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Elaboration and characterization of self-compacting concrete based on local by-products

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Abstract

The building industry is increasingly using self-compacting concrete (SCC) in order to improve many aspects of buildings construction. If the limestone filler is traditionally used in the SCC, marble powder and granulated blast furnace slag are the less. The valorization of such wastes in self-compacting concrete as mineral admixture could be an interesting ecological and economical alternative, which allow extending the use of these by-products. The objective of this study is not only to remove the fear of using by-products available locally but also to study the influence of limestone powder replacement by marble powder and granulated blast furnace slag on fresh and hardened properties of SCC under two different curing modes. For this purpose, a comparative study was conducted on a reference SCC with limestone's filler (SCC LP) which was replaced by marble powder (SCC MP) as a calcic material and granulated blast furnace slag (SCC GBFS) as a pozzolanic material. At fresh state, the slump-flow test, T_{500} test, V-funnel, air content and L-box test were conducted to characterize the workability of fresh concrete in order to assess filling and passing abilities according to the European guidelines. The hardened properties that were determined included compressive and tensile strength determined at 3, 7 and 28 days. Monitoring the evolution of total shrinkage and weight changes up to 120 days were performed. As well the relationship between the shrinkage and weight loss. All SCC mixtures showed compliance with European recommendations (EFNARC). Considering the results obtained by various by-products, the most edifying is the performance acquired by GBFS samples, for both modes of curing. Regarding the SCC MP, the results are satisfactory and this promotes their extension in Algeria.

Keywords: Self-compacting concrete, granulated blast furnace slag, marble powder, limestone filler, shrinkage, weight change.

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1. Introduction

The use of self-compacting concrete is widespread across the world. However, the manufacture of this construction product requires the use of fines. At first, the main motivation for using mineral admixtures was cost reduction. More recently, environmental arguments began to prevail, in particular the need to decrease the overall CO_2 production related to the use of cement in concrete (Habert and Roussel, 2009) and the depletion of natural resources. For several years, the incorporation of mineral admixtures such as flyash, blast furnace slag and limestone filler in concrete mixtures became a widespread and a documented practice. Several studies show the benefits of using mineral admixtures in the SCC (Melo and Carneiro, 2010; Craeye et al., 2010; Unal et al., 2006; Sahmaran et al., 2006; Ye et al., 2007; Poppe and Schutter, 2005; Dinakar et al., 2008; Bilodeau and Malhotra, 2000). Their introduction allows the modulation of concrete characteristics as rheology, early age resistance, shrinkage and cracking sensitivity, sustainability, temperature rise. Well as the improvement of several properties of SCC, the partial substitution of cement with mineral admixtures offers several economic and environmental benefits. However, among the effective means that exist to ensure their economic and environmental benefit is the use of additions that are very cheap and available in large quantities in Algeria as the granulated blast furnace slag from ElHajar- Annaba and marble powder from Flifla- Skikda.

The purpose of this study is not only the extension the use of this concrete type incorporating abundant additions in the region, but also to study the influence of limestone powder replacement by marble powder and granulated blast furnace slag on the fresh and hardened properties of SCC under two ripening modes. For this purpose, a comparative study was conducted on a reference SCC with limestone's filler (SCC LP) which was replaced by marble powder (SCC MP) as a calcic material and granulated blast furnace slag (SCC GBFS) as a pozzolanic material. At fresh state, the slump-flow test, T_{500} test, V-funnel, air content and L-box test were conducted to characterize the workability of fresh concrete in order to assess filling and passing abilities according to the European guidelines (EFNARC, 2002).Mechanical properties, included compressive and tensile strength, was determined at 3, 7 and 28 days. Monitoringthe evolution of total shrinkage and weight changes up to 120 days were performed. As well the relationship between the shrinkage and weight loss.

2. Materials and concrete mixtures

2.1 Materials: In the production of SCC, Portland Cement CEM II/42.5, a sand 0/3 mm, coarse aggregate 3/8 mm and 8/15 mm, were used. Besides, two different by-products were used as substitutes for limestone powder (LP) in the SCC: Granulated blast furnace slags (GBFS) from Al-Hajar, Annaba and marble powder (MP) from a marble quarry in Flifla, Skikda. The limestone powderUF20is from Khroub, Constantine. The properties of cement and by-products used in this study are presented in Table1.

