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New Trends in Concrete-Polymer Composite Materials and Systems

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Abstract

Polymers, representing 1 % only of building materials used in construction industry, have a major impact on performance of materials and systems due to their synergic action with cementitious materials. Appropriate combination of polymers and classical construction materials provides opportunities for innovative applications and systems, for improved performance and for increased durability. Particularly in restoration and retrofitting, polymer based materials highly contribute to sustainable construction activity. This paper highlights the innovations, new approaches and durability assessments, presented at the International Symposium on Polymers in Concrete in Guimarães, Portugal, 2006. Emphasis is put on microstructure formation, modification by means of hardener free epoxy resin by polymers in solution or by recycled particles, bond assessment and bond improvement, durability of bond under moisture and temperature effects, epoxy bonded external reinforcement for strengthening and concrete protection by means of coatings.

Keywords: Concrete, Polymers, Composite Materials, Durability, Sustainability.

Neue Entwicklungen bei den zusammengesetzten Werkstoffen und Systemen aus Beton und Polymeren

Zusammenfassung

Polymere machen unter den Werkstoffen des Bauwesens zwar nur 1 % aus, sie haben aber dennoch wegen der synergetischen Wirkung im Zusammenhang mit Zement gebundenen Werkstoffen einen bedeutenden Einfluss auf die Eigenschaften von zusammengesetzten Werkstoffen und Systemen. Geeignete Kombinationen von Polymeren und herkömmlichen Wirkstoffen des Bauwesens bieten interessante Möglichkeiten für innovative Anwendungen und die Entwicklung neuer Systeme. Die Eigenschaften können dadurch verbessert und die Beständigkeit erhöht werden. Insbesondere bei der Restaurierung und dem Instandsetzen tragen die Werkstoffe, die unter Verwendung von Polymeren hergestellt sind, dazu bei, die Nachhaltigkeit im Bauwesen zu erhöhen. Dieser Beitrag stellt die Innovationen, neue Ansätze und Aspekte der Dauerhaftigkeit, die anlässlich des "International Symposium on Polymers in Concrete", in Guimarães, Portugal, vorgetragen wurden, in den Vordergrund. Besonderer Nachdruck wird dabei auf die Bildung des Mikrogefüges, Veränderungen von härterfreien Epoxidharzen durch gelöste Polymere oder durch rezyklierte Teilchen, Bestimmung und Verbesserung der Haftfestigkeit, Beständigkeit der Haftfestigkeit unter dem Einfluss von Feuchtigkeit und Temperatur, Epoxid verklebte außen liegende Bewehrung zur Erhöhung der Festigkeit und zum Schutz von Beton durch Beschichtungen, gelegt.

Stichwörter: *Beton, Polymere, Zusammengesetzte Werkstoffe, Beständigkeit, Nachhaltigkeit.*

1 Introduction

Cement concrete and polymers have long been considered to be complementary construction materials. Polymeric materials were used for finishing and protection. Cement concrete was the load bearing structural material. However, it was soon recognized that the synergetic action between polymers and classical building materials offered great opportunities for improvement and for a wide range of new and innovative properties and applications in construction and other industries. Today the use of polymers is part of an intensive search for more performing and sustainable construction materials [1].

The International Congresses on Polymers in Concrete (ICPIC) aim to create a synergy between researchers and practitioners all over the world, dealing with the innovative possibilities of concrete-polymer composites.

The first international congress was organized in London in 1975. During the three decades since then there have been dramatic changes in the way of thinking about industrial processes and about the approach and evaluation of new and innovative materials. ICPIC captures these evolutions and innovations in its triennial congresses, and promotes their introduction in the field by regional symposia, e.g. in Asia and in the Latin part of the world. The International Symposium on Polymers in Concrete (ISPIC) 2006 in Guimarães, Portugal, was set up as such a regional symposium, stressing participation from countries with Portuguese and Spanish as national languages. An International Symposium on Polymers in Concrete offers a forum for discussion and transfer of technology, exchange of experiences and opportunity for training of newcomers as well as opportunity to encourage research and development, for learning and meeting of regional needs. The framework of research trends and the state-of-the-art in concrete-polymer composites (C-PC) technology, to which ISPIC 2006 was intended to contribute, was presented by L. Czarnecki [2, 3], and is visualized in the scheme of Figure 1. ISPIC 2006 contributed to increased knowledge on: microstructure building; concrete modification by means of epoxy without application of a hardener, by means of polymers in solution and by means of recycled particles; bond assessment and durability of bond under thermal and moisture actions; epoxy bonded external reinforcements; concrete protection; polymer impregnated textile reinforcement for concrete. Highlights of the Symposium are presented here after.

