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Durability of mortar and concretes containing slag with low hydraulic activity

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ABSTRACT

Granulated blast furnace slag has been widely used as a partial substitute for Portland cement in many applications because of advantages which include cost reduction, reduction in heat evolution and improvement of durability properties. However, the effectiveness of slag depends on its hydraulic reactivity. In this paper, the results of an experimental study on the effect of slag with low hydraulicity on the mechanical and durability properties of concrete and the performance of mortar under sulfate attack are discussed. Special attention is given to gas permeability and water absorption of slag concrete. The durability of slag concrete is improved at long term at low Water/Binder ratio. Sulfate resistance of mortar is improved by slag replacement up to 30%.

1. Introduction

Compressive strength which is usually used to estimate concrete quality is a first order parameter in good concrete structural design. Currently, the importance of concrete durability is being more and more accepted. Thus, it represents a major consideration in structural design. The durability of concrete is directly affected by its performance in aggressive environments or indirectly by the shape of its porous structure and, consequently, its permeability. Permeability of concrete is believed to be the major index for durability, as it governs the transport of liquid and gaseous phases into concrete and affects durability properties such as carbonation, sulfate attack, and alkali-aggregate reaction [1,2].

Ground granulated blast furnace slag (GGBFS), which is produced as a by-product during the manufacture of iron, is among the most used mineral additions, as this is an effective way for cement manufacturers to preserve environment, increase cement production and improve the durability properties of concrete. GGBFS, when mixed with cement, reacts with the hydroxide of calcium resulting from clinker hydration to form additional hydrated calcium silicate. The resulting cementing matrix presents good chemical resistance and a more refined pores structure [3,4]. The addition of slag in concrete, especially at high rates, can have the disadvantage of low strength at early ages [5]. In addition, the use of GGBFS in concrete improves compressive strength at latter age, reduces heat of hydration and reduces permeability [6]. However, the effectiveness of slag depends on its hydraulic reactivity, which is mainly influenced by the reactive glass content and composition, chemical composition and fineness [7,8]. Indeed, slag cement with good compressive strength can be obtained by using clinker with high C_3S content or with high fineness. However, the pozzolanic reaction of slag, which improves durability of concrete performance, is related to the hydraulic activity of slag.

The low hydraulic activity slag is usually either used as aggregates in road construction, put in infill or as cement replacement material at a low rate not exceeding 20% [9]. Bougara et al. [10] proposed a mechanical activation of Algerian slag by increasing its fineness (>3600 cm^2/g) to allow wider use (30–50%). However, few investigations have been carried out to evaluate the effect of similar low reactivity slag on concrete durability under severe environmental conditions. Deteriorations of concrete are frequently observed in structures exposed to groundwater or soils containing high concentrations of sulfate, particularly in the south and south-east of Algeria and hence the need to investigate concrete sulphate resistance [11].

Several researchers have shown the beneficial effect of using blast furnace slag in sulphatic environment. Indeed, Higgins [12] found for 60% slag concrete an expansion ten times lower than that for control concrete conserved in sodium sulfate. Nevertheless, the beneficial effect of slag is proportional to the chemical composition and fineness of cement and slag used, and is attributed to the decrease in the overall rate of C_3A and the reduction of the amount of $Ca(OH)_2$ resulting from the pozzolanic reaction of slag [13].

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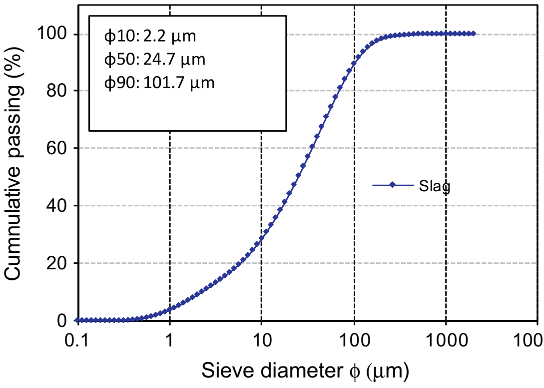

Fig. 1. Laser granulometry of slag.

This paper reports on an experimental study on the effect of Algerian low activity slag as cement replacement on properties of hardened concretes and durability of mortars under sulfate attack.

