WORKABILITY, SHEAR STRENGTH AND BUILD OF WET-PROCESS SPRAYED MORTARS

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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 sprayed mortars. The workability properties of seven commercially available pre-packaged repair mortars and six laboratory designed fine mortars were examined using the Tattersall Two-point viscometer, the slump test, a build test and a vane shear strength test. The Two-point apparatus was successful with low-workability mortars and the flow resistance and torque viscosity of the mortars was determined. The vane shear strength test provided an instantaneous reading of the shear strength of the mortars and is compared with their slump. The build value, a measure of sprayability, is then compared with these two workability parameters and the flow resistance in order to determine their inter-relationship.

Keywords: Mortars, Rheology, Wet-process, sprayed concrete, Two-point test, Workability, Slump, Build.

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INTRODUCTION

This paper presents the results from work that is being undertaken as part of a three year research programme at Loughborough University, funded by the Engineering and Physical Science Research Council and supported by substantial industrial collaboration from Balvac Whitley Moran, Fibre Technology, Fosroc International, Gunform International Ltd and Putzmeister UK Ltd. The main aims of this project are:

1. to gain a fundamental understanding of the influence of the pumping/spraying process, mix constituents and proportions on the fresh and hardened properties of wet-mix sprayed concrete;
2. to improve the wet-mix spraying process, in particular operator environment, maximum conveying distances and stop-start flexibility;
3. to specify, measure and optimise in-situ properties, particularly strength, bond and durability;
4. to disseminate information in appropriate form to practising engineers to promote and accelerate the use of wet-mix sprayed concrete for repair in the UK.

The main emphasis of the research project is on mortars and small aggregate concretes (<10 mm) applied in thin layers (<100 mm) at controlled low/medium output rates (< $5m^3$/hr), in some cases with mesh or fibre reinforcement. This paper concentrates on the fine mortars which contain aggregates with a maximum size of 2-3mm and this group has been further divided into pre-packaged proprietary mixes (designated P1 to P7) and designed mixes (D1 to D6). A large range of pre-packaged proprietary mortars have been developed for hand application and there are a number of pre-packaged proprietary mortars being developed specifically for wet spraying. We have been pumping, spraying and testing both the relatively sophisticated pre-packaged materials and the more basic designed mixes in order to characterise their performance and hence identify the constituents and proportions within the mixes that produce sprayable mortars with adequate hardened properties.

RHEOLOGICAL TESTING OF MORTARS

Recent work conducted by Beaupré[1] investigated the rheological properties of sprayed concrete and the relationship between pumpability and sprayability, including the development of predictive models based on yield and flow resistance determined from tests conducted with a rotational viscometer. Sprayability can be defined as a property that incorporates parameters such as adhesion (ability of plastic mix to adhere to the surface), cohesion (influencing the thickness that can be built-up), and rebound. Beauprè termed this shootability and found a linear relationship between build-up thickness and the yield value of the mix after spraying, and concluded that shootability increases with flow resistance, and is thus in conflict with pumpability which has the opposite relationship. This research examines further the relationship between build-up thickness, pumpability and shear resistance.

Most authors (Tattersall and Banfill[2] and Beaupré[1]) use the simple Bingham model to express cement paste flow curves as this has been proved to give reasonably accurate and repeatable results within the boundaries of accuracy of the apparatus. For a Bingham fluid the relationship between the shear stress (τ) and shear rate (γ) is given by:

$$\tau = \tau_o + \mu.\gamma \quad (1)$$

where τ_o is the yield stress, above which there is a linear relationship between τ and γ characterised by the plastic viscosity μ. Mortar can be observed to be a shear thinning liquid in which the viscosity decreases when the shear rate increases. It also possesses a yield value: a minimum shear stress that must be applied before the mortar can begin to flow. If this shear thinning effect is permanent then this behaviour is known as irreversible structural breakdown, whereas if the structure reforms after shearing it is said to be thixotropic. This structural breakdown, together with Equation 1 is shown in Figure 1(a).

