CONCRETE SOCIETY

Technical Report

No 39

Polymers in Concrete

Report of a
Concrete Society
Working Party

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TECHNICAL REPORT NO. 39

POLYMERS IN CONCRETE

A Technical Report of The Concrete Society's
Technical Development Centre, prepared by a
Working Party of its Materials Group

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The Working Party was originally led by Mr W.O. Nutt, of Estercrete Ltd, who died shortly after the 5th International Congress on Polymers in Concrete, 1987 – Brighton, UK where the first draft for comment was considered.

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1. INTRODUCTION

The incorporation of polymers in mortar and concrete mixes produces materials ostensibly similar to conventional ordinary Portland cement bound concretes but with many superior attributes. All or part of the cement content is replaced by polymers – synthetic resins of high molecular weight. The polymer addition alters many of the characteristics of the concrete, most notably its mechanical properties and chemical resistance. While such materials have been in use for over 25 years, it is only in the last decade that they have become of commercial significance in several countries.

The strict definition of a polymer encompasses a wide range of materials. The intention here is to be concerned only with those polymers incorporated with or replacing Portland cement in concrete such that the design properties of the resulting binder matrix are significantly different from conventional Portland cement hydrates. All mixes are defined as concrete, i.e. any mix designed to have physical properties dependent on aggregates held in a binder matrix, e.g. including mortars.

Many admixture materials are polymers, but are used with Portland cement in minor additions to alter the rheology of the concrete mix, rather than the structure of cement hydrates. Such agents are not generally acknowledged for consideration as polymers in concrete. Polymer products are also incorporated in concrete as aggregates (e.g. expanded polystyrene beads in lightweight concrete) or reinforcement (e.g. polypropylene fibres) in Portland cement concretes. Since the properties of the set concrete are derived from the substantially unaltered cement hydrate matrix these polymer products are not covered in this review.

This Technical Report is intended to provide engineers, concrete technologists and material scientists with a review of the types of polymer, the methods of using them in concrete, and the many ways in which these materials may be employed. Because of the wide and varied range of possible uses, no attempt is made to provide a comprehensive and detailed description of all product applications. Similarly, the literature covering the development and use of polymers in concrete is extensive, so each chapter contains a selection of references rather than a full bibliography.

The Technical Report starts with an explanation of polymers, how they work, and how they compare, as binders in concretes, with cement. The different types of polymer concretes are then defined and classified and the more common applications described. The Report covers the polymer dispersions (in water) which are used to modify conventional mortars and concretes as partial or complete replacement of the gauging water: included are the criteria for selection, the properties obtained and the conditions for use. Concretes bound only with polymers are then detailed, followed by those containing a minor proportion of cement in the polymer binder.

Many polymer concretes are applied to set and hardened conventional concretes, so practical methods for preparing the concrete interface to achieve adequate adhesion are described. Since polymer concrete mixes show important rheological differences from cement concretes in the un-set state, the requirements for mix designs with resin binders are briefly explained. Finally, there is a review of the tests for acceptance and performance of polymer concretes which are used in many countries.

In this report, the three different types of concretes and mortars incorporating polymers are described as PCCs, RPCCs and PCs respectively. These abbreviations, PCC (Polymer Cement Concrete) and PC (Polymer Concrete) are widely used in Europe, but in some technical publications, especially in the USA, PCCs are also termed PPCCs (Polymer Portland Cement Concrete) and LMCs (Latex Modified Concrete). The term RPCC (Reactive Polymer Cement Concrete) is a new proposal to describe those PCCs in which the polymer undergoes chemical change (further polymerisation/cross-linking) at the same time as the cement hydration is proceeding.

This revised Technical Report provides an introduction to the technologies and applications currently associated with polymer concretes. It concentrates on UK experience and refers to overseas data where it is considered relevant to the developing UK scene. Excluded from this report are:

a. Polymer impregnated concrete.

b. Polymer fibre reinforced concrete.

c. Solid polymer aggregate concrete.

2. TYPES OF POLYMER AND MECHANISMS

The word POLYMER (Gk. *poly meros* – many parts) describes materials which contain long molecular chains made up from many units. For example, if 'A' represents a molecular unit, a chain may be represented as follows:

-A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-

The letter A represents a molecular repeat unit or the chemical building block for building long chains. The single unit (A) from which long chains are made is known as a MONOMER. All monomers are chemically unsaturated, i.e. they have chemical groups or bonds with a capacity for further chemical reaction. They are generally gases or volatile liquids. A polymer may comprise a long chain (sometimes with smaller side branches) built up from identical molecules, in which case it is termed a homopolymer (Gk. *homos* – same). A polymer with different characteristics, but retaining some of the original features, can be obtained by incorporating molecules of a second monomer into the chain. This is then termed a co-polymer. The proportions of the two monomers may be infinitely varied in a regular or random pattern, or may be built up with various sections of the complete chain comprising all one monomer or the other. Thus:

A-B-A-B-A-B-A-B- or A-A-B-A-B-B-A-B-A or A-A-A-A-B-B-B-B-B-A-A-A-A

This representation of chains as straight lines is only a convention for convenience. In reality their form is very much coiled and entangled.

2.1 Thermoplastics

Most long-chain (including some shorter branch chains) polymers are called thermoplastics because they become plastic or deformable when heated and can be easily processed under heat and pressure. Thermoplastics can generally be remoulded if reheated and are normally suitable for recycling.

Because of their structure, many long-chain polymers do not suddenly change from solid to liquid at a well defined melting point. For each, there is a temperature at which there is a notable change in behaviour.The polymer becomes softer and more workable and exhibits plastic flow, similar to Plasticine or putty. This is known as the glass transition temperature or Tg. Above the Tg, segments of the molecular chains are able to rotate easily and slip past each other when a load is applied – i.e. the material undergoes plastic flow.

The properties of polymers depend upon chemical structure, molecular symmetry and the interaction between chains. The forces of attraction between the molecular chains depend upon the molecular units involved but are reduced as the distance between the chains is increased. Polymers are often based on more than one monomer so that the properties of the resultant 'co-polymer' are better than the properties of polymers based exclusively on the separate monomers (see 4.5).

Although many thermoplastics will stretch, most do not return to their original dimensions when the stress is relieved. Clear rigid PVC, a thermoplastic, is a glassy plastic with a Tg above 60°C. The Tg can be lowered and the material made flexible by the addition of a plasticiser. This is because plasticisers open up the structure and thereby reduce the molecular attractive forces between the chains, lowering the Tg. Some long-chain polymers with low molecular attraction can be stretched elastically. For example, butyl rubber, from which elastic bands are made, can be stretched to five times its original length and return rapidly to its initial dimensions and shape after release of stress. Such materials are said to exhibit rubber-like behaviour and are often referred to as elastomers.

2.2 Thermosets

When the polymer chemist arranges chains in which some of the molecular units have spare bonds (reactive sites), linkages can be made to occur between the chains, creating a rigid cross-linked three-dimensional network or structure. For example, if 'B' has spare bonds, a chain may be represented as follows:

-A-B-A-B-A-B-A-B-A-B-A-B-A-
| | | | | |

Polymers made from longer versions of this chain, with a potential to cross-link (in this case at each B site), are known as unsaturated polymers.The cross-linked polymers may be represented as follows:

-A-B-A-B-A-B-A-B-A-B-A-B-A-
| | | | | |
- A-B-A-B-A-B-A-B-A-B-A-B-A-

Cross-linkable and cross-linked polymers are known as thermosetting polymers. Cross-linking or curing prevents the chains from slipping past each other and makes the material harder and more rigid, with lower creep and greater heat resistance. Nevertheless, some thermosets, including those used in the construction industry, become less rigid at elevated temperatures and a glass transition temperature may be determined. For more practical purposes, the Heat Distortion Temperature (HDT)(1) gives an indication of the upper temperature limit to load bearing applications.

2.3 Polymer latices, emulsions or dispersions

The polymers used in concretes are available in various physical forms, including powders, solution, dispersions, and also as expanded solids (e.g. polystyrene beads).

A dispersion is a two-phase system, comprising very fine globular particles of polymer (the dispersed phase) suspended in a non-solvent liquid (the continuous phase, usually water). Because the polymer particles are so tiny, their surface area/mass ratio is extremely high, so gravity has far less effect upon them than do surface energy forces. These provide a repellency force between the particles, enabling them to remain in suspension. The permanence of the suspension may depend upon the presence of other surface-active chemicals within the dispersed phase. The terms emulsion and latex are used to describe some dispersions and preferences for terminology vary between different industries, but for the purposes of this report they may be regarded as synonymous(2).

Examples of latices, or emulsions, used in concrete are polyvinyl acetate (PVA), polyacrylates and natural rubber. Co-polymers are also used including styrene butadiene rubber (SBR), styrene acrylates, ethylene/vinyl acetate and vinyl acetate/'vinyl Versatate'. Plasticised polymers are used in some cases. The discrete particles, expressed as solids content in water, are typically around 50% but some polymer latices in the 45-70% solids range are also readily available. Bottles of polymer latices at lower solids (20-25%) are often used on site in conjunction with pre-blended bags of aggregates and cement so that no further addition of water is required.

When a polymer latex is applied as a thin film, the water evaporates and capillary action draws the particles together. When the ambient temperature is above what is known as the Minimum Film Forming Temperature (MFFT) of the polymer latex, the polymer particles can coalesce, because the repellent forces between the discrete particles produced by the surface-active agents are overcome. Most water-based coatings contain a coalescing solvent which facilitates this action and so lowers the MFFT.

A significant proportion of the polymers supplied in the UK for use in concrete are in the form of polymer latices. They are manufactured by specialist chemical manufacturers in large (10-20 tonne) reactors from unsaturated monomers such as vinyl acetate, methyl methacrylate, styrene, butadiene and ethylene. Controlled polymerisation is carried out in the presence of surfactants, water and other additives to form the milky latices. These polymer latices are generally supplied to specialist manufacturers who may add fillers and other ingredients to tailor-make products for specific end users. In volume applications, the chemical supplier may deliver direct to site ready for use, but in general, the chemical supplier will not incorporate all the critical minor ingredients to ensure optimum performance of the polymer in concrete or mortar mixes.

2.4 Polymer solutions

When polymers are dissolved in organic solvents or water, the molecular chains open up and are dispersed throughout the solvent to give a clear solution. Films may be formed from polymer solutions simply by evaporating the solvent or water, but many polymers used in solutions contain reactive groups, which may cross-link in situ to form harder, tougher films. Strictly speaking, these should be known as reactive resin solutions. Such reactive resin solutions can be either one-pack or two-pack materials. The most common one-pack types are conventional alkyd resin-based gloss paints and moisture-curing polyurethanes. In the case of alkyds, as with the older oil paints, cross-linking occurs by reaction with atmospheric oxygen and for polyurethanes with water vapour in the atmosphere. In both cases, the cross-linking is speeded up by the addition of an accelerator by the resin solution manufacturer.

