COMPARISON BETWEEN PORTLAND CEMENT CONCRETE AND GEOPOLYMER CONCRETE BASED ON METAKAOLIN AND GRANULATED BLAST FURNACE SLAG WITH THE SAME BINDER VOLUME

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Abstract
Under the serious concerns of environmental degradation due to the greenhouse gas emissions of ordinary Portland cement (OPC) industry, geopolymer concretes have been qualified as a good alternative to OPC concretes. Geopolymer concretes, known by their good mechanical and durability properties, possess different fresh and hardened behaviours as compared to OPC concretes. This reason is one of the main obstacles that hinder the deployment of these concretes worldwide. Furthermore, geopolymer concretes developed in the literature are mostly based on fly ash while only few works were carried out on geopolymer concrete based on a blended mix of metakaolin (MK)/granulated blast furnace slag (GBFS). In this context, this paper aims to compare the fresh and hardened properties of geopolymer concrete based on MK and GBFS as well as OPC self-compacting concrete (OPSCC) with the same volume of binder. At fresh state, the workability evolution during the first hour after mixing was followed. At hardened state, mechanical strengths, dynamic modulus of elasticity, water porosity and shrinkage are investigated with a special attention to the early age behaviour.

Keywords:
Geopolymer concrete; Metakaolin; Granulated blast furnace slag; Mechanical properties; Physical performances.

1 INTRODUCTION

Over the past few years, considerable attention has been paid to geopolymer concretes in order to limit the environmental impact of OPC industry on one hand, and to minimize the non-renewable raw materials supply on the other hand [Ma 2018].

Geopolymer binders are the result of the aluminosilicate precursor activation by an alkaline solution [Davidovits 2013]. Among several geopolymer formulations proposed in the literature, it has been shown that the blended metakaolin-granulated blast furnace slag based geopolymer provide suitable properties without any heat curing treatment [Hasnaoui 2019], which is generally used to accelerate the geopolymerization of fly ash based geopolymers and to enhance their matrix performances [Pavithra 2016].

Geopolymer concretes are known by their resistance to high temperature and fire [Saavedra 2017]. In addition, they have showed a good mechanical and durability properties. However, they exhibit different fresh and hardened behaviours compared to OPC concretes, which raises serious questions about their application in the construction field. The comparison between geopolymer and OPC concretes have been addressed by several investigations [Bakri 2013; Noushini 2016]. Nevertheless, the majority of the compared geopolymer concretes are based on fly ash as raw material with a binder volume different from that of reference OPC concretes. Moreover, the fast loss of workability and the drying shrinkage problems, which are the main issues that hinder the utilisation of these concrete worldwide, are often overlooked while focusing on the mechanical properties.

In this context, the present study aims to evaluate the fresh and the hardened behaviours of blended GBFS-MK geopolymer concretes through the comparison with an OPSCC by keeping a constant binder volume for both materials.

2 MATERIALS AND EXPERIMENTAL TESTS

2.1 Materials

In the present investigation, the following materials were used:

- Portland cement (CEM I 52.5) for the formulation of OPSCC with a density of 3.14 and a specific surface area (Blaine) of 0.42 m^2/g.
- Limestone fillers Betocarb HP-FER from Omya (France) to enhance the rheological properties of OPSCC. It is characterized by a density of 2.7 and a specific surface area of 0.55 m^2/g.
- Tempo 9 (Sika) superplasticizer. It was added as admixture to OPSCC to achieve the target slump flow class SF2 (Slump flow between 660 and 750mm).
- Granulated blast furnace slag (GBFS) from ECOCEM (France). In table 1, it can be observed that it is reach in calcium (42.3%) with a total aluminosilicate species (Al_2O_3 and SiO_2) of 47.1%.
- Metakaolin M1200S (MK) produced by IMERYS (France). It is a high reactive precursor thanks to its purity and its higher fineness (19 m^2/g).
- Sodium silicate solution (SS) manufactured by Fisher (France) used to ensure the geopolymerization process. The dry extract represents 31.8 % by weight and its molar ratio SiO_2/Na_2O (MR) is 2.1.
- Sodium hydroxide (NaOH), with 99% of purity, mixed with SS and the added water in order to increase the alkalinity of the activation solution.
- Fine aggregates (FA) are 0/4 mm silico-calcareous rolled sand, while coarse ones (CA) are 4/10 mm silico-calcareous crushed aggregates. The grading curves of the used aggregates are presented in Fig. 1.

