INFLUENCE OF THE SUPERPLASTICIZER TYPE ON THE COMPRESSIVE STRENGTH OF REACTIVE POWDER CONCRETE FOR PRECAST STRUCTURES

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1. INTRODUCTION

Reactive powder mortar (*RPM*[*]) is a special high-strength, fiber-reinforced, superplasticized, silica-fume system with improved homogeneity because traditional aggregate are replaced by very fine sand with particle size in the range of 150-400 μm [1]. Potential applications of *RPM* include prestressed structures without passive reinforcement, pressure precast pipes, impermeable containers for hazardous fluids or nuclear wastes.

In previous investigations the influence of the cement type and silica fume brand on the water-cement ratio (*w/c*) and compressive strength of *RPM* was investigated [2].

This paper reports the influence of the superplasticizer type (naphthalene, melamine and acrylic polymer) on the *RPM* performance in terms of water-cement ratio and compressive strength.

2. MATERIALS

Two ASTM Type V portland cements (*A* and *B*) were selected. The main differences were the C_3A content and the Blaine fineness: the C_3A content was 0% and 4% whereas the specific surface area was 340 and 530 m^2/kg for cement *A* and *B*, respectively. Many other portland cements were used to study the performance of *RPM*. However, for the sake of brevity, only the results with cement *A* and *B* will be examined in the present paper.

Three silica fume brands (*W*, *G*, *D*) were used which were different with respect to colour (white, grey and dark respectively), particle size, minor components and unburnt content (Table 1). The most important characteristics seems to be the bulk gravity which is much lower for the *G* silica fume than for the others. This indicates that the *W* and *D* silica fume brands were available in a densified form, whereas the *G* brand was a loose un-compacted silica fume.

Fine natural sand (150-400 μm) and pure precipitated silica (SiO_2 > 99.8%) were also used in agreement with the composition proposed by Richard and Cheyrezy for *RPM* with 200 MPa compressive strength [1]. Steel fibers were used with an aspect ratio of 31 (length: 11 mm,

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[*] *In the original work (1), the reactive powder mortars were erroneously called "reactive powder concretes" (RPC). Hereafter, they will be referred to reactive powder mortars (RPM).*

Table 1 - Composition and properties of silica fume.

Silica fume brand	W	G	D
Colour	White	Grey	Dark
SiO_2 (%)	94.43	98.87	95.12
mean particle size (μm): - without superplasticizer - with superplasticizer	 0.69 0.62	 13.87 0.76	 63.59 0.73
Unburnt (%)	0.0	0.0	1.6
Bulk gravity (g/cm^3)	0.45	0.12	0.47

diameter: 0.35 mm). Three different types of superplasticizers were used: a) 30% aqueous solution of acrylic polymer (*AP*); b) 40% aqueous solution of sulfonated melamine-formaldehyde condensate (*SMF*); c) 40% aqueous solution of sulfonated naphthalene-formaldehyde condensate (*SNF*).

3. MIXTURES

Tables 2 and 3 show the mixture composition, the water to cement ratio (*w/c*) as well as the water to binder ratio (including silica fume) of the 18 mixtures (2 cements x 3 superplasticizers x 3 silica fume types) manufactured with cement *A* and *B*, respectively. The amount of water coming from the aqueous solution of the superplasticizers was included in the *w/c* as well as in the water to binder ratio.

The amount of the dry *AP* superplasticizer was 1.36% by mass of cement as in the original mixture proposed by Richard and Cheyrezy [1]. The amount of the dry *NSF* or *MSF* superplasticizer (1.78%) was selected after preliminary tests in order to find the best performance in terms of water reduction at a given workability level. In other words, no significant further reduction in the mixing water was recorded when amounts of *SNF* or *SMF* higher than 1.78% were used.

