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Research Paper

Effect of the fineness of mineral additions on the behavior of low impact environment self-compacting mortars

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ABSTRACT

The aim of this experimental work is to analyze the effect of mineral additions fineness on the hydration of self-compacting mortars, as well as their behavior in the fresh and hardened states. To do this, cement was partially replaced with a fixed rate of 20% for natural pozzolan and 30% for slag. The additions were ground to three different fineness. The results showed that the use of slag is favourable to the formulation of self-compacting mortars, the workability has been considerably improved, the increase in its fineness, meanwhile, reduces the dosage of superplasticizer up to 46%. For the pozzolan, on the other hand, not only was the workability reduced, but the increase in fineness implies an additional demand for superplasticizer up to 16%. Mortars based on additions release less heat, nevertheless, this reduction is accompanied by a drop in compressive strength at a young age. However, the increase in fineness lets to accelerate the initial hydration, inducing additional strength, and to generate heat comparable to that of the reference mortar. Nonetheless, in the case of excessive grinding, the heat release must be taken into account in order to avoid the thermal cracking.

1 Introduction

Cement, the essential component of concrete, is one of the largely used material on a global scale [1], its annual production was around 4.1Gt in 2022 [2]. By its manufacturing process, it is one of the most important sources of greenhouse gas emissions in the world [3], corresponding to a global average of 950 kg of CO₂ released per ton of cement [4]. Cement therefore appears to be a key parameter for reducing CO₂ emissions, and more generally the environmental impact of the "concrete" material, in fact, in the total CO₂ emitted in a concrete composition, 74 to 82% of emission is dedicated to cement [5]. Hence, this environmental optimization results in the reduction of the cement dosage of concrete and which can therefore be undertaken by the substitution of cement by mineral additions; natural additions which are found in abundance such as natural pozzolan, or industrial in the form of waste such as slag from blast furnaces. This has become a common practice, the subject of many researches, as reported by several authors [6, 7]. Nonetheless, apart from their use for ecological purposes,

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these additions have functional advantages such as improving workability and reducing the demand for water [8, 9] by supplying fine particles, improving mechanical properties [10, 11], and the durability of concrete [12, 13], as well as the reduction of the heat of hydration [14]. It is to be noted that there are other economic order interests such as their cost prices. In particular, for the additions from the industry for which the cost is generally equal to the costs of transport and handling, in addition to the reduction in fuel consumption.

Mineral additions in the raw state present a low reactivity which is the reason why a preliminary treatment must be carried out before use. Mechanical activation by grinding is considered one of the most widespread processes in cement factory. However, according to Öner [15], several researchers have confirmed that the separate grinding is favourable to the mechanical activation of additions. Moreover, grinding mixed clinker and slag all together does not allow the degree of fineness of each component to be controlled, which limits the activation of the slag, in particular in its participation in hydration reactions; hence, this leads to a reduction in mechanical performances. This is the case of the slag of EL Hadjar (Far East of Algeria), because Behim et al. [16] have shown that Algerian cement factories currently use a low rate of around 20% for the production of cement to slag because of the limitation of its fineness, which is around 3000 cm²/g obtained by inter-grinding the slag and the clinker. Consequently, the separate grinding process was recommended, which allows the increase in the fineness of the slag and therefore doubles the proportions of the slag without reducing the compressive strength. In addition to fineness, the substitution rate must be carefully selected to ensure optimal use of additions, indeed, by working on local materials; Bougara et al. [17] consider that the optimal rate of slag is around 25%, while Ezziane et al. [18] assert that the optimal substitution rate for pozzolan is 15% for normal temperature and up to 20% for high temperature.

The use of these additions has become inevitable for reducing the cost and the environmental impact relative to the use of a large volume of cement and synthetic admixtures for the formulation of innovative concretes such as self-compacting concretes, which are considered one of the most relevant development in the industry of construction [19]. In fact, these concretes are characterized by their high fluidity and their installation in the narrow and strongly confined zones without vibrations, under the effect of their own weight [20] presenting the advantage of the improvement of the pumpability and the reduction of nuisance and implementation time [21], by dint of these advantages as well as the diversity of their applications, they have found their way into many projects successfully carried out around the world, whose requirements were very varied, for instance: (i) the reconstruction of The Padgett-Thomas Barracks and Law Barracks at the Citadel Military College in Charleston, South Carolina, of which more than 6500 m³ and 3600 m³ were poured respectively in order to have a perfect finish of the edges and surfaces to be painted directly [22, 23]; (ii) the design of the walls of NASA's largest vibro-acoustic test chamber, the SCC was used to pour around the 24 horns, used to blow high pressure nitrogen gas, these horns are installed in the wall forming a non-transferable labyrinth for ordinary concrete [24]; (iii) work on the reconstruction of the I-35 W Bridge in Minneapolis, Minnesota (USA), where SCC was used for the pouring of certain piles with 2.40 m in diameter heavily scraped, and as it was a mass casting, the SCC was made with 60% pozzolan [25].

Nevertheless, to ensure the self-compacting character while remaining stable with high deformability to resist segregation and bleeding, the different formulation practices have converged towards the increase of the quantity of cement, fines and the limitation of the content and the maximum size of the aggregates with the use of new generation superplasticizers. Nevertheless, the formulation of these concretes has proven complex compared to ordinary concretes because of the combination and interaction of a large number of materials and additives [26] which in order to ensure well-defined characteristics (fluidity and stability), can present incompatibility problems. Thus, to be successful at a formulation, it is required to have a clear understanding of the role of each constituent in the mixture, and its effect on the properties of both fresh and hardened states [27]. Occupying a large volume in SCC, the mortar represents the most significant phase that allows a lubrication between particles and the overall stability of concrete, its required characteristics are similar to those of concrete [28], which makes the mortar a base with the workability properties of SCC on which its properties could be studied and evaluated [29]. Indeed, the evaluation and optimization of the self-compacting mortar represents the main part of the formulation process of self-compacting concretes [30]. This practice has become common across several researches [31-35] for the investigation of the properties of MAP in the fresh and hardened states, as well as the stability, under the influence of chemical admixtures and mineral additions in substitution of cement.