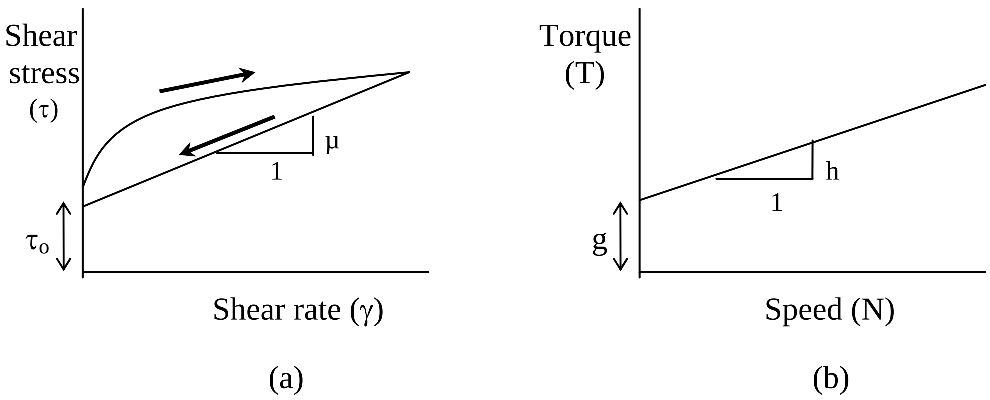


Figure 1. Typical flow curve for mortars. (a) Stress-strain. (b) Torque-speed.

Tattersall first used a Hobart food mixer to plot flow curves based upon the power needed to drive an impeller in fresh concrete[3]. He later developed a more accurate rheometer with a hydraulic transmission, termed the two-point test apparatus (Mk II). Tattersall found that when the torque (T) was plotted against the speed (N), the relationship was almost linear (Figure 1(b)):

$$T = g + h.N \tag{2}$$

where g is the intercept on the torque axis and h the slope of the line. Beaupré referred to g as the flow resistance, and h as the torque viscosity. This equation is of the same form as the Bingham model (Equation 1) 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[4]) but most investigations work with the direct parameters (which are of course equipment dependent).

MATERIALS AND MORTAR MIXES

The research has investigated a range of proprietary repair mixes (mainly developed for hand application) and six designed mixes. For the latter, the ordinary Portland cement conformed to BS12:1989[5] and the silica fume was a proprietary undensified powder. The sands were a crushed Portland stone sieved to a maximum size of 3mm and a building sand graded between 75μmm and 2.36mm. Some mixes also included an SBR in a 3:1 water:SBR suspension. The proportions of the mixes designed for the project are given in Table 1 and the constituents of the pre-packaged mortars are shown in Table 2.

The mortars were mixed using a 0.043m^3 capacity forced action paddle mixer. The pre-packaged mortars were mixed according to the manufacturers instructions with 3.3 to 4.0 litres of water per 25Kg bag and a mixing time of approximately 4 minutes. The designed mixes were mixed in the same way and in all cases the 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. The mortar was pumped through a Putzmeister TS3/EVR variable speed worm pump and then down a 25mm diameter rubber hose at an approximate rate of 6 l/min, depending on the mortar. The mortar was then sprayed with an air pressure of approximately 300 kPa.

Table 1 Proportions of designed mixes (by weight).

Mix	Crushed stone	Building sand	OPC	Silica fume	SBR:Water	Liquid/cement-itious ratio
D1	3	0	1	0.05	1:3	0.65
D2	2	1	1	0.05	1:3	0.55
D3	1	2	1	0.05	1:3	0.48
D4	0	3	1	0.05	1:3	0.44
D5	3	0	1	0.05	0:3	--
D6	4	0	1	0.05	0:3	--

Table 2 Composition of pre-packaged mortars.

