

THE INFLUENCE OF MATERIALS ON THE PERFORMANCE OF REACTIVE POWDER CONCRETE

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ABSTRACT

The influence of portland cement and silica fume type on the performances of Reactive Powder Concrete (RPC) mixtures was studied. Only by using a C₃A-free portland cement, in combination with a white silica fume brand, the w/c ratio was as low as 0.18, and the compressive strength was as high as 200 MPa at 3 days after a thermal treatment at 160°C. However a strong reduction in the early compressive strength was recorded.

The replacement of the white silica fume by other silica fume types (grey or dark), as well as the substitution of the other portland cements for the C₃A-free portland cement caused an increase in the w/c and a reduction in the compressive strength (110-160 MPa). However, with these mixtures there was no reduction in the early compressive strength.

INTRODUCTION

Reactive powder concrete (RPC) is a special high strength, fiber-reinforced, superplasticized, silica-fume concrete with improved homogeneity because traditional coarse and fine aggregates are replaced by very fine sand with particle size in the range of 150-400 µm. Although RPC is rather a mortar than an actual concrete mixture, because of the absence of coarse aggregate, the original term (*Reactive Powder Concrete*) coined by the inventors (Richard and Cheyrezy) of this material will be used in the present paper. According to Richard and Cheyrezy (1994), with ordinary curing at room temperature or steam curing at 90°C, the compressive strength can reach up to 200 MPa (RPC 200).

Additional improvements in compressive strength up to 800 MPa (RPC 800) and in flexural strength up to 100 MPa, can occur with special treatments including prolonged compaction of the fresh mix at the moulding stage and during setting, and subsequent hot curing up to 400°C. Because of these sophisticated treatments the manufacturing process of RPC 800 looks like that of a ceramic material. On the other hand RPC 200 can be placed by casting techniques and curing conditions as those usually adopted for *in situ* placed or precast concrete structures. By using this technique, RPC 200 structures have been proposed or can be expected to be done in the field of special concrete constructions, as well as in the area of mechanical engineering (moulds for metallic parts of cars) or environmental applications (watertight containers of hazardous fluids).

SCOPE

This investigation is a part of a larger research project to study the influence of the component materials - including cement, silica fume, superplasticizer and steel fibers - on the performance reactive powder concrete without changing the mix proportion adopted by Richard and Cheyrezy (1994). The reason why this project was undertaken is due to the fact that the extraordinary performances of RPC 200 in terms of strength, fracture energy and Young's modulus - are related to a particular mix composition (Table 1) without qualification of the specific role played by each ingredient. In other words, one does not know, for instance, whether a low C₃A portland cement (Type V in Table 1) is necessarily required or even other portland cements can be advantageously used to produce RPC 200.

In the present paper the effect of portland cement and silica fume type upon the RPC performances will be examined, whereas results of a study on the influence of the other two ingredients (superplasticizer and steel fibers) will be published in a subsequent paper.

Table 1: Composition of RPC 200 according to Richard and Cheyrezy (1).

Portland cement - Type V	955 kg/m ³
Silica fume (18 m ² /g)	229 kg/m ³
Fine sand	1051 kg/m ³
Precipitated silica (35 m ² /g)	10 kg/m ³
Superplasticizer (polyacrylate)	13 kg/m ³
Steel fibers	191 kg/m ³
Water	153 kg/m ³

EXPERIMENTAL

Since the present paper is specifically devoted to investigate the influence of portland cement and silica fume type on the performance of RPC 200, these ingredients were thoroughly characterized and their properties were related with the concrete performances in terms of water requirement at equal workability and compressive strength under different curing conditions. All the other ingredients (superplasticizer, fine sand, steel fiber and a precipitated silica) of the concrete mixture reported in this investigation were not changed.

Materials

A carboxylic acrylic ester (CAE) polymer has been used as a superplasticizer in the form of 30% aqueous solution (Collepardi et al.1993). The same amount (13 kg/m³) of dry polyacrylate in all the mixes was used as shown in Table 1 (1.36% by weight of cement).

The same amount (1051 kg/m³) of fine natural sand (150-400 µm) was used as shown in Table 1.

