Influence of cementitious additions on rheological and mechanical properties of reactive powder concretes

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Abstract

Following needs of concrete market and the economic and ecological needs, several researchers, all over the world, studied the beneficial effect which the incorporation of the mineral additions in Portland cement industry can bring. It was shown that the incorporation of local mineral additions can decrease the consumption of crushing energy of cements, and reduce the CO\textsubscript{2} emission.

Siliceous additions, moreover their physical role of filling, play a chemical role pozzolanic. They contribute to improving concrete performances and thus their durability.

The abundance of dunes sand and blast furnace slag in Algeria led us to study their effect like cementitious additions.

The objective of this paper is to study the effect of the incorporation of dunes sand and slag, finely ground on rheological and mechanical properties of reactive powder concretes containing ternary binders.

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1. Introduction

The reactive powder concretes RPC belong to the family of the ultra high performance concretes (UHPC). These concretes are materials with cementitious matrix from which the proportion of the various granular components were optimized in order to obtain high mechanical performances and an improved durability [1]. These performances are mainly related to the densification of the concrete matrix. Which is ensured by a judicious choice of cementitious additions [2,3]. The latter can be natural or industrial waste. Their substitution for cement fulfills as well ecological as economic requirements. This double advantage results in the management and recycling waste which leads to the reduction of cement consumption, and thus CO\textsubscript{2} emission. Reactive powder concretes, consisted of siliceous fine minerals mixture, are a new generation of concretes [4,5]. These minerals have pozzolanic reactivity (fixing of lime, resulting from cement hydration in the form of second-generation C-S-H), thus allowing to improve compactness and performances of concretes [3,6,7,8,9].

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In this investigation we were interested in studying the effect of a binary siliceous addition, locally available, on the rheological and mechanical properties of the RPC. This addition is a mixture of blast furnace slag \textit{S} and dunes sand finely ground \textit{SD}.

2. Used materials:

Materials used in this study are of local origin, except silica fume imported from Canada which is used for comparison. Physical and chemical properties of these materials are presented in tables 1 and 2, respectively:

Table 1: Physical characteristics of, cement and additions used.

| Component             | Cement CEM II | Silica fume SF | Crushed dunes sand DS | Slag S |
|-----------------------|---------------|----------------|-----------------------|--------|
| Real density (g/cm$^3$) | 3.13          | 2.20           | 2.73                  | 3.16   |
| Fineness Blaine (cm$^2$ / g) | 3605          | /              | 5000                  | 3230   |
| Fineness B.E.T (cm$^2$ / g) | /             | 200 000        | /                     | /      |

Table 2: Chemical composition of materials

| Components | Cement | Silica fume SF | Dunes Sand DS | Slag S |
|------------|--------|----------------|---------------|--------|
| SiO$_2$    | 19.35  | 96.00          | 94.90         | 39.59  |
| Al$_2$O$_3$| 3.50   | 0.90           | 1.48          | 9.73   |
| Fe$_2$O$_3$| 3.09   | 0.60           | 0.48          | 3.56   |
| CaO        | 62.31  | 1.58           | 0.90          | 41.23  |
| MgO        | 1.82   | 0.20           | 0.97          | 3.38   |
| SO$_3$     | 1.90   | 0.45           | 0.03          | 0.67   |
| Na$_2$O    | 0.16   | 0.17           | 0.10          | 0.01   |
| K$_2$O     | 0.59   | 0.96           | 0.20          | 0.58   |
| Cl$^-$     | 0.019  | /              | /             | 0.007  |
| LOI        | 5.98   | /              | /             | -1.33  |
| R, Ins     | 1.59   | /              | /             | /      |

For the confection of RPC, we have used the dunes sand in its natural state, which have a fineness modulus Mf=0.95. In order to reduce mixing water, a polycarboxylate superplasticizer has been used. This polycarboxylate is a hydrocarbon consisting of long carbon chain with the molecular structure:
The product is compliant with EN934-2 and was chosen to improve the properties of concrete. According to ASTM C494 it is classified Type F (water reducer). The product is manufactured by a company of Algeria. It is a Yellowish liquid (30% of dry powder) with a density of 1.07 and a pH of 6-6.5. Concrete mixes tested are containing 15% of binary addition (10+5) %. The various compositions tested are presented in the following table:

