The hardened performance of wet process sprayed mortars [Published title: The performance of hardened wet-process sprayed mortars]

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This paper, which reports on part of a three year research project into wet-process sprayed mortars and concretes for repair, investigates the hardened performance of wet process sprayed mortars. Seven commercially available pre-packaged repair mortars were pumped and sprayed through a worm pump, three through a piston pump and two through a dry spray machine. A laboratory designed mortar was also worm and piston pumped. The properties measured included compressive and flexural strength, tensile bond strength, hardened density, modulus of elasticity, air permeability, sorptivity and drying and restrained shrinkage. In-situ test specimens were extracted from 500mmx500mmx100mm deep sprayed panels. Tests were also conducted on corresponding cast specimens and, where possible, on specimens that had been sprayed directly into a cube or beam mould. A new test to quantify the degree of reinforcement encasement has been developed and an initial investigation into the measurement of the restrained shrinkage of in-situ repairs is presented. The compressive and flexural strengths of the laboratory mix were comparable with the best of the commercially available pre-blended mortars. The values for modulus of elasticity, when compared with the compressive strength, were lower than published formulas for this relationship would suggest, especially at lower strengths. The air permeability of most of the mortars was lower than that for normal wet-cured concrete and decreased with an increase in compressive strength. The sorptivity values showed no clear relationship with the compressive strength. The type of wet-process pump was found to have little effect on the in-situ compressive and flexural strengths, but did affect the bond strength, although mainly due to the stream velocity and w/c ratio rather than the pumping process. The pump type also effected the reinforcement encasement with higher stream velocities producing better encasement. The mixes exhibited a wide range of drying shrinkage, but the data from the restrained specimens suggest an actual repair is influenced as much by ambient conditions as it is by the mix proportions.

1 Introduction

Sprayed mortar can be defined as a mortar 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 project 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 projected into place. The rheological properties of the mix in the wet process are obviously critical, and these properties were examined by the authors in a previous paper[1] . The mortar's hardened properties are of equal importance, so that a durable and long lasting repair can be obtained, and it is these properties that this paper will investigate.

This paper describes the findings of part of a three year Government and industry funded research programme into wet process sprayed concrete for repair, and more specifically the hardened properties of a range of fine mortar mixes, which are defined as mixtures of cement, aggregate with a maximum particle size of 3mm, water and any admixtures. The mortars tested include seven commercially available pre-packaged concrete repair mortars and a generic mix design consisting of crushed Portland stone, Portland cement (PC), silica fume and a styrene butadiene liquid additive (SBR). Previous work on the hardened performance of sprayed mortars is discussed, together with the experimental methods used to measure the hardened characteristics of the fine mortars. The results of the tests are presented and the relationship to their cast properties is discussed.

2 Wet process sprayed mortars

Wet process sprayed application offers a number of advantages over cast and hand-applied repairs, including the reduction or elimination of formwork, the construction of free form profiles and faster and more efficient construction[2]. It can also provide enhanced hardened properties if properly placed. The performance of a repair material is clearly critical to the success of the remedial works to which they are applied and careful consideration should be given to the choice of repair material and to the properties relevant to the application. Manufacturers of concrete repair materials (both for hand and sprayed applications) provide a range of data on the performance of their products but it is often unclear how they were tested and whether the test samples were cast, taken from a test panel or taken from in-situ concrete.

The interaction between the substrate and the repair material is also critical and substantial work has been conducted in this area, although little of this is specific to sprayed repair[3,4]. During the service life of a structure, strength and modulus of elasticity incompatibilities between a repair and the parent concrete can lead to cracking and occasionally to complete failure. Drying shrinkage can also reduce a repair's long-term structural effectiveness due to internal tensile stresses causing the repair to crack. The permeability of the repair material has a direct influence on the durability of the structure as this influences the rate of ingress of aggressive substances into both the repair and the parent concrete. Previous works published by the authors have discussed both the materials, installation and physical properties of sprayed concrete[5] and the associated application methods and quality considerations[6].

Hills[7] conducted tests on both wet and dry sprayed concrete, and compared results with those from cast concrete. He concluded that the performance of the sprayed concretes did not appear significantly different from those of properly compacted cast mixes of similar composition and he argued that it was the modified mix design needed for sprayed concretes that altered the hardened properties, not the method of placement. However, more recently Banthia *et al*.[8] have argued that cast and sprayed concrete are of a different nature, with the spraying process affecting the internal arrangement of constituents and hence the strength and durability. Rebound, although found to be low (<10%) in this investigation, produces an increase in the in-situ cement content of the mortar which also influences strength and durability.

Work conducted by Gordon[9] on wet-sprayed pre-bagged repair mortars concluded that the wet-spray process achieves greater compaction than hand application and that the materials tested achieved compressive strengths approximately 30% higher when wet-sprayed than when hand applied. Increases in fresh wet density, bond strength and build were also recorded. Initial results for drying shrinkage also showed similar shrinkage rates for prisms (70x70x270mm) sawn from a sprayed panel (both wet and dry) and cast prisms of the same size.

Although there is little published data on mix designs for low volume wet-sprayed mortars for small scale repair, work has been conducted on the long term performance[10] and on the structural effectiveness[11] of sprayed concrete repairs. Low volume wet-sprayed mortars have also recently been used to investigate the strengthening of masonry arch bridges[12]. More published data exists on high volume wet-process sprayed concretes (mainly for tunnelling) and Malmberg has shown that the most consistent quality of sprayed concrete is achieved with site-batched wet-process sprayed concrete when compared with wet process using ready mix concrete and with the dry process[13].

3 Mix designs

The laboratory designed mix contained Portland cement (conforming to BS12:1996[14]) and crushed Portland stone sieved to a maximum size of 3mm in a ratio of 1:3 by weight, together with silica fume (as an undensified powder) and an SBR in a 3:1 water suspension.

There are several hundred commercially available concrete repair systems and Emberson and Mays[4] categorised these into nine generic types. Of these, two of the most widely used are the SBR-modified cementitious and the Portland cement/sand mortar types. Commercial considerations prevent the publication of the formulations of these pre-packaged mortars, but they typically contain all or most of the following constituents, depending on the type:

(i) a combination of fine aggregates from 75μm to 2mm in diameter;

(ii) lightweight fillers, 75μm to 300μm in diameter;

(iii) Portland cement in a ratio of 1 : 1.3 - 3.4 with the aggregate;

(iv) silica fume (approximately 5% of the Portland cement);

(v) admixtures such as an SBR;

(vi) polypropylene fibres up to 6mm in length; and

(vii) chemical shrinkage compensators.

The pre-packaged mortars tested in this investigation have been designated *P1* to *P7* and the method by which they were pumped and sprayed has been designated either *w* (for a small diameter worm pump), *W* (for a large diameter worm pump), *d* (for dry spray) and *p* (for a piston pump). *P2w* is therefore pre-bagged mix *P2* which has been pumped and sprayed through a small diameter worm pump. The laboratory designed mix is designated *D1*. The gradings (of the combined aggregate and cementitious components) of the mixes are shown in Figure 1, and the constituents of the mortars in Table 1. All the mortars in Figure 1 were wet graded and the particles collected in each sieve were dried, weighed and examined under a x40 magnification microscope. A visual assumption was then made to determine what proportion of each sieve was aggregate, lightweight filler or cementitious material and the weight of each was calculated accordingly. The *w/c* ratio in Table 1 is the water/total cementitious value and the *Agg/c* value is the aggregate (including filler)/total cementitious value.

3 Trial Procedure

The mortars were mixed using a 0.043m^3 capacity forced action paddle mixer according to the manufacturers instructions, with 3.3 to 4.0 litres of water per 25kg bag of dry material for approximately 4 minutes. Water was added to the designed mixes 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. Trials were conducted with four types of pump, the majority with a Putzmeister TS3/EVR[15] variable speed worm pump with a 25mm diameter rubber hose, an air pressure of 300 kPa and an output of approximately 6 l/min. Three of the mixes were pumped with a Reed B-10 piston pump and sprayed using a 25mm diameter rubber hose, a 365cfm compressor and an output of approximately 80 l/min. Two mixes were pumped with a Reed SOVA dry spray gun using a 25mm diameter rubber hose, a 365cfm compressor and an output of approximately 50 l/min. One mix was pumped with a Uelzener Putzknecht S30 UE45/7 large diameter worm pump using a 32mm diameter rubber hose, a 125cfm compressor and an output of approximately 50 l/min.