The same amount (191 kg/m³) of steel fibers was used as that for RPC 200 by Richard and Cheyrezy. However, the available steel fibers used in the present work were slightly longer (11 mm vs. 13 mm) and thicker (0.35 mm vs. 0.18 mm) than those used by Richard and Cheyrezy (1994).

The same amount (10 kg/m³) of pure precipitated silica (SiO₂ > 99.8%) as that indicated by Richard and Cheyrezy. The mean particle size of the precipitated silica used in the present work was 0.012 µm.

Three portland cements (*A*, *B* and *C*) have been used which were different with respect to the C_3A content and/or Blaine fineness. Table 2 shows the main properties of these cements and their characterization in terms of ASTM and ENV 197/1 standard specifications. Portland cement brands *A* and *B*, with a Blaine fineness of 300 and 530 m^2/Kg respectively are both type V according to ASTM C-150 and are similar to the cement used by Richard and Cheyzy (1994). Portland cement *C* with a C_3A content of 11% and a Blaine fineness of 520 m^2/Kg corresponds to ASTM Type III and CE I 52.5R (according to ENV 197/1).

Three silica fume brands (*W*, *G*, *D*) have been used which were different with respect to colour (white, pale grey and dark respectively) as well as for the chemical analysis of the minor components (Table 3). It is difficult to understand whether or not the content of carbon or other elements such as sulphur and calcium, is responsible for the colour. On the other hand, according to Edwards-Lajnef et al (1995), the colour is also related to the retrieval level of the furnace where the silica fume is collected.

An other interesting aspect of the characterization of silica fume is effect of a dispersing agent on the particle size distribution. Figures 1 and 2 show the laser granulometry of the three silica fume brands in aqueous suspension without and with 1% of acrylic superplasticizer respectively. The laser granulometry of the white silica fume (Figure 1-2) does not depend on the presence of superplasticizer, and the mean particle size is 0.62 μm and 0.69 μm with and without superplasticizer (Table 3), respectively. On the other hand the particle size distribution of grey and dark silica fumes is strongly depending on the presence of superplasticizer (Figure 1-2). The mean particle size of *G* and *D* silica fume brands, in the absence of superplasticizer, is 13.9 μm and 63.6 μm respectively. In the presence of superplasticizer, the mean particle size becomes about 0.7 μm for grey and dark silica fume brands (Table 3).

From SEM observations of silica fume samples it is concluded that the morphology is substantially the same independent of the brand type. The three silica fume brands (*W*, *G* and *D*) all appear in form of the typical agglomerates of round grains with the particle size in the range of 0.1 - 1 μm . However, on the basis of laser granulometry measurements, the white silica fume agglomerate appears to be much more dispersible in a pure aqueous phase than the others (Figure 1). On the other hand, in the presence of superplasticizer there is no substantial difference in the dispersion of the three silica fume brands (Figure 2).

Table 2: Composition and properties of portland cements.

Cement Brand	A	B	C
SiO ₂ (%)	20.59	20.79	19.62
Al ₂ O ₃ (%)	3.66	4.32	7.50
Fe ₂ O ₃ (%)	6.10	4.40	5.24
CaO (%)	63.78	64.58	61.48
MgO (%)	0.95	1.03	0.90
K ₂ O (%)	0.48	0.52	0.64
Na ₂ O (%)	0.26	0.14	0.18
SO ₃ (%)	2.50	2.68	3.50
C ₃ A (%)	0	4.00	11.20
Blaine (m ² /kg)	340	530	520
ASTM type	V	V	III
ENV 197/1 type	CE I 42.5R	CE I 52.5R	CE I 52.5R

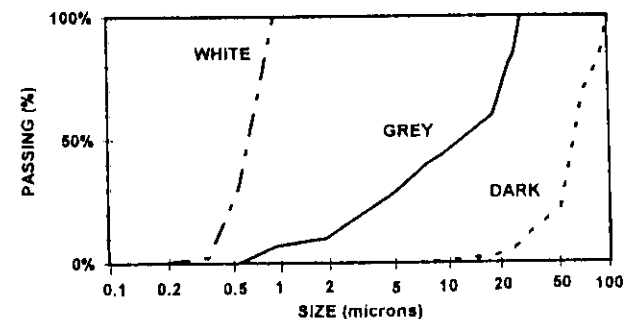


Figure 1: Particle size distribution of white, grey and dark silica fume in the absence of superplasticizer.

