LOW-VOLUME WET-PROCESS SPRAYED CONCRETE: PUMPING AND SPRAYING

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ABSTRACT

This paper, which reports on part of a three year research project into wet-process sprayed concrete for repair, examines the influence of rheology on the pumping and spraying of fine concretes. The performance of ten laboratory-designed fine concretes were examined using a rotational viscometer (two-point test), the slump test, a build test and a vane shear strength test. Visual grading and a sorptivity test were used to quantify the degree of reinforcement encasement which is a crucial factor in long term performance. Taken together, these tests form a rheological audit of each concrete which can help guide the design of sprayable, but also durable concretes.

The two-point apparatus was successful for determining the flow resistance and torque viscosity of fine aggregate concretes, including those with air entrainment. The vane shear strength test was successful in providing an instantaneous reading of the shear strength of the concretes and is compared with their slump. The concretes were pumped and sprayed through a piston pump to assess their suitability and to measure their adhesion to a substrate by build thickness. This value is a measure of sprayability and is converted into values of maximum shear and tensile stress which are then compared with the workability parameters (slump, shear strength and flow resistance) in order to determine their inter-relationship. These relationships are also compared with those obtained from a separate study of mortars.

On its own, the sorptivity test did not accurately assess the encapsulation of the reinforcement. However, when considered with a visual grading of the cores, a more reliable indication can be obtained of the potential durability of the finished concrete, as well as the degree of encapsulation of the reinforcement. We demonstrate the conflict in selecting mix proportions that satisfy requirements for both installation and product quality.

1 Introduction

Sprayed concrete can be defined as a concrete conveyed through a hose and pneumatically projected at high velocity from a nozzle into place. In the wet process the constituents (cement, aggregate, admixtures and water) are batched and mixed together before being fed into the delivery equipment or pump. The mix is then conveyed under pressure to the nozzle, where compressed air is injected to spray the mix into place. This differs from the dry process in which the dry constituents are batched together before being conveyed under pressure down the delivery hose to the nozzle, where pressurised water is introduced and the mix sprayed into place. The rheological properties of the mix in the wet process are critical from the mixing stage through to placement (unlike in the dry process where a powder has to be conveyed pneumatically). The concrete's hardened properties are also important, but are of little consequence if the fresh material can not be pumped and placed. Conversely, a mix that has been installed 'satisfactorily' may not perform well due to inherent defects.

This paper describes the findings of an investigation into the rheological properties of a range of fine concrete mixes. It formed part of a three year Government and industry funded research programme into wet-process sprayed concrete for repair, which has resulted in an industrial guide published by the Concrete Society[1]. This paper follows on from an earlier paper[2] on the rheological performance of wet-process sprayed mortars and some comparisons with these results are made here.

Ten laboratory-designed fine concrete mixes consisting of combinations of a 5 mm maximum uncrushed river sand, Portland cement, silica fume and water were investigated. Additional constituents in some mixes were superplasticiser, steel and polypropylene fibres, crushed Portland stone and a coarse (2-8 mm), smooth aggregate. Nine mixes were sprayed with a wet-process piston pump and one with a dry-process gun. The experimental methods used to measure the rheological characteristics have been described elsewhere[2,3] and only an outline is given here. The results of the tests are presented and their relationship to the pumpability and sprayability of the concretes is discussed. Comparisons are also made with the relationships found for mortar mixes[2]. The hardened performance of these fine concretes is described elsewhere[4].

