Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization,
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Main Proceedings ed. J Zachar, P Claisse, T R Naik, E Ganjian. ISBN 978-1-4507-1490-7
http://www.claisse.info/Proceedings.htm

Transport Properties of Mortars and Concretes Modified with Ground Granulated Blast Furnace Slag

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ABSTRACT

Mechanical characteristics and durability of ground granulated blast furnace slag cement composites depends on the hydraulic activity of the slag. Algerian Blast furnace slag is characterized by a quite slow reactivity. Porosity and transport properties of mixes containing up to 50% OPC replacement are compared and analyzed. Mechanical strength, pore size distribution and capillary water absorption are studied after 28 and 90 days of wet curing. The durability of blast furnace slag cement concrete is evaluated through nitrogen permeability and water penetration depth under pressure. First observations seem to indicate finer porosity and lower water absorption than with 100% CEM I 52.5 mortars. Moreover, lower permeabilities to nitrogen and water are also observed for 50% blast furnace slag substitution.

INTRODUCTION

Currently, the use of supplementary cementitious materials is widespread all over the world. It contributes to the decrease in CO_2 emissions of the cement industry, which accounts for about 5% of the total world emissions [Brand 2004]. In addition, using ground granulated blast furnace slag (GGBFS) cement contributes to recycling by-products thereby increasing the production of cement while preserving the environment. Presenting a latent hydraulic character when it is present in cement, its hydration is related to its hydraulic activity particularly with its dissolution. The dissolution of glass of slag is ensured by the hydroxylic attack (of ions OH- in the presence of water) resulting from the hydrolysis of Portlandite $Ca(OH)_2$ produced by hydration of clinker [Regourd, 1995; Glasser 1996]. Nevertheless, this process is conditioned by the hydraulicity of slag which is mainly influenced by its fineness, its chemical composition and its contents of glass [Neville, 2000; Pal, et al. 2003]. The products of hydration formed in the cementing matrix are mainly additional calcium silicates and aluminates hydrate (CSH, CAH). The resulting cementing matrix presents good chemical resistance and a more refined pore structure [Cheng et al. 2005; Han et al. 2006]. The mechanical performance and durability of concrete is improved. El-Hadjar steel company located in the East of Algeria produces annually about 300 thousand tons which are used mainly in local cement factories at rates not exceeding 20%. This low rate of substitution is justified by the low reactivity of this slag. Indeed, previous studies have shown a limited hydraulicity of this slag [Kenai, et al., 2008; Hadj-Sadok et al. 2008]. However, the same sources report a good chemical resistance to aggressive environments of cement containing this slag, especially for substitution rate exceeding 30%. In addition, it was shown, by considering mechanical strength, a possibility of a larger use of this slag by increasing its fineness [Behim, et al. 2004]. However, few studies were conducted on its effect on durability, in particular on the transport properties of concrete. These properties, which depend mainly on the porosity and the shape and dimensions of the internal structure, are good indicators of the service life of concrete. Indeed, all the mechanisms of degradations, utilize a process of transport in concrete, either in gas phases or in liquid phase [Baroghel-Bouny 2004].

EXPERIMENTATION

Materials used

Ordinary Portland cement (OPC) type CEM I 52.5N with a fineness of 4200 cm²/g was used for mortar mixes. For concretes mixes, OPC type CEM I 42.5 with fineness of 3900 cm²/g was used. The GGBF used in this work was from the iron steel company of El Hadjar (Algeria). The GGBS was ground in a laboratory mill to a Blaine fineness of 4150 cm²/g. Its laser grain size distribution with comparison to OPC (CEMI 52.5N) is presented in figure 1. The chemical composition of cements used and the slag are given in Table 1.

Standardized sand with maximum particle size of 2 mm was used for mortars mixes. The sand used for concrete mixes was a siliceous sand of 5 mm maximum aggregates size. The fineness modulus and the density of the sand obtained are 2.75 and 2.58 respectively. The coarse aggregates used were natural crushed limestone stone, with granulometry 8/15 mm (G_1) and 15/25 mm (G_2). A polycarboxylate superplasticiser with a density of 1.11 was used.