The mortars were sprayed into 500x500x100mm deep panels whilst trying to minimise both voidage and rebound. One panel in each trial contained a 500x250x50mm thick grit-blasted concrete substrate to determine the bond strength and a second panel a reinforcement cage to assess the degree of bar encasement. Samples were also produced by spraying into 100mm cube and 500x100mm beam moulds in order to assess the suitability of this production method. Further specimens were cast in two layers on a vibrating table for the determination of compressive and flexural strength, elastic modulus and comparison with samples from panels and moulds. All panels were floated immediately after spraying, sealed with a curing membrane and then moved into a laboratory at room temperature within 2 hours ready for stripping and sawing the following day.

4 Test Methods

The test methods followed existing standards where appropriate and these were mainly for concrete (rather than mortars) to enable direct comparison with the larger aggregate mixes that were sprayed in parallel with these mortars, the results of which are presented elsewhere[16]. In some instances, new test methods were developed specifically for this project and these are described briefly below.

Sampling

All material within 50mm of the panel edge was discarded to avoid the effects of rebound entrapment of rebound around the edges of the moulds. The panels were then sawn across their width into 100x100mm sections, which were then cut to length into 400mm long beams and 100mm cubes. 229x75x75mm prisms were also sawn for elastic modulus and drying shrinkage tests. All samples were sawn approximately 24 hours after spraying and then cured under water at 20 ± 2^{0}C. The sprayed and cast specimens were struck and cured in the same manner.

Strengths

Compressive tests were carried out at 7 and 28 days in accordance with BS1881[17] with the exception that the sawn cubes were capped with a plaster. The flexural tests were carried out at 28 days in accordance with BS1881[18] under four-point bending, the two sawn sides in contact with the loading points. The results quoted for these tests are the average of two specimens. Observations were also made of the quantity and size of air voids within the specimens, especially those obtained from spraying directly into cube moulds.

The tensile bond strength was measured by a core pull-off test (using the Limpet apparatus) at 7 and 28 days. The substrate mix design was based upon previous work[19] and each 250x500x50mm substrate was grit-blasted on one side to produce a surface roughness index (SRI) of approximately 220mm. The surface was wetted and left until saturated surface dry prior to spraying. Five 55mm diameter partial cores were cut through the repair material and into the substrate to a depth of approximately 10mm and a 50mm diameter steel dolly was then glued to the top of the core and an axial tensile load applied at a rate of 2kN/min to failure.

Density

The hardened densities of the cubes were calculated by weighing in air and determining their volume from measured dimensions. Care was taken to ensure that no voids were present, especially with the specimens struck from a sprayed cube mould.

Modulus of elasticity

The secant modulus of elasticity was measured at 28 days by a test based upon BS1881[20] and work recently completed by Jones[21]. The specimen strains were recorded over a gauge length of 85mm using four LVDTs, the average of which was used to calculate the modulus. The load was applied at a rate of 0.5mm/min and the load and deformations were digitally recorded using a data acquisition system.

Drying shrinkage

Prisms to monitor shrinkage vary according to different standards, although even the largest are too small to spray directly into a mould. Specimens 75x75x229mm were therefore cast to BS1881[22] and also sawn from sprayed panels. Pairs of demec pips were glued to three of the longitudinal faces on a 200mm gauge length and the specimens were stored in a climatic cabinet at 20^{o}C and 50% RH. Strain readings were taken at 1,2,3,4,7,14,21 and 28 days and then at 30 day intervals until a constant length was achieved. Each shrinkage value quoted is an average of strains measured across six faces of two prism specimens.

Air permeability and sorptivity

The air permeability was measured with apparatus based on the work of Lovelock[23] and developed by Hudd[24]. An air pressure of 50psi ($3.45x10^5$ N/m^2) was applied to 20mm x 55mm diameter samples, that had been cored, cut to length and oven dried at 50^0C for 14 days. The water sorptivity of the same specimens was determined according to the RILEM[25] method in which the dry samples are placed in water to a depth of 2mm and the weight gain over time recorded for a period of four hours. Samples for both the air permeability and the sorptivity were wet-cured for 28 days and then oven dried at 50^0C for 14 days prior to testing.

Reinforcement encasement

This test consisted of a 500x500mmx100mm deep panel fitted with steel reinforcement of differing diameters, as shown in Figure 2(a). Advice was sought from contractors on the positioning and sizing of the reinforcing bars[26-28]. The panel was sprayed to obtain as complete encasement as possible. At 28 days the intersections of the bars were all cored and each core was visually examined for imperfections, i.e. laminations, shadowing and voids. A 5mm disc was cut from the bottom (i.e. moulded face) of the 55mm diameter core and discarded (Figure 2(b)); a 20mm thick disc was sawn from the same end and a sorptivity test conducted on both the disc and the remainder of the core (where possible, as occasionally the voidage behind the reinforcement caused the core to fragment during sawing). The sorptivity was then related to the density of the reinforcement at the bar intersection.

Restrained shrinkage

This crude test was developed to represent a typical on-site sprayed repair. Second-hand 593x897x50mm paving slabs, which would minimise substrate drying shrinkage, were grit-blasted on the face for repair. Half the substrate was covered with reinforcing mesh at a depth of 30mm and the remainder un-reinforced. The substrate (as with the bond test) was saturated surface dry and sprayed to a depth of approximately 60mm. The repair was floated and a curing membrane applied. Three pairs of demec pips were fixed on a 200mm gauge length on both the reinforced and un-reinforced sections and strain readings were taken at similar intervals as for drying shrinkage. The back of the substrates were also instrumented to monitor the movement of the substrates.

5 Test results

Compressive strength

Figure 3 shows the equivalent cube strengths of the worm pumped mortars, obtained from in-situ cores and cubes cut from panels and the cast and sprayed cubes. The mortars with the lowest strengths of 26.8-33.9 MPa were, as expected, obtained with the render/profiling and lightweight repair mortars (P3w and P7w). The simple laboratory designed mix D1w produced the highest strengths compared to the more sophisticated (and therefore expensive) pre-bagged mortars. The relationship with water/cement ratio is as expected (Figure 4), the trend being similar to data produced by Hills[7].

The in-situ cube strengths are generally higher than the corresponding cast cubes, due mainly to the greater compaction obtained with the spraying process (see densities in Table 2). It is generally agreed that in-situ sprayed concretes produce higher strengths than for similarly cast mixes[28,9] although the opposite has also been observed[29]. The fall in the cast cube values as the w/c ratio decreases is also typical for insufficiently compacted concrete[30], adequate compaction when cast being difficult to obtain with several of the mortars (P5, P6 and P7). The lightweight mortar P7 had a high water/cementitious ratio due to the low proportion of cement and the high proportion of lightweight filler. P5w, P6w and P7w have low cast cube strengths as these specimens contained a large number of air voids, even after considerable vibration. There is a good correlation between the in-situ cube strengths and the cubes sprayed in moulds, despite the difficulty in obtaining a sample with no voids and low rebound (samples with excessive voidage being discarded).

Figure 5 shows the compressive cube strengths of mixes P2, D1, P1 and P5 sprayed through different pumps. This shows a small difference in the in-situ cube strengths for the wet-process pumps (small and large diameter worms and a piston pump) for both P1 and P2 but a larger increase when mixes P1 and P5 are dry sprayed, the latter being expected due to their lower water/cementitious and aggregate/cementitious ratios resulting from the high aggregate rebound with this process. The higher values for the sprayed mould cube strengths using the small diameter worm pump, compared with the piston pump for D1 and P1, could be attributed to the difficulty in spraying a 100mm cube mould with the larger nozzle and higher output of the piston pump.

Flexural strength

Table 3 shows a similar trend to the compressive strength results, with the cast beams in general having the lowest flexural strengths and the in-situ beams the highest. Problems were again encountered with voidage and rebound when spraying into the beam moulds, badly affected beams being discarded. The relationship between the flexural and compressive strength (Figure 6) is in line with data for cast concrete[30].

Tensile bond strength

The vertical and overhead bond strengths of the small worm pump mortars are shown in Figure 7(a) and the 7 and 28 day bond strengths of mortars P1, P2 and P5 through different pumps in Figure 7(b). All the pre-packaged mortars achieved at least 1.7 MPa at 28 days, with the exception of the lightweight mortar P7, which comfortably exceeds the Concrete Society minimum bond strength of 0.8 MPa. Figure 7(b) shows that the type of pump affected the bond strength. Due to the large amount of aggregate rebound the dry process produces a repair that is rich in cement with a correspondingly higher bond strength (P1d and P5d). Piston pumping P1p produced a lower bond strength than worm pumping (P1w) and the compressive strength was also lower (Figure 3(b)). In contrast, mix P2W (large worm pump) produced a much lower bond strength than P2w and P2p, despite having a similar compressive strength.

