EPSRC Grant Final Report

Grant Number GR/K52829

Wet Process Sprayed Concrete Technology for Repair

S A Austin and P J Robins

Department of Civil & Building Engineering

Loughborough University

April 1999

Contents

1 Introduction

This research project has proved to be unique in both its focus and scope, and has produced a substantial array of knowledge and performance data for wet process sprayed mortars/concretes for repair. The drivers behind the original proposal were to gain better control of the installation process (and hence performance) and to improve the working environment; these have proved to be highly relevant and increasingly represent current industry thinking, which is recognising the inevitable decline in the acceptability of the alternative dry process.

The project has been very successful in producing, with a variety of pumping and spraying equipment, a wide range of mortars and fine aggregate concretes with performance appropriate to repair applications, both in terms of installation and properties of the hardened material. Results have been disseminated during the project and have culminated in the preparation of a Guidance document for practitioners, to be published by the Concrete Society. The work has also influenced, due to its unique nature, the development of several draft CEN standards for sprayed concrete[1-4].

2 Aims and objectives

The aim of the research programme was to advance the understanding and technology of the wet process, with an emphasis on mortars and small aggregate concretes, to enable it to be specified and used with confidence for repair in the United Kingdom.

The four objectives were:

(i) 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;

(ii) to improve the wet-mix spraying process, in particular operator environment, maximum conveying distances and stop-start flexibility;

(iii) to specify, measure and optimise in-situ properties, particularly strength, bond and durability;

(iv) 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.

3 Methodology

The first activity was to identify a set of 6-8 repair scenarios, and their performance requirements, to cover the range of repair situations commonly encountered in the UK. This was achieved by conducting a survey and interviews with local authorities, consultants, contractors and material suppliers.

The original proposal identified a further five main activities, with iteration between them to balance the investigation of production and of materials performance. As a result of our initial studies, and the advice of our industrial steering group, the project identified three types of repair mortar/concrete that were ripe for development and the activities in the programme was consequently structured to reflect this. The three types were:

- mortars(< 3mm aggregate), pre-blended and bagged by specialist material suppliers
- mortars(< 3mm aggregate), designed and laboratory/site batched
- fine (< 6mm aggregate) concretes, designed and laboratory/site batched

The first two categories can be installed by worm and piston pumps, whereas the fine concretes are restricted to piston pumping. This order was also logical from the point of view of research. The first type was available in the form of materials developed for hand-applied repair, from which we were able to gain experience and performance data (that also served as a benchmark) which could then be the platform for the development of our own designed mixes. We also conducted the majority of the research (and all the initial work) with a small worm pump, purchased by Putzmeister UK for the project, as it was likely that any mix working with such a pump would also be suitable for larger worm and piston pumps. The construction of a dedicated spraying facility (Figure C.1) at the University allowed field trials to be conducted locally, interspersed with appropriate laboratory work. Two-point test apparatus was purchased as requested in the proposal, and this was supplemented by a Viskomat to test the fine mortars, bought from Departmental funds.

Figure C.1 Loughborough spraying facility

As originally envisaged, the work encompassed both relatively scientific tests to gain insights into what makes a material pump and spray, together with basic material property tests to characterise performance. The latter can also be used for quality control and this aspect was given additional emphasis in the project, following the comments made in the grant announcement. The programme also included simpler, more pragmatic tests that were appropriate to quantify important aspects of installation (including build thickness and reinforcement encasement).

A sprayed concrete publications library and database has been created and maintained containing over 800 entries. However, there is still very little quantitative data available on wet process for repair. Exceptions include [5-11] and there are several recent references in professional journals regarding uptake of the technique [12-14].

