6. Aging factors affecting adhesion

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6.0. Introduction

The durability of the adhesion between building components is one of the most important features of the durability of the structure. This not only includes the features of the adhesives and the substrate, but is also depending on the durability of the interface between the adhesive and the adherents [1]. Moisture, temperature, and other environmental parameters affect the interface in a manner different than they affect either the adhesive or the adherent. Durability assessment therefore can only be obtained from tests on composite samples. A general description of the aging factors affecting the adhesion is hard to accomplish since the broad variety of the adhesives. In this chapter, the environmental as well as the mechanical effects on the adhesion phenomenon are briefly described. In the second part, the findings are illustrated by a number of case studies in which the influence of temperature, humidity and environmental conditions are considered.

Adhesion is mostly looked at as the adhesion strength between different building components, achieved by an adhesive. In this case, the behaviour of the adhesive, mostly a polymeric "glue" and of the joints are topic of discussion. Modified materials, such as latex modified cement mortar or concrete, however, show improved adhesion properties which makes the use of an adhesive between the different components redundant. The durability assessment of these materials varies from the durability of the pure adhesive joint with an adhesive. The development of adhesion for polymer modified cement mortar or concrete, is attributed to the high adhesion of polymers [2]. The adhesion is usually affected by polymer-cement ratio, type of polymer and properties of the substrate. A general approach however is given in this chapter. The findings are illustrated with some practical applications of polymer modified mortar and concrete.

6.1. General

6.1.1. Environmental effects

Adhesives, as structural fasteners; are unique in the way that their stiffness can change with environmental conditions without any change in the loading on a structure which might be assembled by them. For polymers, additional durability concerns are raised by the intrinsic visco-elastic or time dependent behaviour of the mechanical properties. That is, not only will flow grows to be of critical size as for metals, but stiffness and strength characteristics will degrade with time to the extent that rupture may occur without the formation of a well defined flaw or crack. Further, the mechanical properties of polymers are strongly influenced by temperature, moisture content, aging, and other factors. Most of these effects associated with polymer memory are well known and are directly related to the molecular structure [3]. Brinson discussed the methods used to attain the durability of adhesions and pointed out that lap specimens produced good qualitative information when the joint

has been exposed to environmental effects, especially moisture and temperature [1]. One advantage of lap shear testing was indicated to be that they include mixed mode failure effects similar to prototype joints. Limitations were related to the lack of a detailed knowledge of the stress field and associated deformation and failure mechanism in the joint.

Fracture specimens were indicated to have become popular as a means of evaluating the effects of surface treatments and joint durability. Their great advantage is described as a simple, well defined tensile stress state for which failure mechanisms can be readily understood. Their limitation was due to the lack of mixed mode information more like that needed for prototype design.

The parameters affecting the environmental durability of adhesive joints are presented in table 1 [4]. The most important parameters, affecting the polymer are temperature and moisture.

Parameter		Comments
Water		Activity, bonding concentrations. pH and soluble aggressive ions. It absorbed by adhesive, may plasticise and toughen.
Temperature		Rate of degradation promoted by elevated temperature: also creep effects. may aid post-curing. may plasticise and toughen cured adhesive.
Oxygen		Contribution to metallic corrosion and polymer degradation.
Adhesive	composition	Interfacial contact. Air voids. Chemical type affects cured structure. bulk properties. interfacial composition and stability.
	cure schedule	low temperature curing implies inferior performance.
Adherends	metals	Surface stability.
	concrete	Surface dryness and coherence. permeability.
	composite	moisture content. permeability.
Surface pretreatment		A most important factor. Specific to particular adherends and solvents. the adhesive, Failure of primer (if applicable). Bonding conditions.
Stress	internal	Cure shrinkage, temperature variation, swelling by moisture. Strained bonds more susceptible to attack.
externally applied		probably increases the rate of diffusion of an ingessing medium. stress-corrosion. Stressed polymer, with an increased free volume may retain more water (than an unstressed polymer.
Joint design		Stress concentration/tensile forces at or near interface reveal sensitivity towards environmental attack.
Time		Duration of exposure. application of stress and adhesive viscoelasticity.

Table 1: Parameters affecting environmental durability [4]

6.1.1.1. Temperature in polymers

Most adhesives are based on polymeric materials and as such exhibit properties which are characteristic of polymers. This is particularly so when considering their response to temperature variation. At a certain temperature, known as the glass transition temperature T_g, polymers change from relatively hard, elastic, glass-like substances to relatively viscous rubbery materials. The transition temperature varies from one polymer to another.

The influence of temperature on basic mechanical properties of the hardened adhesive, such as the bulk flexural modulus and shear strength is illustrated in figures 1 and 2 [5]. The most noticeable feature of the curves is the rapid deterioration in both stiffness and strength at a temperature close to the measured T_g of the adhesive.
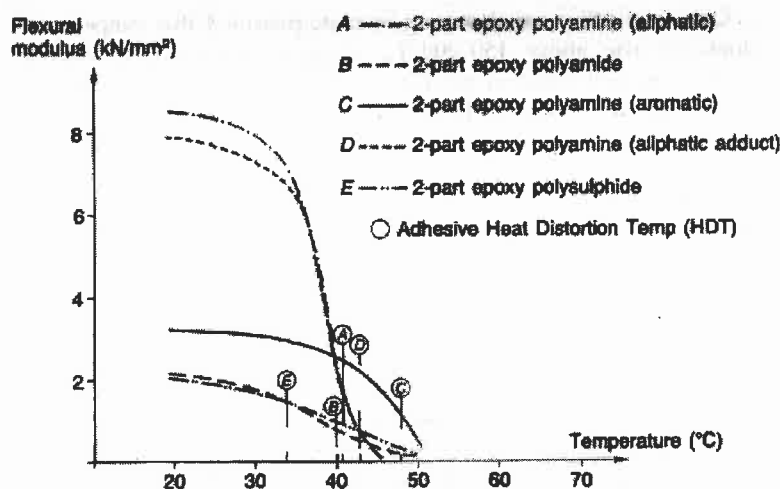

Figure 1: Temperature dependence of bulk adhesive flexural modulus

Provided the temperature does not rise above 150-200°C, when a chemical deterioration occurs, the reduction in mechanical properties above the T_g is reversible on cooling. Indeed, stiffness and strength may even be enhanced due to post-cure effects at the elevated temperature. On the debit side, T_g will be lowered by water absorption into the polymer.