2 Microstructure Formation

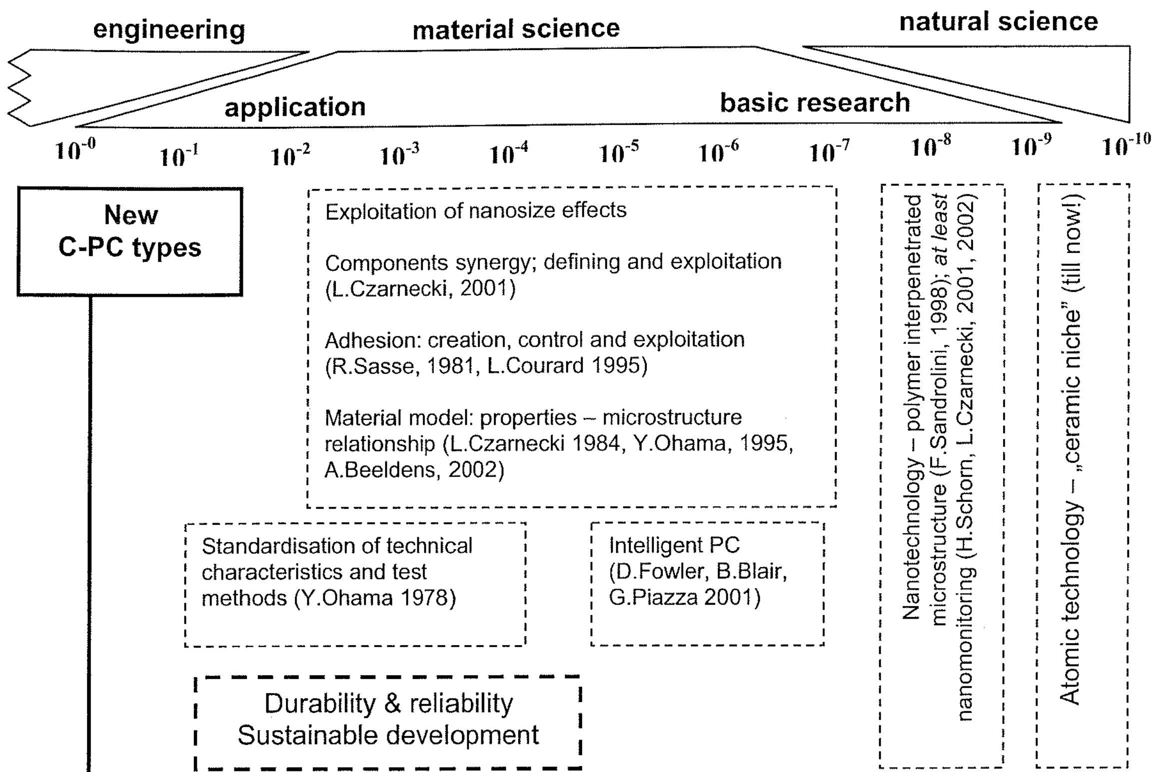
2.1 Polymer Dispersions

Usually, polymer-modified cement concrete or mortar is prepared by mixing polymer dispersions or redispersible polymer powders with the fresh mixture. The influence of polymer modification on the microstructure is twofold. Due to the presence of the polymers and surfactants, a retardation of the cement hydration is observed. On the other hand, due to the film formation or due to the interaction between the cement hydrates and the polymer particles, the tensile strength of the binder matrix as well as the adhesion strength between the aggregate and the binder phase are enhanced.

The mutual influences between the cement hydrates and the polymer particles and film can be incorporated in an integrated model of structure formation [4]. At ISPIC 2006 in Guimarães, the four-step model proposed by Beeldens was presented. This model is based on the three-step model of Ohama, but stresses the positioning of the processes on the time scale and the interaction between the different components (Fig. 2).

When a dry curing period is included, cement hydration and polymer film formation coincide and encapsulation of unhydrated cement particles is possible. Further, the formation of an interstitial phase, consisting of inorganic and organic precipitates in the bulk phase is pointed out. For an optimal benefit of polymer modification, the amount of these phases should be limited since those polymers are contributing less to the final properties of the material. Based on this integrated model, optimal curing conditions are pointed out. A long period of water or moist curing (up to 28 days) during which the cement hydrates develop should be followed by a period of curing at lower relative humidity, promoting the polymer film formation. Estimation of the minimum quantity of polymer to develop a continuous network – „the continuity threshold of polymer phase in concrete" has been proposed by P. Łukowski [5] using the percolation theory (Fig. 3).

The minimum content of polymer in relation to Portland cement has been estimated as equal to 6 % by mass. This result is in very good agreement to both experimental and stereological results. The treatment of percolation phenomena as the transformation of a discontinuous structure into a continuous one seems to be an effective method for analysis of the polymer composite microstructure.



1995	J.Sustersic	Steel Fibre Reinforced Concrete & Polymer Fibre Reinforced Concrete
1998	F.Sandrolini	recycled polymer/ recycled filler
	D.Kruger	lightweight PCC
	Y.Ohama	green PCC
	V.Vidaurre	void-free PC
2001	M.Kawakami	ultralight PCC
	Y.Ohama	self-repairing PCC
2004	H.Joo, Y.Ohama	slag PCC
	D.Jolley, D.Kruger	fly ash PCC
	E.Knapen, D.Van Gemert	sound absorbing PCC
	T.San-Jose	Glass Fibre Reinforced Polymer – Polymer Concrete
2005	Idea acc. D.Fowler	– monomer vapour impregnated concrete – PC-PCC multilayer composites – containment vessels for toxic/hazardous wastes (PC, PIC) – PC panels – steel or aluminium framing members

Figure 1: Map of C-PC research trends [2]

2.2 Water-soluble Polymers

When water-soluble polymers are added instead of polymer dispersions, the polymer molecules are supplied on a molecular scale, improving the approach of the relatively large cement grains by the polymers. In the absence of surface active agents, these water-soluble polymers tend to require a lower proportion in order to be comparably effective as polymer dispersions for some applications.

At ISPIC 2006 in Guimarães, the addition of small amounts of water-soluble polymers (1% of cement weight) is discussed [6]. The microstructure of cement hydrates formed at the air void surfaces is strongly influenced by polymer modification, as shown in Figure 4. Because of their strong affinity to the gas-water phase, the presence of the water-soluble polymers is expected at the air void surfaces. Water molecules are bound to the polymer particles until sufficient forces are exerted, e.g., by cement hydration.