Two-component reactive resin solutions are generally based on organic solutions of thermosetting resins, epoxy, unsaturated polyester, acrylic or polyurethane resins, which are described in 2.5.

2.5 Two-component reactive resins

A large proportion of polymers supplied in the UK to produce polymer concretes (PC's or RPCC's where the polymer is the principle binder), either under factory conditions or on site, are two-component reactive resins. These are polymers whose final reaction, to cross-linked thermosets, takes place at the point of application. Such resins include epoxies, unsaturated polyesters and, to a lesser extent, reactive acrylics and polyurethanes. They are generally available to the construction industry through specialist manufacturers(3) and often need specialist skills and experience for site application. The majority of specialist manufacturers and many of the specialist contractors offering such services belong to the Trade Association, FeRFA. The secretariat of this federation can provide a list of firms who are members and details of the products and services they offer (4).

It is important to understand that all polymerisation and curing processes are exothermic and that there is a rise of temperature which is related to the number of chemical links involved in the reaction. The curing reaction also involves shrinkage as the molecular structure becomes cross-linked and more tightly knit. With epoxy resin systems, most of the heat generation and the shrinkage occur before the resin has set. Therefore, there is little post-gelation shrinkage (approximately 1%). With unsaturated polyesters, most of the heat of reaction and shrinkage occur after gelation, and the shrinkage is much higher (typically 7% volumetrically for an unfilled resin). Adding fillers and reinforcement reduces this shrinkage and also serves as a heat-sink, which reduces the temperature rise produced by the curing reaction. Epoxy resins are, however, generally preferred for most applications owing to their intrinsically lower shrinkage, which in part contributes to their excellent adhesion.

Within each of the types of polymer described above, there is an extensive range of concrete properties dependent upon the polymer itself. Whereas the variation of properties of Portland cements is marginal within the designation, this cannot be said for polymers. Even for a single polymer type, specific properties are unique to the particular polymer composition. In practice, this means that using polymers in concrete technology demands recognition not only of polymer types but also the precise designations, such as the manufacturers' reference, and can seldom be extrapolated to a generic polymer type. Therefore specification must be supported by relevant performance characteristics.

References to Section 2

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3. The British Resin Manufacturers' Association Resin Index, 1986.
4. Tables produced by FeRFA of Member Companies and Associates, specialising in the Formulation and Application of resin mortars, grouts, concrete and related materials with information regarding services and products provided. Also, Application Guides Nos.1, 2, 3 & 4.

Further reading

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3. POLYMER CONCRETES - THE VARIOUS COMBINATIONS

3.1 Polymer cement concrete (PCC)

The polymers in PCC's commonly take the form of fine aqueous dispersions (also called emulsions or latices) of thermoplastic polymers and are used as all or part of the gauging liquids for otherwise conventional mortars and concretes, in which the properties of the binder matrix derive substantially from the hydration of cement.

A major factor to be considered in the design of such mixes is the significant water-reducing effect from some surfactants used to make a stable polymer dispersion. Thus, a low or very low water/cement ratio in mixes gauged with polymer emulsion permits higher strength development by the cement hydrate matrix. Other properties are altered by the presence of polymer in the matrix, including permeability to water, adhesion to substrates, flexural strength, tensile strength, modulus, impact resistance. Most polymers influence the binder matrix by their physical form and presence, especially the extent of polymer continuity, dependent upon the conditions under which polymer particle coalescence is induced.

3.2 Polymer concrete (PC)

Concrete made with aggregates bound only with polymer, i.e. no hydraulic cement content, is referred to as polymer concrete. All polymer concretes are bound with a thermoset polymer matrix. They are made by mixing low molecular weight polymers with aggregate fillers. The polymers convert to high molecular weight polymer by chemical reactions after placement. This creates a cross-linked three-dimensional thermoset polymer system which, as the sole binder, dominates the resultant concrete properties.

A wide range of concrete properties can be designed by selecting the polymer type and its setting mechanism. Mix design principles, while following those appropriate to Portland cement concrete systems, are for commercial reasons aimed at achieving the maximum practicable aggregate content. Polymers have much higher adhesion to the surface of aggregates than cement. Hence the aggregate (even the strongest) is the limiting factor in most strength parameters of polymer concretes.

Sub-sections 3.1-3.3 are discussed in fuller detail in Sections 4, 5 and 6 respectively.

3.3 Reactive polymer cement concrete (RPCC)

The polymers in RPCC's are thermosetting resins in their reactive form. When the reactive polymer is dominant in the binder matrix, the concrete properties are largely controlled by the characteristics of the polymer. The wet (unset) properties of a RPCC are essentially determined by the polymer system, invariably a compound of low molecular weight which converts to a high molecular weight on setting. Thus, RPCC binder matrices consist of a continuous phase of thermoset polymer containing wholly or partially hydrated cement. The ratio of polymer to cement in the matrix can influence the formation of a continuous skeletal structure of inorganic crystallites within the three-dimensional polymer. A substantial degree of coincident polymerisation and formation of cement hydrates is claimed in some products.

Concrete properties, predominantly determined by the polymer binder, can be varied widely and are significantly different from Portland cement concretes in respect of both uncured and hardened characteristics. Polymer cement concrete products are used in applications where their rapid strength gain, their high strength characteristics or their enhanced chemical resistance is required.

4. DISPERSED POLYMERS FOR INCORPORATION IN PCC

The polymer systems under consideration in this section are stable suspensions of polymer particles in aqueous media. Such dispersions occur naturally as rubber latices, but most of the products used in conjunction with hydraulic cements are manufactured from thermoplastic polymers and co-polymers or from synthetic rubbers. Because they are produced by the polymerisation of monomers emulsified in aqueous media, they are generally loosely termed polymer emulsions. The polymer particles in the emulsion are perfectly spherical and typically between 0.05 and 0.25 microns in diameter, although particles of up to 1 micron are common in PVA and natural rubber latices. When these emulsions are allowed to dry, the aqueous component evaporates and the polymer particles coalesce to form a continuous plastic or rubber film. This film-forming capacity is the basis of their use in emulsion paints and, as will be seen later, can also be of great benefit when it is allowed to occur within the developing matrix of a hardened hydraulic cement paste.

4.1 Background

The use of latices in conjunction with Portland cement dates from the early 1920s when various patents were taken out for using rubber latices to improve the flexibility and adhesion of cementitious flooring compositions, particularly on the steel decks of ships. Patents extended application by the use of synthetic rubber dispersions, but it was the urgent development of synthetic rubbers during World War II which provided the impetus for subsequent commercial application. The development of polyvinyl acetate dispersions introduced thermoplastic polymers to this field and during the 1950s attention was given to the development of dispersions specifically for use with Portland cement. From the 1960s, the commercial use of these materials increased considerably and the range of polymers, copolymers and synthetic rubbers now marketed for this purpose is very wide.

4.2 Polymer dispersion/cement combination

As might be expected, the combination of a rubber latex or a polymer dispersion and Portland cement (or other hydraulic cement) produces a hybrid exhibiting the most useful attributes of each material. The product is a semi-liquid slurry which hardens rapidly by chemical reaction to form a solid with considerable compressive strength. It also has much greater flexural and tensile strength than ordinarily hydrated Portland cement and considerable adhesive properties. It displays better chemical resistance than unmodified cement paste, partly because of a substantial reduction in porosity. These properties are not achieved, however, until the hardened product has dried out, although a short period of curing control is necessary to optimise hydration of the cement component. This hybrid material is used as an adhesive in its own right and in modified cementitious grouts, mortars and concretes which reflect the above benefits in their performance.

The hydration of Portland cement produces an agglomeration of calcium silicate hydrates, calcium aluminate hydrates and calcium hydroxide which becomes a matrix to bind particles of sand and larger mineral aggregates. The hardened structure is weak in tension and, when the excess water (required to give mobility to the mixture before hardening) evaporates, voids are formed and shrinkage stresses result in micro-cracking.

Adding a polymer dispersion to the mixing water exerts an influence upon the growth of the calcium silicate hydrates (usually resulting in a finer structure): the water demand is reduced and, as the water is lost by evaporation, reaction or absorption, the polymer particles coalesce to form rubber or thermoplastic films and strands within the developing voids and micro-cracks. These help to prevent crack propagation and increase the tensile strength and fracture toughness of the resulting composite. The presence of the polymer in the micro-voids or pores of the concrete improves its watertightness, resistance to gas and vapour transmission and freeze-thaw stability. There is an overall decrease in the pore volume with a marked reduction in the number of larger pores (greater than 0.2 microns) and an increase in the fine pores (less than 0.075 microns). For these reasons, correctly designed PCCs do not need high compressive strength to achieve good durability. In fact, high compressive strength may result in loss of other desirable properties such as compatibility with a weaker substrate.

4.3 Ancillary chemicals and side-effects

So far, we have considered only the effect upon the hydrated Portland cement of the polymer particles, but we need to be aware that the aqueous medium in which they are dispersed is not pure water. The liquor in which the monomers are emulsified and then polymerised contains chemicals that are necessary to those processes but are not always beneficial to the hydration of Portland cement.

Although some of these chemicals may be consumed in the polymerisation process, others may be added at the completion for various reasons. These include surfactants, anti-foams, coalescing solvents and bactericides.

Surfactants or protective colloids are needed to achieve the original emulsification and also to prevent coagulation of the dispersion by the calcium ions from the cement. When the polymer chemist chooses a surfactant system, he will be considering its effect upon the polymerisation yield and freedom from oversize particles or agglomerates, and its ability to confer good chemical and mechanical stability upon the finished dispersion. The chemist will also need to consider its effect upon the setting and hardening of cement, any foaming effect it might have upon cementitious mortars and the 'trowelability' of polymer-modified mortars – some surfactants are better than others in allowing the release of a little water from the mix under pressure from the trowel. The surfactant lowers surface tension in the mix, which assists dispersion of cement particles, so acting as a cement plasticiser and water-reducing admixture. The polymer particles themselves also have this same benefit. In addition, lowering surface tension assists the cement paste or mortar to wet the substrate to which it is applied, promoting good adhesion. The amount of surfactant in the finished dispersion typically ranges from 2% to 4%.

To counteract the foaming tendency when polymer dispersions are added to cement, it is usually necessary to incorporate an anti-foam chemical. This is often, but not invariably, incorporated by the manufacturer in the polymer dispersion. Sometimes, the anti-foam chemical is stable in the polymer dispersion for short periods only and it is essential to add it immediately before mixing with the cement and aggregates.