After mixing all the ingredients including water in a laboratory pan mixer for 5 min, it was observed that the fresh mixtures were very sticky. Therefore the original flow table test (with 10 drops) did not appear to be adequate to assess the workability behaviour under the vibration required to compact the sticky mix into the molds. Then a modified flow table test was used by substituting a Vebè vibrating table (10 seconds of vibration) for the original flow table.

Cube specimens (40 mm) were consolidated by vibration and then cured at room temperature (20°C). Compressive strength were measured at 1, 2, 3, 14 and 28 days.

4. RESULTS

The results will be examined regard to water to cement ratio and compressive strength.

The *w/c* of the mixtures (Table 2 and 3) was affected by the type of cement, silica fume and superplasticizer:

- Independently of the superplasticizer type, mixtures with cement *A* (a C_3A-free portland cement with low specific surface area) always needed lower *w/c* as compared to the mixtures with cement *B*; similar results were obtained with other portland cements in the presence of the *AP*-superplasticizer [2];
- Regardless of the superplasticizer type, the *w/c* in mixtures with white silica fume was significantly lower than in those with dark silica fume, whereas the grey silica fume performed a little better than the dark one.
- Independently of the cement and silica fume types, the *w/c* in the presence of the acrylic polymer was much lower than that with the *NSF*- or *MSF*-based superplasticizer, although

the amount of *AP* was lower than that of the other admixtures (1.36% versus 1.78% by cement mass).

Table 2 - Composition of superplasticized mixtures with portland cement A.

Mixture No.	1	2	3	4	5	6	7	8	9
Silica fume brand	White			Grey			Dark		
Superplasticizer	AP	SNF	SMF	AP	SNF	SMF	AP	SNF	SMF
Composition (kg/m^3):									
- Portland cement	937	900	876	903	876	847	872	854	847
- Silica fume	225	216	210	217	210	203	209	205	203
- Precipitated silica	9.4	9.0	8.8	9.0	8.8	8.5	8.7	8.5	8.5
- Fine sand	1031	990	963	993	964	932	959	939	932
- Steel fibers	187	180	175	181	175	169	174	171	169
- Superplasticizer*	12.7	16.0	15.6	11.3	15.6	15.1	11.9	15.2	15.1
- Water	169	198	219	199	219	246	227	239	246
W/C	0.18	0.22	0.25	0.22	0.25	0.29	0.26	0.28	0.29
W/(C + SF)	0.14	0.18	0.20	0.18	0.20	0.23	0.21	0.22	0.23
Flow table (mm)	160	150	150	160	150	150	160	160	160

** Dry polymer*

Table 3 - Composition of superplasticized mixtures with portland cement B.

Mixture No.	10	11	12	13	14	15	16	17	18
Silica fume brand	White			Grey			Dark		
Superplasticizer	AP	SNF	SMF	AP	SNF	SMF	AP	SNF	SMF
Composition (kg/m^3):									
- Portland cement	879	847	833	850	793	768	843	787	763
- Silica fume	211	203	200	204	190	184	202	189	183
- Precipitated silica	8.8	8.5	8.3	8.5	7.9	7.7	8.4	7.9	7.6
- Fine sand	967	932	916	935	872	845	927	866	953
- Steel fibers	176	169	167	170	159	154	169	157	153
- Superplasticizer*	12.0	15.1	14.8	11.6	14.1	13.7	11.5	10.7	13.6
- Water	220	246	258	247	293	315	254	299	321
W/C	0.25	0.29	0.31	0.29	0.37	0.41	0.30	0.38	0.42
W/(C + SF)	0.20	0.23	0.25	0.23	0.30	0.33	0.24	0.30	0.34
Flow table (mm)	155	150	150	150	155	150	155	160	155

** Dry polymer*

Therefore the best performance in terms of the lowest *w/c* occurred with the following specific combination: C_3A-free portland cement, white silica fume and acrylic polymer (Table 2, Mixture No. 1 : *w/c* = 0.18). On the other hand, the highest *w/c* was obtained with cement *B*, dark silica fume and melamine-based superplasticizer (Table 3, Mixture No. 18 : *w/c* = 0.42). However, not necessarily the highest compressive strength corresponded to the lowest *w/c*, and this is shown below.

