown in Fig. 2a. The dependence of the early age (3 day) compressive strength on the degree of hydration is also observed by Cyr et al. [14] for mortars containing inert and pozzolanic admixtures in the short term (2 days). This is attributed to the dilution effect, where the compressive strength is related to the percentage of cement replacement used. The dilution effect is a result of replacing cement by a mineral admixture which results in less hydrated cement and lower compressive strength [7,14]. However, at day 7 and 28, the non-evaporable water content measurements on paste specimens decrease with increasing percentages of GGBFS, and is not reflected by corresponding lower measured compressive strengths. This suggests that the lower degree of hydration of the paste containing GGBFS is compensated for by the physical packing effect of the relatively finer GGBFS grains compared to the OPC particles. The physical contribution of mineral admixtures on the mechanical properties has been recognized in the literature as the packing geometry (filler effect) and/or heterogeneous nucleation [6–10,29]. The impact of the packing geometry and the latent hydraulic effect of the GGBFS on the homogeneity of the concrete microstructure is assessed by UPV and hardened density measurements.

4.3. Influence of GGBFS on UPV

Fig. 5 shows that the mean UPV increases with an increase in GGBFS as cement replacement, for concrete with a binder content of 360 kg/m^3 and a w/b ratio of 0.31. The trend is apparent at day 3, 7 and 28 but is most obvious at day 3 at which time the hydration process is dominated by the slower initial rate of hydration of the GGBFS as shown in Fig. 6b. Even though the trend is less obvious at day 7 and 28, the increase in mean UPV with GGBFS content is statistically significant to a 95% confidence level using the *t*-test for mixes (4:0)-M3, (3:1)-M5 and (2:2)-M7. These results show the beneficial effect of the GGBFS on the concrete physical microstructural uniformity at all ages. This is also supported by the corresponding greater hardened density measurements with increasing GGBFS content as reported in Table 4.

For the concrete mixes containing 450 kg/m^3, the UPV results do not indicate that increasing GGBFS increases the UPV measurement. At all ages, as shown in Figs. 5c and 6c, the UPV measurement of mix (3:2)-M10 and (2:3)-M12 are similar. At a w/b ratio to 0.38, the UPV results at 28 days are similar for the (4:1)-M9, (3:2)-M11 and (2:3)-M13. This finding further supports the observation that the hydration process is impeded not only due to insufficient water supply but also availability of physical pore space.

The relationship between the microstructural homogeneity and the amount of hydrated cementing material is examined by comparing the (4:0) mixture to the (2:2) mixture. At 28 days, the paste (4:0) with a w/b ratio of 0.31 has non-evaporable water content approximately equals to that of the (2:2) paste with a w/b ratio of 0.40 (Fig. 3). The corresponding 28-day mean measured concrete compressive strength and UPV for the (4:0)-M3 and (2:2)-M8 are 62 MPa and 4339 m/s and 79 MPa and 4547 m/s, respectively. This indicates that for an approximately equal amount of hydration reactions of the cementing material, the physical effect of the GGBFS particles increases the concrete's density and microstructural homogeneity which in turn yields an increased compressive strength [6–10,29].