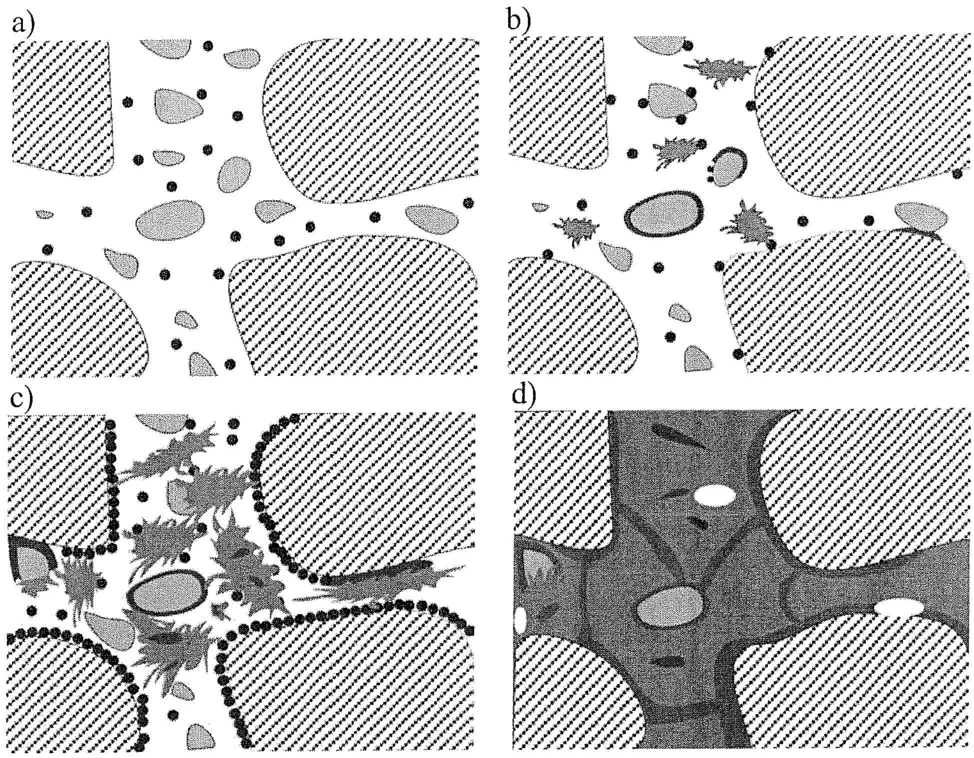


Figure 2: (a) Step 1, immediately after mixing, aggregates, cement particles, polymer particles and mixing water; (b) Step 2, after mixing, the polymer particles interact with the cement particles and the aggregates. In the case a dry curing period is introduced, a continuous film may be formed – polymer particles flocculate together, on restricted places, no coalescence has taken place at this stage; (c) Step 3, cement hydration proceeds, polymer film formation starts on specific spots – polymer particles coalesce together into a continuous film; (d) Final step, cement hydration continuous, the polymer particles coalesce into a continuous film – cement particles are hydrated.

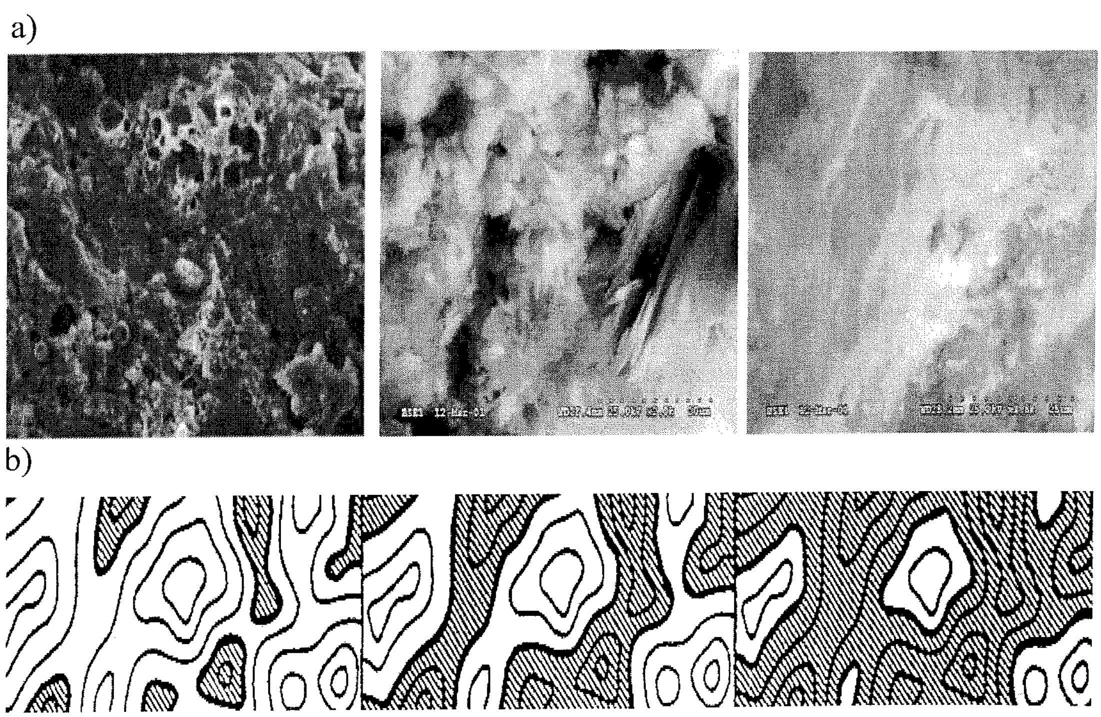


Figure 3: (a) Microstructure of acrylic-cement composite; polymer amount (from left to right): 0%, 5%, 10%; SEM 2000x and (b) schematic presentation of percolation transformation (shaded areas are elements with continuous connection).

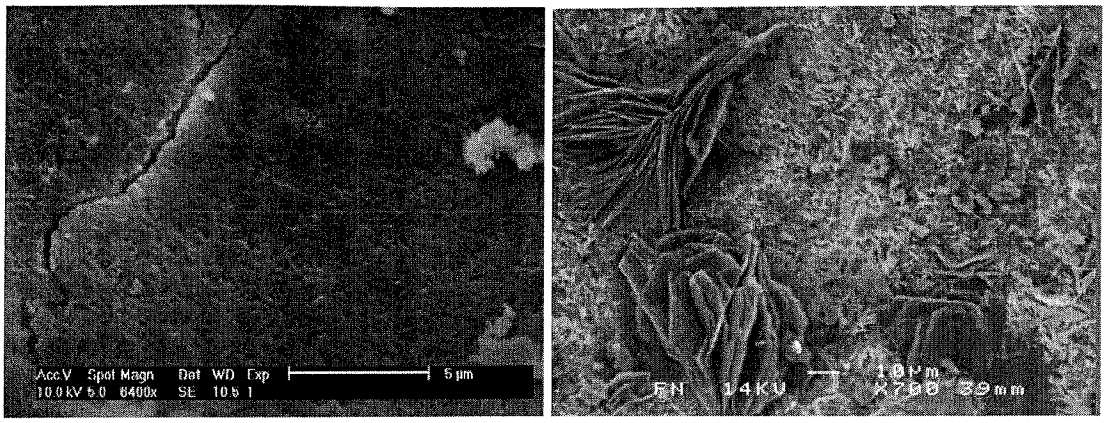


Figure 4: Air void surface in unmodified (left) and 1 % MC-modified mortar (right).