The adhesion properties of polymer modified mortar and concrete is influenced by temperature due to the temperature dependence of the polymers themselves. The latex-modified materials generally show a rapid reduction in strength and deflection with increased temperature [2]. This trend is substantial at temperatures higher than the glass transition temperature of the polymers and at higher polymer-cement ratios.

The curing temperature of the polymer modified mortar or concrete is determined for the structure of the modified mortar or paste. Curing at temperatures blow the minimum film forming temperature of the polymer emulsion prevents the formation of a continuous film throughout the cement hydration [2;

6]. The influence however on the properties of the polymer modified cement mortar or concrete is not yet fully grasped. It seems that even when a latex is not capable to form a proper film, an improvement of e.g. the flexural strength can be noticed due to formation of intramolecular complexes in the polymer modified cement mortar or concrete [7].
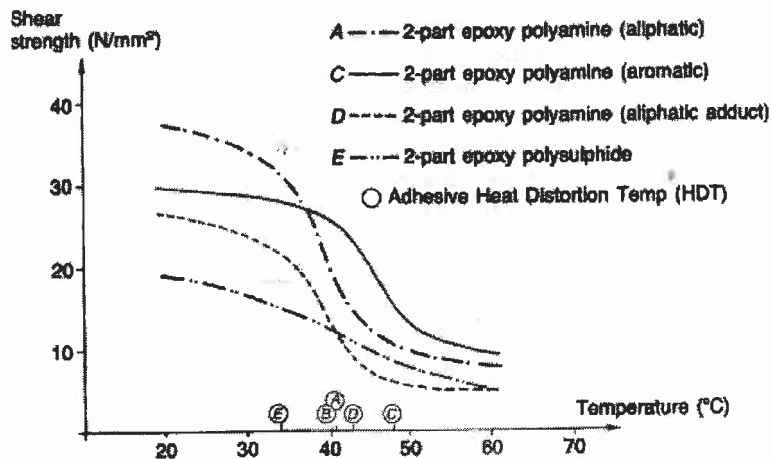
Figure 2: Temperature dependence of bulk adhesive shear strength

The thermal resistance of latex-modified mortar and concrete is governed by the nature, especially glass transition temperature of polymers used, the polymer-cement ratio, the heating conditions and ultimately by the thermal degradation of the polymers. The maximum temperature limit for retaining useful strength properties is found to be about 150°C [2].

6.1.1.2. Moisture

Adhesives are susceptible to the effects of exposure to water or water vapour. Indeed, when cured, the very epoxy groups which give epoxies their adhesive properties also render them hydrophilic [8]. The polar groups which confer to the adhesive properties make the adhesives inherently hydrophilic. This water uptake is accommodated largely by swelling. Water may enter an adhesive either by diffusion or by capillary action through cracks and crazes [4]. Once inside, the water may alter the properties of the adhesive either in a reversible manner, for example by plasticisation, or in an irreversible manner, for example by hydrolysis, cracking and crazing.

When joints are concerned, water has proved to be the most harmful environment. Experience has demonstrated that the main processes involved in the deterioration of joints subjected to the influence of moisture are absorption of water by the adhesive, absorption of water at the interface through displacement of the adhesive and corrosion or deterioration of the substrate surface.

Comyn suggests that water may enter and affect the performance of a bonded joint by one or a combination of the following processes [9]. Firstly, water may enter the joint by:
- diffusion through the adhesive
- capillary transmission along the adhesive/adherent interface (wicking)
- capillary action through cracks and crazes in the adhesive

- diffusion through the adherent if it is permeable.
To the above may be added osmotic pressure gradients.

Secondly, having accessed a joint, water may cause weakening by one or a combination of the following actions:
- reversible alterations to polymer mechanical properties (e.g. plasticisation, swelling)
- induction of reversible bondline swelling stresses
- irreversible alterations to polymer mechanical properties (e.g. hydrolysis, cracking, crazing)
- irreversible adhesive/adherent interface attack by displacing the adhesive.
Interfacial attack is clearly the most damaging action, but adhesive plasticisation also has a profound effect of joint performance.

Effect of water on the adhesive
The influence of water on the adhesive is generally reversible, so that any deterioration in mechanical properties is recovered upon drying. The extent of this influence depends upon the adhesive's composition. All polymers absorb greater quantities of water when above their T_g, so that rubbery materials tend to show greater water absorption than rigid adhesives.
Water uptake by polymers is accommodated largely by swelling. For uptakes of only few mass per cent, volumetric swelling would be of a similar or lower order [10], and barely measurable.
Water depresses the T_g of the adhesives. This is worrying particularly for cold-curing epoxides with typical transitions when dry in the range 40-50°C, and underlines the need to select adhesives whose glass transition temperature do not drop substantially with water sorption. The modulus and strength of the cured polymer matrix are also lowered by water-induced plasticisation, in a manner akin to the organic plasticisers often used to modify the mechanical properties of adhesives.