2 Rheological testing of concretes

2.1 Background

The wet process can be divided into three stages: mixing, pumping and spraying. A clear understanding of what happens to a concrete when it is pumped through a pipeline is fundamental to any study of wet-process sprayed concrete. Early research into the behaviour of concrete in a pipeline was conducted by Dawson[5] in 1949. Ede[6] introduced the idea of a segregation pressure for a concrete, which when exceeded makes the concrete unpumpable. A "go or no go" test was developed by Gary[7] in 1962 and he concluded that for the same slump a concrete may or may not be pumpable. Loadwick[8] established that concrete flows in the form of a solid plug (termed plug flow) and that the velocity distribution is constant across the width of the plug. The pressure bleed test apparatus was developed by Browne and Bamforth[9] who showed that a concrete can change from a saturated to an unsaturated state by excessive loss of mix water due to pressure, thus increasing frictional stress, and even blockage. Beaupré has investigated the rheological properties of sprayed concrete and the relationship between pumpability and sprayability, including the development of predictive models[10]. He also used temporary high air contents as an aid to pumpability when investigating the compromise needed to be reached with the wet-process between pumpability and sprayability. He later applied it in practice to wet-process sprayed repairs where he used high air contents of 15-20% to increase the fluidity (and hence pumpability) of concretes with a low water/cementitious ratio which resulted in in-situ air contents of 5 - 6.8%[11]. Additional details of work conducted into the pumping and spraying of mortars was presented in an earlier paper[3].

Sprayability can be defined as a property that incorporates parameters such as contact adhesion (ability of the plastic mix to adhere to the surface), cohesion (influencing the thickness that can be built-up), and rebound. Beaupré termed this shootability and concluded that shootability increases when the flow resistance is increased, and is thus in conflict with pumpability which has the opposite relationship. The relationship between build-up thickness, pumpability and shear resistance that was previously established for mortars[2] is applied here to the fine concretes.

2.2 *Rheological theory*

Rheology can be defined as the science of deformation and flow of matter, and is concerned with the relationships between stress, strain and time. In terms of fresh concrete, the field of rheology is related to the flow properties of concrete and to its mobility before setting takes place. The rheology of mortars and concretes can be expressed in terms of a shear/strain model, the most common for concrete being the Bingham model[12].

2.3 *Rotational viscometer testing*

The Mk II two-point test apparatus was developed by Tattersall[12] who found

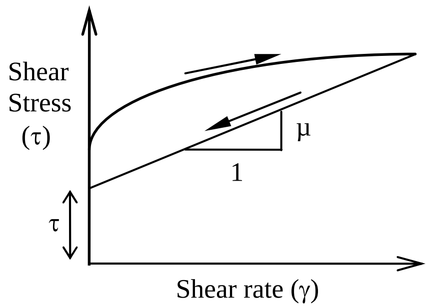

Figure 1(a). Typical flow curve for mortars : Stress-strain

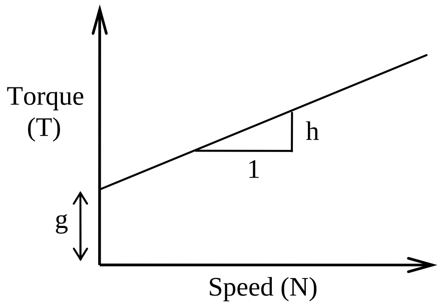

Figure 1(b). Typical flow curve for mortars : Torque-speed

that when the torque (T) was plotted against the speed (N), for decreasing results only, the relationship was almost linear (Figure 1) giving

$$T = g + h.N \qquad (1)$$

where g is the intercept on the torque axis and h the slope of the line. Beaupré[10] referred to g as the flow resistance, and h as the torque viscosity. -This equation is of the same form as the Bingham model and thus it can be said that g is a measure of yield value, and h of plastic viscosity. In principle it is possible to convert g and h to fundamental units equivalent to τ_O and μ by calibration with standard fluids (Banfill[13]) but most investigations work with the direct parameters (which are equipment dependent).

3 Materials and mixes

The proportions of mixes are given in Table 1 and the gradings of the aggregates in Figure 2, which also shows an example total dry grading for mix C1p (aggregate, cement and silica fume). All the mixes contained a 5 mm maximum sized uncrushed river sand and Portland cement conforming to BS12: 1996[14]. C4p and C5p also contained a coarse (2-8 mm) smooth aggregate and C5p contained a crushed Portland stone. C1Sp contained steel fibres with an aspect ratio of 30/.50 (i.e. 30 mm long and 0.5 mm diameter) and mixes CP1p and CP2p contained 19 mm long polypropylene fibres. All the mixes except C2d contained silica fume in the form of a water-based slurry with a 50% silica fume content by weight and all the mixes except C2d, C3p and C3Ap contained a superplasticiser at 1.5% by weight of cement. C2d contained a silica fume powder at 5% by weight of cement. An air-entraining admixture was used in mixes C1Ap and C3Ap.

