The preliminary study of the influence of Blaine fineness covered five Portland cements having specific surfaces ranging from 2,900 to 4,000 cm^2/g. Nine cements were tested in the study of injectability as a function of the grading.

However, knowing what cement grading range is compatible with the grouting of fine cracks is not altogether satisfactory in terms of practical results, because it is invariably difficult to impose a specified grading on commercial cements. Commercially-available cements that meet fixed grading requirements are rare, and so it is useful to attempt to modify the grading curve of a standard cement by adding ultrafines to it. In the light of previous work (5, 6, 7) that had shown that ultrafines substantially improve the fluidity of cement grouts, two silica fumes (one of them a densified condensed silica fume), used in proportions ranging from 10 to 50 % by weight of the final mixture, according to the formulation of the grout, and a slaked lime (chosen for its specific surface of 10.5 cm^2/g), used in proportions ranging from 27.5 to 55 % by weight of the final mixture, were investigated.

The proportions in the combination of lime and silica fume were chosen so that the ratio $\frac{Ca(OH)_2}{SiO_2}$, in moles, would be equal to 1, making the simplifying assumption that the $\frac{C}{S}$ ratio in the CSH formed is equal to 1.

The corresponding grading curve was determined for each mixture.

This part of the research was aimed at altering not only the penetrability but also the other essential properties of the grout: its stability (absence of sedimentation) and mechanical strength values, which must be compatible with those of the material to be repaired.

Moreover, since the deflocculation state of the ultrafines and of the cement is an important factor in the penetrability or injectability of grouts, three types of mixing - very-high-turbulence (HT) mixing; a combination of very high turbulence and ultrasound (HU); and ultrasound dispersion (US)(8) - were tested.

A combination of cement and densified condensed silica fume in the formulation of grouts for prestressing ducts was also investigated. Three Portland cements having different mineralogolical compositions, with C_3A ranging from 11.5 to 4 %, were tested, together with the condensed silica fume and the superplasticizer used previously.

The formulations were aimed at the development of a grout:

- of high fluidity (Marsh cone flow time < 25 s, maintained for 6 h following preparation so that it could be used in precast segmental bridges);
- and perfectly stable, with bleeding < 2 % at 3 h and complete reabsorption at 24 h (French and FIP* recommendations).

Only these two properties (fluidity and bleeding) were investigated.

MATERIALS

The crack and prestressing duct grouts were made with the following materials:

Cements

All cements used in all of the research were French CPA or CE** I Portland cements (9, 10). The preliminary study of the influence of the Blaine specific surface covered cements 1, 2, 3, 4, and 5, the chemical composition and main physical properties of which are given in Table 1.

The role of grading was studied on these five cements and four others, numbered 6, 7, 8, and 9, the chemical compositions of which are also given in Table 1. The grading properties of cements 1 to 9 are given in Table 2 and Fig. 1.

The effect of adding ultrafines was tested only on grouts made with cement B (chemical composition, Table 3; grading curve, Fig. 2).

The grout formulations for prestressing ducts were made with cements A, B, and C, the chemical composition and main physical properties of which are given in Table 3.

Admixture

Only one superplasticizer was used, the French-made product G, based on melamine-formaldehyde resin, with a dry extract content of 33 %. This admixture had no secondary retarding-of-set effect on the cements.

Ultrafines

The slaked lime CH used had a Blaine specific surface (BSS) of 10.5 m^2/g; its grading curve is given in Fig. 2.

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* FIP = International Prestressing Federation
** CE = European Cement

Two types of silica fume: DSF, from the ferrosilicon industry, in densified condensed form, and SF, from the zirconium industry, in raw form, were tested.

Table 4 gives the main properties of these two materials.

The sand filling the column for the injectability test was silica sand and its mineralogical composition matched that of the ISO or CEN* sand used for the testing of cements; the grading curves of the three classes used are given in Fig. 3.

MIXTURE PROPORTIONS

The composition of the grouts (1 to 5) used in the preliminary study of the influence of the Blaine Specific Surface (BSS) was as follows:

cement 100 g
admixture 1 g dry extract

$$\frac{\text{water}}{\text{cement}} = 0.45$$

In the study of the influence of cement grading (grouts 1 to 9), the formulation of the grout for each of the cements was:

cement 100 g
water 75 g

To obtain a clearer picture of the influence of grading, admixture G was not used, but the W/C was increased from 0.4 to 0.75. Beyond this quantity of water, there was extensive sedimentation of the grout.

The investigation of the effect of adding ultrafines led to 58 different formulations, indicated in Tables 5 to 9.

The formulations of the grouts for prestressed concrete (A_1 to A_4, B_1 to B_3, and C_1 to C_5) are given in Table 10. The silica fume content was limited to 10 % so as not to alter the pH of the cement grout (11).