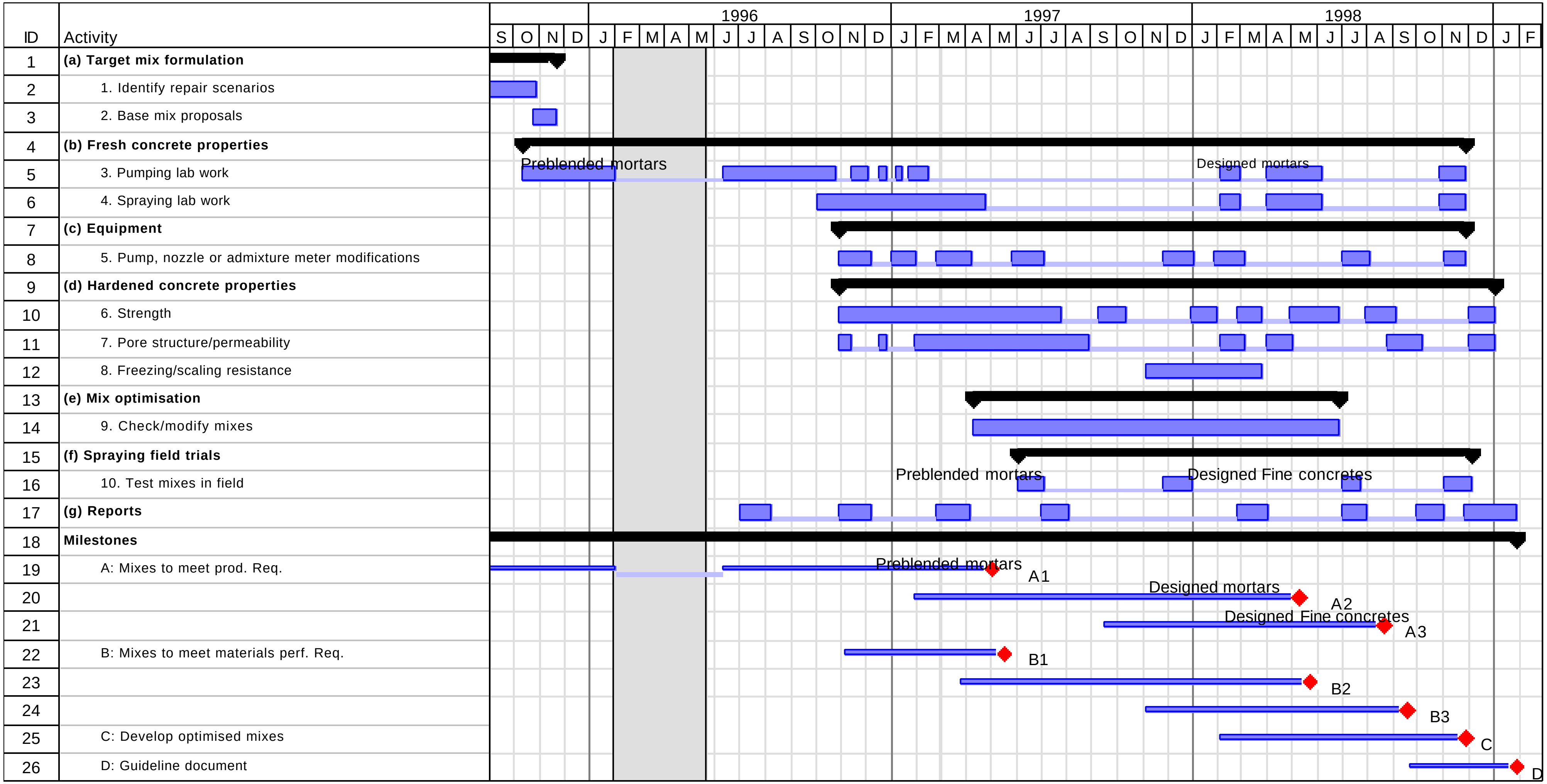
4 Programme

4.1 Research programme

Figure A.1 shows the completed project programme. Whilst there are differences in timings with the original, it can be seen that nearly all the activities envisaged have taken place. The altered timings were a direct result of the selected test methodology described in Section 3, in particular the phasing of the work to cover the three sprayed concrete types. There were some additional investigations, not in the original plan, associated with drying shrinkage (free and restrained) and sample production for routing quality control. The latter involved the production of test specimens by conventional casting (compacted by vibrating table) and direct spraying of samples in steel moulds, in addition to in-situ samples cut from test panels. This allowed these simpler, but potentially unrepresentative specimens, to be evaluated for QC/QA purposes. On a minor note, the testing of freeze-thaw/scaling resistance was omitted from the programme at the suggestion of our collaborators; indeed, our own work on a previous EPSRC project on concrete repair confirmed that freeze-thaw was unlikely to be a problem with these types of mortars (due to their likely low permeability/absorption, which was shown to be the case by our measurements of air permeability and sorptivity).

The 36 month research programme can be seen to have a break of 5 months between January and July 1996. This occurred because of the resignation of the Research Assistant appointed to the project and the subsequent recruitment of his replacement. That the overall project was still completed within the 36 month period without significant curtailment of any activities is a measure of the success of the overall management of the research by the steering group, and of the hard work put in by the replacement RA in getting up to speed quickly with the research.

Figure A.1


ID
Activity
1996
1997
1998
S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1 (a) Target mix formulation
2 1. Identify repair scenarios
3 2. Base mix proposals
4 (b) Fresh concrete properties
5 3. Pumping lab work
6 4. Spraying lab work
7 (c) Equipment
8 5. Pump, nozzle or admixture meter modifications
9 (d) Hardened concrete properties
10 6. Strength
11 7. Pore structure/permeability
12 8. Freezing/scaling resistance
13 (e) Mix optimisation
14 9. Check/modify mixes
15 (f) Spraying field trials
16 10. Test mixes in field
17 (g) Reports
18 Milestones
19 A: Mixes to meet prod. Req.
20
21
22 B: Mixes to meet materials perf. Req.
23
24
25 C: Develop optimised mixes
26 D: Guideline document
Preblended mortars
Designed mortars
Preblended mortars
Designed Fine concretes
Preblended mortars
A1
Designed mortars
A2
Designed Fine concretes
A3
B1
B2
B3
C
D

The scope of the experimental work is evident from Table A.1 which the permutations of variables investigated. This covers the 29 mixes within the three sprayed material categories, the seven pumping/spraying systems, the 19 types of test (carried out during the stages of pumping, spraying and hardened testing) and the three types of specimen production (see above).

4.2 Project management

The project was co-ordinated by a Management Committee consisting of the investigators and representatives from Fosroc, Putzmeister, Gunform, Balvac Whitley Moran and Fibre Technology. The Committee met at 3-4 monthly intervals to receive a formal presentation and report by the Research Assistant, to review the programme (including milestones) and make decisions on the direction of the research. The level of industrial commitment at these meetings was high and went well beyond that envisaged in the application.

5 Industrial Collaboration

The original five supporters of the proposal, Fosroc, Putzmeister, Gunform, Balvac Whitley Moran and Fibre Technology, all participated in the project and assisted in the field trials. Their regular attendance at the steering group meetings proved invaluable, as they gave us insights into the latest industrial developments and thinking, which helped keep the project focused on issues of greatest relevance.

The research was vitally dependent on: the purchase by Putzmeister of a TS3 EVR small worm pump (Figure C.2) for the University (which was used throughout the experimental work); the supply of spraying equipment and personnel by Gunform for field trials; and the supply of materials and expert knowledge by Fosroc. In addition to this pledged support we received substantial assistance from CMS Pozament, Flexcrete Ltd and Ronacrete Ltd, who supplied a range of materials and pre-blended products, and from M-Tec who arranged for us to trial their simple and dual-mixing worm pumps.

Figure C.2 Small worm pump and air compressor

Table A1. Wet Process Sprayed Mortars and Concretes

	Mix type		Preblended Mortars															Designed Mortars												Designed Fine Concretes									
	Mix No.		P1			P2					P3	P4	P5		P6	P7	P8	D1		D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	C1	C1s	C1a	C2	C3	C3a	Cp1	Cp2	C4	C5
	Pump type		p	w	d	p	w	W	w2	w3	w	w	w	d	w	w	d	w	p	p	w	w	w	w	w	w	w	w	w	p	p	p	d	p	p	p	p	p	p
Pumping	Pumped		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	2-Point		•		n/a		•				•	•		n/a	•		n/a	•		•	•	•	•	•	•	•	•		•			•	n/a	•	•			•	•
	Viskomat			•	n/a		•					•		n/a	•	•	n/a	•		•	•			•									n/a						
	Pressure Bleed			•	n/a		•				•	•	•	n/a	•	•	n/a	•		•	•	•	•	•	•	•							n/a						
	Shear Vane		•		n/a	•			•	•				n/a			n/a	•	•	•	•		•	•	•	•	•	•	•			•	n/a	•	•	•	•	•	•
	Slump		•		n/a	•				•			•	n/a			n/a	•		•	•	•	•	•	•	•	•	•	•			•	n/a	•	•	•	•	•	•
	Fresh Density				n/a								•	n/a			n/a	•			•			•			•	•					n/a						
Spraying	Sprayed		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Output						•		•	•			•					•			•	x	•	•	•	x	•	•	x										
	Build thickness		•			•			•	•		•	•		•	•		•	•	•	•	x	•	•	x	x	•	•	x	•	•	•		•	•	•	•	•	•
	Failure stress		•			•			•	•	•	•	•		•			•	•	•	•	x	•	•	x	x	•	•	x	•	•	•		•		•	•		•
	Rebar Enc.		•	•	•	•		•				•							•			x			x	x			x	•	•	•	•	•		•	•	•	
	HS Video		•	•	•	•	•				•					•			•			x				x			x	•	•	•	•						
Hardened performance	Comp. Strength	Ca		•	n/a	•	•	•			•	•	•	n/a	•	•	n/a	•		•	•	•	•	•	•	•	•	•	•	•	•		n/a	•		•		•	•
		In	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•			x				x			x	•	•	•	•	•	•	•	•	•	•
		Sp	•	•	•	•	•		•	•	•	•	•		•	•		•	•	•		x	•	•		x	•	•	x	•	•	•		•	•	•	•		
	Flexural Strength	Ca		•	n/a	•	•				•	•	•	n/a		•	n/a	•													•		n/a	•	•	•		•	•
		In	•	•	•	•	•				•	•	•	•	•	•	•	•	•			x				x			x	•	•	•	•	•	•		•		•
		Sp	•	•		•	•		•	•	•	•	•		•	•		•	•			x				x			x		•	•					•		
	Density	Ca		•	n/a	•	•	•			•	•	•	n/a	•	•	n/a	•		•	•	•	•	•	•	•	•	•	•	•	•		n/a	•		•		•	•
		In	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•			x				x			x	•	•	•	•	•	•	•	•	•	•
		Sp	•	•	•	•	•		•	•	•	•	•		•	•		•	•	•		x	•	•		x	•	•	x	•	•	•		•	•	•	•		
	Bond Str.	In	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•			x				x			x	•	•	•	•	•		•	•	•	•
	Elastic Modulus	Ca		•	n/a		•				•	•		n/a		•	n/a	•															n/a						
		In	•	•	•	•	•	•				•		•		•	•	•	•			x				x			x	•	•	•	•	•	•	•	•		
	Air Perm.	Ca			n/a						•	•		n/a		•	n/a	•															n/a						
		In						•			•	•		•	•	•	•	•	•			x				x			x	•	•								
		Sp									•	•			•	•		•				x				x			x										
	Sorptivity	Ca			n/a						•	•		n/a		•	n/a	•															n/a						
		In	•	•	•	•		•			•	•		•	•	•	•	•				x				x			x	•	•	•	•	•	•	•	•	•	
		Sp									•	•			•	•		•				x				x			x										
	Drying Shrinkage	Ca					•				•	•	•	n/a	•	•	n/a	•												•	•		n/a	•		•		•	
		In	•	•	•	•	•	•			•	•	•	•	•	•	•	•	•			x				x			x	•	•	•	•	•	•	•	•	•	•
	Rest. Shr.	In	•	•	•	•													•			x				x			x	•	•	•	•	•		•	•	•	