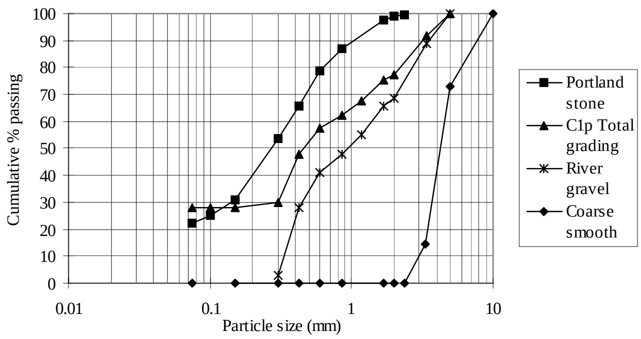

Figure 2. Gradings of aggregates and mix C1p

The concretes were mixed using an integral forced-action paddle mixer on the rear of the Reed B-10 piston pump. Water was added until the desired consistency for spraying was achieved. i.e. workable enough to be pumped but stiff enough not to slough after being sprayed onto a vertical substrate. After mixing, the concrete was loaded into the hopper of the pump. All the wet-process mixes were pumped with the Reed B-10 piston pump and sprayed using a 25 mm diameter rubber hose, a 365 cfm (0.1825 m^3/s) compressor at an output of approximately 80 l/min. C2d was pumped with a Reed SOVA dry-process gun using a 25 mm diameter rubber hose, a 365 cfm (0.1825 m^3/s) compressor at an output of approximately 50 l/min.

4 Testing procedure

Results for six rheological tests are presented: two for workability, one for pumpability and three for sprayability. A brief outline of the test methods is given below, though a more detailed description can be found elsewhere[2]. Taken together, the tests form a rheological audit of a mix as it progresses through the mixing, pumping and spraying process (Figure 3).

4.1 Workability

The workability was measured by the slump test[15] and a modified form of the shear vane test for soils[16]. Two slumps were measured immediately after the concrete had been mixed and if these slumps were significantly different (>15mm), then a third was taken and the average of the two closest values calculated. The shear vane test consists of a torque-measuring device at the head of the instrument together with a set of vanes to provide sufficient shear resistance to register on the torque scale. The maximum torque can then be used to calculate a shear strength for the material (in kPa). This test therefore has potential as it is instantaneous, can be performed in situ and measures a fundamental material property. Between two and three shear vane readings were taken after mixing and an average taken of the two closest values.

4.2 *Pumpability*

The pumpability was characterised with the Mk II version of the two-point apparatus developed by Tattersall[12] with g and h being determined from the decreasing results that follow structural breakdown (Figure 4). A Viskomat rotational viscometer, used to study the pumpability of mortars[2], could not be applied to these concretes, because this instrument is not suitable for aggregates with a maximum size exceeding 2 mm. It should be noted that the precision of determining g and h is dependent on data at low angular speed, which is often difficult to obtain.

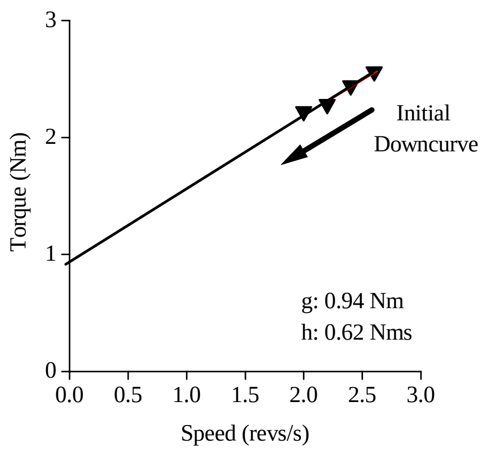

Figure 4. Initial downcurve of two-point test for mix C3Ap

4.3 *Sprayability*

This was assessed both qualitatively (did the material pass through the nozzle) and quantitatively (in terms of the amount of material that could be built up on a grit-blasted concrete substrate[2]). The concrete was sprayed horizontally onto a 300 x 300 mm target area to obtain as large an amount of material as possible on the substrate whilst keeping within the 'target'. The concrete would then fail under its own weight either cohesively, adhesively or by a combination of both. The total weight of material was recorded, together with the failure mode and the maximum depth of build.