Tab. 2: Chemical composition and physical properties of CEM I, GBFS and MK.

Chemical composition (*Wt.%*)	**CEM I**	**GBFS**	**MK**
SiO_2	20.5	35.9	55
Al_2O_3	4.4	11.2	39
Fe_2O_3	2.3	0.3	1.8
TiO_2	0.3	0.7	1.5
CaO	63.4	42.3	0.6
MgO	1.8	8.0	-
$(Na_2O+K_2O)eq$	0.9	0.7	1.0
Specific gravity	3.14	2.91	2.2
Specific surface area (*m^2/g*)	0.42	0.45	19

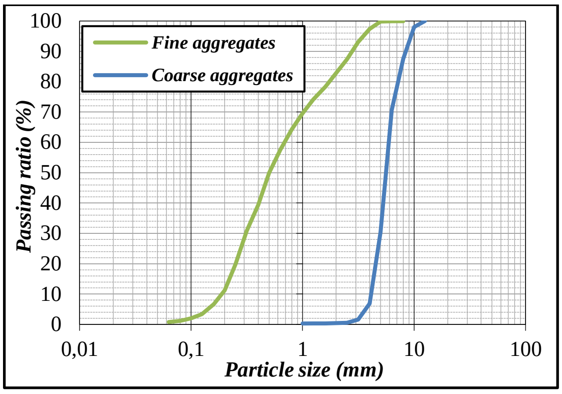

Fig. 28: Grading curves of fine and coarse aggregates.

2.2 Experimental program

Concrete mixtures

Two concretes were manufactured in this work (Table 2), OPC self-compacting concrete (OPSCC), and geopolymer concrete (GC). Since the aim of this study is to compare the two systems with a same binder volume, the Portland binder volume of OPSCC was replaced by geopolymer one. The formulation of the latter was chosen based on an optimization approach carried out in a previous study, where it has been found that the optimal performances in terms of mechanical properties and stability to efflorescence were achieved with: GBFS/MK = 1, GBFS+MK/Activator = 3 and MR of 1.8 [Hasnaoui 2019]. It should be noted that the use of Tempo 9 (Sika) does not show any effect on GC workability because the high alkalinity of the geopolymer mixture.

Test methods

- The workability of the two concretes was evaluated by measuring the slump, for GC, and the slump flow in the case of OPSCC (self-compacting concrete). The test was performed immediately after mixing (6 min) and every 20 minutes during the first hour of setting.
- The air content in the fresh concretes was determined according to the standard NF EN 12350-7.
- Uniaxial compressive and splitting tensile tests were carried out at the age of 3, 7 and 28 days, using a hydraulic press machine with a capacity of 3500 kN. The tests were performed on 11×22 cm cylinders, with a stress rate of 0.5 and 0.05 MPa/s for the compressive and the splitting tensile strength respectively. The recorded values were the average of three measurements.

Tab. 3: Mix proportions of concrete mixtures.

Concrete	**Constituent (kg/m^3)**											
	CEM I	**fillers**	**Sp**	**GBFS**	**MK**	**SS**	**NaOH**	**W**	**FA**	**CA**	**W/C**	**W/S**
OPSCC	314	105	4.6	-	-	-	-	177	914	820	0.43	-
GC	-	-	-	139	139	227	5.4	45	926	830	-	0.50

W = total water ; C = CEM I ; S = GBFS+MK + sodium silicate.