Specimen		Test Status		Pump Type			
Ca	Cast	•	Test completed	p	piston	W	worm (large)
In	In-situ	n/a	Not applicable	w	worm (small)	w2	worm (No2)
Sp	Sprayed mould	x	Not possible	d	dry	w2	worm (No3)

6 Achievements

This section describes the main findings of the research, under six headings. The following section shows how these have contributed to the project meeting its objectives and disseminating the findings.

6.1 Repair Scenarios

Table B.1 contains the repair scenarios generally encountered in the UK, classified in terms of characteristics common to various repair applications, including; purpose; orientation; geometry; reinforcement; substrate; surface finish; construction method and environment [15]. Four main categories of structure require repair, namely R.C. bridges, buildings and tunnels, and masonry structures. The majority of repairs at present are to motorway bridges, with repairs to high rise buildings being the next most common.

The main causes of deterioration of concrete leading to repair are the corrosion of steel reinforcement due to the ingress of chlorides and carbonation, alkali aggregate reaction and the effects of heat following fires. Typical repairs are normally below 2m^2 in size with a depth of 50 to 100 mm. At present most bridge repairs are carried out using flowable concretes, with repairs to high rise buildings mainly carried out by applying hand packing concrete. A smaller proportion of each are carried out with dry sprayed concrete, particularly when the size of repair is above 1m^2

It was found that most repairs are carried out with proprietary pre-blended materials/products from manufacturers. These are used because they are perceived to be of a higher quality than site batching (in terms of the quality assurance of the ingredients) or ready mixed concrete. Contractors and local authorities carry out few, if any, quality control tests on these pre-blended materials, considering it unnecessary and too costly. From the survey it was found that the orientation was divided equally between overhead and vertical applications. However, access to the repair sites can often be difficult, with the space and time allowed to carry out the repair being limited.

It has become clear from the research that the majority of the mixes that were sprayable would be suitable in most of the repair scenarios. More explicit recommendations are made in section 7.

6.2 Rheological behaviour

A rheological audit has been developed (Figure B.1) and tests for each stage within this audit have been used to characterise the pumpability and sprayability of each mix.

	Stage in pumping/spraying process				
	Mixer	**Pump**	**Hose**	**Stream**	**In-situ**
Shear rate	High	Low-medium	Zero (Plug flow)	Zero	Zero
Pressure	Atmospheric	Atmospheric	High (10bar) - Reducing to zero	Atmospheric	Atmospheric
Possible rheological tests	Tattersall two-point		Pressure bleed		Build
	Viskomat viscometer				
	Slump				
	Shear Vane				

Figure B.1 Rheological audit.

The Two-point test apparatus produced useful results with both mortars and fine concretes with low workabilities, although care needs to be taken in conducting the test and interpreting results. Both the grading of the constituents and the presence of polymers had a significant effect on the flow resistance and torque viscosity (Figures B.2 and B.3). A procedure was developed for the Viskomat apparatus, but the results from the pre-blended mortars (e.g. Figure B.4) were less conclusive, particularly the viscosity, due to their low workability and the tendency of some mixes to entrain air or trap polypropylene fibres around the measuring paddle. The effects of mix proportions on pumpability are described in section 6.4.

Table B.1 Repair Scenarios for investigation using wet process sprayed concrete technology.

TYPE OF REPAIR	PURPOSE	GEOMETRY			SUBSTRATE			ENVIRON.	ORIEN.	REINF.	SURFACE FINISH	ACCESS
DESCRIPT.		SIZE	DEPTH	TOL.	PREPARATION	TYPE	SURFACE CHAR.					
bridge soffit	1 cover 2 structural	<2m^3	50-100mm	+/- 10mm	hydrodemolition + grit blasting	concrete	AAR Carbonation Chlorides	atmos.	overhead	mesh fibre	troweled finish, no colour match	limited to night restricted space available.
bridge abutment (marine structures)	1 cover 2 structural	<2m^3	50-100mm	+/- 10mm	hydrodemolition + grit blasting	concrete	AAR Carbonation Chlorides	atmos.	vertical	mesh fibre	troweled finish, no colour match	limited to night restricted space available.
building (water retaining structures + r.c. chimneys)	1 cover 2 structural	<2m^3	50-100mm	+/- 10mm	mechanical hydrodemolition + grit blasting	concrete	carbonation (chlorides in car parks)	atmos.	60:40 vertical: overhead	mesh	troweled, colour match (where no surface coating provided)	external repairs use scaffold, platforms etc.
Fire-damaged structure	structural	<2m^3	50-100mm	+/- 3mm visible +/- 10mm covered	hydrodemolition + grit blasting	concrete	fire-damage	atmos. (substrate absorbs H_2O at high rate)	50:50 overhead: vertical	mesh (replace damaged steel)	troweled where visible, otherwise as shot, no colour match	ok
tunnels	structural	<1m^3	100mm	+/- 10mm	hydrodemolition + grit blasting	concrete	carbonation chlorides	cool (ventilatio n fans) can be damp	overhead	mesh, corroded steel replaced	as shot, no colour match	restricted access to road and rail tunnels, pumping long distances
sewer (masonry tunnels + arch bridges)	strengthenin g	1m^3+	25-50mm (less than 100mm)	+/- 10mm	grit blasting	masonry	deteriorated masonry	warm & damp	curved surface	mesh used (stainless steel)	as shot, no colour match	restricted access through man holes, pumping long distances