The sprayability of the concretes was also assessed in terms of reinforcement encasement, which was quantified in two ways:

1. measuring the sorptivity (by RILEM method 17) of 55 mm diameter cores taken at bar intersections and relating this to the cross-sectional area of the reinforcement within the core; and
2. visually grading these cores on a scale of 1 to 5 using a method proposed by Crom[18] and developed by Gebler[19].

These tests are described fully in previous work on wet-process sprayed mortars[20].

5 Test results

The rheological test results are summarised in Table 2. The mix designs of C1Ap and C3Ap were evaluated on more than one occasion using the shear vane, slump and two-point tests. These additional results were designated C1Ap-1, C1Ap-2 and C3Ap-1.

5.1 Shear vane

The shear vane provides a basic measure of the shear strength of fresh

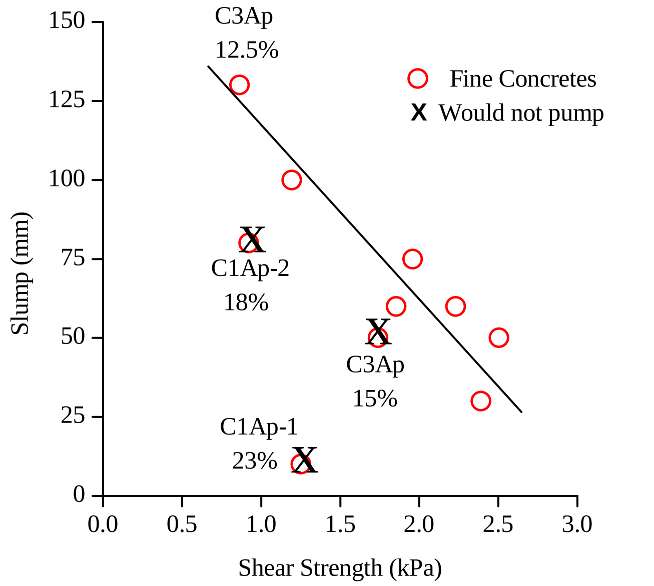

Figure 5(a). Relationship between slump and vane shear strength for fine concretes, including air entrainment

concrete and this is plotted against slump in Figure 5(a). It can provide an instantaneous result exactly where the rheological properties of the material needs to be measured, e.g. in the hopper of the pump. The shear strength has been calculated using the British Standard formulas for the measurement of soil shear strength[16] multiplied by a conversion factor for the increased vane size. As would be expected, for the concretes that pumped, a decrease in shear strength corresponded to an increase in slump. Three of the mixes that would not pump are also shown, together with their air contents before pumping. A reasonable explanation, supported by visual inspection, is that the pressure from the pistons compressed the entrained air rather than forcing the concrete down the line. Mixes with an air content greater than 12.5% failed to pump satisfactory.

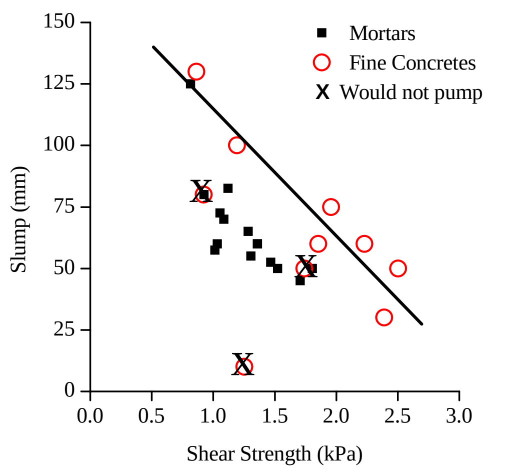

Figure 5(b). Relationship between slump and vane shear strength for fine concretes and mortars

Figure 5(b) compares the shear strength/slump relationship with that of the proprietary repair mortars reported previously. These show lower values of shear strength for a particular slump compared with the fine concretes, which is probably due to the restraining action of the larger aggregates in the fine concretes. Consideration should therefore be given to the mix design of a material, particularly the aggregate grading, when comparing values of slump and shear strength.