Mix	Polymer modified	Fibres	Shrinkage comp.	Lightweight fillers	Mortar description
P1	No	No	Small amount	No	Basic repair mortar
P2	Yes	Yes	Yes	Yes	High build repair mortar
P3	Yes	Yes	Yes	Yes	2-part re-profiling mortar
P4	Yes	Yes	No	Yes	Basic repair mortar
P5	Yes	Yes	No	Yes	Render/repair mortar
P6	Yes	Yes	Yes	Some	Repair mortar
P7	Yes	Yes	Yes	Yes	Lightweight repair mortar

TESTING PROCEDURE

The test methods are described briefly below, two for workability, one for pumpability and one for sprayability and, taken in this order, they enable a rheological audit to be made of a mix as it progresses through the mixing, pumping and spraying process.

Workability

The workability was measured by the slump test[6] and by a modified form of the shear vane test for soils[7]. Two slumps were measured immediately after the mortar 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 was investigated as a simple, portable apparatus which could give an indication of the workability of a mortar at various points in the pumping and spraying process. It consists of a torque measuring device at the head of the instrument together with a set of enlarged vanes to provide sufficient shear resistance to register on the torque scale. The maximum torque was then used to calculate a shear strength for the mortar (in kPa.).

Pumpability

The two-point apparatus was the Mk II version developed by Tattersall[3] which has been found to be satisfactory for medium- to high-workability concretes. The mortars tested here had slumps of between 45 and 80mm and it has been suggested that the apparatus might not be sensitive enough for mortars if the torques exerted on the impeller are too low to give a significant increase in pressure, but sufficient change was observed in this work.

During preliminary trials with the apparatus empty it was found that the recorded pressure at a constant speed decreased over time. The apparatus was therefore always warmed up prior to testing for a period of 2 hours at a speed of 0.9 rev/s, after which the change in recorded pressure with time was negligible. The idling pressures were then recorded between the speeds of 0.6 and 2.6 rev/s at increments of 0.2 rev/s. With the bowl rotating at 0.6 rev/s the bowl was gradually filled with approximately 25Kg of mortar to a level 75mm below the top of the bowl. The speed was then increased incrementally and the corresponding pressures recorded. Once 2.6 rev/s had been reached the speed was reduced incrementally in the same way and the corresponding pressures again recorded. The decreasing results that follow the structural breakdown (Figure 1(b)) were used for calculating g and h.

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 standard grit-blasted 500x500x50mm concrete substrate. The mortar was sprayed horizontally onto a 300x300mm target area to obtain as large an amount of material as possible on the substrate whilst keeping within the ‘target’. The mortar would then fail under its own weight either cohesively or adhesively and the total weight of mortar was recorded, together with the failure mode and the maximum depth of build.

TEST RESULTS

Shear Vane

The shear vane provides a basic measure of the shear strength (in kPa) of a mortar and this can be plotted against slump (in mm), as shown in Figure 2. The shear strength has been calculated using the British Standard formulas for the measurement of soil shear strength multiplied by a conversion factor for the increased vane size. This shear strength can, in principle, be related to the yield stress (τ_o) in Equation 1. As expected, the shear strength decreases as the slump increases. It can provide an instantaneous result exactly where the rheological properties of the mortar needs to be measured, i.e. in the hopper of the pump.