NA Not Applicable

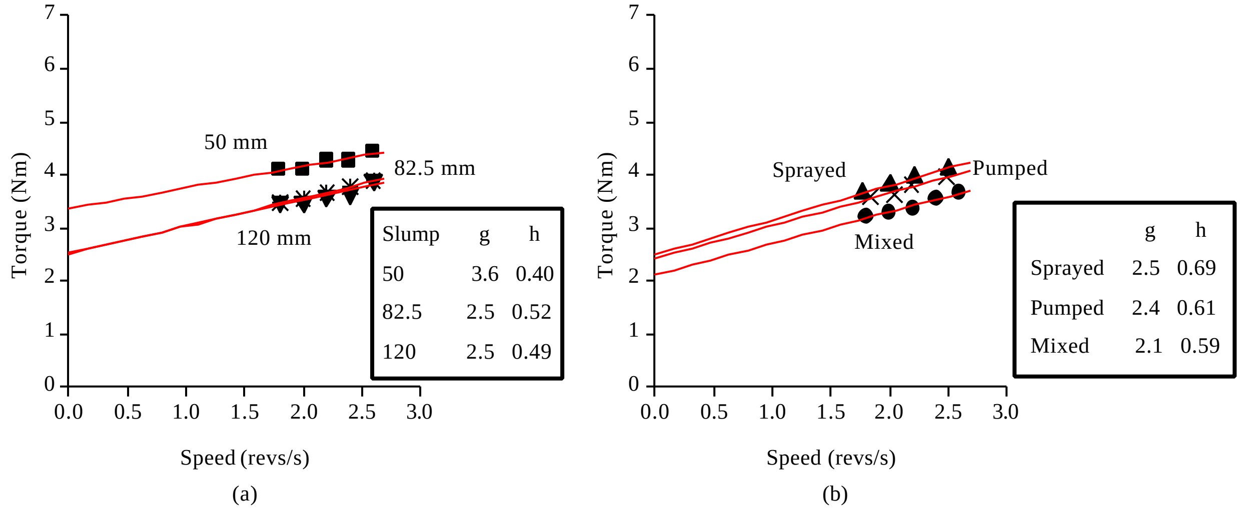


Figure B.2 Two-point test. (a) Effect of slump on mix D1. (b) Effect of mix P2 being mixed, pumped and sprayed

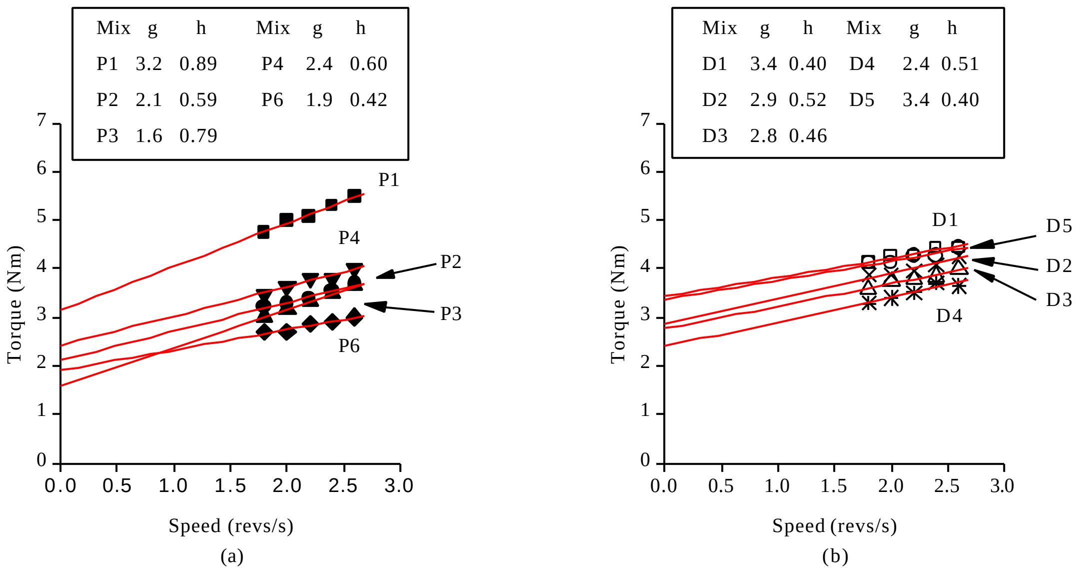
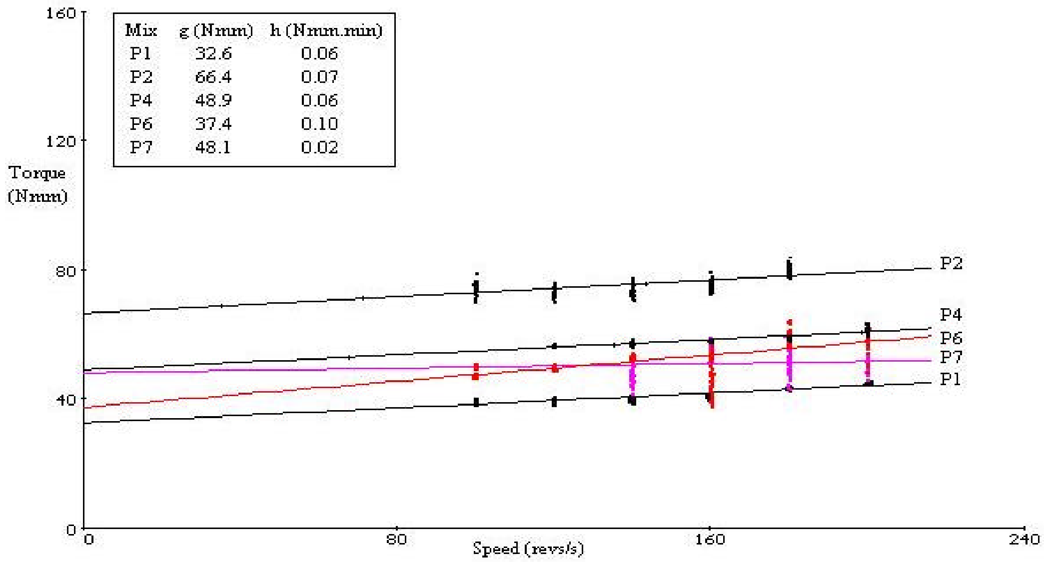


Figure B.3 Two-point test. (a) Pre-packaged mortars. (b) Designed mixes



The pressure bleed test showed that the presence of an SBR significantly influences both the rate and total emission of liquid from the mix under pressure (Figure B.5). The proportion of fine material and the water content of the mix were also crucial factors in the amount and rate of liquid emitted. A shear vane test has been developed which gives an instantaneous measurement of the shear strength of the mortar wherever this property needs to be assessed and has a good correlation with slump (Figure B.6).

