TRANSPORT RESEARCH LABORATORY

The evaluation of tests for repair materials used on concrete pavements

Prepared for Quality Services (Civil Engineering) Division, Highways Agency

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Executive Summary

The objective of this programme of research was to establish a range of laboratory tests that will indicate the likely performance of repair materials when used for arris and patch repairs in concrete pavements.

A number of tests have been used to determine the following properties of repair materials:

i the bond of the repair material to the base concrete, before and after thermal cycling, moisture cycling, freeze/thaw cycling or fatigue loading

ii the shrinkage of the repair material - after 24 hours and 28 days

iii the compressive modulus, tensile strength and development of compressive strength

iv the variation in strength, ease of mixing and placing with changes of mix proportions

v the permeability of the repair material to salt solution and gas

Some of the tests for i) and iii) were undertaken at 5°C, 20°C and 30°C. In some cases, tests were found to be unsuitable. For example, the initial 24 hour shrinkage test and the tensile strength test were not appropriate for mixtures containing coarse aggregate. Also, the permeability tests gave conflicting results and it was found to be impossible to set acceptance criteria for these tests.

Eight repair materials of different generic types were assessed using the laboratory tests. To assess their performance on site, these materials were also used for a limited number of repairs in repair contracts on the A5 in Buckinghamshire and the M11 in Essex. The site performance and the laboratory test results were then compared to determine which were the more relevant tests. Samples of the material chosen by each contractor for the main body of repairs (referred to as the ‘standard’ repair materials) on the above sites were also submitted to the same laboratory tests. These ‘standard’ materials were a microsilica concrete and an air-entrained concrete used on the A5 and the M11 respectively.

The materials were designated either for thin or for thick repairs according to the manufacturer’s recommendations. The materials for the thin repairs (10mm maximum depth) were only used for mid-bay patch repairs. These comprised the epoxy, the polyester, the rapid hardening and the acrylic materials. The thick repairs (greater than 10mm depth) consisted generally of arris repairs and were made using styrene-butadiene rubber (SBR), magnesium phosphate, high alumina, and the standard materials (microsilica concrete and air-entrained concrete).

Acceptance criteria were established for eleven of the laboratory tests. Seven of the ten materials tested achieved the criterion in at least nine of the tests. The remaining three materials, the polyester, the high alumina and the unmodified sand/cement achieved only three, five and six of the criteria respectively. The polyester and the high alumina performed poorly in the full scale trials and the third, the unmodified sand/cement, was not used in the trials. The SBR also performed poorly in the full scale trials as did the acrylic material when laid in the wheeltrack.

In general, there was good correlation between the overall ranking of the repair materials in the laboratory tests and their performance in the full scale trials.

It was apparent from the results of the testing programme that several modifications to the suite of tests would be worthwhile. Deflections of the beams used for the fatigue test could be reduced to be more simulative of strains experienced by pavement slabs. A typical 3.5m long arris repair could be included in any future testing programme to assess the ease of mixing, determine any problems with workability or finishing and indicate if cracking, as observed in the full scale trials, is likely to be a problem. There is also possibly a need for a wheel tracking test, considering the difference in site performance of the acrylic repair material when laid in the wheel tracks compared to that elsewhere in the pavement.

A comparison of costs showed that the resin-based repair materials become more competitive when used in 100mm wide arris repairs compared to the minimum width of 150mm required for other repair materials as specified in the Design Manual for Roads and Bridges. The two standard materials on the trial sites, the microsilica concrete and the air-entrained concrete, compared favourably on cost grounds but were only available in bulk.

It has been noticed that when using repair materials that satisfy the requirement for high early strength, problems can arise in placing and finishing the repair before the material becomes unworkable. An example of this was experienced when the magnesium phosphate was used for an arris repair that extended across a full lane width on the A5 contract.

On the two repair contracts the failure rate of the standard repair materials was approximately two per cent of all the repairs undertaken.

It was very difficult to identify a repair contract that was suitable for trialing the materials designated for thin repairs. There would appear to be a limited market for these materials in the pavement repair field because of the low incidence of shallow spalling. This may be due to the use of improved finishing techniques and because the advantage of using air-entrained concrete is now fully appreciated and pavements are rarely found to be suffering from frost attack.

Great care needs to be taken when considering the trade literature for repair materials because the strength quoted at a given age is often quoted at one temperature only, usually 20°C. However, the experience gained from the repair contracts on the A5 in Bucks and the M11 in Essex has indicated that repair contracts are often undertaken when ambient and slab temperatures are much lower than 20°C. The strength gain of repair materials is then considerably slower than that quoted in trade literature. Consequently, a longer time is required before the road can be re-opened to traffic which may be a problem particularly when repairs need to be completed within the period of an overnight lane closure.

The experience of finding suitable sites to trial the repair materials has highlighted that some maintenance being undertaken is using the repair materials for purposes for which they were not intended. For successful repairs, the cause of the pavement deterioration must be determined and appropriate action taken to arrest the deterioration before any repair material is placed.

1 Introduction

An increasing number of concrete roads are reaching an age and condition when remedial repairs are required. The repair to a concrete pavement must serve to:

a arrest deterioration of the pavement

b restore the structural integrity of the pavement

c provide a safe running surface

d provide an aesthetically acceptable finish

Although there are a large number of proprietary repair materials available for concrete, there is little information on the most appropriate material for surface and joint arris repairs to concrete pavements. Repairs are currently undertaken with reference to Volume 7 (HD32, Pavement Design and Maintenance) of the Design Manual for Roads and Bridges (DOT et al, 1994) which discusses generic repair materials but does not recommend specific materials.

The Transport Research Laboratory (TRL) identified the need to establish appropriate laboratory tests for assessing the suitability of materials for surface repairs and joint arris repairs. The laboratory testing was conducted in 1991 by Cranfield University at the Royal Military College of Science under the management of TRL.

A series of tests were defined which provided a means of assessing in the laboratory, the suitability of repair materials for surface and arris repairs to concrete pavements.

The tests investigated the following factors:

a the ability to bond adequately to the substrate concrete

b the movement, due to shrinkage, thermal and moisture changes, relative to the substrate concrete

c durability under freeze-thaw cycling

d fatigue resistance

e compressive and tensile strength and modulus of elasticity relative to the substrate concrete

f the length of time required before opening to traffic

g permeability to water, gases and aggressive solutions

2 Methodology

The methodology employed consisted of assessing the performance of each of the repair materials in a series of laboratory tests, their ease of application and cost. These assessments were subsequently compared with the performance of the repair materials in a full scale trial.

2.1 Assessment by laboratory tests

A number of laboratory tests were used to investigate the above factors. As one of the most important factors in a successful repair is the bond to the base concrete this was deemed to be one of the most important parameters to determine.

2.1.1 Bond to substrate concrete

There are essentially two methods by which the bond of a repair to the substrate concrete may be measured; the slant shear test and the pull-off test.

The slant shear test is specified in British Standard BS 6319 Part 4 (BSI, 1984) but suffers from the disadvantage that the interface is subject to compression as well as shear stress, yielding results which are unrepresentative of the loading conditions occurring in practice.

At the time of undertaking this project there was no British or European Standard that specified a pull-off test for repair material applied to a concrete substrate, although BS 1881 Part 207, (BSI, 1992a) describes a pull-off test for assessing the in-situ strength of concrete.

There are a number of potential pitfalls with pull-off tests, which include non-axiality of load application and the influence of coring on the interfacial adhesion. However, this test provides a more realistic representation of conditions in service and does have the advantage that it can be performed either in the laboratory or in-situ.

A pull-off test was recommended in a report to the Construction Industry Research and Information Association (CIRIA) for consideration as a European Standard. A test was designed for this programme of research based on these recommendations. These recommendations on pull-off tests and recommendations on other tests have, subsequent to this programme of research, been produced in a series of CIRIA Technical Notes (CIRIA, 1993a, b, c). The pull-off test is now described in draft European Standard prEN 1542.

2.1.2 Movement relative to substrate concrete

The movement of the repair material relative to the substrate concrete can be determined by the testing of a composite repair/substrate sample or by comparing the movement of the independent substrate and repair material.

One method is to use a subjective pass/fail test, for example the Continho ring for restrained shrinkage, on the repair material alone. This is suitable for use by manufacturers in the development and evaluation of new products on a purely comparative basis, but much more research is required to show how such tests correlate with the performance of materials in service. An alternative is to measure the unrestrained length changes of prisms of repair material subject to curing shrinkage, thermal and moisture changes and to compare these with corresponding values for the substrate concrete. However, this type of test is not capable of taking into account the early age shrinkage and would have to be considered with the results from early age testing to BS 6319 Part 12 (BSI, 1992b). In the study for CIRIA, it has been suggested that materials may be ranked for suitability in terms of their strain mismatch.

Although the repeatability of testing on composite specimens has been of some concern it is considered that this type of specimen is most likely to resemble the restraint conditions during service. Consequently, the testing regime adopted was to measure the restrained shrinkage strain in the repair material and the substrate concrete of a composite specimen using a demec gauge. Pull-off tests were undertaken at intervals during the curing process on these specimens. In addition the unrestrained shrinkage of the repair materials was measured up to an age of 48 hours in accordance with BS 6319 Part 12.

2.1.3 Freeze/thaw

It is possible to undertake tests on the repair materials using a standard freeze/thaw test as outlined in BS 5075 Part 2 (BSI, 1982) or ASTM C 666 (ASTM, 1984). Such tests will only give comparisons between the repair materials and/or the concrete substrate.

For this investigation an alternative method was used which subjected the composite repair material/substrate specimen to a freeze/thaw cycling regime as recommended by RILEM (RILEM, 1986). The specimen was examined for defects and subjected to pull-off tests at the end of a predetermined number of cycles.

2.1.4 Fatigue resistance

Fatigue tests on pure repair materials, involving four point bending of prism specimens, were considered to be of limited value since they only provide information of tensile cracking and not on interfacial adhesion resistance.

The CIRIA study recommends the use of concrete beam specimens into which a centrally placed recess is cast. After appropriate substrate preparation, the repair material is cast into the recess and cured. The concrete beam has to be reinforced and the specimen geometry and load configuration carefully designed.

For this research a 150mm deep by 100mm wide concrete beam reinforced with two 10mm diameter high tensile steel bars was used over a span of 1.2m. To simulate cyclic loading conditions in pavements, the beams were repaired in both the flexural tension and compression zones. The beams were cycled in the four point bending rig from 4 to 40% of the ultimate load at a frequency of 5Hz for 10^6 cycles.

Calculations based upon the elastic behaviour of a transformed concrete section predicted the average tensile stresses in the bottom repair at mid-span, under the peak load, to be 5.3N/mm^2. This is likely to induce some flexural cracking in most repair materials. The corresponding stress at the vertical interface between the repair material and the concrete is 2.6N/mm^2, which, with good adhesion, would not lead to debonding. The shear stress at the horizontal interface between the repair material and the concrete in the shear span was calculated to be 0.28N/mm^2.

Subsequent to the application of the fatigue loading, pull-off tests were conducted to detect any loss in interfacial adhesion.

2.1.5 Tensile strength and static modulus

Previous research (Emberson and Mays, 1990) on the implications of property mismatch in large volume patch repairs concluded that the modulus of elasticity of the repair material compared to that of the substrate concrete is more significant than any difference in strength.

For satisfactory performance, the repair materials need to attain tensile and compressive strengths at least equal to those of the substrate concrete. The tensile strength of the repair materials was determined according to BS 6319 Part 7 (BSI, 1985) and the static modulus in compression was determined according to BS 1881 Part 121 (BSI, 1983c). Both were determined over a range of temperatures.

2.1.6 Time to opening

The length of time required before opening a repaired pavement to traffic is determined by the compressive strength of the repair material. This was determined in accordance with BS 6319 Part 2 (BSI, 1983b) or BS 1881 Part 116 (BSI, 1983c). As the gain in compressive strength of these materials is dependent upon the ambient temperature, this testing was performed over a range of temperatures.

2.1.7 Permeability

There are three transport processes which may be relevant to the in-service performance of pavement repair materials: water and gas permeability and chloride ion diffusion. Tests to measure gas permeability and chloride ion diffusion were selected for this investigation.

The gas permeability was determined according to a method (Lydon and Mahawish, 1991) that involves applying nitrogen gas under pressure to a central injection point on one face of a cylinder of the repair material and measuring the volume of gas permeating through the specimen.

The most aggressive solution that highway pavements are subjected to, in normal service, arises from the use of de-icing salts. The chloride ion diffusion coefficient of the repair materials was determined using a method conforming to the recommendations of the Concrete Society (Concrete Society, 1988). A thin slice of the repair material formed a barrier, in a tank, between a solution of sodium chloride and water. The water was analysed at intervals to determine the presence of chloride ions, and from this, the chloride ion diffusion coefficient of the repair material was determined.

2.2 Assessment by ease of mixing

This phase of the investigation was approached in two stages, the first being laboratory based and the second consisted of in-situ trials.

The laboratory stage involved a subjective assessment of the mixing process for each repair material, particularly in terms of the time to completion and the resulting workability. In addition, the effect of varying the content of the liquid component of the mix constituents by ±5% on the compressive strength gain with time was assessed.

The in-situ trials involved undertaking an arris and a surface repair on concrete road slabs within the TRL site. The repairs were carried out in accordance with the DOT/C&CA manual (Mildenhall et al, 1986).

2.3 Assessment by cost

For the cost assessment exercise, three sizes of repair contract were selected based on information supplied by the Highways Agency. A Specification and Bill of Quantities, for a repair contract, in accordance with Volume 4 (Bills of Quantities for Highway Works) of the Manual of Contract Documents for Highway Works (DOT et al, 1991a) and the DOT/C&CA manual were submitted to an experienced concrete repair contractor for costing purposes.

2.4 Assessment by full scale trials

The repair materials were used under contract conditions on two major repair contracts, on the A5 at Milton Keynes and the M11 between Junctions 7 and 8. On the A5 contract, lane-width arris repairs were undertaken, whilst on the M11, one material was used for a lane-width arris repair and the other materials for patch repairs. The repairs were assessed at the time of laying and by visual inspection after at least one year's service.

3 Substrate concrete and repair materials

An air entrained and a non-air entrained substrate concrete mix was developed. The repair materials were selected after consultation with repair material suppliers and one product from each generic type was tested. The standard materials used on the two full scale repair contracts were also used in most of the laboratory tests.

3.1 Substrate concrete

The substrate concrete mix design was carried out using ordinary Portland cement and Cerney limestone gravel aggregates to produce a pavement quality concrete complying with the strength requirements of Volume 1 (Specification for Highway Works) of the Manual of Contract Documents for Highway Works (DOT et al, 1991b). The air entrained concrete was only used for the specimens subjected to freeze/thaw cycling. The 28 day compressive strength of the substrate concrete used for the composite specimens and for the mix used for the fatigue testing specimens is shown in Table 1. The results presented are the average of three cubes strengths determined according to BS 1881 Part 116.

Table 1 Compressive strength of substrate concretes

	28 day compressive strength (N/mm^2)	
Batch	*Composite specimens*	*Fatigue specimens*
1	48.9	58.1
2	47.3	54.7
3	41.3	60.6
4	49.2	56.5
5	44.0	59.6
6		52.2
AE 1	45.2	
AE 2	43.3	
Mean	45.6	57.0
Standard deviation	3.0	3.1

3.2 Proprietary repair materials

An approach was made to 32 repair material producers/suppliers asking for their views on the generic types of material that should be included in this investigation. A total of 21 responses was received and these contained suggestions of materials within each current product range that fitted into one or more of the seven generic types identified. One material of each generic type was selected based on further discussions and past experience, only one material was used from any individual producer/supplier. All the proprietary repair materials were purchased from independent builders' merchants to ensure that the materials employed in the research programme were typical of those available for use in highway repair schemes.

An eighth repair material, an unmodified ordinary Portland cement/sand mortar designed by RMCS (Cranfield), was selected as a comparative control.

The generic types of repair materials identified were:

- Epoxy resin
- Polyester resin
- Rapid hardening modified cementitious
- Acrylic modified cementitious
- SBR modified cementitious
- Magnesium phosphate cement
- High alumina cement
- Unmodified cementitious (sand/cement)

3.3 Standard repair materials

The repair materials selected by the contractors on the A5 and M11 repair contracts were a microsilica concrete and an air entrained concrete, respectively.

3.3.1 Microsilica concrete

The mix design used in the full scale repairs was unsuitable for use in the laboratory tests as the dispersion of the microsilica slurry is more efficient in large batch sizes. After consultation with the supplier and several trial mixes, a suitable mix design for a 130kg batch was derived.

3.3.2 Air entrained concrete

As it is easier to get the required air content of the concrete under laboratory conditions, the dosage of air entrainment admixture used in the laboratory tests was different to that used in the full scale repairs. Therefore, trial mixes were conducted to provide the same final percentage of air entrainment for the 130kg batch of concrete in the laboratory as that specified in the full scale repairs.

4 Experimental procedures

The procedures adopted for making the substrate concrete bases, laying the repair materials on the substrate concrete to form the composite specimens, for the pull-off testing and/or the other laboratory tests, are indicated below.

4.1 Preparing the substrate concrete

For each batch of concrete the following procedure was adopted:

- Eight specimens 200mm square by 100mm deep were prepared.
- Two 100mm cubes were made to BS 1881 Part 108 (BSI, 1993d).
- The specimens were stored under damp hessian for 24 hours.

- The specimens were demoulded and wrapped in saturated paper towelling and sealed in polythene bags for 26 days.
- At the end of this curing period the specimens were removed from the bags and allowed to dry in the laboratory for 24 hours.
- The surface laitance was removed from the bottom cast surface of each specimen with a needle gun and the specimen placed in a mould ready for application of the repair mortar.

4.2 Forming the composite specimens

The depth of the moulds used to manufacture the composite specimens depended upon the thickness of repair material to be applied. This was dictated by the maximum aggregate size of the repair material and the manufacturer's recommendations; a thickness of 10mm was used for the epoxy, polyester, modified cementitious and acrylic repair materials, whilst a thickness of 50mm was used for the SBR, magnesium phosphate, high alumina, unmodified sand/cement and the two standard repair materials. After placing the substrate concrete in a mould on a flat and level surface, the following procedure was adopted for applying the repair materials:

- In accordance with the manufacturer's instructions, the substrate concrete was primed for the epoxy, rapid hardening, acrylic and SBR materials.
- The repair material was mixed in accordance with the manufacturer's instructions and applied to the prepared substrate concrete surface.
- The repair material was compacted by hand and trowel to a level, even surface.
- With the exception of the specimens for the shrinkage testing, the specimens were cured in accordance with the manufacturer's recommendations and demoulded after 24 hours.
- The unmodified sand/cement, SBR and standard repair materials were wrapped in saturated paper towelling and sealed in clearly labelled plastic bags for 13 days. The remaining composite specimens were stored in air for 13 days. The labelling included the date cast, material type and batch number.
- For each batch of repair material, one test cube was made. The polyester and rapid hardening cubes were 40mm side, the epoxy, acrylic, SBR, magnesium phosphate, high alumina and unmodified sand/cement were 70mm side and the standard repair materials were 100mm side.
- The cubes were cured and then tested for compressive strength at 28 days. The unmodified sand/cement, SBR and standard repair materials were cured in water, the others in air.

The results of the 28 day compressive strength for the repair materials are shown in Table 2. All the repair materials were tested according to BS 6319 Part 2 except the standard repair materials which were tested to BS 1881 Part 116.

Table 2 Compressive strength of repair materials

Material	*28 day compressive strength (N/mm^2)*	*Standard deviation (N/mm^2)*
Epoxy	71.0	10.2
Polyester	113.2	12.5
Rapid hardening	33.9	10.0
Acrylic	44.2	4.6
SBR	44.2	5.9
Magnesium phosphate	59.9	10.0
High alumina	52.6	9.1
Unmodified sand/cement	55.4	13.0
Microsilica concrete	81.5	13.3
Air entrained concrete	62.2	6.9

4.3 Pull-off testing

The pull-off test was used to assess the condition of the composite specimens after they had been used in many of the laboratory tests. The procedure for the pull-off testing was as follows:

- The top surface of the repair material was prepared by grit blasting.
- A template was used to mark the four coring positions. Figure 1 shows the coring positions on a composite specimen.

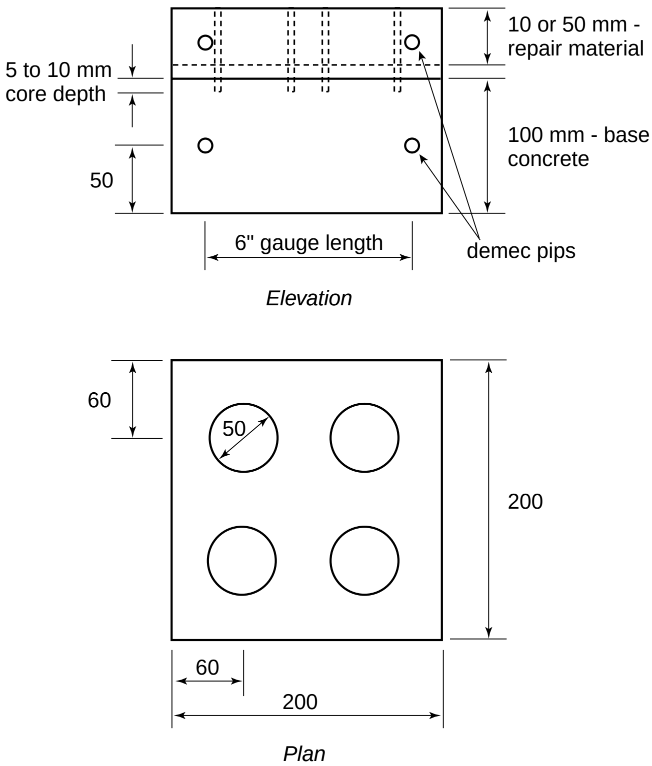


Figure 1 Position of core holes and demec pips

- With the composite specimen securely clamped, a core was drilled through the repair material and into the substrate concrete for 5 - 10mm. A pillar drill was used with a 50mm diameter coring bit.
- The coring bit was lubricated with water during the drilling process. The surface of the specimen was wiped clean prior to bonding the dolly.

