MECHANICAL AND DURABILITY PROPERTIES OF ENVIRONMENTALLY FRIENDLY ULTRA HIGH PERFORMANCE CONCRETE (UHPC)

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Abstract

This paper deals with mechanical and durability performances of more sustainable Ultra-High Performance Concrete (UHPC) by integrating high volumes of Blast Furnace Slag (BFS). Three substitution rates of cement by slag are explored (30%, 50% and 80%). Results show that a slag content of 30% improves slightly the compressive strength of concrete, whereas the strength of UHPCs containing 50% and 80% of slag are significantly reduced, particularly at early age. At 3 days, when the slag content increases, the porosity of UHPC mixtures with high slag content increases. In contrast, at 90 days, the volume of capillary pores decreases greatly and the global pores network becomes finer, when cement is substituted by BFS. This, results in decreasing gas permeability (1.5-6 times) and chloride diffusion (up 4 times). Results show also that all tested UHPCs have quite the same CO_2 depth, after an exposure of 1 year. Indeed, the decrease of porosity, when BFS is added, is balanced by the decrease of pH, which promotes CO_2 diffusion.

Résumé

Le présent article traite des performances mécaniques et de durabilité d'un Béton Ultra-Haute Performance (BUHP) plus durable, avec des teneurs en laitier élevées. Trois taux de substitution du ciment par des laitiers des hauts fourneaux (LHF) sont explorés (30%, 50% et 80%). Les résultats montrent qu'une teneur de 30% de laitier améliore légèrement la résistance à la compression, alors qu’avec 50% et 80% de LHF, la résistance à la compression chute significativement. A 3 jours, lorsque la teneur en LHF augmente, la porosité du béton augmente. A 90 jours, la réaction des LHF induit une diminution de la porosité capillaire et le réseau poreux devient plus fin. Ainsi, la perméabilité au gaz et la diffusion des ions chlore diminuent significativement. Les résultats montrent aussi que tous les bétons testés ont une profondeur de carbonatation similaire, après une année d’exposition au CO_2. En effet, la diminution de la porosité, due à l’ajout des LHF est équilibrée par la diminution du pH, qui favorise la diffusion de CO_2.

1. INTRODUCTION

Ultra-High Performance Concrete (UHPC) is a cement-based composite material, developed by Richard and Cheyrezy in the beginning of 1990s with compressive and tensile strengths of more than 150 MPa and 8 MPa, respectively [1-4]. This ultra-high mechanical performance can be fulfilled by optimizing the particle packing density of cementitious compounds, which reduces considerably the concrete porosity [4]. Consequently, UHPC develops great resistance to aggressive environments and agents, like carbon dioxide, chlorides and sulphates. However, UHPC has particular drawbacks because of the excessive cement amount in the range of 800–1000 kg/m^3 which has negative impact from economic and environmental standpoint [2]. Iin order to limit these drawbacks, supplementary cementing materials (silica fume, fly ash, slag…) could be considered as promising alternatives, which improve in the same time concrete properties, particularly in long term. Blast Furnace Slag, a by-product from steel manufacture, is advantageous in aggressive environments. Its chemical composition is closed to that of Portland cement. BFS is used as partial substitution of Portland cement in concrete at levels commonly between 20% and 80%, depending on application and required properties. Its incorporation reduces the concrete porosity, increases its mechanical properties and enhances its resistance to aggressive agents [5-8]. Yazici et al. [5] observed a higher drop of compressive strength at 2 days with 40% of slag while at 28 days the strength was close to that of reference UHPC. Gupta [6] observed the same trend for UHPC with 0.18 water-to-cement ratio. Indeed, a decrease in compressive strength at 7 days by 2, 7 and 15% was occurred for 40, 60 and 80% of slag content, respectively. Whereas a growth is measured from 28 days. Duan et al. [7] showed that BFS has a positive impact on pore refinement and ITZ enhancement of concrete, which results in improving its mechanical and durability properties. These results agreed with those of Yanzhou et al. [8]. These authors investigated the effect of phosphorous slag powder on mechanical properties and microstructure of reactive powder concrete. They showed that for thermally-treated UHPC, with 35% of slag, 64% of pores have a diameter between 2-10 nm.