Table1. The characteristics of cement and by-products used

Component (%)	Cement	LP	MP	GBFS
SiO_2	27.83	0.06	0.15	38.89
Fe_2O_3	3.12	0.02	0.04	4.09
Al_2O_3	6.21	0.09	0.08	7.07
CaO	57.22	51.97	54.86	40.71
MgO	0.94	0.01	1.03	4.56
SO_3	2.02	0.01	0.07	0.04
Specific gravity	3.15	2.7	2.75	2.9
Blaine (cm^2/g)	3891	3900	3500	2000

A super plasticizer high range water reducing admixture (HRWRA) based on modified polycarboxylic ether (Conforms with the standard EN 934) was also used and tap water of the laboratory.

2.2 *Mixture proportions:* The Chinese method developed by Su et al. (2001) has allowed us to identify a SCC composition based on limestone filler. The main consideration of the Chinese method is that the spaces between the aggregates will be well filled with the paste (cement, fillers and water). A coefficient of packing factor (PF) is introduced to adjust the relative content of aggregates and paste. Table 2 presents the composition and labeling of the SCC mixture.

Table 2. Concrete composition in $1m^3$.

Materials (kg/m3)	Cement CPJ 42.5	LP	Sand 0/3	Gravel 3/8	Gravel 8/15	SP	Water	W/C
SCC LP	410	130	850	298	428	9.72	204	0.50

Two other mixtures were performed by replacing the limestone filler by two by-products of different nature, marble powder and granulated blast furnace slag with maintaining the same mix design.

2.3 Experimental procedure: For the characterization of SCC mixtures the following tests were conducted: At fresh state, theslump-flow test, T_{500} test, V-funnel, air content and L-box test were conducted to characterize the workability of fresh concrete to assess filling and passing abilities according to the European guidelines (EFNARC, 2002).

70 mm×70 mm×280 mm prismatic specimens were used for the determination of tensile strength, while cylindrical specimens 100 mm × 200 mm were used for the determination of compressive strength. After demolding, the specimens were kept in an ambient atmosphere room (the relative humidity and the temperature were about 50 ± 5% and 23 ± 2°C respectively) and in water until testing (compressive and tensile strength)which was performed at 3, 7, 14 and 28 days. The maximum strength of each specimen was recorded and the average of three samples was considered the compressive strength at the specific day.

The shrinkage specimens of 70x70x280 mm were demoulded after 24 h. The first length measurement was made at 0,5 h after demoulding and the specimens were then left in a room of 23±2°C with a relative humidity of 50 ± 5% and in water. Measurements were carried out for four months.

3. Results and discussion

We present the characterization results of mixtures in order to generate a set of information rich enough to be able to link the composition of concretes with their performance. In this study, fresh and hardened properties of SCC were investigated using local by-products of different nature such as granulated blast-furnace (GBFS) as a pozzolanic material, marble powder (MP) and limestone filler (LP) as calcium materials.

3.1 Workability: The fresh concrete characterization was limited to the tests recommended by the EFNARC (2002), namely the slump-flow test, T_{500} test, V-funnel, air content and L-box. The results of each composition are shown in Table 3:

Table 3. Workability test result of SCC mixtures.

	Slump flow (mm)	T_{500}(s)	L-Box	V-Funnel (s)	Air void content (%)	Unit weight (Kg/m^3)
SCC LP	740	4,52	0,86	16	1.30	2402
SCC MP	750	4,32	0,89	20	1,80	2360,28
SCC GBFS	755	4	0,87	16	2,49	2356,85

Comparing the results with the SCC criteria, it can be seen that all SCC mixtures exhibited satisfactory properties as fresh concrete. The slump-flow values for SCC with LP, MP and GBFS immediately after the mixing process are presented in Table 3.The slump flow of self-compacting concrete can vary from 650 mm to 800 mm (EFNARC 2002); all mixtures are in this category. From Table 3, we see improvements in the workability of SCC when replacing the limestone powder by marble powder or granulated slag. This can be explained by the increased surface area of the LP particles that increases the water demand (Sahmaran et al., 2006).