The vertical bond strengths are compared with compressive strength in Figure 8. This shows that the mortars in this study (except P7) possess a relatively narrow range of vertical bond strengths (1.7-2.25 MPa), despite having a broad range of compressive strengths (25-57 MPa). As previously mentioned, P7 was a lightweight material and had both a low vertical and overhead bond strength.

Density

The densities in Table 2 show that in general the in-situ mortars possess the highest densities and the cast mortars the lowest. P5, P6 and P7 had a large number of voids in the cast cubes, even after several minutes vibration and therefore possess a significantly lower density than the corresponding in-situ and sprayed cubes. The dry process mortars all had a higher density than either the wet process worm or piston pumped mortars. The piston pumped mortars (P2p and D1p) produced higher densities than the corresponding worm pumped mortars (P2w and D1w) although the density of the piston pumped mortar P1p was lower than P1w.

Modulus of Elasticity

The elastic modulus is compared with the in-situ compressive strength in Figure 9. There is no agreement on the precise form of this relationship for sprayed concrete[30], but that from ACI 363R-92[31] for concrete is shown for comparison. The results obtained show significantly lower modulus values, especially at lower strengths. This is due to the lower density combined with the type and proportion of aggregate within these fine mortars. The data is important, however, as it is desirable for the elastic modulus of the repair and the substrate to be as similar as possible.

Drying shrinkage

The drying shrinkage results for the 75x75x229mm in-situ prisms are shown in Figure 10. A wide range of results was obtained, despite all the pre-blended mixes being described as 'low shrinkage'. P3w contained a shrinkage compensator (as did P2W) which explains the initial expansion of the specimen - minimum shrinkage being vital for a re-profiling render designed to be applied in thin layers. The mortar which shrank the greatest at the fastest rate was the lightweight mortar P7, which would be expected due to the very high water/cementitious ratio. Figure 11 shows the 28 day shrinkage for mortars P1, P2 and P5 after they have been cast, dry sprayed and worm and piston pumped. The first shrinkage measurement for P1w was taken 2 days after spraying and so the 28 day shrinkage would be expected to be greater than shown when compared with the results taken 1 day after spraying, as a large proportion of the shrinkage occurs within the first 24 hours. However, mortar P2 contains a shrinkage compensator and so the overall 28 day shrinkage shown for P2 and P2w is actually lower than shown. The dry sprayed mixes, P1d and P5d, shrunk considerably less than their equivalent wet sprayed or cast specimens, probably due to their lower water content. The results for mortar P5 (Figure 12) show very little difference in the shrinkage rates between cast and in-situ prisms when wet-sprayed.

Air permeability and sorptivity

The results for the air permeability and sorptivity are shown in Table 4 and their relationship with the in-situ compressive cube strength in Figure 13. The air permeability test was carried out on the bottom 20mm thick section of the core and it is these results that are presented in Figure 13, together with the sorptivity tests, also conducted on the bottom section of the core. A relationship between oxygen permeability and compressive strength for concretes that have been wet-cured for 28 days[30] is shown for comparison. As would be expected, the air permeability decreases as the compressive strength increases, with most of the mortars having a lower permeability than concrete. However, the sorptivity does not show a clear relationship with the compressive strength. Recent work by Al-Kindy[32] has shown that sorptivity decreases with an increase in compressive strength, with the sorptivity of a 50 MPa concrete being 1.5-2 times lower than similarly cured 30 MPa concrete, the decrease being attributable to the increased cement content and lower w/c ratio. The lack of a clear relationship in the current study between compressive strength and sorptivity is possibly a result of the difference in mix constituents and proportions of the pre-blended mortars, Al-Kindy's results being based on concretes made with the same constituents .

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 14. Several methods for quantifying the density of reinforcement were compared including: summing the bar diameters, summing the bar cross-sectional areas, calculating the total projected bar area within the core and calculating the area of bar overlap. The standard deviations for these methods were very similar and the area of bar overlap was chosen as this gave the broadest spread of results. In general, the sorptivity of the pre-bagged mortars does not increase greatly as the density of reinforcement increases. 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 mortar being concentrated directly beneath the bars.

The piston pumped laboratory designed mortar D1p had the highest sorptivity in this test, as did the worm pumped D1 (Table 4), probably due to the higher absorption of the aggregate (2.5% at 30 minutes compared to approximately 1% with other aggregates). Mortar P2 had the lowest sorptivity, the large diameter worm pumped P2W being lower than the small diameter worm pumped P2w, especially at the denser levels of reinforcement. This could be attributed to the higher velocity, and therefore more complete encasement, of the larger diameter worm pump. This higher velocity can also explain the lower sorptivity of the piston pumped D1p compared with the worm pumped D1 (Table 4). However, the difference between P1p and P1d is very small with the higher velocity piston pump producing only slightly lower sorptivity than the dry spray pump.

Cores were visually graded on a scale 1 to 5 in accordance with the recommendations of Gebler[33] , based on a grading system originally proposed by Crom[34]. Each of the core grades relates to the quantity and size of imperfections visible on the surface of the core. A grade 1 core has a good paste content throughout, without laminations, sand areas or large hollows. Small air bubbles to a maximum dimension of 1.3 mm are acceptable. There are no sand pockets, hollows or shadows behind any of the reinforcing bars. At the other end of the scale, a grade 5 core can have flaws greater than 25 mm thick and 38 mm in length. Gebler[33] states that a core grade of 1 or 2 is generally used for acceptance of a nozzleman on projects demanding high quality workmanship. Although the visual grading is subjective, the grading criteria are explicit and good correlation between independent gradings can be achieved by experienced engineers[33].

Figure 15 shows the core grades for three of the pre-blended mortars. Note that the P4w cores that produced a grade 5 were so full of voids that sorptivity tests could not be carried out. Figure 15 shows a contrasting behaviour between the two worm-pumped mortars, P2W and P4w. P4w core grades increase significantly with increasing overlap area, whereas P2W grades do not. The most probable reason for this is the difference in the stream velocity of the different worm pumps; P4w being applied with a small diameter low output pump, and P2W with a larger diameter medium output pump. The mortar P1d applied by the dry process exhibits a slightly less well defined trend, though an increase in core grade with increasing overlap area is discernible.

The two methods of assessing the encasement (Figures 14 and 15) show similar trends, with P2W producing little change in encasement with increasing overlap area, and P4w showing the largest changes.

Restrained shrinkage

The restrained shrinkage of several mortars, with and without mesh reinforcement, is shown in Figure 16. The results are the average of three gauge readings measured directly from the face of the repair, with no allowance for the movement of the substrate. Mortars D1p and P2p were sprayed 6 months before mortars P1p and P1d and were therefore cured under very different temperature and humidity conditions. This could explain the large difference in the shrinkage curves for the two spray trials. Mortars D1 and P2 expanded in the first few days, partly due (for P2 only) to the presence of shrinkage compensators but also due to the ambient temperature and humidity fluctuations. This influence of the ambient conditions could also explain the sharp decrease in the rate of shrinkage for mortars P1p and P1d after 42 days and the expansion of mortars D1p and P2p after 14 days. The much greater rate of shrinkage of P1p and P1d compared with D1p and P2p could be attributed to the dates on which they were sprayed. P1p and P1d were sprayed on the 18 and 19th of June (i.e. the beginning of summer, therefore a faster rate of shrinkage due to a higher ambient temperature) and D1p and P2p were sprayed on the 18th of November (i.e. the beginning of winter, therefore a slower rate of shrinkage). The laboratory designed D1p and the shrinkage compensated pre-packaged P2p had very similar shrinkage profiles until approximately 250 days.

The reinforcement mesh had very little influence on the shrinkage profiles for all the mortars, with the mesh-reinforced P1p, P1d and D1p actually shrinking slightly more than the corresponding un-reinforced mortars. The main purpose of reinforcement mesh is to eliminate cracking, yet no cracking was observed on either the reinforced or un-reinforced sections of the slabs.

Table 6 shows free shrinkage strains calculated from the restrained shrinkage specimens for P1p and P1d. These strains have been determined from the strains in the repair and substrate assuming that the substrate does not shrink and hence it is the shrinkage of the repair that causes a compressive stress (and hence strain) in the substrate. For simplicity, the problem has been treated as a linear one, assuming perfect bond between the substrate and the repair. Note that the calculated free shrinkage strains in Table 6 are similar in magnitude to the strains measured on the surface of the repair, suggesting that despite being restrained at the interface with the old paving slabs, the surface of the repair was still able to shrink with little effect from the restraint.