- Dynamic modulus of elasticity, at the age of 3, 7 and 28 days, was determined using E-Meter K II apparatus, which is based on the resonance frequency measurement. The test was performed according to the standard ASTM C-215 (Fig. 2).

Fig. 29 : Dynamic modulus of elasticity test using E-Meter K II instrument.

- Dry bulk density and water porosity were measured via the vacuum saturation method in accordance with the standard NF PN 18-459. For each concrete, three cylinders (11 × 5 cm) were tested.
- Drying shrinkage measurement was performed according to the ASTM C426. For both OPSCC and GC, beams of 10 × 10 × 50 cm were casted with a steel pins placed on the beam end surfaces (Fig. 3). In order to evaluate the water evaporation phenomenon, the weight loss of beams was also followed.

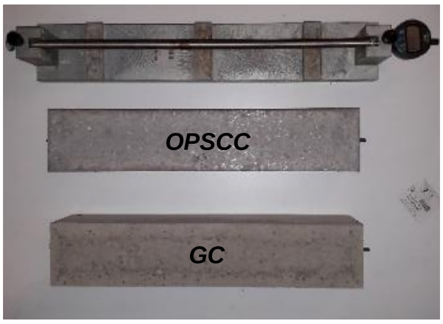

Fig. 30 : Drying shrinkage measurement apparatus and concrete beams.

The beams were demolded 24 hours after molding, and they have been stored at 20°C and 50% RH during all the test period. The length change of specimens was measured during 35 days after molding using a digital indicator.

The shrinkage strain (in microstrain) was then calculated by the following equation:

$$\varepsilon(t) = \frac{L_0 - L_t}{L} \tag{1}$$

Where:

- L_0 is the mean initial length measurement.
- L_t is the length measurement at the time t,
- L is original effective length.

3 RESULTS AND DISCUSSION

3.1 Fresh state: workability loss and air content

Fig.4 and Fig. 5 show the obtained slump flow and slump for OPSCC and GC respectively. From these figures, it can be established that OPSCC satisfies SF2 class recommendations (660 – 750 mm). By replacing OPC binder volume by geopolymer one, the obtained GC was a flowable concrete (S4 class). The difference of workability for the two systems, despite the identical content of binder, is mainly due to the high finesses of MK on one hand, and the absence of plasticizer admixture in GC mixture on the other hand.

It should be noticed that tempo 9 (Sika), as well as other polycarboxylates admixtures, often used for OPC based materials, is useless in the case of GC due to the high alkalinity of the geopolymer mixture. Hence, GC was formulated without admixtures.

Both concretes have shown a loss of workability during the first hour after mixing. However, it seems that workability loss is more accelerated in the case of GC, notably after 40 minutes. It is well known that geopolymers based on GBFS possess a rapid setting time compared with OPC materials [Lee 2016], due to the high content of calcium, which explains the obtained results.

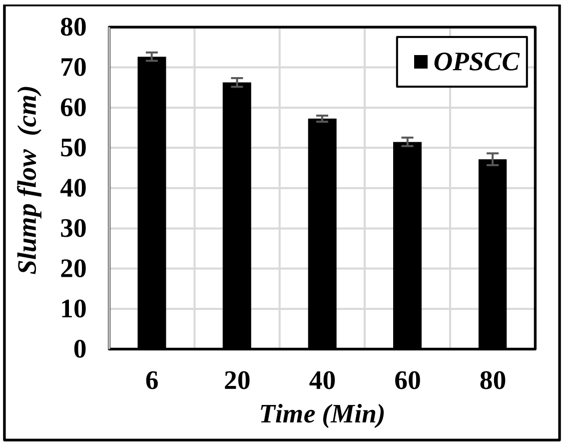

Fig. 31: Slum flow evolution of OPSCC as function of time.