The fracture toughness of adhesives, generally increases with absorbed water, because of the greater plastic deformation [11]. Cohesive strength however, may sooner or later be reduced sufficiently to offset the increased toughness. The general implication is that the toughness benefit of unmodified or initially tough products such as the rubber-modified adhesives is negated through a loss of cohesive strength [12].

Effect of water on the interface
The most important factor in the long term durability of bonded joints is the stability of interfacial adhesion against moisture. The absorption of water and its transport to the interface with the adherent can lead to irreversible changes, such as adhesive displacement by moisture and corrosion. Ultimately, the area of bond supporting the load diminishes until it can no longer sustain it, and joint failure occurs.

Widespread evidence indicates that the type of failure of joints alters under the influence of moisture, from cohesive failure within the adhesive layer to interfacial separation. Water, in fact, displaces the adhesive when secondary valency bonds exist and in doing so applies stress to the fewer number of chemisorbed bonds which may be present. Adams and Wake state that if the adhesive/adherent bond results solely from simple physical adsorption (secondary bonds), then the relative energies from adsorption of water to the substrate and adhesive compared with the energy of adsorption of adhesive to substrate determine the equilibrium situation [13]. Adhesive displacement is consequent upon a

film of water existing preferentially at the interface if access is gained through defects, if the adhesive absorbs more than a few mass per cent of water , and if a high energy substrate surface is present. If the adhesive/adherent bond involves chemisorption, then displacement can only occur after hydrolytic destruction of the chemical bond.

The intrinsic stability of the interface in the presence of moisture may be assessed theoretically from the thermodynamic arguments advanced by Gledhill and Kinloch [4]. They extended the deduction of the thermodynamic work (W_a) to the calculation of the work of adhesion in a liquid environment, and showed that this value was negative for an epoxy/ferric oxide interface. Kinloch and Comyn present further predictions that bonds between epoxies and glass, aluminium, and iron and steel are unstable in water, whilst bonds to carbon-fibre composites are stable [8]. Thus bonds to high-energy polar adherents are calculated to be unstable in the presence of moisture, what is borne out by experience [4].

Techniques for increasing interfacial stability

Interfacial stability is largely depending on the rate and diffusion of water in the adhesive. To avoid the displacement of the adhesive from its substrate, water diffusion should be avoided. This can be attained by taking adhesives which are essentially hydrophobic. This may be achieved by the use of highly cross-linked polymers, polymers containing plate-like fillers, the incorporation of hydrophobic additives, and polymers possessing only enough polar groups for adhesion [4]. Bolger discussed the balance of an optimum concentration of polar groups with polymer mobility [14]. Mastronardi showed how the presence of hydrophobic coal-tar blended with the epoxy polymer matrix of coatings strongly reduced the affinity with water, minimising water transport and maximising durability [15]. Bowditch and Stannard describe an inherently hydrophobic cold-curing epoxy for steel bonding [16]. Coupling agents may also be mixed into the adhesive [4]. Coupling agents, also known as adhesion promoters have the ability to enhance resin adhesion to surfaces such as glass or metal. The most popular type are silanes which can either be mixed with the adhesive itself or applied to the substrate as a primer.

Water resistance of polymer modified cement mortar or concrete

Latex-modified mortar and concrete have a structure in which the larger pores can be filled with polymers or sealed with continuous polymer films. In general, the effect of polymer filling or sealing increases with a rise in polymer content or polymer-cement ratio. These features are reflected in reduced water absorption, water permeability, and water vapour transmission. As a result the latex-modified mortar and concrete have an improved waterproofness over ordinary mortar and concrete. This is favourable for the durability of the adhesion, since the water will be prevented to reach the transition layer. On the other hand, latex modified mortar or concrete have poorer water resistance so that their strength is decreased when exposed to water or high humidity. The poor water resistance is most probably caused by a partial re-emulsification (or re-dispersion) of the polymer phase in the latex-modified materials [2]. Re-drying will usually allow the strengths to be recovered if irreversible chemical change in the polymer phase has not taken place. The adhesion strength of latex-modified mortars after 14-day water immersion, started after the dry curing of the material. As can be seen in figure 3 [2], adhesion is reduced under wet conditions. However, the adhesion strength of most latex-modified mortars after water immersion is still larger than that of unmodified mortar.
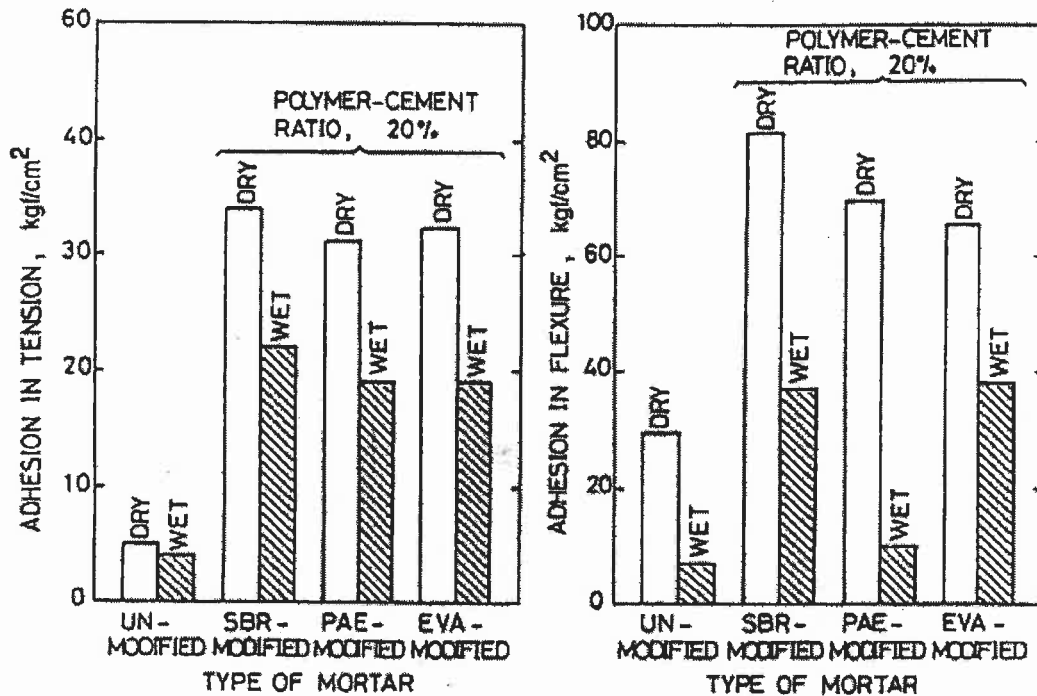
Figure 3: Effect of water absorption on adhesions in tension and flexure of latex-modified mortars [2]