2. Experimental program

2.1. Materials used

Ordinary Portland cement (OPC) type CEMI, with a fineness of 3100 cm^2/g was used for all concretes and mortar mixes. The GGBFS used in this work was from the iron and steel company of El-Hadjar (Algeria). Its glass content is 92%. The GGBFS was ground in a laboratory mill to a Blaine specific area of 4150 cm^2/g it is laser granulometry is presented in Fig. 1. The chemical composition of the cement and the slag are given in Table 1.

The fine aggregates used for mortars were standardized sand with maximum particle size of 2 mm. The sand used for concrete mixes was a siliceous sand of 5 mm maximum aggregates size. The fineness modulus and the specific gravities of the sand were 2.75 and 2.58 respectively. The coarse aggregates used were natural crushed limestone stone, having a maximum size of 15 mm (G1) and 25 mm (G2). A polycarboxylate modified concentrate superplasticiser (SP) with a density of 1.11 was used.

2.2. Mix proportions and specimen preparation

For the various concrete mixes used in the present study, the binder (cement + slag) content was 365 kg/m^3. The percentage of GGBFS used was 0%, 15%, 30% and 50% as mass cement replacement. The W/B (Water/Binder) ratio was kept constant at 0.65 for mixes without superplasticisers and at 0.42 for mixes with superplasticisers. The different concrete mixtures used in this work are presented in Table 2.

The mortar is realized with W/B ratio of 0.5. The binder (B) consists of OPC cement and different rates of GGBFS (0%, 10%, 20%, 30%, 50% and 60%).

The specimens were cast in steel moulds and compacted in two layers using choc table for mortars and vibrating table for concretes. The specimens were demoulded after 24 h and cured under water saturated with lime at a temperature of 20 °C until time of testing.

2.3. Tests procedures

2.3.1. Concrete tests

Compressive strength of concrete was conducted according to EN 12390-3 standard [14] at 28 and 90 days on cubic prisms of 70 mm in size. The results reported are the average of three samples.

Water capillary absorption was carried out using cubic prisms of 70 mm in size. In order to ensure single direction of water flow, specimens were sealed by epoxy resin on the sides and stored in water on their cross section with a constant water height of 4 mm (Fig. 2). The preconditioned of samples is carried on according to AFREM recommendation [15]. After 28 and 90 days of water curing, water absorption of the samples was measured after 1, 4, 9, 16, 36, 49, 64 and 81 min. For one dimensional flow, the sorptivity coefficient (*S*) is determined by the following equation:

$$Q/A = S \times \sqrt{t} \tag{1}$$

where *Q*/*A* is the cumulative water absorption per unit area of inflow surface, *S* is the sorptivity coefficient ($kg/mm^2/h^{0.5}$) and *t* is the elapsed time.

Nitrogen permeability of the different concrete mixes was measured at 90 days, on preconditioned cylindrical specimen 150 mm (diam.) × 50 mm using Cembureau apparatus as shown by the schematic diagram in Fig. 3. Test and preconditioned procedures are detailed elsewhere [16]. For concrete mixtures with W/B ratio = 0.65, three inlet pressures (1.5, 2 and 2.5 bars) were used for each specimen. However, in the case of concrete mixtures with W/B ratio = 0.42, four inlet pressures (1.5, 2, 2.5 and 3 bars) were

Table 1
Chemical composition of cement and slag used.

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	Loss on ignition	SO_3	CaO
OPC	65.7	21.7	5.20	2.70	0.70	0.44	0.70	0.3	0.6
Slag	42.84	41.20	9.19	3.44	2.12	0.7	0.10	0.2	0.15

Table 2
Composition and properties of concrete used.

Concrete	W/B	Binder (kg/m^3)		Aggregates (kg/m^3)			SP[a] (%)	Slump (mm)	Compressive strength (MPa)		
		Cement	Slag	Sand 0/5	G1 8/15	G2 15/25			7 days	28 days	90 days
A0	0.65	365	0	734	468	655	–	75	–	36.47	42.05
A15		310	55	734	468	655	–	80	–	33.03	35.69
A30		205	110	734	468	655	–	97	–	28.48	40.16
A50		182.5	182.5	734	468	655	–	104	–	16.57	33.42
B0	0.42	365	0	734	468	655	1.8	55	51.85	61.71	65.57
B15		310	55	734	468	655	1.8	61	43.18	60.98	63.17
B30		205	110	734	468	655	1.8	58	43.34	59.93	65.31
B50		182.5	182.5	734	468	655	1.8	64	24.77	53.52	62.11

[a] SP: Superplasticiser per weight of cement.