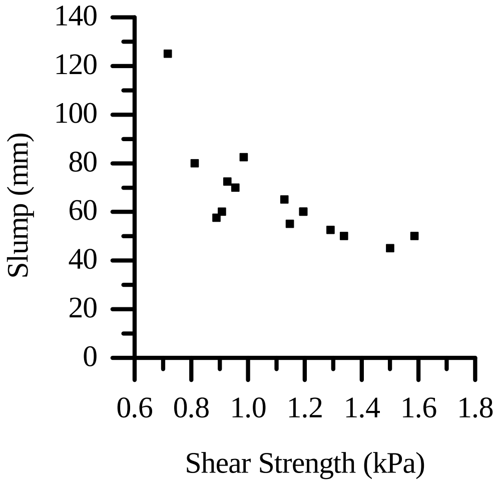
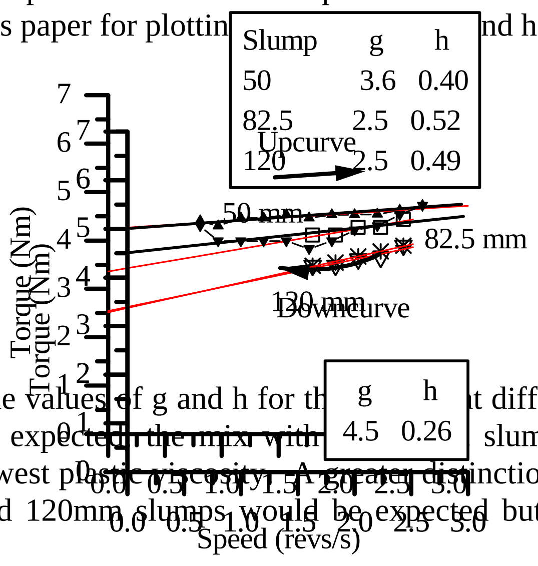
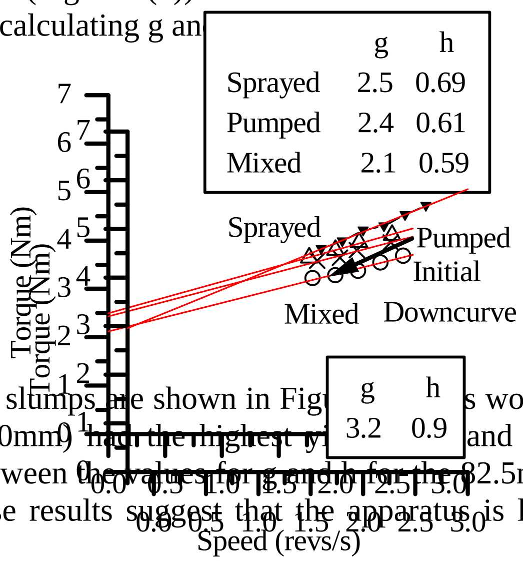


Figure 2. Shear vane Vs slump

Tattersall Two-Point Test

Figure 3(a) shows the results obtained from the two-point test on the mix P1. The figure shows a distinct up curve and down curve which was typical for all the mortars tested. However, approximately half way along the down curve the torque appears to increase as the impeller speed decreases. This is due to the mortar not falling into the impeller sufficiently and therefore not creating a high enough reading above the idling pressures. A regression line drawn through these points, as shown in Figure 3(a) provides misleading values of g and h. The points from the initial part of the down curve (Figure 3(b)) have therefore been used in this paper for plottin[g] ... nd hence calculating g an[d h]





The values of g and h for th... t different slumps are shown in Fig... s would be expected ... the mix with ... slump (50mm) had the highest y... and the lowest plastic viscosity. A greater distinction between the values for g and h for the 82.5mm and 120mm slumps would be expected but these results suggest that the apparatus is less

Figure 4. Two-point test. (a) Effect of slump on mix D1. (b) Effect of mix P1 being mixed, pumped and sprayed

Figure 3. Two-point test, mix P1. (a) Upcurve and downcurve. (b) Initial downcurve

sensitive for mortars at higher slumps. Figure 4(b) shows the g and h for the mortar P2 after it has been mixed, pumped or sprayed. The increase in both g and h as the mortar is pumped and then sprayed would be expected as the excess air is forced out of the mortar during the pumping and compacting operations.