For this reason, the use of these additions requires a perfect knowledge of their behaviour and influence on self-compacting concretes without excluding the calorimetric aspect, since the incorporation of the additions modifies the way in which the concrete is hydrated, the modification of the kinetics of hydration can be observed and usually discussed on the evolution curves of the release of the heat of hydration [36], the pozzolanic additions contribute to the hydration through the pozzolanic reaction between the silica provided by the addition and the hydroxide of calcium liberated following cement

hydration, to form C-S-H gels [37]. However, before chemically reacting, these finely ground additions can speed up or slow down hydration by various physical effects, which can be divided into an effect of dilution due to the decrease in the quantity of cement by the substitution according to the rate, and a nucleation effect, which results in the precipitation of the hydration products on the fine particles of the additions serving as nucleation sites [38]. In this respect, the fineness expressed in specific surface of the additions becomes a very significant parameter. Nonetheless, increasing the dosage of fines or fineness to improve the quality of the SCCs risks making a highly exothermic concrete, which risks compromising its durability.

In this context, and although the effect of the fineness of mineral additions on the properties of ordinary concrete has been widely studied, the present research is interested in studying the influence of the fineness of the slag from the blast furnaces of El Hadjar and the natural pozzolan of Beni Saf on the behaviour of the self-compacting mortars in the fresh and hardened states by substituting the cement with fixed rates and by varying only the fineness in order to try to explore the effect of the fineness of the additions not only in relation to mechanical activation, but to the overall behaviour of mortars with the aim of optimizing them with the efficient exploitation of additions, and ensuring sustainable development.

2 Materials and experimental program

2.1 Materials

In order to conduct this study, all the mixtures were made using standardized siliceous sand of natural origin, with an absolute density of 2.64, made up of particles of generally isometric and rounded with a silica content of 98.5%. Its absorption rate is 0.2% with a fineness modulus of 2.60. Complies with the requirements of the NF EN 196-1 standard [39], and Portland cement of CEMI 42.5 type conforming to NF EN 197-1 standard [40] with an absolute density of 3.15, Blaine surface of 3880 cm²/g, and a characteristic strength of 42.5 MPa at 28 days, the mineralogical composition of the cement is given in Table 1 and the chemical composition in Table 2. Two mineral additions of different nature, their compositions are given in Table 2 were used:

- Artificial: the granulated blast furnace slag of El-Hadjar (Annaba Steel Complex) obtained by cooling by water jet (water quenching), it takes the form of light gray spherical grains and particle size class 0 to 5 mm, with an absolute density of 2.94.
- Natural: the pozzolan of Benisaf, which is in the form of a natural rock of volcanic origin, with an absolute density of 2.74.

Table 1 – Mineralogical composition of the used cement (%) *

Elements	C ₃ S	C ₂ S	C ₃ A	C ₄ AF	limits of acceptance according to Standards	Results
Cement	51.35	22.63	3.70	13.87	NF EN 197-1 [40]: C ₃ A ≤ 5%	3.70

*Calculated according to the composition of BOGUE

Table 2 – Chemical composition of cement, slag and pozzolan (Mass%)

Elements	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	LOI*	limits of acceptance according to Standards	Results
Cement	21.45	4.31	4.56	61.43	1.24	0.39	0.61	2.28	3.72	NF EN 197-1 [40]: SO ₃ ≤ 3.0%	2.28
										LOI ≤ 5.0%	3.72
Slag	36.51	11.32	0.65	42.48	6.41	0.42	0.50	0.33	1.14	NF EN 197-1 [40]: CaO+MgO+SiO ₂ ≥ 66.66%	85.20
										(CaO+MgO)/ SiO ₂ > 1	1.33
Pozzolan	46.40	17.50	10.50	10.50	3.80	3.40	1.50	0.40	4.31	ASTM C618-19 [41]: SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ ≥ 70 %	74.40
										SO ₃ ≤ 4.0%	0.40
										LOI ≤ 10.0%	4.31

*LOI :Loss on ignition

These additions have been ground into three different fineness degrees. The admixture used is a new generation high water-reducing superplasticizer, made of modified ether polycarboxylate, introduced in a liquid form with a recommended dosage range of 0.3 to 2%, an absolute density of 1.065, 30% of dry extract, and a chlorine content of less than 1g/L.

2.2 Formulation

Within the framework of this research, seven mixtures were studied and formulated according to the OKAMURA method [42] called the general method with the recommendations proposed by Domone and Jin [29] for the relationship selection of Sand/Mortar (S/M), Water/Binder (W/B) and Superplasticizer/Binder (Sp/B) ratios, and which must check the two conditions: a spread (slump flow diameter) included between 250 and 300 mm, and a V-funnel flow time between 2 and 10s. The reference mortar was made with cement without any addition (noted SCM-R); for the other mortars, the cement was replaced by mineral additions at fixed rates; 30% for the slag noted (SCMS-F1, SCMS-F2, SCMS-F3) and 20% for the pozzolan, noted (SCMPZ-F4, SCMPZ-F5, SCMPZ-F6), as described, F1 to F3 represents the various fineness of Slag, and F4 to F6 represents the various fineness of Pozzolan. The workability was kept constant at a spread (slump flow diameter) of 280 ± 5 mm for all mixtures. Consequently, the dosage of superplasticizer has been adjusted for each case by reformulating the mixture, in order to maintain the same targeted spread. The ratios (W/B) = 0.40 and (S/M) = 0.45 were kept constant for all the mortars. The different compositions are summarized below in Table 3, whereas the properties of each component are provided in table 2.

The mixing process was done by a mortar mixer with a capacity of 5l, mixing sand, cement and dry addition for 30s, then 70% of the effective water was introduced during mixing over 1 minute, just after, 30% of the remaining water mixed with the superplasticizer was introduced for 1 minute, after 3 minutes of mixing, the mortar was put to rest for 2 minutes, then re-mixed for 30 seconds before testing. The tests were carried out under standard conditions of 20 ± 2 °C.

Table 3 - Composition of the self-compacting mortars studied

Series	Mixtures Names	SSB* (cm ² /g)	Substitution (%)	Cement (Kg/m ³)	Slag (Kg/m ³)	Pozzolan (Kg/m ³)	Sand (Kg/m ³)	W/B	S/M	Sp/B
Reference	SCM-R	3880	0	767	0	0	1178	0.4	0.45	0.60
Slag-based Mortars	SCMS-F1	F1=3625	30	543	217	0	1178	0.4	0.45	0.40
	SCMS-F2	F2=4250	30	543	217	0	1178	0.4	0.45	0.35
	SCMS-F3	F3=5220	30	543	217	0	1178	0.4	0.45	0.32
Pozzolan-based Mortars	SCMPZ-F4	F4=3660	20	622	0	135	1178	0.4	0.45	0.62
	SCMPZ-F5	F5=4230	20	622	0	135	1178	0.4	0.45	0.65
	SCMPZ-F6	F6=5250	20	622	0	135	1178	0.4	0.45	0.70

* Surface specific Blaine of cement, slag, and pozzolan, (F1,F2,F3 : Fineness of Slag, F4,F5,F6: Fineness of Pozzolan) (SCM: Self-compacting mortar, SCM-R: Reference Mortar, SCMS: Slag-based mortars, SCMPZ: Pozzolan-based mortars)

2.3 Experimental program

2.3.1 Fineness control

The fineness is determined by the Blaine method according to the NF EN 196-6 standard [43] in the form of a mass surface using the Blaine air-permeability apparatus which consists of measuring the time taken for a fixed quantity of air to pass through a bed of compacted powder at specified dimensions and porosity, the mass surface of the powder is proportional to time.