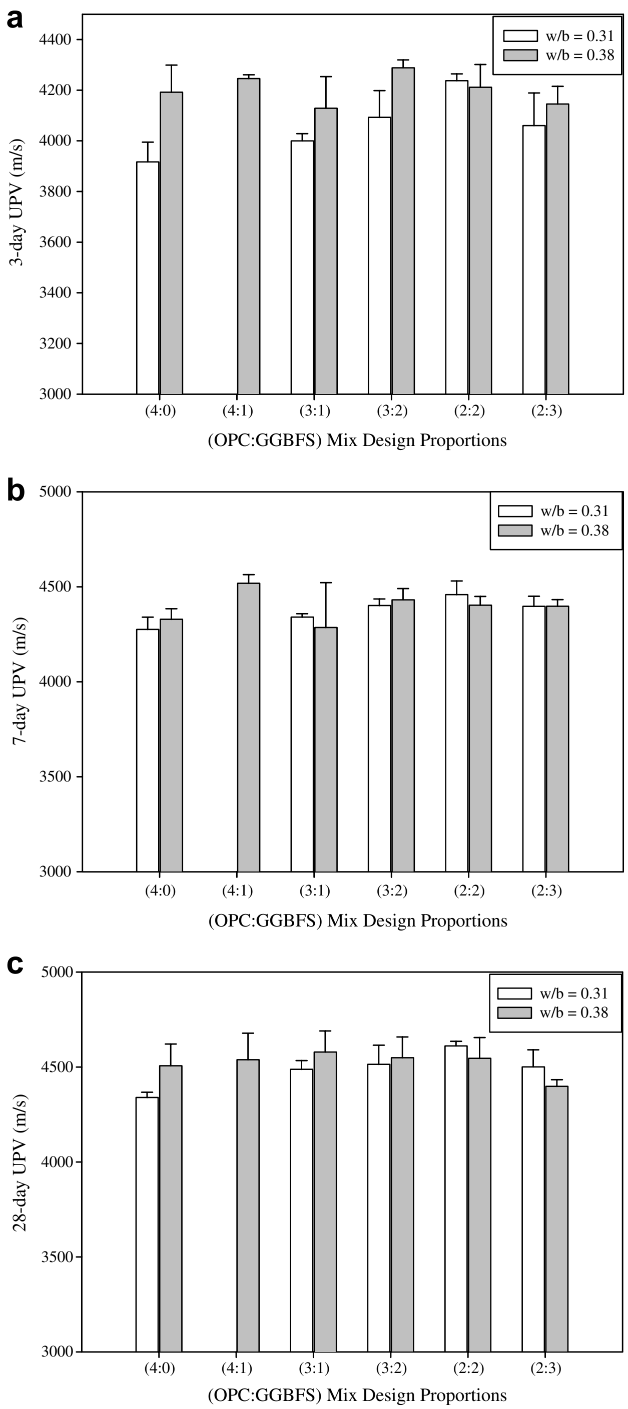

Fig. 5. Influence of GGBFS and w/b ratio on UPV measurements (a) 3 days, (b) 7 days and (c) 28 days.

4.4. Interplay between GGBFS, water content and evolution of mechanical properties and their influence on scaling resistance test

Laboratory de-icer scaling resistance test for concrete, such as MTO LS-412 and ASTM 672, which is performed

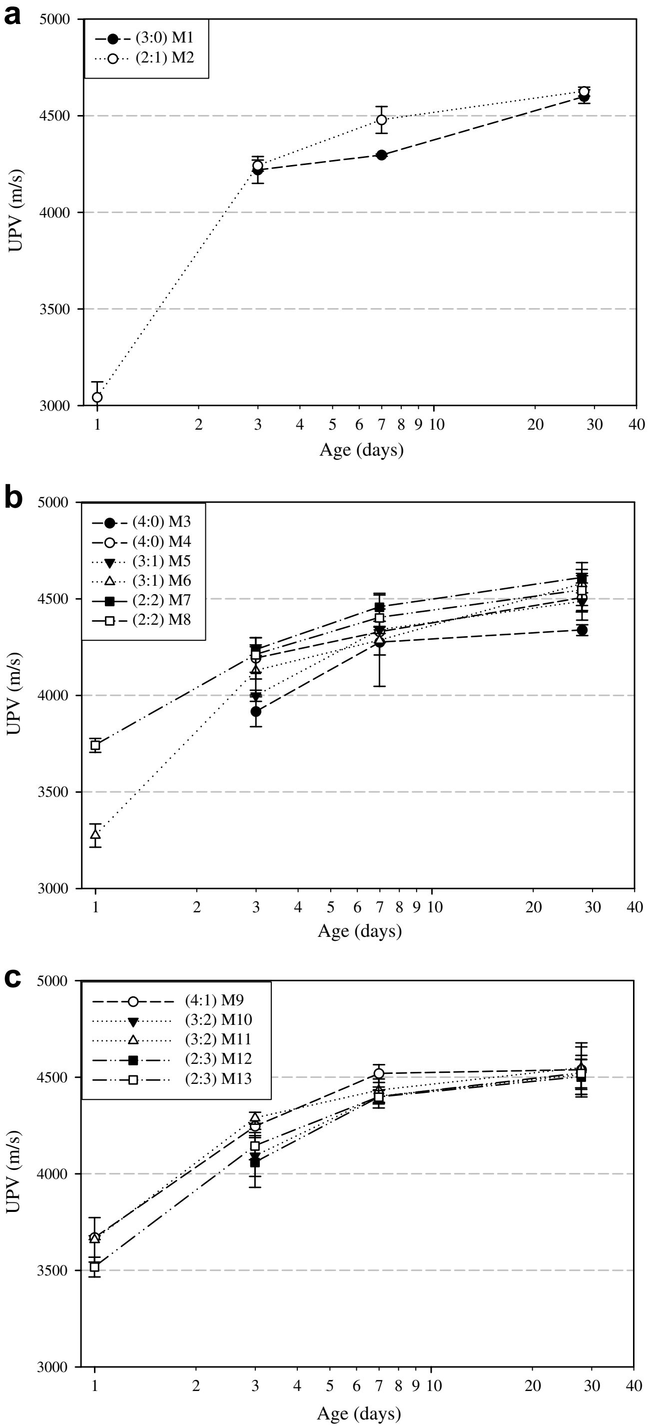

Fig. 6. Ultrasonic pulse velocity development for concrete with a total cementing material content of (a) 270 kg/m^3, (b) 360 kg/m^3, and (c) 450 kg/m^3.