Rubber and neoprene latices benefit from the inclusion of an antioxidant. Some SBR dispersions also contain anti-oxidants, although they are not generally considered necessary in dispersions destined for use with Portland cement. Alkalis such as sodium hydroxide or ammonia are often used to neutralise the acidity necessary for some polymerisation reactions. Sodium hydroxide can accelerate the setting of Portland cement, while the odour of ammonia can arouse objections from site operatives.

Polymer emulsions can be degraded by bacterial or fungal attack and a low level of an appropriate bactericide is incorporated.

Plasticisers or a coalescent may also be added to lower the minimum film-forming temperature (MFFT).

4.4 Minimum film-forming temperature (MFFT)

When the aqueous medium from a polymer dispersion is allowed to dry, the polymer must have a degree of mobility and flexibility if it is to coalesce to form a continuous film. For each system, there is a lower limit to the temperature at which conditions are suitable for film formation. This is known as the minimum film-forming temperature. Below that temperature, only a powdery deposit will form. The MFFT can vary considerably according to the test method.

Some polymer dispersions which do not film-form at normal ambient temperatures have, nevertheless, been found to give useful improvements to cementitious mortars. It can be argued that there will be no skinning effect with these materials which might interfere with trowelling. However, they do not give the wide range of properties obtained with film-forming latices.

The choice and proportion of monomers largely determines the MFFT, although other components, such as the emulsifier, can have an influence. The MFFT for systems to be used with cement is usually <5°C and this is achieved by the co-polymerisation of hard and soft monomers or by adding a plasticiser or coalescing solvent to a hard polymer.

Manufacturers publish MFFT figures for their products in isolation, although as there is no agreed test method the results can vary. However, the MFFT of a system in use can be greatly influenced by the other components of the mortar or concrete. Thus, some systems with MFFT well above this figure can be shown to give good performance, but not necessarily good adhesion, at low curing temperatures. It is quite possible that hydraulic cement in the system lowers the effective MFFT of the polymer dispersion. One theory is that the growth of hydration products from the cement forces the polymer particles together and thus encourages their coalescence.

4.5 Classification of polymer dispersions

The polymers used in these dispersions fall into two broad chemical groups:

a. synthetic rubbers – styrene-butadiene (SBR) is the principle type, but polychloroprene (neoprene) is also used where there is no contact with steel reinforcement.

b. thermoplastic polymers – based upon vinyl or acrylic esters (more commonly acrylic) of carboxylic acids, which have a vinyl or acrylic 'backbone', -CH-CHR-, in which the (R) groups, are other chemical species and can vary widely in type and properties.

Attempts are often made to differentiate between the performance of SBR and acrylic polymers in PCCs. However, any attempt at generalisation is immediately contradicted by the broad spread of properties and performance available from each group. While the division into the two groups can be made on the basis of their chemical origin, it is unwise to regard the final dispersions as falling into any neat, distinctive group.

There are many dispersions which must be individually assessed and modified by the formulating chemist by incorporating other chemicals to obtain a polymer dispersion that will confer optimum properties to the polymer-modified mortar or concrete to fulfil a particular purpose.

The major aspects of an emulsion which determine its performance are:

- choice of monomers and proportions of co-monomers
- molecular weight distribution and degree of cross-linking
- particle size distribution
- components of the water phase (residual surfactant/emulsifier and breakdown products from the initiator).

Clearly, these factors are partly interrelated but, broadly speaking, the choice and proportions of monomers affect the strength properties and wear resistance of the cementitious composition. They will also largely determine the effect of water and chemicals on these properties, although polymers of similar monomer ratios but different molecular weights will give a difference in performance. From their chemical origins, the following are the principal polymer types:

Polyvinylacetate homopolymers (PVAs)

In the 1960s and 1970s, PVAs were widely used in the building industry as versatile bonding agents and also to produce polymer-modified mortars and renders. However, for the reasons given below, they proved unreliable in long-term performance and are now only recommended for dry service conditions. A consideration of PVAs is worthwhile as they provide a good illustration of how the chemical and physical properties of a polymer can influence the performance of cement. In addition, these materials are related to more advanced derivatives that are now widely employed.

PVAs have many features that make them an attractive proposition for use with cements. As they can be made with a variety of water phases, it is relatively straightforward to achieve good compatibility with cement and eliminate problems such as set retardation. Flexibility in the choice of water phase also allows the adhesion to be optimised, and the ability to make polymers of high molecular weight ensures good strength properties and wear resistance. PVAs, however, have two major shortcomings, one due to the physical properties of the polymer and the other to its chemical properties.

PVA, irrespective of the method of preparation, readily absorbs water. This causes significant weakening of the polymer and, in a cement system, means that the wet performance of a PVA-modified material is no better, and often worse, than the unmodified control.

PVA is also readily hydrolysed, especially under alkaline conditions, to give polyvinyl alcohol and acetic acid, both of which are water-soluble. This has led to a lack of confidence in the long-term performance of PVA/cement systems in any applications other than dry, interior situations.

Co-polymers of vinyl acetate and the vinyl ester of versatic acid (Va/VeoVa)

The risk of PVAs giving poor performance in wet conditions led to an investigation of the co-polymerisation of vinyl acetate (VA) with a variety of hydrophobic monomers. VeoVa, the vinyl ester of the proprietary Versatic Acid, was one of the first.

The co-polymerisation of VeoVa with VA led to a significant improvement in wet performance and resistance to hydrolysis. Va/VeoVa co-polymer emulsions soon gained widespread acceptance, although currently they are mainly as powders. Following the superior performance of other co-monomers in wet conditions, some manufacturers developed VA/VeoVa further by, for example, incorporating additional groups into the backbone to react specifically with the calcium ions released from the cement.

Co-polymers of vinyl acetate and ethylene (VAE)

The use of ethylene as the hydrophobic co-monomer was a later modification made feasible by the development of high pressure technology needed to obtain high molecular weight and medium-high ethylene levels. At these high pressures, VA and ethylene co-polymerise readily to give high molecular weight products. This results in a more hydrophobic co-polymer which shows a corresponding improvement in performance under wet conditions. To obtain this level of performance demands the optimum ratio of ethylene/vinyl acetate and the correct choice of emulsifier. The production conditions must also be optimised to give a high molecular weight. If this is achieved, a VAE copolymer dispersion can not only give performance equivalent to that of a VA homopolymer under dry conditions (i.e. good strength and adhesion) but can maintain good performance in wet conditions. However, for service under permanently wet conditions, other polymer dispersions are generally recommended.

Other VA co-polymers

Other types of vinyl acetate co-polymers such as laurates, maleates and acrylates have been used in cement, but they have been replaced by systems giving better all-round performance, notably VAE's, styrene butadiene and acrylics.

Styrene butadiene rubber copolymers (SBRs)

The combination of styrene, which gives hard polymers, with an appropriate amount of butadiene, which gives soft polymers, produces a co-polymer of suitable film formation characteristics to be used with cement-based systems. Both monomers are hydrophobic and the co-polymers reflect this, giving good performance in both wet and dry conditions. Wear resistance is generally very good and SBR-modified mortars are widely used in industrial flooring. The emulsions contain surfactants which can lead to excessive aeration of the mortar when mechanical mixing is used and so a suitable anti-foam agent is usually incorporated.

Acrylics

Although commonly considered as a single category, the acrylics are a widely varying family of monomers and polymers whose properties range from hard resilient products to very soft materials which retain their flexibility well below freezing point. In general, the products used with cement-based systems are from the middle of the spectrum. The performance of the emulsions tends to be characterised by outstanding wear properties and resistance to chemicals. Poor adhesion in wet conditions can be a problem and special priming techniques need to be used for the best results. As with the SBRs, soap-like emulsifiers are commonly used and, therefore, the addition of carefully selected anti-foams is essential to avoid excessive aeration when mixed mechanically.

Styrene-acrylics

As acrylic monomers are generally expensive, the styrene-acrylics were developed in an attempt to achieve comparable performance at reduced cost by incorporating the cheaper co-monomer styrene. Thus, the general comments made for acrylics apply to the styrene co-polymers, although their properties in general are slightly poorer, but by careful formulation their performance can often be as good as unmodified acrylics. They have fairly good wear and abrasion characteristics, and the improvement in strength is substantial in both wet and dry conditions.

Redispersible polymer powders

A further stage in the development of polymer dispersions for use with cement has been the use of re-dispersible polymer powders (RPP). Most are based on the VAE and VA/VeoVa co-polymer systems described above, although acrylic polymer powders are now being used increasingly.

RPPs are made by spray drying an emulsion polymer. This requires the correct choice of polymer dispersion and stabilising system to ensure redispersibility on drying. Emulsion polymers can be stabilised by small molecular species, e.g. surfactants or emulsifiers, or by macromolecular materials which are themselves polymers; usually colloids (colloids are substances which appear to dissolve but cannot pass through a membrane; i.e. they are gelatinous). To spray dry an emulsion polymer and produce an RPP which readily redisperses in the cementitious mix, it is necessary to use a colloid – generally polyvinyl alcohol. The quantity, molecular weight and hydrolysis grade of polyvinyl alcohol incorporated need to be carefully selected to ensure full redispersion of the resulting powder, especially when softer copolymers are used. Further proportions of colloids are often added to the emulsion after manufacture but before spray drying, to improve redispersibility and to prevent lumps forming. These additions can impair the performance of the powder under wet conditions and the extent to which this happens largely depends on the skill of the manufacturer in balancing the need for full redispersibility against the need for good performance in the wet. A quantity of inert filler, typically 5 -10%, is generally blended with the RPP as an anti-caking agent. Although the dosage of RPP is generally lower than when a polymer dispersion is used, a correctly formulated RPP can give performance nearly equivalent to that of the precursor emulsion.

Redispersible polymer powders are increasingly being used in proprietary factory-produced PCC mortars. The range of materials offered by the major manufacturers is quite extensive. A range of co-polymer hardness is offered, as are specialist grades which give pseudo-plastic rheology, e.g. for external rendering. Other grades are available which generally rely on the introduction of other additives before spray drying and skill in the correct choice of the spray drying conditions.

Selecting a polymer dispersion

The selection of a polymer dispersion is really a matter for the formulating chemist. The engineer should only specify the performance he requires from the polymer-modified mortar or concrete. Specifying a generic polymer type will not assist towards obtaining the most suitable product but plays into the hands of commercial interests who seek to promote polymers produced from particular feedstocks.