- The surface of the aluminium dolly was grit blasted and degreased with acetone. Care was taken to ensure that the surfaces of the repair material and dolly were not contaminated by handling prior to bonding.
- The epoxy resin adhesive was mixed and an even layer applied to the surface of the repair material and the four dollies bonded in place. Care was taken to ensure that the cored groove was cleared of any excess adhesive.
- The adhesive was allowed to cure for 24 hours, where the time of testing permitted, at 20°C.
- The pull-off test was performed as per the manufacturer's instructions, the equipment used is shown in Figure 2.
- The pull-off load was recorded and the mode and location of the failure plane was noted.

Figure 2 Pull-off test

4.4 Laboratory tests

The procedures adopted for the range of laboratory tests were as follows:

4.4.1 Bond to substrate concrete

Four sets, 32 substrate concrete specimens, were prepared in accordance with the procedure described in section 4.1. Thirty specimens, three for each repair material, were used to test the ten repair materials.

- Ten specimens, one for each repair material, were conditioned for two hours at temperatures of 5°C, 20°C or 30°C to simulate repairs carried out at different temperatures.
- The repair material was mixed at 20°C and applied to the temperature conditioned substrate.
- The composite specimens were cured at the conditioning temperature for 14 days as described in section 4.2.
- The composite specimens were prepared for the pull-off test at 15 days using the procedure described in section 4.3.
- The samples were conditioned at 5°C for two hours and one pull-off test performed. The specimens were then raised to 20°C for two hours and a further pull-off test performed. Finally the temperature was raised to 30°C for two hours and a third pull-off test performed.

A further four sets of specimens were prepared and the complete procedure was repeated to obtain a second result for each test.

4.4.2 Movement relative to substrate concrete

As described earlier, this consisted of two tests; one to determine the early age material shrinkage and one to determine the relative shrinkage of the repair material and the substrate concrete in the composite specimen.

4.4.2.1 Early age material shrinkage

The unrestrained shrinkage of all the repair materials, except the two standard materials which contained too large an aggregate, were determined according to the principles of BS 6319 Part 12, which became effective after the testing was undertaken. The main deviation from the British Standard was that a perspex box was used to enclose the apparatus as opposed to the apparatus being placed in an environmental chamber. The apparatus is shown in Figure 3.

- The trough was lined with polytetrafluoroethylene (ptfe) and sprayed with a silicone release agent to minimise any restraint.
- A layer of repair material was spread approximately 10mm thick into the shallow, insulated trough.
- Thin hardboard strips were attached to each end of the repair materials and the change in length between the strips was continuously monitored by transducers.
- A thermocouple was attached to the base of the trough to monitor any change in temperature.

The British Standard requires the apparatus to be enclosed during the test. However, in practice on highway pavements, such an enclosure will not always occur. The effect of this will not be important for resin based systems but may significantly influence the shrinkage of the cementitious-based systems. Consequently, unenclosed tests were also undertaken on some of the cementitious repair materials to supplement results obtained in earlier work.

4.4.2.2 Shrinkage of composite specimens

Four sets, 32 substrate concrete specimens, were prepared in accordance with the procedure described in section 4.1. Thirty specimens, three for each repair material, were used to test the ten repair materials.

- The composite specimens were prepared in accordance with the procedures described in section 4.2 but allowed to cure, uncovered in the laboratory environment, at approximately 20°C.
- The specimens were demoulded 24 hours after placing the repair material. Demec pips were attached to one side of each specimen at the locations shown in Figure 1.
- Demec readings were taken on both the substrate concrete and the repair material for up to 28 days. The onset of any cracking or delamination was also recorded.
- The specimens were prepared for the pull-off test according to the procedure in section 4.3.

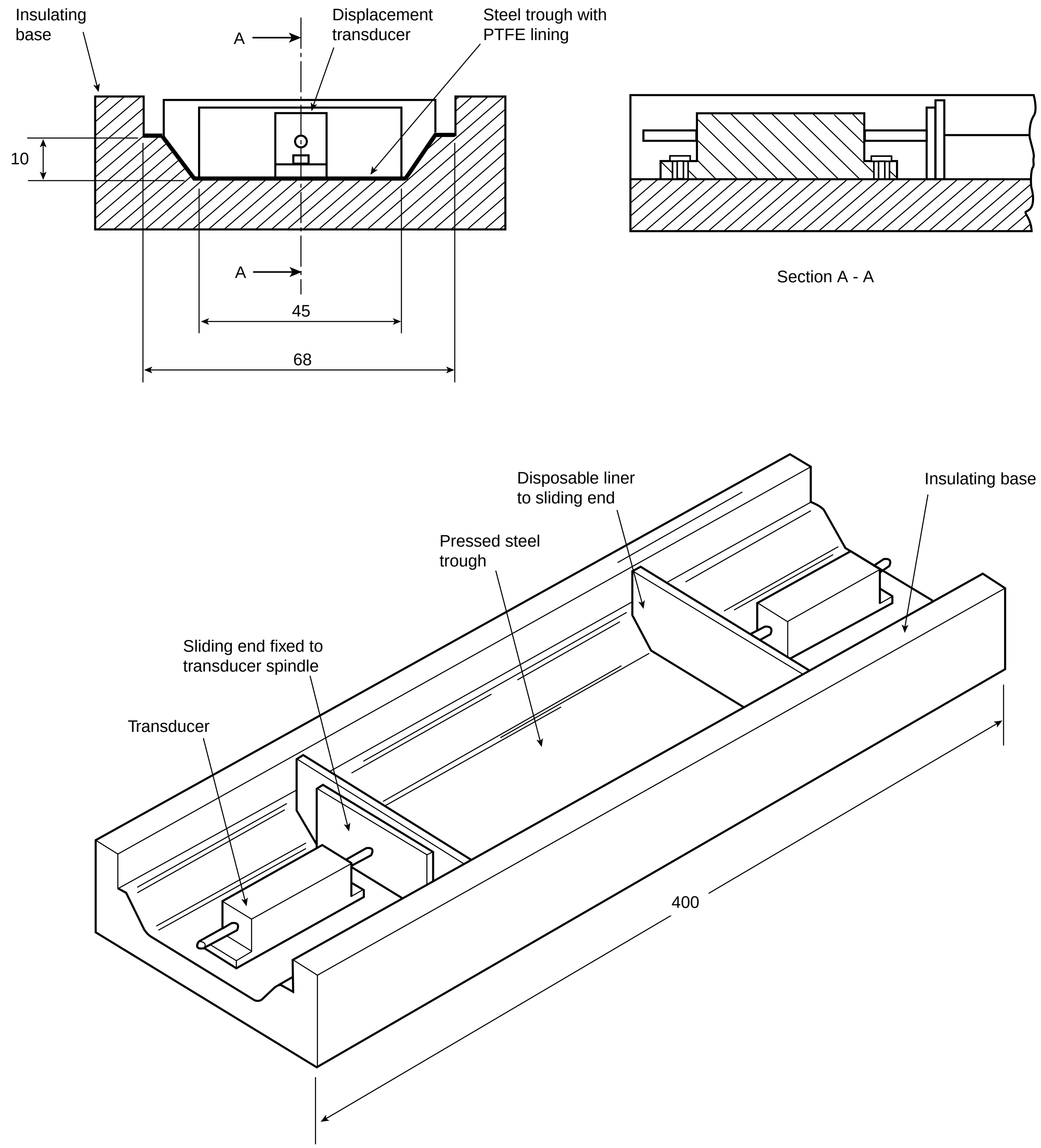


Figure 3 Early age shrinkage apparatus

- The pull-off tests were undertaken at various ages for the different repair materials depending upon the stated strength development of the material. The ages of test are shown in Table 3.
- The minimum time period between bonding of the dolly and the pull-off test was one hour.

4.4.2.3 Thermal cycling

Two composite specimens of each repair material were prepared in accordance with the procedures described in sections 4.1 and 4.2.

- At the end of the standard curing period, specimens were subjected to a thermal cycling regime between -5°C to +40°C within an environmental cabinet. These temperatures were selected to represent the normal extremes in UK conditions.
- The six hour thermal cycling pattern illustrated in Figure 4 was continued for a period of four weeks.
- The specimens were then removed from the cabinet, allowed to return to 20°C and pull-off tests conducted at 3 locations in accordance with the procedure in section 4.3.

Table 3 Testing ages for the pull-off tests on shrinkage specimens

Repair material	*Age at pull-off test* 2 hours	6 hours	24 hours	2 days	7 days	14 days	28 days
Epoxy			*	*	*		*
Polyester	*	*	*				*
Rapid hardening	*	*	*				*
Acrylic	*	*	*				*
SBR				*	*	*	*
Magnesium phosphate	*	*	*				*
High alumina			*	*	*		*
Unmodified sand/cement				*	*	*	*
Microsilica concrete			*	*	*		*
Air entrained concrete			*	*	*		*

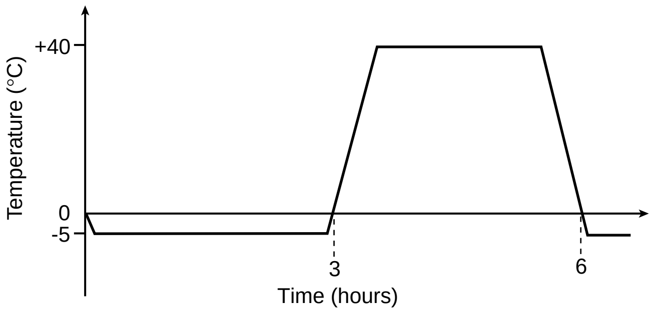


Figure 4 Thermal cycle

4.4.2.4 Moisture cycling

Two composite specimens of each repair material were prepared in accordance with the procedures described in sections 4.1 and 4.2.

- At the end of the standard curing period, the specimens were subjected to the six hour wet/dry cycling regime, illustrated in Figure 5, within an environmental cabinet. The cycles were designed to simulate ‘thunder showers’ on a warm concrete pavement.

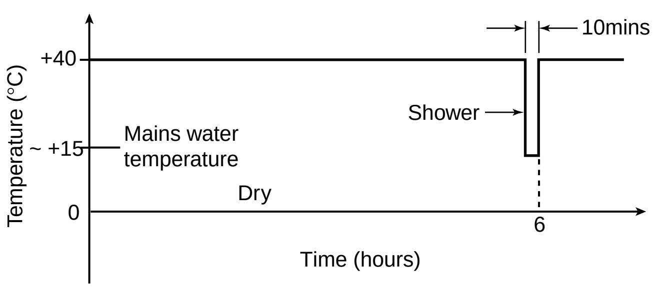


Figure 5 Moisture cycle

- The moisture cycling pattern was continued for a period of 2 weeks.
- The specimens were then removed from the cabinet, allowed to return to a surface dry condition at 20°C and pull-off tests conducted at 3 locations in accordance with the procedure in section 4.3.

4.4.3 Freeze/thaw cycling

Two composite specimens of each repair material were prepared in accordance with the procedures described in sections 4.1 and 4.2 but with the additional use of an air entraining agent within the substrate concrete.

- At the end of the standard curing period, the specimens were immersed in containers filled with 3% by weight of sodium chloride solution.
- The containers were introduced into a freeze-thaw cabinet and cycled between -18°C and +20°C every 12 hours for a period of 2 weeks. The cycle regime was based upon preliminary tests in which the temperature at the core of each specimen was recorded.
- The twelve hour cycling pattern is illustrated in Figure 6.

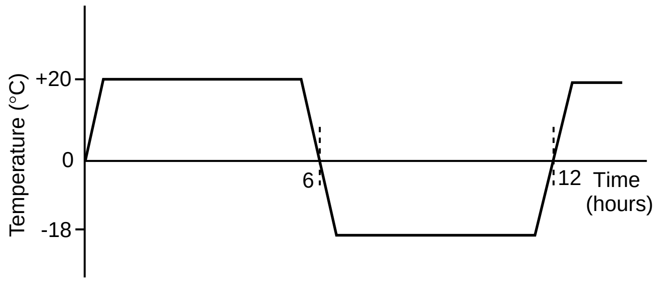


Figure 6 Freeze–thaw cycle

The duration at the maximum and minimum temperatures was extended beyond that recommended by RILEM to enable the specimens themselves to reach the temperature of the surrounding liquid.

- At the end of this period the specimens were removed from the cabinet, allowed to return to a surface dry condition at 20°C and pull-off tests conducted at 3 locations in accordance with the procedure in section 4.3.

4.4.4 Fatigue resistance

The fatigue specimens were reinforced concrete beams 150mm deep, 100mm wide and 1.3m in length. Two 10mm diameter hot rolled high tensile steel deformed reinforcement bars were placed adjacent to the tension face at an effective depth of 100mm. The latter depth was selected so that the reinforcement cage did not intrude into the repair zones. Recesses for these repair zones were formed using polystyrene blocks 700mm long on both the tension and compression faces and either 10mm or 25mm deep. A diagrammatic view of the beams is shown in Figure 7.

- Two fatigue specimens were cast for each repair material using a substrate concrete mix and allowed to cure under damp hessian and polythene cover for 28 days. Two additional specimens were cast without recesses for control purposes.
- The beams were allowed to dry for 24 hours and the surface area of the recesses prepared using a needle gun.
- Temporary formwork was clamped to the sides of the specimens and the same repair material cast into both tension and compression face recesses.

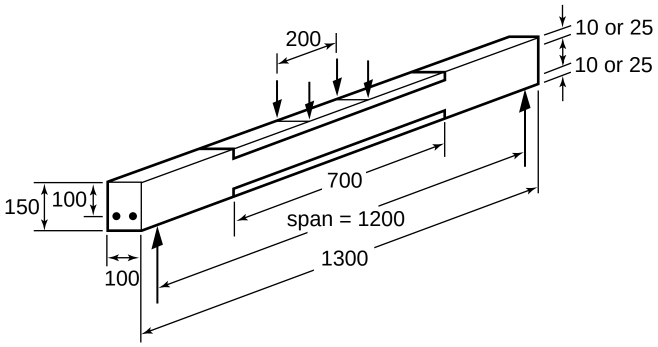


Figure 7 Diagrammatic view of fatigue specimen

- The repair materials were cured under sealed polythene for 14 days.
- The beams were cycled in a four point bending machine with loadings between 1kN and 10kN at a frequency of 5Hz for 10^6 cycles.
- Throughout the fatigue test any delamination was noted.
- At the conclusion of the load cycling, four pull-off tests were conducted on each beam in accordance with the procedure in section 4.3.

4.4.5 Tensile strength and static modulus

For each repair material a prism specimen and two ‘dog bone’ specimens of the dimensions shown in Figure 8 were cast at 5°C, 20°C and 30°C.

- The specimens were cured at the temperature of manufacture, the resin specimens in air and the cementitious materials wrapped with damp towelling in polythene bags.
- The ‘dog-bone’ specimens were tested in tension according to BS 6319: Part 7 at ages of 2 and 28 days.
- The prism specimens were used to determine the modulus of elasticity in compression at an age of 28 days in accordance with BS 1881 Part 121. Three loading cycles were conducted on each specimen.

This programme of testing for tensile strength and static modulus was repeated on a second set of specimens.

4.4.6 Time to opening

Six cubes of each repair material were cast, to the dimensions given in section 4.2, at temperatures of 5°C, 20°C and 30°C.

- Curing followed the same procedure described in section 4.4.5 but cubes were extracted for the determination of compression strength to BS 6319 Part 2 at the time periods specified in Table 3.
- Additional testing was undertaken at 24 hours for the SBR and sand/cement materials, and at 2 and 7 days for the polyester, rapid hardening, acrylic and magnesium phosphate materials.

The above procedure was repeated twice for all the repair materials except for the standard repair materials, for which the procedure was repeated once.

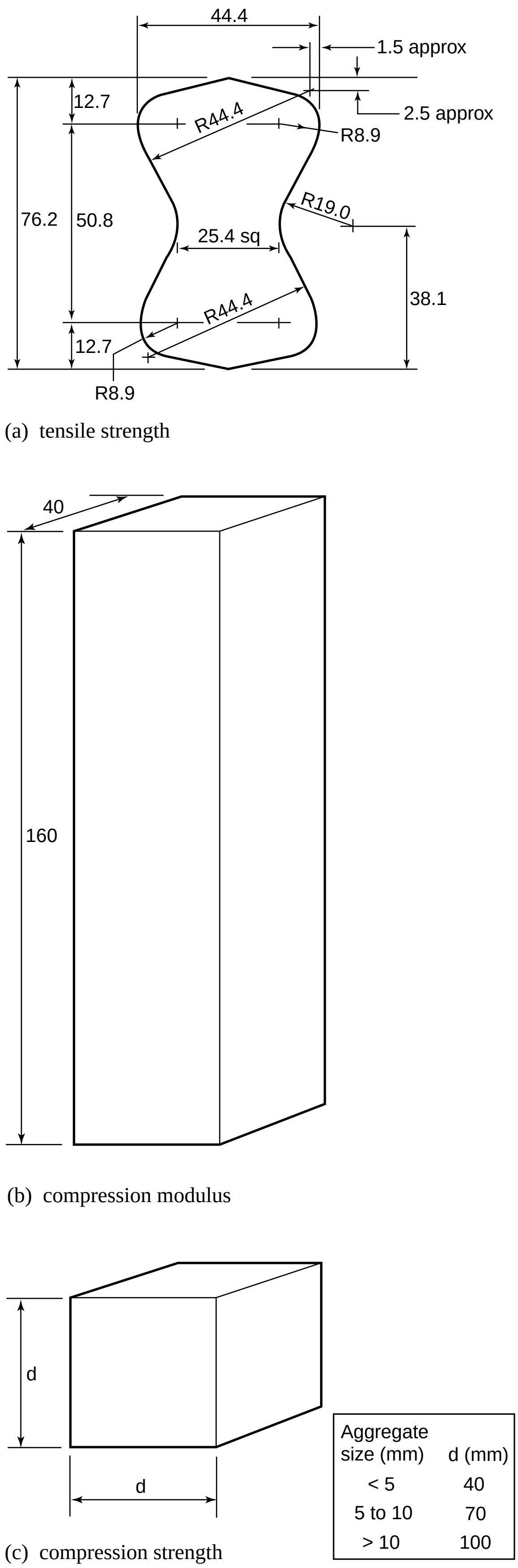


Figure 8 Strength and modulus specimens

4.4.7 Permeability

The permeability testing was undertaken on the eight proprietary repair materials using the following procedure:

- Two cylinders, 200mm long and 100mm diameter, were prepared of each repair material.
- The cementitious products were cured for 14 days in damp, sealed polythene bags and the resin materials in air.
- After 28 days, two discs 5mm in depth were sawn for the chloride ion diffusion testing and another sample of 50mm depth was sawn for the gas permeability tests.
- The discs were sealed in polythene bags and dispatched for testing.

4.4.7.1 Nitrogen gas permeability

- The 50mm deep discs were weighed immediately after opening the sealed bags and conditioned at 20°C and relative humidity of 65%.
- The discs were weighed and the moisture content checked until equilibrium was achieved.
- The discs were placed in the apparatus shown in Figure 9. A sensitive regulator valve on a high-pressure cylinder of oxygen free nitrogen gas controlled the pressure into the specimen.
- The gas was directed either to a simple U-tube or to an inverted gas cylinder. The burette in the former was graduated in 0.1ml and the latter in 1ml units. The former was used with low permeability discs and the latter with high permeability discs.
- Tests were carried out at a range of pressures, generally between 1 and 5 bar, three runs were undertaken at each pressure.
- The permeability coefficient was calculated from:

$$D_s = \frac{2\,V\,p_o\,L\,\eta\,10^{-5}}{A\,(\,p^2\ -\ p_a^{\,2}\,)}$$

where D_s = permeability coefficient (m^2)

V = volume rate of permeating gas (m^3/s)

L = path length (m)

η = coefficient of viscosity of the gas (Ns/m^2)

A = cross-sectional area through which the gas permeates (m^2)

p = inlet pressure of the gas (bar)

p_0 = pressure at which volume flow rate is measured (= 1 bar)

P_a = outlet pressure of the gas (= 1 bar)

4.4.7.2 Chloride ion diffusion

A number of twin cell test rigs were constructed from 100mm nominal diameter pvc pipe as illustrated in Figure 10. Throughout the test, the rigs were positioned on a stable, level bench.