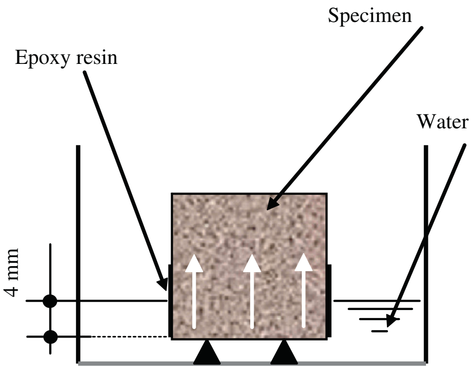

Fig. 2. Schematic diagram of water absorption test.

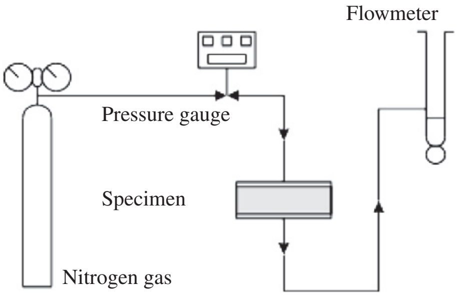

Fig. 3. Schematic diagram of gas permeability test.

used. The gas permeability coefficient is given by following equation:

$$k = (2 \cdot P_a \cdot Q \cdot L \cdot \mu)/A \cdot \left(P_0^2 - P_a^2\right) \tag{2}$$

where Q is the volume flow rate (m^2/s^{-1}), L is the sample thickness (m), P_0 is the inlet pressure ($N\,m^{-2}$), P_a is the outlet pressure assumed in this test to be equal to atmospheric pressure ($N\,m^{-2}$), A is the sample cross-sectional area (m^2), and μ is the dynamic viscosity of nitrogen gas at test temperature ($1.76\ 10^{-5}\ N\,s\,m^{-2}$ at 20 °C).

2.3.2. Mortars durability tests

Sulfate resistance was evaluated using normalized mortar samples previously stored in water at 20 °C during two months. They were immersed in two different sulfate solutions which were renewed every two months (5% sodium sulfate (Na_2SO_4) and 5% magnesium sulfate ($MgSO_4$)), while a set of control samples was stored in 20 °C water. The compressive strength was evaluated on 40 × 40 × 160 mm samples, after 2, 3, 6 and 10 months of immersion. The relative compressive strength after a given time of exposure was calculated as the ratio of compressive strength in sulfate solution to the compressive strength in water. In addition, expansion was measured during 12 months of immersion on prismatic sample (25 × 25 × 285 mm), according to ASTM C-267 standard [17].

Table 3
Chemical indices of slag.

Chemical indexes	Calculated values	Requirement for good performance [18–20]
$I_1 = (CaO + Al_2O_3 + MgO)/SiO_2$	**1.31**	1.3–1.4
$I_2 = (CaO + 0.56Al_2O_3 + 1.4MgO)/SiO_2$	**1.24**	>1.65
$I_3 = (CaO + MgO + 2/3Al_2O_3)/(SiO_2 + 1/3Al_2O_3)$	1.15	>1
$I_4 = CaO/SiO_2$	1.04	Max. 1.4
$I_5 = (CaO + MgO)/(SiO_2 + Al_2O_3)$	0.89	1.0–1.3
$I_6 = (CaO + MgO)/SiO_2$	**1.09**	>1.4

Table 4
Hydraulic efficiency index of slag *h*.

	7 days		28 days	
	CEM I – 32.5	CEM I – 52.5	CEM I – 32.5	CEM I – 52.5
σ_1 CEM I (MPa)	25.75	35.25	36.35	58.5
σ_2 (50%CEM I + 50% slag) (MPa)	12.85	19.00	25.73	41.0
$h = \sigma_2/\sigma_1$	**0.50**	**0.54**	**0.70**	**0.70**