4.6 Applications

Adhesives

Although polymer dispersions are combined with thickeners and inert fillers to produce adhesives for fixing tiles, gluing timber and other applications in the construction industry, this report is concerned only with their use in combination with hydraulic cements. A slurry of cement in a polymer dispersion is generally a better adhesive than either of the constituent materials used alone. This may be most strikingly demonstrated by bonding a sheet of plate glass to a block of concrete with a cement/latex slurry. When this has hardened and dried out fully, the bond is such that cracks cannot be propagated in the glass; striking the glass with a hammer will only produce conchoidal fractures immediately beneath the point of impact. However, the use of polymer emulsion/cement slurries as direct adhesives for bonding dissimilar substrates is comparatively limited, although they are widely used to promote the adhesion of cementitious mortars or concretes to existing hardened concrete, rock, quarry tiles and other substrates. Such adhesive mixtures may also contain inert fillers, notably silica sand. There is thus some overlap into the field of polymer modified mortars, but where such mortars are used to bond artefacts they may rightly be considered as adhesives. They are used to fix slip bricks, glass blocks, kerb stones, ceramic floor and wall tiles to concrete and to steel. In all these applications, suitably formulated, they provide very durable adhesives for all manner of exposed situations, submerged areas (e.g. swimming pools) and many chemical and food-processing situations. Polymer/cement adhesives are also used in housing refurbishment schemes to bond insulation, usually to the outer face of walls whose thermal properties are below standard.

In laying concrete floors, the interface between the floor slab and the screed or topping is the focus of any shrinkage stresses. Careful surface preparation, thorough compaction and the total elimination of water loss over an extensive curing period can produce a sound bond, but these ideals are difficult to achieve. It has been shown that the 'natural' cementitious bond develops strength rather slowly, so that if the curing control is less than perfect the increase in early shrinkage can rupture the bond before it is strong enough to withstand the shrinkage stresses, often leading to a 'hollow' floor. Although a hollow-sounding floor may still perform adequately for most purposes, if it is accompanied by curling or cracking, expensive remedial work may be required.

The use of a polymer dispersion as a bonding aid or primer to the prepared concrete slab can markedly reduce the risk of debonded screeds. It can be shown that, with such a bonding aid, the bond develops strength much more rapidly and so is better able to resist shrinkage stresses. While a neat polymer dispersion can be used for this purpose, it is more usual to make it into a slurry with Portland cement, as this gives a stronger and more water-resistant bond. It is vital, however, to ensure that the application of this bonding aid proceeds only just ahead of the screed laying; if the slurry dries out, a poor bond is likely to be obtained. Attempts to rectify the situation by a further application of the bonding aid is generally not recommended as it can give inferior results. On the other hand, some neat polymer dispersions may be used as bonding aids without this risk; they are reactivated by the application of wet concrete even after they have been dry for several hours.

Polymer dispersion/cement slurries and grouts

Polymer dispersion/cement slurries, usually incorporating fine inert fillers such as silica flour, are used as levelling compounds in the preparation of floors to provide a smooth levelled surface before overcoating or laying sheet flooring materials. The thickness of the compound will usually vary from 0 to 5 mm, any major imperfections or adjustments to a level being carried out previously with a polymer-modified mortar. Polymer dispersion/cement slurries may also be used as an all-over coating to provide a damp-proof membrane. In one case, a three-coat system of SBR/cement has been found to have a water vapour transmission well below the 14 g/square metre/day maximum limit that has been suggested for damp-proof membranes for ground floors. This system has advantages over the more conventional polythene film damp-proof membranes in that the subsequent screed can be bonded to it.

Polymer/cement grouts are also used as protective coatings to steel sheet and steel reinforcement. They have been used for many years as a treatment for the steel cages cast into autoclaved aerated cement units. They are also used as the steel reinforcement primer in many concrete repair systems. In some proprietary formulations, sodium nitrite or some other corrosion inhibitor is included in the grout.

Another interesting use of these grouts is in the resurfacing of airfield runways and hardstandings with a grouted macadam. An open-textured macadam is first laid to the required levels and then a polymer modified cement grout is vibrated into this, filling all the voids and producing a composite which has much of the fuel resistance of a concrete slab, while retaining much of the flexibility, economy and speed of construction of tarmacadam.

Mortars – screeds

Polymer-modified cementitious mortars and fine concretes have been used for many years to overcome the deficiencies found in traditional screeds, including their tendency to debond and curl and their poor abrasion resistance, often due to the practical difficulties of compacting thick screeds. Their use is covered in BS 8204 Part 3 'Code of Practice for polymer cementitious wearing surfaces.'

Polymer modification has made possible the application of thin screeds (typically 6-25 mm) which are more easily compacted and well bonded to the substrate. They exhibit slightly lower shrinkage, mature more quickly and have excellent abrasion resistance and low permeability. The outcome is better resistance to aggressive liquids and to freeze-thaw cycling. Their disadvantage is the higher material cost, but this is offset by the lower thickness required, although this in turn offers less scope for accommodating errors of level in the original slab.

Polymer-modified screeds can mature and dry very quickly and this alone can often justify their use where vinyl tiles or an epoxy coating are required to be applied at an earlier age. After 24 hours damp curing, three days drying-out is often sufficient to bring the moisture content down to the recommended level at which surface treatments may be applied.

Polymer-modified screeds are widely used to produce hard-wearing floors in factories and warehouses, and in North America they find extensive application as overlays for bridge decks. They are specified by the Federal Highway Administration for their freeze-thaw resistance and low permeability to water and water-borne contaminants and thus protect the steel reinforcement from de-icing salts.This operation is often carried out on an impressive scale; a continuously moving train of plant carries out the surface preparation, screed mixing, application and finishing in one pass, with the SBR dispersion being supplied by tanker. A recent development has been the formulation of polymer-modified cementitious flowing floor screeds which can be rapidly laid in large areas by pumping and simply levelling with a rake. These are generally laid in two stages: a base coat thick enough to allow for remedial measures on old floors and a 7-10 mm topping. Large areas of both base coat and topping can be laid in a single day to produce an abrasion-resistant floor topping that can be subjected to full service conditions within a few days.

Mortars – renders

Polymer-modified cementitious mortars are used as waterproof renders for lining cellars, swimming pools, etc. and additionally for their chemical resistance in food factories and the lining of sewers and manholes. As abrasion-resistant renderings, they are used to line industrial coal bunkers, etc. and for sea defences.

Polymer/cement adhesives are also used for bonding external insulation in the refurbishment of dwellings. In such schemes, a final protective render of polymer-modified mortar is usually applied to the insulation. The improvement in chemical resistance brought about by including a polymer dispersion in a cementitious mortar not only relates to the effect of aggressive liquids but is also shown in a reduction in permeability to gases. Many proprietary polymer-modified cementitious rendering systems have been shown to have resistance to carbon dioxide diffusion many times greater than quality concrete. This has proved of value in upgrading the 'effective cover' of reinforced concrete members where the steel reinforcement was installed too close to the surface. Around 5-10 mm of PCC rendering can provide carbon dioxide resistance equivalent to at least 50 mm of dense concrete cover.

Mortars – masonry

Polymer mortars are recommended by many brick companies for their superior adhesion and durability when used with engineering bricks and coping stones for parapets, footings and other exposed areas. These same properties also make them ideal for fixing glass blocks for the secure lighting of structures. Fixing kerbstones is another application for polymer mortars.

Mortars – concrete repair

With strict adherence to current Codes of Practice, reinforced concrete structures can be very durable. However, in a few cases, inadequate design, especially poor detailing, or poor construction practices have left a legacy of sadly deteriorating buildings and structures. Their repair and reinstatement now account for a significant proportion of the construction industry's turnover. In the field of concrete repairs generally, cementitious mortars incorporating polymer dispersions are proving very beneficial and have largely replaced epoxy resin mortars. The durability of simple cementitious mortar repairs had been found unreliable for a variety of reasons (high porosity, rapid carbonation, poor bond, etc.) and resin-based mortars appeared to provide a more satisfactory answer, having excellent adhesion and outstanding chemical resistance even in thin layers. These are not without their disadvantages, however, and polymer-modified cementitious materials that can be applied in thicknesses above about 8 mm are now widely used for the repair of reinforced concrete. It should be stressed, however, that adding a polymer dispersion to a sand/cement render of mediocre design will not result in a repair mortar with good durability. The optimum performance will be obtained only with carefully graded sands, cements and possibly pozzolanic materials, usually with chemical admixtures to reduce the water/cement ratio, control workability, etc.

Because of the sophistication of such formulations, it is generally recommended that such repair composition should be factory-prepared, so that only the liquid component needs to be added on site. Thus, a bottle of polymer dispersion is supplied with each bag of pre-blended powder. In many cases, a spray-dried polymer dispersion is incorporated as part of the powder pre-blend and only a measured quantity of water needs to be added on site to produce repair mortars with excellent long-term performance.

4.7 Practical guidance notes

The advisability of factory preparation and checking of multi-component complex mix designs has already been stressed, but this need not necessarily apply to the more conventional mixes used in floor screeds, where the only change from normal good practice is to add a polymer dispersion to the gauging water.

The quantity of polymer dispersion normally recommended is about 10% polymer solids (i.e. about 20% of a 50% dispersion) based upon cement weight. The optimum amount will depend upon the 'fines' content of the mix: where the total surface area of the cement and sand is high, a greater proportion of polymer dispersion will be required – hence the need to ensure that washed sand is used.

The water/cement ratio should be kept to the minimum consistent with a good workable mix, by ensuring that whatever water is required is used to dilute the dispersion before adding it to the dry materials. Allowance should be made for the water content of the sand. Mixing with neat dispersion and then adding water to give the required workability slightly increases the water demand. Virtually all polymer-modified materials need a forced action mixer for their preparation because of the lower water/cement ratio and higher cohesion of the mix. Free-fall conventional concrete mixers are unlikely to give satisfactory results and so pan or drum mixers such as the Creteangle, Screedmaster, Pennine, Croker-Lind or Mixal should be used.

Although overmixing should be avoided because of the risk of excessive air entrainment, some formulations such as those incorporating powder polymer, may appear to be very dry during the initial stages of mixing and then develop a more workable consistency after about three minutes. The temptation to add extra water at that dry stage must be resisted. It is also important to assess the workability of mixes by working with a trowel or squeezing with a gloved hand, not relying on appearance, because they can often look deceptively dry. Some modification to application techniques is required with these materials because of the dual nature of the setting process: hydration of the cement and evaporation/film-forming of the polymer dispersion. The quantity of material mixed should not exceed that which can be comfortably laid in half an hour. It should then be laid, compacted and finished as the work progresses; any attempt to go back later to wet-up and polish the surface in the traditional manner may result in a torn surface with inferior durability. Over-trowelling should be avoided as it may raise blisters and cause the polymer dispersion to bleed to the surface. For the same reason, vibratory compaction is not usually recommended, although some specialist contractors have developed effective techniques for laying polymer-modified cementitious floor screeds employing special vibratory floats.