The water content was kept constant for all mixtures in this study. So GBFS needs less water and it has provided more slump flow, this phenomenon is explained by the characteristics of the slag grains surfaces that allow better intergranular sliding in the paste (Manai, 1995). The fine particles of the admixture (GBFS) fill the available voids between the mortar particles, thereby increasing the compactness of the mixture by enhancing the overall arrangement of the particles in the matrix (Yahia et al., 2005). Therefore the amount of water which occupied the voids is released into interstitial solution, which results in a better flow.

From Table 3, we observe that both the required times for reaching 50 cm slump-flow (T50) and the V-funnel flow times are in good agreement to that of the values given by European guidelines (EFNARC 2002). So the replacement of limestone fillers by marble powder and granulated slag guaranteed a level of suitable viscosity to decrease the risk of segregation and improve the workability. GBFS mixture has the lowest viscosities and V-funnel flow times compared to the other mixtures.

The L-box ratio characterizes the filling and passing ability of SCC. The blocking ratio of SCC containing various byproducts is given in Table 3. All mixtures of SCC are within this target range which should be between 0.8 and 1.00. When LP is replaced by MP and GBFS, it has not negatively affected the blocking ratio because of the concurrent decrease in viscosity. It can be noted that each SCC investigated in the present study has adequate filling capability and passing ability.

The results of air void content and unit weight of SCC with various byproducts can be seen in table 3. Air void content of SCC is increased when LP was replaced by MP and GBFS. Replacing LP by MP and GBFS for the same w/p ratio has affected the water demand for lubrication of the mineral admixture particles. Moreover, this situation affects the void content of concrete. Because of this increase in void content, the unit weight of these SCC mixtures has also decreased. The slump flow is related to the air void content; an increase of the air void content would allow an increase in the slump flow. By replacing LP by MP and GBFS in SCC, the unit weight can decrease while obtaining improved workability.

3.2 Compressive strength: Figure 1 (a / b) represents the compressive strength test results of SCC in two ripening modes (ambient/ saturated).

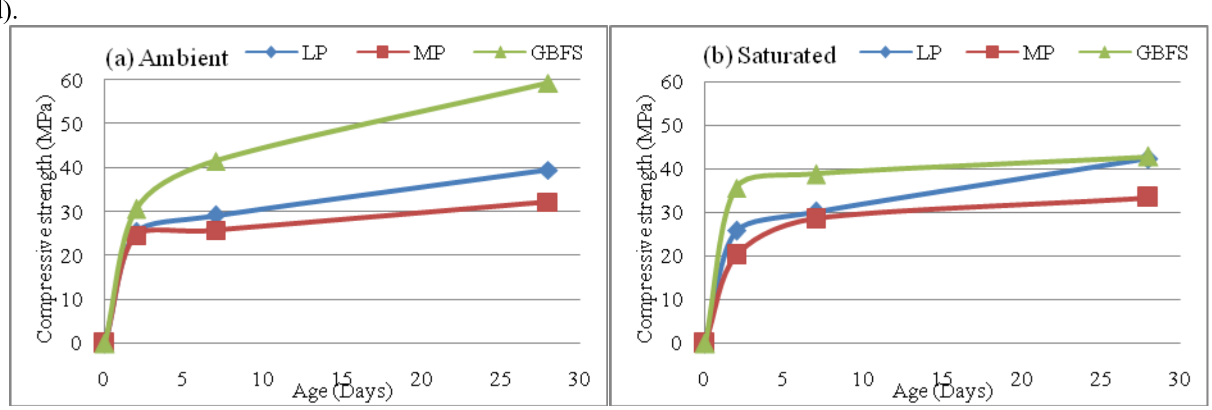

Figure 1. Compressive strength test results of SCC in two ripening modes(ambient/ saturated).

According to Figure 1, the test results showed that the compressive strength for GBFS mixture was higher than the mixtures containing LP and MP for all maturities regardless of the ripening mode. Indeed, the slag used is reactive but its kinetics is very slow (Behim and Boucetta, 2009), despite this the resistances obtained at 7 days are higher than those developed by LP and MP mixtures.