- A 5mm thick disc of repair material was sealed between the two cells using silicone sealant.
- The apparatus was filled with distilled water for 24 hours to test for leaks and to saturate the specimen.
- The apparatus was drained and a base solution of saturated calcium hydroxide introduced to the lefthand cell, whilst that in the righthand cell additionally contained one mol/litre of sodium chloride.
- The chloride ion level in the lefthand cell was monitored daily for a period of 28 days, then at longer intervals, using a chloride ion electrode regularly calibrated against standard chloride solutions.

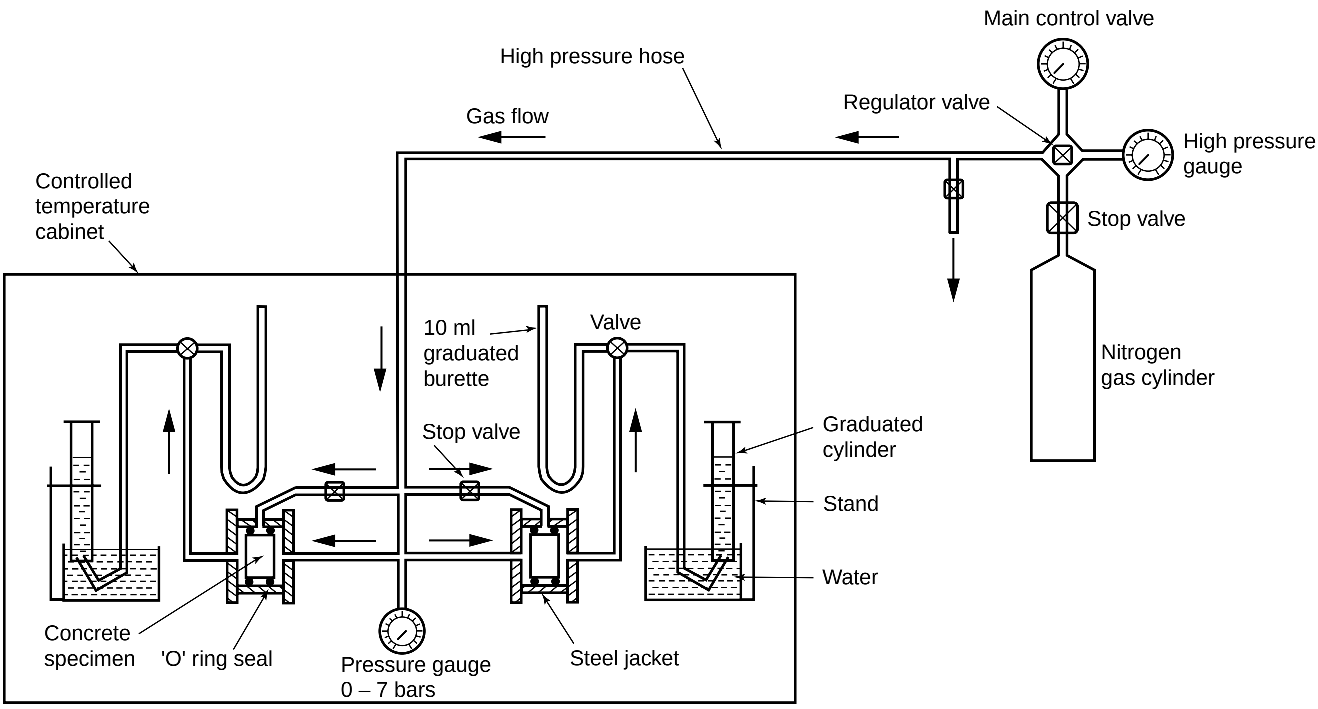


Figure 9 Nitrogen gas permeability apparatus

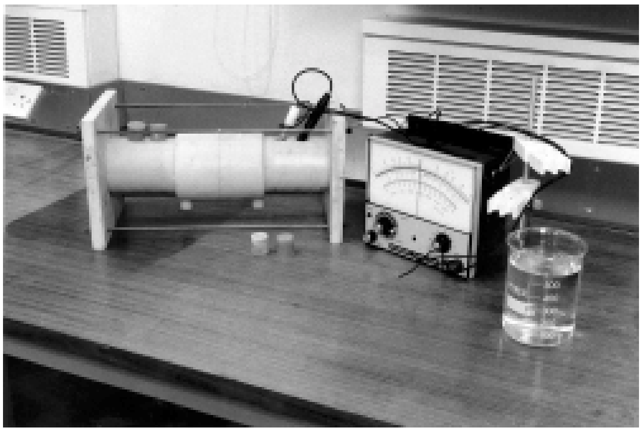


Figure 10 Chloride ion diffusion rig

- Throughout the testing, the two cells were kept full using distilled water in order to avoid any hydrostatic pressure across the specimen.
- The diffused chloride ion concentration was plotted against time to obtain the mass transport rate (J), by applying Fick's first law, the chloride ion diffusion coefficient (D_c) was determined as follows:

$$J = \frac{V}{A} x \frac{dC_2}{dt} = \frac{D_c}{L} (C_1 - C_2)$$

where V = volume of solution in each cell (cm^3)
A = cross-sectional area of the disc (cm^2)
L = thickness of the disc (cm)
C_1 = chloride ion concentrations in cell 1
C_2 = chloride ion concentrations in cell 2
t = time (s)

Two tests were undertaken on each repair material.

4.4.8 Ease of mixing

This was assessed by varying the amount of liquid component used and by undertaking pavement repair trials at TRL. These assessments were not undertaken on the standard repair materials.

4.4.8.1 Effect of mix proportions

- Batches of repair materials were prepared in which the weight of the liquid component was increased or decreased by 5% about the recommended norm.
- Six cubes, of dimensions given in section 4.2, were cast from each material and cured as in section 4.2 and the compressive strength determined at the same ages as in section 4.4.6.
- A subjective comparison of the effect of batch variability on ease of mixing and placing was made for each material.

4.4.8.2 Pavement repairs at TRL

Repairs were undertaken on a damaged pavement next to the concrete batching plant. These consisted of arris and patch repairs. The repairs were approximately 450mm by 900mm for the 50mm deep repairs undertaken with the sand/cement, high alumina, magnesium phosphate and SBR; and approximately 150mm by 900mm for the 10mm deep repairs undertaken with the rapid hardening, acrylic, epoxy and polyester. Typical cross sections are shown in Figure 11.

- The substrate was prepared in accordance to the recommendations in the DOT/C&CA manual.
- The SBR and sand/cement materials were cured by covering with wet hessian and polythene.
- The polyester resin was laid in 200mm wide strips to limit differential shrinkage.
- A subjective assessment of the ease of mixing, placing and finishing was made for each material.

5 Assessment of cost

The previous tests were designed to provide an assessment of the relative technical performance of the ten repair materials used in this study. However, the relative costs of the materials were also considered.

A repair specification and a bill of quantities for three hypothetical concrete pavement repair contracts, small, medium and large, were prepared in accordance with the requirements of the Bills of Quantities for Highway Works. The size of the contracts are shown in Table 4.

Table 4 Size of concrete repair contracts

Contract size	*Surface repair (m^2)*	*Arris repair (m)*
Small	200	500
Medium	500	1500
Large	1000	2500

Separate 'bill' sheets were priced for each of the ten different repair materials by an experienced contractor. It was assumed that the duration of the contract would be the same for all the repair materials. Any factors which represented a constant overhead for each material, (eg lane closure costs), were therefore omitted from the rates. If the contract duration was to vary depending on the material used, then the traffic management cost would need to be considered.

The alternative depths to be priced for each repair material are shown in Table 5. The minimum permitted width of arris repairs is 150mm except for resin materials where 100mm is allowed. The epoxy and polyester were therefore priced for 100mm and 150mm widths.

The priced bills of quantities were evaluated and summarised in the following formats:

a Cost of surface repairs (£/m^2).

b Cost of arris repairs (£/m).

c Cost of small repair contract.

d Cost of medium repair contract.

e Cost of large repair contract.

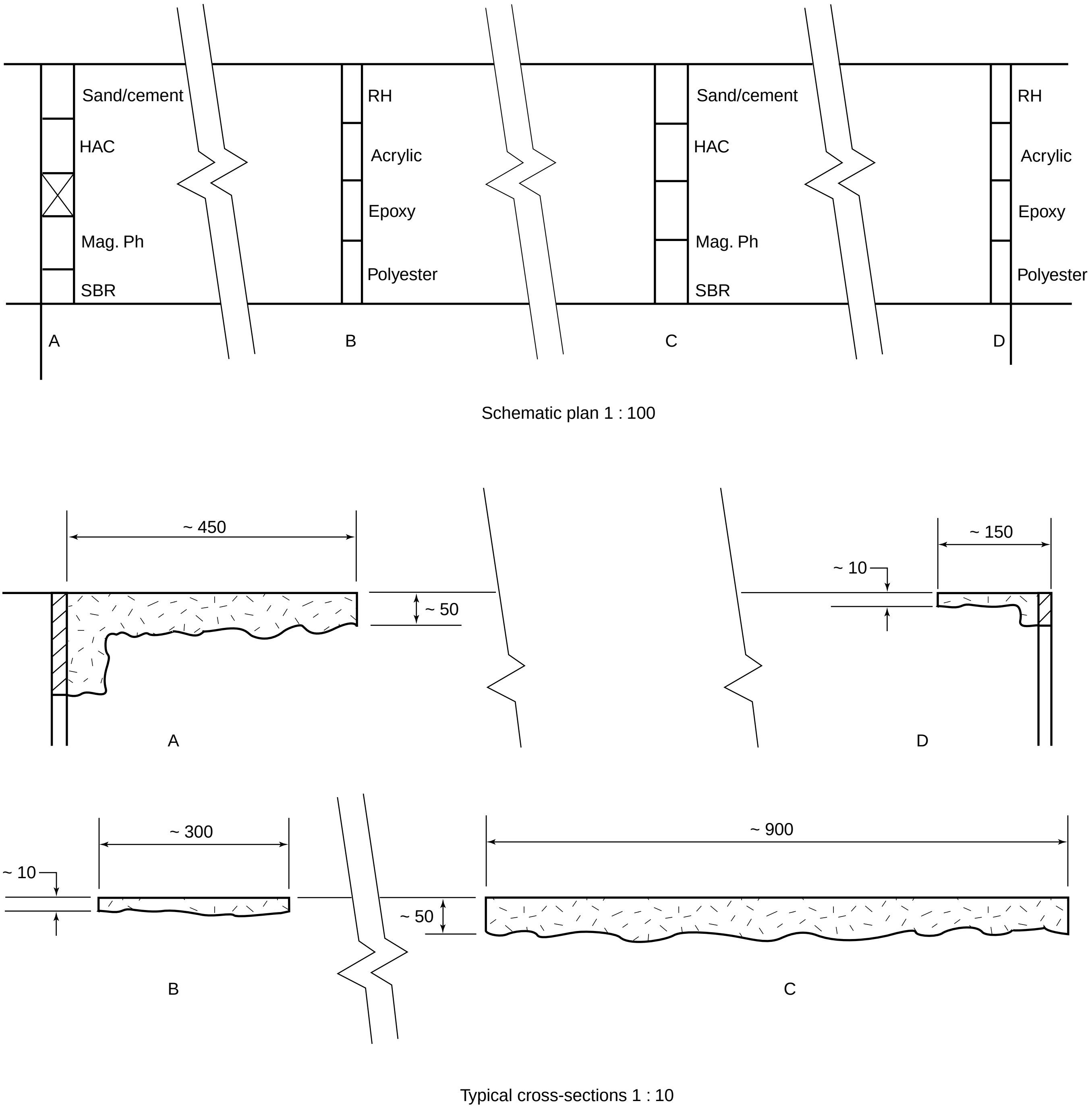


Figure 11 Pavement repairs at TRL

Table 5 Depth of repair material priced in the contract

Material	*Depth of repair (mm)* 10	50	100
Epoxy	✓	✓	
Polyester	✓		
Rapid hardening	✓	✓	
Acrylic	✓		
SBR		✓	✓
Magnesium phosphate		✓	✓
High alumina		✓	✓
Unmodified sand/cement		✓	✓
Microsilica concrete		✓	✓
Air entrained concrete		✓	✓

6 Full scale repair trials

A repair contract conducted on the A5 at Milton Keynes in the Autumn of 1993 was used to trial two of the materials appropriate for thicker surface and arris repairs; the high alumina and magnesium phosphate products. The standard material used for repairs on this contract was the microsilica concrete. The repairs were subsequently inspected in November 1995.

A second repair contract carried out on the M11 between Junctions 7 and 8 in the Autumn of 1994 was used to trial the SBR material in arris repairs and the epoxy, polyester, rapid hardening and acrylic materials in thin surface patch repairs. The standard material used for repairs on this contract was a ready-mixed air entrained concrete.

For these trials, a representative from the repair material supplier/producer was invited on site to ensure that the materials were laid and cured in the correct manner. Some representatives actually laid the materials in the trial, others instructed the contractor and kept a watching brief.

7 Discussion of results

For each test or property, the repair materials were ranked in order of performance and points awarded, with the best material being given the highest marks, either 10 or 8 depending upon the number of materials tested. Table 6 shows the scores for all the materials and tests. It should be noted that the standard repair materials were not put through all the tests as these were tested after the initial laboratory testing of the proprietary repair materials. No effort has been made to give more importance to any one test or property. An extra point was awarded for any material which passed the acceptance criteria for a particular test. The notes accompanying Table 6 explain the basis for awarding points to the tests.

The results for each test are discussed in more detail below.

7.1 Bond to substrate concrete

A general acceptance criteria for the bond strength between repair materials and a concrete substrate used by the industry is 1.5N/mm^2. For the tensile pull-off test used in this work, the acceptance criteria has been reduced by 20% to 1.2 N/mm^2. This represents the lower values recorded in a test of this nature as compared with those in a direct tension test (Emberson and Mays, 1990).

Table 6 Summary of technical performance

Material	*Test:* *Bond to substrate concrete*	*Short term shrinkage*	*Long term relative shrinkage*	*Bond on rel. shrinkage specimens*	*Thermal cycling*	*Moisture cycling*	*Nitrogen permeability*	*Chloride ion permeability*	*Freeze/thaw cycling*	*Fatigue resistance*	*Compressive modulus*	*Tensile strength*	*Time to opening*	*Percentage no. of passes*	*Total percentage score*	*Ranking*
Epoxy	3*	8*	9*	10*	10*	6*	6	5	4	5*	6	9*	5*	82	73	2
Polyester	2	1	10*	1	1	1	6	1	2	3	4	10*	10*	27	42	8
Rapid hardening	7*	3*	8*	6*	8*	10*	3	8	8*	9*	6	6*	3*	91	73	2
Acrylic	10*	7*	7*	2	8*	7*	4	2	7*	8*	7*	8*	4*	91	70	5
SBR	7*	6*	5*	9*	4	6*	8	6	6*	7*	8*	6*	1	82	68	6
Mag Phosphate	9*	5*	4*	8*	6*	4*	8	3	6*	2	3	4*	9*	82	62	7
High Alumina	1	4*	3*	4*	2	2	1	8	3	1	9*	1	9*	45	41	9
Sand/Cement	4*	2*	2*	4*	3	3	2	4	1	4	10*	2*	2	54	38	10
Microsilica	9*		1*	5*	5*	8*			10*	10*	1	7*	7*	90	72	4
A E concrete	5*		6*	8*	10*	10*			9*	6*	2	3*	6*	90	74	1
Note	(1)	(2)	(3)	(1)	(1)	(1)			(1)	(1)	(4)	(5)	(6)			

** = above acceptance criterion*
(1) Acceptance criterion >1.2N/mm^2
(2) Acceptance criterion <2000 microstrain
(3) Acceptance criterion <300 microstrain
(4) Acceptance criterion 30 ± 10kN/mm^2
(5) Acceptance criterion > 3.2N/mm^2
(6) Acceptance criterion 25N/mm^2 at 2 days

The results for this testing are presented to reflect the effect of curing at different temperatures, 5°C, 20°C or 30°C, and the effect of testing temperature, 5°C, 20°C or 30°C, in Figures 12 and 13 respectively.

Epoxy	In general, curing at 30°C was shown to be beneficial but testing at 30°C was shown to be detrimental.
Polyester	Performed poorly in all tests, no bond achieved when cured at 5°C, temperature of test had little effect.
Rapid hardening	Testing at 30°C proved slightly detrimental but the acceptance criteria was always met.
Acrylic	Satisfactorily achieved the acceptance criteria.
SBR	Benefitted from curing at 30°C, testing at high temperature after curing at low temperature had a detrimental effect.
Magnesium phosphate	Large difference in results when cured at 5°C indicating possible poor performance at low temperature.
High alumina	Unsatisfactory results at all test and curing temperatures.
Sand/cement	A wide scatter in the results made it difficult to distinguish any trends, although no benefit seems to have been achieved by testing or curing at 30°C.
Microsilica concrete	Performed well at all temperatures except when tested at 30°C.
Air entrained concrete	Curing at 30°C was detrimental, whilst curing at 5°C appeared to be beneficial.

The polyester and high alumina materials performed poorly in this test, both consistently below the acceptance criterion. Only the rapid hardening material was consistently above the acceptance criterion.

7.2 Movement relative to substrate concrete

This testing is presented as the shrinkage of the individual repair materials, the relative shrinkage of the composite specimens and the pull-off results from the composite specimens used in this part of the programme.

7.2.1 Shrinkage of repair materials and composite specimens

The results of the short term shrinkage testing to BS 6319 Part 12 on the repair materials and the unenclosed testing are shown in Figures 14 and 15 respectively. The long term relative shrinkage of the composite specimens is shown in Figure 16.

The technical performance assessment for shrinkage was based on the maximum strain recorded, whether expansion or shrinkage. The results in Figure 14, the enclosed testing, were used for the short term shrinkage assessment.

An acceptable repair material shrinkage was deemed to be 2000 microstrain, equivalent to 20 x 10^{-4} in Figure 14, based upon visual observations during the bond to base concrete tests. The polyester debonded from the substrate concrete at an early age due to thermal contraction. None of the other materials exhibited this behaviour, and as such, the early age shrinkage was satisfactory for these.

An acceptable relative shrinkage between the repair material and the substrate concrete was deemed to be 300 microstrain as this reflected the upper limit observed with all the materials in the long term testing.

Epoxy	Showed virtually no unrestrained short term movement and very little long term relative shrinkage.
Polyester	Had a very high initial unrestrained shrinkage but with very little subsequent long term relative shrinkage.
Rapid hardening	Fairly high unrestrained short term shrinkage but very little long term relative shrinkage.
Acrylic	The unrestrained enclosed test showed initial expansion followed by shrinkage, there was little long term relative shrinkage.
SBR	Initially showed expansion in the enclosed test but shrinkage when unenclosed, the long term relative shrinkage was slight.
Magnesium phosphate	Showed expansion in the short term unrestrained test but the long term test showed a relative shrinkage. There was large variability between samples.
High alumina	Expansion occurred in the short term unrestrained test when enclosed but relative shrinkage occurred in the long term. The unenclosed short term results indicated shrinkage.
Sand/cement	Showed the largest unrestrained expansion when enclosed but relative shrinkage occurred in the long term tests. When unenclosed the short term results indicated shrinkage.
Microsilica concrete	Continued to shrink at a constant rate relative to the substrate concrete.
Air entrained concrete	Exhibited very little long term shrinkage relative to the substrate concrete.