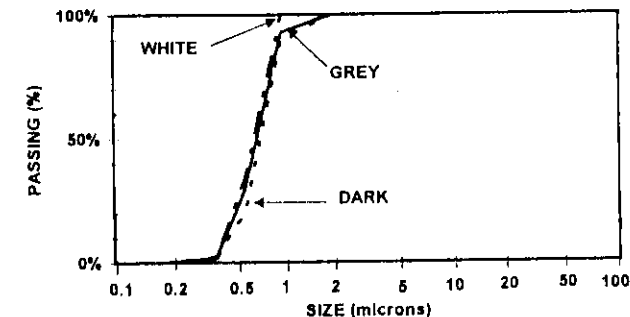


Figure 2: Particle size distribution of white, grey and dark silica fume in the presence of superplasticizer.

Table 3: Composition and properties of silica fume.

Silica fume brand	W	G	D
Colour	white	pale grey	dark
SiO ₂ (%)	94.43	98.87	95.12
Al ₂ O ₃ (%)	2.48	0.01	0.02
SO ₃ (%)	0.01	0.23	0.54
K ₂ O (%)	0.04	0.08	0.91
Na ₂ O (%)	0.01	0.00	0.01
CaO (%)	0.04	0.23	0.49
MgO (%)	0.01	0.01	0.02
TiO ₂ (%)	0.21	0.08	0.23
MnO ₂ (%)	0.20	0.01	0.21
Fe ₂ O ₃ (%)	0.46	0.30	0.40
mean particle size (μm) from laser granulometry:			
- without superplasticizer	0.69	13.87	63.59
- with superplasticizer	0.62	0.76	0.73
Unburnt (%)	0.0	0.0	1.6

Preparation of Specimens

By changing the portland cement type (*A, B, C*) and the silica fume brand (*W, G, D*) nine different mixtures were manufactured (Table 4). The same batch quantities of the ingredient as those shown in Table 1 have been adopted except for the water content which was adjusted for each mix in order to attain to the same plastic consistency (about 150 mm on flow table test). The amount of mixing water, at equal cement content, and therefore the water/cement were strongly depending on the type of cement and silica fume brand.

The actual batch quantities of each mix were necessarily different from the nominal ones (Table 1) depending on the amount of required mixing water for the same workability level.

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

Table 4: Effect of cement and silica fume type on the water/cement ratio.

Mix	AW	BW	CW	AG	BG	CG	AD	BD	CD
Silica fume brand	White			Pale Grey			Dark		
Cement type - C ₃ A (%)	A	B	C	A	B	C	A	B	C
- Fineness (m ² /kg)	340	530	520	340	530	520	340	530	520
Flow table (mm)	160	155	155	160	150	155	160	155	155
W/C	0.18	0.25	0.26	0.22	0.29	0.28	0.26	0.30	0.33
W/(C + SF)	0.14	0.20	0.21	0.18	0.23	0.22	0.21	0.24	0.26

The data of Table 4 indicate that, for a given cement, the W/C is lower with the white silica fume brand and higher with the grey or dark ones. This seems to be related with the fact that the white silica fume brand can be dispersed into individual grains even in the absence of superplasticizer (Figure 1), so that a higher amount of the acrylic polymer is available to reduce the W/C of the cement mix for a given workability. On the other hand, grey and dark silica fume brands appear to be agglomerated in the absence of superplasticizer (Figure 1), and a certain amount of acrylic superplasticizer is consumed to disperse the silica fume agglomerates into individual grains (Figure 2). The difference in the W/C of cement mixes with grey and dark silica fume brands could be tentatively ascribed to the amount of unburnt coal (Table 3).

For a given silica fume brand, the W/C depends on the type of cement. The reduction in the specific surface area and in particular in the C₃A content of the cement appear to favour a significant reduction in the W/C.