Table 3: Concrete mixes tested

|                | RPC control | RPC 1 | RPC 2 | RPC 3 | RPC 4 | RPC 5 | RPC 6 |
|----------------|-------------|-------|-------|-------|-------|-------|-------|
| Cement (Kg)    | 882         | 750   | 750   | 750   | 750   | 750   | 750   |
| SF (Kg)        | -           | 88    | 44    | 88    | 44    | -     | -     |
| DS (Kg)        | -           | 44    | 88    | -     | -     | 88    | 44    |
| Slag (Kg)      | -           | -     | -     | 44    | 88    | 44    | 88    |
| Sand (Kg)      | 1235        | 1235  | 1235  | 1235  | 1235  | 1235  | 1235  |
| Superplasticizer (%) | 1.8  | 1.8   | 1.8   | 1.8   | 1.8   | 1.8   | 1.8   |
| Water (Kg)     | 212         | 212   | 212   | 212   | 212   | 212   | 212   |
| W/B            | 0.24        | 0.24  | 0.24  | 0.24  | 0.24  | 0.24  | 0.24  |

3. Cement-Superplasticizer compatibility and saturation point:

Our tests have been carried out on mixtures made up of 15% of binary addition (10% X+5% Y) in substitution of the used Portland cement.

Before starting our tests on the concrete, the compatibility of cement; in the presence of the various additions and superplasticizer; has been tested. This test enabled us to determine; the saturation points with the superplasticizer of the different grouts cement mixed with a W/B ratio of 0.35.

The variation of flow time according to dosage of Superplasticizer; with six (6) measurements and standard deviation ranging from 1.9 to 2.1 seconds, are presented in figure 1 below:

![Dosage of SP30 corresponding to saturation point of control’s grout T](image1)

a) Grout without addition

![Dosage of SP30 corresponding to saturation point of a grout SF+DS](image2)
b) Grout with SF+DS

![Dosage of SP30 corresponding to saturation point of a grout DS+SF](image3)
c) Grout with DS+SF

![Dosage of SP30 corresponding to saturation point of a grout SF+S](image4)
d) Grout with SF+S
These results show that the flow time of various cement grouts; with and without additions; is influenced by the proportion in SP. It decreases as the proportion of the Superplasticizer increases and stabilises once reaching a given content of the Superplasticizer, knowing as optimal content or the saturation point.

The measured saturation points; with the Marsh’s cone; varies according to the components and the nature of the used grout. It is reached at 0.8% of Superplasticizer for the cement grout without addition (control).

In the presence of the grout containing slag (S) and dunes sand (DS) (10%DS+5%S and 10%S+5%DS), the saturation point is reached at only 0.6% of superplasticizer. The additions reduce the quantity of superplasticizer. Dunes sand has a large fineness more than that of the Slag. Which leads to a lower flow times in grout containing the dunes.

In addition, although the quantity of cement decreases with the incorporation of the SF in the combination with the DS or the S, the saturation point increases and reaches the value of 1%. This is due, to the high fineness of the silica fume (SF) compared to the slag (S) and to that of the crushed dunes sand (DS).

4. Workability measurement:

The binders used in concrete mixes are of 15% of binary addition (10%X+5%Y). The various proportions of the anhydrous components of the concretes tested are summarized in table 4:

| Table 4: Concrete mixes tested                        |
|-------------------------------------------------------|
| **RPC T** | **RPC1** | **RPC2** | **RPC3** | **RPC4** | **RPC5** | **RPC6** |
|--------------------------------|----------|----------|----------|----------|----------|----------|
| Cement (Kg) | 882      | 750      | 750      | 750      | 750      | 750      |
| SF (Kg)    | -        | 88       | 44       | 88       | 44       | -        |
| DS (Kg)    | -        | 44       | 88       | -        | -        | 88       |
| Slag (Kg)  | -        | -        | -        | 44       | 88       | 44       |
| Sand (Kg)  | 1235     | 1235     | 1235     | 1235     | 1235     | 1235     |

Optimization of the couple quantities (water/binder; Superplasticizer) on the RPC was given using maniabilimeter LCPC with standard mortar B in order to obtain an appreciably constant workability [10].
Table 5: Workability of concrete as a function in superplasticizer dosage (SP) with W/B=0.20

| % SP | RPC control | RPC1 | RPC2 | RPC3 | RPC4 | RPC5 | RPC6 |
|------|-------------|------|------|------|------|------|------|
| 1.4  | > 7 min     | > 7 min | > 7 min | > 7 min | > 7 min | > 7 min |
| 1.6  | 113 s       | 210 s | 130 s | 126 s | 108 s | 109 s | 109 s |
| 1.8  | 108 s       | 179 s | 134 s | 119 s | 100 s | 98 s  | 99 s  |

Our results in table 5 show that the rheological behaviour is influenced by the proportion of Superplasticizer. More the proportion of the superplasticizer increases more the consistency of the mixtures decreases. The flow Times remain however very high even after reaching a proportion of 1.8% of Superplasticizer. In an economic concern aiming the use of the RPC on building site, we preserved a constant proportion of additive (1.8%) while increasing the quantity of mixing water [10].