In this context, the objective of this research is to assess the effect of slag content on mechanical strengths of UHPCs for both early and later ages. Moreover, the influence of BFS on pore structure and durability properties of UHPCs is investigated thanks to specific experimental techniques.

2. EXPERIMENTAL PROGRAM

2.1 Used materials

Materials used in this study are of local origin (France). The cement used is a CEM I 52.5 N PM ES (Le Teil´s plant). Its chemical composition is provided in Table 1. It contains 97% of clinker and 2.8% of gypsum. The mass percentages of principal constituents of main clinker phases, given by Bogue's formula are: 67.8% of C_3S, 16.6% of C_2S, 4.0% of C_3A and 7.2% of C_4AF. In the present study, two types of mineral admixtures have been considered: Blast Furnace Slag (BFS) and Silica Fume (SF). BFS comes from Ecocem's plant and Silica Fume is commercialised by Condensil, as S95 B DM. Their main physical properties and chemical composition are given in Table 1. Crushed Quartz (CQ), used as a partial substitution of SF, comes from Sibelco and commercialised as C500. It contains more than 99.1% of SiO_2 and its specific area and density are 10435 cm²/g and 2.65, respectively. Quartz Sand (QS), containing more than 99% of SiO2, comes from Sibelco and commercialised as CV32. Its specific area and density are 124 cm²/g and 2.65, respectively. In the present study, an acrylic copolymer superplasticizer (Sika Viscocrete Krono 20 HE) is used. It is produced by Sika and its density and dry extract are 1.085 and 41%, respectively.

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Table 1: Chemical compounds (mass percentage), fineness and density of used materials

Compounds	Cement	Silica Fume	Blast Furnace Slag
CaO	65	0.3	43.9
SiO_2	22	95	37.4
Al_2O_3	2.78	-	10.9
Fe_2O_3	2.42	-	0.7
K_2O	0.17	-	0.24
MgO	0.76	-	6.5
Na_2O eq	0.24	0.08	0.46
SO_3	2.2	0.06	0.1
MnO	0.01	-	-
TiO_2	0.17	-	0.5
Cl-	<0.1	0.1	0.01
S^{2-}	<0.1		0.8
Specific area (cm²/g)	3555 (Blaine)	250000 (BET)	4450 (Blaine)
Density (-)	3.17	2.24	2.9

2.2 Manufacturing of UHPC mixtures

The considered reference mix of UHPC is designed by Cheyrezy et al. [1] and Mounanga et al. [3]. In their studies, authors have used white silica fume and a water-to-cement ratio of 0.16. As this kind of SF is no longer commercialised in France, grey silica fume is used in our research. Therefore, a preliminary study to optimise water-to-cement ratio and superplasticizer’s type and content was suggested [9]. The proposed new mix design is provided in Table 2. To reduce the environmental impact of UHPC, cement is partially substituted with slag. Three levels have been explored and provided in Table 3. These levels are volume percentages. SF, QS, CQ and water contents are kept constants. SP content was adjusted to obtain the same concrete workability, with a mini slump flow Ø = 30 cm, for all mixtures.

Table 2: Constituents of reference UHPC mixture

	CEM I 52.5 PM ES	QS	SF	CQ	SP	Water
Mass Ratio	1	1.1	0.25 * ¾	0.25 * 1/4	1.8%	0.175

Table 3: UHPC mix proportions

Mix Designation	$UHPC_1$	$UHPC_2$	$UHPC_3$	$UHPC_4$
Cement (%)	100	70	50	20
Slag (%)	0	30	50	80

2.3 Testing methods

The concretes were prepared by first mixing the solid components (cement, SF, CQ, BFS and QS) during 30 s. Solution of dissolved superplasticizer and water was then added at ambient temperature and compounds were mixed for 3 min. An intensive Eirich mixer was used [10], providing high mixing energy and allowing more cohesion of particles. At the end of the mixing phase, the workability of different concretes was measured through mini-slump tests. Then, prismatic and cylindrical samples were plastic-wrapped and stored in fog room, before testing.