By comparing the W/C ratio of the cement mixes of the present work (Table 4) with that of the original *RPC 200* (W/C = 0.15 in Table 1 from reference 1), it seems that only the mix *AW* of the present work (W/C = 0.18) is similar to that indicated by Richard and Cheyrezy (1994).

Casting and curing

Cube specimens (40 mm) were cast by vibration and then cured in three different conditions (Figure 3):

- room temperature*: always at 20°C;
- steam curing*: heating from 20°C to 90°C in 7 hours, then at 90°C for 9 hours with a cooling process from 90°C to 20°C in 5 hours, and finally at 20°C up to 28 days;
- air thermal treatment*: at 20°C for 1 day, then at 160°C in the air for 1 day, and finally at 20°C up to 28 days. This special treatment, which has been used by Richard and Cheyrezy (1994) with a maximum temperature up to 400°C, may be adopted only when the specimens can be demoulded. In the present work this thermal treatment started always after 1-day of room temperature curing except for the specimens of mixes *AW* and *AD* (Table 4). For these mixes, which at 1 day were not yet hardened the thermal treatment started after 2 days of preliminary curing at 20°C.

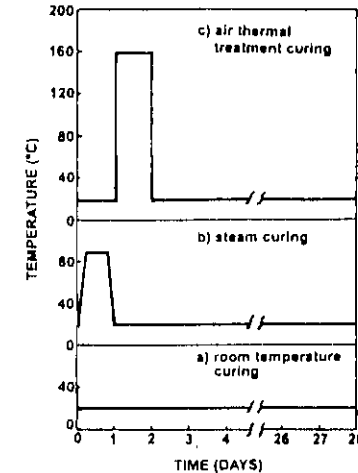


Figure 3: Temperature versus time of the three curing conditions.

Compressive strength

Figures 4-12 show the compressive strength results as a function of the curing time from 1 day to 28 days.

Cement A

Figures 4-6 indicate the compressive strength trend for the mixes *AW*, *AG* and *AD*. With the thermal treatment at 160°C, the compressive strength of the mixes *AW* and *AG* were about 180-200 MPa (Figures 4-5). These values are in the same range as that indicated for the original *RPC 200* by Richard and Cheyrezy (1994). Even the W/C of the mix *AG* (0.22) and in particular that of the mix *AW* (0.18) was very close to that indicated by Richard and Cheyrezy for *RPC 200*. The water/cementitious material ratio (including silica fume and precipitated silica) was as low as 0.14 for the mix *AW*. By taking into account that in the present work steel fibers with a less favourable aspect ratio were used (length/diameter of 31 instead of 72), the

compressive strength data of the *AW* and *AG* mixes are in a good agreement with that of the *RPC 200* indicated by Richard and Cheyrezy. When the C_3A -free cement *A* was combined with the dark silica fume brand (mix *AD*) the maximum compressive strength (Figure 6) at the same curing conditions (160°C) was lower (140 MPa) probably because of the higher *W/C* (0.26).

The early compressive strength of the mixes with cement *A* was very low, particularly in combination with the white and dark silica fume brands (Figures 4 and 6). At 1 day the specimens of these mixes were still soft at room temperature so that they could not be demoulded and therefore the thermal treatment at 160°C (Figure 3) was delayed after a preliminary curing of 2 days at room temperature. Even at the end of the steam curing process (90°C) the compressive strength was very low when the C_3A -free cement *A* was used in combination with the white (Figure 4) and dark (Figure 6) silica fume brands. It would seem that when the C_3A -free cement *A* is combined with the white or dark silica fume brand, the amount of acrylic superplasticizer proposed by Richard and Cheyrezy (13 kg/m³ as dry polymer) is too much. Incidentally, this dosage is 4-5 times larger than that recommended for ordinary concrete mixes (Colleparidi et al. 1993). The dosage of acrylic superplasticizer used in the present work, in agreement with that proposed by Richard and Cheyrezy, was very effective in reducing the *W/C* (0.18-0.22), but it caused a strong retardation in the early cement hydration. However, with the thermal treatment at 160°C after a preliminary curing at room temperature of 2 days - when the material was definitely hardened - there was a significant strength increase (195 MPa with the white silica fume brand and 140 MPa with the dark silica fume brand).