The free shrinkage of the 76x76x229mm prisms taken from in-situ and stored at 20^{0}C and 50% relative humidity are also shown for comparison in Table 6. The shrinkage of these laboratory stored prisms are considerably greater (up to 3 times in the case of P1p) than the free shrinkages deduced from the restrained specimens left outside in ambient conditions. Clearly quoting shrinkage results from tests conducted under laboratory conditions should be done with caution when discussing in-situ repairs and their performance.

Wet sprayed and dry sprayed concrete compared

Table 5 shows the properties of the 3 mortars that were dry sprayed in this investigation together with comparable wet-sprayed data where available. As expected, the compressive, flexural and bond strengths are all higher for the dry sprayed mixes, as are the values for elastic modulus and density. This is due to the lower water/cementitious ratio and higher in-situ cement content of the dry sprayed mixes (this lower water/cementitious ratio was also the reason for the strengths and density of P1 being lower when piston pumped than when worm pumped). The mixes also had a lower drying shrinkage at 28 days when dry sprayed than when wet sprayed. The initial shrinkage measurements for P1worm and P8dry were taken 2 days after spraying, compared with 1 day for the other mortars and so the 28 day drying shrinkage could be expected to be higher for these two mixes than is shown in the table.

6 Conclusions

The results of the hardened property tests on these wet process mortars (proprietary and designed) show conclusively that such mortars are suitable repair materials for wet mix application. Though slightly out-performed by the dry process mortars in terms of compressive and bond strengths, the healthier working environment and the greater control of the mix constituents makes the wet process a better choice as a repair process. Of particular attraction to the designer/specifier are the knowledge that the mix specified, once pumped and sprayed, will be the mix in-situ (without the uncertainty of the water content controlled by the nozzleman in the dry process, and the further effect of differential rebound). Furthermore, with the low volume pumps used in this study, the ability to obtain representative quality control specimens by spraying directly into steel moulds is another advantage in terms of convenience and cost.

Compressive and Flexural Strength

The relatively simple laboratory designed mortars possessed high compressive and flexural strengths compared with the commercially available pre-blended mortars. Their is a good correlation between the in-situ and the sprayed mould compressive cube strengths, providing that no large voids or excessive rebound is present. However, it was very difficult to remove all the voids from several of the pre-blended mortars, even with substantial vibration.

The different types of wet-process pumps (small and large diameter worms and piston pump) seemed to have little effect on the compressive and flexural strengths of the mortars. However, the output of the pump and the size and design of the nozzle did influence properties such as reinforcement encasement, bond strength, and the compressive strengths of the sprayed moulds- the small worm pump being best able to spray directly into a cube mould with minimum voids, therefore producing a higher compressive strength.

Tensile Bond Strength

The mortars all possessed a relatively narrow range of bond strengths compared with their compressive strengths and they all comfortably exceeded the Concrete Society minimum recommended bond strength of 0.8 MPa (with the exception of the lightweight mortar). The different types of wet-process pump affected the bond strength, but this was probably due more to the stream velocity and water/cementitious ratio than the actual pumping process. However, more tests would need to be done than presented here to accurately report a trend.

Modulus of Elasticity

The results for the modulus of elasticity, when compared with the compressive strength, show significantly lower values than published formulas of this relationship would suggest, especially at lower strengths.

Drying Shrinkage

The dry sprayed mixes shrank less than the equivalent wet-sprayed or cast mixes, as was expected. The cast and the in-situ prisms exhibited very similar rates of drying shrinkage, suggesting that cast prisms could be used for quality control purposes to measure and monitor in-situ drying shrinkage.

Air Permeability and Sorptivity

The air permeability of most of the mortars is lower than for wet-cured concrete and decreases with an increase in compressive strength, as would be expected. However, sorptivity does not appear to show a clear relationship with the compressive strength.

Reinforcement Encasement

Two methods for assessing the reinforcement encasement were investigated, visual grading and sorptivity measurement. In general, the sorptivity (which was related to the amount of voidage behind the bars) did not increase greatly as the density of reinforcement increased. The sorptivity values in this test also seemed to be influenced by the absorption of the aggregate. Visual grading of the cores on a 1 to 5 system was found to be simple to perform and produced results in line with the sorptivity assessments. The type of pump (with their corresponding differences in output and stream velocity) affected the encasement of the mortars with the higher-velocity piston and large-diameter worm pumps producing better encasement than the small-diameter worm pump.

Restrained Shrinkage

The shrinkage strains of the repair suggest that the shrinkage of a sprayed repair is influenced more by the ambient conditions (mainly temperature and humidity, but also rain, wind and sunlight) than by the composition of the mix itself. The inclusion of mesh within the repair also seems to have little effect on the measured values of shrinkage taken from the face of the repair.

7 Acknowledgements

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8 References

1 AUSTIN,S.A., ROBINS, P.J.R. AND GOODIER, C.I. The Rheological Performance of Wet-process Sprayed Mortars. Submitted to *Magazine of Concrete Research, 1999.*

2 AUSTIN, S.A., ‘Repair with sprayed concrete’, *Concrete,* Vol. 31, No 1, January 1997, pp. 18-26.

3 MANGAT, P.S., LIMBACHIYA, M.K., Repair Material Properties which Influence Long-Term Performance of Concrete Structures. *Construction and Building Materials*, 1994, Vol. 9, No.2, pp. 81-90.

4 EMBERSON, M.K. AND MAYS, G.C. Significance of property mismatch in the patch repair of structural concrete, Part 1, Properties of repair system. *Magazine of Concrete Research*, 1990, 42(152), pp. 147-160.

5 AUSTIN, S.A., ROBINS, P.J.R. (eds.). *Sprayed Concrete: properties, design and installation,* Whittles Publishing, Latheronwheel, UK (ISBN 1-870325-01-X) and McGraw Hill, USA (ISBN 0-07-057148-1), 1995, 382 pp.

6 AUSTIN, S.A., ‘Concrete repair with sprayed concrete; methods and quality issues’, *Procs. of Int. Conf. on Deterioration of Reinforced Concrete in the Gulf and Methods of Repair,* Muscat, Oman, December 1996, pp. 165-185.

7 HILLS, D.L., Site-produced sprayed concrete, *Concrete,* 1982, 16(12). pp. 44-50.

8 BANTHIA, N., BINDIGANAVILE, V., CHAN, C. Shotcrete: Is it just another Concrete? *Procs. Int. Conf. on Infrastructure Regeneration and Rehabilitation*, University of Sheffield, UK, June 28th, 1999.

9 GORDON, K., Wet-spraying of pre-packaged mortars for concrete repair, *Proc. of European seminar and workshop on sprayed concrete,* Loughborough University, Loughborough, UK, 3 Oct. 1991, pp.9.

10 MANGAT, P.S. AND O'FLAHERTY, F.J., Long Term Performance of Sprayed Concrete Repair in Highway Structures, *Sprayed Concrete Technology,* E&FN Spon (ISBN 0-419-22270-7), London, 1996.

11 MAYS, G.C. AND BARNES, R.A, Sprayed Concrete Repairs - Their Structural Effectiveness, *Sprayed Concrete Technology,* E&FN Spon (ISBN 0-419-22270-7), London, 1996.

12 PEASTON, C.H., CHOO, B.S. AND GONG, N.G., Sprayed Concrete for the Strengthening of Masonry Arch Bridges, *Sprayed Concrete Technology*, E&FN Spon (ISBN 0-419-22270-7), London, 1996.

13 MALMBERG, B., Quality and Quality Variations of Wet and Dry Mix Shotcrete - Experiences from Grodinge Railway Track Project, *Shotcrete for Underground Support VII*, Proc. of the Engineering Foundation Conf., Telfs, Austria, June 11-15, 1995, pp.251-258.

14 BRITISH STANDARDS INSTITUTION. *Specification for Portland cements*. BS12:1996, British Standards Institution, London.

15 PUTZMEISTER LTD., Carrwood Road, Chesterfield Trading Estate, Sheepbridge, Chesterfield, Derbyshire, S419QB.

16 AUSTIN,S.A., ROBINS, P.J.R. AND GOODIER, C.I. The Pumping and Spraying of Fine Aggregate Concretes (paper in preparation).