The SCC LP has shown the best performance both at 7 days and at 28 days compared to the SCC MP. This is due to the physical nature of limestone fillers which governs the compressive strength due to the denser matrix and the better dispersion of cement grains (Bonavetti et al 2003). Furthermore, The calcareous grains promote the formation of heterogeneous nucleation responsible for the early reaction products of CH and CSH, which will accelerate the hydration of cement clinkers (especially C_3S) and consequently increase the compressive strength values at early ages (Sari et al., 1999; Lawrence et al., 2005).

While the marble powder, which is not pozzolanic or completely inert, reacts with the alumina phases of the cement. If the cement contains an appreciable amount of tricalcium aluminate (C_3A), the calcium carboaluminate will be produced from the reaction between calcium carbonate ($CaCO_3$) of the marble powder and C3A (Bonavetti et al., 2001; Vuk et al., 2001; Uysal et al., 2011). And this can justify our result because the cement used has a low tricalcium aluminate (C_3A) around 9.87% which results in strength slightly lower than SCC based on limestone filler.

It was observed, from Figure 1, that the resistances of saturated specimens are higher compared to samples stored in ambient atmosphere for MP and LP mixtures because hydration is significantly reduced when the relative humidity inside the capillary pore system is less than 70% (Neville, 2002). But we notice the opposite for GBFS mixture because saturated specimens has lower resistance than those stored in an ambient atmosphere.

3.3 Flexural tensile strength: Tensile strength is one of the most important fundamental properties of concrete. All concrete typically has low tensile strength (10% of compressive strength) and a low strain capacity (Najim et al., 2012). However, tensile strength is important in highway design and airfield slabs when shear strength and crack resistance are a priority. The addition of LP, MP and GBFS to SCC exacerbates these shortcomings. The tensile strength test results of the GBFS, MP and LP mixtures, under two ripening modes (ambient/ saturated), are represented in Figure2 (a / b).

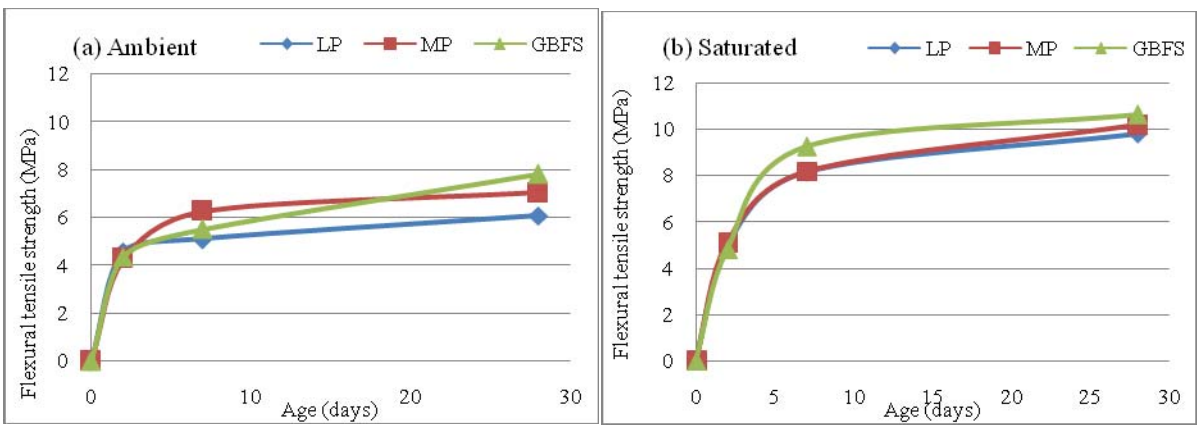

Figure 2. Flexural tensile strength test results of SCC in two ripening modes(ambient/ saturated).

It can be seen from figure 2that the 28 day tensile strengths of the MP mixtures were slightly higher than that of LP mixture. But the GBFS tensile strengths were higher than both MP and LP, as was seen for compressive strengths. This may occur because the dense microstructure in SCC mixes leads to increased brittleness and thus decreases the Flexural tensile strength. In SCC mixes, high powder contents can increase shrinkage resulting in micro-cracking within the ITZ (Najim et al., 2012) which affects tensile strength. It was found from figure 2 that the tensile strength of SCC immersed in water have better results with a significant difference compared to samples stored in an ambient atmosphere. This difference is around 26.7%, 31.1% and 38.2% for specimens of granulated slag, fine marble and limestone fillers, respectively. We also note that the tensile strength is more sensitive to the type of curing compared to compression strength. The water lost by autodessiccation due to chemical reactions of the cement hydration, must be replaced by water from the outside. It was concluded that the moisture content of the preservation medium has a significant influence on the strength of concrete (Dreux, 1985).