On the other hand, when the C_3A -free cement *A* was combined with the grey silica fume brand (Figure 5), there was no retardation in the early cement hydration and therefore the 1-day compressive strength was quite high at room temperature (30 MPa) and even higher with the steam curing process (155 MPa).

It is difficult to explain the different influence of the silica fume brand on the strength development of the *RPC 200* system based on a C_3A -free portland cement. The white silica fume brand did not need any superplasticizer to be dispersed (Figure 1). On the other hand, the grey silica fume appeared in form of agglomerates in the absence of superplasticizer (Figure 1) and a certain amount of the acrylic polymer adsorbed on the grey silica fume surface was required to produce a particle dispersion as good as that of the white silica fume (Figure 2). This could mean that, with the same dosage of superplasticizer, there was more acrylic polymer available in the aqueous phase when white silica fume was used and this excess could be responsible for the retardation in the early hydration of a C_3A -free portland cement.

On the other hand, the presence of a certain amount of unburnt coal in the dark silica fume brand (Table 3) could be responsible for the retardation in the early hydration when a C_3A -free portland cement is used in combination with a very high dosage of acrylic superplasticizer.

Cement B

Figures 7-9 show the strength development of mixes *BW*, *BG* and *BD*. Although the cement *B* ($C_3A = 4\%$) is a type V portland cement (ASTM), as that indicated by Richard and Cheyrezy (1994), the results in terms of *W/C* and compressive strength are quite different with respect to the original *RPC 200*. Even in the mix *BW* with the best performances (Figure 7), the *W/C* (0.25) is significantly higher than that (0.15) of the original *RPC 200*.

It is confirmed that even with the cement *B*, as well as with the cement *A*, the silica fume brand plays a very important role in affecting the *W/C* and the early compressive strength:

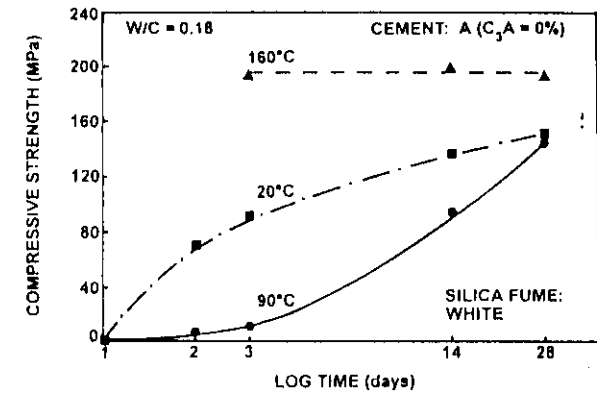


Figure 4: Compressive strength versus time for cement *A* and silica fume *white*.

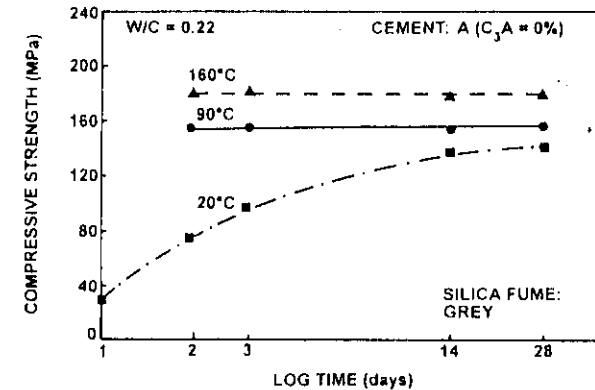


Figure 5: Compressive strength versus time for cement *A* and silica fume *grey*.

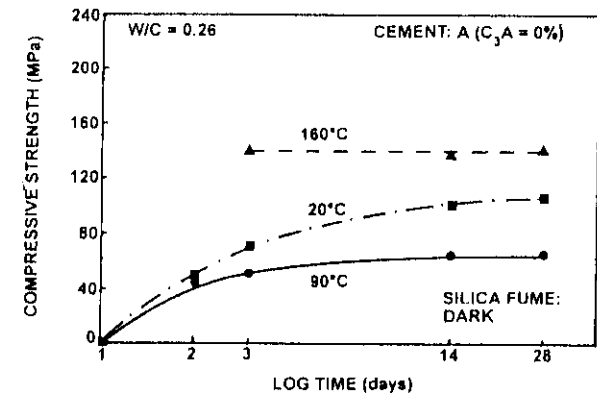


Figure 6: Compressive strength versus time for cement *A* and silica fume *dark*.