2.3.2 Workability tests

The optimization of the mortars was carried out jointly by a flow spread cone test (Fig.1), and a V-funnel flow test (Fig.2) for mortar, according to the EFNARC [30] specifications. The spread (slump flow diameter) was measured in two perpendicular directions, the mean value was taken. The flow time was counted just when the funnel was opened until the light point appeared, the mean of the three tests was retained.

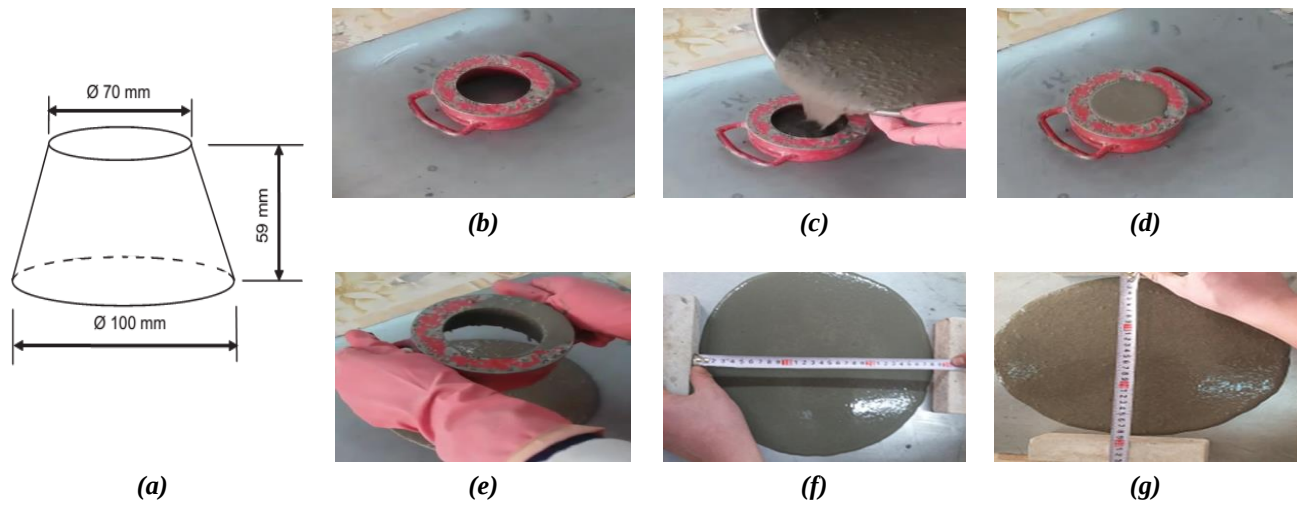


Fig. 1 – (a) The schematic diagram of spread cone; (b) to (g) Mortar flow spread cone test

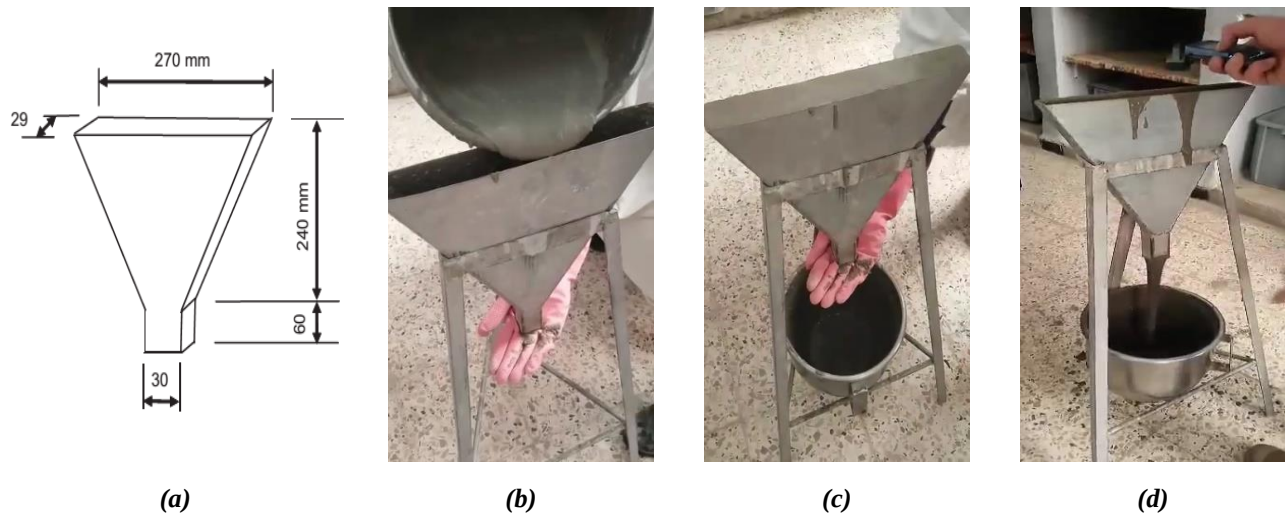


Fig. 2 – (a) The schematic diagram of V-funnel; (b) to (d) Mortar V-funnel flow test

2.3.3 Hydration heat tests

The hydration heat tests were carried out according to the NF EN 196-9 standard [44] by the Langavant method using a semi-adiabatic calorimeter inside a chamber conditioned at 20°C, (Fig. 3). The principle consists in introducing a freshly prepared mortar sample into a calorimeter in order to quantify the quantity of the released heat according to the evolution of the temperature. The hydration heat at a given time is equal to the sum of the heat accumulated in the calorimeter and of the heat dissipated towards the ambient medium during the entire duration of the test. The heating of the mortar is compared to the temperature of an inert sample in a reference calorimeter.

The tests were carried out over a period of 5 days for each mixture, the variation in the temperature was recorded on the acquisition chain from the introduction of the vase into the calorimeter at an interval of 10 min. The expression of the heat released at a given time is given by the following expression [44]:

$$q(t) = \frac{C}{m_c} \Delta\theta + \frac{1}{m_c} \int_0^t \alpha \Delta\theta dt \quad (1)$$

with :

m_c : mass of cement or binder contained in the test box.