6.1.1.3. U.V. radiation and weathering

The effect of U.V. radiation or sunshine can be divided into two main effects: a photochemical effect and an energetic effect [6]. Photo- degradation under ultraviolet radiation can cause breakdown of the material, leading to discolouring, loss of toughness and embrittleness.

When sunlight falls onto a polymer, the molecules absorb energy of certain wavelengths in the UV range. This is particularly so for the ester groups and the aromatic rings which are strong UV absorbers. The absorbed energy can cause the rupture of covalent bonds, according to different mechanisms, e.g. photo-oxidation and photo-fries reactions [17]. According to the photo-oxidation reactions, the UV radiations are absorbed by impurities in the polymer, and as a result hydrogen atoms are abstracted from the methyl groups, forming a free radical and thus initiating a chain scission reaction which propagates the reaction. In photo-oxidation, chain scission is favoured over cross-linking, particularly near polymer chain ends resulting in the formation of low molecular weight compounds. At short wave lengths, degradation free radicals tend to recombine into products, while under long wavelengths they react separately, forming structures with phenolic end-groups [18].
Besides the photochemical action, responsible for dissociation of molecules and the energetic action, providing energy to accelerate reactions of degradation, other complementary effects may be observed, such as differential dilatation due to different dilatation coefficients or vanishing of volatile components and modification of the material structure.
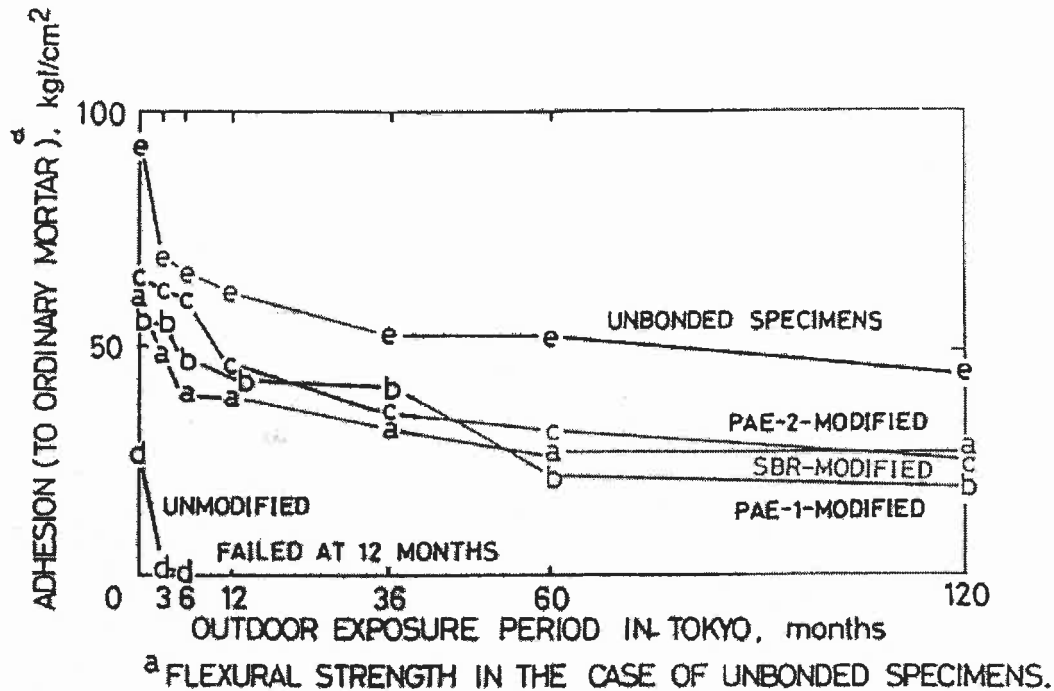
Figure 4: Adhesion durability of latex-modified mortars[2]

The resistance of the adhesion of latex-modified mortar or concrete against U.V. radiation and weathering is largely depending on the durability of the latex-modified material itself. Under long-term outdoor exposure, involving frost action and carbonation, latex modified mortar shows increased resistance to weathering in comparison with conventional mortar and concrete. Durability of latex-modified mortars in term of adhesion to ordinary cement mortar after 10-year outdoor exposure in Tokyo is shown in figure 4. In contrast to unmodified mortar-bonded specimens which failed within one year of outdoor exposure, most latex-modified mortar-bonded specimens had a satisfactory adhesion for practical use after the 10-year exposure.

6.1.1.4. Chemical attack

Failure of the adhesion due to chemical attack can be caused by the degradation of the polymer or by the degradation of the adhesion itself. In the latter case, failure is often caused by osmotic pressure. Generalizations, however, are to be avoided since not only the nature of the chemicals, their concentration, and the temperature of the environment conspire to influence the chemical resistance, but also the type of polymer used, the additives, the properties of the polymer and the application conditions are influencing factors.