Mix proportion, specimen preparation and curing

The mortar mixes (M0, M30 and M50) had proportions of 1 binder: 3 Sand and Water/Binder (W/B) ratio of 0.5. The binder for mortar M0, M30 and M50, was obtained by partial replacement of cement by 0, 30 or 50% of slag, respectively. All replacements were made by mass of cement. Mortar specimens were cast according to European Standard [EN 196-1 1995]. They were demoulded after 24 h and cured in fog room at 20 ± 2°C and 95% relative humidity until the age of testing.

The concrete mix (C0, C15, C30 and C50) had a total binder (cement + slag) content of 365 kg/m^3, fine aggregate content of 734 kg/m^3 and coarse aggregate (G_1+G_2) content of 1123 kg/m^3. The percentage of GGBS used was, respectively, 0, 15, 30 and 50% as mass cement replacement. The W/B was kept constant at 0.42 for all mixes. Specimens were cast in steel moulds and compacted with vibrating table. After casting, concrete specimens were left covered in the fog room for 24 h, and then demoulded and stored in water saturated with lime at 20 ± 2°C until the test age.

Table 1. Chemical Composition of Cements and Slag Used

	SiO_2	CaO	Al_2O_3	MgO	Fe_2O_3	CaO libre	SO_3	Loss ignition
OPC (CEM I 42.5)	21.87	62.41	5.32	1.06	3.28	0.17	2.73	2.02
OPC (CEM I 52.5)	18.40	61.30	5.60	0.9	3.80	0.20	3.30	2.20
Slag	31.20	42.84	9.19	2.12	3.44	-	-	0.20

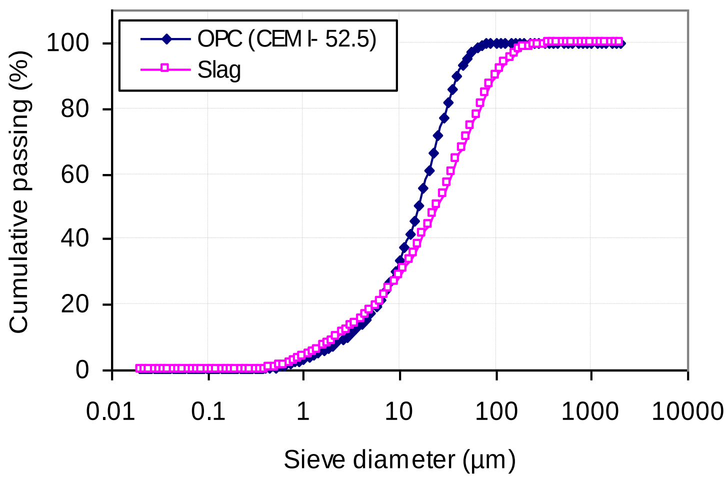

Fig. 1. Laser Granulometry of Cement and Slag

Mortar test procedure

For compression strength test, three prismatic specimens of 40x40x160 mm are made and compression strength is measured according to EN 196-1 at 7, 28 and 90 days of age.

Total free water porosity (*Pw*) was determined by water absorption tests on cylindrical specimens (80 mm (diam.) × 40 mm) after 28 and 90 days curing according to the procedure given by AFREM. First, the specimen is heated to 105°C until dry (less than 0.1% mass change in 24 h). After weighing, specimens are immersed in a container of water at 20 ± 2°C. Each specimen is removed from water, wiped off with a damp cloth and weighed (wet mass). The immersion continues until there is no variation of mass greater than 0.1% after 24 h.The pore size distributions of the different mortars studied have been investigated using Mercury Intrusion Porosimetry (MIP). A Pascal 240 porosimeter was used. The apparatus Intrusion was examined in a pressure range up to 200 MPa, allowing investigating pore to which the radius is included between 7.5 µm and 3.7 nm. The test is realised on mortar samples, of approximately 2 cm^3, oven-dried at 50°C in presence of silica gel until constant mass. The porosimetry test was carried out at 28 and 90 days, and for each mix at least two samples were tested.

90 days wet cured cylindrical samples of 80 mm (diam.) and 40 mm height are dried in an oven at 45 ± 5 °C until constant weight (minimum 7 days) were used for water absorption by capillary test. Samples are then stored in water on their cross section with a constant water height of 2 mm. Water absorption was measured at 4, 9, 16, 36, 49, 64 minutes and 4, 8 et 24 hours and water absorption coefficient *S* is determined in accordance with EN 1305.