- the white silica fume brand determines a lower W/C with respect to the grey silica fume brand, which in turn requires a lower amount of mixing water with respect to the dark silica fume brand;
- the white silica fume brand seems to retard the early strength development (at 20°C as well as at 90°C) with respect to the dark silica fume brand and in particular to the grey one.

Cement C

Figures 10-12 show the strength development of the cement mixes *CW*, *CG* and *CD*. The fineness of the cement *C* is the same as that of the cement *B* (Table 2). However, the C_3A content of the cement *C* (11%) is much higher than that of the cement *B* (4%). The influence of the silica fume brand on the performances of the mixes with cement *C* is similar to that recorded with cement *A* and *B*:

- the white silica fume brand determines the highest reduction in the W/C ratio, but it reduces the early compressive strength at 20°C as well as at 90°C (Figure 10);
- with the grey silica fume brand the W/C is a little higher than that with the white silica fume brand, but the early strength development is better (Figure 11);
- in the presence of the dark silica fume brand the W/C is still higher and the compressive strength at later ages is lower (Figure 12).

CONCLUSIONS

Approximately similar strength from a reactive powder concrete, as reported by Richard and Cheyrezy (1994), was obtained in this investigation provided that the following ingredients were used:

- A zero- C_3A portland cement with low specific surface area ($340 \text{ m}^2/\text{kg}$);
- white silica fume with no unburnt carbon at all and mean particle size about $0.7 \mu\text{m}$.

A compressive strength of about 200 MPa was obtained at 3 days for this mixture (W/C = 0.18) after a thermal treatment at 160°C. However, the early compressive strength at 20°C or 90°C was very low.

When the C_3A -free cement was replaced by other portland cements with a higher C_3A content (4-11%), the W/C increased and the about 160 MPa compressive strength was attained after the thermal treatment at 160°C.

Although the white silica fume brand performed better than other silica fume brands (grey or dark) in terms of lower W/C, this silica fume reduced the early compressive strength at room temperature as well as in the steam curing process particularly when a C_3A - free portland cement was used.

The grey silica fume brand was less dependent on the type of cement. It was a little less effective than the white silica-fume in reducing the W/C, but it was much more effective for early strength development. The compressive strength at later ages after the thermal treatment at 160°C was in the range of 160-180 MPa.

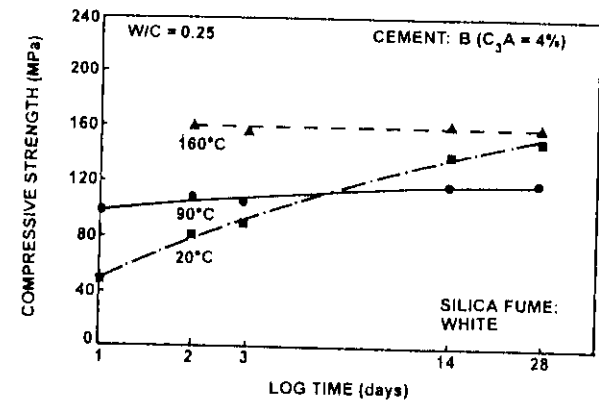


Figure 7: Compressive strength versus time for cement *B* and silica fume *white*.

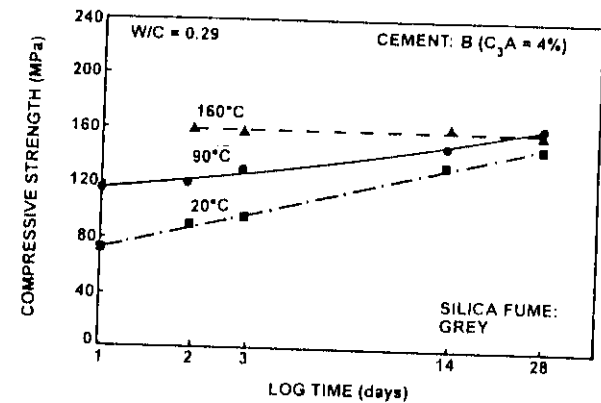


Figure 8: Compressive strength versus time for cement *B* and silica fume *grey*.