3.4 Total shrinkage: Figure 3(a/b) summarizes the evolution of measured total shrinkage of SCC. The total shrinkage of the prisms provided with plots was also measured during the maturation phase in the open air and under water. Shrinkage was observed regardless of the nature of the mineral admixture and the curing method.

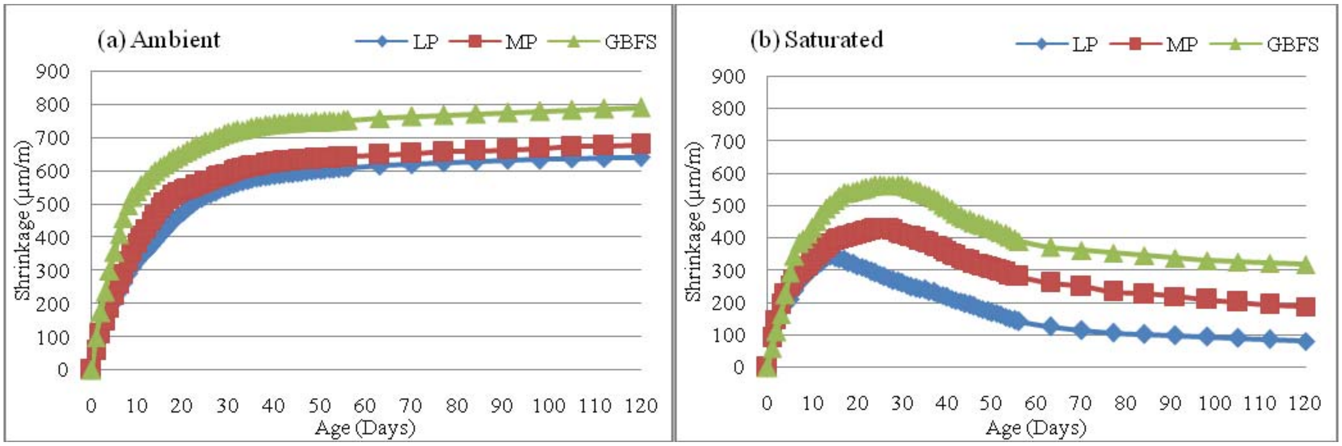

Figure 3.Total shrinkage of SCC specimens.

At ambient temperature(figure 3a),there are significant shrinkage deformations which are characterized by the loss of stored water in the capillary pores. The GBFS specimens are slightly more sensitive to shrinkage than MP and LP specimens respectively 789,98µm/m, 678,63 µm/m et 638,87 µm/m.

The limestone filler can have a positive effect in reducing drying shrinkage of SCC, if it is used with adequate finesse and proportion (Turcry, 2004; Assié, 2005). As shown in Figure 3a, self-compacting concrete containing limestone filler represents the lowest shrinkage because the limestone filler is the finer among all the mineral admixtures used.

For water curing (figure 3b), generally the specimens present swelling due to water absorption phenomenon. This information shows that the relative humidity is lower in concrete compared to saturated medium. While in our case there was shrinkage, this shrinkage is related to the concrete autodessiccation (self-drying) during the hydration.

Brue (2009) explained this phenomenon as follows: The water present in the microstructure is gradually consumed by the hydration reaction. Due to the very low permeability, the surrounding water cannot fill this consumption immediately. Therefore follows cavitation and balance air/water/solid is set up, leading to capillary pressure in the fluid (negative pressure). As the system has a no macroscopic stress (neglecting the weight) the solid is isotropically compressed to balance the capillary depression (Brue, 2009). This compression at a macroscopic scale is called the autodessiccation shrinkage or self-drying shrinkage, leading to deformations in large part irreversible.