5.2 *Two-point test*

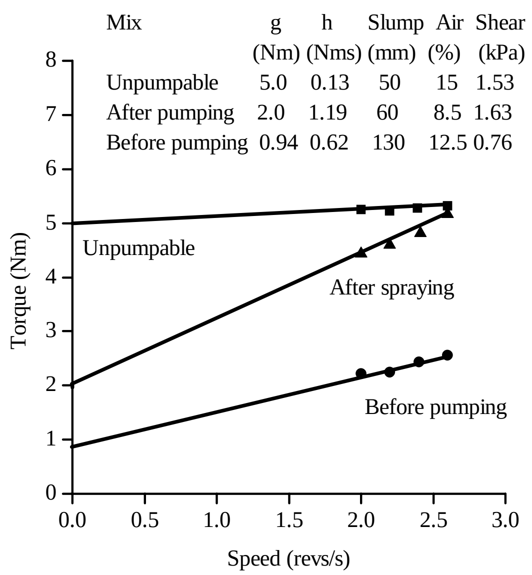

Figure 6(a). Two-point test : mix C3Ap

Figure 6(a) shows the values of g and h for mix C3Ap before pumping and after spraying. The increase in both g and h as the concrete is pumped and then sprayed is to be expected, as air is forced out of the mix on impact (in this case, reduced from 12.5 to 8.5%). This is also reflected in the reduction in slump (from 130 to 60 mm) and increase in shear strength (from 0.76 to 1.63 kPa). Also shown is a mix made with the same proportions as mix C3Ap but with a higher initial air content of 15%. This would not pump due to the high value of g (5.0 Nm) resulting from the high air content, demonstrating that the two-point apparatus can be helpful in predicting the pumpability of mixes with and without air-entrainment.

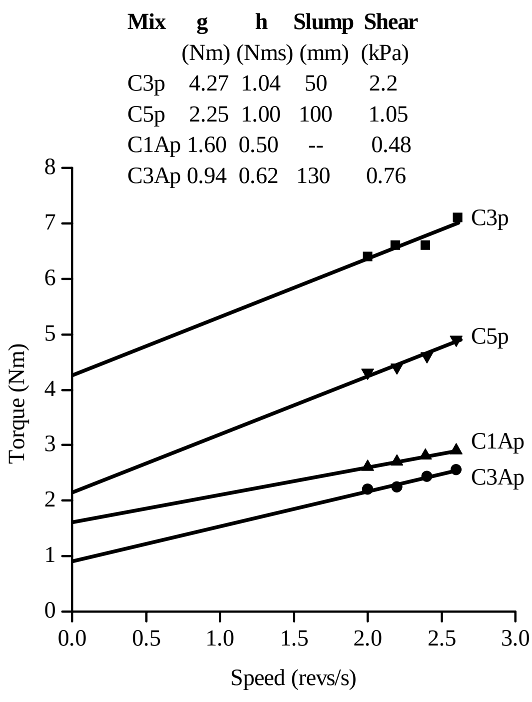

Figure 6(b). Two-point test (a) mix C3Ap (b) all mixes

The two-point test results for four of the mixes before pumping are shown in Figure 6(b). The air-entrained mixes C3Ap and C1Ap had the lowest values of g and h, which was to be expected[21]. The non-superplasticised mix C3p had the highest g, which is consistent with the mix having the lowest slump (50 mm) and the highest shear strength (2.2 kPa) of the mixes in this investigation. These results suggest that the value of h could have a large influence on the pumpability of air-entrained concretes. The addition of air entrainment seems to reduce the values of g and h, but a too greater reduction in the value of h (below approximately 50 Nms) may render a concrete unpumpable.