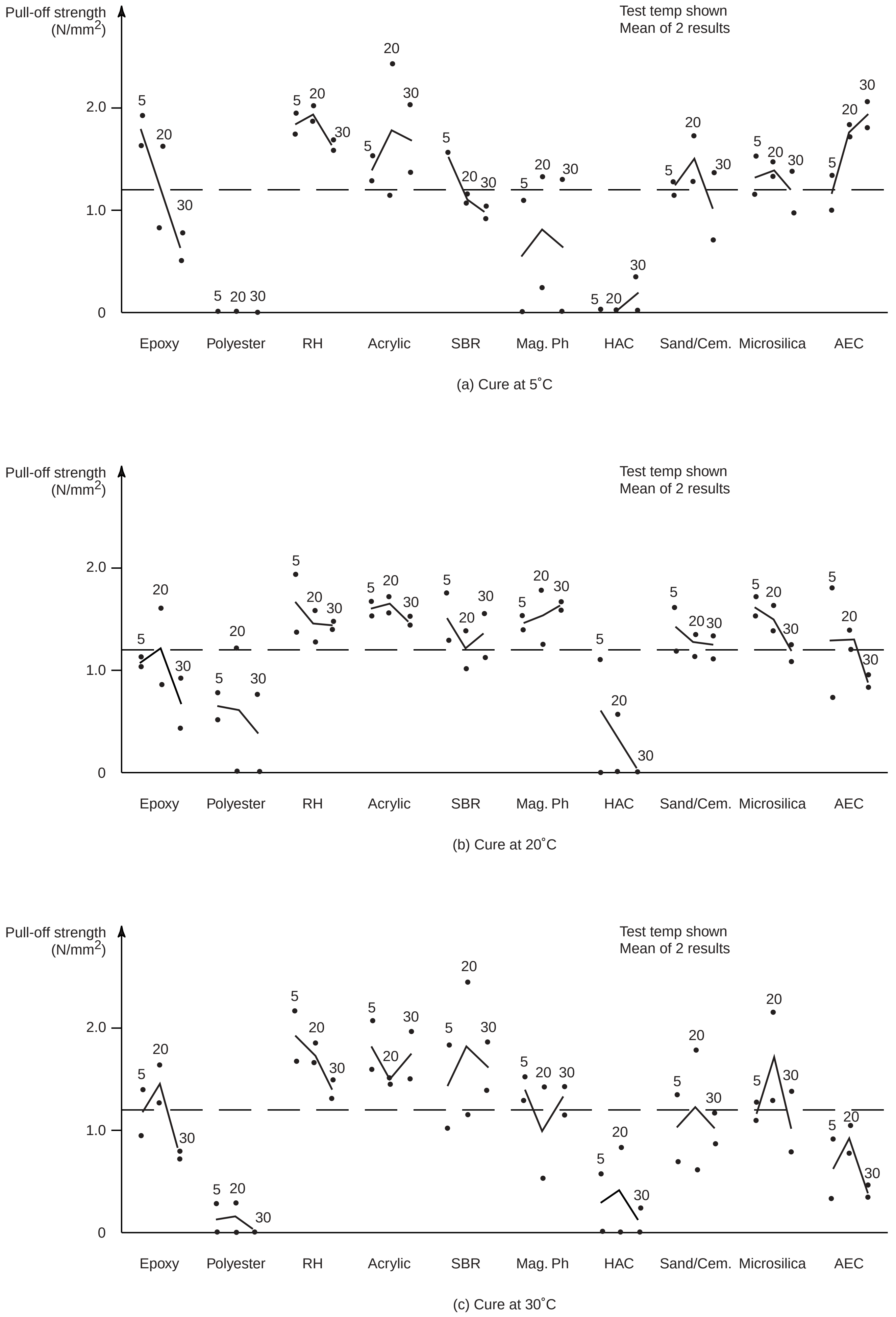


Figure 12 Bond to substrate concrete at various curing temperatures

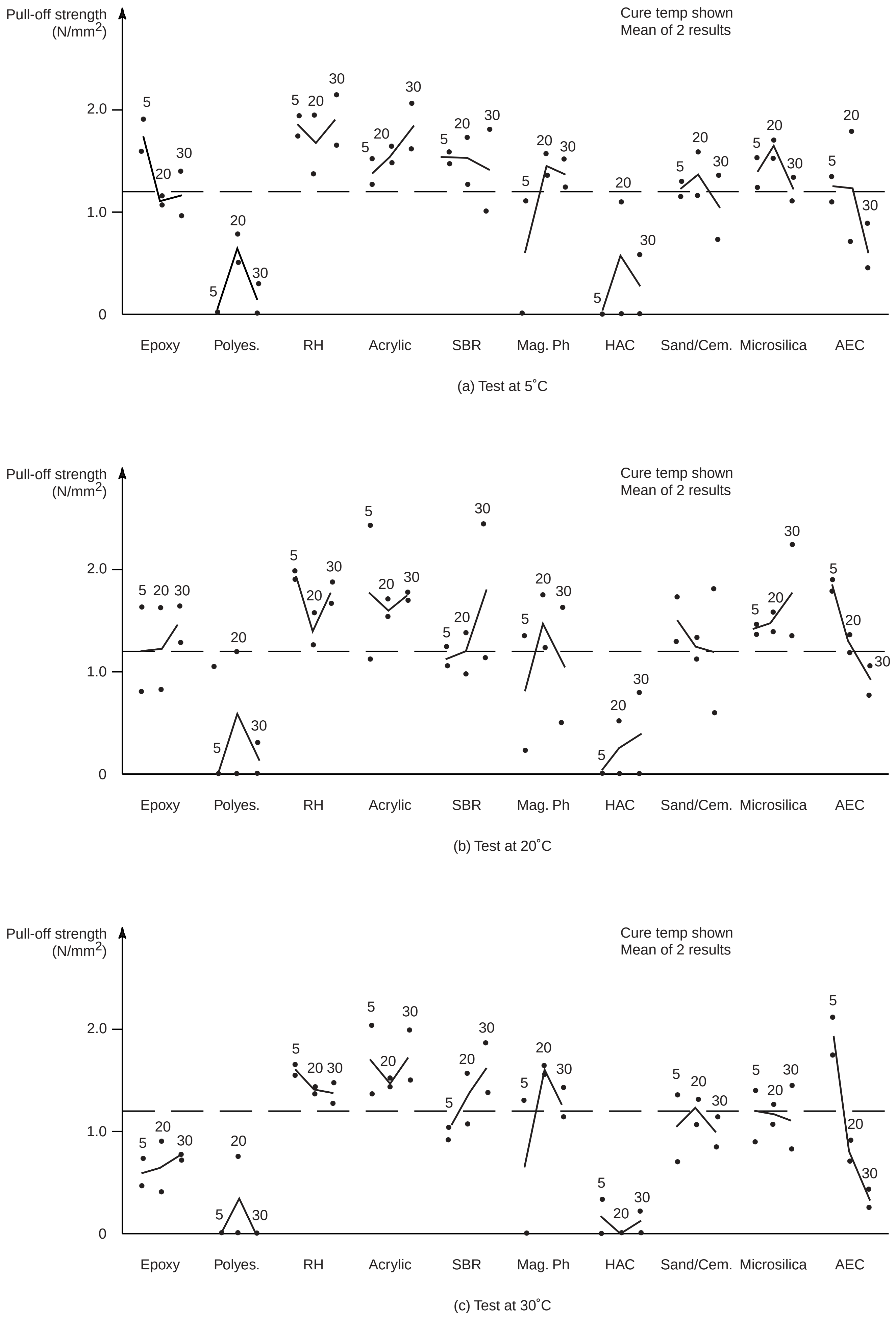
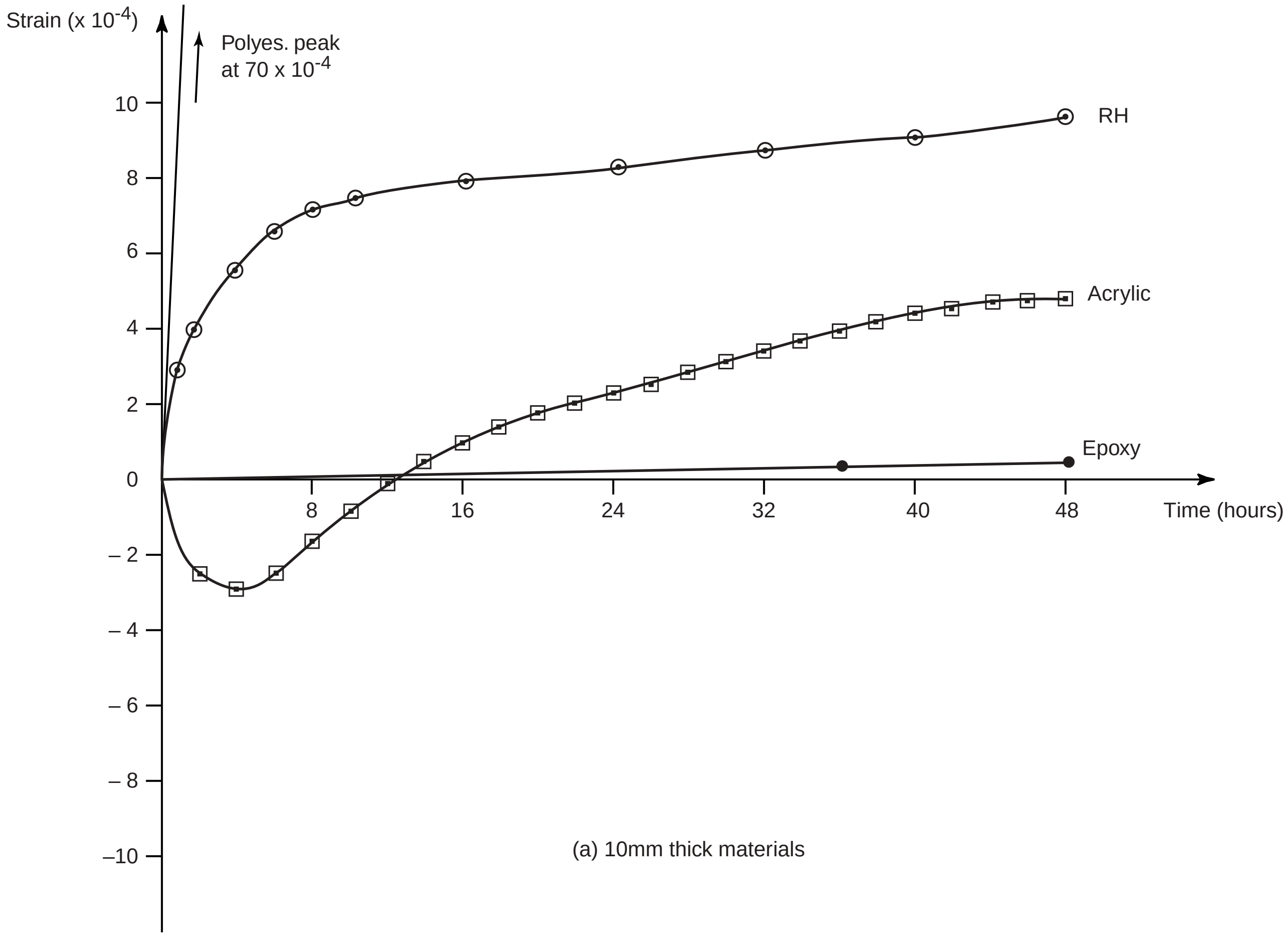


Figure 13 Bond to substrate concrete at various test temperatures



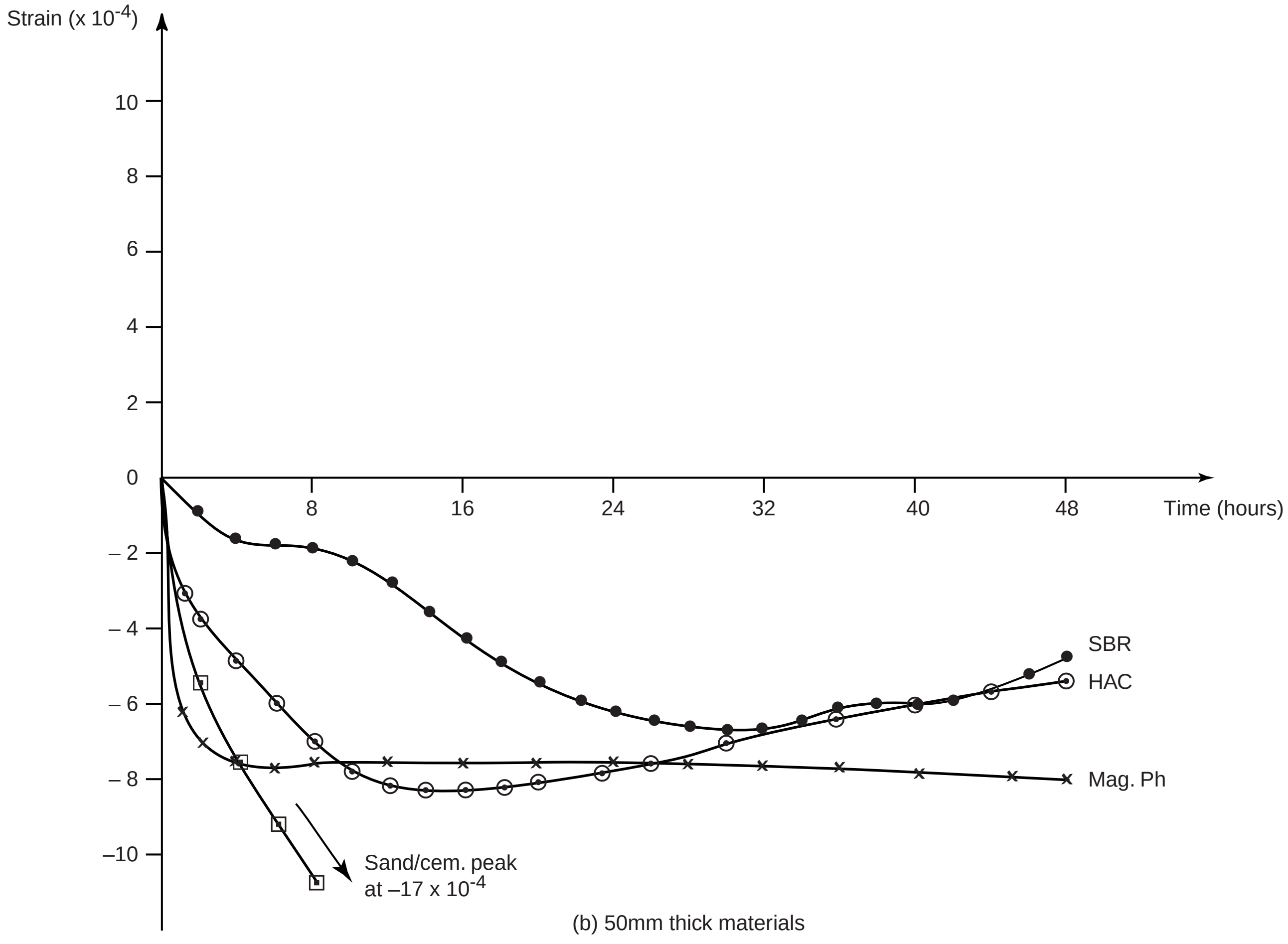


Figure 14 Material shrinkage (sample enclosed)

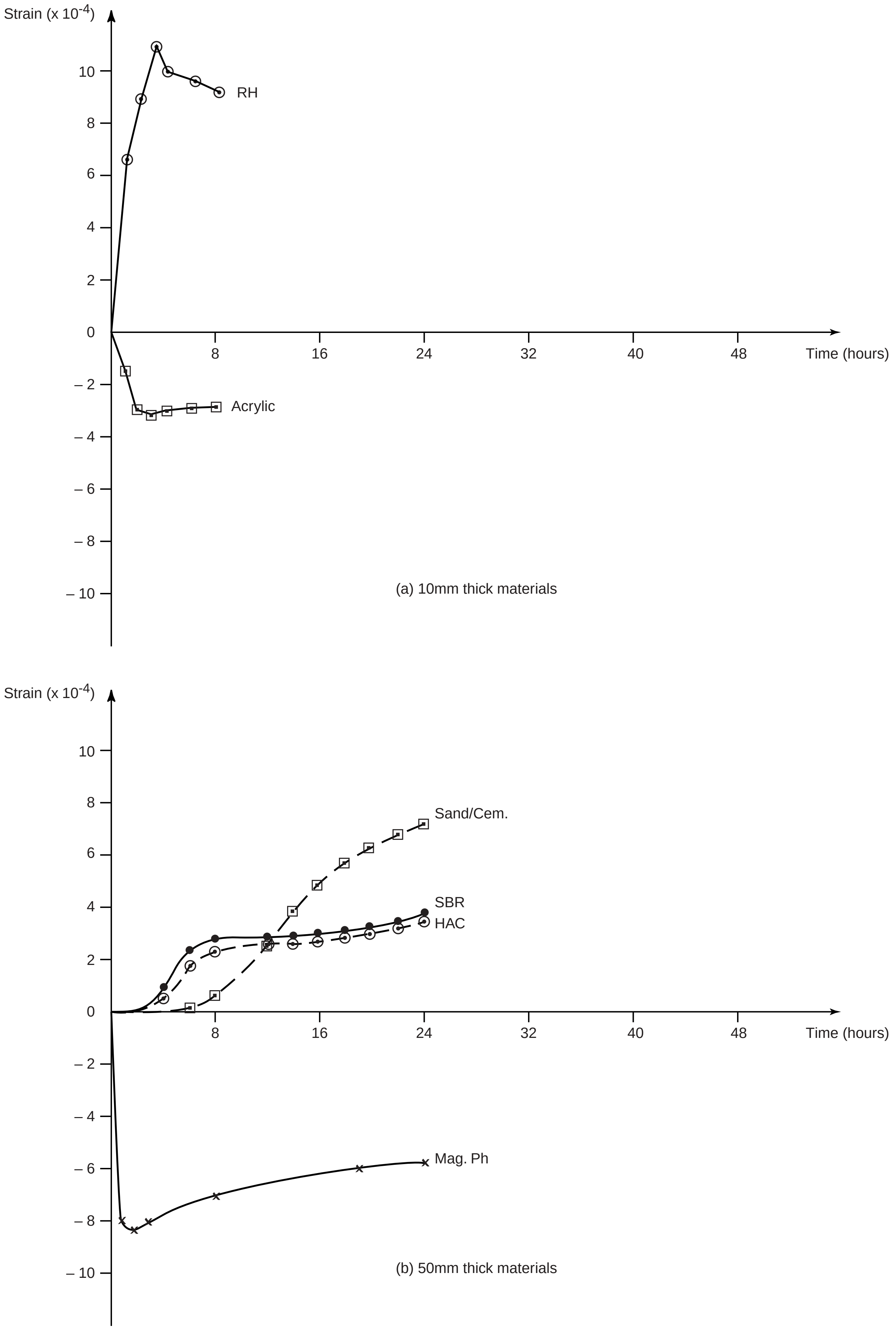


Figure 15 Material shrinkage (sample not enclosed)

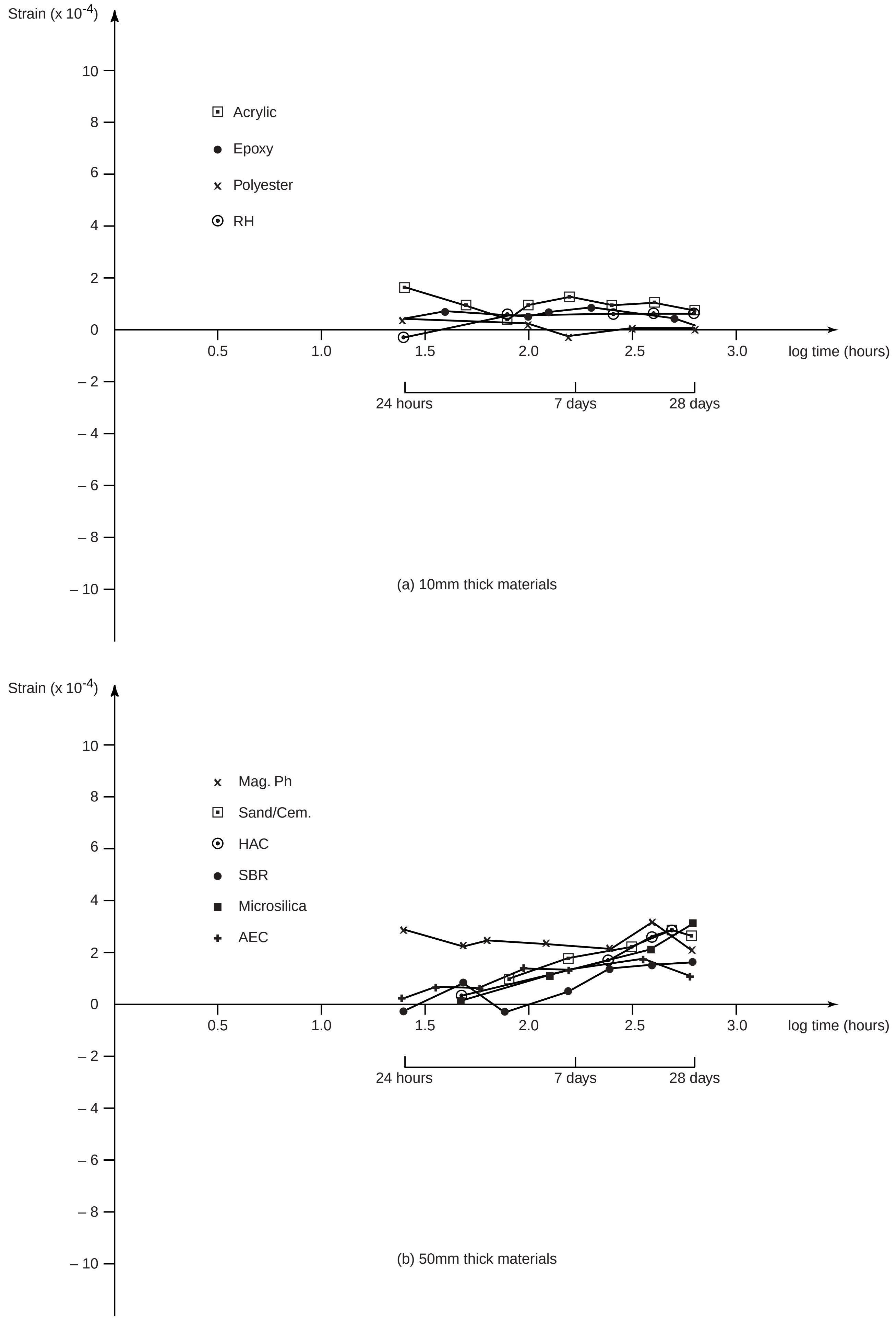


Figure 16 Post 24 hour shrinkage relative to substrate

All the materials with the exception of the polyester, which debonded from the substrate concrete, were deemed to have past these tests.

It was interesting to note that in the unenclosed test the SBR, sand/cement and high alumina all exhibited shrinkage whereas they exhibited expansion in the enclosed test. This brings into question the usefulness of the test on the unrestrained repair material alone.

7.2.2 Pull-off testing of composite shrinkage specimens

The comments below are based upon the development of pull-off strength over a 28 day period from casting the composite specimens for the relative movement assessment, the results are shown in Figure 17 and summarised in Table 7.