From Figure 3b, we noticed a decrease in shrinkage for all specimens after 20 days, so according to Brue (2009), the gradual resaturation cancels the capillary depression that caused the autodessiccation. Despite this, themacroscopic shrinkage remains significant. At 120 days, GBFS and MP specimens reached a higher shrinkage value than LP specimens (317,94 µm/m, 187,93 µm/m et 80,95 µm/m, respectively).

3.5Weight changes: The different results obtained for samples of different admixtures and curing methods clearly indicate in terms of amplitude and kinetics, that at first time, the kinetics of the weight changes increases rapidly in 5±1 day and after this tolerance, there was a decrease in the kinetics. The amount of water migration in ambient environment is higher than the water penetration in saturated environment in the concrete. Figure 4 (a/b) summarizes the evolution of measured weight changes of SCC.

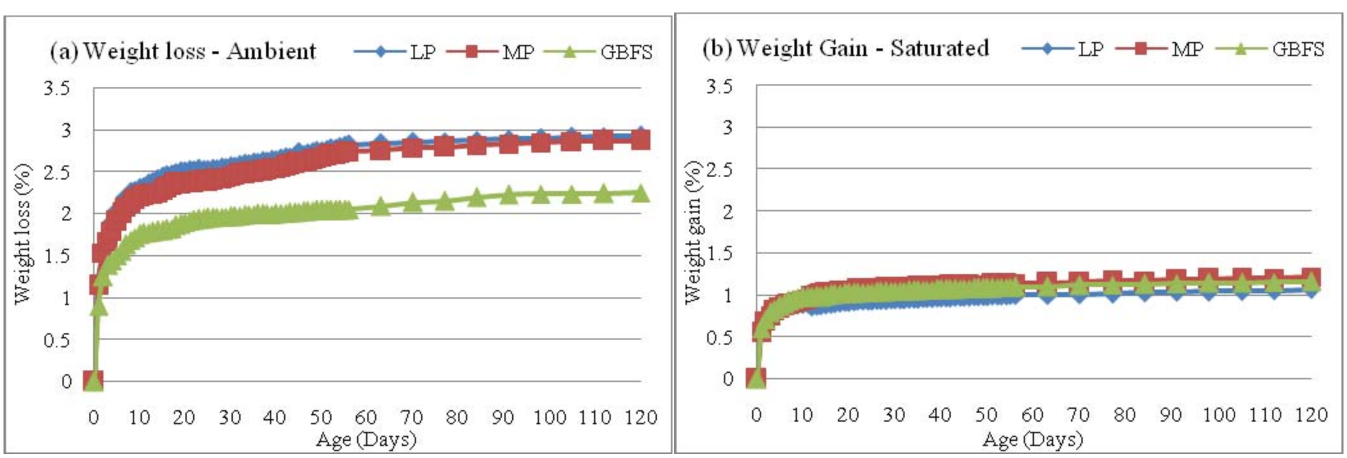

Figure 4. Weight changes of SCC specimens.

From the Figure 4 (a/b), we found that the weight loss in air curing is higher than the weight gain in saturated medium for all cases but the differences between the two variations changes with fines nature. For limestone powder and marble powder the difference is more important than granulated blast furnace slag (GBFS = 3,401 / MP = 4,078 / LP = 3,993) mainly due to their fineness, highlighting the decrease in capillary pores. The capillary pores strongly influence the transfer properties of concrete, especially when they are interconnected. So in conclusion, the finesse is a major factor for this kind of demonstration. In addition, the fines nature seems to have an influence effect (Nepomuceno et al., 2012).

For specimens in saturated medium (Figure 4b), we note that the MP samples have a higher swelling than the other two. In parallel GBFS specimens undergo higher water penetration compared to LP specimens. The magnitude of swelling compared to LP specimens is around 13,6% for MP specimens and 8,35% for GBFS specimens. Ripening concrete continuously in water, after demolding, increases in volume and mass. This swelling is caused by the absorption of water by the cement gel. Water molecules act against the forces of cohesion and tend to repel the gel particles, causing subsequently a small expansion (Neville, 2002). For specimens in an ambient medium (Figure 4a), we note that the water evaporation of LP specimens is faster than GBFS specimens and with relative similarity to MP samples.