- To assess the compressive strength, 40 x 40 x 160 mm specimens were tested. The measurements were carried out using 300 kN press machine. The specimens were tested at 3, 7, 28 and 90 days and the average of three specimens was reported. Splitting tensile strength was carried out on cylindrical specimens of 110 mm diameter by 220 mm height. The specimens were tested using 2000 kN press machine. For each mixture, two cylinders were tested and the mean value of the recorded data was reported.
- The pores size distribution and total porosity of each UHPC are assessed thanks to mercury intrusion technique, at 3 and 90 days, for 1 cm^3 samples. To stop the hydration reaction at 3 days, a cubic sample of 1 cm^3 is immersed in methanol, before drying at 105°C and testing.
- Accelerated chloride diffusion is carried out on 2.5 cm-thick samples, according to XP P18-462 [11], under an electric field of 30 V. After one month, the chloride depth was measured and apparent diffusion coefficient calculated.
- Carbonation test is conducted according to the standard specification XP P18-458 [12]. The UHPC specimens were exposed to 50% of CO_2 in the carbonation box and the penetration depth is measured after a duration of six months and one year.
- Gas permeability is carried out, in the GeM laboratory on 5 cm-thick samples, according to XP P18-463 [13]. To measure the low gas flow, through tested concrete, a high precision flowmeter was used.

3. RESULTS AND DISCUSSION

3.1 Mechanical properties

Figure 1 (left) provides the test results on compressive strength of different studied UHPC at 3, 7, 28 and 90 days. Compared to $UHPC_1$ mixture, it is exhibited that a slag content of

30% improves slightly the strength for all ages. Thanks to their high specific area, slag particles act as nucleation sites [14], which compensates for the decrease of compressive strength that could occur at 1 day. BFS hydrates slowly [9], which supports that a content of 30% performs a physical role, leading to an enhancement of bond strength between the components of matrix skeleton at 7 days and in the long term. In contrast, it was revealed from Figure 1(left), that there was a drop of 1day compressive strengths of $UHPC_3$ (50% of slag) and $UHPC_4$ (80% of slag), by 26% and 66%, respectively. This result highlights the latent hydraulic reaction of slag, which decelerates the strength development of concrete. Since 7 days, the produced portlandite promotes the reaction of slag, which improves the compressive strength of UHPCs with high BFS content. Consequently, at 28 days, the gap between reference concrete and both $UHPC_3$ and $UHPC_4$ decreased and reached respectively 11% and 22%. Between 28 and 90 days, the compressive strength of $UHPC_4$ develops very slowly. Indeed, with 80% of slag content, a small quantity of portlandite is produced, and rapidly consumed. Therefore, the enhancement of compressive strength results only from hydraulic reaction of slag. The reaction of the later is not promoted, as the pH is low.

Figure 1 (right) shows the splitting tensile strength of studied UHPCs at 3 and 28 days. Despite the absence of fibers, tensile strength of developed UHPC, at 28 days, are high and exceed 8 MPa. The behavior of tensile and compressive strengths is commonly influenced by similar factors. However, the interfacial zone between paste and aggregate, in presence of slag, seems improved, which explains the reduced gap between tensile strength of $UHPC_1$ and that of other UHPCs.