17 BRITISH STANDARDS INSTITUTION. *Testing Concrete: Method for Determination of the Compressive Strength of Concrete Cubes*. BS1881: Part116: 1983, British Standards Institution, London.

18 BRITISH STANDARDS INSTITUTION. *Testing Concrete: Method for Determination of Flexural Strength*. BS1881: Part118: 1983, British Standards Institution, London.

19 AUSTIN,S.A., ROBINS, P.J.R. AND PAN, Y., Tensile Bond Testing of Concrete Repairs, Materials and Structures, 28, 1995, pp.249-259.

20 BRITISH STANDARDS INSTITUTION. *Method of Determination of Static Modulus of Elasticity in Compression*. BS1881: Part121: 1983, British Standards Institution, London.

21 JONES, P.A., Flexural Modelling of Steel Fibre Reinforced Sprayed Concrete, *PhD Thesis*, Loughborough University, August 1998, pp.145-155.

22 BRITISH STANDARDS INSTITUTION. *Determination of Changes in Length on Drying and Wetting (Initial Drying Shrinkage, Drying Shrinkage and Wetting Expansion)*. BS1881: Part5: 1970, British Standards Institution, London.

23 LOVELOCK, P.E.R., Laboratory Measurement of Soil and Rock Permeability, Institute of Geological Science, London, 1970.

24 HUDD, R.W., Measurement of Concrete Permeability, *PhD Thesis*, Loughborough University, 1989.

25 RILEM Technical Committee 14-CPC, Tentative Recommendations No 11.2, *'Absorption of Water by Capillary'*, Mater. Struct., Vol.7, No 40, 1974, pp.295-297.

26 DUNLOP, A.J., Gunform International Ltd, 33 Carsthorne Rd, Carr Lane Industrial Estate, Hoylake, Wirral, Merseyside, L47 4FB.

27 ROXBRUGH, G., Balvac Whitley Moran, Birchwood Way, Somercotes, Alfreton, Derbyshire, DE55 4QQ.

28 CODE OF GOOD PRACTICE. *Sprayed Concrete Association.*

29 BANTHIA, N., TROTTIER, J.F., BEAUPRE, D., Steel-Fiber-Reinforced Wet-Mix Shotcrete: Comparisons with Cast Concrete, *Journal of Materials in Civil Engineering*, Vol. 6, No3, August 1994.

30 NEVILLE, A.M., *Properties of Concrete*, 4rd edition, Longman, London, UK, 1995, p.270.

31 ACI 363R-92, State-of-the-art report on high-strength concrete, *ACI Manual of Concrete Practice Part 1: Materials and General Properties of Concrete*, 55pp., Detroit, Michigan, 1994.

32 AL-KINDY, A. , Macro and microclimate effects on cover zone properties of field cured concrete, *PhD thesis*, Loughborough University, December 1998, p.306.

33 GEBLER, S.H., Construction practice and quality control, *Sprayed Concrete: Properties, Design and Application* (Eds. Austin, S.A. and Robins, P.J.), Whittles Publishing, Latheronwheel, UK, 1995, pp.204-228.

34 CROM, T., *Dry mix shotcrete nozzleing,* The Crom Corporation, Gainsville, Florida, 40pp.

Table 1 Composition of pre-packaged mortars.

Mix	Pump	W/c ratio	Agg/c ratio	Polymer Modified	Poly. Fibres	Shrinkage Comp.	Filler	Description
P1w	Worm	0.59	2.3	N	N	Some	N	Basic repair
P1d	Dry Spray	-	2.3	N	N	Some	N	mortar
P1p	Piston	-	2.3	N	N	Some	N	
P2w	Worm	0.41	1.45	Y	Y	Y	Y	High build
P2p	Piston	-	1.45	Y	Y	Y	Y	Repair mortar
P2W	L.Worm	-	1.45	Y	Y	Y	Y	
P3w	Worm	-	1.58	Y	Y	Y	Y	2-part re-profiling
P4w	Worm	0.47	2.31	Y	Y	N	Y	Basic repair mortar
P5w	Worm	0.39	1.33	Y	Y	N	Y	Repair mortar
P5d	Dry Spray	-	1.33	Y	Y	N	Y	
P6w	Worm	0.45	1.62	Y	Y	Y	N	Repair mortar
P7w	Worm	0.90	3.42	Y	Y	Y	Y	Lightweight mortar
P8d	Dry Spray	-	-	Y	N	N	-	Dry Spray
D1w	Worm	0.38	2.86	Y	N	N	N	Lab. Designed
D1p	Piston	0.39	2.86	Y	N	N	N	Mortar

Table 2 Mortar density

(kg/m^3)	P1w	P1d	P1p	P2w	P2p	P2W	P3w	P4w
Cast Cube	1815			1851	1850	1920	2077	1924
In situ Cube	1973	2115	1843	1886	1993	1950	2092	1984
Sprayed Mould	1987	2044	1800	1887	1924		2071	1959

	P5w	P5d	P6w	P7w	P8d	D1w	D1p
Cast Cube	1400		1662	1278		2088	
In-situ Cube	1654	1895	1783	1433	2220	2096	2230
Sprayed Mould	1660		1792			2118	2193

Table 3 28 day flexural strength

(N/mm^2)	P1w	P2w	P2p	P3w	P4w	P5w	P6w	P7w	D1w	D1p
Cast Beam	4.8	5.9	6.5	7.2	5.1	4.6		3.4	6.7	
In-situ Beam	6.2	6.2	7.9	8.8	5.5	6.4	6.2	5.3	8.0	7.3
Sprayed Mould	6.0	7.7	7.1	8.4	4.7	5.9	7.0	4.7	6.1	5.6

Table 4 Air permeability and sorptivity

	Air Permeability ($x10^{17}m^2$)			Sorptivity ($mm/min^{0.5}$)					
Mortar	Cast	In-situ	Mould	Cast		In-situ		Mould	
				Top	Bot.	Top	Bot.	Top	Bot.
P1p						0.040	0.034		
P1d						0.033	0.027		
P2p						0.027	0.017		
P3	4.9	2.7	4.1	0.013	0.014	0.011	0.010	0.017	0.015
P4	4.6	3.0	2.7	0.023	0.022	0.018	0.019	0.017	0.020
P5d		0.57				0.013	0.011		
P6		6.1	5.2			0.025	0.025	0.018	0.022
P7	5.8	4.4	3.7	0.016	0.019	0.016	0.017	0.013	0.015
P8d		0.49				0.028	0.028		
D1	0.5	0.5	0.4	0.036	0.040	0.042	0.041	0.030	0.031
D1p		1.78				0.033	0.023		

Table 5 Dry spray results

Mortar	Cube Strength (Mpa.)	Density (kg/m^2)	Flexural Strength (N/mm^2)	Bond Strength (Mpa.)	Modulus of Elasticity (kN/mm^2)	Sorptivity (mm/ $min^{0.5}$)	28 Day Shrinkage microstrain
P1cast	35.8	1815	4.8	-	21.4	-	-
P1worm	38.8	1973	6.2	1.85	23.5	-	663*
P1 piston	33.6	1843	5.4	1.4	-	0.037	828
P1dry	53.0	2115	7.3	2.80	24.7	0.030	643
P5cast	40.0	1400	4.6	-	-		1531
P5worm	45.7	1654	6.4	2.00	-		1367
P5dry	58.1	1895	9.1	2.76	25.9	0.012	840
P8dry	71.0	2220	9.2	-	36.6	0.028	742*

Note: * denotes first shrinkage sample reading taken 2 days after spraying

Table 6 Restrained shrinkage values

Mix	Substrate strain	Calculated free shrinkage	Repair surface shrinkage	Prisms free shrinkage
P1p	260	602	623	1771
P1d	337	788	710	1310