Excellent chemical resistance of the material can be obtained by specification of the proper material. For example in the case of an epoxy resin, the chemical resistance of the cured resin highly depends on the hardener used [19]. The chemical resistance is also related to the thermal stability of the polymer. In the case of epoxy resins, the factors tending to promote thermal stability also tend to

improve chemical resistance, such as the presence of aromatic groups, the cross-linking density of the resin [19].

Chemical attack of the adhesion system results often in a delamination of the adhesive and the adherent due to blister formation as a result of an osmotic pressure. The formation of blisters is a well-known phenomenon in industrial floors. Osmose is defined as the diffusion of water molecules into a solution through a semi-permeable membrane due to a concentration difference [20]. To obtain blister formation by osmose, four parameters are relevant: the presence of water, which can be present in the concrete or at the surface; a semi-permeable membrane, which can be the concrete surface or the surface coating; a solution, which is present in the blister and the capability of pressure building, which depends on the strength of the coating. If all four are present, following mechanism can take place: between the adhesive and the adherend, between the top layer and the concrete, osmose promoting products can dissolve in water. This results in a highly concentrated solution. Through the semi-permeable membrane, e.g. the coating, water will enter into the blister to reduce the concentration difference and the volume of the blister will be enlarged. This phenomena can take place immediately after application of the coating or after several years. The blisters will grow until one of the following criteria is fulfilled [20]:
- the concentration difference between the solution in the blister and the surrounding is approximately zero. This is obtained when the blister has a substantial volume and when sufficient water in the concrete or at the upper surface is present. This results in large blisters and is mainly obtained in the case of soft coatings with bad adhesion properties.
- the volume of the blister is limited. The osmotic pressure will rise until the amount of molecules which are pushed back through the membrane are equal to the amount of molecules passing through the membrane to decrease the concentration of the solution in the blister. This results in small blisters and is occurring in the case of a rigid coating with good adhesion properties.
- the water supply from the concrete or from the environment is limited. The magnitude of the blisters will decrease again.

6.1.1.5. Biological attack
The influence of biological attack on the adhesion has not been studied deeply. It is however plain that mechanisms which are effecting the concrete and the adhesive will also deteriorate the adhesion between the different components.
Biological attack can be divided into corrosion due to the presence of mosses and algae on the surface of the material and corrosion due to decalcification and expansion caused by gypsum formation or ettringite formation in the concrete, as is known by the biogenic sulphuric acid corrosion. This type of corrosion is very severe for concrete. Corrosion rates up to 10 mm/year are measured [21].

The biogenic sulphuric acid corrosion is mostly present in sewer pipes. The sulfate, present in the sewer water is altered into sulphide by anaerobic bacteria. This sulphate can escape into the sewer atmosphere in the form of H_2S. In the condense layer on the sewer pipe surface, above the average water level, the gas is again altered into sulphuric acid by aerobic bacteria (Thiobacilli Thiooxidans). The sulphuric acid will react with the CaOH and C-S-H-crystals in the concrete. It is known that polymer sewer pipes are much more resistant to this type of corrosion. The influence of polymer modification of the concrete however is not fully understood yet. The presence of the polymer film seems to retard the corrosion, but is not able to avoid the leaching out of the concrete [22].

6.1.2. Mechanical loading

Whilst the properties and behaviour of adhesives in bulk form are linkable to their composition, the behaviour of joints constructed with adhesives is less predictable. In particular, joint behaviour is determined largely by the joint's geometrical configuration and by the way in which it is loaded, since these factors control the nature and magnitude of the resulting bondline stresses and stress concentrations. To a large extent, and provided that a reasonable amount of care in the design of the joint has been taken, the adhesive's stiffness determines the general behaviour. However, because the stiffness of adhesives changes with loading and environmental conditions, consideration must be given to the effect of these conditions on joint behaviour [4].

6.1.2.1. Cyclic/fatigue

Fatigue of a material is a progressive fracture which consists of the cumulation of damage resulting from sustained, long-term loading of a constant, variable or cyclic nature [23]. Local modifications which appear in the material structure under load may lead to a kind of stabilisation, for example, in the form of permanent deformation. The word fatigue is used, however, for such situations where there is no stabilisation but rather a gradual increase in damage.

The fatigue strength of materials means the maximum value of stress which may be supported indefinitely and is indicated in relation to the static strength under single, short-term, loading. The strength under cyclic loads is always presented as decreasing with time, and it may be stated that the fatigue strength does not exist at all for concrete-like materials. It means that after a sufficiently high number of cycles failure occurs.

The fatigue performance of an adhesive under cyclic loading is related to the adhesive's visco-elastic response and its resistance to crack propagation, or fracture toughness. At low frequencies and high temperatures, visco-elastic effects were predominate. At higher frequencies and lower temperatures, fracture due to crack propagation either within the adhesive layer or at the adhesive/substrate interface tend to control the number of load cycles that can be sustained prior to failure.

For most applications fatigue resistance in shear is of overriding importance, and slow-cycle loading is likely to be the most detrimental in allowing cumulative creep. Fatigue performance is also related to the joint configuration, and the resulting nature of the stress and strain distribution within the adhesive layer. [4]

6.1.2.2. Creep

To determine the long-term behaviour of a material either stress relaxation or creep tests may be used. The former involves monitoring the time-dependent change in stress which results from the application of a constant strain to a specimen at constant temperature. Conversely creep can be thought of as time-dependent flow under constant load which may lead to fracture or creep rupture. Stress, time and temperature are the most important parameters for creep.