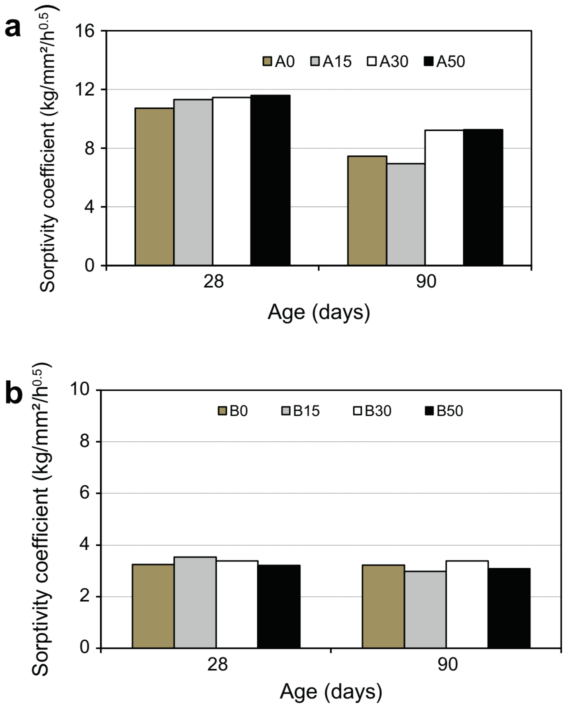

Fig. 4. Coefficient of absorption of concrete with: (a) W/B = 0.65 and (b) W/B = 0.42.

3. Results and discussion

3.1. Hydraulic activity of slag

The hydraulic activity of the GGBFS was evaluated by the chemical indexes recommended by different standards, as well as those developed in literature [18,19] (Table 3). Among the calculated indexes for the slag used, three indexes are out of the recommended values. Moreover, the hydraulic efficiency index *h* (NF P 18-506) [20], which is the ratio of compressive strength of mortar with 50% cement and 50% slag to that of mortar with cement only, was evaluated at 7 and 28 days using two Portland cements with different compressive strength classes (Table 4). According to the standard, the hydraulicity of the considered GGBFS is classed as low to almost medium. Similar results on the reactivity of the same slag were found by other researchers [9]. Based on a study on compressive strength, evolution of heat of hydration and microstructural development of cement pastes with 50% slag, Bougara et al. [21] have also shown the low activity of Algerian slag in comparison with a known UK slag.

3.2. Concrete performances

3.2.1. Compressive strength

The development of compressive strength of concrete mixtures with and without GGBFS for different W/B ratios with age is given in Table 2. In concrete with W/B ratio = 0.65, a reduction of compressive strength with the increase of GGBFS content at the age of 28 days is observed. This reduction is more pronounced for concrete mixture containing 50% of GGBFS as cement replacement. At 90 days wet curing, compressive strength for concrete mixtures incorporating 15% and 30% of GGBFS were found to be comparable to that of OPC concrete. Kenai and Amrane [22] found that up to 35% of Algerian slag can be used without affecting the mechanical properties of concrete and attributed the lower replacement level to the low reactivity of the slag used.

The reduction of W/B ratio from 0.65 to 0.42 seems to have a beneficial effect on the compressive strength of concrete mixtures containing GGBFS.

Despite a low compressive strength at early age (7 days) of GGBFS concrete, a good activation of GGBFS for substitution rate below 30% seems to occur after 28 days moist curing. At 28 days of age, a comparable compressive strength to that of concrete reference B0 was obtained for concrete mixtures B15 and B30. However, a noticeable reduction in strength ($\sim$13%) is observed for B50 concrete mixtures compared to concrete mixture without GGBFS. At 90 days, compressive strength of GGBFS concrete with 0.42 W/B ratio was similar to that of OPC concrete, independently of the rate of GGBFS. The chemical composition of the slag and especially the low alumina content and the higher manganese and iron oxide contents have led to the low compressive strength at early age and to the slow development of compressive strength at later ages [21].

3.2.2. Water capillary absorption

Fig. 4 illustrates the sorptivity coefficient of concrete mixtures with respect to GGBFS content for W/B ratio of 0.65 and 0.42 at the age of 28 and 90 days. It can be seen that the coefficient of sorptivity decreases with age of curing and W/B ratio. Nevertheless, the presence of GGBFS generates an increase in the sorptivity for concrete mixtures with W/B ratio of 0.65 at 28 and 90 days of curing. As the W/B ratio decreases to 0.42, the sorptivity coefficient at the age of 28 days is similar for all concrete mixtures studied in the present work. At the age of 90 days, a slight reduction of sorptivity coefficient is noticed for concretes containing GGBFS, particularly for concrete mixture B50 where the value of coefficient is 3.05 kg/mm^2/h$^{0.5}$ compared to 3.23 kg/mm^2/h$^{0.5}$ for concrete mixture B0. Alexander and Magee [23] have found that concrete with 50% of GGBFS as cement replacement and a W/B ratio of 0.49 decreases the capillary absorption coefficient by 9% in comparison with concrete mixtures without GGBFS. This has been confirmed by other researchers particularly for higher than 50% GGBFS content [24]. This reduction can be explained by the more refined structure of the pores and the reduction of the capillary porosity, which is due to the formation of the secondary *CSH* gel issued from the pozzolanic reaction of slag [3].