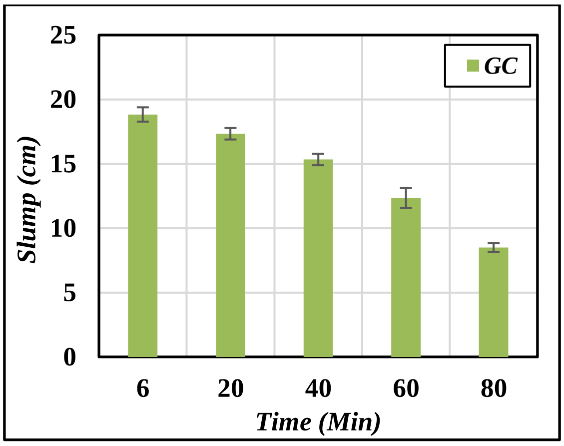

Fig. 32: Slump evolution of geopolymer concrete (GC) as function of time.

The air content obtained for OPSCC was 2.1 %, while it was 1.3 % for GC. The low air content in GC is due to the incorporation of MK, which ensure a good packing density thanks to its high specific surface area (19m^2/g).

3.2 Hardened state

Physical properties

The dry bulk density and the water porosity of OPSCC and GC are given in Tab. 3. As has been expected, GC shows a low bulk density as compared to OPSCC, since the density of Portland cement is higher than that of both GBFS and MK.

Although the air content in GC was lower than that of OPSCC at the fresh state, water porosity of GC was found to be around 20% higher than that of OPSCC. In fact, the extra water used to ensure the flowability of GC, plus the considerable amount of liberated water during the geopolymerization process are evaporated, which leads to create micropores in the geopolymer matrix and to increase the porosity.

The low porosity of OPSCC can be also interpreted by the incorporation of limestone fillers, which enhances the compactness.

Tab. 4 : Physical properties of OPSCC and GC.

Concretes	Dry bulk density (g/cm^3)	Water porosity (%)
OPSCC	$2.24^{\pm 0.1}$	$13.80^{\pm 0.1}$
GC	$2.20^{\pm 0.1}$	$16.49^{\pm 0.1}$

Mechanical properties

Compressive and splitting tensile strengths at 3, 7 and 28 days are presented in Fig.6 and Fig. 7 respectively. These figures reveal that, both OPSCC and GC show good mechanical strengths. Compressive strength of OPSCC at 28 days is, however, higher than that of GC. The splitting tensile strength show the same trend. This difference may be explained by the fact that water to cement ratio (0.43) is lower than effective water to solid ratio in the case of GC (0.5), although the volume of binder is the same in both mixtures. Furthermore, a part of the difference is due to the curing conditions, which are not the same for both materials (20°C ; 50%RH for GC and water immersion for OPSCC).

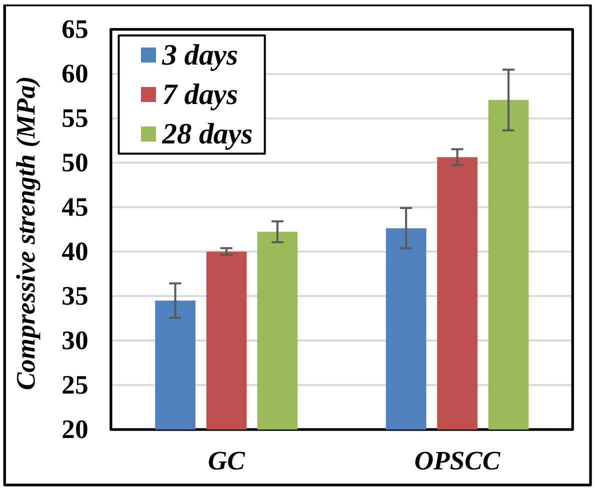

Fig. 33: Compressive strength evolution of geopolymer and OPC concretes.