$\Delta\theta$: mortar heating difference to the ambient temperature

α (J/h °C) : coefficient of total heat loss of the calorimeter given by the calibration. Its expression [44] is given by:

$$\alpha = a + b \times \Delta\theta \quad (2)$$

C (J/°C) : thermal capacity of the calorimeter evaluated by the following equation:

$$C = 0,80(M_c + M_s) + 3,80 \times M_w + 0,5 \times M_b + \mu \quad (3)$$

with :

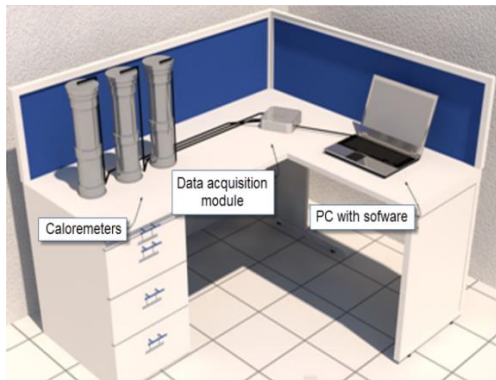
0,80 (J/°Cg) : Mass thermal capacity of cement (binder) and sand.

3,80 (J/°Cg) : Mass thermal capacity of hydration water.

0,5 (J/°Cg) : Mass thermal capacity of the box.

μ (J/°C) : Thermal capacity of the empty calorimeter.

M_c , M_s , M_w , M_b : Mass of binder (cement + addition), sand, water and box.



(a)



(b)



(c)

Fig. 3 – (a) The schematic diagram of experimental device for measuring the heat of hydration; (b) and (c) experimental device for measuring the heat of hydration

2.3.4 Mechanical strengths

The compressive strength was evaluated in accordance with the NF EN196-1 standard [39] (Fig. 4). The mortars were poured into standardized steel prismatic molds of (40x40x160 mm) dimensions, then stored in a climatic chamber, demolding was carried out after 24 hours. The specimens were then stored in water tanks at a temperature of 20° C, and they were removed from the water 10 min before the test. The compressive strengths tests were carried out at the age of 1, 3, 7, 28 and 56 days on half prisms after having broken the specimens into two parts by bending in accordance with the article 9.3 of the NF EN 196-1 standard [39]. The bending tests, due to their low values especially at a young age generally undetectable by the machine, have been neglected.

3 Results and discussion

3.1 The effect of additions on the workability

In order to study the effect of the fineness of the additions on the workability of the self-compacting mortars, a reference mortar was formulated by fixing the parameters (W/B) = 0.40 and (S/M) = 0.45, and by varying the dosage of the superplasticizer amongst its recommended dosage ranges, the adopted dosage is 0.6% giving a spread of 280 mm which will

be considered fixed. All the obtained mortars have a homogenous appearance; without segregation or bleeding in accordance with the specifications of the EFNARC [30].

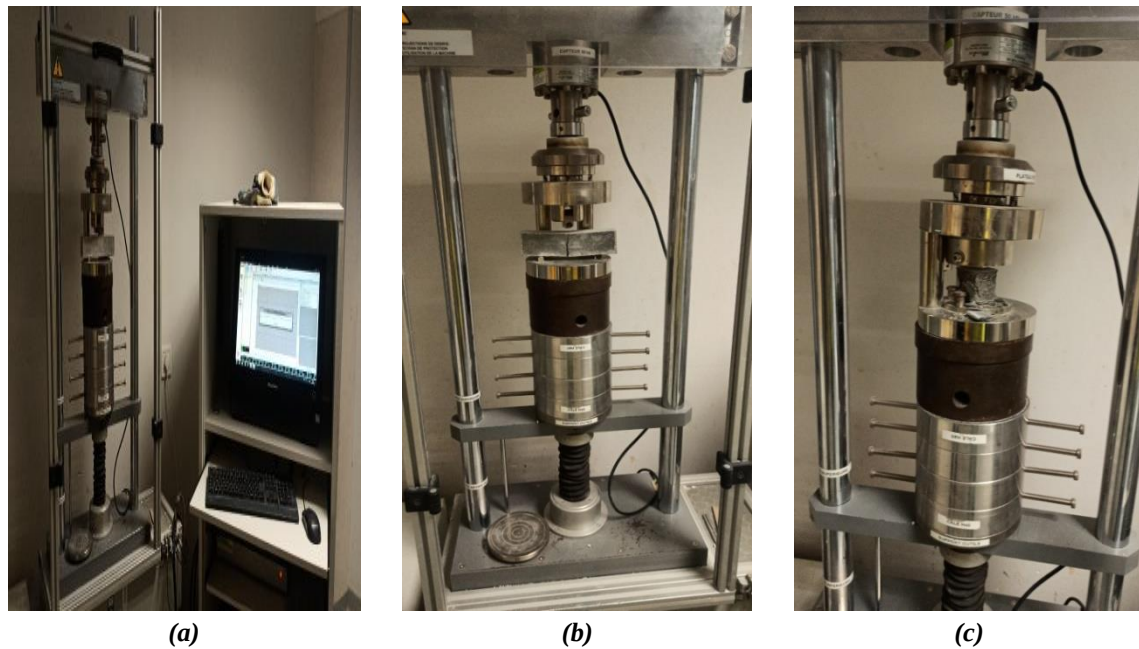


Fig. 4 – (a) Experimental device for measuring mechanical strength; (b) Flexure three-point test; (c) Compressive test

The obtained results are presented in Figures 5 and 6. According to the results, it can be seen that the introduction of slag improves the workability of the mixture, in fact, a reduction in the dosage of the superplasticizer is observed. However, the increase in the fineness reduces further the dosage by up to 46% for the same spread value. This may be due to the combined effect of smooth morphology and similar particle shape of slag offering a better inter-granular slide in the mixture [45] in addition to their vitreous structures [46] which are characterized by their very low absorption rate. However, the improvement in the workability with the increase in the fineness of the slag can be explained by the filling of the voids by the fine particles of the slag in the mortar favouring the slide effect, which improves the workability further and considerably reduces the dosage of superplasticizer.