3.2.3. Nitrogen permeability

The gas permeability results of GGBFS concrete mixtures with W/B ratio of 0.65 and 0.42 are presented in Fig. 5. From this figure, the low hydraulic reactivity of the GGBFS used in the present work can be noticed for concrete mixtures with the higher W/B ratio of 0.65. It can be also seen that the use of higher GGBFS content increases the gas permeability. This result can be partially explained by the low compressive strength of A15, A30 and A50 concrete mixes compared to that of concrete reference (A0). For concrete mixtures with W/B of 0.42, the positive effect of reducing the W/B ratio is noticed, as the gas permeability values were similar to

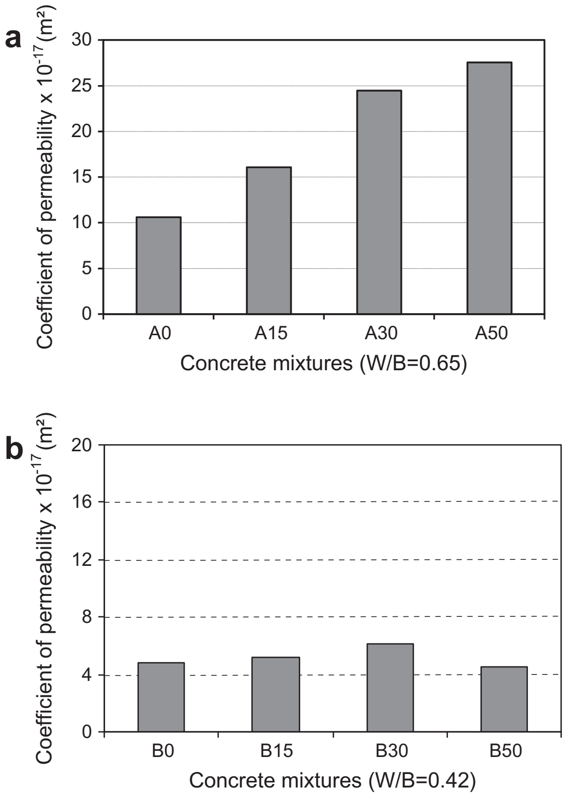

Fig. 5. Gas permeability coefficient of concrete with: (a) W/B = 0.65 and (b) W/B = 0.42.

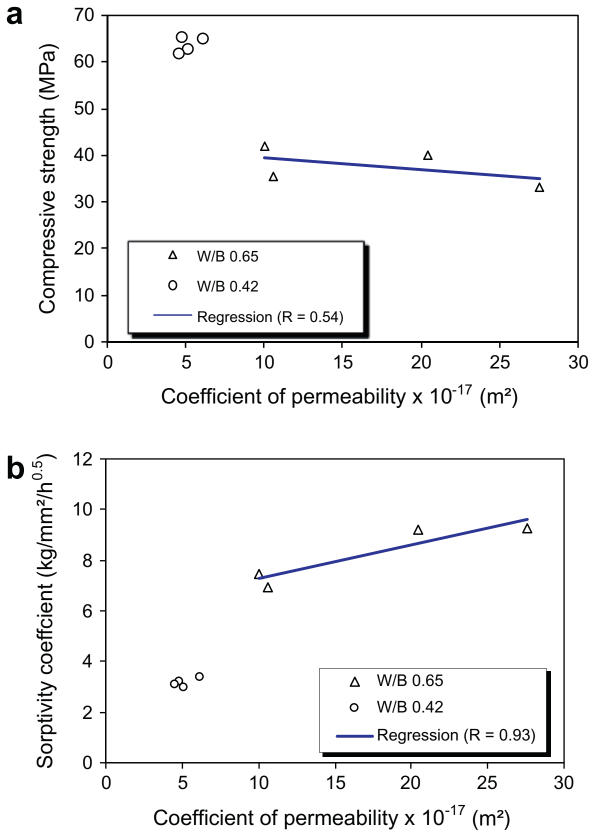

Fig. 6. Relationship between gas permeability coefficient and (a) compressive strength and (b) water absorption coefficient.