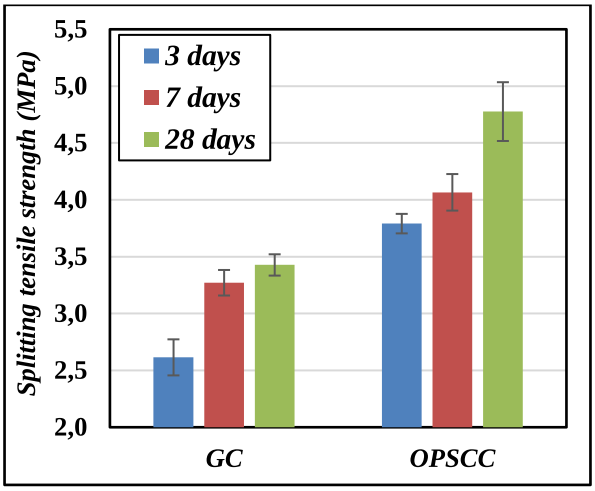

Fig. 34: Splitting tensile strength evolution of geopolymer and OPC concretes.

In terms of strength evolution, it can be established that only a slight improvement was recorded for GC from 7 to 28 days, whereas a considerable enhancement was observed for OPSCC during this interval. This is due to the fast hardening process of the geopolymer matrix, where it has been shown that this binder can achieve more than 90% of its maximal strength at early age [Davidovits 2008].

Fig. 8 shows the evolution of dynamic modulus of elasticity of both OPSCC and GC. This latter have shown a very low dynamic modulus of elasticity, around 40 % lower than that of OPSCC at 28 days. In fact, geopolymer are known by their low stiffness compared to OPC materials. This low rigidity depends mainly on the physical nature of the geopolymer binder itself rather than on porosity. Indeed, previous study showed that, even with low porosity, the rigidity of geopolymer materials is lower than that of OPC ones [Mobili 2017].

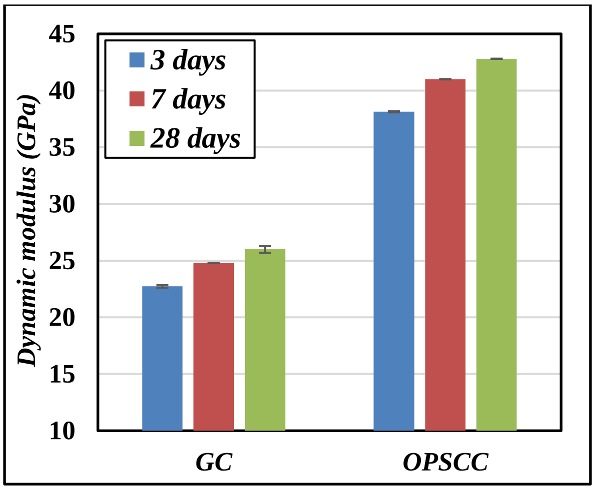

Fig.35: Dynamic modulus evolution of geopolymer and OPC concretes.

Drying shrinkage

The percentage of weight loss and the drying shrinkage of OPSCC and GC as function of time are presented in Fig. 9 and Fig. 10. Both properties of GC was higher than that of OPSCC. The same trend of drying shrinkage was observed with OPC and alkali activated slag mortars [Chi 2012]. Since geopolymer matrix is not a hydraulic binder, it is expected that the water evaporation rate is more important than that of OPSCC. This considerable amount of weight loss result in a high drying shrinkage, which achieve 1184 microstrain for 3.95 % of weight loss at 35 days.