Concrete test procedure

Gas permeability of concrete mixes was measured after 90 days of curing, on preconditioned cylindrical specimen 150 mm (diam.) × 50 mm using Cembureau method [Kollek 1989]. Nitrogen gas was used in this investigation. Four inlet pressures (1.5, 2.0, 2.5 and 3.0 bars) were used for each specimen. The gas permeability coefficient is given by equation (1).

$$k = (2.P_{a.}Q.L.\mu) / A.(P_0^2.-.P_a^2) \quad (1)$$

Where Q is the volume flow rate (m^3/s^{-1}), L is the sample thickness (m), P_0 is the inlet pressure (Nm^{-2}), P_a is the outlet pressure assumed in this test to be equal to atmospheric pressure (Nm^{-2}), A is the sample cross-sectional area (m^2), and μ is the dynamic viscosity of the fluid at test temperature (Nsm^{-2}).

Water penetration depth under pressure for concretes mixtures was determined in accordance to DIN 1048**,** after 90 days curing. Before the test, the samples are oven-dried at 105°C until the mass became constant. In this investigation, 3 bars water pressure was applied at the bottom of the cube specimen of 150 mm in size for 24 h (Figure 2). At the end of the test, the specimen was removed from the permeability cell and then split into two halve in order to measure the penetration depth. The results presented are the average of two samples.

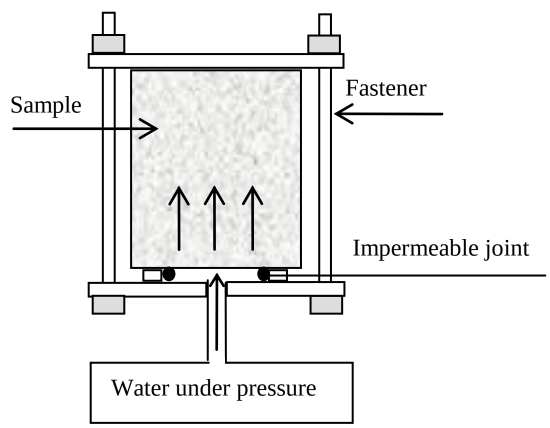

Fig. 2. Schematic Diagram of Water Penetration under Pressure Test

RESULTS AND DISCUSSIONS

Porosity and pore size distributions

Total water porosity, mercury porosity, threshold pore access radius and average radius for different mortar at 28 and 90 days are shown in table 2. Cumulative intruded pore volume curves obtained for different slag mortar are provided in figure 3. Figure 4 shows the corresponding pore size distributions (differential intruded pore volume). The presence of slag increased the porosity of mortars as compared to control specimens at both 28 and 90 days of age. This increase is due mainly to the reduction in the quantity of clinker and to latent hydration of slag. Similar behaviour was observed by other researchers [Shi et al., 2009]. However, it is expected that a comparable porosity will be obtained at later ages.

At 28 days, the pores distribution of slag cement mortar is coarser than that of OPC mortar. The threshold pore access radius and the average radius of pores are higher in mortars M30 and M50 as compared to M0 mortar. At 90 days, on the other side, the pores size distribution for mortars with slag seems to evolve to smaller pores size comparable to that of OPC mortar. Indeed, the threshold pore access radius is comparable for the three studied mortars (approximately 35 nm), which is smaller than that at 28 days (38-40 nm), for all mortars studied. The average radius is less significant in slag cement mortars. However, even after 90 days, mortars with slag (M30 and M50) have a volume of pores higher than that of OPC mortar. This could be due to the high porosity of the CSH resulting from the hydration of slag [Perlot et al. 2006]. Indeed, the increase in the pores volume for mortars with slag (particularly M50) compared to M0 mortar, (Figure 3.b) is produced mainly in the fraction of small pores < 50 nm and particularly between 20 and 4 nm. This class of small pores is attributed to the porosity of the CSH gel which is more present in the matrices containing slag cement [Han et al. 1996; Baroghel-Bouny 1994].