Table 7 Average pull-off strengths in N/mm² of composite specimens

Material	*Standard test (Figure 17)*	*Thermal cycling (Figure 18)*	*Moisture cycling (Figure 19)*	*Freeze/thaw cycling (Figure 20)*
Epoxy	2.2	2.2	1.3	1.0
Polyester	0.9	0	0.2	0.8
Rapid hardening	1.6	1.9	1.7	1.7
Acrylic	1.1	1.8	1.5	1.6
SBR	1.8	1.0	1.3	1.4
Magnesium phosphate	1.6	1.6	1.3	1.4
High alumina	1.2	0.1	0.7	0.9
Sand/cement	1.2	0.5	1.1	0.1
Microsilica concrete	1.4	1.6	1.6	1.9
Air entrained concrete	1.7	2.4	1.7	2.0

Epoxy	Showed a marked improvement with time.
Polyester	A decrease in performance with time was recorded, supported by visual evidence of the repair debonding due to shrinkage.
Rapid hardening	A significant improvement with time was noted.
Acrylic	This showed a slight improvement with time but still failed to achieve the required strength.
SBR	Showed an increase in strength with time.
Magnesium phosphate	Showed an increase in strength with time.
High alumina	A slight decrease in performance with time was noted.
Sand/cement	A slight decrease in performance with time was noted.
Microsilica concrete	Achieved adequate bond strength within 48 hours.
Air entrained concrete	Developed good tensile bond strength with time.

The only materials not to achieve an average pull-off strength in excess of 1.2 N/mm² at 28 days were the polyester and acrylic. The rapid hardening achieved the strength in approximately 12 hours and the epoxy and magnesium phosphate achieved it by approximately 7 days. The SBR, high alumina, sand/cement and air entrained concrete had achieved the strength when first tested at one or two days.

7.2.3 Thermal cycling

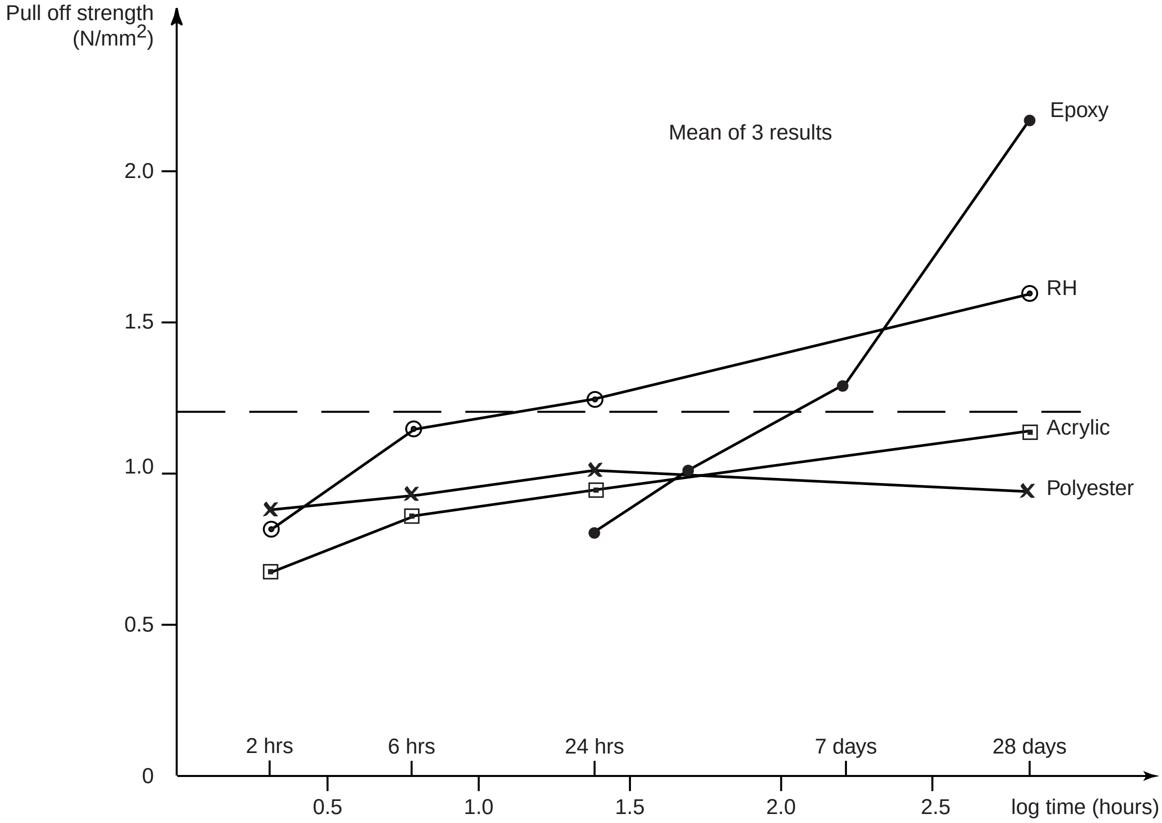
The results of the pull-off testing after the thermal cycling are shown in Figure 18. By comparing these results with the 28 day pull-off strength achieved during the shrinkage of composite specimens test, shown in Figure 17 and Table 7, it is possible to gauge the effect of thermal cycling.

Epoxy	There was a large difference between the two batches, the average value being similar to that found earlier.
Polyester	Performed very poorly.
Rapid hardening	Did not seem to be affected by the test regime.
Acrylic	Some improvement due to the thermal cycling.
SBR	A wide spread of results with the thermal cycling being detrimental.
Magnesium phosphate	Did not seem to be affected by the test regime.
High alumina	Performed poorly.
Sand/cement	A wide scattering of results with one batch performing very poorly, the other batch seemed unaffected by the test regime.
Microsilica concrete	Batch 2 appeared to improve with the thermal cycling regime but batch 1 performed less well, a similar average result was achieved to the standard test.
Air entrained concrete	A fairly wide spread of results, with possibly some benefit having been derived from the thermal cycling for this material.

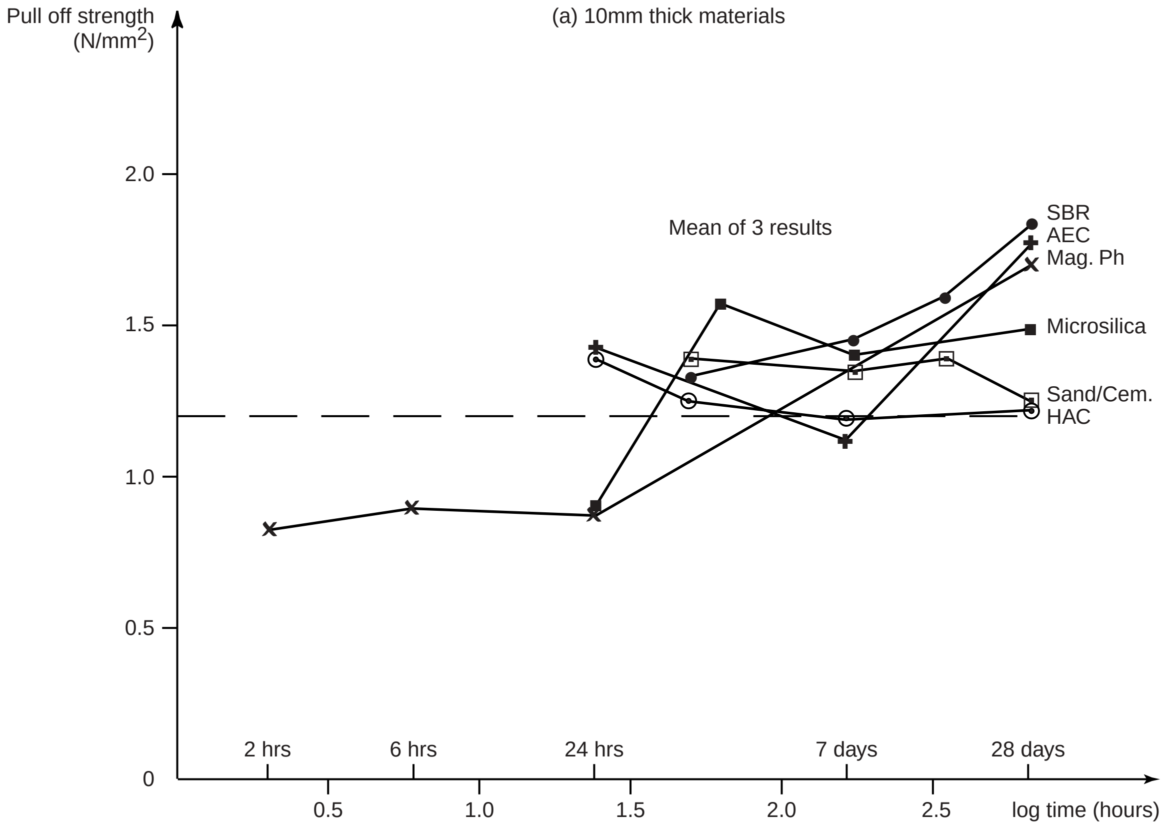
The only materials whose average value from the two batches failed to reach the acceptance criterion were the polyester and high alumina. The SBR and the sand/cement were just below the acceptance criterion, although the average value of one batch of each did achieve it. For all the other materials the average value satisfied the acceptance criterion.

7.2.4 Moisture cycling

The results of the pull-off testing after the moisture cycling are shown in Figure 19 and Table 7. These have been assessed in the same manner as those for the thermal cycling.



(a) 10mm thick materials



(b) 50mm thick materials

Figure 17 Shrinkage of composite specimens

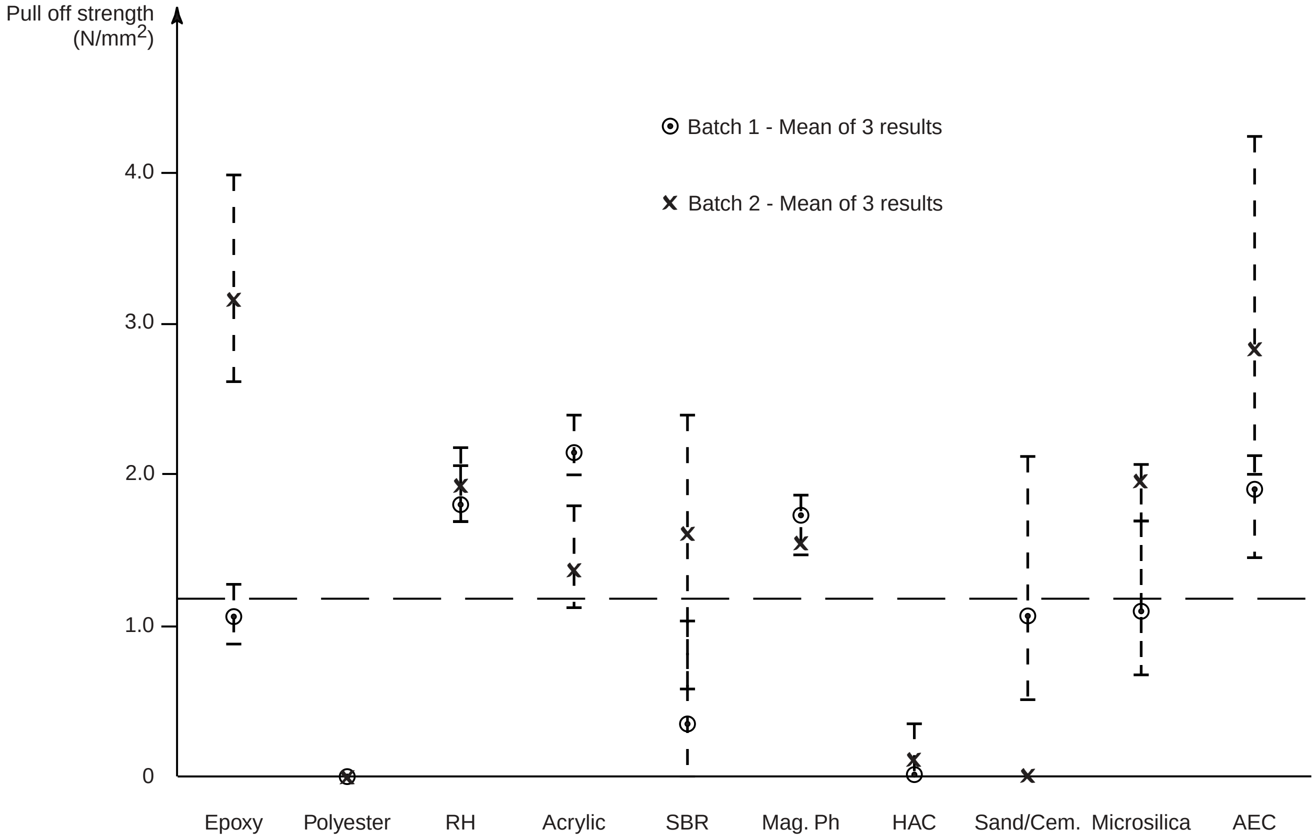


Figure 18 Pull-off strength after thermal cycling

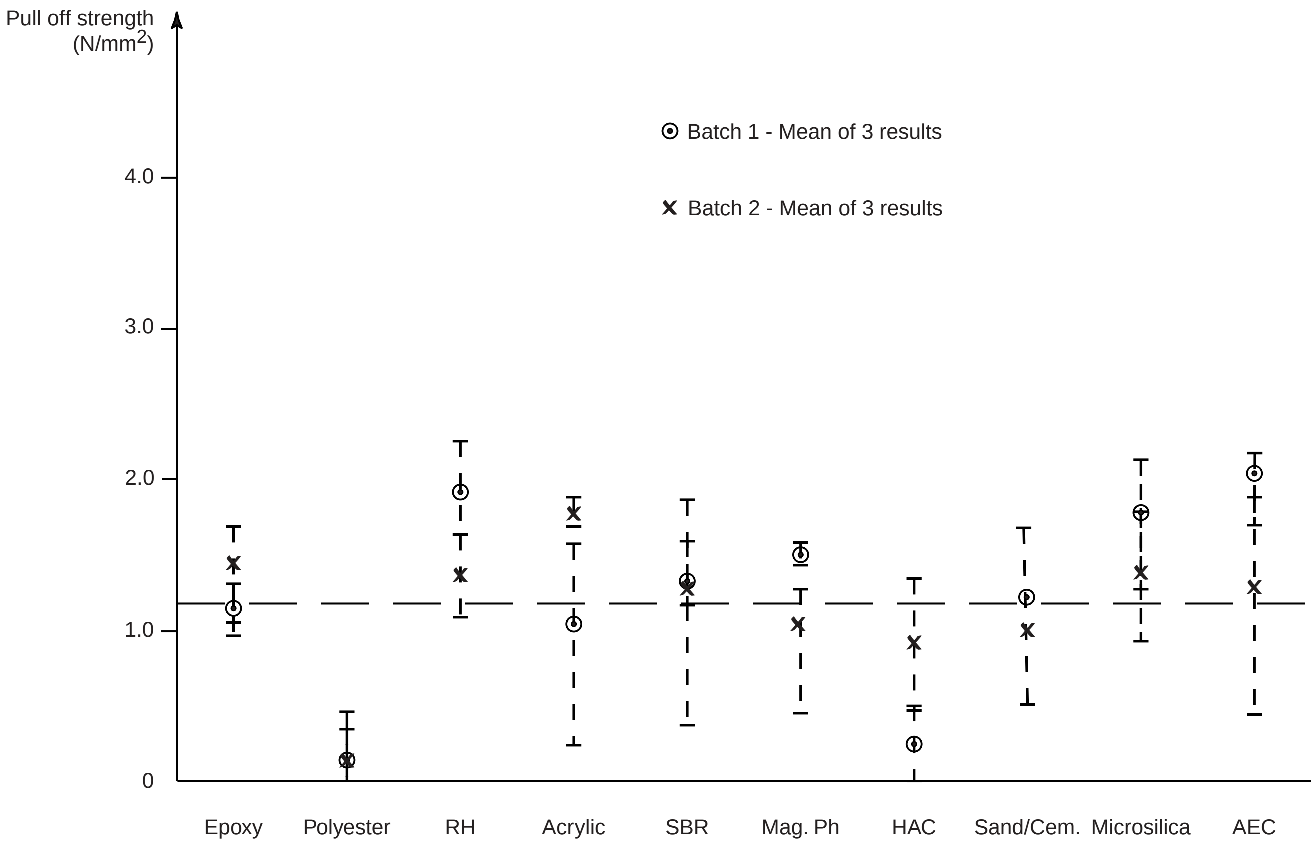


Figure 19 Pull-off strength after moisture cycling

Epoxy	The two batches produced similar results with a reduction in performance.
Polyester	Performed very poorly.
Rapid hardening	Seemed to be unaffected by the testing regime.
Acrylic	Very variable results between batches, with the second batch showing an improvement from the standard results.
SBR	Both batches were adversely affected.
Magnesium phosphate	The average value of the two batches was only slightly affected by the testing regime.
High alumina	Performed poorly.
Sand/cement	Unaffected by the testing regime.
Microsilica concrete	Unaffected by the testing regime.
Air entrained concrete	There was a wide spread of results, however, the mean value of the two batches was similar to that in the standard testing.

The average pull-off strength for all the materials reached the acceptance criterion, except for the polyester and high alumina.

7.3 Freeze/thaw cycling

The results of the pull-off testing after the freeze/thaw cycling are shown in Figure 20 and Table 7. These have been assessed in the same manner as those for the thermal and moisture cycling.

Epoxy	There was high variability between batches, with both batches performing poorly compared to the standard test and the overall average failing to meet the acceptance criterion.
Polyester	Batch 2 appeared to be relatively unaffected by the test regime but batch 1 performed poorly. The average being similar to the standard.
Rapid hardening	Unaffected by the test regime.
Acrylic	Both batches gave similar results and a slightly improved performance.
SBR	Batch 1 was unaffected but batch 2 was adversely affected.
Magnesium phosphate	There was some variation between batches but the average value was similar to the standard testing.
High alumina	Both batches failed to meet the acceptance criteria.

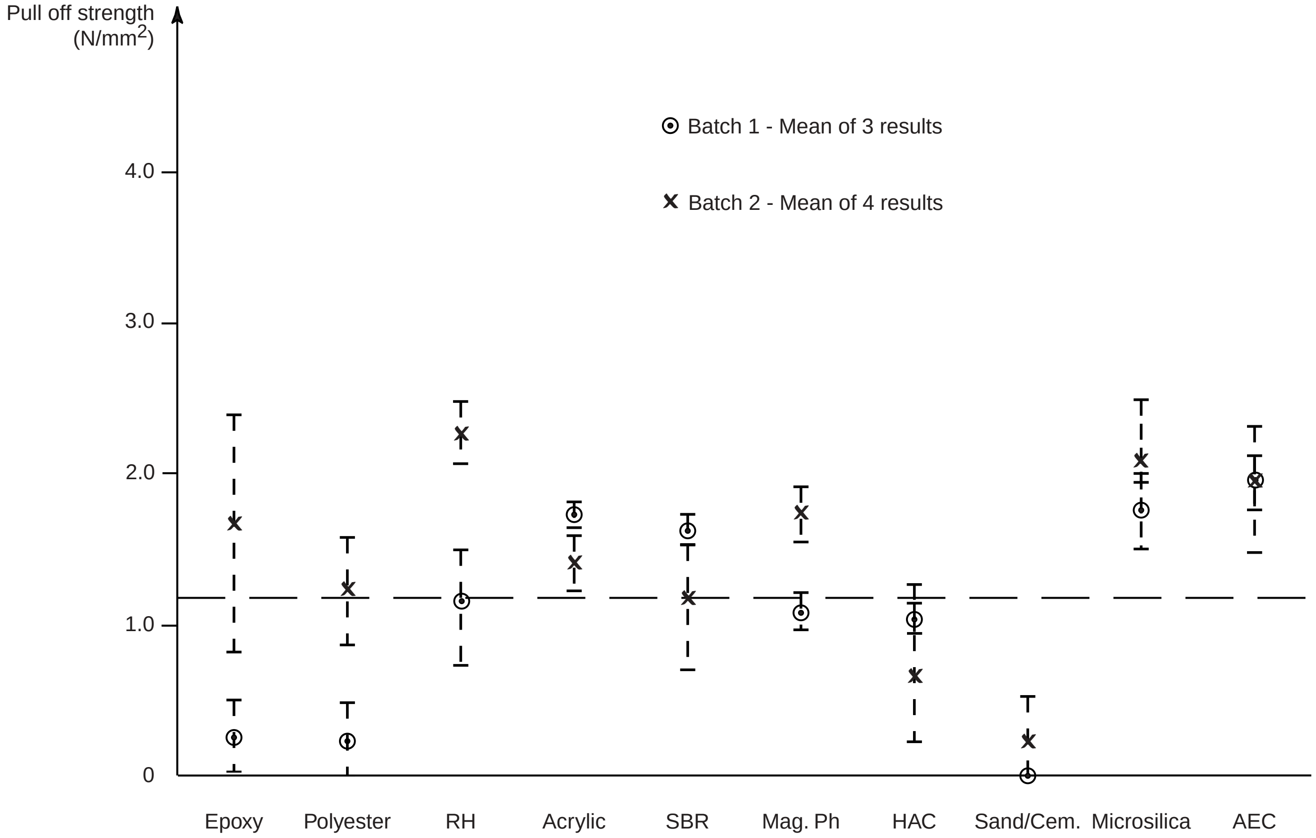


Figure 20 Pull-off strength after freeze/thaw cycling

Sand/cement	This material shows most susceptibility to the testing regime with both batches performing poorly.
Microsilica concrete	Both batches were unaffected by this testing regime with slightly better average results.
Air entrained concrete	Both batches gave similar results and were unaffected by the testing regime.