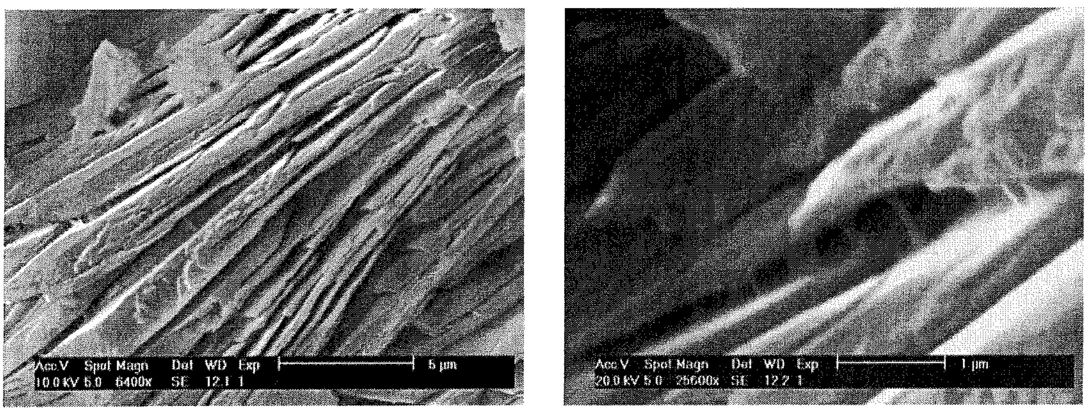


Figure 5: Polymer bridges between a stack of layered $Ca(OH)_2$ crystals in 1 % MC-modified mortar.

Unmodified mortar beams have a smooth internal pore surface at the micrometer scale. The air void surfaces of mortars modified with methylcellulose (MC) are characterized by an abundant efflorescence of $Ca(OH)_2$ crystals, surrounded by needle-like C-S-H. The $Ca(OH)_2$ plates are formed parallel towards each other and they are almost undistorted. Methylcellulose has a high swelling capacity and can swell to forty times of its dry volume in water. The presence of methylcellulose at the air void surfaces results in a very aqueous environment which promotes crystal formation.

In Figure 5, a stack of layered and undistorted $Ca(OH)_2$ crystals is shown, formed inside an air void. Polymer bridges are detected between the $Ca(OH)_2$ layers, which act as an additional bond, gluing the layers together. Because $Ca(OH)_2$ crystals are the weak link in the binder matrix and the surfaces of those crystals form preferred cleavage sites, the strengthening by polymer bridges may result in an improvement of the overall strength of the binder matrix.

3 Innovative Modification

3.1 Polymer-modified Mortars using Hardener-free Epoxy Resin with Nitrite Type Hydrocalumite

Conventional epoxy-modified mortars and concretes have an inferior applicability due to the two-component mixing of the epoxy resin and hardener, the toxicity of some hardeners like polyamine or polyamide, and the obstruction of cement hydration by the polymer. However, even without hardeners the epoxy resin can harden in the presence of the alkalis or hydroxide ions produced by the hydration of cement in the epoxy-modified mortars. Such new epoxy-hydraulic cement systems provide an increase in the flexural strength and a marked improvement in the carbonation or chloride ion penetration resistance.

In hardener-free epoxy-modified mortars with polymer-cement ratios of 20 % or less, the hardening degree of the epoxy resin is 50 to 90 %, and unhardened epoxy remains. It is considered that the unhardened epoxy resin may be sealed with hardened epoxy resin phase in the epoxy-modified mortars. The epoxy resin phase forms self-capsuled epoxy resin. The self-capsuled epoxy resin can be broken at cracking of the epoxy-modified mortar under loading. The unhardened resin in the self-capsuled epoxy phase may fill microcracks, thus providing a self-healing capacity to the mortar.

Nitrite-type hydrocalumite [$3CaO.Al_2O_3.Ca(NO_2)_2.nH_2O$] is a corrosion inhibiting admixture or anti-corrosive admixture which can adsorb the chloride ions (Cl^-) causing the corrosion of reinforcing bars and liberate the nitrite ions (NO_2^-) inhibiting the corrosion as expressed by the formula:

$$3CaO.Al_2O_3.Ca(NO_2)_2.nH_2O + 2\,Cl^- \rightarrow 3CaO.Al_2O_3.CaCl_2.nH_2O + 2\,NO_2^- \qquad (1)$$

It provides excellent corrosion-inhibiting property to the reinforcing bars in concrete. Consequently, polymer-modified mortar with superior corrosion inhibiting property and durability is expected when combining the use of nitrite-type hydrocalumite and hardener-free epoxy-resin, with beneficial use as an effective repair material for deteriorated reinforced concrete structures [7]. A testing program was executed with various nitrite-type hydrocalumite contents and polymer-binder ratios. The following conclusions could be drawn from the experiments:

- to maintain a constant consistency, the water-binder ratio of hardener-free epoxy-modified mortar with calumite must be increased lightly with increasing calumite content or polymer-binder ratio. This is ascribed to the porous layered structure of calumite, and to the absence of surfactants in the epoxy resin;
- increasing calumite content improves the corrosion inhibiting property of hardener-free epoxy-modified mortars, but decreases compressive strength, adhesion to mortar substrates and waterproofness, and increases drying shrinkage. Increasing the polymer-binder ratio improves flexural strength, adhesion to mortar substrates and waterproofness.

At calumite contents up to 10 % of cement binder and polymer-binder ratio of 10 % the hardener-free epoxy-modified mortar satisfies all the quality requirements specified in JIS A 6203, as given in Table 1.

3.2 Lightweight Particles as Aggregate

Particulate composite materials represent a very versatile class of materials because they offer the possibility of optimizing the final physical-mechanical characteristics by working on the mix design and changing the microstructure, and they enable a better exploitation of waste by-products and residues of different origin, otherwise disposed as landfill or industrial waste [8]. The use of fillers of average size 2.5 μm, originating from granite treatment, was combined with tyre rubber waste (0.063-2.0 mm), in polyester mortar. Control of grain size distributions of both low and high modulus phases and moulding factors enables the production of high performance mortars.