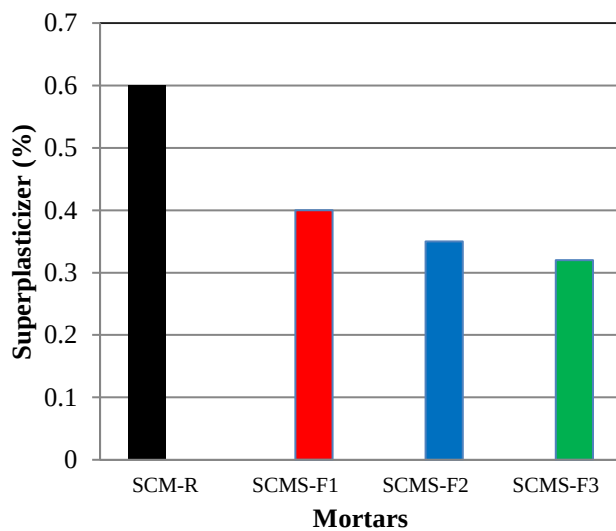


Fig. 5 – Required dosage in superplasticizer for slag-based mortars

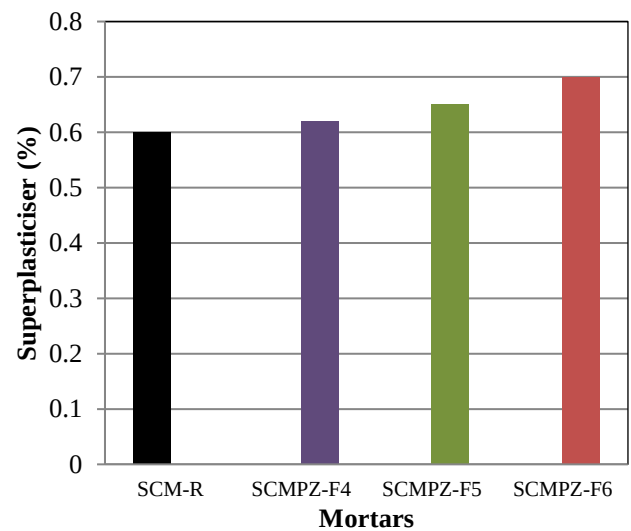


Fig. 6 – Required dosage in superplasticizer for pozzolan-based mortars

In contrast to the slag, the substitution of cement by pozzolan reduces the workability of the mortars. This reduction is noted for the three studied fineness, which goes from 0.62% for the ground fineness of $3660 \text{ cm}^2/\text{g}$ to 0.7% for the ground fineness of $5250 \text{ cm}^2/\text{g}$. This can be explained by the rough and irregular shape of its micro porous particles with a high absorption rate [45]. These results comply with those found by Hammat et al [35], who state that the increase of the content and the fineness of natural pozzolan decrease the slump flow of self-compacting mortar. Furthermore, Celik et al [47] have confirmed that the quantity of water necessary to reach a normal consistency increases with the increase of the pozzolan content.

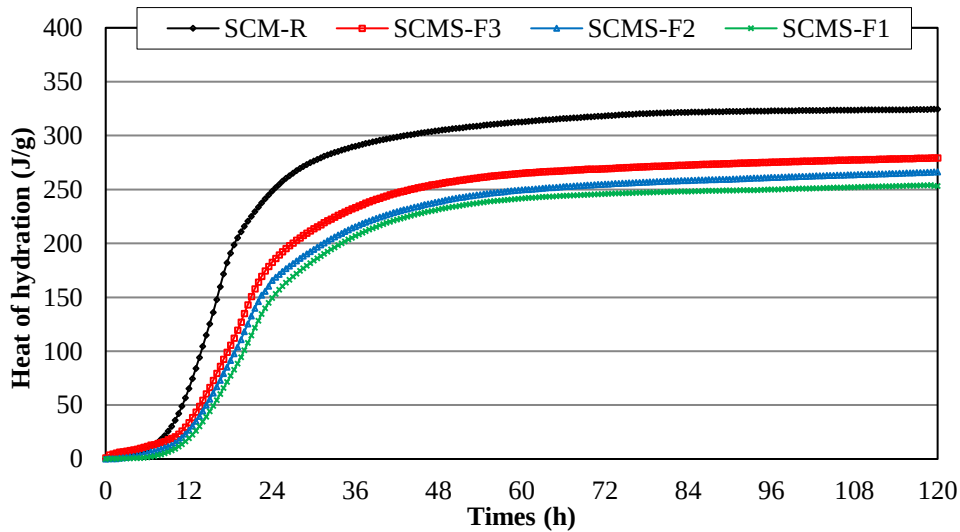


Fig. 7 –Hydration heat of slag-based mortars for 120h

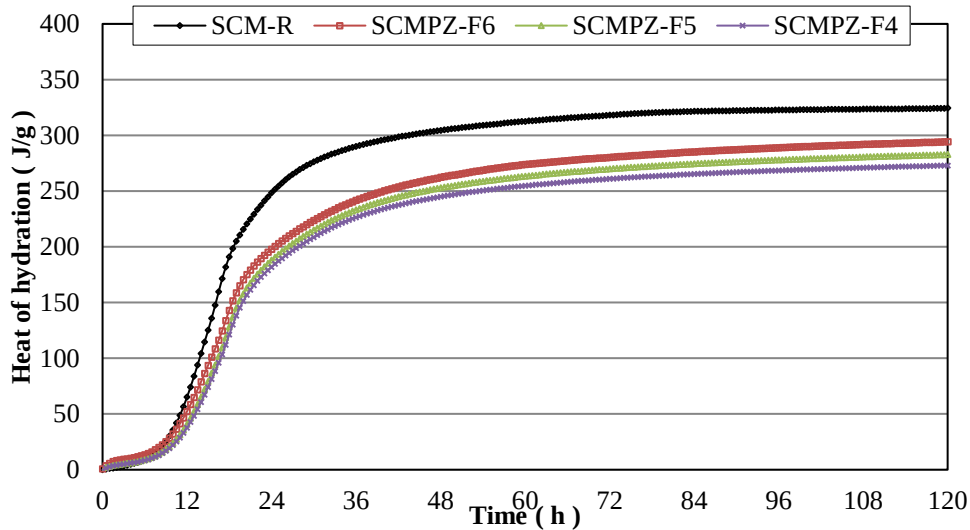


Fig. 8 –Hydration heat of pozzolan-based mortars for 120h

3.2 The effect of additions on the hydration heat

Figures 7 and 8 represent the evolution of the release of cumulative heat as a function of the time during 120 hours of the mortars made by replacing the cement with a fixed rate of 30% for blast furnace slag, and 20% for natural pozzolan. These additions are ground to different fineness. It can be seen that the addition-based mortars release considerably less heat than the reference mortar, at 120 h for instance and for the greater fineness of around $5200 \text{ cm}^2/\text{g}$, a reduction of 16% and 10% was recorded for slag and pozzolan respectively. This reduction tends to become more significant with the decrease in fineness, which can reach 22% for instance in the case of slag ground to $3625 \text{ cm}^2/\text{g}$.