Results of creep tests on the bulk adhesive and on composite samples are not necessarily comparable. The difference in the reduction in stress concentrations which will occur in the joints is a contributing factor.

Creep rate varies with the stress level. The higher the stress, the greater the creep rate. The existence of an equilibrium stress is suggested [8]. Above this stress level, the material will creep to failure.

If the sustained stress is lower than the equilibrium value, indefinite creep will not occur.

6.1.2.3. Abrasion and impact resistance
Results of abrasion and impact tests, which report the influence on the adhesion, are not reported. However, it is plain that a failure of the adhesive or the adherent will consequently result in the failure of the adhesive bond.

The abrasion resistance as well as the impact resistance of latex-modified mortar and concrete depend on the type of polymer added, the polymer-cement ratio and on the abrasion or wear conditions. In general, the resistance is considerably improved with an increase in polymer-cement ratio [2]. In both cases, data however vary markedly between the different testing methods.

6.2. Experimental data
A selection of experimental data is presented in this chapter. Due to the large variety in applications, type of products and design, it is not possible to give an all-embracing overview of the tests carried out on real size structures or field tests. Some particular cases are highlighted.

The long-term behaviour tests emphasize the importance of the environmental conditions; especially temperature and moisture, on the behaviour of the adhesive bounds. The results of the tests carried out on polymer modified cement concrete stresses the influence of polymer, added as emulsion to the concrete on the adhesion.

6.2.1. Long term data
The long-term performance of rehabilitations is of prime importance for the design engineer, who is personally responsible for the safety of the building users, and that during a very long period. Long-term performance is an approximate synonym of durability. Durability of a material or a building component is its ability to resist changes in its state or, in other words, of its properties. Of utmost importance in rehabilitation is real life experience, gained in case-studies. They fill the gap in theoretical knowledge about prediction of the service life or durability of materials and systems. The durability evolutions in strengthening of reinforced and prestressed concrete constructions is discussed.

Extensive research has been done to study the long term behaviour of the glued composite: steel plate, epoxy adhesive or concrete. Pioneering work was done at EMPA-Zürich [24]. Corrosion and creep measurements were undertaken on a great number of long term exposed beams (1950 mm x 200 mm x 150 mm) strengthened with an externally bonded steel plate. This project started in 1977 and went on more than 10 years. After the exposure period no difference in static behaviour up to failure was observed. Different preparations of the bonding surfaces were compared, to check if rusting and debonding had occurred and, if so, how it could be prevented.

Additional tests were carried out in other countries [25]. Grit blasting proved to be the most appropriate preparation for both the steel and concrete bonding face. The epoxy adhesive, with and

without primer, seems to have no significant influence on the corrosion behaviour. Creep of the adhesive layer is slightly higher than normal concrete creep. The creep difference increases with time although the variation is very small. It does not affect the mechanical behaviour of the steel-concrete composite element. Fatigue tests showed no fatigue failure, except at very high tensile stress variations ($?s = 310$ MPa) in the bonded plate. In that case plate separation from the concrete can occur, but the fatigue cracks can propagate in the concrete, as well as in the adhesive layer, depending on the specific system conditions [26].

Based on these positive experimental results, a durable external reinforcement will be obtained if the following conditions are fulfilled:

- relatively hydrophobic adhesives must be used, with a suitable rheology to ensure complete wetting of the steel surface;
- grit blasting is the minimum appropriate steel surface pre-treatment;
- stress levels in the anchoring zones must be limited, especially in fatigue loading;
- design engineers and contractors must be trained and familiar with the technique. Only certified adhesives should be used.

One of the methods for checking the durability of the glued connection under atmospheric conditions is the tear-off test on small cylinders, glued to the concrete surface. A great number of cylinders were glued on three repaired bridges over the Nete-Canal at Lier (Belgium). Cylinders were glued on surfaces permanently in the shadow, and on surfaces heated up by sun radiation. Over a ten year period each time, six cylinders were tested both in the summer and winter period. After 10 years no decrease in strength could be observed [27].

The rheological behaviour of an epoxy bonded steel-concrete connection is being studied on a concrete plate reinforced with two epoxy bonded steel plates only. The loaded plate is shown in Figure 5.
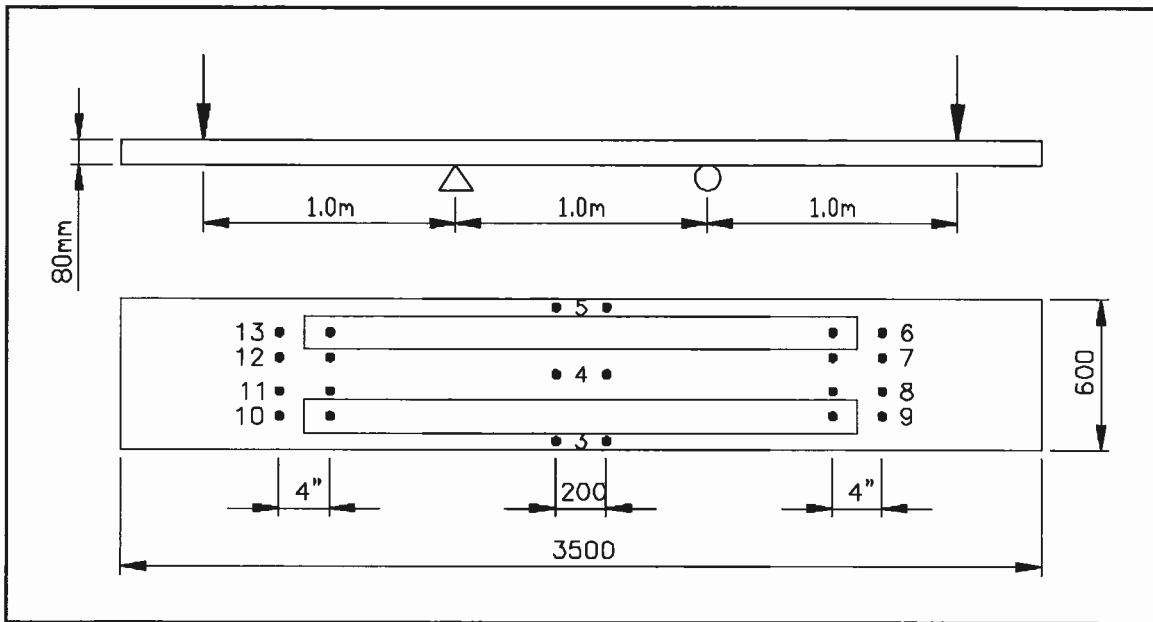
Figure 5: Externally reinforced concrete plate for outdoor exposure