Branco et.al. [9] reports on an ongoing research on the use of industrially rejected cork to produce lightweight concrete with improved resistance against polar liquids, heat and sound. The cork industry worldwide yearly consumes about 280 000 tons of cork, of which about 20 to 30 % is rejected. 10 to 30 % of sand and coarse aggregates were replaced by cork granules. The obtained lightweight concretes still behaved better than comparable lightweight concretes (aerated, no fines, cellular and foamed).

Table 1: Quality levels of hardener-free epoxy-modified mortars with calumite at polymer-binder ratio of 10 %

Test item	Quality requirements in JIS A 6203	Test results
Flexural strength (MPa)	> 8.0	9.8 ~ 10.3
Compressive strength (MPa)	> 24.0	43.7 ~ 50.8
Adhesion to mortar (MPa)	> 1.0	1.0 ~ 1.2
Water absorption (%)	< 10.0	1.3 ~ 1.6
Water permeation (g)	< 15.0	1.3 ~ 1.5
Length change (%)	0 to 0.150	0.07 ~ 0.10

4 Bond Assessment

The adhesion between repair material and concrete substrate is one of the most important factors that affect the reliability and durability of repair. A high adhesion allows higher tolerance on non-compatibility of properties of both materials [10]. This is also reflected in the European Standard EN 1504-10 (2003) and ACI Concrete Repair Manual (2003), where the bond quality is the main requirement on the repair system. Adhesion depends on various phenomena taking place in the interfacial zone. Among others, the quality of the concrete substrate resulting from surface treatment belongs to the most important factors. This implies that before any repair operation, an effective assessment of the concrete substrate has to be performed. Besides the surface preparation of concrete, evaluation of the cohesion of the superficial concrete is requested for adhesion and durability reasons.

Many authors describe the influence of the surface preparation technique on the superficial cohesion of concrete or the adhesion. However, research on the real effects of the surface preparation technique just started with the quantification of superficial microcracking or roughness. The investigation described in the ISPIC'06 paper by Courard et al. [11] concerned the influence of concrete substrate strength and preparation technique efficiency. Three types of concrete (C30, C40 and C50) and four types of surface preparation have been combined in twelve different concrete slabs. The quality of the superficial concrete has been characterized according to different destructive and non destructive techniques: surface roughness (Average Texture Depth test according to EN 13036-1:2000), compressive strength, superficial cohesion (pull-off test), Impact Echo measurements and cracking quantification (microscopical observations). A self-compacting polymer-cement mortar has been applied and adhesion has been evaluated by means of pull-off tests.

The following conclusions may be drawn from the present investigations concerning the concrete substrate evaluation and the adhesion of repair systems:

- the quality of concrete substrate surface (roughness and microcracking) strongly depends on the surface preparation technique used (Fig. 6 a,b); microcracking was observed mainly in the superficial zone of concrete (2 cm) and the number and orientation of microcracks depend on type and "aggressiveness" of the treatment; additionally relatively low effect of concrete strength on the surface quality was observed;
- bond strength (Fig. 6 c) after hydrodemolition and sandblasting is greater than the threshold minimum values for laboratory performance, while it is close to the limit for polishing and scabbling; in the case of polishing, all failures during pull-off test appeared at the interface between concrete substrate and repair mortar (Fig. 6 d). Scabbled (needle hammered) surfaces present ruptures near to the interfacial zone, due to microcracks;
- there is no clear relationship between the class of concrete strength and the pull-off strength. The concrete strength class had no influence on bond strength for sandblasting or hydrodemolition but it had an effect in the case of polishing and scabbling; the concrete strength had no effect on the failure mode in the pull-off test.

These conclusions lead to the following consideration: microcracking is really an essential parameter in the evaluation of the quality of the concrete substrate before repairing. However, it remains a very difficult property to clearly evaluate, necessitating long preparation and laboratory investigations: an on-site test like surface permeation, as already used in metal welding technology, should be soon developed in order to simplify concrete surface assessment.

The pull-off test is commonly used to test the bond strength. However, non-destructive methods (NDT) are preferred for this purpose, especially in the case of large-area structures. A majority of NDT methods mentioned in EN 1504-10 and ACI Concrete Repair Manual for repair efficiency assessment are based on propagation of stress waves. Particularly, the ultrasonic method and the impact-echo method are recommended. In the selection of an NDT method, many factors should be taken into account, e.g. type and size of defects at the interfacial zone, type of repair material (cement or polymer), thickness of overlay, roughness of concrete substrate.

Garbacz [12] analyzed the usability of impact-echo and ultrasonic methods for the assessment of the quality of various repair systems. The overview shows the usefulness and limitations of ultrasonic and impact methods for the assessment of various repair systems. However, often they can be used as complementary methods.