Table 2. Water Porosity (P_W) and Mercury Porosity (P_{Hg}) Threshold Pore Access Radius (r_t) and Medium Radius Pore (r_m) of Cement Slag Mortar

		28 days				90 days		
	P_{Hg} (%)	P_W (%)	r_t (nm)	r_m (nm)	P_{Hg} (%)	P_W (%)	r_t (nm)	r_m (nm)
M0	10.96	17.74	35	34	10.95	15.99	36	33
M30	12.53	17.93	40	38	11.50	17.10	37	30
M50	14.55	19.51	40	36	13.42	18.36	36	27

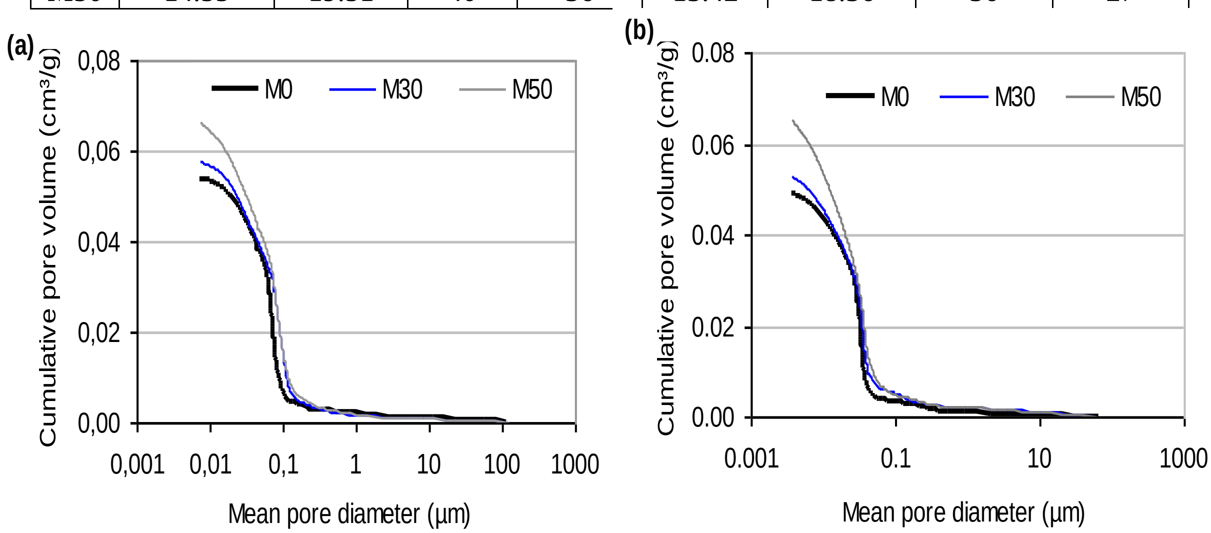

Fig. 3. Cumulative intruded pore volume at 28 days (a) and 90 days (b) for slag cement mortar