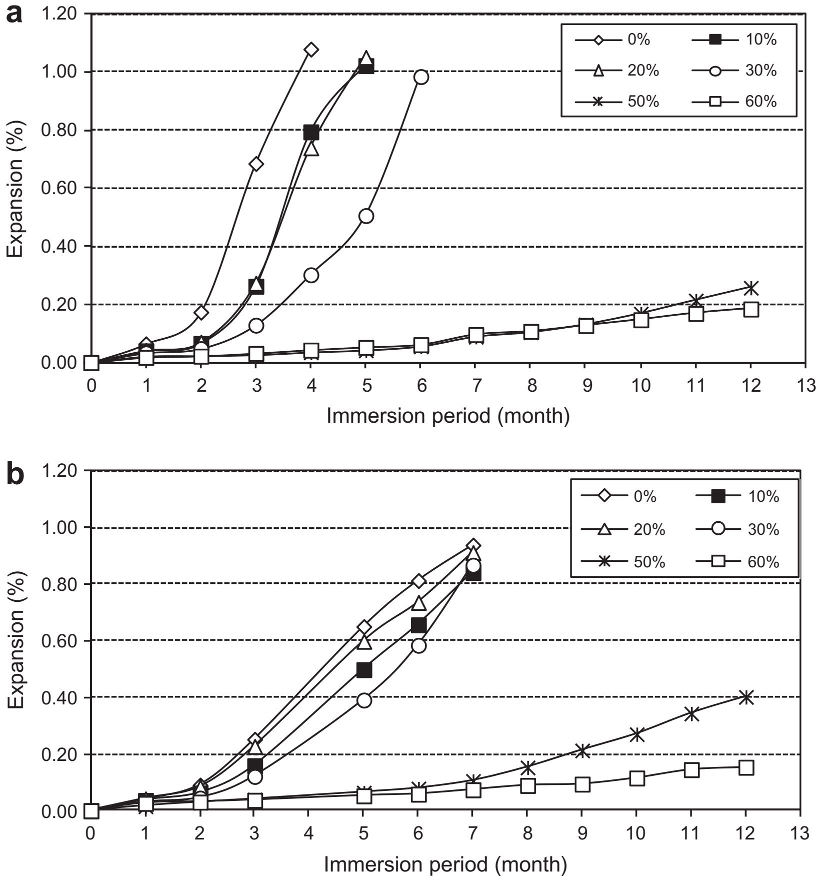

Fig. 7. Expansion of mortar immersed in (a) 5% Na_2SO_4 and (b) 5% $MgSO_4$.

that of concrete with GGBFS and range from 4.50×10^{-17} m^2 to 6.15×10^{-17} m^2 and even a slight reduction is recorded for concrete mixtures containing 50% of GGBFS. Several researchers reported a reduction of the gas permeability for water cured concretes containing more than 50% slag as cement replacement after the age of 28 days [23–25]. Nevertheless, this improvement of gas permeability is conditioned by the activity of slag and a prolonged water curing period for concrete [7,26]. The reduction of the W/B ratio reduces the capillary porosity and consequently the spaces between the grains of clinker and the slag. This leads to a relative increase in the volume of hydrates in the cementing matrix, encouraging the activation of slag by calcium hydroxide $Ca(OH)_2$ resulting from the hydration of clinker [7,27].

3.2.4. Correlations

The correlations between gas permeability coefficient and both compressive strength and sorptivity coefficient, for normal and GGBFS concretes at 90 days are represented in Fig. 6.

For concretes with W/B ratio = 0.65, a linear correlation is observed in the two relationships showing a decrease in gas permeability with increasing compressive strength and with decreasing sorptivity. However, the permeability coefficients exhibits a better correlation with water absorption ($R = 0.93$) than with compressive strength ($R = 0.54$). This can be attributed to the fact that the studied properties depend on different parameters of the porous structure. Indeed, the compressive strength is mainly ruled by the matrix porosity while the gas permeability and the capillary water absorption are mostly linked to the specific parameters of the porous structure, as the mean radius, the tortuousity and the pores size distribution [26,28]. No correlation could be given for W/B ratio = 0.42 as the ranges of the values of compressive strength, permeability coefficient and sorptivity coefficient were small.