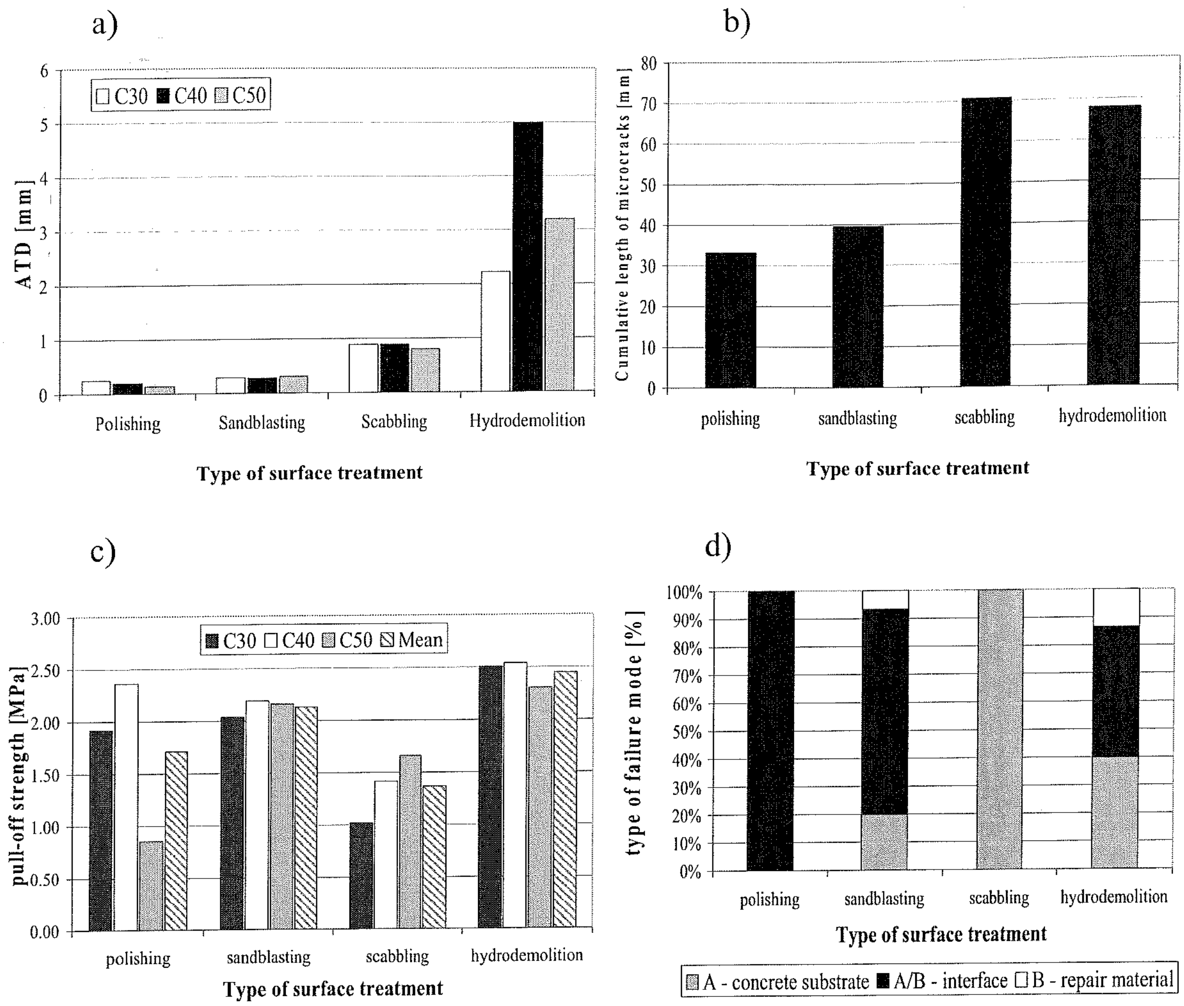


Figure 6: Average texture depth (a), mean cumulative crack length (b), pull-off strength (c) and fracture mode (d) for repair systems after various surface treatments of concrete substrate.

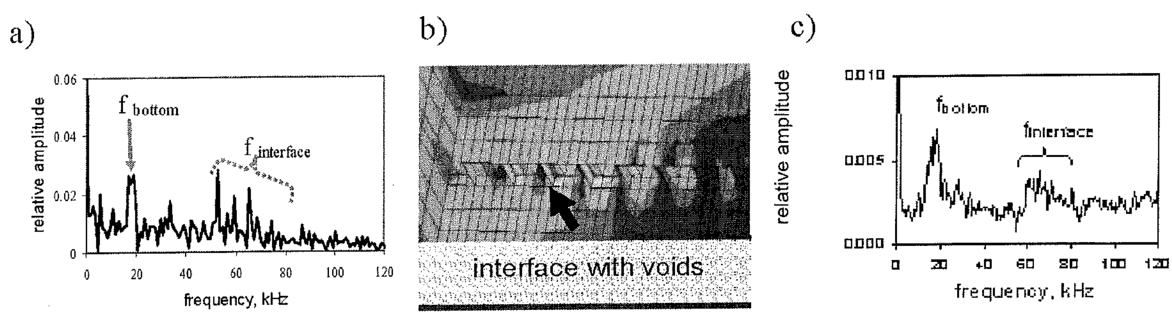


Figure 7: Experimental frequency spectrum for repair systems with concrete substrate after hydrodemolition (a); visualization of interaction between stress wave and air voids at the interface (b); the results of computer simulation with FEM repair model corresponding to experiments (c)

The impact-echo method has limited sensitivity to the natural heterogeneity of concrete, but it is useful for the detection of larger and deeper located defects. Courard et al [11] showed that the concrete substrate surface quality, especially the presence of large voids at the bond interface, can influence the recorded frequency spectra. Computer simulation with a finite element model of the repair system (Fig. 7) confirmed that possibility [13].

5 Durability

The performance of concrete and the durability of structures are now, more than ever, subject to intensive research. Special attention has been drawn to the durability of epoxy resins and fiber reinforced polymers (FRP), the durability of concrete coatings and the use of hydrophobing agents in concrete.

The durability of bonds with polymers, especially when they are subjected to severe environmental conditions, is still not well known. This issue strongly hinders their wide spread use as the lifetime of the bond can not be well defined. Lettieri et al. [14] studied the effect of aging, both natural and artificial, of three cold-curing epoxy resins. The mechanical, thermal and colour properties are analysed after exposure to both an environment with 70 °C and 75 % RH and natural weathering. The accelerated aging, with both high temperature and high levels of relative humidity, led to different behaviours of the epoxy resins under study. Results show that a plasticization effect occurred due to water absorption in two of the resins studied.

Lettieri et al. [14] observed that the post-cure counteracted in part the decrease of the glass transition temperature (T_g) due to the plasticization effect of water. The changes seem to be reversible and follow the cyclic climatic conditions. Furthermore it was observed that the higher temperatures achieved, during the warmer months, are apparently sufficient to promote variations of the properties of these resins.

In a similar study, two commercial epoxy composites, carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP), and three epoxy adhesives were subject to both a natural and artificial environmental loading. Specimens where exposed to 40 °C and 90 % RH for six months. Tensile tests were performed on the composite materials before and after the exposition to artificially simulated severe environments. Again the combination of humidity and temperature can be severe for the properties of thermosetting resins as the glass transition temperature of the resins is approached as reported by Frigione et al. [15].

Polymers can be used to increase the durability of concrete. One possibility is the use of polymeric-based coatings [16]. Another possibility is the use of polymeric admixtures in the production of concrete. It is important to assess the benefits achieved from the use of polymers in concrete for both cases.