5.3 Build test

The build value (in mm) and corresponding mass of concrete sprayed onto the substrate for each of the mixes is shown in Table 2. The shear stress at the substrate at failure was then calculated from these values and the cross-sectional area at the base of the concrete (approximately 300 mm square). The maximum tensile stress at failure due to the moment was also calculated by idealising the concrete on the substrate as a frustum of a square-based pyramid. Its volume, and therefore dimensions, could be calculated from the mass, fresh wet density, the area of the base and the height of the frustum (i.e. the build value). Simple bending theory was then applied to calculate the moment and hence the maximum tensile stress in the freshly sprayed concrete at failure. It should be noted that the failure stresses reported here are the stresses that the concrete is subjected to due to its own weight, and they are not a measure of the tensile shear *strength* of the material. This method is also only an approximate idealisation for comparing the build of the different materials (as the analysis assumes plane sections remain plane, linear elastic behaviour and a homogenous material).

The relationship between the maximum tensile and shear stresses and the build is shown in Figure 7. At the higher builds, the maximum tensile bending stress is greater than the maximum shear stress for each concrete and at lower builds the opposite is true. The steel-fibre mix C1Sp has a lower maximum shear and bending stress than might be expected. This is due to the steel fibres increasing the cohesiveness of the concrete, thus producing a high build with a narrow cross-section. Thus the build value was high (320 mm) and the mass low (11.6 kg), therefore producing low maximum shear and tensile bending stresses.

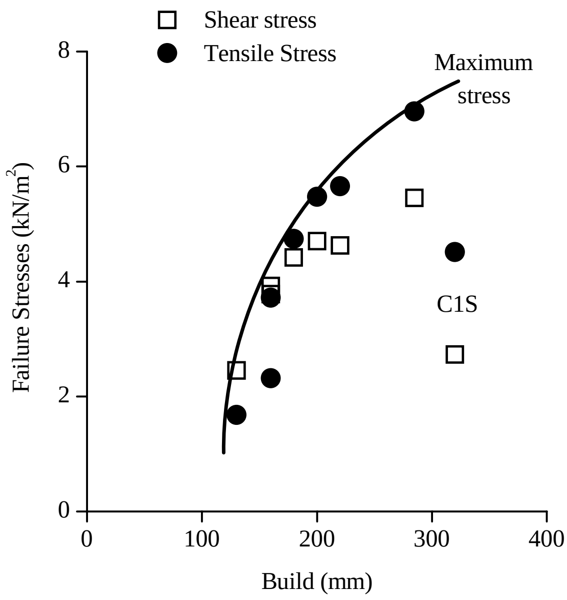

Figure 7. Build value compared with maximum shear and tensile stresses at failure

Figure 8 (a) shows the relationship between the slump before pumping and the maximum tensile and shear stresses in the concrete at failure in the build test, which indicates a decrease in both stresses as the water content (and slump) increase. This was verified visually as most samples failed cohesively (i.e. in shear). Note that at higher slumps the maximum shear (flow) stress is higher than the tensile stress, which is observed in practice as at higher slumps the concrete fails cohesively (i.e. it shears) rather than adhesively. The opposite relationship was found for mortars[2]. However, the mortars were relatively stiff mixes (higher surface area at similar water contents) with low slumps (45-60 mm). As such, the mortars were on the ascending branch of the relationship (Figure 8 (b)) where tensile failure (adhesion) dominates.

Beaupré[10] reported that an increase in the value for g (the flow resistance, obtained from the MK III) produced a corresponding increase in the build value. The relationship between these two parameters in this study is shown in Figure 9, where a similar trend is shown. However, more tests are needed to confirm this due to the limited results.

Figure 10 presents the relationship between the vane shear strength immediately before pumping and the maximum tensile and shear stresses at failure. These results indicate an increase in the failure stresses with an increase in vane shear strength (as slump decreased). This is in contrast to the results for mortars where an increase in the failure stresses corresponded to a decrease in the vane shear strength[3]. However, this is explained by the argument put forward above for slump where increasing workability reduces strength, and cohesion (shear) controls failure.