The two-point test results for all the mortars, both the pre-packaged and the designed mixes, are shown in Figures 5. They were all mixed with water prior to testing until the desired consistency for pumping and spraying had been achieved. Of the pre-packaged mortars, the mortar with both the highest g and highest h is mix P1 which had the most ‘basic’ mix design of all the pre-packaged mortars tested, and contained no polymers, fibres or lightweight fillers. The mix with the next highest value of g, mix P4, was also known to have a relatively basic mix design. These two mixes were also the cheapest commercially of all the pre-packaged mortars tested. The two mixes which were known to be highly polymer-modified (P6 and P3) had the lowest values of g, although their corresponding values of h were very different. The mix P3 is a two-part (powder and liquid) re-profiling mortar which has been formulated to enable it to be applied in thin layers without it separating or being too ‘sticky’, which could explain why it had the smallest value of g. The designed mixes in Figure 5(b) show a clear trend dependent upon the mix design: the greater the proportion of crushed Portland stone within the mix compared with the building sand then the greater the value of g. The addition of SBR to a mix, in this case mix D5 having no SBR and mix D1 being an identical mix containing a 3:1 water:SBR solution, appears to have little effect on either g or h. This is in contrast with the pre-packaged mortars where the highly polymer-modified mortars possessed a lower value of g.

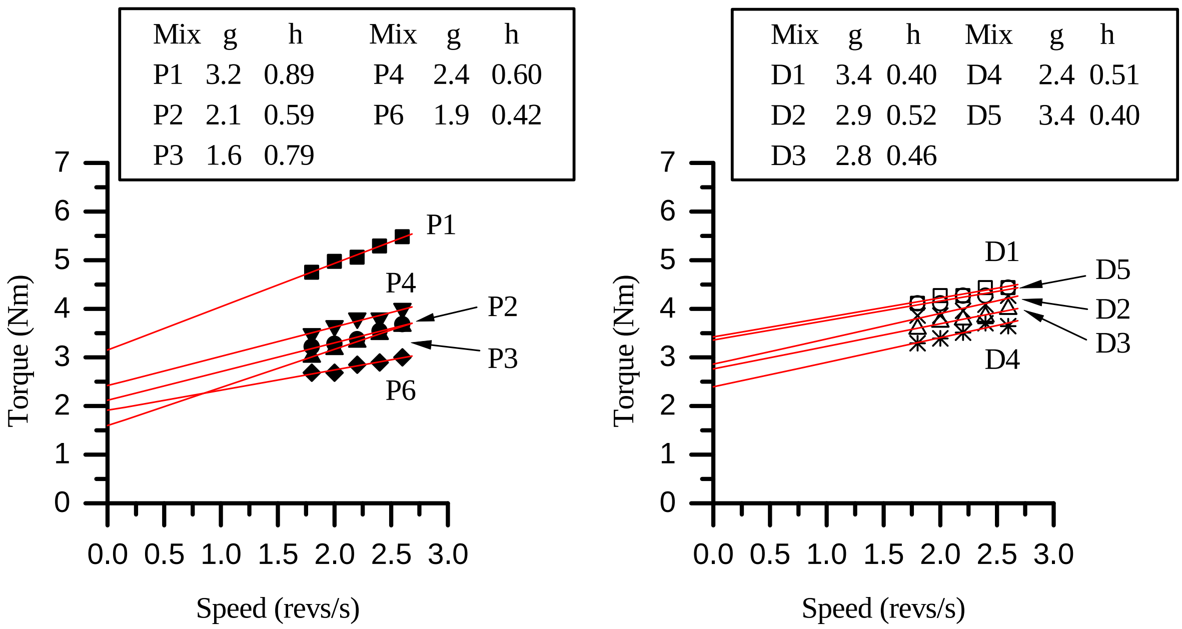


Figure 5. Two-point test. (a) Pre-packaged mortars. (b) Designed mixes

Build Test

The build values (in mm) obtained for each of the mixes are shown in Table 3. The mass of the mortar sprayed onto the substrate was also measured and this was used, together with the cross-sectional area of the base of the mortar (usually 300mm square) to calculate the maximum shear force produced between the mortar and the substrate. The bending stress was calculated by idealising the mortar on the substrate into the frustum of a square-based pyramid (i.e. a square-based pyramid with the top 'sliced' off parallel with the base). The volume, and therefore the dimensions of this frustum, could be calculated using the mass, the fresh wet density, the area of the base and the height of the frustum (i.e. the build value). This shape was then used to calculate the maximum moment and therefore the maximum bending stress of the mortar.