The numbers indicate the different measuring bases. The loads, applied in a third-point bending test, were applied on 30-day-old concrete, whilst the glue had been cured for 7 days in laboratory conditions. The total load was 9.6 kN.
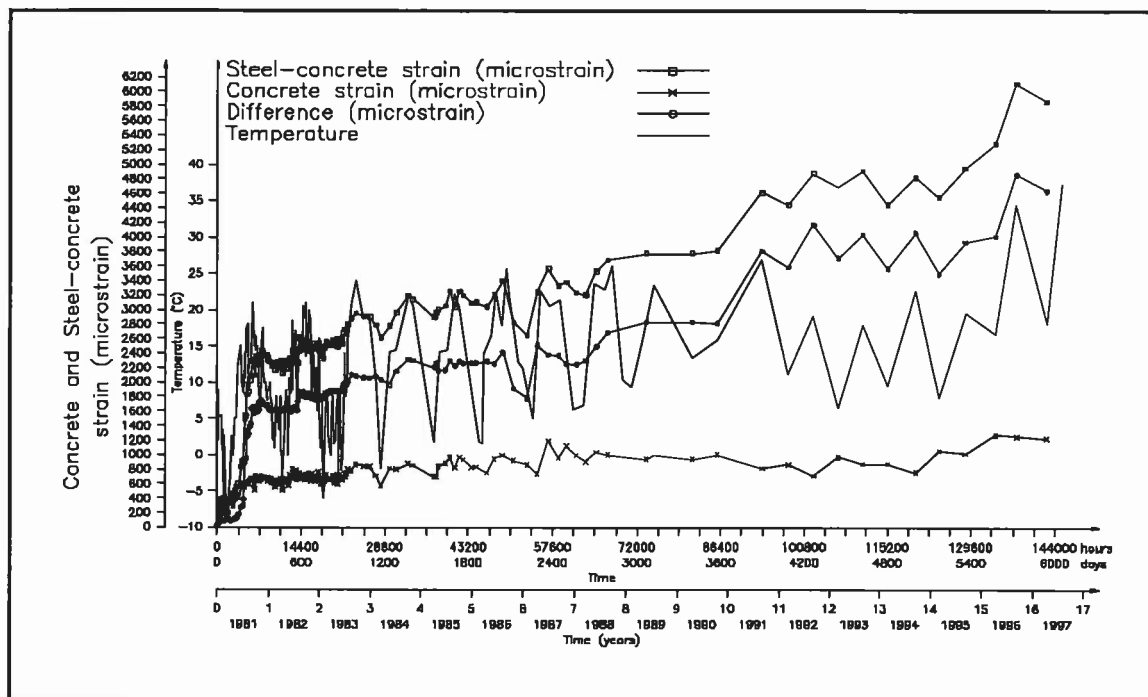
Figure 6: Evolution of temperature and strains in period 1981-1997

The creep test started on 05th November 1981. The rheological behaviour of the glue is evaluated by comparing the evolution of the strain on the steel-concrete bases with the evolution of the concrete-concrete strains. The evolution over 16 years is shown in Figure 6.

Studying the temperature evolution on the same figure indicates that the first warm period had an important effect on the behaviour of the glue. An analogous variation has not been measured since. The differential creep seems to increase with time, although the variation is very small.

On 12th August 1997 at 5 pm the plate structure collapsed, as shown in Figure 7.

Figure 7: Strengthened plate, collapsed after 16 years of outdoor exposure

Figure 8: Stretched surface of glue layer

The epoxy bond between steel plates and concrete failed after 15 years and 9 months of climatic exposure. The collapse took place at 17h30, at which moment the ambient temperature was still 30 °C after a very hot day with maximum temperature of 37 °C. Intense vibrations had been caused during the day by rehabilitation works on the sewer system at a distance of 2 m from the plate support. The theoretical shear stress in the glue layer was about 0.12 N/mm², but the maximum shear stress at the plate ends could amount up to 1.5 N/mm². The shear span to depth ratio was 1000/80 = 12.5 and the unplated length 400 mm. The rupture of the epoxy glue was due to viscous flow of the epoxy. This can be derived from the surface aspect of the glue after rupture, as shown in Figure 8.

The surface shows successive zones, where the glue has stretched between the steel plate and the concrete. The collapse time, several hours after the hottest moment of the day, proves that the collapse happened through an accumulation of damage in the joint, amplified by viscous flow. The fracture also happened at the plate ends, which were most exposed to direct sun radiation and heating.