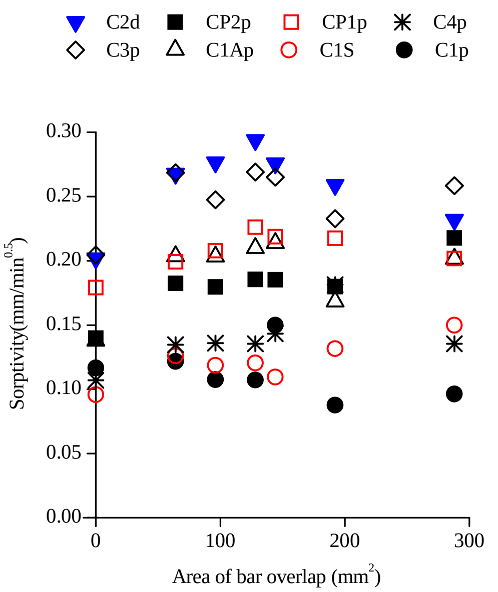

Figure 11. Sorptivity compared with area of bar overlap

5.4 Reinforcement encasement

The influence of the density of reinforcement on the sorptivity of the top of the core (i.e. the material just behind the bars) is shown in Figure 11. The tops of the cores produced a wider sorptivity range than the corresponding bottom slice of the core, probably due to the voids produced in the concrete being concentrated directly beneath the bars which were encapsulated within the tops of the cores. The surface of the top cores in contact with the water in the sorptivity test therefore contained a greater number of voids than the surface of the bottom slice, which had been sprayed against the flat mould face. The projected area of bar overlap was chosen as a measure of the reinforcement density as this gave the broadest spread of results. Other methods are discussed elsewhere[2]. In general, the sorptivity does not increase greatly with the density of reinforcement and appears to reach a maximum at a bar overlap area of around 130 mm^2 (equivalent to two 8 mm diameter bars overlapping an 8 mm bar) and then decreasing up to 200 mm^2. This is in contrast to the mortars, which showed a small, but clear increase in sorptivity with reinforcement density. This difference can be explained by the higher particle velocity from the piston pump compared with the worm pump used to spray the mortars[3]. The fine concretes also produced higher values of sorptivity (0.09 – 0.29 $mm/min^{0.5}$) than the mortars (0.01 – 0.09 $mm/min^{0.5}$) due mainly to the latter's finer grading and higher cement and silica fume content.

The dry process mix C2d produced the highest sorptivity, probably due to the entrapment of sandy rebound material, which is problematic with this process. The other mix with a high sorptivity was the non-superplasticed mix C3p. This could be attributable to the higher water/cementitious ratio of this mix compared with the other wet-sprayed mixes. However, whilst the lowest water/cementitious ratio (C4p) produced the lowest sorptivity, the general trend is not clear.

A different view emerges if we consider a visual interpretation of concrete quality. Figure 12 shows cores taken from

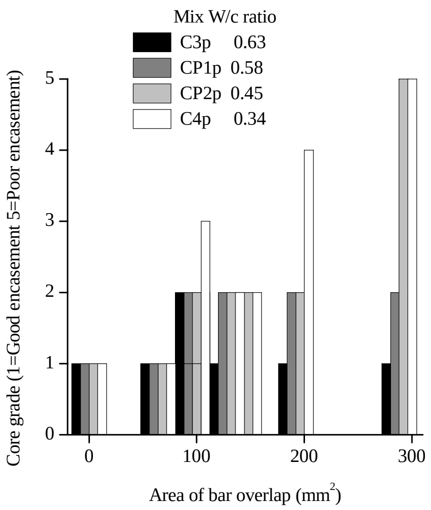

Figure 12. Core grade compared with area of bar overlap

four of the mixes graded on a scale of one to five (Gebler[18]). C4p shows a clear increase in grading value with an increase in the projected area of bar overlap, possibly due to the high proportion of larger (2-8 mm) aggregate, the low water/cementitious ratio (0.34) and the low slump (30 mm) compared with the other mixes, which could all contribute to an increase in the number and size of the voids. C3p produced very little voidage, even at bar overlap areas of 288 mm^2 (equivalent to a 12 mm bar overlapping two other 12 mm bars), possibly due to the