Table 3. Build test results.

Mix	Build (mm)	Mass (kg)	Max. shear (N/m2)	Bending stress (N/m2)	Failure mode
D1	210	21.4	2571	2120	Adhesive
D2	300	27.3	3279	4922	Cohesive
D3	280	24.2	2907	3872	Adhesive
D5	270	26.8	3219	3521	Cohesive
D6	220	23.2	2787	2357	Adhesive
P1	320	41.5	3816	3476	Cohesive
P2	270	13.0	3147	3002	Cohesive
P3	230	----	2308	2375	
P4	290	26.6	3728	3662	Adhesive
P5	300	49.5	5946	4374	
P6	200	32.2	3868	1566	
P7	350	----	2460	3853	

Figure 6(a) shows the relationship between the build-up thickness and the slump of the mortar before pumping. This agrees with the results presented previously by Beaupré[1] who showed that it is not possible to predict the build-value of a mix simply by measuring the slump immediately before pumping. However, the results seem to indicate an increase in build for an increase of slump. This seems the reverse of what would be expected but at the low workabilities tested here, an increase in slump would produce a slightly wetter, and

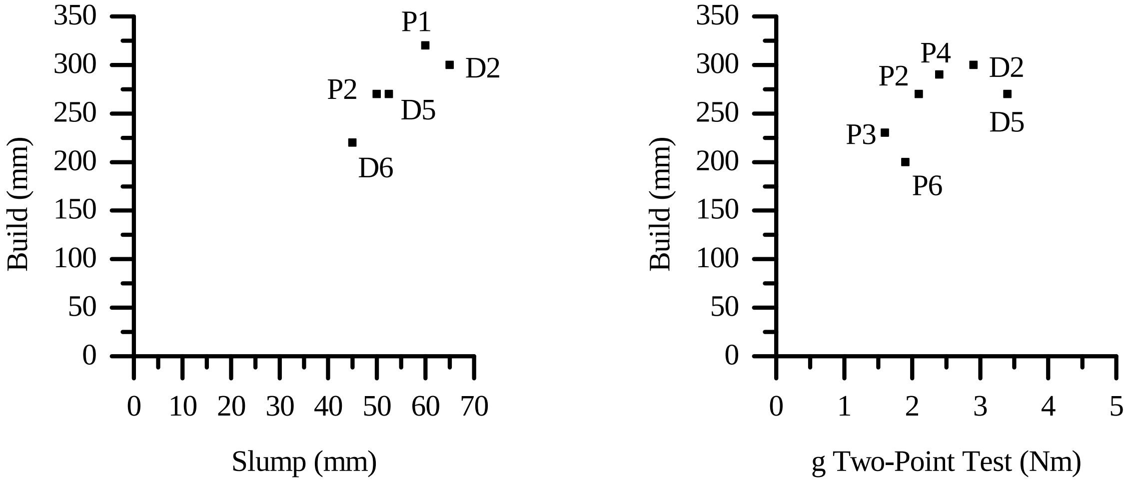


Figure 6. Build value. (a) Slump. (b) g Two-point test

therefore more cohesive mix, thereby increasing the build.

Beaupré also reported a good relationship between ‘g’ (the flow resistance, obtained from the Two-point test) and the build value. The relationship between these two parameters in this study are shown in Figure 6(b). The trend is not as strong as that found by Beaupré (who tested 10mm aggregate sprayed concretes with build values from 10 to 350mm) compared to the mortars presented here which have build values between 200 and 300mm. It can be assumed that the line of best fit passes through the origin as a material with zero g (e.g. water) will also have a build-value of zero. It can also be noted that the pre-packaged re-profiling mortar designed to be easily trowelled (P3) had the lowest value of g.