6.2.2. Durability of polymer modified porous concrete

Porous concrete is characterised by a large porosity, up to 25% water accessible porosity. It is used among other applications, as top layer on highway roads to reduce noise production and to ameliorate water drainage. The role of the polymer modification is not only to ameliorate the durability of the concrete, but also to provide sufficient strength to withstand the traffic. Due to the addition of polymer emulsion, especially the adhesion between the binder matrix and the aggregates is increased. To emphasize the importance of the aggregate-matrix adhesion for porous concrete, the transition between two aggregates in the material is shown in figure 9 [28]. Clearly, the small polymer modified cement layer is visible between both aggregates. Adhesion, on micro-scale, therefore has a significant role
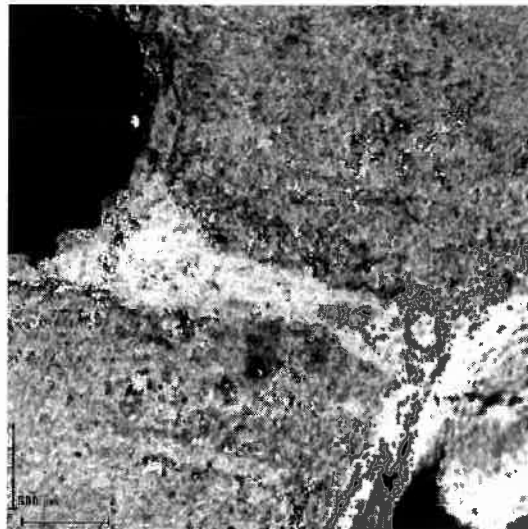

Figure 9: Polymer-cement layer between two aggregates in porous concrete

in the properties of the material.

In an extensive test program, different characteristics of the porous concrete were investigated.

Durability properties as there are the resistance against freezing and thawing cycles, against de-icing salts and against temperature variations were determined. Different types of polymer emulsions were used and tests were carried out on mortar as well as on porous concrete. The conclusions from the research are summarised here.

Figure 10 represents the transition zone between two aggregates, after the sample is etched with HCl. Clearly, the adhesion between the polymer film and the aggregate is visible. An enlargement is given in figure 11. [28]
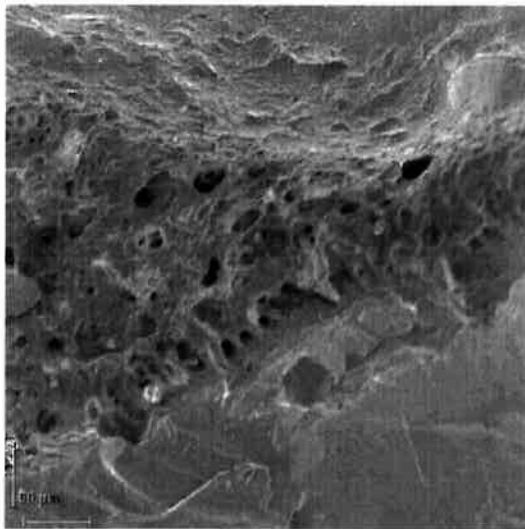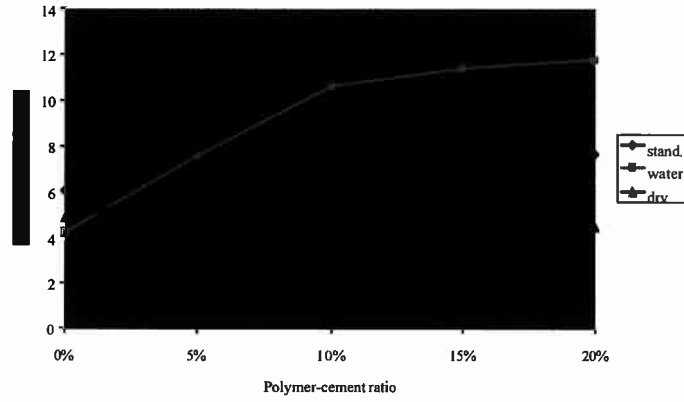

Figure 10: Mortar, modified with 15% SAE, after etching (200x)
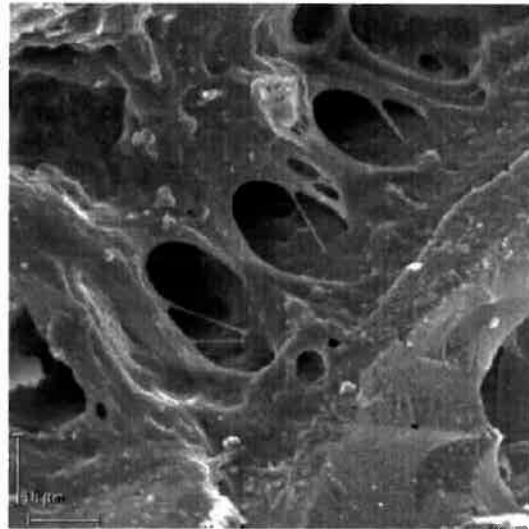
Figure 11: Enlargement of figure 10 (1000x)

The adhesion strength of the aggregate-mortar composition sample was tested by a direct tensile test on real scale samples [22]. Figure 12 gives the results of the test, carried out on a aggregate-mortar sample, modified with SAE-polymer emulsion (styrene acrylic ester emulsion). The results indicate an increase of the adhesion strength with increasing polymer-cement ratio. Also the influence of the curing method is presented. The adhesion strength, as well as other properties of the modified mortar or concrete is favoured by a wet curing period, to allow cement hydration, followed by a dry curing period, which is in favour for polymer film formation. A combination of both conditions lead to an optimum polymer-cement co-matrix in which the aggregates are embedded.

Durability tests on porous concrete indicated a significant reduction on corrosion and material loss for the samples, modified with more than 5% polymer emulsion. This amount of polymer was needed to form a continuous interpenetrating network of cement hydrates and polymer film in the co-matrix.

Figure 12: Adhesion between aggregate and mortar

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