The average value of the rapid hardening, SBR, acrylic, magnesium phosphate, microsilica and air entrained concrete met the acceptance criterion. The high alumina, polyester and epoxy average values fell just below the acceptance level whilst the sand/cement performed poorly.

7.4 Fatigue resistance

The comments below relate to the performance during the fatigue test. The pull-off strengths achieved after this test are shown for the relevant positions at the end, or the centre, of the repair in Figure 21. The acceptance criterion of 1.2N/mm^2 is required in the pull-off test.

Epoxy	Threequarters of the underside repair on one of the beams fell out at the start of the test. The centre of the repairs, both top and bottom, failed to meet the acceptance criterion.
Polyester	The underside of the beams gave higher pull-off strengths than the top, but only one position met the acceptance criterion.
Rapid hardening	The pull-off strengths met the criterion at all locations.
Acrylic	The pull-off strengths met the criterion at all locations. It is interesting to note that the bond strengths exceeded those determined at 28 days, possibly indicating that the strength was increasing with time.
SBR	The criterion was met in three of the testing locations.
Magnesium phosphate	The required strength was not achieved at any of the locations. Being a stiff material it would be susceptible to stress concentrations and fatigue loading which is demonstrated in the results.
High alumina	The entire soffit repair fell out of one beam and the remaining test results were very poor.
Sand/cement	The pull-off strengths met the criterion in all locations except the bottom edge of the repair.
Microsilica concrete	On one beam an 80mm long delamination occurred. There was only one location where the required pull off strength was not achieved and this was where the repair material had cracked. The pull-off strengths were again higher than those recorded at 28 days.
Air entrained concrete	On one beam a 100mm long delamination occurred. The strength criterion was exceeded at three locations, with one failure being within the concrete substrate.

The microsilica concrete, air entrained concrete, rapid hardening and acrylic were the only materials to achieve the pull-off criterion. The magnesium phosphate, epoxy and high alumina performed poorly. The occurrence of delamination, however, at the ends of the standard repair materials indicates that these materials may have some susceptibility to fatigue loading, perhaps because of their relatively high modulus of elasticity as compared to that of the substrate concrete. However, it must be appreciated that this may be a particularly severe test for road pavements and may be more relevant with a lower level of loading.

7.5 Tensile strength and static modulus

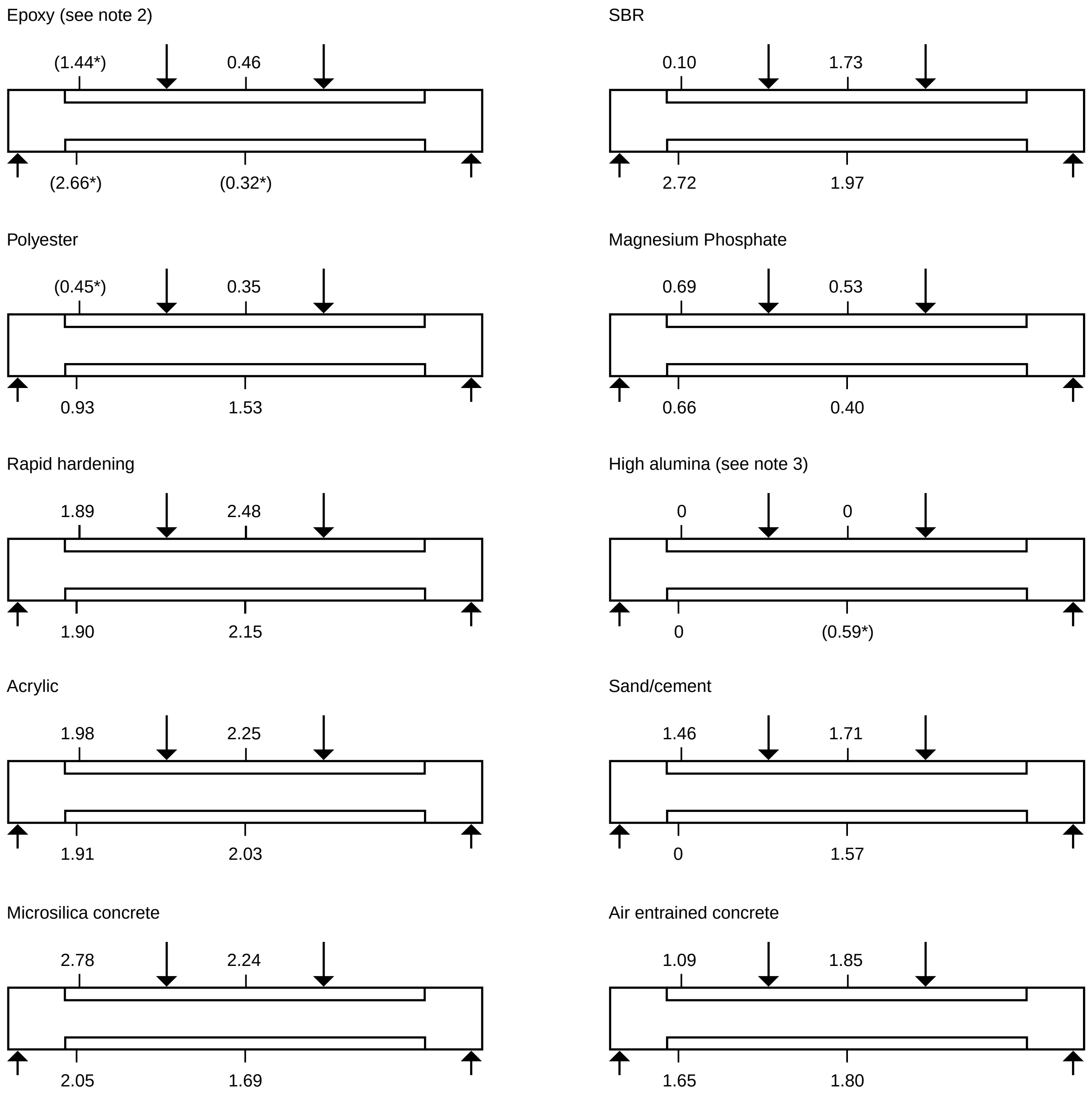
The acceptance criterion for the tensile strength has been set at 3.2N/mm^2 at 28 days, which is eight per cent of the characteristic cube strength.

The acceptance level for the static compression modulus has been based upon a representative value for concrete of 30kN/mm^2 with a tolerance of ±10kN/mm^2. This is based on previous work by Emberson and Mays. Low modulus repair materials were found to generate stress concentrations and hence the possibility of cracking in the bonded concrete, whilst high modulus repair materials attract load and may be vulnerable to adhesion failures at the repair/substrate interface.

7.5.1 Tensile strength

The results of the testing at 2 days and 28 days are presented in Figure 22. The strength achieved at 28 days has been used in the technical performance assessment in Table 6.

Epoxy	Only the samples cured at 5°C and tested at two days failed to achieve the 3.2N/mm^2. Generally the results were very high.
Polyester	Exhibited very high tensile strength at all temperatures and both ages.
Rapid hardening	Met the strength requirement at all temperatures and both ages. There was little gain in strength after 2 days.
Acrylic	Failed to achieve the 3.2N/mm^2 strength at 2 days when cured at 5°C. At 28 days easily met the acceptance criterion for all the cure temperatures.



Notes:

1. Average of 2 beams except where marked (*)
2. 75% of soffit repair fell out of one epoxy beam
3. 100% of the soffit repair fell out of one HAC beam

Figure 21 Post-fatigue pull-off strengths (N/mm^2)

SBR	Failed to achieve the 3.2N/mm^2 strength at 2 days at all temperatures. At 28 days met the acceptance criterion for all cure temperatures.
Magnesium phosphate	Met the strength requirement at all temperatures and both ages. There was little gain in strength after 2 days.
High alumina	Failed to achieve the required strength at any temperature at 2 or 28 days.
Sand/cement	Only achieved the 3.2N/mm^2 strength at 30°C at 2 days but by 28 days had achieved the criterion at all temperatures.
Microsilica concrete	The tensile strength was adversely affected by curing at 5°C and 30°C with the required strength only being met at 20°C at 2 days although at 28 days the acceptance criterion was nearly achieved at all temperatures.

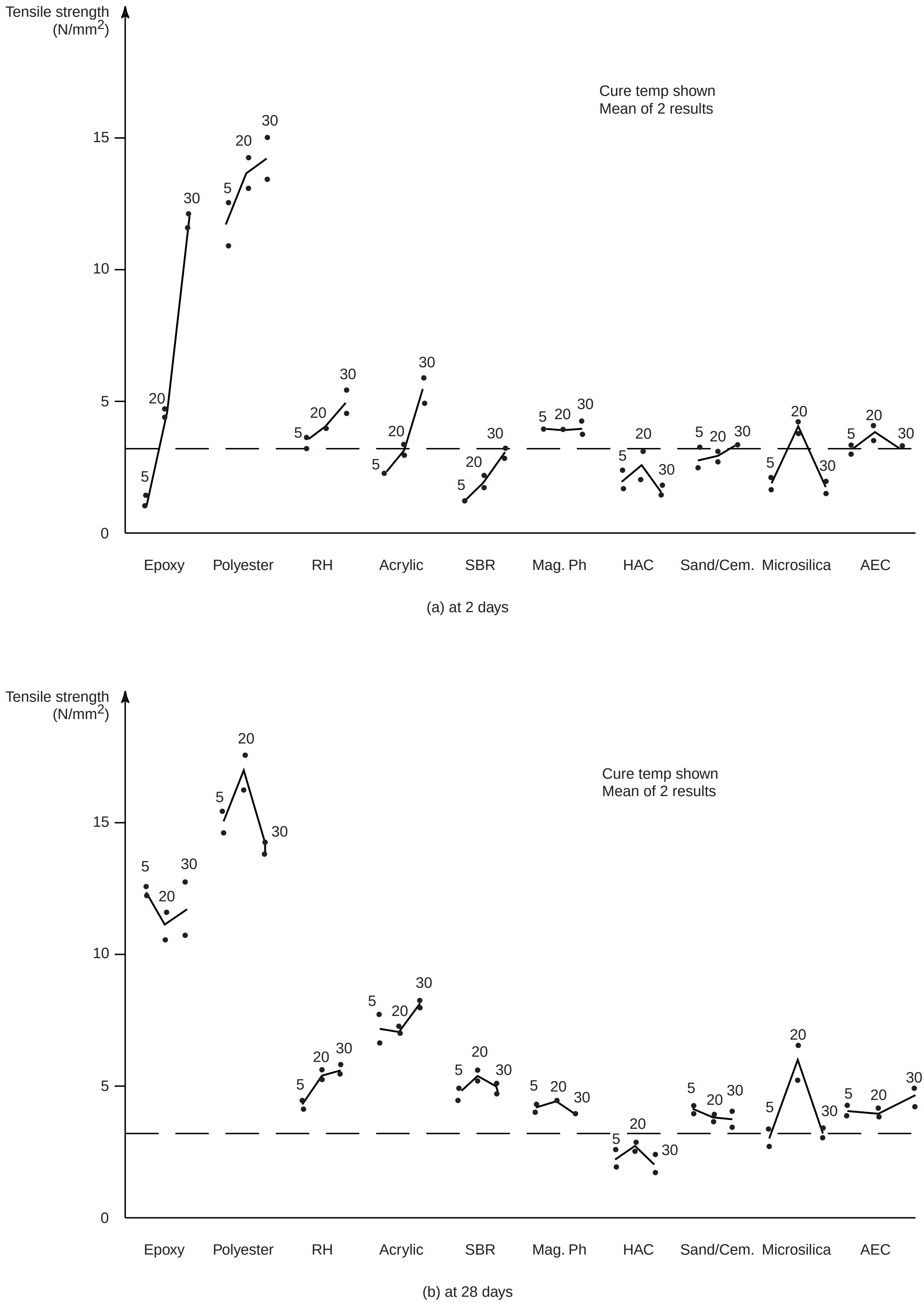


Figure 22 Tensile strength at various temperatures

Air entrained concrete	This material achieved the required strength within 2 days and was little affected by the curing temperature.

The epoxy and polyester achieved very high tensile strengths but the high alumina performed poorly. The other materials all achieved similar strengths.

This test is more suitable for repair materials with fine aggregate and some tensile bond failures occurred at the surface of the coarse aggregates within the microsilica and air entrained concrete materials. A more suitable test for materials with coarser aggregates may be the tensile splitting test specified in BS 1881 Part 117 (BSI, 1983e).

7.5.2 Static modulus

The results of the static compressive modulus testing undertaken at 28 days are presented in Figure 23. The performance assessment in Table 6 was based on how close the results were to 30kN/mm^2, the acceptance criterion was 30 ± 10kN/mm^2.

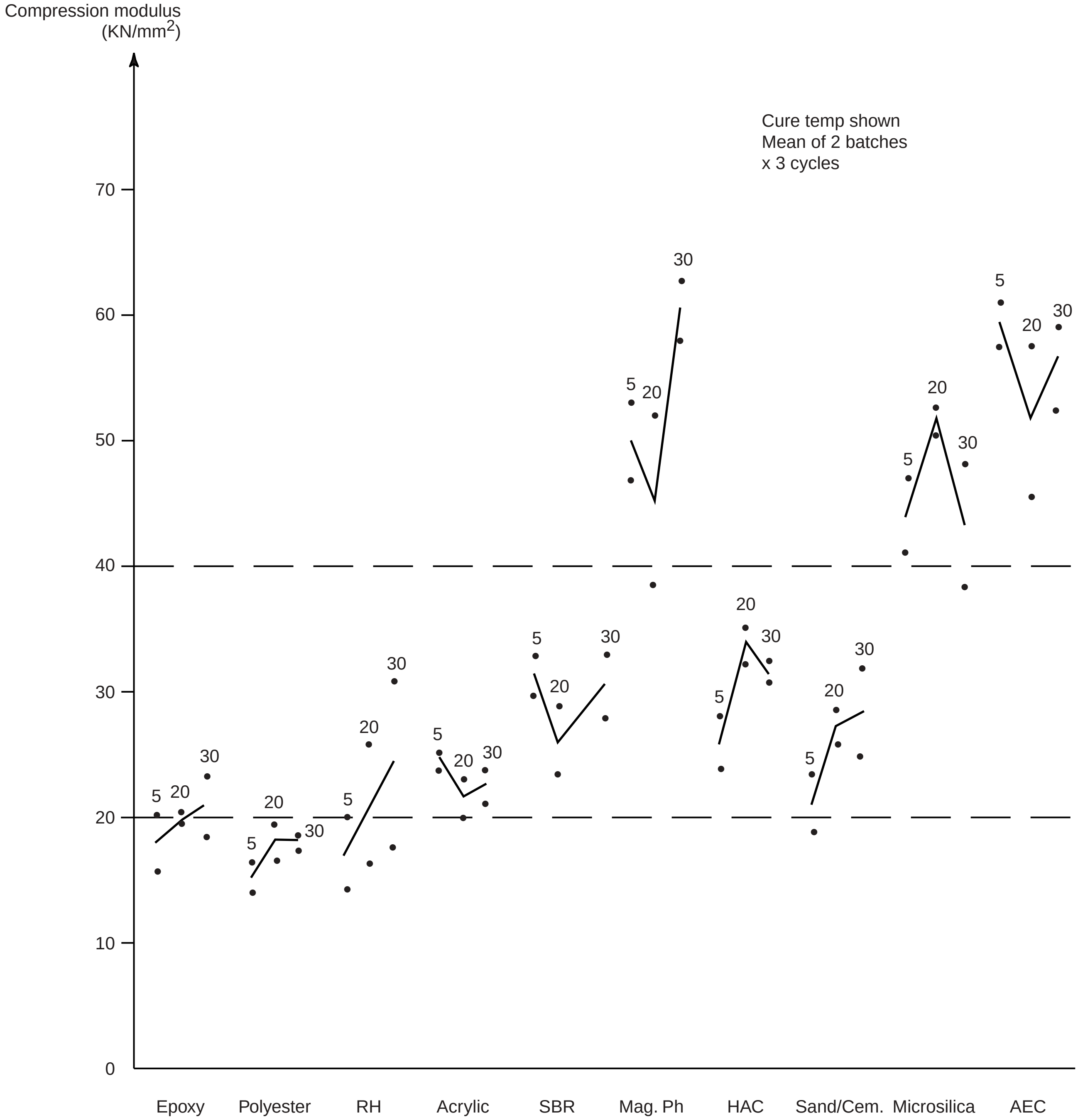


Figure 23 Compression modulus at various temperatures

Epoxy	The temperature had a slight influence on the results with the average value just meeting the criteria at 20°C and 30°C.
Polyester	Failed to meet the acceptance criteria, being more flexible than concrete.
Rapid hardening	The temperature had a greater influence than on the epoxy, the average value just met the criterion 20°C and it was easily met at 30°C.
Acrylic	The temperature had little influence and the criteria was achieved at all temperatures.
SBR	Very similar results to those achieved with the substrate concrete. Met the criteria at all temperatures.
Magnesium phosphate	Failed to meet the acceptance criteria. A very stiff material with a very high modulus at all temperatures.
High alumina	Very similar results to those achieved with the substrate concrete. Met the criteria at all temperatures.
Sand/cement	Very similar results to those achieved with the substrate concrete at 20°C and 30°C. The average values met the criteria at all temperatures.
Microsilica concrete	Failed to meet the acceptance criteria. Had a very high modulus in comparison to the substrate concrete.
Air entrained concrete	Failed to meet the acceptance criteria. Had a very high modulus in comparison to the substrate concrete.

The polyester was too flexible, as was the epoxy and rapid hardening at low temperature. The magnesium phosphate and the two standard repair materials were too stiff.

7.6 Time to opening

The requirement was set as a compressive cube strength of 25N/mm^2 at 48 hours, as detailed in the Specification for Highway Works. The results are shown in Figure 24.

Epoxy	The strength development of the epoxy was greatly influenced by the curing temperature, requiring over 2 days at 5°C to achieve the 25N/mm^2.
Polyester	Achieved the required strength at all temperatures within 2 hours.
Rapid hardening	The required strength was achieved within 2 days at all temperatures.
Acrylic	The temperature had little influence and the required strength was achieved at all temperatures in 2 days.
SBR	Required 7 days to achieve the required strength at 5°C and over 2 days at 20°C.
Magnesium phosphate	The required strength was achieved within 2 hours at all temperatures.
High alumina	Had easily achieved the required strength when tested at 24 hours.
Sand/cement	Required longer than 2 days to achieve the required strength at 5°C.
Microsilica concrete	Reached the required strength within 24 hours at all temperatures, and at approximately 6 hours at 30°C.
Air entrained concrete	Reached the required strength within 24 hours at all temperatures, and at approximately 6 hours at 30°C.

All of the materials achieved the strength requirement of 25N/mm^2 at 48 hours except the sand/cement and SBR at 5°C and the SBR at 20°C. An estimate of the time required for the repair materials to achieve the 25N/mm^2 is given in Table 8.

Table 8 Estimated time in days to achieve a strength of 25N/mm^2 for opening

Material	*Test temperature* 5°C	20°C	30°C
Epoxy	1.5	0.4	0.14
Polyester	0.05	0.05	0.04
Rapid hardening	2.0	1.4	1.0
Acrylic	1.5	1.4	0.8
SBR	7.0	5.3	1.8
Magnesium phosphate	0.09	0.07	0.07
High alumina	0.4	0.3	0.4
Sand/cement	3.0	1.3	0.9
Microsilica	0.9	0.5	0.3
Air entrained concrete	0.9	0.6	0.23

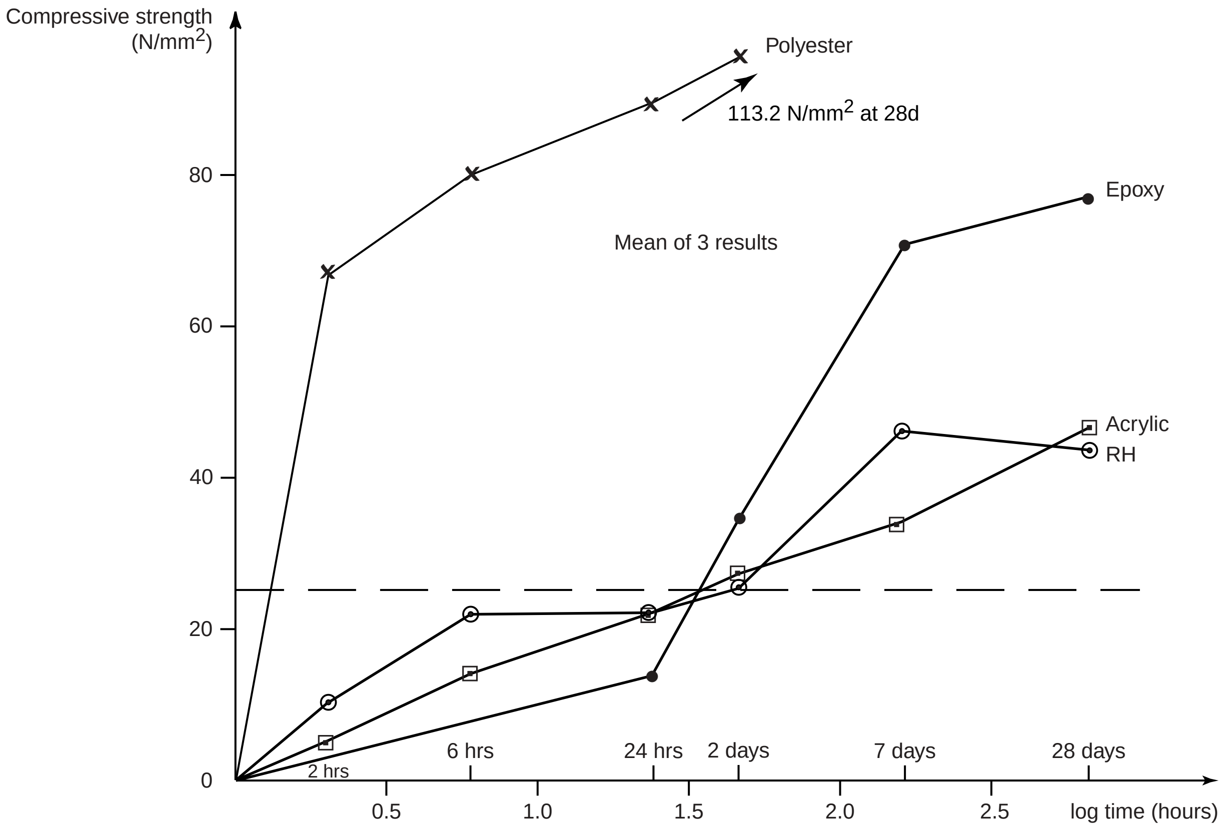
7.7 Permeability

The comments on the nitrogen gas permeability and chloride ion diffusion are combined below. The results are presented in Tables 9 and 10 respectively.