Figure 7 presents the relationship between the build-value and the vane shear strength immediately before pumping. These results indicate an increase in build for a decrease in vane shear strength. As in Figure 6(a), this seems the opposite relationship to what would be expected but at these low workabilities a decrease in shear strength could produce an increase in the cohesiveness of the mortar, and therefore a corresponding increase in build. As the vane shear strength decreases further (due to an increase in workability) a point is reached where the mortar no longer fails due to the tensile stresses being exceeded but by a shear (i.e. flow) failure. At this point the maximum build is obtained. This point is difficult to establish here due to the workabilities of the mixes being within a narrow range. It can be noted that the mix D5 possesses a higher build value than the mix D1(which is identical to the mix D5 except for the addition of SBR), yet approximately the same shear value. The mix P1 also contained no SBR yet possessed the highest build value of all the mixes tested (except for the lightweight mortar, P7(not shown)) which suggests that the presence of a polymer could reduce the build-value for a given shear strength. However, more work would be needed to confirm this hypothesis as it might be expected that polymers would increase the build-value.

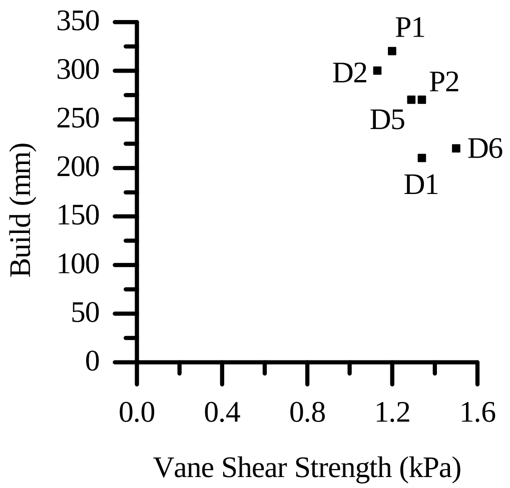


Figure 7. Build value Vs vane shear strength

CONCLUSIONS

This paper has presented and discussed a variety of data on the rheological performance of wet-sprayed fine mortars. A rheological audit has been developed and tests for each stage have been used to characterise the pumpability and sprayability of each mortar. A shear vane test has been developed which can give an instantaneous measurement of the shear strength of the mortar where ever this property needs to be assessed. A good correlation with the slump of a mortar has been found and a possible relationship has been presented relating the vane shear strength to the build of the mortar.

The Two-point test apparatus produced satisfactory results with fine mortars with low workabilities, although care needs to be taken in the conduct of the test and interpretation of the results. The grading of the constituents and the presence of polymers both had a significant effect on the results obtained.

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REFERENCES

1. BEAUPRÉ, D. Rheology of high performance shotcrete. PhD Thesis, University of British Colombia, 1994.
2. TATTERSALL, G.H. AND BANFILL P.F.G. The rheology of fresh concrete. Pitman, London, 1983.
3. TATTERSALL, G.H. Workability and Quality Control of Concrete. E&FN Spon, London, 1991.
4. BANFILL, P.F.G. Rheological methods for assessing the flow properties of mortar and related materials. Construction and Building Materials, 1994, Vol. 8, Number 1, p 43-50.
5. BRITISH STANDARDS INSTITUTION. Specification for Portland cements. BS12:1989, British Standards Institution, London, 1989.
6. BRITISH STANDARDS INSTITUTION SPECIFICATION, Method for determination of slump, BS1881:Part102:1983, British Standards Institution, London, 1983.
7. BRITISH STANDARDS INSTITUTION. Specification for soils for civil engineering purposes, Part 9. In-situ tests, BS 1377:Part 9:1990, British Standards Institution, London, 1990.