PREPARATION OF TEST SPECIMENS

Grouts 1 to 9 were prepared using a very-high-turbulence (HT) screw mill having a power of 600 W at 8000 rpm. The mixing time for each of the grouts was 6 min.

A single 6-min mixing at very high turbulence was used for formulations HT 1a to HT 5c. Formulations HU 6 to HU 10 were

* CEN = European Standardization Committee

exposed to ultrasound for 2 min, then mixed in the HT device for 4 min.

Formulations US 11 to US 15 and US I to US V were mixed by ultrasound for 2 min only.

The characteristics of the ultrasound device are: power 250 W, frequency 20 kHz.

All grout specimens submitted to the cylinder splitting test (Brazilian test) were cylinders 22 mm in diameter and 50 mm high, obtained by sawing the sand columns, injected and hardened to the age of 28 days. After injection, each column was kept in a room at 95 % RH and 20 $\pm$ 2°C until 28 days. The cylinders were sawn 24 hours before the date of testing.

The grouts for prestressing ducts were prepared with a 1500-rpm, 1500-W screw mixer of a type routinely used at prestressing sites.

TEST METHODS

Injectability Test

This test is defined in the recommendations of RILEM TC-52 RAC (Resin Adherence to Concrete) and in French standard NF P 18-891.

It has been used in the researches of the ICCROM* on injections for the re-attachment of paintings or mosaics [12].

The apparatus used is shown in Fig. 4.

This test gives a procedure for determining the injectability of a product in a capillary network and its adherence to concrete by measurement of the splitting strength of cylindrical mortar specimens produced by the injection of a sand column.

The principle of the test consists of injecting the product, at constant pressure, into a transparent plastic tube filled with graded sand and kept in a vertical position.

The column is injected from its lower end; the time the grout takes to reach the various reference marks drawn along the tube is measured.

* ICCROM = International Center for the Study of the Preservation and the Restoration of Cultural Property, Rome, Italy.

Measurement of the Fluidity of Grouts for Prestressing (French standard NF P 18-358)

The fluidity of the grout, in seconds, is determined by measuring the time a liter of grout takes to flow out through an orifice of specified dimensions from a flow cone or "Marsh" cone.

The dimensions of the flow cone are as shown in Fig. 5. It must be rugged, easy to handle, and made of a material that does not react with cement. Aluminum and its alloys must be avoided. The total volume between the bottom of the nozzle and the filling level is 1850 ± 50 ml.

A sieve having a 3-mm mesh and a diameter of 155 mm is needed to eliminate granular components and any clumps that form during mixing, which might disturb the flow. This sieve is placed at the top of the cone.

The fluidity measurement is made as follows:

The measured time between the end of preparation of the grout and the start of outflow must not exceed 1 min.

After the cone is filled, and before any measurement is made, a few milliliters of grout are allowed to flow out freely to drive out any residual water. The receiver is set in place with the flow nozzle of the cone still held closed. The chronometer is started when the flow nozzle is opened and stopped when 1 liter of grout (measured in the receiver) has flowed out.

Measurement of the Bleeding (Stability) of Prestressing Grouts

The test consists of measuring the quantity of water that bleeds at the surface of the cement grout, left at rest and protected from any evaporation.

A 100-cc test tube of glass or other transparent material, graduated in cubic centimeters, 25 mm in diameter and 25 cm high, perfectly clean and dry, is placed on a stable horizontal surface protected from jolting in an air-conditioned room at 20 ± 2°C and 65 % relative humidity.

Immediately after the fluidity tests, the graduated test tube is filled with a sample of the same grout to a graduation between 95 and 100; this initial graduation is recorded. After 3 h, the quantity of water that has bled to the top surface of the grout, left at rest and protected from evaporation, is measured. During this time, the test tube is covered with a plate or a rubber stopper.

Bleeding is measured directly by reading the number of cubic centimeters of water covering the cement paste.

In each test, a second reading of bleeding is taken 24 h after preparation to determine the total percentage of water reabsorbed or bled.

Determination of Grading Curves of Cements and Cement-Ultrafine Mixtures

The grading curves of all cements and cement-ultrafine mixtures were determined using an automatic laser particle size analyzer for powders in suspension, range 0.5 to 560 microns.

TESTING OF SPECIMENS

Measurement of Injectability of Grouts for Cracks

This measurement was made by the standardized test method. The sand in the column was dry.

In the investigation of the influence of fineness, the time taken by the grout to advance each 5 cm in the column was recorded.

In the investigations of the other parameters (grading, influence of ultrafines), only the time the grout took to reach the top of the column, a height of 36 cm (A, Fig. 4), was measured.

In all cases in which this height was not reached, or in which there was no continuous flow of grout from the sand column after the 36 cm had been injected (failure to fill test tube C, Fig. 4), the measurement was rated impossible, since the injection of such a grout is not satisfactory.