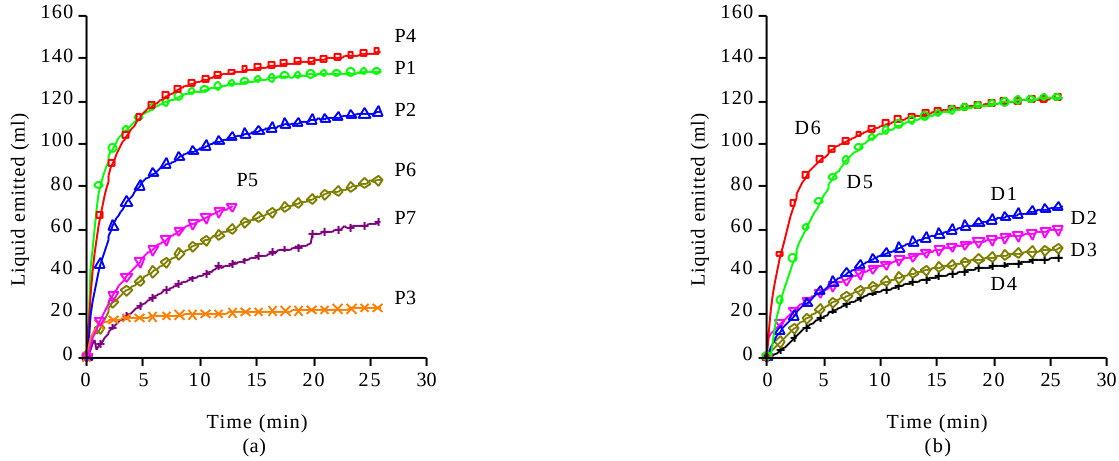


Figure B.5 Pressure Bleed Test. (a) Pre-Packaged Mixes, (b) Designed Mixes

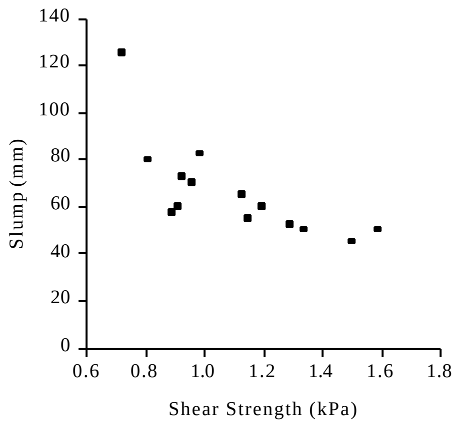


Figure B.6 Vane shear strength vs slump

A new method that defines the build in terms of the maximum shear and tensile bending stresses generated at failure has been outlined which enables a more detailed and scientific analysis of the sprayability of the mortar to be made and a relationship between these stresses, the slump and the vane shear stress of the mortars has been found (Figures B.7 and B.8).

High-speed video(Kodak Ektapro EM and HS systems) was obtained using EPSRC central pool equipment running at up to 4,500 fps. The latter determined the spray stream velocity to be 9-11 and 20-25 m/s with the small worm and piston pumps. Frame-by-frame inspection revealed the stream to consist of varying sizes of flocs of material that adhere to the surface. Some materials had a considerably slower outer stream of flocs, that still impacted the surface. With the worm pump the small amount of waste (< 5%) was due mainly to accretion of material at the nozzle that regularly became dislodged, rather than rebound (Figure C.3); investigation of four nozzle types has shown that this may be minimised (and the stream made more uniform) by changing the design of the nozzle orifice.

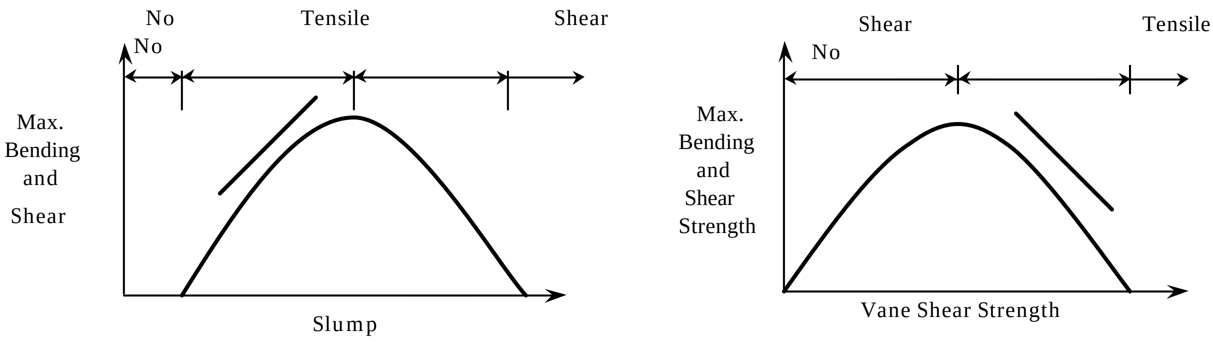


Figure B.7 and B.8 Max bending and shear strength vs slump and vane shear strength

Figure C.3 High-speed photograph of nozzle and mortar stream

6.3 Performance of hardened material

Specimens were produced by: sawing from sprayed timber test panels (termed in-situ); forming by spraying directly into steel moulds; and forming by vibrating-table casting in steel moulds.

Compressive and Flexural Strength

The in-situ compressive cube strengths were higher than their cast equivalents, for both the pre-blended and laboratory designed mixes, due to the greater compaction of the spraying process (Figure B.9). The densities of the mortars also followed this same trend (Table B.2). Their was a good correlation between in-situ and sprayed mould compressive cube strengths, providing that no large voids or excessive rebound was present.

The relatively simple laboratory designed mortars possessed compressive and flexural strengths comparable with the best of the commercially available pre-blended mortars. For example, the in-situ cube strength for the designed mix was 53 MPa, which compared with the range of 33–46 MPa for the pre-blended materials (when worm pumped).

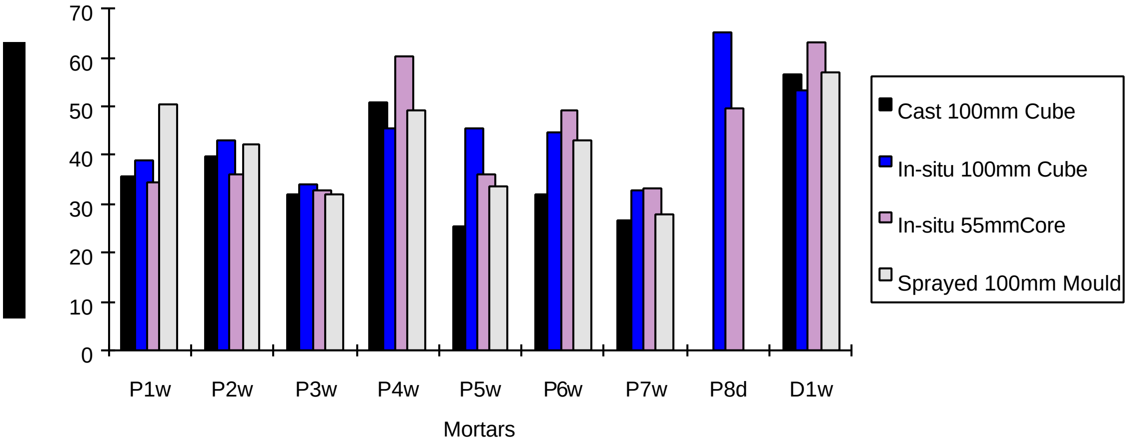


Figure B.9 Compressive strengths of mortars

(kg/m³)	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 B.2 Mortar density

As expected, dry spraying produced higher compressive, flexural and bond strengths than either worm or piston pumping. The different types of wet-process pumps (small and large diameter worms and piston pump) seemed to have little effect on the in-situ compressive and flexural strengths of the mortars (Figure B.10). However, the output of the pump and the size and design of the nozzle did influence the compressive strengths of the cube specimens sprayed directly into the moulds- the small worm pump (with the lowest output) achieving the best compaction with this technique.

Tensile Bond Strength

The mortars possessed a relatively narrow range of bond strengths (1.7-2.3 MPa) despite having a much broader range of compressive strengths (25-57 MPa), but all comfortably exceeded the Concrete Society minimum recommended bond strength of 0.8 MPa (with the exception of the lightweight mortar), see Figure B.11(a). The dry sprayed mortars, as was expected, had higher bond strengths than when wet sprayed. The type of wet-process pump affected the bond strength, but this was probably due more to the stream velocity and w/c ratio than the pumping process (Figure B.11(b)).