Figure 1 shows the compressive strength as a function of the hydration time (1-28 days) in mixtures with cement *A*. In the presence of white silica fume (Fig. 1A), the strength at early ages with the *AP*-based superplasticizer was much lower than that with the *SNF*- or *SMF*-based admixtures. However, at later ages the mixture incorporating *AP* attained higher strength with respect to the corresponding cement mixtures with the *SNF* or *SMF* superplasticizer: the 28-day compressive strength was about 160 MPa with *AP* versus about 100 MPa with *SNF* or *SMF*. This behavior can be explained in terms of a strong retardation of the cement hydration caused by the *AP* superplasticizer at early ages, whereas at later ages the lower *w/c* of this mixture (0.18) is responsible for the higher strength level. The early strong retardation caused by the *AP* admixture can be ascribed to the high dosage of this superplasticizer (4-5 times higher than the usual dosage, i.e. 0.3% of dry polymer by cement mass) and the specific combination of the white silica fume with a C_3A-free portland cement having a low specific surface area.

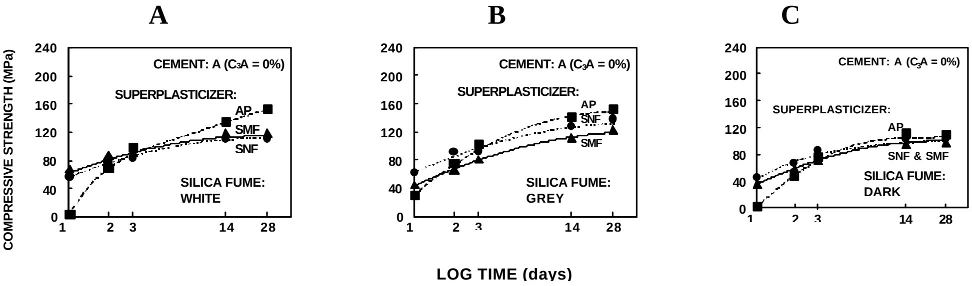

Figure 1:
Compressive strength versus time for mixtures with cement *A* and white (A), grey (B) or dark (C) silica fume.

The substitution of the grey silica fume for the white one reduced the retardation of the cement hydration at 1-day caused by the *AP* admixture but also reduced the 28-day compressive strength (Fig. 1B) because of the higher *w/c* (0.22 vs. 0.18, Table 2). The acrylic polymer performed better than *SNF*- and *SMF*-based superplasticizers in terms of both lower *w/c* (Table 2) and higher strength after 2 days.

In the presence of the dark silica fume (Fig. 1C), again the hydration of the C_3A-free portland cement was strongly retarded by the *AP* superplasticizer. However, at later ages (after 3 days) there is no significant difference in the compressive strength of superplasticized mixtures regardless of the specific admixture.

The only property of silica fumes which could explain their different effect on the 1-day strength of *RPM* with a C_3A-free portland cement seems to be the densification characteristics. The *G* silica fume, with a bulk gravity of 0.12 g/cm^3 (Table 1), was a loose and un-densified powder, whereas *W* and *D* silica fumes (with a bulk gravity of 0.45-0.47 g/cm^3) were available in form of compacted and densified powders. Therefore, since the individual grains of *W* and *D* silica fumes were less dispersed at the end of the mixing time (5 min), they adsorbed a lower amount of the *AP*-superplasticizer and this caused a strong retardation in the cement hydration with respect to the loose and un-densified *G* silica fume. This effect - as it will be examined later - is aggravated by the presence of a low-fineness C_3A-free portland cement which adsorbs a lower amount of superplasticizer with respect to other portland cements with higher fineness and richer C_3A content [3].