Measurement of Mechanical Strength Values of Grouts for Cracks

The Brazilian or splitting test was carried out in accordance with French standard NF P 18-408. Before testing, each specimen was weighed to the nearest tenth of a gram and its dimensions measured to within 0.5 mm. The specimen was then placed on its side in direct contact with the press plates. The load was applied continuously and without jolting. The loading rate was a constant 0.05 MPa/s for the duration of the test, with a tolerance of 0.01 MPa/s.

Measurement of the Fluidity and Bleeding of Grouts for Prestressing Ducts

These measurements were made in accordance with the standardized testing methods.

TEST RESULTS AND DISCUSSION

Influence of the Blaine Specific Surface (BSS) of the Cement

Examination of the results of the sand column injectability tests on the grouts made with cements 1 to 5, presented in Table 11, shows that cements having a small specific surface (< 3,000 cm^2/g) produce grouts incapable of penetrating the 0.63/1.25-mm sand of the column. With higher BSS values (> 3,000 cm^2/g), it is possible to produce grouts of satisfactory injectability (case of cement no. 4), but the specific surface criterion is not adequate, since with cement no. 5 (BSS = 4,000 cm^2/g) the grout penetrates the sand of the column only to a height of 20 cm, then clogs or "cakes" beyond this point, while with cement no. 4 (BSS = 3,560 cm^2/g), the injectability of the grout is perfect.

Influence of Grading of Cement

Table 2 shows the relationship between the injectability of the grouts and the percentages of grains larger than 32 µm in the cements with which they are made. It can be seen that for a grout to be injectable the size of the largest cement grain must not exceed 80 µm and the proportion of grains larger than 32 µm must not exceed 12 %; this is the case with cements 4, 6, 7, and 8. The use of a coarser sand (1.60/2.50 mm) in the column, representing crack openings larger than 0.4 mm, shows that the injectability of grouts 3, 5, and 9 is good in this case. With these cements, not more that 7 % of the grains are larger than 80 µm and less than 25 % are larger than 32 µm.

Analysis of the grading curves of these nine cements (Fig. 1) reveals the existence of three different grading ranges.

French experience with grouting polymers (epoxy resins, polyesters, polyurethanes, polymethyl methacrylate, etc.), both in a research context (4, 13) and for official product approvals (14), has made it possible to define three different degrees of injectability for the purpose of regulations: high, medium, and low.

Fig. 6 gives the total penetration times in the 0.63/1.25-mm sand column that mark the limits between these three categories, together with the injectability curves of various polymers (approved for the grouting of cracks) and of the cement grouts formulated in this research.

It can be seen that, if the grading of the cement is carefully chosen, the resulting grouts fall into the high injectability category, and their penetrability is comparable to or better than that of the best grouting resins.

Changes made by Ultrafines

Injectability of grouts made with only one component (cement, silica fume, or lime) (Table 5)--The grading curve of cement B (Fig. 2) shows 30 % over 32 µm and 10 to 12 % in excess of 80 µm. In line with the previous results, the grout made with this cement cannot be injected (Table 5, grouts HT 1a to HT 1f). It should be noted that increasing the W/C ratio from 0.75 to 2 and adding superplasticizer fails to improve its injectability, but on the contrary aggravates the behavior of the grout, because the clogging of the column that occurs with a W/C ratio of 0.75 is replaced by a sedimentation or separation of the grout into two distinct phases, a liquid phase very rich in particles smaller than 80 µm, which penetrates the column quite readily, and a phase containing cement particles larger than 80 µm that deposits at the bottom of the injection vessel (B, Fig. 4) and is not injectable at all.

As for the slaked lime, its grading curve is correct (Fig. 2) and the grouts made with it are perfectly injectable (formulae HT 2a to HT 2c, Table 5).

Investigation of the injectability of grouts made with silica fume alone reveals the importance of deflocculating this substance. For example, even though the grading curves of these materials are more than satisfactory (the maximum particle size is of the order of 2 µm), a grout made with densified condensed silica fume cannot be injected at W/C ratios less than 1.75 even with 3.33 % superplasticizer, while a grout made with undensified silica fume penetrates readily at a W/C ratio of 1.50 (Table 5, formulae HT 3a to HT 3c and HT 3d).

In the case of densified condensed silica fume, fine grains agglomerate to form flocculates in the grout. These flocculates resemble grains, or clusters of grains, larger than 80 µm and sufficient to provoke clogging by the grout.

This can be seen in the grading curves of Fig. 7, where, to eliminate "agglomerates" of 32 µm and larger (curve e, Fig. 7), it was necessary to disperse the silica fume for 10 min with the ultrasound apparatus of the laser particle size analyzer. This agrees with the results found in investigations of the dispersion of kaolinitic ultrafines using ultrasound (15).