Shrinkage

The cast and the in-situ prisms exhibited very similar rates of drying shrinkage (within 200 µm maximum of each other after 1 year, usually less), suggesting that cast prisms could be used for Quality Control purposes to measure and monitor in-situ drying shrinkage (Figure B.12). As expected, dry sprayed mixes shrank less (typically 700 µm at 28 days and 150 µm after 1 year) than the equivalent wet-sprayed or cast mixes due to their lower water contents.

Restrained shrinkage specimens of the mortars and fine concretes, both with and without mesh reinforcement, were kept on site under ambient conditions. 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.

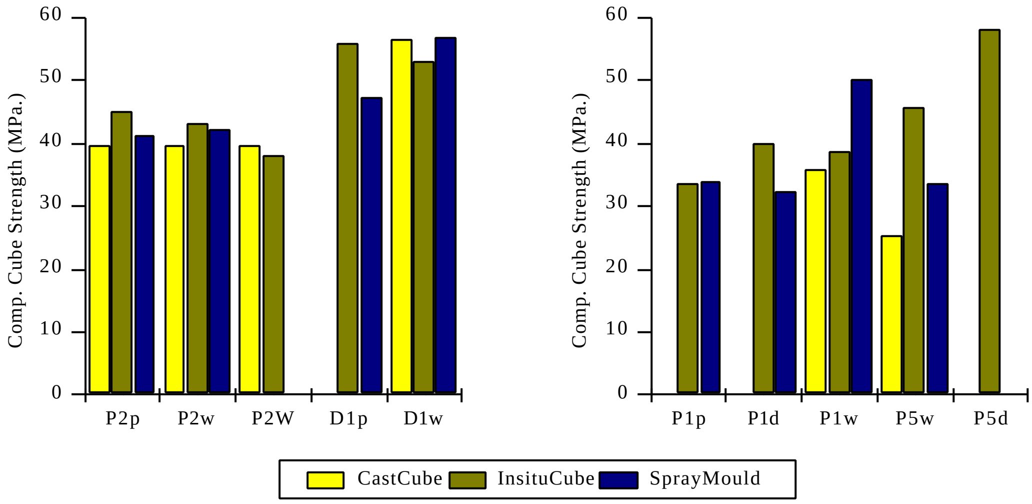


Figure B.10 Compressive Cube Strengths: Different Pump Types

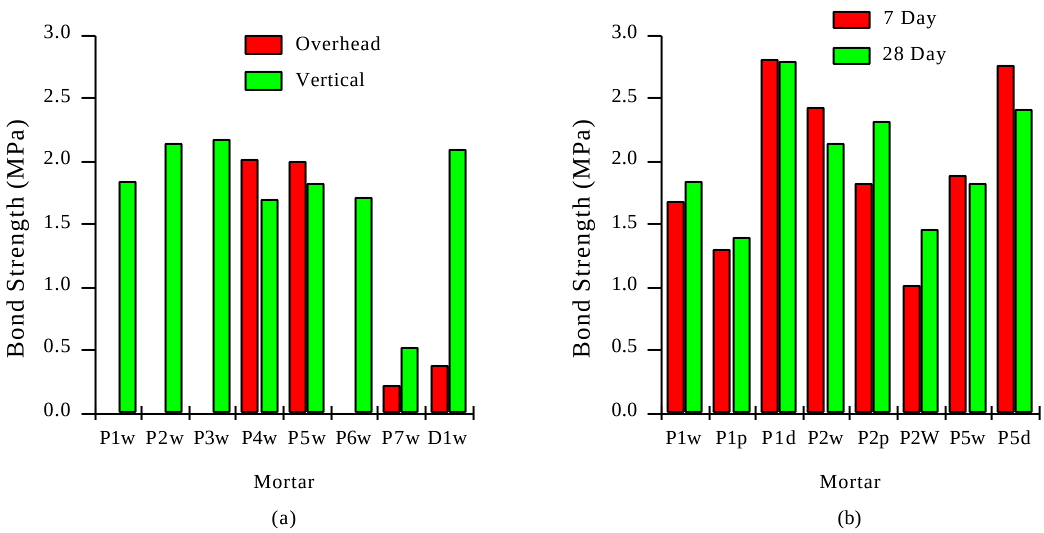


Figure B.11 Bond Strength (a) Overhead and Vertical at 28 days(b) Different Pumps at 7 and 28 Day

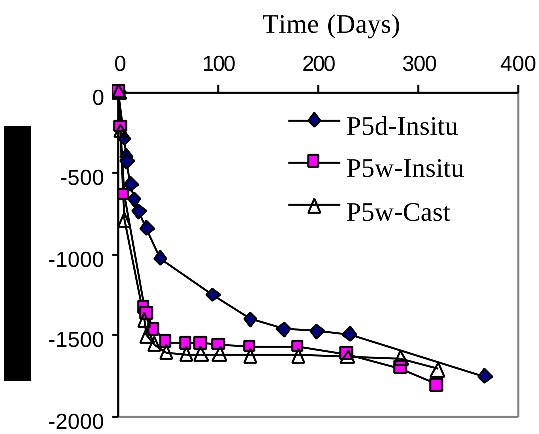


Figure B.12 Drying shrinkage of P5w and P5d

Reinforcement Encasement

A test was devised to measure the degree of encasement (Figure C.4) where the density of reinforcement was related to the sorptivity of the mortar behind the reinforcing bars. In general, the sorptivity did not increase greatly as the density of reinforcement increased (Figure B.13). The type of pump (with their corresponding differences in stream velocities) affected the encasement with the higher-velocity piston and large-diameter worm pumps producing better encasement than the small-diameter worm pump.

(a) (b)

Figure C.4 Test for reinforcement encasement (a) 58mm cores (b) reinforced panel

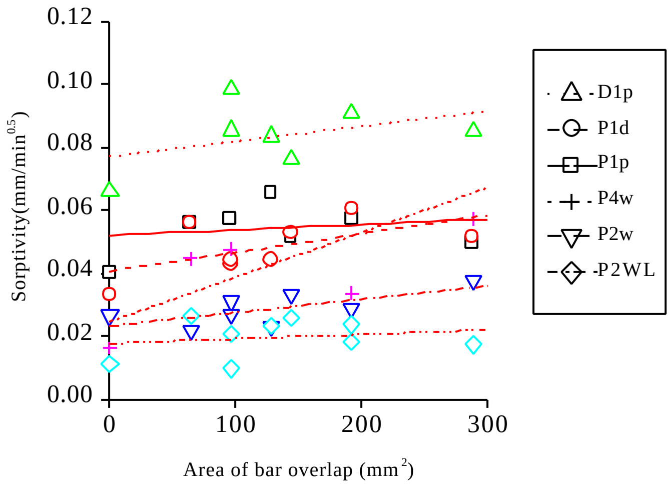


Figure B.13 Sorptivity vs area of bar overlap

6.4 Materials and mixes

There are many commercially available concrete repair systems for hand applications (including flowables) and Emberson and Mays [16] categorised these into nine generic types. Of these, two of the most widely used are the SBR-modified cementitious and the OPC/sand mortar types. Commercial considerations prevent the publication of the formulations of the eight pre-blended mortars used in this project, but they typically contain all or most of the following constituents: fine aggregates (75µm to 2mm); lightweight fillers (75µm to 300µm); OPC in the ratio of 1.3-3.4:1; silica fume (typically 5% of the OPC); admixtures such as SBR; polypropylene fibres; and sometimes chemical shrinkage compensators.