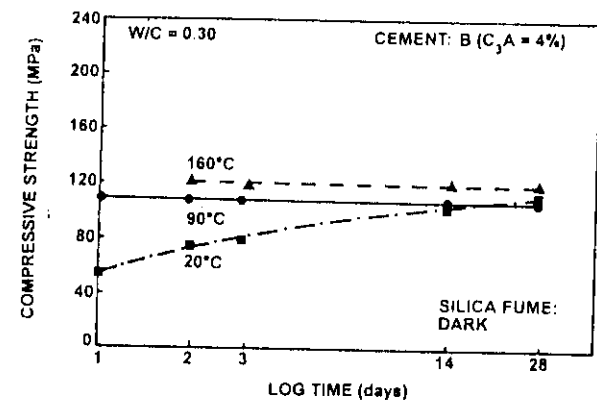


Figure 9: Compressive strength versus time for cement *B* and silica fume *dark*.

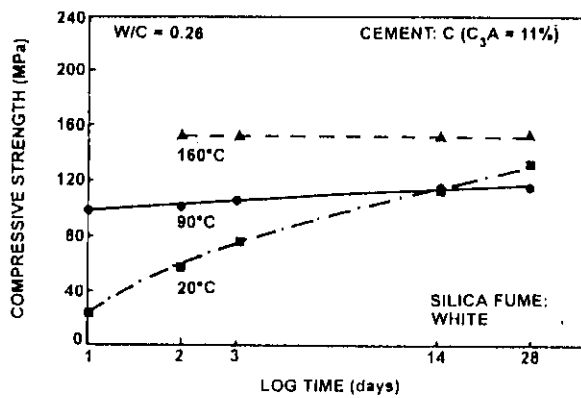


Figure 10: Compressive strength versus time for cement C and silica fume white.

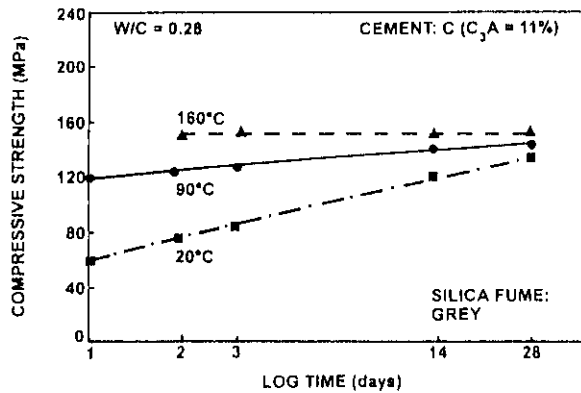


Figure 11: Compressive strength versus time for cement C and silica fume grey.

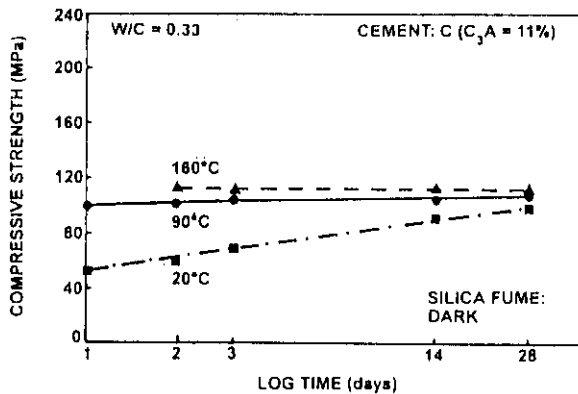


Figure 12: Compressive strength versus time for cement C and silica fume dark.

The dark silica fume brand (with a carbon content of 1.6%) was less effective than the other silica fume brands in terms of W/C and strength. The compressive strength at later ages after the thermal treatment at 160°C was in the range of 110-140 MPa when the dark silica fume brand was used.

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