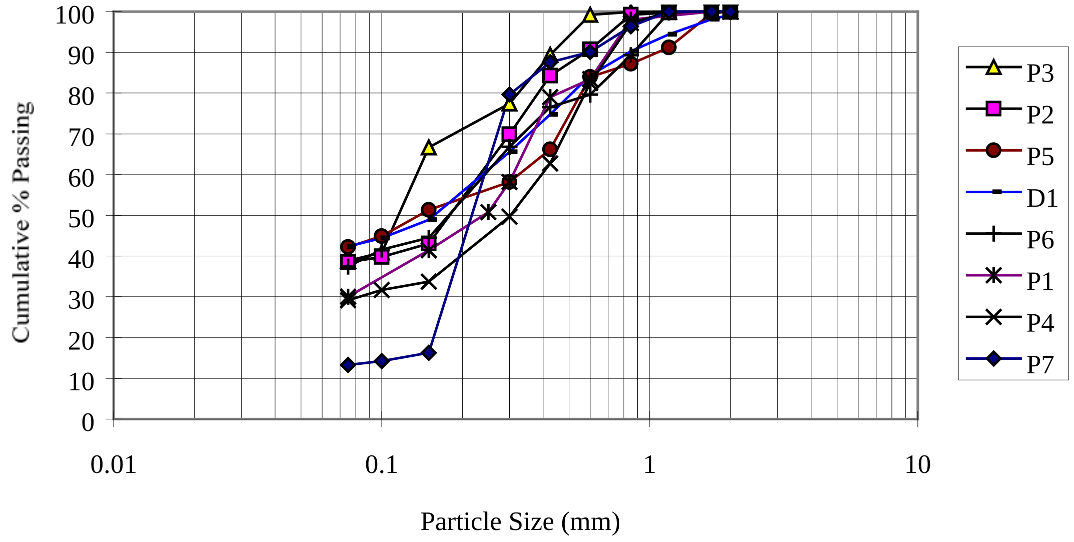


Figure 1. Combined gradings of pre-blended and designed mortars

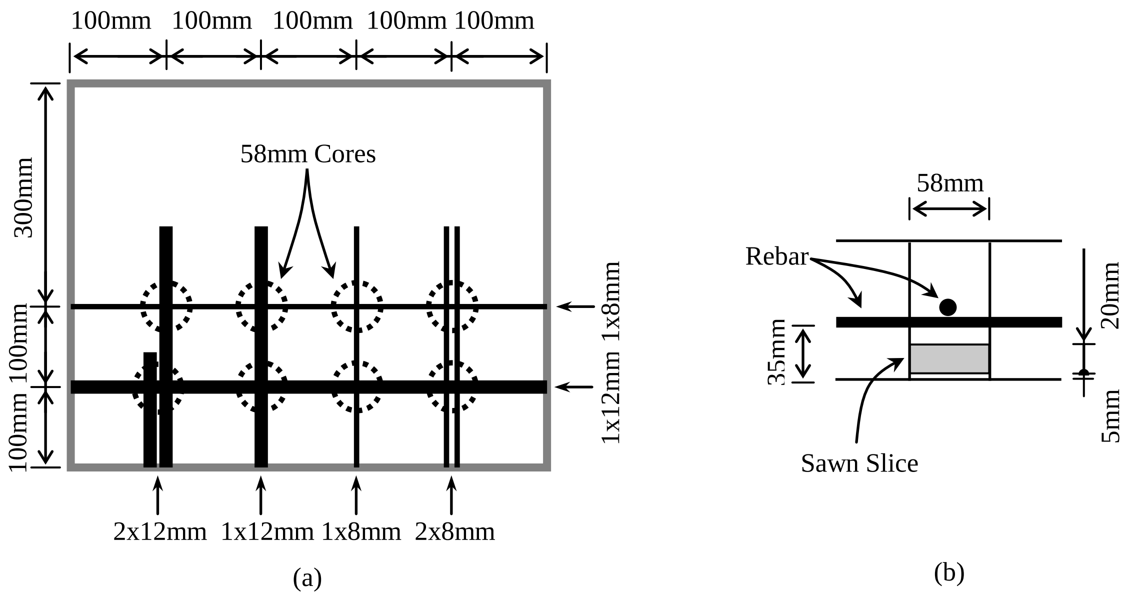


Figure 2. Reinforcement encasement test (a) plan view (b) core side view.