The simpler laboratory designed mortars were combinations of crushed Portland stone and a typical local building sand sieved to a maximum size of 3mm in a ratios of 3:0 to 1:2 by weight, together with OPC, silica fume (as an undensified powder) and an SBR in a 3:1 water suspension.

The laboratory designed fine concretes were combinations of a Type M river sand, OPC with (5% by weight of cement) silica fume slurry with an aggregate/cementitious ratio of 2.8:1 by weight and superplasticiser (1.5% weight of cementitious). Some of the mixes also contained crushed Portland stone, a coarse (2-8mm) smooth aggregate and steel (30mm hook ended at 80 kg/m^3) or polypropylene (at 0.9 and 5 kg/m^3) fibres. These fine concretes were successfully pumped and sprayed using a piston pump, and though the mix designs for wet mix spraying fine concretes are relatively sophisticated (usually containing silica fume, superplasticiser and sometimes fibres) they can be readily site batched, provided a suitably graded aggregate is available.

A total of 11 laboratory mortars mixes were designed for the spraying trials, of which 8 were successfully pumped and sprayed. The other three mixes were designed (successfully) to be un-pumpable, to test our understanding and ability to predict what mixtures would/would not pump. Of particular significance is that the best of the laboratory designed mortars performed as well as and produced hardened properties that were equal to, or surpassed, the pre-blended proprietary materials. For worm pumping the grading of a mortar is very important. In order to pump successfully, the voids content of the combined dry constituents (aggregate, OPC, fillers, silica fume) must be kept to a minimum in order to minimise bleeding of the wet mix. Pressure bleed tests, air void measurements and wet and dry gradings were used to optimise the mix designs of the designed mortars. A broad range of gradings for the designed mortars was selected deliberately for pumping trials; the results enabled a grading for worm pumping to be determined (Figure B.14).

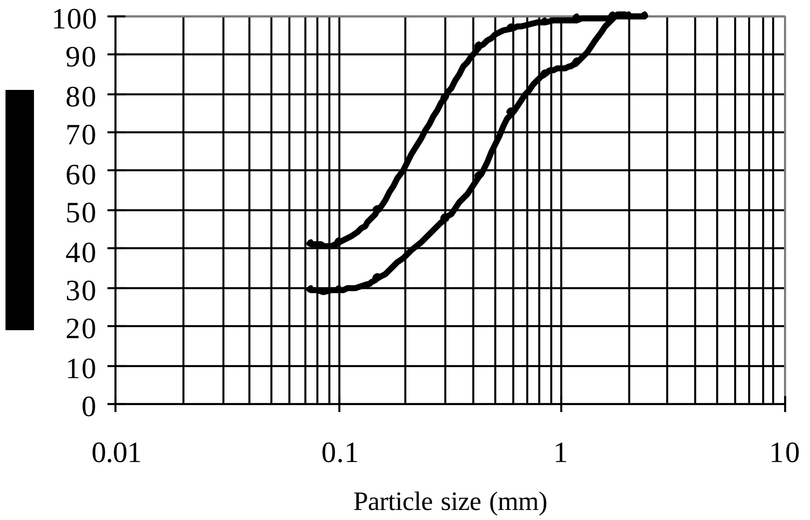


Figure B.14 Grading zone for worm pumping

The research also showed that care must be taken in the use of lightweight repair mortars as the compressive, flexural and bond strengths were all considerably lower and the drying shrinkage greater than the non-lightweight mortars.

The use of a high level air entrainment as means of improving pumpability/sprayability (by increasing mobility in the line without increasing slump in-situ, as air is knocked out during spraying) was investigated. Like Beaupre [5] this was successful with the piston pump, but only if the air content of the wet mix less than 18%. Above this level the mix was too compressible to pump. At this level, the in-situ content was 6% and strength increased by around 10 MPa (due to lower water content). Superplasticiser or cement could be omitted to just maintain the strength.

6.5 Equipment

All the proprietary pre-blended mortars could be pumped and sprayed with a small worm pump. The project was successful in demonstrating that much simpler designed mixes can be site batched and sprayed successfully using a small worm pump, provided the overall grading of the material (aggregate and cementitious) is kept within defined limits (Figure B.14).

Two of the pre-blended and one laboratory designed mortars were sprayed with a piston pump (Figure C.5) and produced similar in-situ properties to worm pumping. One of the pre-blended mixes was successfully pumped and sprayed through five different wet process pumps (4 worm plus 1 piston) showing that a wide variety of pumps are suitable for wet mix spraying of repairs. The project evaluated the latest technology in dual-mixing worm pumps (Figure C.6) which undoubtedly offers significant advantages over current equipment in providing better mixing, automation of water addition, pump controls fitted to the nozzle and improved re-circulation / clearing to assist stop / start flexibility. Three pre-blended and one designed mortar were also sprayed using a dry process machine. As expected the dry process produced a much dustier working environment, significant rebound, but increased strength (Figure B.10) and bond properties.

Figure C.5 Piston pump

Figure C.6 Dual-mixing worm pump

Nine laboratory designed fine concrete mixes were wet sprayed using a piston pump and one was dry sprayed. Again the grading of the aggregate is important, though not as critical as for worm pumping.

Experimentation with different nozzles (section 6.2) demonstrated the benefits of improved designs. The operating environment was cleaner and safer than the dry process, particularly with the worm pumps (although care must be taken when clearing blockages not to discharge in the spraying area). The effect of hose length was not investigated in depth, as the collaborators advised that the pump would be kept close to the spraying area in most instances. Stop / start flexibility could be enhanced by use of hydration suspension / activation admixtures (common in high volume tunnelling), but this complication (and cost) of materials and dosing equipment was deemed inappropriate by the industrialists.

6.6 Testing and quality control

Densities, compressive cube and flexural beam strengths were obtained from cast specimens of the batched material, from specimens that were obtained by spraying directly into a mould, and from specimens sawn from the in-situ sprayed panel. The in-situ densities and strengths were generally higher than the cast values due to the better compaction from the spraying process. Densities and strengths from specimens obtained directly spraying into cube and beam moulds were comparable with the in-situ values, provided that voids and rebound were minimised. It was also found that the drying shrinkage of cast and in-situ prisms were similar.

Whilst in-situ properties are clearly the most desirable for quality control purposes, it seems that with low volume output worm pumps, acceptable results can be obtained by spraying directly into moulds (a quicker, cheaper and more convenient option). These could be supplemented when required by testing samples sawn from in-situ / test panels.

A shear vane test has been developed (section 6.2 and Figure C.7) by modifying the vane of an item of soils equipment. This has great potential because it: (i) is a simple and quick site test that uses hand held equipment; (ii) can be inserted into the mix within a mixer, open pump hopper or fresh pumped or sprayed sample (tracing rheological audit trail); and (iii) measures an engineering property. Existing site methods do not have these advantages and tend to measure the spread of a non-standard sample.