3.3. Sulfate attack

3.3.1. Expansion

The expansion of the mortars immersed in the 5% Na_2SO_4 and 5% $MgSO_4$ solutions is presented in Fig. 7. A higher expansion is observed for the samples stored in the Na_2SO_4 solution, by comparison to the ones stored in the $MgSO_4$ solution.

The incorporation of GGBFS into the cement leads to a diminution of the expansion for the mortars stored in the two sulfate solutions. The OPC-based mortar reached a maximum expansion (>1%) after only four months immersion in the Na_2SO_4 solution. Then, the mortar with 30% GGBFS showed an expansion diminution of about 73% compared to the OPC mortar. The same tendency was observed for the mortars stored in the $MgSO_4$ solution, for which after 6 months of immersion, 10% and 30% GGBFS led to a reduction of about 19% and 28%, respectively. The mortars with 50% and 60% GGBFS presented in the two solutions a low expansion, not exceeding 0.06% after six months and 0.40% after 12 months immersion. The low expansion of the GGBFS cement mortars was observed by several researchers, notably for cements containing more than 50% GGBFS and particularly in sodium sulfate environment [12,28]. The high expansion in the OPC mortar is attributed to the formation of secondary ettringite, characterized by cracking and bursting. In the case of slag cements, the C_3A level is lower. Besides, the slag, thanks to its pouzzolanic reaction consuming calcium hydroxide (CH), leads to a diminution of the gypsum formation, and thus of the ettringite. This can explain the diminu-

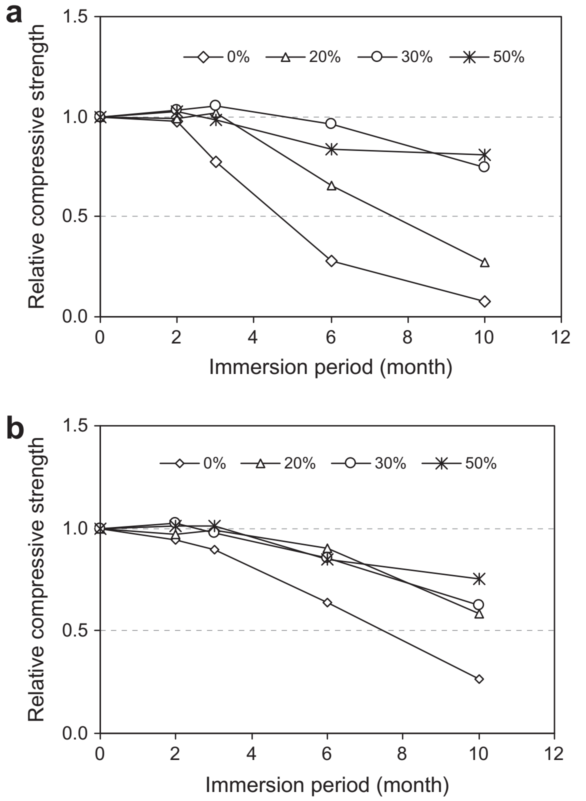

Fig. 8. Relative compressive strength for mortars immersed in (a) 5% Na_2SO_4 and (b) 5% $MgSO_4$.

tion of the expansion observed for cements with more than 30% GGBFS.

3.3.2. Compressive strength

Fig. 8 presents the relative compressive strength of mortars placed in the two sulfate solutions. In the sodium sulfate (5% Na_2SO_4), a strength decrease for the OPC mortar sample is observed at every age and becomes very important after 10 months. However, for GGBFS mortar, we observe a strength increase till three months followed by a strength loss. Nevertheless, for 30% and 50% GGBFS, this loss remains relatively low (18–25% after 10 months). Likewise, the samples stored in magnesium sulfate were subjected to a strength decrease (Fig. 8b), in particular after 6 months immersion. However, after 10 months immersion, compared to the GGBFS mortars (especially with 50%), the mortar without addition underwent a high strength loss, up to 73%. Moreover, for mortars with 30% and 50% GGBFS, the strength loss of the samples immerged in $MgSO_4$ is higher than for the ones immerged in Na_2SO_4. Several studies [28–30] showed a lower resistance of slag cements in the magnesium sulfate than in the sodium sulfate. This can be explained by the aggressive attacks of the magnesium sulfate, resulting in the formation of hydrated magnesium silicates (MSHs), which are slightly cohesive and lead to strength loss.