On the other hand, by examining the curves of the accumulated heat for 24 hours as shown in Figures 9 and 10, it's noted that during the first hours of hydration and in particular for the greatest fineness, an accelerating effect was observed for the two additions, which manifests itself during the first hours, and which tends to diminish later, whereas for the other fineness the curves are practically similar in the same interval.

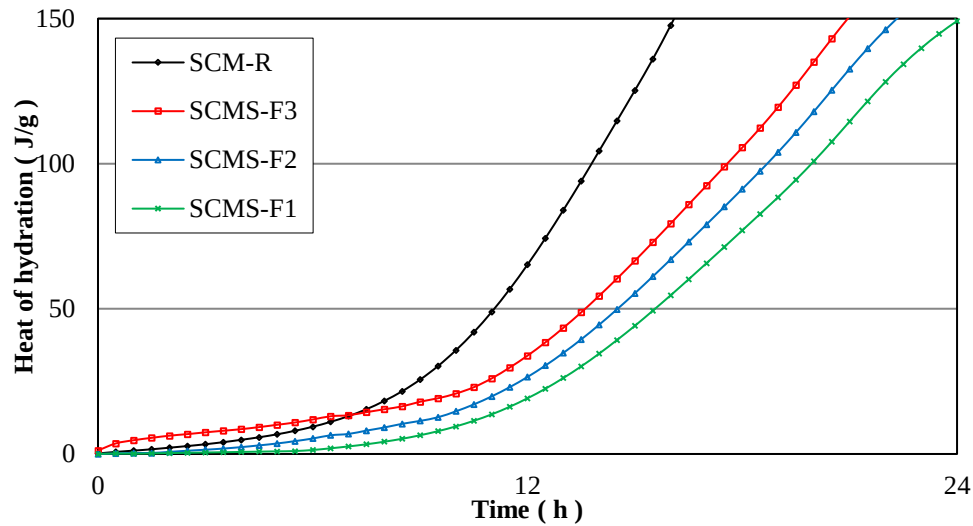


Fig. 9 – Hydration heat of slag-based mortars for 24 hours

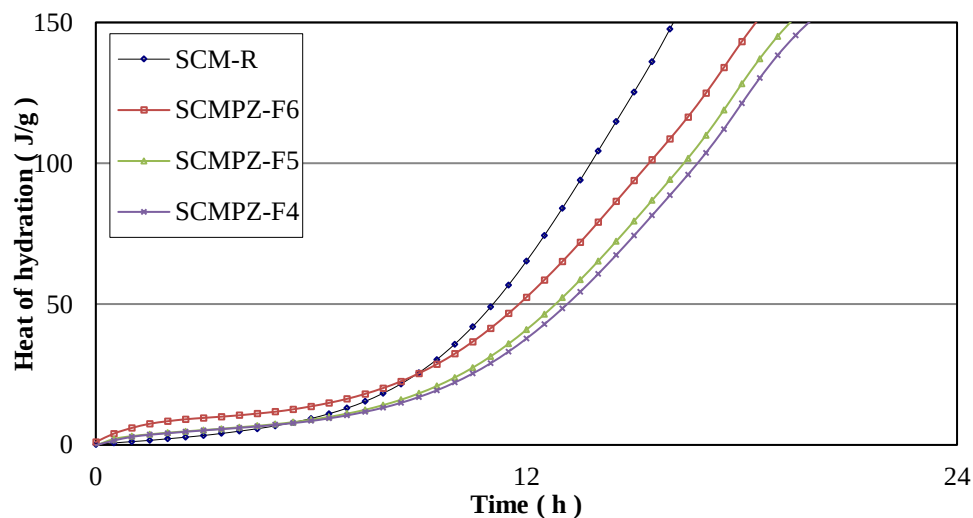


Fig. 10 – Hydration heat of pozzolan-based mortars for 24 hours

By analyzing the heat flow represented in figures 11 and 12, it is clear that the mortars based on mineral additions are less exothermic than the reference mortar. For example, for a fineness of approximately $5200 \text{ cm}^2/\text{g}$, the exothermic peak is 14.84 j/g.h and 18.44 j/g.h for the slag and the pozzolan respectively, whereas that of the reference cement is 24.27 j/g.h . Furthermore, the kinetic of appearance of these peaks is significantly different. In fact, the peak of the cement appeared at 4h, while for the slag and pozzolan the peaks appeared at 6.30h and 5.30h respectively. Therefore these peaks are both decreased and delayed. However, this reduction leads to an extension of the dormant period of the addition-based mortars compared to the reference mortar. Nevertheless, for each addition, the fineness increases and accelerates the formation of the peak and therefore, decreases the dormant period, by varying the fineness from $3600 \text{ cm}^2/\text{g}$ to $5200 \text{ cm}^2/\text{g}$ which goes, for example, from 7:30 min at 6h, for the slag, and from 6h36 min to 5h for the pozzolan. This remark is noted for all mortars made from additions.