The polymeric-based coatings could be used for the surface protection of concrete. The coatings should delay the penetration of water and delay the ingress of aggressive agents, while allowing the concrete to breathe by a water vapor diffusion mechanism. Three different products were tested: silicon, acrylic and epoxy. Results show that the performance of the products varies with the type of exposure conditions. Therefore, the selection of the products should be case specific. The performance of epoxy resins was much better than that of the other products studied.

Pires et al. [17] compared the physical and mechanical properties of concrete produced with the incorporations of polymeric admixtures. Different types of water resisting admixtures where studied: acrylic ester copolymer (PA), mixture of calcium stearate and sulphonated melamine polymer (EC), and sodium oleate (OS). The organic water resisting admixtures hydrophobes the walls of the capillaries of the cement whereas the mineral water resisting admixtures precipitate the insoluble salts in the capillaries, closing them.

Figure 8 presents the results from capillary absorption tests of different mortar and concrete mixes, with varying percentages of hydrophobing agents. The best performance was obtained by a mixture of calcium stearate and sulphonated melamine (EC), 1.5 % by mass of cement. A water resisting admixture composed by acrylic ester copolymer was also tested, but in order to obtain the same performance a larger dosage of more than 2.0 % was necessary, becoming economically uninteresting. The experimental results in Figure 8 also show that the water resistant admixture do not transform the concrete into a complete water resisting material.

6 Epoxy Bonded External Reinforcements

In one decade the technique of concrete strengthening by means of epoxy bonded carbon fibre reinforced epoxy laminates has become a worldwide spread technology. The technique of epoxy bonded steel plates already existed around 1970 but with the availability of CFRP laminates an explosive development took place. In research emphasis was put on appropriate design methods, in particular for the evaluation of force distribution in the anchoring zones of bonded reinforcements and for the design of column confinement.

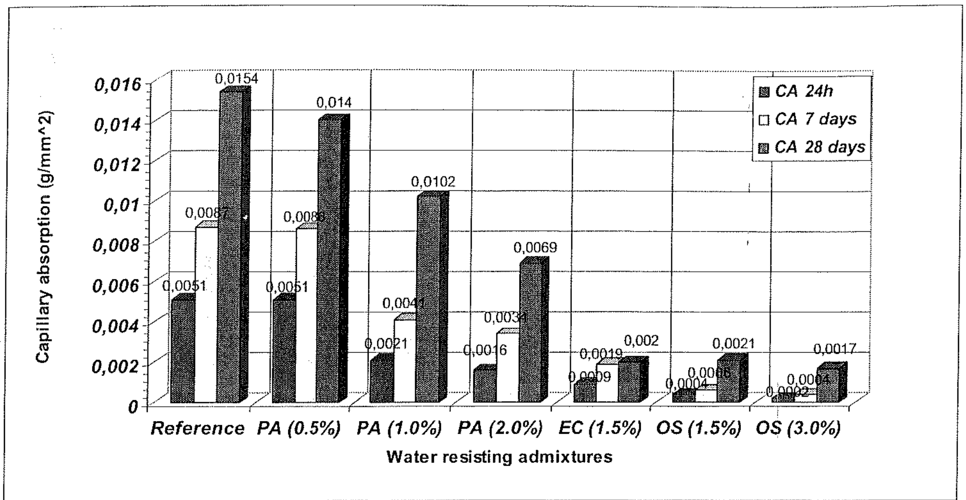


Figure 8: Effect of different polymeric admixtures on the capillary absorption of concrete.

For the applications of flexible CFRP-sheets, as used in column wrapping, epoxy resins with lower glass transition temperature Tg are used. Typical values of Tg for these resins range from 35 to 50 °C. Such Tg are approaching the temperatures occurring in constructions, certainly in warm and hot climates. In the concrete box girder bridge Nossa Senhora da Guia in Portugal temperatures of 37 °C and 45 °C were measured at the inner and the outside surfaces of the box respectively. Such temperatures not only affect the adhesive quality, but also cause temperature gradients that induce considerable additional strains in the CFRP reinforcement [18].

Preparation of the bonding surface is known to be of prime importance in the performance of epoxy bonded reinforcements. Preliminary application of repair mortar on a degraded concrete surface can enhance the concrete quality in such a degree that the repaired, degraded surface approaches the quality of a non degraded surface [19]. Based on extensive experimental work, reliable design models and methods are available for bending design, anchorage detailing, and column confinement [20]. Most design models are related to ultimate limit state. It must be stressed that for serviceability limit state, appropriate modeling is needed.

7 Polymer Impregnated Textile Reinforcement for Concrete

Textile reinforced concrete enhances the possibilities in the design and production of high-strength thin-walled structures. Focus has been put on textiles made of glass, basalt, carbon and high-module polymers. The contribution of the textile reinforcement to the performance of the composite stays far below the expectations, based on the intrinsic qualities of the textile fibres. The bond and load-bearing behaviour must therefore be optimized. The main reason for the low efficiency lies in the inhomogeneous force transmission between the individual filaments in the textile yarns. While the outer filaments are embedded in the cementitious matrix and take most of the load, the inner filaments of the textile contribute only minor to the load transmission, probably only by friction. Different strategies for the improvement of the bond behaviour have been studied, such as the improvement of the cement penetration in the textiles, the use of hybrid yarn structures, and the application of polymers.

Due to the small diameter (150-200 nm) of the particles aqueous polymer dispersions better penetrate into the core region of the roving. Using a polymer-impregnated textile reinforcement in cement matrix gives a bond of fibre-matrix-interface which is primarily realized by hydration products. Polymer particles can interact with hydration products to improve the bond. By impregnating the reinforcement with an uncured polymer, the friction and adhesion between all filaments in the roving is increased due to the presence of polymer particles and consequently the load transfer capacity increases too. The load capacity considerably exceeds that of the untreated reinforcement [21].

The impregnated uncured textile reinforcement is strongly hygroscopic. After mounting in the fresh concrete the rovings suck in water that contains fine

Figure 9: Penetration and intermingling of polymer agglomerates and hydration products between textile filaments [21].