Table 4
Hardened density of concrete (kg/m^3)

Mix#	(OPC:GGBFS)		3 day	7 day	28 day
M3	4:0	Mean	2419	2428	2389
		σ	10	8	15
M5	3:1	Mean	2447	2466	2430
		σ	14	5	10
M7	2:2	Mean	2447	2457	2432
		σ	18	3	9
M10	3:2	Mean	2457	2472	2445
		σ	15	14	11
M12	2:3	Mean	2448	2465	2451
		σ	1	16	17

at 28 days, is it discriminatory towards concrete containing high percentages of GGBFS because the latter hydrates slower in comparison to OPC concrete? By reviewing the mechanical and physical properties of the 13 mixes, one observes that the compressive strength, UPV and hardened density measurements do not reflect the observation that increasing the GGBFS content decreases the amount of chemical hydration reactions at 28-day. These results show that lower amount of hydration reactions of the cementing material containing GGBFS is compensated for by the physical filler effect of the fine GGBFS grains. However, the measurements of non-evaporable water content for the six pastes, which provides a measure of the degree of hydration, revealed that the degree of hydration depends on the percentage of GGBFS, w/b ratio and the curing regime. These findings show that the measurements of compressive strength, density and UPV at 28-day do not reflect the same trend as those measured for non-evaporable water content. This implies that concrete containing high percentages of GGBFS, although displays high values for compressive strength, density and UPV, according to Figs. 3 and 4, still possesses a high percentage of unhydrated cement and GGBFS particles.

Using the same cementing material proportions as presented in Table 2, the implications of GGBFS as cement replacement on the salt scaling resistance were investigated using MTO LS-412 test method [20,31]. The tests were conducted on concrete containing 0% to 60% GGBFS as cement replacement at 28 days [31], 120 days [20], and 2 years [31].

The data in Table 5 shows that increasing the GGBFS as cement replacement or the w/b ratio increased the scaling losses of concrete when tested at 28 days and 120 days. The results also revealed that after two years, mixes containing 40%, 50% and 60% GGBFS as cement replacement have 42%, 45% and 23% lower scaling mass losses,

Table 5
Influence of age, total binder and w/b ratio on cumulative mass loss after 50 freeze–thaw cycles

Reference		[31]	[20]	[31]
Age		28 days	120 days	2 years
w/b ratio		0.31	0.38	0.38
GGBFS (%)	Binder Content (kg/m^3)	Cumulative Mass Loss (kg/m^2)		
0	360	0.28	0.4	1.45
25	360	0.31	0.5	0.86
40	450	0.39	0.81	0.47
50	360	0.72	1.47	0.81
60	450	0.73	2.44	1.88

respectively, in comparison to the mass losses at 120 days. Mixtures containing 0% and 25% GGBFS have an increase of 260% and 70% in their mass losses, respectively, when tested at two years. In comparison to the evolution of compressive strength from 28 days to 120 days for a binder content of 360 kg/m^3, strength of mixes that contain 0%, 25% and 50% GGBFS increased by 0%, 11% and 9%, respectively, and for a total binder of 450 kg/m^3, the strength of mixes containing 40% and 60% GGBFS increased by 19% and 8%, respectively. These results indicate that the strength of concrete containing GGBFS continued to increase by at least 10% from 28-day to 120-day and that the mass loss due to scaling decreased significantly after 2 years for the mixtures containing more than 25% GGBFS as cement replacement. These results demonstrate that testing the mechanical properties of concrete containing high percentages of GGBFS as cement replacement at 28 days can be misleading since the chemical hydration reactions continue for these mixtures. Moreover, testing the freeze–thaw de-icer salt scaling performance of concrete at 28 days can also be misleading since the scaling test results have yielded better performance for OPC concrete at 120 days compared to 2 years and worse performance for concrete containing GGBFS as cement replacement at 120 days compared to 2 years.

5. Conclusions

Findings from this study reveal the following:

- Owing to the greater degree of hydration, increasing the w/b ratio from 0.31 to 0.38, increases the compressive strength of concrete containing up to 60% GGBFS as cement replacement.
- The compressive strength, hardened density and UPV measurements developed by 28 days for concrete containing up to 60% GGBFS as cement replacement are similar or superior to OPC concrete.
- For the same degree of hydration, the physical effect of the GGBFS particles lead to an increase in the density, microstructural homogeneity and compressive strength of the concrete.
- The 28-day compressive strength of concrete mixtures with a total cementing content of 450 kg/m^3 is found to be influenced by the pore space available more than the amount of mix water and the percentage of GGBFS added.
- At 3-day, the evolution of compressive strength is similar to that of non-evaporable water content measurements. The trend is however found to differ at 28-day.
- Degree of hydration of paste containing varying percentages of GGBFS depends on the amount of GGBFS, w/b ratio and the curing regime.
- Compressive strength of concrete increases 10–20% from 28 days to 120 days depending on the percentage of GGBFS and binder content. This implies that the compressive strength of concrete at 28-day needs to be re-evaluated for concrete containing high percentages of GGBFS.
- Based on the measurements of non-evaporable water content and mass loss due to scaling, it is concluded that the scaling resistance test for concrete at 28-day is favorable towards OPC concrete and provides lower resistance for concrete containing high percentages of GGBFS as cement replacement.

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