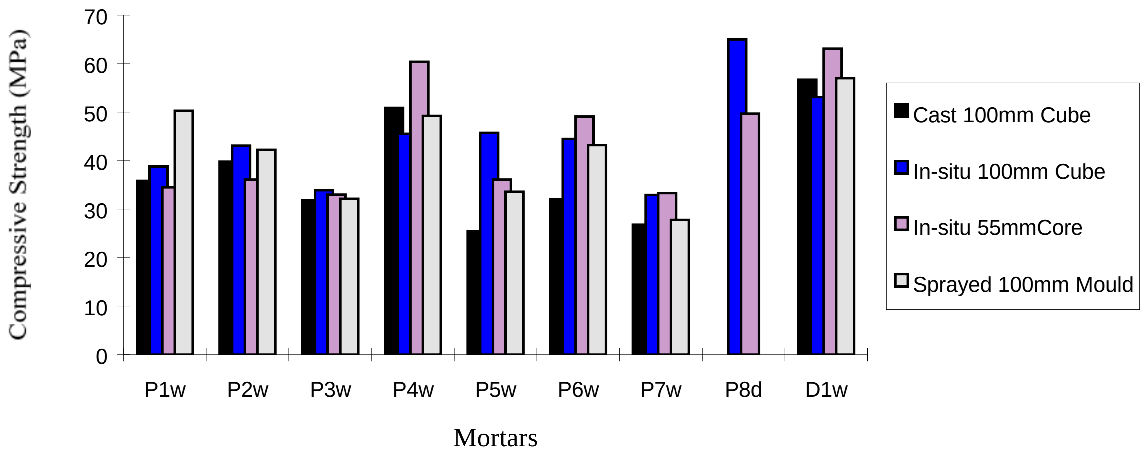


Figure 3. Compressive strengths of mortars

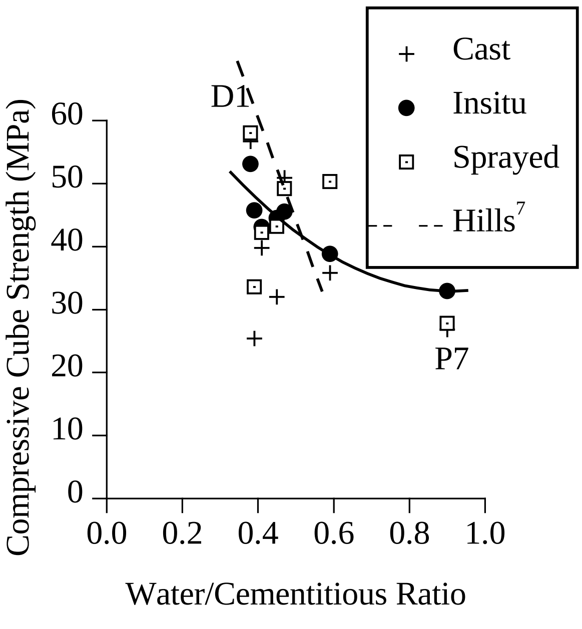


Figure 4. Compressive cube strength Vs. Water/cementitious ratio

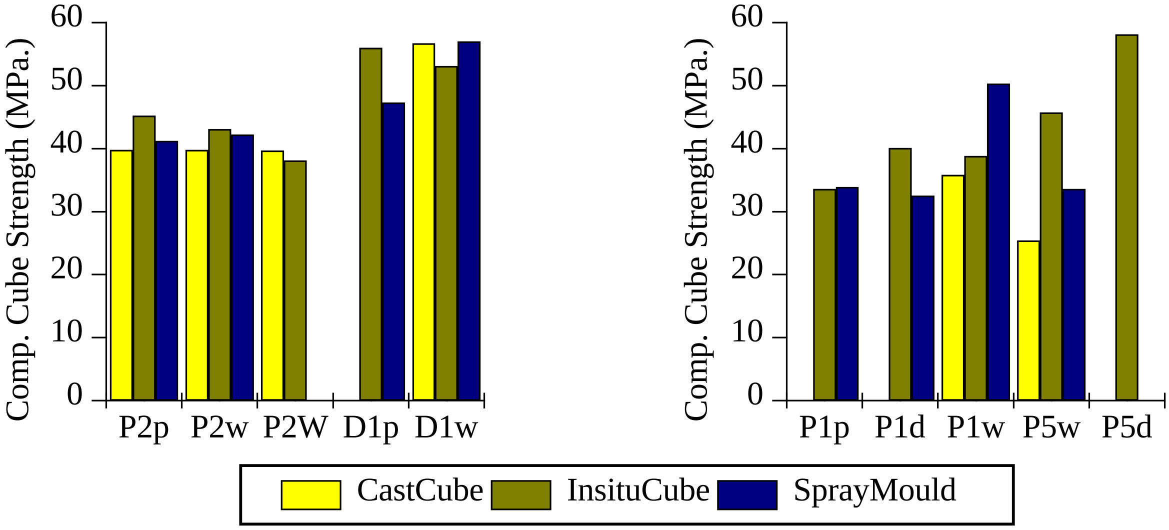


Figure 5. Compressive Cube Strengths: Different Pump Types

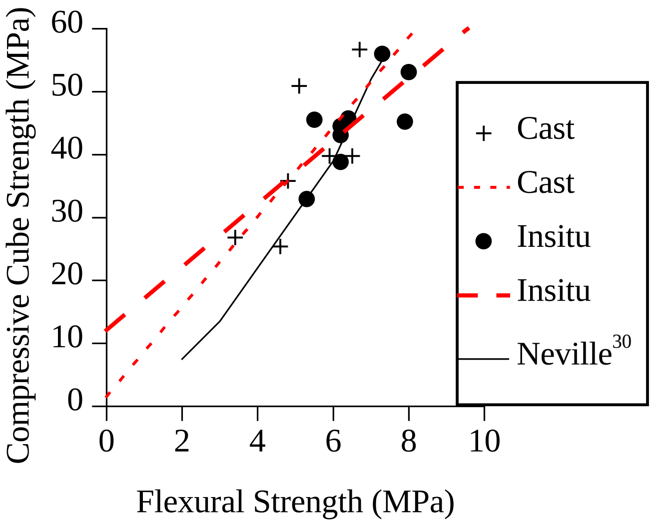
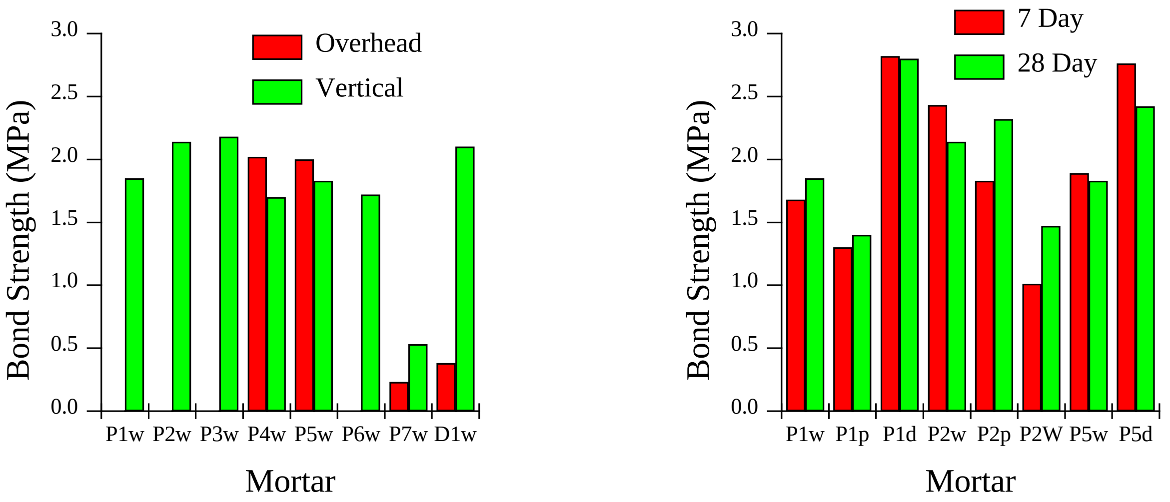


Figure 6. Compressive cube strength vs Flexural strength



(a) (b)

Figure 7. Bond Strength (a)Overhead and Vertical at 28 days(b)Different Pumps at 7 and 28 Day