Figure C.7 Hand-held shear vane

7 The objectives, associated deliverables and their dissemination

The achievements described above demonstrate clear new insights in our understanding of the pumping / spraying process and of the influence that equipment, mix constituents and their proportions have on fresh and hardened properties of wet-mix sprayed concrete, meeting Objective (i). It has been shown that a satisfactory production process and operator environment can be achieved with a variety of pumps and nozzles. The latest technology can undoubtedly produce a very clean and well controlled product delivery that approaches the conditions of an off-site manufacturing process (Objective (ii)). The project has defined the target repair categories and produced a wide range of mortar and fine concrete mix types, both simple and sophisticated, that have strength and durability performance levels that usually equalled or exceeded those of current (hand applied) repair products, meeting Objective (iii). The project has thus developed a repair technique with appropriate performance and flexibility (albeit not always at the level of the dry process) and a healthier working environment, producing Deliverable 1.

The research team recognise the importance of dissemination into and beyond the academic community. This has been, and continues to be, undertaken by publication in conferences [17-19], academic and professional journals (the latter raising industrial awareness) [20-23] plus internal reports [15, 24-25] and a related edited work[26]. A major output of the research is the Guideline Document which was intended to be a Departmental report, but is now to be published by the Concrete Society [27] which will give achieve excellent accessibility for the industry and disseminate information in appropriate form to practising engineers to advance the use of wet-mix sprayed concrete for repair in the UK, achieving Objective (iv) and producing Deliverables 2 and 3.

8 Implications for engineering practice

The project has demonstrated that low volume wet spraying is a healthier, cleaner and more controllable process (compared with dry spraying). It can produce consistently high quality mortars and fine concretes suitable for the range of structures currently repaired in the UK (see Table B.1).

Proprietary pre-bagged products are suitable, including many materials designed for hand application, but mixes designed specifically for spraying offer significant benefits. However, a method has been developed to assist in the design of manually batched mixes that have an in-situ performance equal to or better than factory pre-blended products (and will also be cheaper). Our understanding of what pumps and sprays and why has been advanced significantly (partly through the concept of a rheological audit) and can help engineers work from a more scientific basis in terms of the interaction of constituents, process and performance.

A range of existing pumping equipment has been evaluated and all proved suitable, from small worm to 100mm piston pumps. Undoubtedly the process is less dependent on operator skill than the dry process and can encase reinforcement satisfactorily. However, improvements can still be made to nozzle design and automation of metering, mixing and controlling pumps, which will enhance the spraying process and in-situ performance. Modifies working procedures should be adopted to suit the process, in terms of appropriate cycles and methods of advance preparation, batching, application and finishing.

Appropriate quality control should be regarded as a critical part of all contracts (but is not always so at present). The project has produced a large array of data against which mixes and products can be benchmarked. It has also developed a number of tests, covering pump/spray-ability and hardened performance that demonstrate the soundness of the wet process, and can also be adopted for site use.

9 References

1. CEN TC104/WG10 ENBBB Part 1 Sprayed Concrete - Methods for sampling fresh and hardened concrete, Draft 4, September 1998.
2. CEN TC104/WG10 ENBBB Part 3 Sprayed concrete - Determination of flexural and residual strengths of fibre reinforced beam specimens, Draft 4, August 1998.
3. CEN TC/WG10 ENBBB Part 4 Sprayed concrete - Determination of Bond Strength, Draft 2, May 1998
4. TC104/WG10 ENAAA Part 1 Sprayed Concrete – Part 1: Definitions, specifications, requirements and conformity, Draft 5, December 1998.
5. Beaupre D, *Rheology of high performance shotcrete*. PhD Thesis, University of British Colombia, February 1994.
6. Norris P. (1999), 'Wet mix sprayed concrete helps to set the ground rules', *Concrete*, Vol.33, No 5., May 1999.
7. NF P 95102 (1992), *Repair and Strengthening of Concrete and Masonry Constructions -Shotcrete*, French Standardisation Association (AFNOR), Paris, France.
8. Jomha A I J and Suhr J, 'New repair technique short down time and strong protection', *Deterioration and repair of reinforced concrete in the arabian gulf*, 1st ed., Vol.1, ACI/Concrete Society, Bahrain, 1997, pp.367-375.
9. Collins M P, Adebar P, Seabrook P T, Kuchma D, Sacre P, 'External repair of cracked grain silos', *Concrete International*, November 1997, pp 22-28.

10. Heere R, Morgan D, Banthia N, Yogendran Y, 'Evaluation of shotcrete repaired dams in british columbia', *Concrete International*, March 1996, pp 24-29.
11. Bubshait, A A, Tahir B M, Al-Gahtani A, 'Repair with Silica fume shotcrete: a case study', *Durability of Building Materials and Components*, 7th ed., Vol 1, E&FN Spon, London, pp 1263-1272, 1996.
12. Osbourne J, 'Set to spray', *Concrete Engineering International*, September 1998, pp 11-15.
13. Oliver, A, 'Down to Design', *New Civil Engineer*, 1st October 1998, pp 16-20.
14. Lane, I R, Chaplin K J, 'Testing the spray option', *Concrete Engineering International*, July / August 1998, pp 40-42.
15. Seymour J and Turner N J, 'Wet process sprayed concrete technology for repair - repair scenarios', *Internal Report*, Department of Civil and Building Engineering, Loughborough University, U.K, November 1995.
16. 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*, 42(152), 1990, pp 147-160.
17. Austin S A, Robins P J, Seymour J and Turner N, 'Wet process sprayed concrete technology for repair', *Sprayed Concrete Technology* E&FN Spon, London, 1996, pp 157-165.
18. Austin S A, 'European developments in sprayed concrete', *Procs Concrete Institute of Australia Biennial Conference CIA99*, Sydney, May 1999 (invited).
19. Austin S A, Robins P J and Goodier C I, 'Workability, shear strength and build of wet-process sprayed mortars', accepted for publication in *Procs Int Congress on Creating with Concrete*, Dundee, September 1999.
20. Austin S A, Robins P J and Goodier C I, 'The rheological performance of fine mortars in wet process sprayed concrete', in press *Magazine of Concrete Research*, November 1998.
21. Austin S A, Robins P J and Goodier C I, 'The hardened performance of wet process sprayed mortars', submitted to *Magazine of Concrete Research*, April 1999.
22. Austin S A, 'Repair with sprayed concrete', *Concrete*, Vol. 31, No 1, January 1997, pp 18-26. (Invited).
23. Austin S A, Robins P J and Goodier C I, 'Sprayed repair', *Concrete Engineering International*, Vol. 2, No 4, May-June 1998, pp. 47-51 (Invited).
24. Turner N J and Seymour J, 'Wet process sprayed concrete technology for repair - mix design', *Internal Report*, Department of Civil and Building Engineering, Loughborough University, U.K, December, 1995.
25. Seymour J / Goodier C I, Quarterly progress reports, *Internal Reports*, No.1-11, Department of Civil and Building Engineering, Loughborough University, U.K, June 1995-February 1999.
26. Austin S A (ed), '*Sprayed concrete technology*', E&FN Spon (ISBN 0-419-22270-7), London, 1996.
27. Austin S A, Robins P J and Goodier C I, *Construction and repair with wet process sprayed concrete and mortar - good concrete guide*, (in press), Concrete Society, 1999.