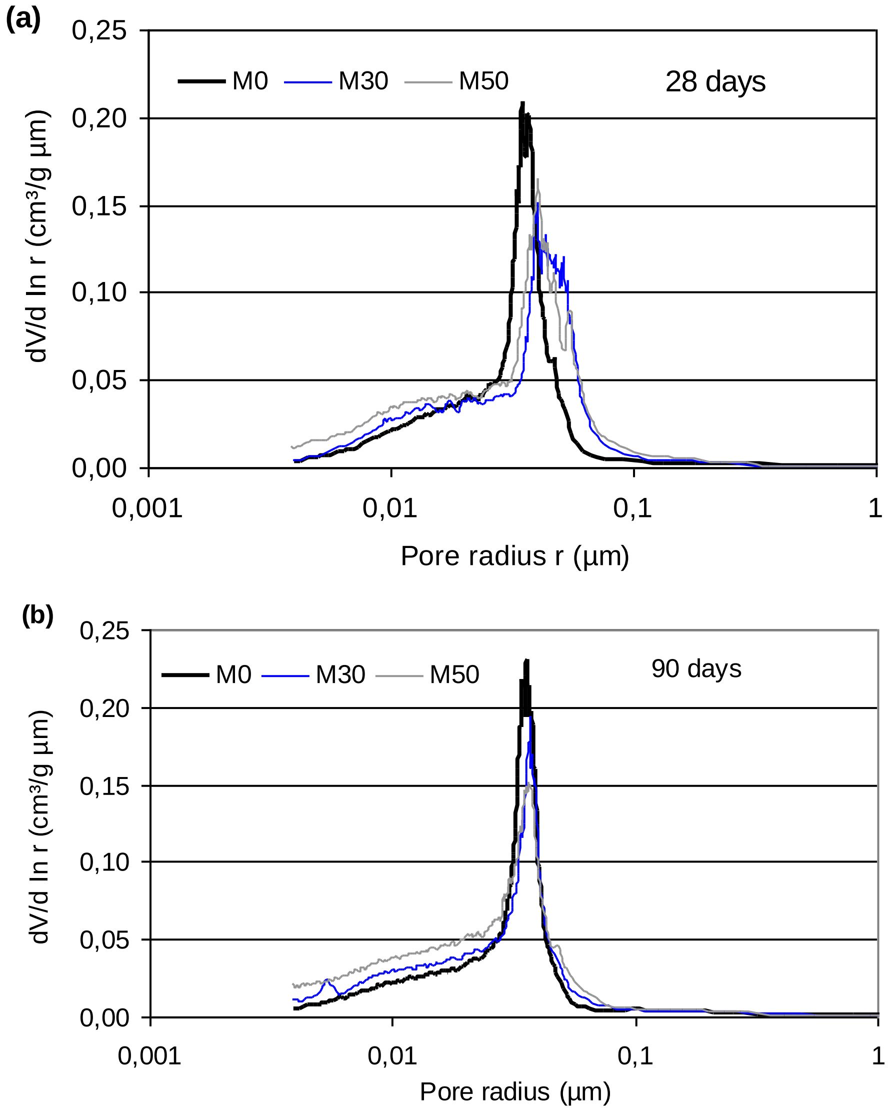

Fig. 4. Pore Size Distribution at 28 Days (a) and 90 Days (b) for Slag Cement Mortar

Compressive strength

The results of compressive strength development of mortars containing ground granulated slag as cement replacement material can be seen in figure 5. The addition of slag resulted in strength decrease of mortars at all replacement levels at 7 and 28 days. This can be explained by the latent hydration and lower hydraulic activity of slag used in this investigation. At 90 days, compressive strength of mortars with 30% slag was found to be comparable to that of mortars without slag. However, a strength reduction of about 18% is recorded for mortar containing 50% of slag. Similar strength decrease was observed by other investigators researches [Kenai et al. 2008; Behim et al. 2004]. However, it should be noted that this decrease can be compensated for with proper mixture proportions. Figure 6 shows the relationship between compressive strength and total water porosity of all mixtures at both 28 and 90 days of age. An increase in compressive strength is associated with an increase in total porosity and a good linear correlation (R^2 = 0.89) is observed between the two properties.