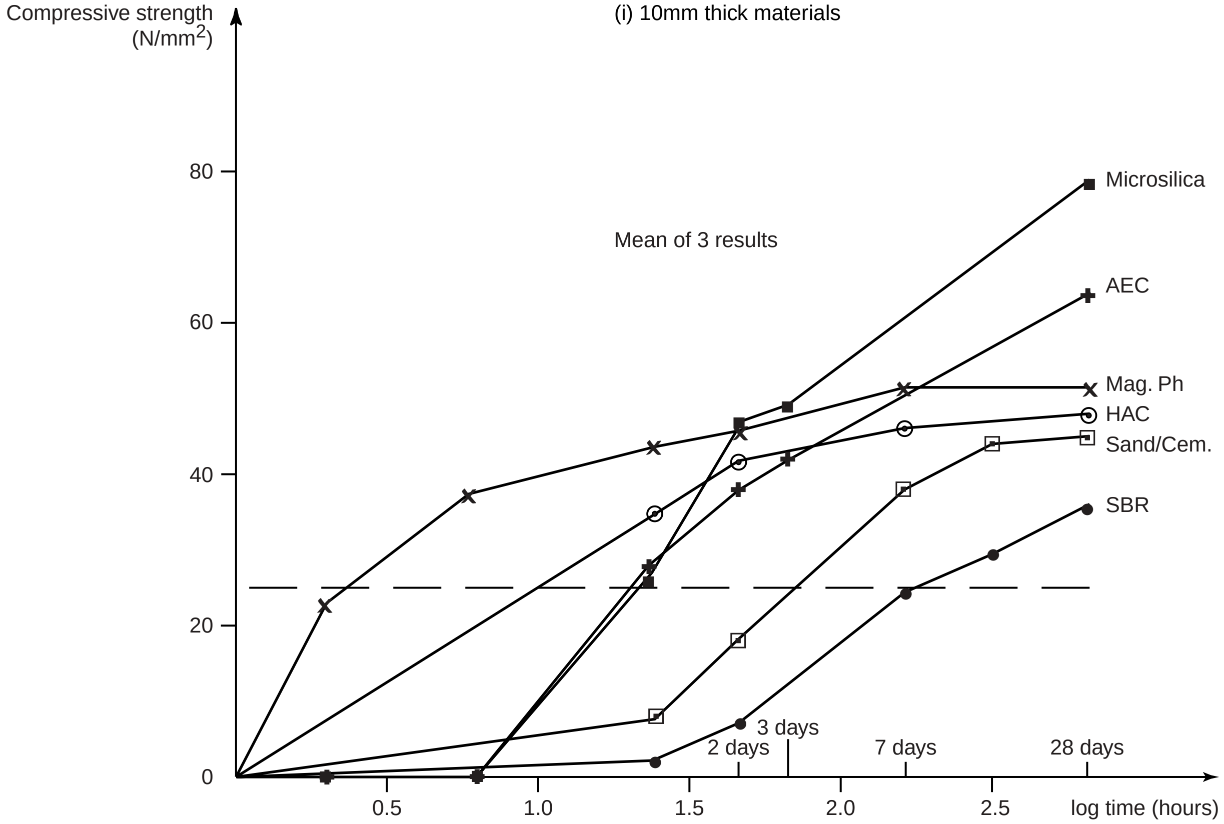
Results from the nitrogen gas permeability test that were less than 0.1 x 10^{-17} m^2 were deemed to be unreliable with the apparatus used.

Two of the chloride ion diffusivity tests, on the epoxy and the high alumina, were repeated because of a large variation in the performance of the original specimens.

In general there was poor correlation between the two test methods and the difficulty in defining an acceptance level combined to diminish the value of these tests. Consequently, the standard repair materials were not used in these testing regimes.

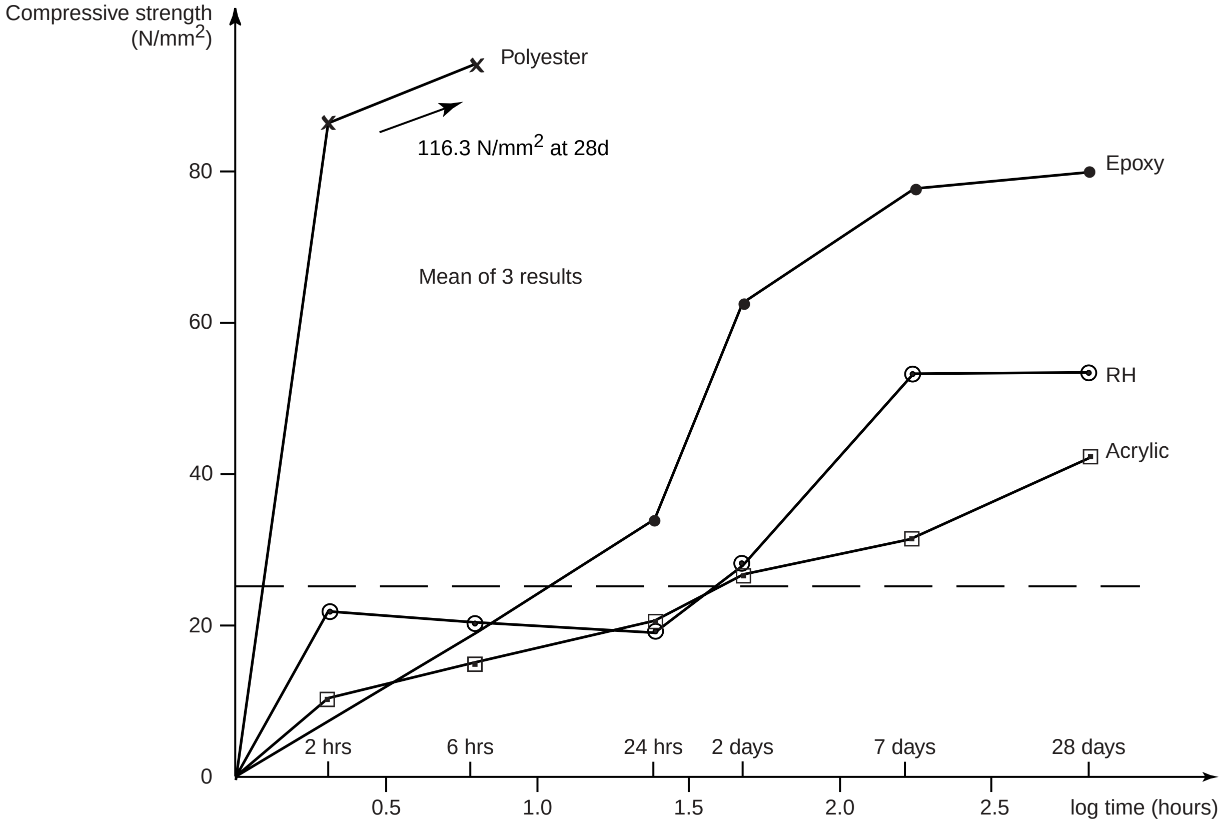


(i) 10mm thick materials

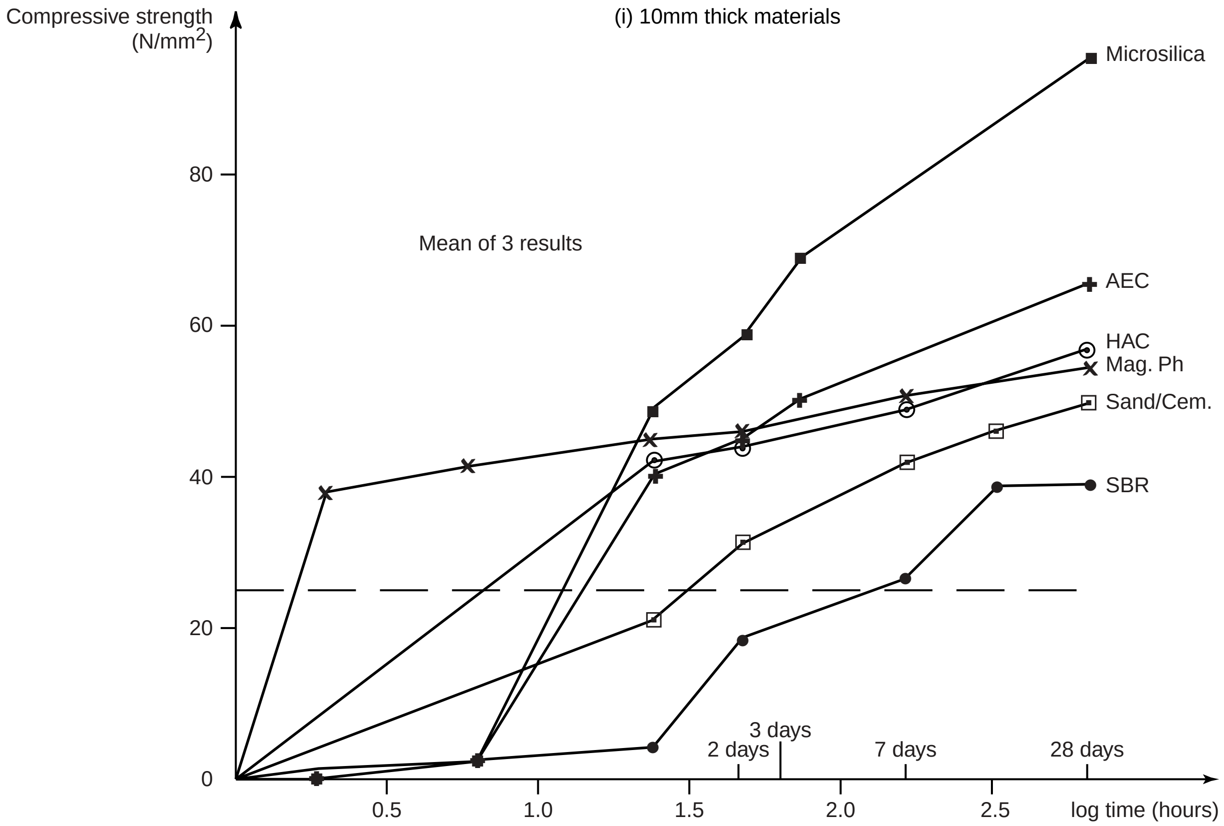


(ii) 50mm thick materials

Figure 24a Time to opening 5ºC

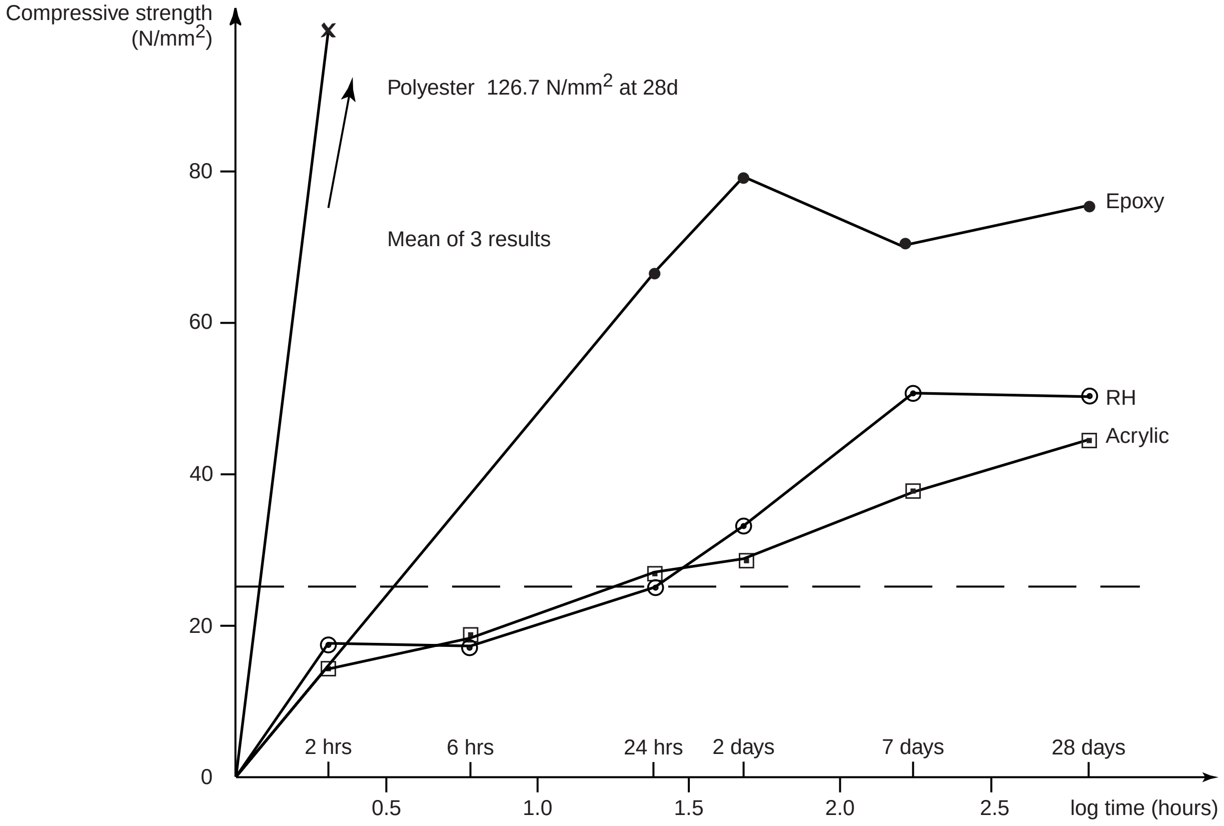


(i) 10mm thick materials

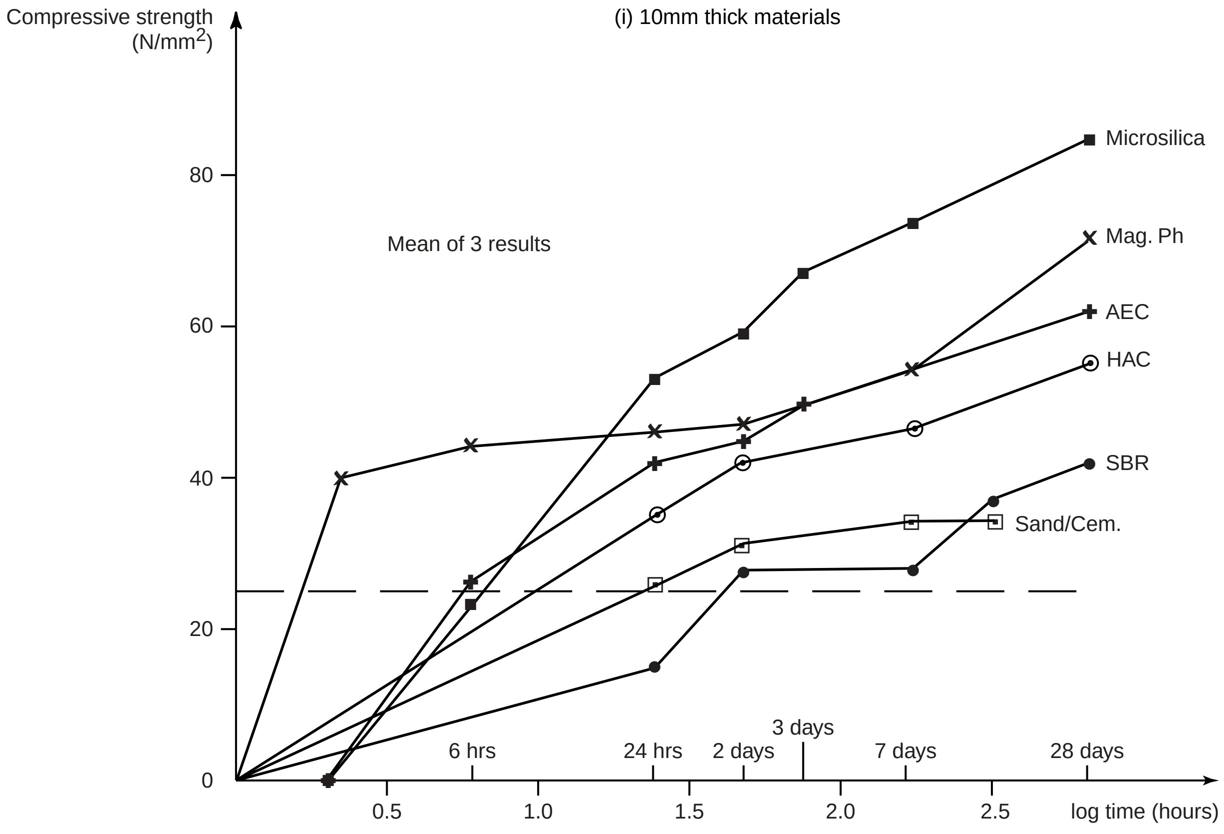


(ii) 50mm thick materials

Figure 24b Time to opening at 20°C



(i) 10mm thick materials



(ii) 50mm thick materials

Figure 24c Time to opening at 30°C

Table 9 Results from the nitrogen gas permeability test

Gas pressure (bar)	*Permeability (m^2 x 10^{-17})* Epoxy 1	Epoxy 2	Polyester 1	Polyester 2	Rapid hard. 1	Rapid hard. 2	Acrylic 1	Acrylic 2	SBR 1	SBR 2	Mag Pho 1	Mag Pho 2	High alumina 1	High alumina 2	Sand/cement 1	Sand/cement 2
1	†	1.04	0.93	-	6.42	0.35	1.50	0.84	-	-	-	-	74.5	42.3	3.86	7.47
2	†	0.71	1.60	0.24	5.27	0.27	1.15	0.42	-	-	-	-	-	-	3.5	-
3	†	0.47	1.52	0.51	4.71	0.15	1.90	0.25	0	*	-	0	-	-	2.56	1.43
4	†	-	-	0.40	4.01	0.10	1.56	0.11	0	*	-	0	-	-	2.55	6.05
5	†	-	-	-	-	-	-	-	-	*	*	0	-	-	-	-
Mean	0.82		0.86		2.66		0.93		0		0		58.4		3.9	

Notes:
- = Not tested at this gas pressure
** = These values were about 3.5 x 10^{-20} m^2 and not reliable*
0 = No measurable change over several hours
† = The epoxy 1 specimen was too short to test

Epoxy	Showed medium permeability to both chloride ion and nitrogen gas. The repeated chloride ion test produced a lower result.
Polyester	Highly permeable to chlorides but only medium to nitrogen gas.
Rapid hardening	Low permeability to chlorides and medium to the nitrogen gas. There was a large difference between the two specimens in the nitrogen gas test.
Acrylic	Highly permeable to chlorides but only medium to nitrogen gas.
SBR	Low permeability to chlorides and negligible permeability to the nitrogen gas.
Magnesium phosphate	Totally contrasting results with high permeability of chlorides and negligible permeability of nitrogen gas.
High alumina	Totally contrasting results with low permeability of chlorides and high permeability of nitrogen gas. The chloride ion test was repeated but confirmed the original result.
Sand/cement	Showed medium permeability in both tests.

Table 10 Results from the chloride ion diffusion test

Material	*Chloride ion diffusivity coefficient (cm^2 / s)*	
Epoxy	12.7 x 10^{-9}	0.5 x 10^{-9}
Polyester	79.6 x 10^{-9}	
Rapid hardening	1.43 x 10^{-9}	
Acrylic	66.4 x 10^{-9}	
SBR	3.77 x 10^{-9}	
Magnesium phosphate	50.2 x 10^{-9}	
High alumina	1.43 x 10^{-9}	2.15 x 10^{-9}
Unmodified sand/cement	16.7 x 10^{-9}	

The high alumina was significantly more permeable to the nitrogen gas than all the other materials. However, the results were similar to those determined for a range of concretes in earlier work by Lydon and Mahawish.