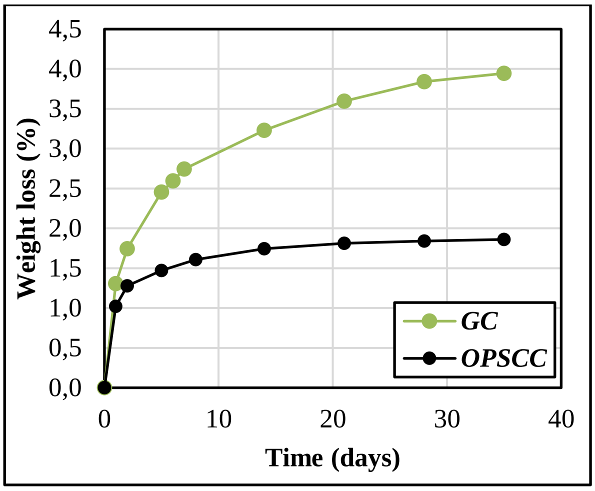

Fig. 36: Weight loss percentage of OPSCC and GC stored at 20°C and 50% RH.

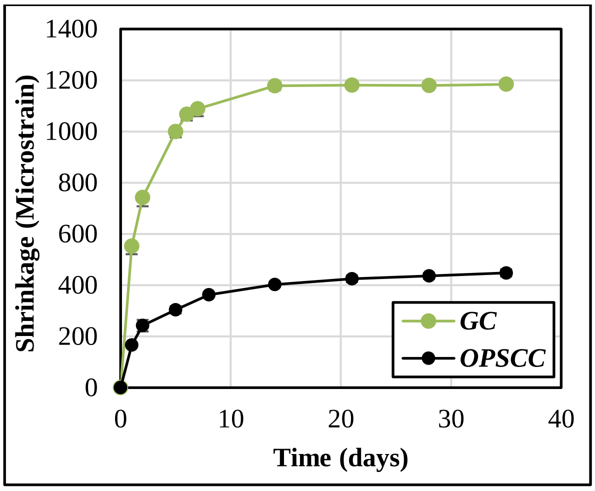

Fig. 37: Dry shrinkage of OPSCC and GC stored at 20°C and 50% RH.

The difference of the binder system can be clearly observed in the kinetic of water evaporation and shrinkage phenomenon. For OPSCC, the increase of weight loss leads to an increase of the drying shrinkage, which is commonly known for OPC based materials. However, in the case of GC, the correlation between the weight loss and the drying shrinkage is true until 14 days, then, we observe a stabilization of shrinkage while the weight loss continue to increase. This means that, for GC based on MK and GBFS, the effect of water evaporation in drying shrinkage is more significant at the early age, where more than 80% of the total strain is achieved at 7 days. After this age, the effect of water evaporation on the shrinkage is not significant. This is explained by the fact that the mechanical performances of GC become highly important at early age.

4 CONCLUSIONS

The main objective of this investigation is the comparison between geopolymer concrete based on MK-GBFS mix and OPC concrete with the same binder volume. From the obtained outcomes, the following conclusions may be withdrawn.

- The volume replacement of OPC binder for a self-compacting concrete by a geopolymer one, without admixture, leads to obtain a flowable geopolymer concrete with a S4 class of workability.
- The replacement of the binder volume of OPSCC leads to obtain GC with a good mechanical strength. Nevertheless, the extra water and the low relative humidity (RH) upon curing induced a decrease of these mechanical performances.
- GC possess a lower air content than that of OPSCC at the fresh state. However, at the hardened state, the high water evaporation rate induces an increase in water porosity, which is around 16% higher than that of OPSCC.
- For the same volume of binder, the stiffness of GC based on blended MK-GBFS mixture is around 40% lower than that of OPSCC.
- The drying shrinkage of GC is three times higher than that of OPSCC. Nevertheless, it takes place mainly at the early age before stabilization. This trend is completely different from that of OPSCC where the strain still increasing with the water devaporation.

The findings of this study reveal that the use of geopolymer concretes as an alternative for OPC one, must not be based only on rheological behaviour and mechanical strengths, but it should also take into consideration the other properties, as well as the stiffness, the transfer properties and the deferred behaviour.

5 ACKNOWLEDGMENTS

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