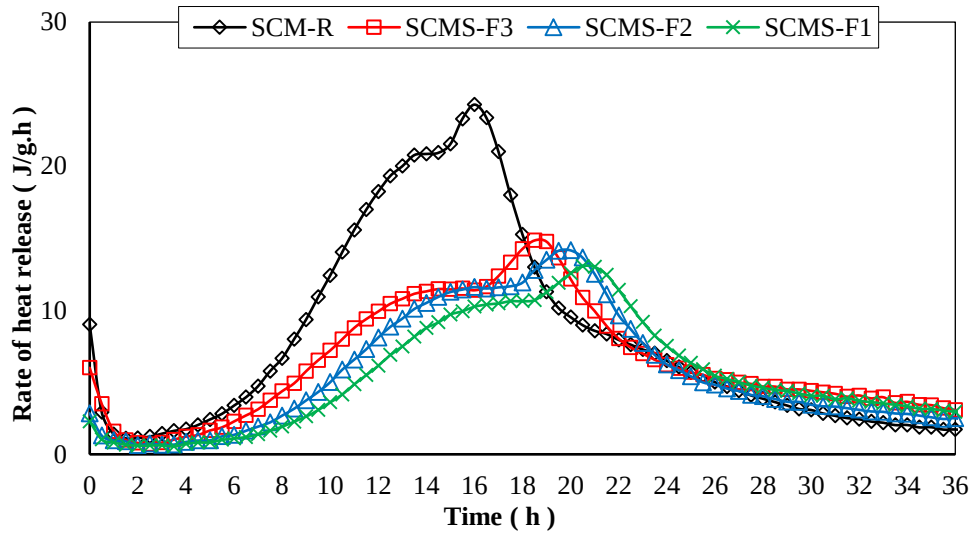


Fig. 11 – Heat flow of slag-based mortars

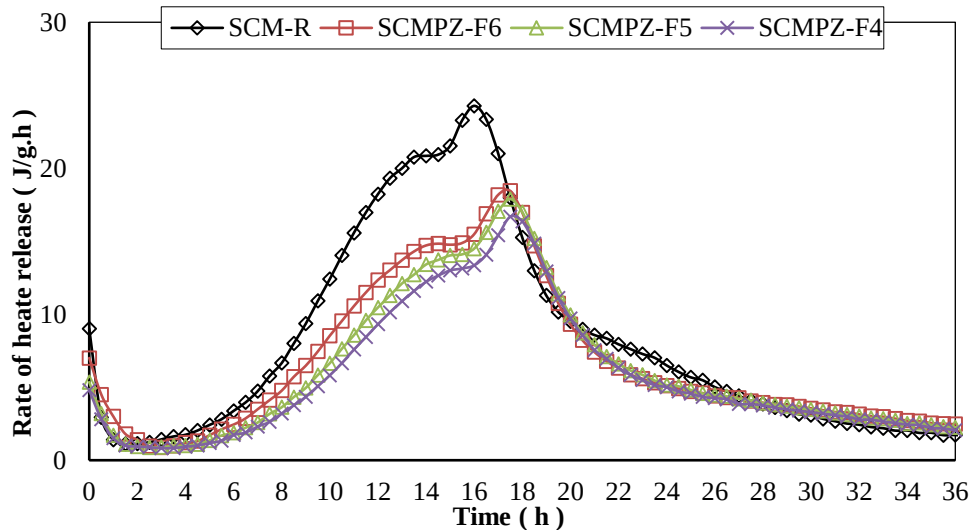


Fig. 12–Heat flow of pozzolan-based mortars

The incorporation of mineral additions modifies the process and the kinetic of cement hydration. Indeed, the hydration of cement is characterized by the dissolution-crystallization principle, after mixing and in contact with water, the hydration of C_3S results in the release of calcium hydroxide following the formation of new hydrated phases. These hydrates could partly precipitate on the mineral surfaces offered by the additions, thus forming a heterogeneous nucleation site. In this regard, the greater the fineness of the addition is, the more surfaces are available [48] explaining the acceleration of the hydration shown in Figures 9 and 10. In this case, the thickening of the hydrate layer, which forms around the cement grain will be less important. Thus, facilitating the diffusion phenomenon governing the dissolution of the anhydrous grain, which accelerates the hydration of the clinker by the rupture of the protective layer which surrounds the surface of the grains of the cement by the effect of the osmotic pressure due to the passage of water from the solution to the interior of the layer [49, 50]; thus favouring the hydration of the cement and the reduction of the dormant period. In addition, the increase in the concentration of Ca^{2+} ions accelerates the dissolution of the acid film which has formed around the slag grains allowing the continuation of the hydration reactions through the pozzolanic reaction, which by consuming lime accelerates the speed of dissolution of the clinker Alite [51]. The sequence of the hydration process leads to the consumption of portlandite by the pozzolanic reaction due to the presence of the amorphous silica provided by the addition, which generates an additional stimulation of the hydration of the anhydrous grain that is added to the heterogeneous nucleation [52]. These chemical and surface phenomenon are linked to the fineness of the addition, the greater the fineness is, the greater the acceleration of the hydration and the more the dormant period is attenuated.

The appearance of the hydration deceleration levels in Figures 11 and 12 can be explained by the imbalance in the ionic concentration of the solution; the drop in pH and the Ca^{2+} ions leading to an imbalance between the speed of dissolution and the speed of precipitation. The longevity of the deceleration level is all the greater for mortars based on additions and in particular for the greater fineness. This may be due to the consumption of portlandite by the pozzolanic reaction, as well as the lowered rate of Ca^{2+} caused by the dilution effect; because the dissolution of one mole of C_3S releases 03 moles of Ca^{2+} cations [53].

3.3 The effect of additions on compressive strengths

It can be noticed in figures 13 and 14 that the introduction of additions to the mixtures leads to a reduction in compressive strengths due to the substitution (dilution effect). Despite this, at a very early age (one day), it was found that the mortars based on slag and pozzolan gave compressive strength similar to that of the reference mortar in particular, for the great fineness. This can be explained by the space-filling effect of the additions, which improves the compactness of the mixture by filling the intergranular voids [54], as well as the surface effect of the additions, which results in the formation of heterogeneous nucleation sites, which favours hydration and leads to the development of early strength [37], this is directly followed by the pozzolanic reaction. These effects have been observed by a number of researchers [52, 55].