Figure 2 shows the compressive strength as a function of the hydration time (1-28 days) in mixtures with cement *B*. These results are representative of the performance of *RPM* with other portland cements as obtained in the laboratories of the authors of the present paper.

In general, the performance in terms of *w/c* was much better with cement *A* (Table 2) than with cement *B* (Table 3). However, the compressive strength development was not always in agreement with the *w/c* data. For instance, the mixture No. 10 with cement *B*, white silica fume and *AP* superplasticizer (*w/c* = 0.25) performed much better than the corresponding mixture No. 1 with cement *A* (*w/c* = 0.18) in terms of 1-day compressive strength: 45 MPa (Fig. 2A) versus 1 MPa (Fig. 1A). This difference can be ascribed to the specific combination of the *AP* admixture (at very high dosage of 1.37%) with a low specific surface area C_3A-free portland cement which was responsible for the retardation of the early hydration of cement *A*.

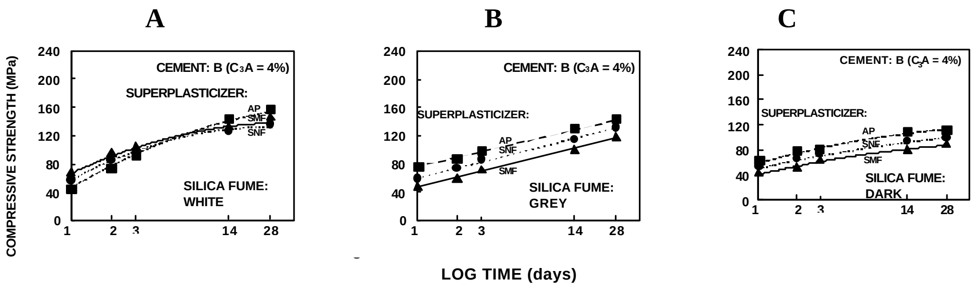

Figure 2:
Compressive strength versus time for mixtures with cement *B* and white (A), grey (B) or dark (C) silica fume.

5. CONCLUSIONS

The acrylic polymer admixture performed better than *SNF*- or *MSF*-based superplasticizers in terms of lower *w/c*, regardless of the cement and silica fume type used in manufacturing *RPM* mixtures.

However, when a C_3A-free portland cement with low specific surface area (340 m^2/kg) was used, the 1-day compressive strength was much lower with the *AP* admixture than with the *SNF*- and *SMF*-based superplasticizers particularly in the presence of white or dark silica fumes. This behavior should be related with a specific retarding effect on the early hydration of this cement caused by *AP* in the presence of densified silica fumes (white and dark-colored). With other portland cements, and in the presence of a loose un-densified silica fume (grey-colored), the *AP* superplasticizers did not cause any early retardation.

At later ages (after 3 days) the compressive strength of *RPM* mixtures with the *AP* admixture were always higher than with *SNF*- or *SMF*-based superplasticizers independently of the cement and silica fume type.

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SUMMARY

Reactive Powder Concrete (RPC) is a new family of ultra-high strength concrete (compressive strength = 200 MPa) that has already used in a prefab plant in Canada. RPC was used to build a footbridge consisting of concrete precast segments - without any passive reinforcement - assembled on site.

In the present study the influence of the superplasticizer type on the RPC performance - in terms of w/c and compressive strength - was studied.

The acrylic polymer (AP) admixture performed better than the naphtalene (SNF) or melamine (SMF) based superplasticizers in regard to lower water-cement ratio and higher compressive strength at ages after 3 days.

The 1-day compressive strength of the RPC with the AP admixture was much lower than that of the corresponding mixtures with SNF or SMF when a C_3A*-free portland cement* *with a low specific surface area was used. This was due to a strong retarding effect of the early hydration when this cement was used in combination with some silica fume types. With other portland cements, the retarding in the early hydration caused by AP did not occur and therefore the 1-day compressive strength was quite higher.*

The 28-day compressive strength of RPC specimens, cured at room temperature, were strongly dependent on the type of cement, silica fume and superplasticizer. However, the highest values obtained in this investigation (160-180 MPa) were lower than those reported by the inventors of RPC (170-230 MPa).