3.3.3. Flexural strength

The results for the relative flexural strength for specimens immersed in sulfate solutions are given in Fig. 9. After two and three months of immersion, the flexural strength was higher for specimens immersed in sodium sulfate solutions (5% Na_2SO_4) than that for specimens immersed in water. This could be due to the filling of pores by products resulting from the reaction of sodium sulfate with cement hydration products ($Ca(OH)_2$) to form gypsum and ettringite that gives a denser microstructure [11]. After this, the flexural strength is reduced because of micro cracking caused by the sulfate attack. However, the decrease is small after six months immersion for 30% and 50% of GGBFS cement replacement in comparison to 20% replacement level and OPC specimens where the losses were 65% and 85% respectively. After 10 months of immersion, only 50% slag cement replacement level present a slight decrease of about 15%.

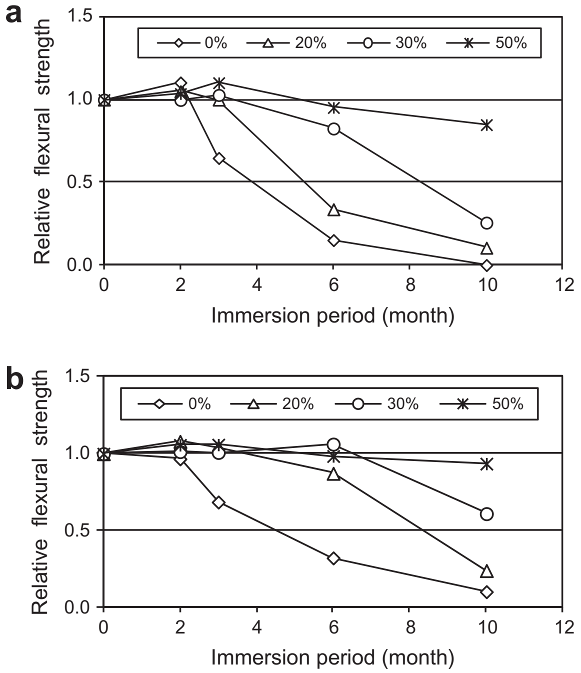

Fig. 9. Relative flexural strength for mortars immersed in (a) 5% Na_2SO_4 and (b) 5% $MgSO_4$.

The immersion in magnesium sulfate solution of 30% and 50% GGBFS specimens present no loss in flexural strength after six months of exposure. After ten months of exposure, OPC and 20% and 30% GGBFS specimens present 90%, 76% and 39% loss of flexural strength, respectively. The performance of 50% GGBFS specimens was much better as they lost only about 10% of their flexural strength.

4. Conclusion

Based on the results of this experimental study, the following conclusions could be drawn:

- Chemicals composition and the compressive strength results confirm the low reactivity of the studied GGBFS.
- The incorporation of up to 30% of low reactivity GGBFS as cement replacement could be used without considerably affecting the mechanical properties of concretes mixtures with higher W/B ratio (0.65). However, reducing the W/B ratio to 0.42 leads to a greater activation of the GGBFS and gives satisfactory concrete mechanical properties, in particularly at long-term for up to 50% GGBFS replacement level.
- Gas permeability and water capillary absorption coefficients of concrete mixtures with a W/B ratio of 0.65 increases with increasing GGBFS content as cement replacement at the age of 28 and 90 days.
- Reducing the W/B to 0.42, water capillary absorption coefficient was found to be similar for all concrete mixtures at the age of 28 days. A slight reduction of the water capillary coefficient

was observed for concrete mixtures with GGBFS at the age of 90 days. Concrete mixtures with 15% and 30% of GGBFS present similar gas permeability coefficients. However, the incorporation of 50% of GGBFS reduces slightly the gas permeability.

- The incorporation of more than 30% of low reactivity GGBFS leads to a notable enhancement of the mortars efficiency against sodium and magnesium sulfate attacks. This results in a limited expansion and a good conservation of the compressive strength.
- A lower resistance of slag cements is observed in the magnesium sulfate solution than in the sodium sulfate solution.

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