3.6 The link between shrinkage and weight loss: The evolution of shrinkage according to the weight loss for different compositions is reported in Figure 5.

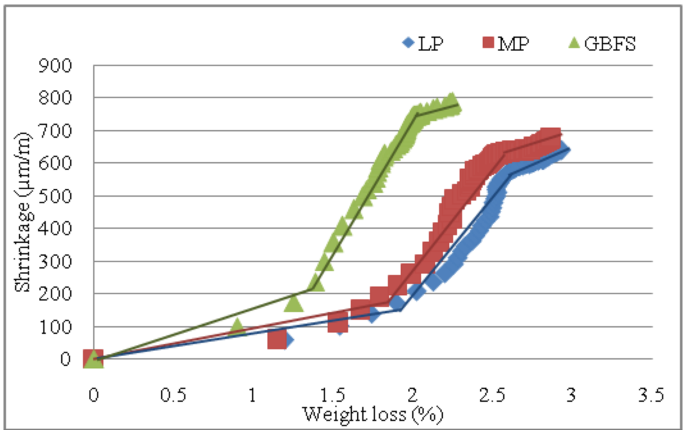

Figure 5. The link between shrinkage and weight loss of SCC specimens.

In the literature, the shrinkage / weight loss curves show three phases. We observe a "dormant" area at the beginning for all SCC specimens. Indeed, the micro-cracks in specimen surface hide the deformation of contraction related to the departure of water (Khelidj et al., 1998). Granger (1995) shows on the contrary that there is a crack in the skin due to intense moisture gradient between the surface and the heart of the concrete (Benboudjema, 2002 ; Turcry, 2004). This cracking considerably reduces the amplitude of the measured shrinkage. Then, an area where the shrinkage is proportional to the weight loss is observed with a rapid development after the first five days. The three concrete reached the last phase i.e. the stable phase in which the shrinkage exceeds 80% of the final value. We note in Figure 5 that the weight loss required to initiate the shrinkage depends on the nature of by-product. Because the weight loss needed to begin the shrinkage of LP specimens is higher than GBFS specimens and similar to MP specimens. In addition, during the second phase, the development of shrinkage is much more progressive for GBFS specimens.

4. Conclusions

This paper aimed to compare several properties of self-compacting concrete containing different minerals admixtures. Laboratory tests were performed to determine some fresh and hardened properties of SCC mixtures. As a result of this experimental study, the following conclusions can be drawn: The water demand and workability are controlled by particle shape, particle packing effect, particle size distribution and the smoothness of surface texture. So GBFS needs less water and it has provided more slump flow, because the characteristics of the slag grains surfaces allow better inter granular sliding in the paste. Other mixtures containing LP and MP had a reduction in workability when comparing to GBFS. The nodular and angular shape of LP and MP hinder the workability of the SCC. This explains the relatively negative effect of LP and MP on the fresh concrete properties. Among the by-products considered, the GBFS provided the best fresh state performance when added to concrete.

The results showed that the replacement of LP by GBFS increases both compressive and tensile strength. For the two other mineral admixtures, LP specimens give better resistance compared to MP. Shrinkage is observed regardless of the by-product nature and the curing methods. At ambient temperature, the replacement of limestone powder by marble powder did not affect the total shrinkage; however the replacement of limestone powder by granulated blast furnace slag increased the total shrinkage. For water curing, all SCC exhibit shrinkage instead of swelling, this shrinkage is related to the concrete autodessiccation (self-drying) during the hydration. After 20 days, the total shrinkage of all specimens decrease so according to Brue (2009), the gradual resaturation cancels the capillary depression that caused the autodissiccation. Despite this, themacroscopic shrinkage remains significant. The GBFS specimens have the higher total shrinkage value and MP specimens have the lowest. Considering the results obtained by various by-products, the most edifying is the performance acquired by GBFS samples, for both modes of conservation. Concerning the MP simples, there sults are satisfactory. These conclusions relate only to the concretes studied; further studies are necessary to extend these conclusions to other concretes.

Nomenclature

SCC Self-compacting concrete.
GBFS Granulated blast furnace slag.
MP Marble powder.
LP Limestone powder

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