The need for careful curing control of these materials must not be neglected. Conventional curing compounds are acceptable if the mortar is not to be coated subsequently with a decorative or protective coating. However, curing with polyethene sheeting carefully sealed around the edges is generally preferred. Usually this curing control is only needed for a day or so and then slow drying out is necessary to ensure the formation of the polymer film both on the surface and within the body of the mortar so that the enhanced chemical and abrasion resistance is developed.

5. PURE RESIN-BOUND AGGREGATE MORTARS AND CONCRETES (PC)

It is widely acknowledged that conventional mortars and concretes produced from sand, aggregates, cement and water have several inherent properties which make them unsuitable for some applications. The disadvantages include poor resistance to many chemicals, low tensile and flexural strength, slow rate of development of strength and often poor bond when applied directly to hardened concrete in thin layers.

A number of synthetic resin binders are available that can be formulated by incorporating carefully selected and graded dry powders, sands and aggregates to give a range of grouts, mortars and concretes with outstanding properties including high chemical resistance, high tensile bond and shear bond strengths, excellent abrasion resistance and good mechanical properties (compressive, tensile and flexural).

In the main, four chemically different types of synthetic resin binder are used in the production of grouts, mortars and concretes generally on site but also, to a limited extent, for factory-produced precast units. These are epoxy resins, unsaturated polyester resins, unsaturated acrylic resins and polyurethane resins (or elastomers). Furane resins are also used to a limited extent in the formulation of highly acid-resistant grouts for chemically resistant tiles and bricks.

5.1 Epoxy resins

Epoxy (or epoxide) resins were first developed in the early 1940s. Initially, they were investigated for applications in dentistry but have so far not proved suitable. However, it was realised that epoxy resins could be formulated to produce high-strength materials with excellent adhesion, resistance to a wide range of chemicals and good electrical insulation properties. Development over the past 30 years has established a very wide range of applications for epoxy resins from highly critical structural adhesives in aircraft construction, DIY adhesives, glass fibre reinforced resins for high-performance yachts, high-performance carbon-fibre reinforced golf club shafts and racing car parts, chemically resistant lacquers for lining food and beverage cans, encapsulation resins for both heavy electrical and microprocessing components to specialist adhesives, mortars, grouts, etc. for the construction industry.

5.2 Polyester resins

Unsaturated polyester resins were discovered in the mid-1930s and were initially used in formulating lacquers, particularly for wood finishing and low-pressure laminating resins. Glass fibre reinforced polyesters have now developed into a major industry. They are employed in the construction of boats, from sailing dinghies and ocean-going yachts to anti-magnetic minesweepers and for specialist car bodies, chemically resistant storage tanks and silos. At the other end of the market, they appear in a range of home-use kits for car body repair and other DIY work. In the UK, these normally employ modified curing systems (generally amine-accelerated benzoyl peroxide systems) which can cope with typical building site conditions (cold and damp), rather than the systems (e.g. MEK peroxide systems) used under factory conditions.

5.3 Reactive acrylic systems

Over recent years, reactive resins based on acrylic monomers, particularly methyl methacrylate monomers (MMA) which cure by similar mechanisms to unsaturated polyester resins, have been increasingly employed in the construction industry. Typical applications include heavily filled floor toppings and very low viscosity injection/impregnation systems. Some of the acrylic resin systems exhibit less shrinkage than conventional polyester resins but, because they are based on MMA, they tend to be volatile with a strong odour and also highly flammable with flash points around 10°C. Low-viscosity reactive acrylic resin systems with safe handling profiles are being developed and should become increasingly important over the coming years, but raw material costs are significantly higher than for the reactive resins in current use.

5.4 Polyurethane resins

Polyurethane resin systems are being applied to a limited extent in the construction industry, mainly as sealants, heavy-duty floor finishes, wall and floor paints, sealers and formwork coatings. There are two distinct types of polyurethanes: systems based on hydroxyl polymers and reactive isocyanates with a similar cure mechanism to epoxy resins; and systems based on one-pack moisture-curing polyurethane resins. These moisture-curing systems are reactive resins which can be applied as very tough coatings which depend upon the presence of atmospheric moisture to promote curing. The one-pack moisture cured polyurethanes depend upon atmospheric moisture to promote cross-linking and give tough binders. The reaction, however, releases carbon dioxide gas so that only thin coatings or semi-porous mortars or concretes can be produced. In general, both two-pack and moisture-curing one-pack polyurethane do not bond reliably under damp conditions without special priming systems.

5.5 Properties of resin-bound mortars and concretes

Compared with conventional cement-bound concretes and mortars, the major differences with materials based solely on resin (polymer) binders include: the lower modulus, much lower heat resistance and the higher coefficient of thermal expansion. With increased filler loadings, the modulus of filled resin systems increases and the coefficient of thermal expansion decreases so that heavily filled polymer concretes tend to be more compatible with conventional concrete. Less filled systems can also be formulated to exhibit good compatibility with concrete over a limited service temperature range by producing lower modulus systems which can absorb the thermal expansion differences without causing bond failure in the weaker (in shear) concrete.

In theory, creep may be considered to be a problem. In practice, for service at normal ambient temperatures, resin concretes and mortars are generally subjected to stresses below 20% of ultimate strength so that creep is very seldom a problem – providing, of course, that composition is appropriate to the service conditions and has been correctly mixed and applied. Most resin compositions lose their high-strength characteristics around 60-80°C and should therefore not be used in load-bearing applications where there is a risk of high temperatures or fire. At higher temperatures, resin mortars do not disintegrate and generally remain intact and retain their high strength when normal temperatures are restored.

In most applications, resin-bound mortars and concretes are bonded directly to concrete. It is therefore important to appreciate that there are significant differences in the mechanical and physical properties of conventional cementitious materials and the resin-bound materials. Unless this is fully understood, there can be problems of incompatibility between the concrete substrate and the resin composition. Table 1 gives a comparison of the physical and mechanical properties of resin-bound materials and conventional concretes and mortars.

	Epoxy resin grouts, mortars and concretes	Polyester resin grouts, mortars and concretes	Cementitious grouts, mortars and concretes	Polymer modified cementitious systems
Compressive strength N/mm²	55 - 110	55 - 110	20 - 70	10 - 80
Compressive modulus E-value, KN/mm²	0.5 - 20	2 - 10	20 - 30	1 - 30
Flexural strength N/mm²	25 - 50	25 - 30	2 - 5	6 - 15
Tensile strength N/mm²	9 - 20	8 - 17	1.5 - 3.5	2 - 8
Elongation at break %	0 - 15	0 - 2	0	0 - 5
Linear coefficient of thermal expansion per °C	25 - 30 x 10^{-6}	25 - 35 x 10^{-6}	7 - 12 x 10^{6}	8 - 20 x 10^{-6}
Water absorption, 7 days at 25°C, %	0 - 1	0.2 - 0.5	5 - 15	0.1 - 0.5
Maximum service temperature under load °C	40 - 80	50 - 80	In excess 300° dependent upon mix design	100 - 300
Rate of development of strength at 20°C	6 - 48 hours	2 - 6 hours	1 - 4 weeks	1 - 7 days

Table 1. A comparison of typical products used in concrete repair

5.6 Applications of resin concretes

Resins binders are used in the construction industry in many diverse applications from lightly filled adhesives to polymer concretes containing less than 6% resin by weight.

Adhesives

Because of their flexural, tensile and compressive strength, polymer concretes can be used as gap-filling adhesives. Variations in the profiles of the substrates being bonded can be taken up by the thickness of the adhesive layer. In some instances, resin mortars containing approximately 15% by weight resin binder are used in applications such as bonding precast units, architectural slip bricks and bonding/bedding of manhole frames, where the thickness of the resin is more than 10 mm. For other adhesive applications, where the adhesive thickness is generally 1-3 mm, the resin binder content of the adhesive is 35% by weight or more. Such applications include bonding new concrete to old to achieve monolithic integrity between the two layers without the extensive use of mechanical connections. Using resins to bond new to old concrete has been well proven for over two decades, but in the UK it is rarely used by civil engineers. In Japan, it has become an established engineering practice for more than 20 years .

Other adhesive applications include:

1. Bonding concrete to concrete – segmental construction.
2. Bonding steel to concrete for structural strengthening.
3. Bonding starter bars, wall tiles, panel fixings into concrete masonry, etc.
4. Bonding glass to glass and glass to concrete in architectural design concepts.
5. Timber adhesives – restoration of old buildings.
6. Bonding non-slip/non-skid treatments to bitumen and concrete roads and timber walkways.
7. Fixing brick slips, chemical-resistant tiles and similar applications .
8. Installing road markers.

Industrial flooring

A significant proportion of the total tonnage of resins used in the construction industry is for industrial floor finishes, ranging from penetrating resin sealers through floor paints to heavy-duty mortar toppings for improving the performance and appearance of concrete floors/sub-floors. There are many hectares of resin floor toppings which have proved satisfactory in service for more than 20 years.

Bedding materials

Since the mid-1960s, resin mortars and grouts have had significant applications in the installation of bridge bearings. Here, epoxy resin mortars with a compressive strength of at least 65 N/mm^2 have largely been used. In general, the performance has been very satisfactory but some of the formulations used in the late 1960s did tend to lose strength if the bedding was subject to very wet or partial immersion service conditions. There have also been problems, because of totally unsuitable mixing methods, in preparing the resin mortar bedding. The most common mixing malpractice was to tip the graded aggregate from the resin mortar pack on to a 'spot board' and then separately pour the liquid resin and curing agent components on to the heaped sands. The operative then thoroughly wetted out the sand by shovelling the three components together, often ending up with some of the sand wetted with neat resin, some with neat hardener and some with a crude mixture of resin and hardener quite unlike the recommended mixing ratio. The wrongly mixed mortar often went hard but strength was often below 5 N/mm^2, resulting in rapid failure under load.

Resin repair mortars for reinforced concrete

Over the past few years, the repair of concrete structures damaged by reinforcement corrosion has become a significant part of the UK construction industry workload. Once the cause of the problem has been properly established it should, wherever possible, be repaired with like materials. However, the possible thickness for the repair material is often such that cementitious mortars will not give adequate protective cover for the steel reinforcement, so that polymer repair mortars are often used for small repairs.

Where the cover is less than 12 mm and the areas to be repaired are not extensive, epoxy resin mortars are popular. However, it is important to note that, with epoxy resin (or other reactive resin binder) mortars, the protection of the steel reinforcement (unlike cementitious material whose high alkalinity helps prevent reinforcement corrosion by passivation) depends upon the total impermeability of the envelope and this requires very careful application. One recent development in the field of epoxy resin repair mortars has been the introduction of lightweight low-slump mortars based on hollow sphere fillers which enable easy application on vertical and overhead work, generally without the need of support during cure. Such lightweight mortars can develop compressive strengths up to approximately 60 N/mm^2.