RESUME

Les Réactive Powder Concrete (RPC) représentent une nouvelle famille de bétons ultrarésistants (résistance à la compression = 200 MPa) qui ont été utilisés dans une usine de préfabrication à Sherbrooke, au Canada, pour la réalisation de certains éléments préfabriqués ne contenant pas d'armature attachées. Ces éléments, sont destinés à la construction d'une passerelle piétonnière d'une portée de 70 mètres.

Cette étude à permis d'évaluer l'influence du superfluidifiant sur les prestations des RPC en terme de rapport eau/ciment et de résistance à la compression. L'étude à mis en evidence que le superfluidifiant à base de polymères acryliques (Acrylic Polimer: AP) est plus efficace que les superfluidifiants traditionnels à base de naphtalène ou mélaminique. En effet il permet de realiser des mortiers avec un rapport eau/ciment plus bas (pour la même ouvrabilité initiale) et avec des résistances à la compression plus importantes après 3 jours.

Les résistances à la compression à 1 jour, des mortiers en poudre réactive adjuvantés avec le polymère acrylique sont nettement plus basses que les valeurs obtenues pour les mortiers réalisés avec des polymères à base de naphtalène ou de mélamine alors que le ciment utilisé est sans C_3A *et caractérisé par une surface spécifique basse. Dans les mortiers réalisés avec du ciment Portland contenant de l'aluminate tricalcique, l'effet retardateur du polymère acrylique sur l'hydratation du ciment ne se manifeste pas et, par conséquent, les résistances mécaniques à la compression à un jour, sont particulièrement élevées. L'étude révèle enfin que les résistances mécaniques à 28 jours* (R_{c28}) *des échantillons de mortier à poudre réactive dépendent du type de ciment et de fumée de silice ainsi que du type de superfluidifiant utilisé.*

ZUSAMMENFASSUNG

RPC (Reaktive Powder Concrete) ist ein neuartiger Beton der Familie Hochfester Betone mit extrem hohen Festigkeiten (Druckfestigkeit bis 200 N/mm^2*), der in einem Fertigteilwerk in Kanada eingesetzt wurde. RPC wurde hierbei beim Bau einer Fußgängerbrücke verwandt, die aus Betonfertigteilen - die keinerlei "schlaffe" Bewehrung enthielten - vor Ort montiert wurde.*

In der vorliegenden Studie wurden RPC-Rezepturen mit unterschiedlichen Portlandzementen, Mikrosilica und Stahlfasern bei Raumtemperatur hergestellt. Untersucht wurde der Einfluß von Fließmitteln auf das Verhalten des RPC in Bezug auf W/Z-Wert und Druckfestigkeit. Fließmittel auf Acrylpolymer-Basis (AP) lieferten hierbei geringere W/Z-Werte und höhere Druckfestigkeiten nach 3 Tagen, im Vergleich zu Fließmitteln auf Naphthalin-Basis (SNF) oder Melamin-Basis (SMF).

Bei C_3A*-freiem Portlandzement mit geringer spezifischer Oberfläche, als Bindemittel lag die Druckfestigkeit des RPC nach 1 Tag mit AP als Zusatzmittel deutlich nledriger als bei den entsprechenden Mischungen mit SNF oder SMF. Bei anderen Portlandzementen trat dieser verzögernde Effekt in Verbindung mit AP nicht auf, so daß hier die Druckfestigkeiten nach einem Tag deutlich höher ausfielen. Die 28-Tage-Festigkeiten des RPC bei Raumtemperatur, waren stark abhängig vom Zementtyp, der Mikrosilica und dem Fließmittel.*