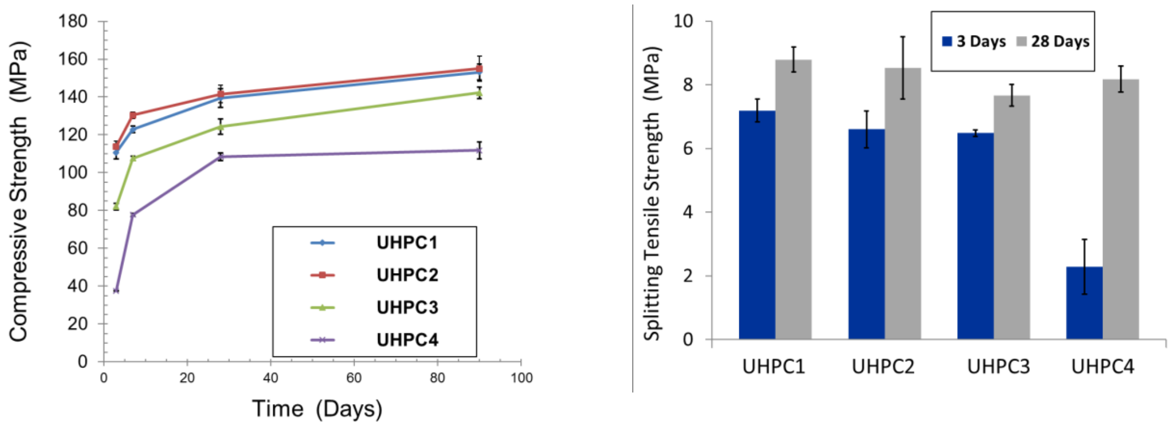

Figure 1: Compressive strength (left) and splitting tensile strength (right) of UHPCs

3.2 Mercury intrusion porosimetry

The results of total porosity of the UHPC specimens at 3 and 90 days are shown in Table 4. Figure 2 shows the quantitative distribution of the pores size, for different studied concretes. The diameter pore of 0.003 µm is the detection limit of the porosimeter. Thereby, for gel pores, only diameters between 3 nm and 5 nm are considered.

For BFS contents of 50% and 80%, the total porosity at 3 days increased by 91% and 129%, respectively. As evidenced by Abdulkareem et al. [9], for high slag contents, the concrete hydration reaction is decelerated by the latent one of BFS. Consequently, the hydrates develop slowly, which explains the high volume of capillary pores and the high total porosity of $UHPC_3$ and $UHPC_4$. At 90 days, the volume of capillary pores decreases greatly. Indeed, the pore structure of the paste is changed during the slag reaction with portlandite and alkalis, liberated through cement hydration. Therefore, the generation of slag reaction products fills large capillary voids and reduces the capillary porosity. Moreover, the pores are filled with calcium silicate hydrates (C-S-H) instead of portlandite. As a result, C-S-H gel formed from reaction of slag has finer gel pores [15] and the diameter of most probable pore is 3-4 nm.

Table 4: Total porosity of UHPC mixtures

Mixtures	$UHPC_1$	$UHPC_2$	$UHPC_3$	$UHPC_4$
Total porosity_3 days (%)	5.5	4.5	10.5	12.6
Total porosity_90 days (%)	4.8	3.9	2.5	4.0

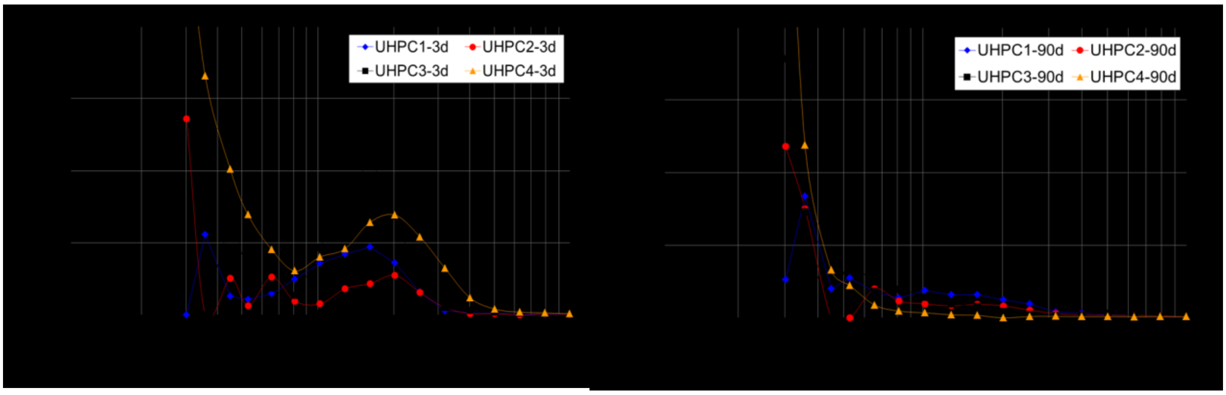

Figure 2: Pore size distribution of studied UHPCs at 3 days (left) and at 90 days (right)

3.3 Durability properties

Table 5 summarises measured durability properties for studied concrete.