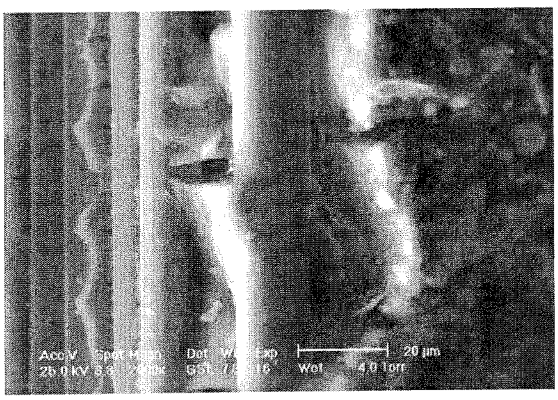


Figure 10: Uncovered filaments in the core zone of a roving, embedded in cement matrix, polymer/cement ratio of 15 % [21].

particles of the cement paste. A small part of the polymer particles migrates into the concrete that encircles the roving. With progressing hydration the generated CH- and CSH-phases penetrate in this dispersion liquid and use the stored water for further hydration product formation. Losing this water the polymer particles further converge and coagulate by cohesion between the particles forming compact clusters or they accumulate as single small polymer spheres at the filament surfaces (Fig. 9).

Both effects result in a more effective and deeper fill-in zone, and thus a better composite behaviour. Polymer modification of the cement matrix leads to similar processes, but the effect of the polymer is much less pronounced. The penetration of cement hydration products and polymer particles into the roving rapidly decreases from surface to roving depth (Fig. 10). Therefore, the combination of polymer impregnation of the roving with polymer modification of the matrix will be subject of further investigations.

The influence of curing of the polymer before mounting it in the cement matrix is discussed by Dilthey et al. [22]. Alkali-resistant glass textiles were impregnated with liquid polymers, completely cured and after curing embedded in the concrete. Polymers used were acrylic dispersions and epoxy resin. The bond behaviour of impregnated rovings in the concrete matrix was tested by means of double sided roving pull-out tests (Fig. 11).

Because of the high cohesive strength of the hardened epoxy resin comparatively high bond forces were transmitted into the concrete via shear bond. With the selected embedding length of 30 mm roving failure occurred at a crack opening of 0.6 mm. In contrast to this, the softer acrylic dispersions led to complete pulling out of the impregnated glass roving. However, the inner filaments were not damaged, due to the good load transmission between the polymer coated filaments.

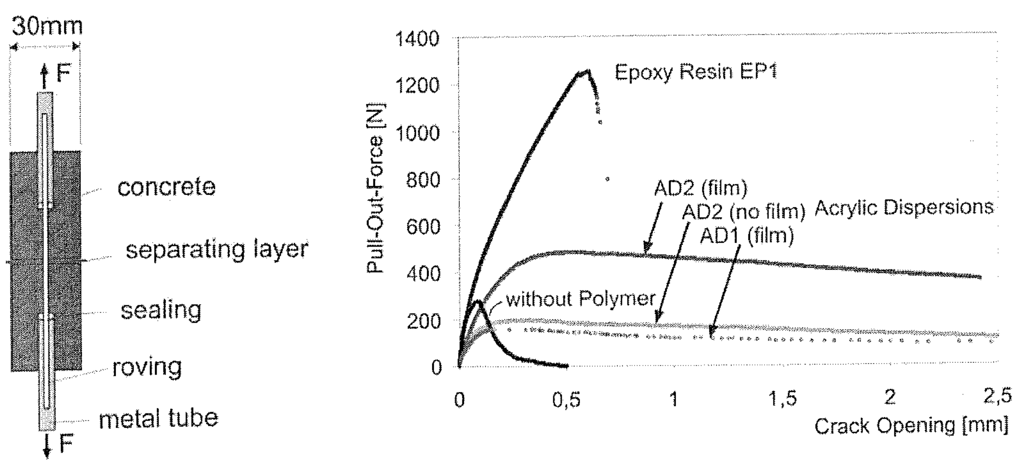


Figure 11: Pull-out test of glass rovings with different polymer impregnation [18].

8 Conclusions

The use of polymers in construction industry is steadily growing. The synergic action of polymers and cement mortar and concrete offers great opportunities for improvement and for a wide range of new and innovative applications. Society and environment require corrective actions to be taken continuously. The use of polymers should be well-considered to guarantee better performance and improved sustainability.

Polymers are no longer special construction materials that replace classical mineral or organic building materials. They are now one vital component in the production of composite and sustainable building materials. They will further allow the development of new and durable constructions, as well as new and durable restoration and retrofitting techniques. The output of ISPIC'06 proofs that the Concrete-Polymer Composites are still innovative knowledge based materials.

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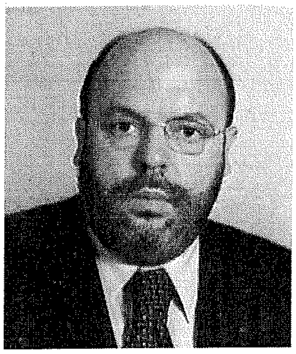

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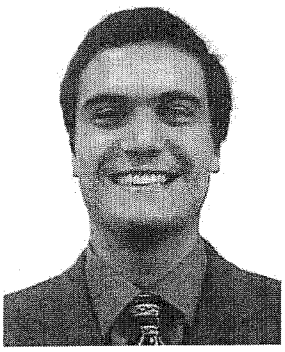

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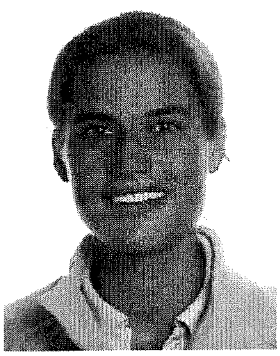

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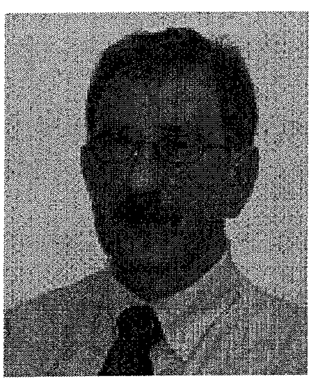

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