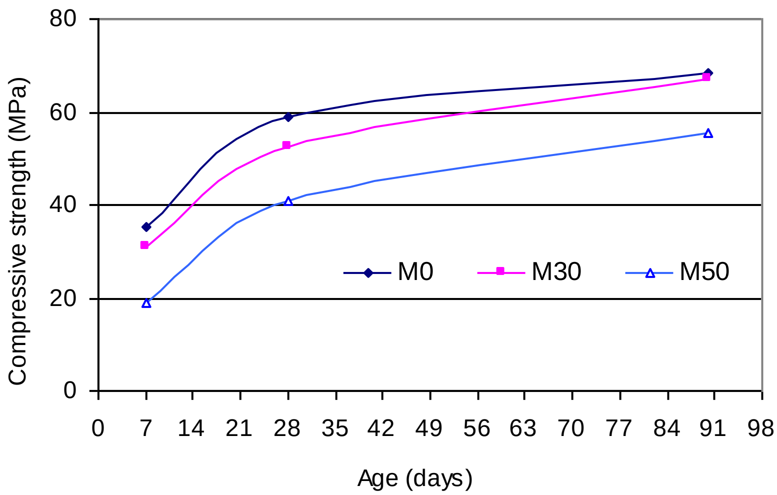

Fig. 5. Development of Compressive Strength of Slag Cements Mortars

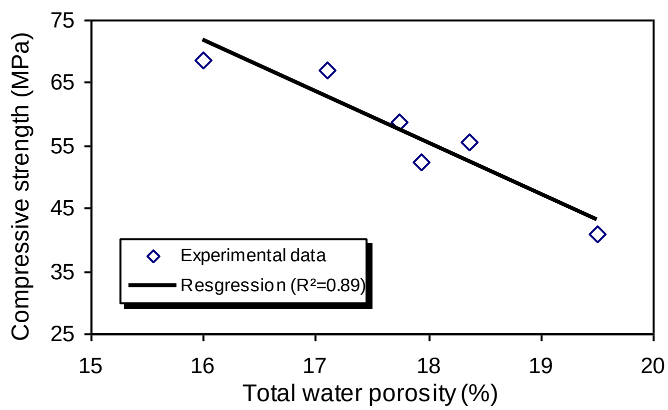

Fig. 6. Correlation between Compressive Strength and Porosity

Capillary absorption

Figure 7 shows the capillary water absorption per unit area as a function of square root of time for all mortar mixtures. Water absorption coefficient *S* (Table 4) was calculated by the gradient of the linear section (between 0 and 8 hours) of the curves presented in figure 7. The evolution of capillary absorption up to 8 hours seems to be comparable for the three studied mortars. Between 8 and 24 hours, M50 mortar presented a low water absorption compared to mortars M0 and M30.

Water absorption coefficient is slightly lower for mortars M30 and M50 compared to that of M0. This can be explained by the more refined structure of mortars containing slag cement following the formation of the CSH gel product by hydration of the slag [Jiang, and Grandet, 1989]. At 90 days, the average radius of the pores was lower in mortars with 30 and 50% of slag than that in the OPC mortar (Table 3). Alexander and Magee [1999] also observed a decrease of the coefficient of water absorption in concrete with 50% of slag and a water/binder of 0.49 in comparison with concrete without slag. This has been confirmed by other researchers, particularly for higher than 50% slag as cement replacement [Guneyisi and Gesoglu 2007].

Table 4: Water Absorption Coefficient of Slag Cement Mortar

	M0	M30	M50
S (mm/h ^{0,5})	5.99	5.75	5.55

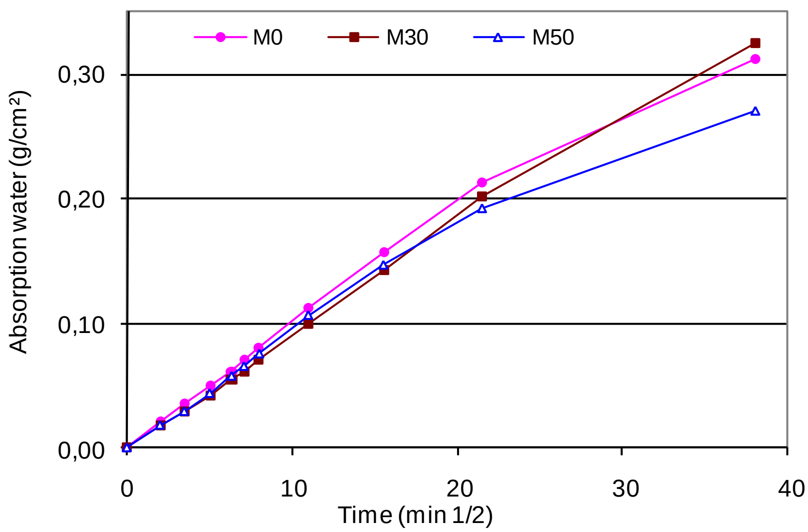

Fig.7. Water Absorbed per Unit Area of Slag Cement Mortar at 90 Days

Gas permeability

The results of the gas permeability of slag concrete mixtures are presented in figure 8. The gas permeability values were similar to those of concrete with and without slag and range from 4.50 $\times 10^{-17}$ m² to 6.15 $\times 10^{-17}$ m² with a slight decrease observed for concrete mixtures containing 50% of slag. GGBF have been found to have a significant reduction in permeability of concrete [Guneyisi and Gesoglu 2007], particularly, those containing more than 50% slag as cement replacement after 28 days of age [Alexander and Magee 1999]. Nevertheless, this improvement of gas permeability is conditioned by the activity of slag and a prolonged water curing period for concrete [Shi et al. 2009]. The low variation of gas permeability coefficient may be explained by the low W/B (0.42) ratio used which led to a more dense structure of concrete with and without slag. Consequently, the pozzolanic effect of slag is not very effective especially since the slag used had a medium hydraulic activity.