The polyester, acrylic and magnesium phosphate had significantly higher chloride ion diffusion rates than the other repair materials and would lie in the high diffusion category in the Concrete Society report on permeability testing. The rapid hardening, SBR and high alumina would be in the low diffusion category.

7.8 Ease of mixing

The investigation involving varying mix proportions, subjectively considered the effect on the ease of mixing and placing, and also the effect on the strength of the material. The repair trials at TRL also permitted a subjective assessment of the ease of mixing etc. and an early small-scale assessment of the performance of these materials.

7.8.1 Effect of mix proportions

The effect of varying the mix proportions on the strength of the materials and on the ease of mixing and placing is shown in Tables 11 and 12 respectively.

Epoxy	25N/mm² was achieved within 24 hours for all mixes.
Polyester	The high, early strength was not affected by the change in mix.
Rapid hardening	The additional 5% liquid was detrimental to the strength development with only 25N/mm² achieved after 7 days.
Acrylic	The changes to the normal mix improved the strength and achieved the 25N/mm² after 24 hours.
SBR	The early strength was improved with the mix changes and also a slight improvement in the long term strength.

Table 11 Effect of varying mix proportions on compressive strength (N/mm²)

		Variation of mix proportion		
Material	*Age*	*+5%*	*Standard*	*-5%*
Epoxy	24 hours	72	35	64
	7 days	71	78	66
	28 days	61	80	61
Polyester	2 hours	90	86	70
	6 hours	98	94	96
	24 hours	110	103	104
	7 days	113	112	106
	28 days	121	116	119
Rapid hardening	2 hours	11	22	17
	6 hours	12	18	19
	24 hours	11	16	20
	7 days	25	54	40
	28 days	32	54	52
Acrylic	2 hours	16	10	17
	6 hours	23	15	23
	24 hours	25	21	32
	7 days	42	32	47
	28 days	57	42	61
SBR	24 hours	9	4	11
	14 days	40	39	42
	28 days	43	39	48
Magnesium phosphate	2 hours	27	37	29
	6 hours	41	41	25
	24 hours	52	45	61
	7 days	54	50	73
	28 days	77	54	83
High alumina	24 hours	48	41	48
	7 days	63	49	63
	28 days	56	57	58
Sand/ cement	24 hours	24	21	28
	7 days	56	41	56
	14 days	62	46	71
	28 days	65	50	66

Magnesium phosphate	The early strengths were lower but the 28 day strengths higher with the changed mixes.
High alumina	Only the 7 day strengths were improved with the mix changes.
Sand/cement	All the strengths were improved with the changed mixes.

7.8.2 Pavement repairs at TRL

The comments on the pavement repairs at TRL are included in Table 12.

7.9 Assessment of cost

In Table 13 the repair materials have been ranked in ascending order of cost, the cost relative to the cheapest material is indicated. It was found that the ranking order was independent of the contract size.

The figure in brackets for the resin materials indicates the relative cost if a 100mm width can be used for the arris repair as opposed to the minimum of 150mm for the cementitious materials.

This exercise was undertaken approximately four years after the start of the project, at this time no costs were available for the high alumina as it was no longer being distributed.

7.10 Full scale repair trials

The sites of the two repair contracts were inspected in November 1995. The high alumina, magnesium phosphate and microsilica concrete, used for repairs on the A5 at Milton Keynes were two years old and the epoxy, polyester, acrylic, rapid hardening, SBR and air entrained concrete, used for repairs on the M11 were one year old.

Epoxy	Performed well with no cracking evident. This is consistent with its high ranking on technical performance.
Polyester	Had to be removed, within 24 hours of placing, due to extensive cracking. This performance is consistent with its low overall ranking in the laboratory tests, although it scored well on tensile strength and time to opening.
Rapid hardening	Showed no signs of deterioration which is consistent with its top ranking in the laboratory trials. However, it had a coarse surface texture, Plate 1 (see page 36), which is consistent with the relatively short workable life referred to above.
Acrylic	Suffered fine map cracking at approximately 150mm centres in those patches located under the nearside wheel tracks as shown in Plate 2 (see page 36). Patches under the offside wheel track and between the wheel tracks had performed well. This material was ranked fifth overall in the laboratory tests, the movement relative to substrate concrete results being particularly poor and perhaps a pointer to the observed cracking.
SBR	All of the arris repairs had fine longitudinal cracks at spacings varying between 100mm and 200mm, accompanied by debonding from the substrate concrete as shown in Plate 3 (see page 36). The failure to reach the acceptance criteria in the thermal cycling test may be a pointer to its performance in service.

Table 12 Effect of varying mix proportions on ease of mixing

Material	*Change in liquid proportion*	*Mixing*			*Placing*			*Comments on pavement repairs at TRL (Undertaken with standard proprietary mix)*
		Good	*OK*	*Poor*	*Good*	*OK*	*Poor*	
Epoxy	+5%			✓	✓			Easy to mix when using a drill.
	0			✓	✓			Did not require dry surface before priming.
	-5%			✓	✓			Easy to place.
Polyester	+5%			✓			✓	Needed a dry concrete surface.
	0			✓			✓	Needed a drill and paddle to mix.
	-5%			✓			✓	Difficult to place, finish and clean tools.
Rapid hardening	+5%	✓				✓		Can be mixed in a mixer or with a spade.
	0	✓			✓			Easy to place but went off quickly and therefore difficult to finish.
	-5%	✓			✓			
Acrylic	+5%	✓				✓		Was easy to mix, place, compact and finish.
	0	✓				✓		Primer was easy to mix but was not packed separately.
	-5%		✓		✓			
SBR	+5%		✓			✓		Required a bond coat.
	0	✓			✓			Very easy to place and compact.
	-5%		✓		✓			Harder to finish than the unmodified sand/cement.
Magnesium phosphate	+5%	✓				✓		Mixed well in mixer but material hardened too quickly.
	0		✓		✓			Had to finish each repair as one progressed.
	-5%		✓		✓			Very difficult to clean mixer and tools.
High alumina	+5%	✓			✓			Was easy to mix but was too dry and 'bony'.
	0	✓			✓			Compaction and placing was difficult.
	-5%		✓			✓		Hardened very quickly.
Sand/cement	+5%	✓				✓		Mixed easily in the mixer.
	0		✓			✓		Had to weigh out individual components.
	-5%		✓				✓	Easy to place, compact and finish.

Table 13 Relative costs of the repair materials

Material	*Repair thickness (mm)*		
	10	*50*	*100*
Sand/cement		1.00	1.00
Microsilica		1.00	1.00
A E concrete		1.01	1.01
SBR		1.18	1.18
Rapid hardening	1.00	1.32	
Acrylic	1.05		
Magnesium phosphate		1.37	1.38
Epoxy	1.12 (1.02)	1.77 (1.61)	
Polyester	1.24 (1.12)		

Magnesium phosphate

The contractor experienced some difficulty in placing and finishing the magnesium phosphate material in full lane width arris repairs before the product started to harden. One repair had to be replaced immediately after placing and the remaining arris repairs showed some evidence of surface aggregate loss on the later placed material (see Plate 4). Plate 5 shows a surface patch repair, of area approximately 0.1 to 0.2m^2, with no sign of any deterioration. These observations suggest that this material is suitable for small areas when rapid strength gain is required.

High alumina

All of the arris repairs with this material had fine longitudinal cracks at spacings varying between 100mm and 400mm as shown in Plate 6. This performance was consistent with the poor performance of this material in all but the compressive modulus and time to opening tests.

Microsilica concrete

The microsilica concrete showed no signs of deterioration other than an occasional fine longitudinal crack. The material appears to be capable of achieving good quality repairs as shown in Plate 7 (see page 37). The performance is consistent with the results of the laboratory tests, the one anomaly being the low score achieved on account of its relatively high static compressive modulus.

Plate 1 Rapid hardening modified cementitious (M11)

Plate 2 Acrylic mortar (M11)

Plate 3 SBR mortar (M11)

Plate 4 Magnesium phosphate (A5)

Plate 5 Magnesium phosphate (A5)

Plate 6 High alumina cement (A5)

Plate 7 Microsilica concrete (A5)

Air entrained concrete	Showed few signs of deterioration other than where there were associated structural problems as shown in Plate 8. The performance is consistent with the results of the laboratory tests, the two anomalies being the low scores achieved for compressive modulus and tensile strength.

Plate 8 Air entrained concrete (M11)

The epoxy, rapid hardening, magnesium phosphate, microsilica and air entrained concrete performed well in the trials. However, the epoxy and rapid hardening materials were only used for patch repairs and not arris repairs. The performance of the acrylic, the SBR and the high alumina was disappointing in that the acrylic failed under loading in some patches whilst the SBR and high alumina materials, used for arris repairs, cracked longitudinally at regular centres. The polyester was not suitable for these types of pavement repairs.

8 Discussion of the laboratory tests

Comparing the service performance with the evaluation of technical performance from the laboratory tests, it appears that there is generally good correlation with those tests involving composite specimens. However, the correlation is not so good with the tests measuring properties of the pure repair material, particularly the compressive static modulus and time to opening tests. The time to opening tests were not necessarily consistent with the performance in service as this parameter is more important in deciding when to open the road. Given that many of these repairs are essentially non-structural it is perhaps not surprising that the tests on the basic repair materials do not correlate as well as the tests on the composite specimens.

The standard repair materials were not used in the series of laboratory evaluations to determine the ease of mixing. This omission meant that any handling difficulties associated with these materials were not accounted for. However, the fact that they were used on actual contracts implies that there were probably no problems. The ease of mixing results have not been included in the summary of technical performance in Table 6.

8.1 Pull-off test

The pull-off test was found to be a valid means of measuring the bond of the repair to the substrate concrete. The only difficulties encountered were that:

i In the case of poorly bonded materials the cores tended to debond during the coring process.

ii The act of coring tended to leave the repair surface damp, hence, care was needed in cleaning to obtain good bond between the dolly and the repair material.

In general the test was fairly quick, easy to carry out and gave repeatable results.

The composite specimens proved to be a suitable size to use. They were easy to manufacture and handle, also sufficiently large to permit four pull-off tests per specimen. It was sometimes beneficial to cast a trial specimen to determine a method of operation with a particular repair material.

8.2 Bond to substrate concrete

This gave a good indication of how well the different materials bonded to the substrate concrete. It may be better in future to cure and test at the same temperature (5°C, 20°C and 30°C).

8.3 Movement relative to substrate concrete

There were four tests in this category, one undertaken on the individual materials and the others on the composite specimens.

8.3.1 Shrinkage tests on repair materials

The short term unrestrained shrinkage test has the disadvantage that it does not represent the true restrained behaviour that occurs in practice. It does measure the early movements of the repair material which the test on the composite specimen does not. An ideal test for assessing the restrained shrinkage of repair materials has yet to be devised.

8.3.2 Shrinkage tests on composite specimens

This test clearly demonstrated how the repair to concrete bond changed with time.

8.3.3 Thermal cycling

There was considerable variation between batches for some of the materials. This could be due to sample variation or variation in temperature between different positions in the cabinet. Some materials were shown to be very susceptible to thermal effects.

8.3.4 Moisture cycling

A specialist cabinet had to be constructed for this test but it did demonstrate a weakness in two of the materials.

8.4 Freeze/thaw cycling

This was a more practical test to conduct than the RILEM standard test from which it was adopted. There was again wide variation between batches but the test demonstrated a susceptibility to freeze/thaw cycling for some of the materials.

8.5 Fatigue resistance

The loading regime on the beams was sufficient to have a pronounced effect on some of the materials. The problem with the magnesium phosphate found in the laboratory trials has not at this early age appeared in the full scale trial on the A5. It may be that the loading on the beams should be reduced.

8.6 Tensile strength and static modulus

There was little variation between batches when determining the tensile strength and the repeatability of the results was good. Some materials were temperature susceptible.

The static compressive modulus test showed which materials would behave in a similar manner to concrete when under load. There was a large variation in results for some of the materials and some variation with temperature. The three materials which performed worst in this test, performed well in the road repairs. This therefore questions the applicability of the test for these repair materials.

8.7 Time to opening

This demonstrated the gain in compressive strength with time which is important in determining when the repaired pavement can be opened to traffic. The effect of temperature on the gain in strength was also demonstrated in this test. The results for some of the materials were variable but this may be due to the smaller size of specimen tested when compared to normal concrete testing.

8.8 Permeability

The chloride ion diffusion test was found to be very sensitive to sample preparation as voids or large aggregate particles in the specimen can influence the results. It appeared from the results that there were different internal transport processes for the chloride ions and nitrogen gas with some materials more permeable to one than the other. These differences and the problem of setting acceptance criteria devalued the use of these tests.

8.9 Ease of mixing

This was assessed by varying the mix proportions and the use of the materials for the pavement repairs undertaken at TRL.

8.9.1 Effect of mix proportions

The ±5% variation in the liquid component of the mix was too small to have a pronounced effect on the materials. However, it did alter the subjective assessment on approximately half of the mixes. The variation in mix did have an influence on the strength development.

8.9.2 Pavement repairs at TRL

Using the repair materials in a site situation was a valuable experience and revealed some of the practical problems involved with the materials.

9 Conclusions

The laboratory tests indicated the materials that were unlikely to perform well. The top four rated materials in the tests were also those materials that performed best in practice. However, the two materials rated next were very close in the rankings to the top four and there was no indication that they could present problems when used on site. The principal conclusions are:

a The polyester, high alumina, and sand/cement materials performed poorly in the laboratory tests and would be unsuitable for the type of repairs to concrete highway pavements considered in this report.

In the full scale repair trials, the sand/cement was not used, the polyester performed poorly and there was cracking in the arris repairs carried out with the high alumina.

b The microsilica concrete, air entrained concrete, epoxy and rapid hardening were the top four materials judged by the laboratory tests.

These four materials all performed well in the full scale trials but the epoxy and rapid hardening materials were only used in patch repairs.

c The acrylic, SBR and magnesium phosphate performed satisfactorily in the laboratory tests and were rated fifth, sixth and seventh respectively.

In the full scale trials the acrylic material performed well in some patches but cracked under load in the nearside wheelpath. The SBR displayed longitudinal cracking when used for arris repairs. The magnesium phosphate was used in arris and patch repairs and performed well, the only problem with this material being that the rate of setting was too quick to properly finish the arris repair.

In terms of the cost of those materials most suitable for thin repairs, the modified cementitious materials (rapid hardening and acrylic) were less expensive than the resin materials (epoxy and polyester) although the epoxy becomes more competitive if used for narrower repairs. For thicker repairs, the microsilica and air entrained concretes were less expensive than the SBR modified and magnesium phosphate materials. These relative costs appear to be independent of contract size.

10 Recommendations

It is recommended that the suite of tests used in this programme is developed further. It is considered that the tests on the composite specimens provided the most useful data. However, the one test on the repair material that is of importance is the determination of compressive strength at a range of temperatures, the time to opening test. For non-structural repairs the measurement of compressive modulus and tensile strength may be unnecessary. The permeability tests were of limited usefulness as it was difficult to set an acceptance criteria and also the transport mechanism through the sample appeared different for the nitrogen gas and chloride ions leading to conflicting results for the two tests. The only other test that may be worth retaining is the short term shrinkage test.

It is recommended that the ease of mixing test should be used in the laboratory evaluation programme to warn of possible difficulties with materials having relatively short workable lives.

It is also suggested that the laboratory tests are supplemented by two further tests. One that simulates a long, narrow arris repair is required because two of the five materials used for arris repairs suffered from cracking at discrete centres across the repair and this was not discernible from the suite of laboratory tests employed. The second is a wheel load test on a composite specimen to warn of the problem experienced with the acrylic material in the wheeltrack.

The experience of finding suitable sites to trial the repair materials has highlighted that in some maintenance situations, the repair materials were being used for purposes for which they were not intended. For successful repairs, it is recommended that the cause of the pavement deterioration must be determined and appropriate action taken to arrest the deterioration before any repair is carried out.

The best repair materials are only as good as the workmanship of the applicator and the preparation of the substrate, hence, it is recommended that consideration be given to an approval scheme for applicators in addition to one for approval of repair materials.

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12 References

American Society for Testing Materials (1984). *Standard method of test for resistance to rapid freezing and thawing*. American Society for Testing Materials ASTM C 666. ASTM, Pennsylvania, USA.

British Standards Institution (1982). *Air entraining admixtures*. British Standard BS 5075: Part 2. British Standards Institution, London.

British Standards Institution (1983a). *Testing concrete. Part 121, Method for determination of static modulus of elasticity in compression*. British Standard BS 1881: Part 121. British Standards Institution, London.

British Standards Institution (1983b). *Testing of resin and polymer/cement compositions for use in construction. Part 2, Method for measurement of compressive strength*. British Standard BS 6319: Part 2. British Standards Institution, London.

British Standards Institution (1983c). *Testing concrete. Part 116, Method for determination of compressive strength of concrete cubes*. British Standard BS 1881: Part 116. British Standards Institution, London.

British Standards Institution (1983d, amended 1993). *Testing concrete. Part 108, Method for making test cubes from fresh concrete*. British Standard BS 1881: Part 108. British Standards Institution, London.

British Standards Institution (1983e). *Testing concrete. Part 117, Method for determination of tensile splitting strength*. British Standard : BS 1881: Part 117. British Standards Institution, London.

British Standards Institution (1984). *Testing of resin and polymer/cement compositions for use in construction. Part 4, Method for measurement of bond strength (slant shear method)*. British Standard BS6319: Part 4. British Standards Institution, London.

British Standards Institution (1985). *Testing of resin and polymer/cement compositions for use in construction. Part 7, Method for measurement of tensile strength*. British Standard BS6319: Part 7. British Standards Institution, London.

British Standards Institution (1992a). *Testing concrete. Part 207, Recommendations for the assessment of concrete strength by near-to-surface tests*. British Standard BS 1881: Part 207. British Standards Institution, London.

British Standards Institution (1992b). *Testing of resin and polymer/cement compositions for use in construction. Part 12, Methods for measurement of unrestrained linear shrinkage and coefficient of thermal expansion*. British Standard BS6319: Part 12. British Standards Institution, London.

Concrete Society (1988). *Permeability testing of concrete*. Concrete Society Technical Report No. 31. Concrete Society, Slough.

Construction Industry Research and Information Association (1993a). *Standard tests for repair materials and coatings for concrete. Part 1: Pull-off tests*. Construction Industry Research and Information Association, Technical Note 139. CIRIA, London.

Construction Industry Research and Information Association (1993b). *Standard tests for repair materials and coatings for concrete. Part 2: Permeability tests*. Construction Industry Research and Information Association, Technical Note 140. CIRIA, London.

Construction Industry Research and Information Association (1993c). *Standard tests for repair materials and coatings for concrete. Part 3: Stability, substrate compatibility and shrinkage*. Construction Industry Research and Information Association, Technical Note 141. CIRIA, London.

Department of Transport, Scottish Office Industry Department, The Welsh Office and the Department of the Environment for Northern Ireland (1991a). *Manual of Contract Documents for Highway Works, Vol 4, Bills of Quantities for Highway Works*. The Stationery Office, London.

Department of Transport, Scottish Office Industry Department, The Welsh Office and the Department of the Environment for Northern Ireland (1991b, amended 1993). *Manual of Contract Documents for Highway Works, Vol 1, Specification for Highway Works*. The Stationery Office, London.

Department of Transport, Scottish Office Industry Department, The Welsh Office and the Department of the Environment for Northern Ireland (1994). *Design Manual for Road and Bridges, Vol 7, Pavement Design and Maintenance. HD32/94, Maintenance of Concrete Roads*. The Stationery Office, London.

Emberson N K and Mays G C (1990). *Significance of property mismatch in the patch repair of structural concrete. Part 1, Properties of repair systems. Part 2, Axially loaded reinforced concrete members*. Magazine of Concrete Research, Vol 42, No 152, pp 147–70.

Lydon F D and Mahawish A H (1991). *Tests of the permeability of concrete to nitrogen gas*. Construction and Building Materials, Vol. 5, No. 1, pp 8–17.

Mildenhall H S and Northcott G D S (1986). *A manual for the maintenance and repair of concrete roads*. Department of Transport and Cement and Concrete Association. The Stationery Office, London.

Rilem (1986). *Resin adherence to concrete. Thermal compatibility tests 1 and 2*. Technical Committee 52–RAC. Draft test recommendations.

Abstract

A need has been identified to establish appropriate laboratory tests for assessing the suitability of repair materials for joint arris and surface repairs in concrete pavements. The authors have defined a series of tests which have been used to assess a number of generically different repair materials in the laboratory. Subsequently, an assessment of the performance of these materials has been undertaken when used in full scale trials under contract conditions on two sites on the trunk and motorway road network.

The repair materials consisted of seven proprietary materials and an unmodified OPC/sand which were assessed using all the laboratory tests. The standard repair materials used on the repair contracts were later tested in the laboratory using a selection of the laboratory tests.

This report details the laboratory tests and the performance of these materials both in the laboratory tests and in the full scale trial. In addition, a cost assessment exercise was conducted for all the materials using three hypothetical repair contracts.

Overall, there appears to be good correlation between the results of the laboratory tests and performance in service. However, recommendations are made for some minor modifications to the laboratory test programme. The cost assessment exercise demonstrated that those materials showing good technical and in-service performance were not necessarily the most expensive. The relative costs between repair materials appeared to be independent of the size of the contract.

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