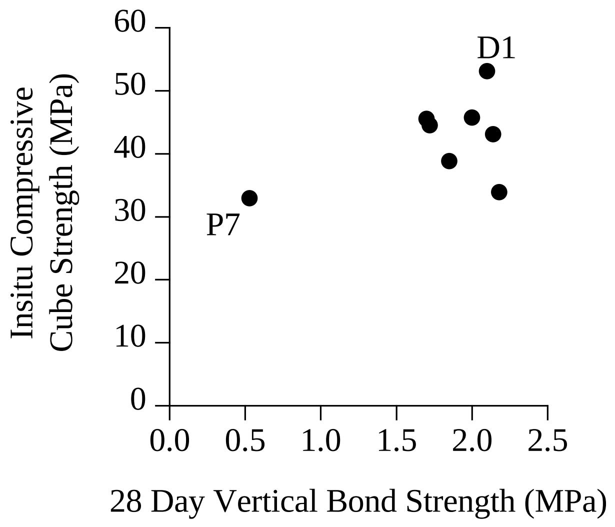


Figure 8. In-situ compressive cube strength Vs. Vertical bond strength

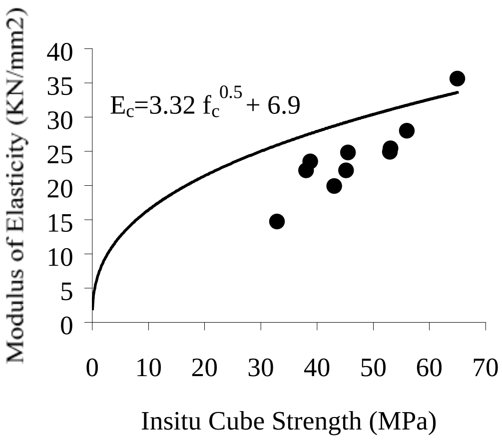


Figure 9. Modulus of elasticity vs insitu cube strength

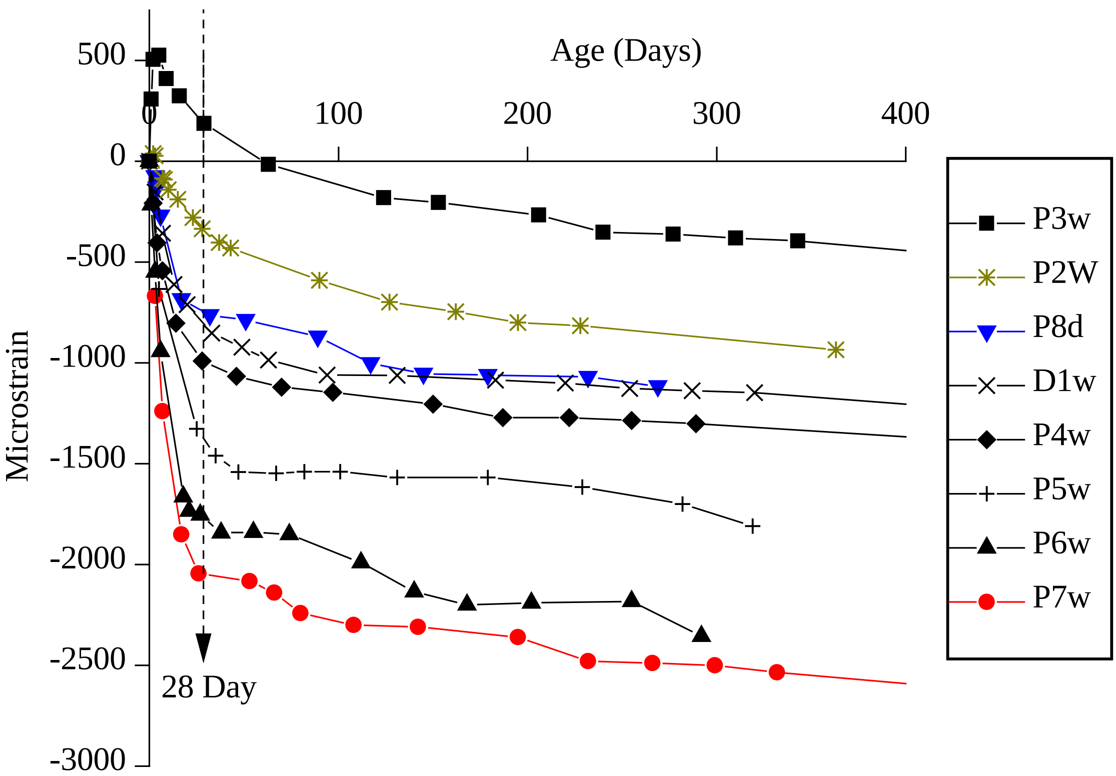


Figure 10. Drying shrinkage of prisms taken from insitu material

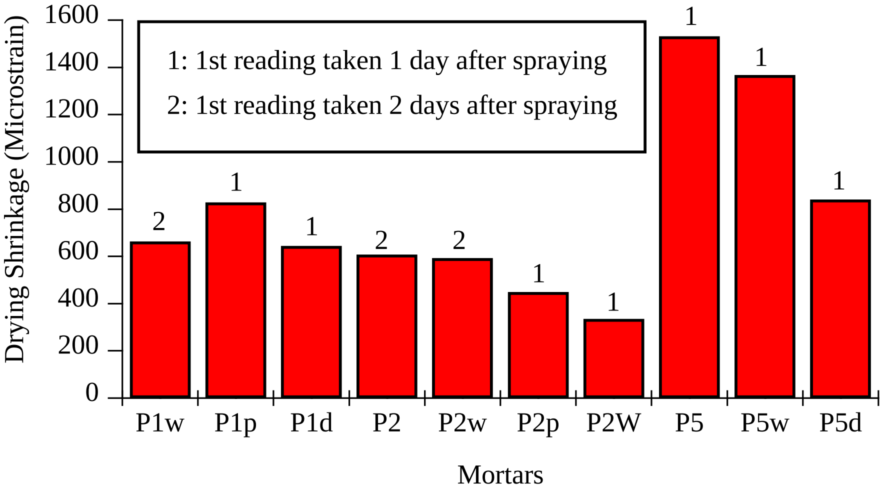


Figure 11. Effect of pump type on 28 Day shrinkage

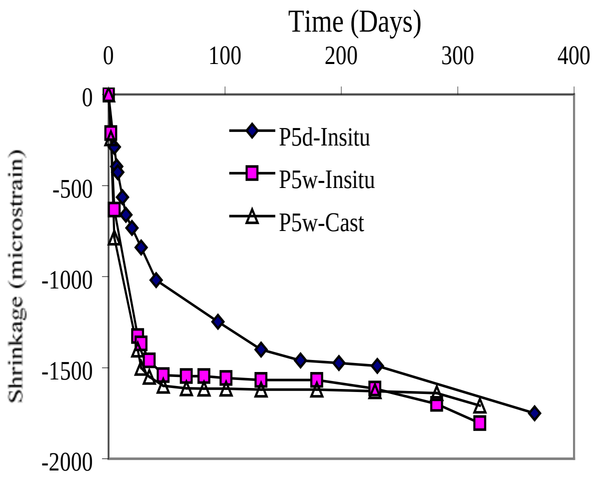


Figure 12. Drying shrinkage of P5w and P5d

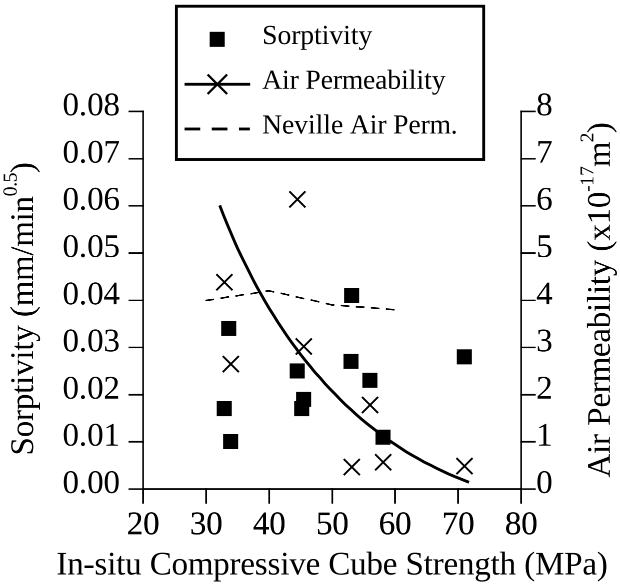


Figure 13. Sorptivity and air permeability Vs. In-situ compressive strength

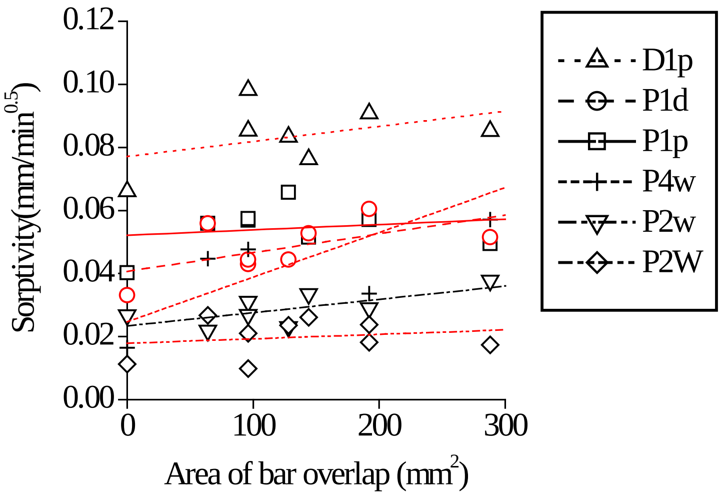


Figure 14. Sorptivity vs area of bar overlap

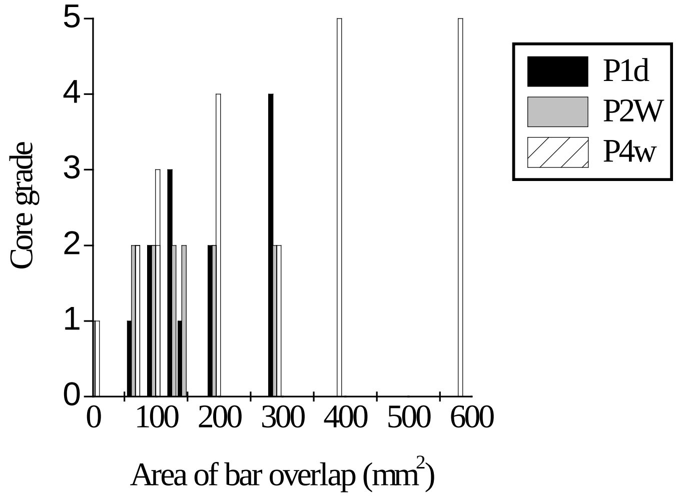


Figure 15. Core grade vs area of bar overlap

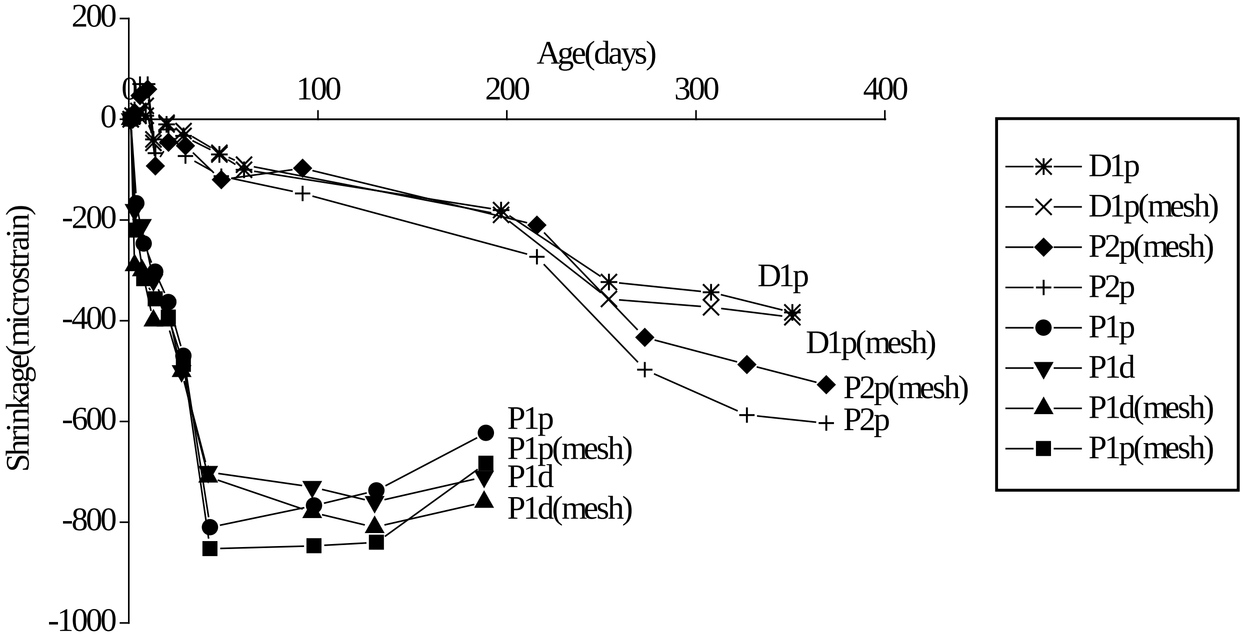


Figure 16. Restrained shrinkage