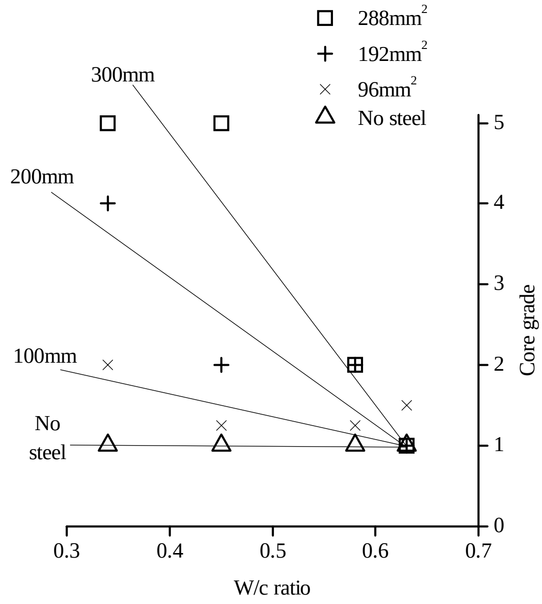

Figure 13. Influence of water/cement ratio

high water/cementitious ratio (0.63) of the mix, although the slump of the mix (50 mm) was only average. CP1p and CP2p exhibited very similar degrees of encasement (ie core grade), the only difference being at the highest area of bar overlap (288 mm^2) where mix CP1p produced less voids than mix CP2p, which may be explained by its higher slump (75 mm compared to 60 mm).

In summary, sorptivity is relatively insensitive to the level of reinforcement, but visual grading is, albeit not uniquely for all mixes. However, Figure 13 demonstrates the interaction of water/cementitious ratio and steel area on the concrete voidage and can be used to identify limits on the former for a given level of reinforcement. The impact of reinforcement level is not well understood and such a chart could be an important design aid.

The two methods of assessing the encasement show similar, but less defined, trends than those found for mortars[2]. The core grading method highlights changes in voidage with respect to reinforcement whereas the sorptivity method reflects the rate of ingress of water into the concrete, both of which are important. The mix with the smallest number of voids (C3p) possessed some of the highest sorptivity values and the mix with the largest number of voids (C4p) possessed some of the lowest sorptivity values. However, it is the durability and integrity of the concrete which is important together with the protection of the reinforcement from corrosion and so these results should be used in combination when assessing the quality of a sprayed repair. In terms of mix design, the results clearly indicate that an optimum combination of workability and water/cementitious ratio must be sought to balance the conflicting requirements of low voidage and sorptivity.

6 Conclusions

This paper has presented and discussed a variety of data on the rheological performance of wet-sprayed fine concretes, some of which has been compared with previous work on wet-sprayed mortar[2]. A rheological audit has been presented and the tests have characterised the workability, pumpability and sprayability of each concrete. A shear vane test was evaluated and can give an instantaneous measurement of the shear strength of the concrete wherever workability needs to be assessed. A good correlation with the slump was found for pumpable fine concretes.

The Two-point test apparatus produced satisfactory results, although care needed to be taken in both conducting the test and interpreting the results. Superplasticiser and air entrainment were both seen to affect the flow resistance and torque viscosity. The results also indicate that this apparatus can help in predict the pumpability of air-entrained mixes.

The slump, build and vane shear strength for different concretes have been presented and a relationship found that links together these three parameters. A method is given that defines the build in terms of the maximum shear stress at the substrate and the maximum tensile stress has been outlined which is consistent with the failure mode (cohesion and adhesion). This enables a more detailed and scientific analysis of the sprayability of the concrete to be made and a relationship is presented between these stresses, the slump and the vane shear stress. A relationship between build and flow resistance from the two-point test was also found.

Two methods for assessing the reinforcement encasement were investigated, visual grading and sorptivity measurement. The density of reinforcement had only a small effect on the sorptivity of the concrete, whilst the visual grading of voidage was a simple test that reflected the encapsulation of the bars. The two methods should be used together when assessing the quality and durability of a sprayed concrete repair.

Taken collectively, these results show that these tests can predict the workability (slump and shear vane), pumpability (two-point test) and sprayability (build, sorptivity and visual grading) of wet-process sprayed concretes. However, a pumping and spraying trial will always be prudent when developing a new concrete mix design.

7 Acknowledgements

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