Water penetration under pressure

Figure 9 shows the water penetration depth for all concrete mixtures with and without slag at 90 days. A reduction of water penetration depth for concretes with 30 and 50% of slag compared to OPC concrete is observed. This could be explained by the refinement of the porous system following the formation of the additional CSH gel. It results in a higher specific surface for the internal structure, which allows a more significant wetting of the walls surface of pores. Conflicting results are reported on the effect of slag on concrete water permeability. Cheng et al. [2005] noted a reduction in water permeability for concretes with 50% of slag. However, Kenai et al. [1996] observed that water permeability of slag concrete with W/B of 0.55 was comparable to that of OPC concrete and explained this by the low reactivity of slag used.

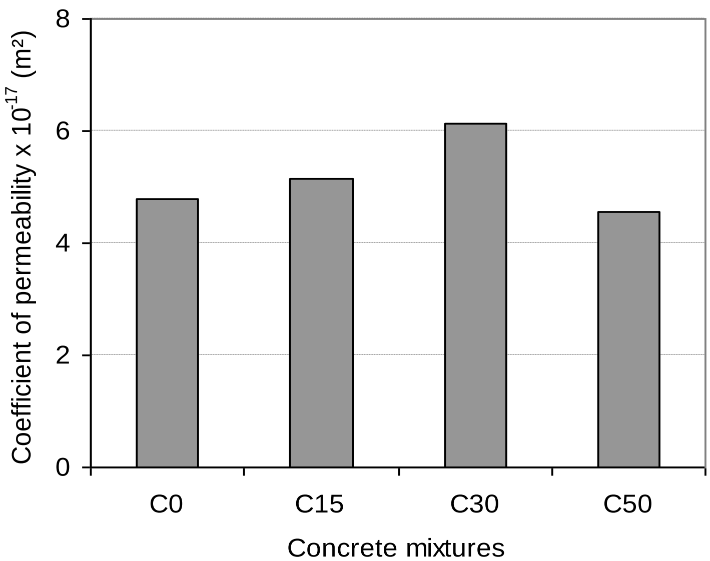

Fig. 8. Gas Permeability Coefficient of Slag Cements Concrete Mixtures

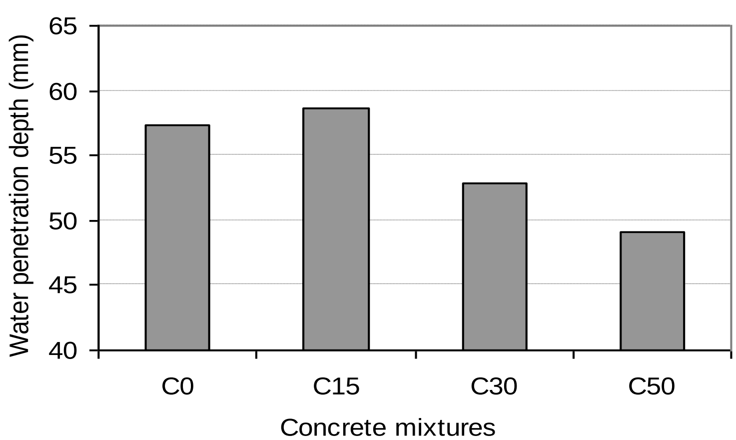

Fig. 9. Water Penetration Depth with Slag Cements Concrete Mixtures

CONCLUSION

The main conclusions to be drawn from the present experimental study are as follows:

- Compression strength was little influenced by the incorporation of 30% of slag to cement. However, 50% of substitution led to a reduction in strength, even after 90 days.
- Porosity of slag mortars is higher at early age than that OPC mortar, but in the long term (90 days), the pore size distribution is more oriented to small pores, especially in the fraction of radius below 50 nm.
- Water absorption of mortar is slightly reduced by the presence of slag, especially for 50% substitution rate.
- Concrete mixtures with 15 and 30% of slag present similar gas permeability coefficients to that of concrete without slag. However, the incorporation of 50% of slag reduces slightly the gas permeability.
- Water permeability of concrete is reduced by cement substitution by slag rate exceeding 30%. This effect is more dominant for concrete with 50% slag.

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