Unsaturated polyester resin-based repair mortars have been restricted to very small repairs because of their high shrinkage. In some countries, reactive acrylic resins are being used increasingly for concrete repair mortars especially where rapid strength development is demanded.

Fast-setting resin grouts for installing and levelling street furniture

Over the past 30 years, some 15,000 tonnes of unsaturated polyester resin grouts and mortars have been used to install or raise manhole frames in roads. Despite the higher cost compared with cementitious materials, the higher strengths of unsaturated polyester resins (particularly flexural, tensile and bond strengths) have made them most cost-effective. Once grouted in with polyester resin mortar, frames seldom require regrouting. In addition, a complete installation can be carried out in less than four hours, so that interruption of traffic flow at peak periods can be avoided.

Grouting-in heavy-duty crane rails

The use of epoxy resin for installing and repairing support systems for heavy-duty crane rails has increased. The excellent mechanical properties and volume stability of the epoxy resin systems has allowed precision placement and long-term serviceability against the high compressive tensile and flexural forces induced under acceleration and braking.

The general practice is to cast a concrete support beam with its upper surface as level as possible and then mount the rail and soleplate using metal shims or levelling screws to level and align it, giving a 10-30 mm bed. The filled epoxy resin grout is then pumped into the void and allowed to cure. In the past, sand/cement and some proprietary cementitious grouts were chosen but suffered from a number of limitations including long cure times, low tensile and flexural strengths and poor resistance to chemical attack. These inadequacies led to costly repair works after only short periods of service.

The first major UK crane rail epoxy grouting job was for the rails for the Goliath Krupp Crane at the Harland and Wolff Ship Yard, Belfast, Northern Ireland in 1967. This large dock permits the construction of giant oil tankers under enclosed workshop conditions. The tankers are built in sections, each weighing approximately 800 tonnes, which are lined up for joining together in the 140 m x 800 m dry dock by a giant crane. The crane, which is 70 m high, runs on steel rails on both sides of the dock. The load of the laden crane is distributed over 16 bogies on each side.

For this contract, a special high-strength epoxy grout was developed and some 280 tonnes of the grout were used. During the development of this grout, there were problems with air entrained in the grout during mixing. If not eliminated, these would have resulted in weakness in the most critical part of the grout, the top 1-2 mm in contact with the soleplate. This was overcome by mixing all 280 tonnes of sand-filled grout in a vacuum mixer on site. The crane has now been in use for over 25 years and no deterioration of the grout has been observed. However, epoxy grouts now available do not, in general, suffer from the same problem of air entrainment as they have been formulated so that a minimum of air is entrained and vacuum mixing is rare.

Another development in the repair of concrete support beams for crane rails in the UK has been the use of epoxy resin concrete to fill any large voids beneath the rail caused by disintegration of the concrete. Voids larger than 100 mm have been filled in a single application. By carefully grading selected silica sands and gravels, it has been possible to achieve high-strength resin concrete with high filler/binder ratios (10-11/1 by weight). These resin concretes can be readily mixed in a planetary mixer and compacted into place with little effort. With these materials, a major repair of concrete support beams and relevelling of crane rails can be carried out within a few days which would be virtually impossible with more conventional cementitious materials.

Resin grouts to replace mechanical fixings

The use of resin grouts for installing dowels, starter bars, holding-down bolts and fixings of all kinds has grown extensively over the past 20 years. The volume of resin grouts, including mining applications, probably exceeds the volume of reactive resins used in all construction applications excluding industrial flooring mortars.

Because of their rapid strength development, polyester resin systems are most common and the holes are generally drilled using a rotary percussion drill with dowel/starter bars mechanically profiled so that the fixing is not relying on adhesion but a mechanically keyed high-strength 'lump' of cured resin locked into a rough hole. Having low shrinkage and high adhesion, epoxy/resin grouts are generally used where the annular gap between the fixing and the prepared holes exceeds 6 mm. The pull-out strengths of holding-down bolts, starter bars etc. installed with resin grouts into 30 N/mm^2 concrete depend upon the strength of the bolt etc. or cone failure in the concrete. It is generally accepted that the pull-out strength will exceed 1 tonne per 25 mm depth of embedment into 25 N/mm^2 concrete – a figure confirmed by tests. For deeper fixings, pull-out strengths are significantly higher but seldom required in practice. It is important to note that the strength of resin fixings falls at temperatures above 80°C or so. Where strength retention under fire conditions is required, the depth of embedment may need to be increased to provide protection. The proposed design should then be fire tested to prove adequacy.

Resin grouts for rock anchors

In the mining industry, polyester resin anchors have been used for more than 20 years to stabilise coal faces and access tunnels. In general, most mining applications are short-term but, in civil engineering, permanent resin rock anchors have been used since the late 1960s. Rock faces 16-20 m high have been stabilised by polyester resin anchor bolts up to 10 m long. On one project on the M6 motorway at Jeffery's Mount in 1970, some 200 rock bolts (20 mm diameter) were resin grouted and loaded to 50 kN in tension. The performance of 1 in 7 of these has since been monitored using load cells and no deterioration of the performance of the resin anchors has been revealed.

Precast resin concretes

Precast resin concretes based on chemically resistant unsaturated polyester resins or reactive acrylic resin binders have been used extensively in Japan, Europe and USA for cast drainage channels, pipes, manholes frames and covers for aggressive environments and similar applications for over 20 years. Other applications overseas include synthetic polyester resin (or acrylic) marble, onyx or artificial stone complete precast bathroom units.

In the past 10 years, production of precast resin concrete components has grown quite rapidly in a limited number of applications: corrosion-resistant drainage systems, feeding troughs for piggeries and similar agricultural components. The commercial exploitation of other architectural components made from polymer concrete has been less successful in the UK than many other countries.

The factory production of precast resin units involves the use of low-viscosity polyester resin (or acrylic) binders filled with carefully selected and graded dry aggregates. Resin concretes with compressive strengths above 80 N/mm^2 can be obtained with resin contents below 8% by weight. To produce components from polymer concretes as cost effectively as possible, sophisticated manufacturing techniques are used to achieve void-free materials at a minimum possible resin binder content.

Although the resin binders are at least 15 times the cost of OPC, the higher costs can be offset by producing equally strong, lighter (thinner) units.

5.7 Polymer concrete mix design

The philosophy of mix design for polymer concretes may be broadly compared to that of conventional concrete mixes – that is, a process by which a material with acceptable plastic and hardened properties for a specific application is produced at optimum cost. There are, however, significant differences in philosophy and therefore in the approach to the design of polymer concrete mixes:

5.7.1 Performance parameters in the hardened material are likely to be different. In conventional concrete, compressive strength and durability are the most common criteria, while polymer concretes are more likely to be judged on one or more of the following factors:

Tensile strength or tensile failure strain

Stiffness

Creep resistance

Wear resistance

Elevated temperature resistance

Impact resistance

Fatigue resistance

Chemical resistance

Bond strength to other materials

Improvements in one of the above categories may lead to improvements in others – for example, tensile strength, creep resistance and fatigue performance. On occasions, however, it may be necessary to prioritise in order to obtain optimum performance in some properties at the expense of others.

5.7.2 In view of the high cost of polymer binders, it is expedient to make every effort to reduce the proportion of resin in the mix. This means in practical terms, using the lowest acceptable workability of mix, together with the most intensive compaction method obtainable (usually a combination of vibration and pressure) and suitably skilled operatives. A further prerequisite for a consistent and reliable product is an acceptable working environment, especially when the additional problem of inclement weather is considered. Although site production of polymer concretes is certainly feasible, adequate organisation and supervision are of paramount importance.

5.7.3 In conventional concrete, the lubricant and the binder (water and cement, respectively) are separate materials and, although the presence of some water is essential to the hydration process, less water (within well defined limits) always results in a better product, provided full compaction is achieved. Since water and cement are batched separately, the performance of the hardened product can vary widely at a given workability owing to variations in cement content. In view of the cost of resin, the prime object of mix design is to produce a fully compacted mix with minimum resin content.

In addition to the cost incentive of employing low-volume fractions of the resin binder, the following properties of the hardened material will generally be increased by using the lowest possible binder content.

a. Elastic modulus (E). Dense natural aggregates have E values more than eight times greater than that of hardened resins so that low-volume fractions of resins are essential to obtain E values of the same order as conventional concrete – 40 kN/mm^2.

b. Shrinkage. The curing shrinkage of the hardened materials is reduced. With resins such as polyester and acrylic, additional strains from the exothermic heat build-up during curing are minimised.

c. Resistance to wear (abrasion resistance).

d. Resistance to creep.

e. Coefficient of thermal expansion (reduced).

In practice, polymer concretes are generally supplied ready batched and so the complexities of mix design are not normally the concern of the end user. As the polymer concrete manufacturing industry increases in maturity and experience, so the correct specification of materials for a particular use should become easier and more reliable.

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6. REACTIVE POLYMER/CEMENT HYBRID-BOUND AGGREGATE CONCRETES (RPCC)

This section describes the performance and applications of thermo-setting resins which are used in concretes and mortars in conjunction with hydraulic cements. Although in these systems sufficient resin is provided for the polymer to form a continuous phase, the cement may still be present in sufficient volume for its hydration products to form a continuous structure within the polymer. Three classes of resin capable of providing a continuous matrix to bind the aggregate in the presence of cement hydrates are polyesters(1), epoxides(2), and polyurethane/isocyanates(3). The mixes must contain enough resin to constitute the continuous phase binder for the aggregates and sufficient cement and water to provide a phase of cement gel and possibly a gel structure.

The presence of the resin as the continuous phase and the cement gel (structure) provide the set mix with a different combination of physical properties from those of either the resin or the cement structure alone. The compressive strength generally approaches that of a conventional cement concrete while the tensile strength is more characteristic of the pure resin concrete. In practice, it is possible to balance the compressive and tensile characteristics by formulation selection.

The mixing and application of these products is particularly critical, so they are only supplied to specialist contractors approved and trained by the manufacturer.

6.1 Applications

Because resins are much more expensive than cements, the resultant polymer concretes and mortars are used in ways which exploit their higher level of performance: thinner layers, high adhesion, rapid strength development and enhanced chemical resistance. The overall economics constrain their wider use but consideration always needs to be given to cost-effectiveness rather than cost.