This dispersion or deflocculation seems to be impossible with the HT mixer, because the grout fails to penetrate the sand column.

Injectability of grouts made with varying proportions of cement, silica fume, and lime (Table 6)--Combining ultrafines with cement B yields grouts that are perfectly injectable in the cases of cement + lime, cement + SF, and cement + lime + SF (formulae HT 1.2a to HT 1.2c, HT 1.3e and HT 4c to HT 4e,

Table 6). Combining densified condensed silica fume (DSF) and cement aggravates the problem found earlier: none of the resulting grout formulations (HT 1.3a to HT 1.3d, HT 4a and HT 4b) is injectable. The very-high-turbulence HT mixer therefore fails to deflocculate the DSF.

It should be noted that the grouts made with mixtures of lime and silica fume, whether densified or not, are perfectly injectable. It would therefore seem that, in the absence of cement, the presence of lime produces satisfactory deflocculation of the DSF (formulae HT 5a and 5b, HT 5c).

The particle size analyses of the various mixtures studied, given in Fig. 8a, 8b, and 8c, clearly show that the addition of varying proportions of lime and silica fume to cement B produce a final mixture having a grading curve different from that of the cement alone, with practically no grains larger than 80 µm and less than 12 % larger than 32 µm. In the case of lime + DSF, there are almost no grains larger than 32 µm.

These results confirm the grading criteria stated earlier for the preparation of hydraulic grouts that exhibit satisfactory injectability in the sand column test.

Tables 5 and 6 show that it is possible to obtain a very broad range of 28-day splitting strength values, with the highest being for grouts made of cement + DSF (1.81 to 1.88 MPa). Grouts made of lime + DSF have low strength values (0.38 to 0.23 MPa), but sands coated with such grouts do have some cohesion and strength, which could be useful for repairs of badly deteriorated masonry, where some consolidation is required but excessively strong repaired zones, or "hard spots", must be avoided.

It should be noted that undensified silica fume (SF) generally gives lower values. Because of this, and because it is difficult to use this type of silica fume in the field, it was dropped from our subsequent research.

Study of Grout Mixing Methods (Tables 7 and 8)--Combining high-turbulence mixing and ultrasound dispersion improved the injectability of the grouts studied above. The cement + DSF and cement + lime + DSF mixtures were made injectable in this way (formulae HU 8a to HU 8c and HU 9a and HU 9b, Table 7).

Using ultrasound dispersion alone accentuated this improvement, and all of the above-mentioned formulae penetrated the sand column without difficulty, except for the grout made with cement B alone, which still tended to sediment, although to a lesser degree (Table 8).

The injectability studies using a column filled with a finer sand (0.160/0.8 mm) show that the improvement in deflocculation brought about by ultrasound mixing is such that the grouts penetrate very easily in spite of the finer porosity of the column, again with the exception of the cement, cement + lime, and cement-lime-DSF (US IV b, Table 9).

Fig. 9 shows the column penetrability curves of the various grouts studied. It shows that on the whole the injectability of the hydraulic grouts formulated in the course of this research is greater than that of grouting resins.

Grouts for Prestressing Ducts--Table 10 shows all results obtained on the grouts for prestressing ducts made with cements A, B, and C. It can be seen that, without the addition of silica fume, these grouts are sufficiently fluid for the injection of prestressing ducts only immediately after preparation. These grouts cannot be used with precast segmental bridges, which require grouts that can be injected and driven in the ducts until at least 6 h after preparation.

When superplasticizers are added to maintain satisfactory fluidity, bleeding becomes so great as to render the grouts unusable (formulae A 2 and B 2).

The main effect of adding silica fume is the complete elimination of bleeding, a primordial property for the protection of tendons, even when there are substantial increases in the water and admixture contents of the grouts (formulae A4 and B3).

Another effect is an improvement of the degree and duration of fluidity; this occurs with all the cements.

The use of silica fume in conjunction with a superplasticizer in prestressing grouts therefore makes it possible to obtain, with any cement, a formulation that does not bleed and that can be injected up to 6 h after preparation.

It should be noted that the use in prestressing grouts of cement A, which has a high C_3A content, is prohibited in France because of the difficulties of injecting it encountered at many sites (the grouts stiffen very rapidly).

CONCLUSIONS

Cements having a high Blaine specific surface (> 3,500 cm^2/g) are more likely than others to yield hydraulic grouts that can be injected into fine cracks without clogging. However, this characteristic is not sufficient to ensure the injectability of a grout. The main criterion identified by this research is the grading of the cement.

The injectabilities of hydraulic grouts made with cements that meet certain grading criteria - no grains larger than 80 µm and less than 12 % of grains larger than 32 µm - are comparable to or better than those of polymers (epoxides, polyester,