- Gas permeability

For gas permeability test, there is any interaction between gas and concrete. Therefore, intrinsic permeability should be proportional to total porosity. Table 5 shows a decrease of k_V by 2.5 times and 1.5 times, for BFS content of 30 and 50%, respectively. For $UHPC_4$, the intrinsic permeability drops by 6 times, in comparison with that of reference UHPC. The Klinkenberg's regression of apparent permeability [16] results in low value of intrinsic permeability. This result could be explained by the abundance of nanopores, as shown on figure 2.

- Carbonation

After 6 months and 1 year of exposure and despite the high concentration of CO_2 (50%), the carbonation depth in all studied concretes is very low. As shown on Figure 2, in presence of BFS, the total porosity of blended UHPCs decreases, compared to that of $UHPC_1$. At the same time, when BFS in incorporated, pH decreases, promoting CO_2 diffusion and balancing the effect of porosity decrease. Therefore, the same carbonation depth is measured, regardless of BFS content.

- Chloride diffusion

From Table 5, it was shown that the apparent diffusion coefficients for blended mixtures of UHPC were lower than that of $UHPC_1$. The incorporation of BFS decreases the total porosity and the pores' interconnectivity. This results in less depth of chloride diffusion. Besides, the presence of BFS increases the binding capacity of concrete [17], which reduces significantly the apparent chloride diffusion coefficient.

If we compare $UHPC_2$, $UHPC_3$ and $UHPC_4$, we notice that the chloride diffusion coefficient is inversely proportional to total porosity. This result could be explained by two factors, acting simultaneously: the pore diameter distribution and the binding capacity. Indeed, despite its high total porosity, $UHPC_4$ has great binding capacity and its pore diameters are lower than 10 nm (Figure 2). The latter is considered as threshold diameter for chloride diffusion [18].

Obtained results on durability properties agreed with literature, except for gas permeability. This later is more than 10^{-19} m², in our case. This result could be explained by the use of a new experimental set up, with high precision flowmeter, which gives better estimation of UHPC permeability.

Table 5: Durability properties of UHPC mixtures

Mixtures	Gas permeability k_v (m²)	Carbonation depth, d (mm)		Chloride diffusion D_{app} (m²/s)
		6 months	1 year	
$UHPC_1$	28.0 x 10^{-19}	1.0	2.0	1.46 x 10^{-14}
$UHPC_2$	10.1 x 10^{-19}	1.0	2.0	0.42 x 10^{-14}
$UHPC_3$	20.0 x 10^{-19}	2.0	2.0	0.56 x 10^{-14}
$UHPC_4$	4.90 x 10^{-19}	0.7	2.2	0.36 x 10^{-14}

4. CONCLUSIONS

A slag content of 30% increases mechanical and durability performances of UHPC. By its fineness and chemical composition, BFS improves the concrete packing, decreases its porosity and increases its binding capacity.

For high BFS content, the porosity of UHPC, at 3 days, is noticeably raised. The larger slag quantity, the higher the porosity. This is ascribed to the latent slag reactivity and its dependency on produced portlandite and mixture's pH. At 90 days, the slag reaction forms hydration products that fill the coarse pores and reduce the capillary ones. Hence pores' interconnectivity decreases, which enhances durability performance of BFS blended UHPCs.

Despite the decrease of mechanical properties, particularly at early age, a high content of BFS decreases significantly gas permeability, chloride diffusion and keep constant the carbonation depth. Hence, BFS could be considered as promising alternative in UHPC. Its use reduces considerably the cement content and then the environmental footprint of concrete.

In further researches, we will focus on improving early age performances, by investigating the effect of chemical and thermal activation on mechanical and durability properties of BFS blended UHPCs.

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