Another constraint is imposed by the commonly found conditions on the application site, especially wet, cold climates. Most resin/cement composites require substrate concrete to be reasonably dry to achieve adhesion. Some internally catalysed polyester/cement systems and specially formulated emulsifiable epoxide resins are exceptions. All require setting and curing temperatures above freezing if the cement hydration is to proceed and the matrix not to be damaged by ice formation. The heat sink effects of substrate concrete normally suffice to require different resin formulation for thin-layer mortar applications. Within these constraints, polyester, epoxide and polyurethane/isocyanate resin cement composite mixes are all used with aggregates chosen to provide mortars suitable for surfacing concrete in situ. Some other substrates such as metals are also suitable.

For floor toppings, a significant impact has been made in replacements of granolithic concrete in industrial uses involving those environments which are chemically or physically aggressive to pure cement-bound mixes. Both special water-initiated cement/polyester and cement/polyurethane /isocyanate resin systems have been developed for and exploited in this use. Polyurethane/isocyanate/cement systems have been used extensively for floor toppings in food-processing factories because of their excellent resistance to steam cleaning and non-taint properties. In general, industrial floor toppings require application in one layer of mortar at least 6 mm thick. Less aggressive conditions use mortar of 3 to 5 mm thickness applied in one or, sometimes, two layers. Finishes with a terrazzo-like ground surface are possible.

The mixes based on polyester and epoxide resin can be used for repairing or filling wide cracks or spalled areas in concrete. Such applications include precast concrete units, roads and airfield pavements. Heavy-duty repairs for pavements, such as broken slab corners or whole bay failures, can be done with concrete based on up to 25 mm aggregates bound with resin/cement composites which enable repair areas to be returned to service within a few hours. Other uses for such resin cement concretes include rapid strength-gain concretes for sea defences, bedding for road furniture and industrial machinery.

Polyester and epoxide-resin/cement-based mixes can be used as adhesive mortars. Many minor applications have been described from bedding concrete structural elements to sticking a decorative face to concrete panels.

6.2 Performance

The role of the resin/cement composite binder in an RPCC is not clearly understood. As in an ordinary Portland cement concrete, the performance is significantly influenced by aggregate/binder ratio and by the physical properties and grading of the aggregate. The resin/cement binder is less thixotropic than a conventional Portland cement/water paste and consequently it is possible to obtain mixes with good workability with higher aggregate/binder ratios.

In general, the rheological properties of RPCC are similar to those of the resin which is the continuous phase rather than the dispersed cementitious phase. Comparisons have been made between mortars based on ordinary Portland cement, cement/polyester RPCC, polyester resin and epoxy resin using the same sand. The cement/polyester RPCC exhibited an early strength growth curve similar to cement but accelerated by around 1:25 (1 hour strength equivalent to 1 day cement strength), whereas the cement-free pure resin-bound systems showed a much faster strength growth. To optimise the cost-effectiveness of RPCC mixes, they can be designed to provide compressive strengths comparable to, but not significantly exceeding, the strengths of conventional cement mixes. By comparison, RPCC mixes are quicker setting, have better adhesion to substrates and exhibit higher tensile strength (double or treble) than cement bound mixes. The durability of RPCC systems is good and some floor toppings based on cement/polyester resins and cement/polyurethane/isocyanate resins have given excellent service for more than ten years. RPCCs resist a wide range of chemicals and foodstuffs and other aggressive environments significantly better than conventional cement-bound mixes but generally worse than PC materials specifically formulated for resistance to named chemicals.

References to Section 6

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CONCRETE ADMIXTURES HANDBOOK. Properties, Science & Technology. Ed.U.S. Ramachandran (BRS. NRC Canada) Noyes Publications Hant Ridge NY USA. (Polymer-Modified mortars & concretes by Ohama).

7. PREPARING CONCRETE SURFACES FOR ADHESION

Polymer concretes and mortars are generally used in contact with conventional concrete for repair or protection. The performance of polymer concretes invariably exploits their enhanced tensile strength. This requires excellent adhesion at the interface between the polymer concrete and the ordinary concrete substrate to give optimum transfer of tensile loads.

All techniques for preparing hardened concrete to permit its interface with polymer concrete to transfer tensile forces require the aggregate to be exposed. The ultimate capacity of the interface to tolerate tensile loads will depend on the adhesion of the polymer binder to the surface of the aggregate and the ability of the cement paste to accept the loads transferred to it.

There are several ways of ensuring these conditions are met. All are costly but there is now more than 25 years' service evidence that the proper initial preparation of the substrate ensures the durability of the subsequent application of polymer concrete.

With normal concrete, only mechanical abrasion can adequately remove the cement paste matrix from around the large aggregate. Excessive applied energy can fracture the large aggregate which may be dislodged from the matrix, or perhaps worse, remain embedded but only weakly held. Abrasion techniques which impart enough force to disrupt the cement matrix but not the aggregate are available.

For those applications of polymer concrete where the cement concrete interface is expected to transfer tensile forces to the full capacity of the substrate design strength, e.g. industrial flooring, at least 30% of the interface will need to be of clean, strong exposed large aggregate. In less demanding applications, e.g. repair of spalled reinforced concrete, at least 10% of exposed aggregate is necessary to ensure transfer of loads imposed by climatic variations, etc. Only when the interface of the concrete substrate has been prepared adequately for its intended function can the properties of the polymer concrete be fully exploited.

The principles for ensuring that the full properties available from polymer concretes and mortars used in conjunction with cement concretes have been well established over several decades and millions of square metres of interface. The following methods for substrate preparation are commonly used:

7.1 Scabblers

Developed from equipment which consisted of a series of pneumatic drills mounted on a pram, scabblers are several return-acting pneumatic cylinders with a hard steel castellated head mounted on the piston. Their effect results from bouncing the head onto the concrete surface at around 200-500 Hertz (according to air pressure) against the relatively low weight of the unit. Combinations of single units or, usually, six/eight pistons mounted in a common cylinder block are available. Scabblers are very efficient on large areas, given a sufficient supply of compressed air, and can be worked in line sequence. There is no provision for removing dust, even airborne dust, and the energy involved should be considered carefully for its effect on the support structure of suspended floors.

7.2 Shot blasting

Shot blasters are totally enclosed mobile machines which impact the concrete surface with steel shot, collect the shot and detritus and separate them so that only the shot is recycled. The effects of the shot impacting the concrete result entirely from the kinetic energy imparted to it by a high-speed rotating disc, being comparable to a high-pressure air-transported shot blast. The intensity of the effect is controlled by the speed of the machine over the surface of the concrete.

By their nature, blasters seek out the weaker points at the concrete surface. If the cement matrix is young or otherwise weak, it will be eroded deeper than the strong matrix. The result can be that the surface profile produced requires larger quantities of polymer concrete to provide a minimum cover to the most exposed aggregates.

Blasters are not always satisfactory. They may remove either too little to provide sufficient texture or remove insufficient contaminated concrete. They can also remove too much, leaving an unacceptably uneven surface if the substrate is of variable quality. Some blasters fitted with vacuum have the great merit of working quietly and being substantially dust-free, leaving the surface of the concrete ready for immediate application of the polymer concrete. They are, however, somewhat cumbersome and require good access conditions, including connection by large-diameter flexible pipe to exterior plant for collecting the detritus. They work best in continuous strips and can prove tedious on a congested site, being unable to gain access under plant and machinery.

Grit blasting gives similar textures to shot blasting: the main difference is that the grit cannot be re-used and is discarded.

7.3 Flails

Machines made with rotating flails are widely used to clean-up contaminated concrete and are particularly effective for removing other trades' spoilings, paints, etc. Few are robust enough to remove much cement matrix from good-quality, well hardened concrete.

Models which carry washer-shaped hardened steel rings on rotating rails can impart sufficient kinetic energy to expose the large aggregate on concrete around 3 to 5 days old. They operate only in relatively narrow bands and take time to prove effective: they are not, therefore, economic for large areas.

A variation of the flail, the needle gun – a hand-held tool for preparing substrates for surface coatings – can be used for small areas.

7.4 High-pressure water jetting

This is an extremely effective method of removing the surface layers of concrete and the plant costs can be quite acceptable when large areas of hardened concrete surfaces are to be exposed. The technique involves pressures of the order of 1000 to 2000 bar and needs skilled operatives.

Although the system involves water waste disposal as well as removal of the concrete surface, it does not have the dust and noise problems of some of the mechanical methods described earlier.

7.5 Exposure of unhardened surface

A well profiled aggregate exposed substrate interface can be achieved on freshly laid concrete by removing the cement matrix before it has hardened. If rotary wire brushes are passed over placed concrete in the presence of running water within 24 hours (from around 6 hours according to conditions affecting the setting and rate of strength gain), the matrix is readily removed and the exposed large aggregate effectively cleaned. When applicable, this is the most efficient method of preparing a concrete interface for a high-strength polymer concrete application.

Non-mechanical preparation, e.g. acid etching, is generally not considered effective but is used by some specialist flooring contractors to prepare good-quality concrete substrates before laying special floor finishes. Apart from the health and safety hazards involved, there are problems of disposal of the etching products. It is also imperative that the etched concrete is rinsed carefully to ensure no etching products remain on the substrate.

8. ACCEPTANCE AND PERFORMANCE REQUIREMENTS FOR POLYMERS IN CONCRETE

Four important points need to be borne in mind when considering the subject of testing:

a. The polymer concrete system under consideration.

b. The application to which the system is to be put.

c. The test being for acceptance by laboratory assessment.

d. The test being for site performance.

a. and b. have been dealt with at length in the body of this report and so this section will concentrate on c. and d. coupled with references to testing.

Irrespective of the fact that the vast majority of poor performances, deficiencies, failures or general problems result from bad design and/or workmanship, practically all the references to testing in standards concentrate on c. – laboratory assessments. Thus, general understanding is limited to the potential of polymers in concrete – not their performance on site.

The main sources of testing information are listed below, both national and international. The recommendations section gives preference for emphasis on future developments.

8.1 International and European

Acting on behalf of EC and EFTA, the European Standards Organisation CEN has allotted the task of agreeing test methods for polymer concretes to CEN TC 104 SC8, which covers 'Materials for the repair and protection of concrete.' The work of SC8 is divided into six Task Groups:

TG1 Materials for the surface protection of concrete

TG2 Repair mortars and concretes

TG3 Structural adhesives

TG4 Materials for crack repair

TG5 Materials for anchoring

TG7 General principles for use of repair materials

TG2 will agree test methods to ensure that repairs of reinforced concrete with mortars and concretes, including polymer-modified mortars and concretes, protect the reinforcement from corrosion and give good long-term durability.