Table 6: Workability according to W/B ratio with 1.8% SP

| W/B   | RPC control | RPC1 | RPC2 | RPC3 | RPC4 | RPC5 | RPC6 |
|-------|-------------|------|------|------|------|------|------|
| 0.20  | 108         | 179  | 134  | 119  | 100  | 98   | 99   |
| 0.22  | 46          | 94   | 16   | 77   | 44   | 38   | 40   |
| 0.24  | 5           | 9    | 5    | 11   | 5    | 4    | 4    |

The tests led to an optimum of 1.8% of dry extract of Superplasticizer compared to the weight of cement with a W/B ratio = 0.24.

5. Activity index

The compressive strength test enabled us to determine the activity index (I.A), by using the following expression:

$$LA = 100 \frac{\sigma_c}{\sigma_{cont}}$$

With:
- \(\sigma_c\): Compressive strength of concrete with additions
- \(\sigma_{cont}\): Compressive strength of control concrete (without additions)

The standard deviation "s" of these testes is in vicinity of 2 %.

Table 7: Activity index of different RPC

|         | 3 days | 7 days | 14 days | 28 days | 90 days |
|---------|--------|--------|---------|---------|---------|
| RPC control | 100    | 100    | 100     | 100     | 100     |
| RPC 1   | 85     | 101    | 105     | 104.5   | 118     |
| RPC 2   | 88     | 98     | 100     | 99      | 97      |
| RPC 3   | 88     | 99.4   | 104     | 105     | 107     |
| RPC 4   | 88.5   | 107    | 103.4   | 104     | 105     |
| RPC 5   | 91.4   | 90.3   | 95.7    | 96      | 97.3    |
| RPC6    | 89.6   | 100    | 99      | 97.5    | 100.3   |
5.1. At early ages (T ≤ 14 days)

Compressive strengths of RPC with additions are lower than that of the control. This is due to the introduction of additions by substitution and their pozzolanic reactions which did not take place yet [11;11;13;14].

From the 7th day, concretes containing a high proportion of amorphous addition (RPC1, 3, 4 and 6) have similar strengths to that of the control. This shows that the pozzolanic reaction of amorphous additions started at this age [12; 13; 14; 15].

Concretes containing 10% of SF (RPC 1 and RPC 3) have similar strengths and largely higher than that of the control. Silica fume has a strong pozzolanic reactivity considering its very high fineness and its amorphous structure. The effect of the 2nd addition (DS or slag) is not detectable at early ages, since it is used in low proportion (5%) [12, 13].

Concrete RPC 6 (with 10% of slag) presents similar strengths to those of the control, which are slightly higher than that of the RPC 5 (with 10% of DS). This explains that the slag, although its low content of SiO₂, is more reactive than the DS at early age.

These results show that the kinetic of pozzolanic reactivity of additions at early ages is influenced much more by its morphology and than its fineness. This result is in agreement with the literature Amorphous materials are more reactive at early ages than crystalline materials [2, 3, 7, 9].

5.2. At advanced ages (T > 14 days)

5.2.1. Reactivity of slag:

Concrete RPC 6 presents similar strengths to those of the control, which are slightly higher than those of the RPC5. This is explained by fixing an important amount of lime with 10% of slag than with 10% of DS.
5.2.2. Reactivity of dunes sand:

Strengths of the concrete RPC 1 are higher than those of the control and the BPR3. This is attributed to the presence of 5% of DS in the RPC 1.

According to these results, it has been showed that dunes sand is introduced with a low proportion (5%), and in the presence of an amorphous addition led to an improvement of properties of concretes at long-term. This is due to its high content of silica and its high fineness, translating the pozzolanic reactivity of SD [11; 12; 13; 14].

The concrete based on binary addition (10% slag +5% SD) has same strengths as those of the control. It represents the economic composition and answers the double economic and ecological advantages.

6. Conclusion:

With an aim of analyzing the rheological and mechanical behaviour of the reactive powder concretes based on local additions. It can be inferred that the proportion of Superplasticizer at the saturation point corresponds to the minimal quantity necessary to ensure the good dispersion of the cement grains.

The proportion of Superplasticizer at the saturation point increases with the fineness of the grout.

The morphology of the addition has a great influence on the pozzolanic reactivity: amorphous additions have a strong pozzolanic reactivity at early ages. Silica fume has a strong pozzolanic reactivity considering its very high fineness and its vitreous state. The amorphous structure makes the ground slag reactive at early ages, but its low silica content influences its long-term pozzolanic reactivity.

The ground dunes sand, although its crystalline state, becomes reactive at long-term, when it is added with 10% of amorphous addition.

The siliceous additions (ground dunes Sand and slag), very abundant in Algeria, make it possible to reduce the consumption of the Superplasticizer and cement proportion satisfying the double economic and ecological advantages.

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