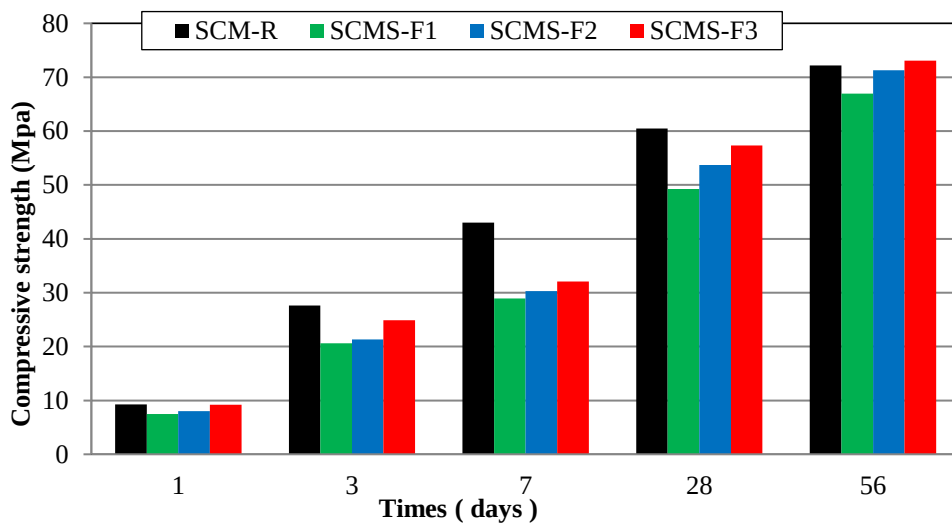


Fig. 13 –Compressive strength of slag-based mortars

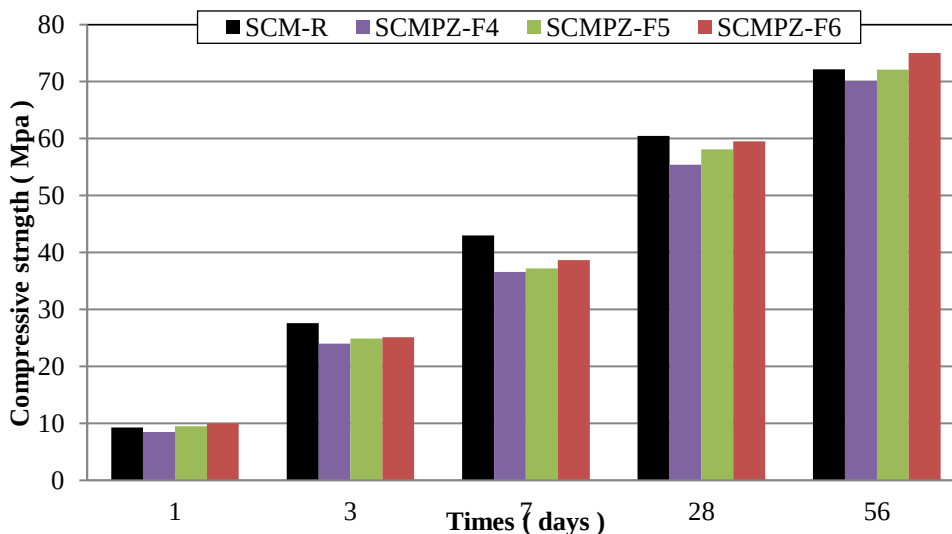


Fig. 14 – Compressive strength of pozzolan-based mortars

As early as three days, pozzolan-based mortars develop compressive strength lower than that of the reference mortar until the age of 28 days. However, this difference is less significant between 7 and 28 days. This can be attributed to the triggering of the pozzolanic reaction of natural pozzolan with the hydration products of C_3S . The said reaction improves the densification of the microstructure by the additional (C-S-H) hydrates, which generates additional strength with a marked magnitude in the long term justifying the improvement of the strengths generated at 56 days. However, this pozzolanic activity is accelerated by the increase in the fineness of the pozzolan, in fact at 28 days for example, an increase of 4.11 MPa was recorded for the increase in the fineness from 3660 cm^2/g to 5250 cm^2/g . These results are consistent with those found by Hammat et al. [35].

At the medium term, slag mortars have lower compressive strengths than those of the reference mortar regardless the fineness, beyond this deadline, the strength difference becomes less important depending on the fineness, In addition, the more the fineness increases, the difference decreases and becomes less remarkable or even vanishes and the strengths exceed that of the reference mortar in the case of long terms; and therefore the effect of fineness is clearly marked. This can be explained by the latent hydraulic properties of the slag because the reaction between the $Ca(OH)_2$ portlandite and the constituents of the slag is slow in the medium term, but which takes its full extent in long-term periods leading to the consumption of the lime by supplying additional hydrated calcium silicate (C-S-H) resulting in better densification of the microstructure and therefore additional strengths [56]. The same effect was observed by Hammat et al. [57].

4 Conclusion

In this study, the effect of fineness of mineral additions on the hydration of self-compacting mortars, as well as their behaviour in fresh and hardened states was studied. The key conclusions are as follows:

The separate grinding enables to better mechanically activate the mineral additions and therefore a better exploitation of the advantages they present. In fact, the increase of the fineness of the slag has proven to be very beneficial for the formulation of self-compacting mortars, the workability is significantly improved which results in the considerable reduction in the demand for superplasticizer inversely proportional to its fineness of the order of 30% to 46% in order to maintain constant workability. However, the opposite effect has been observed for the pozzolan, its excessive grinding is not recommended for the formulation of self-compacting mortars, the demand for superplasticizer becomes significant in proportion to the fineness of the order of 3.3 % to 16 % and consequently bleeding will be inevitable, the formulation has proved to be difficult, which risks limiting the rate of substitution.

The activity of the mineral additions is proportional to their fineness, the increase in fineness accelerates the hydration reactions by the formation of heterogeneous nucleation sites favouring the development of initial compressive strengths, which exceed that of the reference mortar, these strengths tend to decrease in the medium term, with a strength divergence compared to the reference of 10% for pozzolan and 25% for the slag due to the late onset of its pozzolanic activity, nevertheless, the increase in fineness at this stage of 1600 cm^2/g provides 10% of additional strength. The effect of the fineness is clearly pronounced from 28 days onwards with a lower strength difference of around 1.5% for the pozzolan and 5% for the slag. The increase in the fineness leads to the rapid onset of pozzolanic activity, which increases in the long term, generating strengths clearly superior to those of the reference mortars. In this context, in order to have a significant reactivity, the mineral additions must be ground beyond 10% compared to the fineness of the cement used, for this reason, the excessive grinding of the slag does not seem to have a compromising effect on the performance of the self-compacting mortars, which makes it possible to further increase its substitution rate.

Mortars based on additions are less exothermic with a reduction in the final heat of hydration of the order of 14 to 22% for the slag and 9 to 16% for the pozzolan. However, a significant release of heat was observed during the initial hydration, for the great fineness of the additions, by cause of the phenomenon of heterogeneous nucleation, throughout excessive mechanical activation, in order to improve the compressive strengths, the release of heat must be taken into consideration in order to avoid the thermal cracking. The additions showed a certain synergy between the different phenomena: physical, chemical or surface through the different ages. It was therefore interesting to study the influence of a ternary composite of cement, slag and pozzolan in order to develop the performance of self-compacting mortars by exploiting the eventual synergy of the additions.

Abbreviations and notations

Gt : Gigatonne	SCC: Self-compacting Concrete	SiO ₂ : Silica
CO ₂ : Carbon dioxide	SCM: Self-compacting Mortar	Al ₂ O ₃ : Alumina
C-S-H : Calcium silicate hydrate	SCM-R : Self-compacting mortar reference without additions	Fe ₂ O ₃ : Ferric oxide
C ₃ S : Tricalcium silicate	SCMS-F Slag based self-compacting mortar	CaO : Calcium oxide
C ₂ S : Dicalcium silicate	SCMPZ-F:Pozzolan based self-compacting mortar.	MgO : Magnesium oxide
C ₃ A :Tricalciumsilicate	F1, to F6 : Fineness Blaine.	Na ₂ O : Sodium oxide
C ₄ AF : Titracalciumalumino ferrite	SSB : Surface Specific Blaine.	K ₂ O : Potassium oxide
Sp : Superplastisizer	EFNARC: European Federation of National Associations Representing for Concrete.	SO ₃ :Sulphuric anhydride
S/M : Sand/Mortar		Ca ²⁺ : Calcium ions
W/B : Water/Binder		LOI: Loss in ignition
Sp/B : Superplastisizer/Binder		Ca(OH) ² : Portlandite

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