TG2 is considering tests to measure the following performance parameters:

a. Tests to ensure that the mixed materials have the right application characteristics and maintain them for an adequate time at the application temperature to enable repairs to be carried out correctly.

b. Tests for strength and rate of strength development to ensure the materials are more than adequate for their purpose.

c. Tests to ensure that the repair materials are sufficiently dimensionally stable and compatible with the concrete being repaired.

d. Tests to ensure that the materials have low permeability to gases or liquids.

e. Tests to ensure that the repair material has good integrity and bond to concrete under environmental or load cycling conditions likely to be encountered.

Most of these performance parameters are essential for polymer concretes in any application and not just in repairs.

Under the rules of CEN, existing ISO Standards (where appropriate tests have been established) followed by existing National Standards of European Countries have to be considered first. RILEM⁽¹⁾ tests, particularly the nine test methods developed by RILEM Technical Committee 52-RAC, to measure the performance properties of PCC and PC materials when used in conjunction with conventional concrete, are also being considered. Readers can keep up-to-date with the progress of CEN TC 104 SC8 through BSI News.

8.2 France

In France, tests for the adhesive strength of coatings, paints etc. on metals generally refer to a separate Standard (2) but the equipment used has been modified for polymer mortars and concretes. The apparatus is a simple tensile pull-off machine which can be operated in the laboratory or on site. There are three Standards in the P18 (2) series applying to structures.

There is also a very detailed Afnor Document – Special regulations for special products for structures of hydraulic concrete – which lists all the AFNOR Standards for repair materials, both polymer-modified mortars and resin products (2).

8.3 Germany

Several documents (3) had been produced in draft form by the Federal German Minister of Transport before unification. Presumably the same ministry will continue to administer this service for the whole country. The documents cover both mortar/concrete repair systems as well as coatings and specify adhesion limits as well as test methods.

The German Committee on Reinforced Concrete has also published Guidelines for the protection and repair of concrete components. This covers all aspects of concrete repair. Tests methods and acceptance performance limits for repair materials, including polymer modified mortars, resin mortars and adhesives are detailed.

8.4 Netherlands

The Netherlands have produced CUR Recommendation 21 Concrete repairs with polymer-modified cement mortars.(4) This has been prepared on similar lines to the German guidelines. Like most of the European countries, Holland sits on the SC8 committee referred to in sub-section 8.1.

8.5 Italy

Like Japan and the UK, Italy has a series of sequential Standards that deal with organic polymers (5). A separate publication by AICAP discusses recommendations for testing PIC (polymer-impregnated concrete). These recommendations list mechanical properties, absorption, permeability, penetration of aggressive ions and invoke UNI 7928 and 8019 for, respectively, sulfate and frost-resistance tests. It should be borne in mind that PIC is not within the scope of this Report.

8.6 Japan

Japan has a series of Standards covering test methods for polymer-modified mortar and a separate Standard for testing polymer dispersions (6). Of all the sources of information examined, Japan has the longest and most comprehensive number of tests.

8.7 Scandinavia

Where the word 'Nordtest' appears, the draft test methods listed (7) have been prepared by the Scandinavian countries and not by Norway alone. The reference shows that mechanical tests are not so important as tests that relate more closely to the in-situ mechanisms.

8.8 Switzerland

The Swiss have produced a revised edition of their testing programme (8). This contains, in the first section, a number of tests with the accent on tests on the polymeric material. The section also includes tests for water permeability, water vapour diffusion resistance and carbon dioxide diffusion. The second section is more practical and deals with tests in conjunction with concrete such as adhesion and freeze/thaw cycling with de-icing salts. The proposed limits of 1.5 MPA average minimum and 1.0 MPA individual are the same as Germany's.

8.9 UK

The current Standard BS 3619 has been extended from ten to twelve parts, Parts 11 and 12 being at the stage of Drafts for comment(9). Part 4 of the Standard deals with bond strength by the slant shear method, which has been successfully used on site on drilled cores taken at a slant angle through resin-injected cracks. However, it may be seen that the Standard is oriented towards laboratory-made samples and testing. For site adhesive tests of polymeric surface renders and coatings, the bond test for paints, sometimes modified, is used. This site test method has been taken from the ISO Standard.

The Construction Industry Research and Information Association (CIRIA) has a project reviewing existing practical test methods for repair materials and coatings to assist the UK participants at CENTC 104 SC8. (See also 8.1.) A report on this work will be published shortly.

8.10 USA

ACI Committee 503 and the ASTM have produced several Standards. The ACI work towards standard specifications for code-oriented activities associated more with site work, whereas ASTM deals with test methods. The ASTM C882 test is similar to the UK BS 6319/4 slant shear test. The ASTM C503 series includes one or two Standards that advise on how to carry out in-situ operations as well as how to test the efficiency of the polymer system. For example, C503.2 suggests tapping the concrete surface to listen for hollowness and then drilling a core out if there is a problem with adhesion(10).

8.11 Recommendations

It may be seen from the test methods surveyed that there is a preponderance of methods relative to the polymers themselves rather than their performance. This report does not disparage this but suggests that the aims be more closely defined. This delineation could best be actioned via CEN TC104 WG8 in conjunction with ISO, RILEM, and ACI Committee 503 in the production of a series of test methods and codes that could cater for the construction industry in the following ways:

a. Standardised methods of making test specimens and carrying out laboratory tests. Such standards could be used as:

    i. manufacturer's quality control

    ii. disputes concerning alleged changes in the product

    iii. specifying safety levels of specific properties.

b. Standardised methods of sampling and testing on site or sampling on site and testing in the laboratory.

c. Code-oriented documents giving specifiers guidance on site usage and minimum levels of performance for various levels of use.

d. Increase the scope of testing to deal with matters such as thermal cycling, moisture cycling, impact and dynamic loading.

e. Integrate the best of the countries' experiences and prepare a. – c. above as harmonised documents.

References to Section 8

1. RILEM - Technical Committee 52-RAC

1. Pull-off test
2. Dynamic loading test
3. Slant shear test
4. Direct shear test
5. Cylinder tensile test
6. Thermal compatibility Test I
7. Thermal compatibility Test II
8. Four point bending test
9. Injectability test.

2. France

NF.T 20-602 - Determination of adhesion strength by pull-off.

AFNOR Identification No.030 Special Regulations : Special products for hydraulic cement structures.September 1989.

NF.P18-831. Hydraulic binder or synthetic resin-based sealing product - pull off test.

NF.P18-836. Synthetic-based sealing products. Creep test under tensile load at 23°C and 50°C.

NF.P18-855. Products or systems for the application to the surface of hardened concrete. Test for permeability to liquids.

3. Germany

Federal Minister of Transport. Document series No.22003 (GOST 25881-83).

Technical and Supplementary Technical Test Regulations for concrete placement systems using polymer admixtures in mortar/concrete (2 No. documents).

Supplementary Technical Regulations and Guidelines for the Protection and Maintenance of Concrete Components.

German Committee on Reinforced Concrete

4. Netherlands

CUR20 Bond strength of repaired systems.

CUR21 Polymer-modified cement repair materials - Recommendations for repair.

5. Italy

Auxiliary products based upon organic polymers for mixing with cement.

UNI.9532 Determination of bond strength of composite specimens.

UNI.9533 Determination of water penetration under pressure.

AICAP Technical recommendations for polymer-impregnated cement composites.

6. Japan

JIS : A1181 - 186 etc. Methods of test for polymer-modified mortar (pmm).

Manufacture of test specimens.

Measuring methods for the working life of polyester resin concrete.

Method of test for tensile strength of pmm.

Method of test for flexural strength and flexural toughness of pmm.

Method of test for compressive strength and static modulus of elasticity of pmm.

Method of adhesion test for pmm.

Method of test for bond strength of steel bars in pmm.

Method of test for impact resistance of pmm.

Method of test for adhesion durability of pmm after heat cycling.

Method of test for accelerated carbonation of pmm.

Method of test for corrosion inhibiting property of pmm.

Method of test for the chemical resistance of ppm.

Method of test for incombustibility of ppm.

Method of test for thermal expansion coefficient of pmm.

Method of test for splitting tensile strength of polymer concrete and mortar.

Method of test for static Young's modulus of polymer concrete/mortar.

Method of test for abrasion resistance of pmm.

JIS : Al171. Method of manufacture of test sample of pmm in the laboratory.

7. Scandinavia

Nordtest Test method drafts for polymer composites and coatings.

Water vapour diffusion.

Capillary absorption.

Chloride permeability – diffusion cell method.

Chloride permeability – embedded steel method.

Carbonation resistance.

8. Switzerland.

Testing programme on polymer-modified cement mortars.

9. UK

BRITISH STANDARDS INSTITUTION. BS6319: 1984 Testing of resin compositions (PCs) and polymer modified cementitious systems (PCCs) for use in construction.

Pt.1 Method for preparation of test specimens

Pt.2 Method for measurement of compressive strength

Pt.3 (1990) Method for measurement of flexural strength

Pt.4 Method of measurement of bond strength (slant shear method)

Pt.5 Method for determination of density of hardened resin compositions

Pt.6 Method for determination of modulus of elasticity in compression

Pt.7 Method for measurement of tensile strength

Pt.8 Method for assessment of resistance to liquids.

Pt.9 Method for measurement and classification of peak exotherm temperature.

Pt.10 Method for the measurement of the temperature of deflection under a bending stress.

Pt.11 Method for determination of creep in compression and tension.

Pt.12 Method for measurement of unrestrained linear shrinkage and coefficient of thermal expansion.

BRITISH STANDARDS INSTITUTION. BS3900: Part E10: 1979 (ISO 4624) Paints and varnishes. Pull-off test for adhesion.

10. USA

ACI 503R Series. Use of epoxy compounds with concrete. C503.1 Bonding hardened concrete, steel, etc. to hardened concrete. C503.2 Bonding plastic concrete to hardened concrete. C503.4 Standard specification for repairing concrete.

ASTM C03.01 (Draft). Compressive creep of chemical-resistant polymer machinery grouts.

ASTM C307. Test method for the tensile strength of chemical-resistant polymer machinery grouts, mortars, grouts and monolithic surfaces (crmgams).

ASTM C308. Test methods for working and setting times of chemical-resistant resin monolithic surfacings (crrm).

ASTM C321. Test method for the bond strength of crrm.

ASTM C413. Test method for the absorption of crmgams.

ASTM C531. Test method for linear shrinkage & coefficient of thermal expansion of crmgams.

ASTM C579. Compressive strength of crmgams and polymer cement.

ASTM C580. Test method for the flexural strength and modulus of elasticity of crmgams.

ASTM C722. Specification for chemical resistant monolithic resin surfacings.

ASTM C811. Standard practice for surface preparation of concrete for application of chemical-resistant resin monolithic surfacings

ASTM C882. Bond strength for epoxy resin system used with concrete (to hardened or freshly-placed).

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