Reunion Internationale des Laboratoirs d´Essais et
de Recherches sur les Matériaux et les Constructions

Technical Committee 105 C-PC

CONCRETE-POLYMER COMPOSITES

THE STATE-OF-THE-ART REPORT

Prague, September 1990

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1. INTRODUCTION

The TC 105 CPC "Concrete - Polymer Composites" has been established in 1986 as the answer for the needs of an engineering community for better Concrete - Polymer Composites, mainly PCC, PC and PIC understanding.

It has also been evidence of a common believing that concrete needs polymers. Great number of information on this topic have been already distributed:

- over 4 000 papers have been published,
- over 3 000 patents have been awarded ,
- 5 International Congresses have been held,
- 5 Int. RILEM Symposia have been organized.

There is the problem how to organize all available information in general C-PC theory with practical meaning.

The Committee members have been selected from over 100 specialists invited to cooperate. Finally the TC 105 CPC gathered 19 ordinary members and 12 corresponding members from 17 countries: Belgium, Canada, Czechoslovalia, Denmark, España, Finland, FRG, Great Brittain, India, Israel, Italy, Japan, Netherlands, Norway, Poland, USA and USSR under the chairmanship of Prof. Bareš - Czechoslovakia and Secretary - Prof. Czarnecki, Poland.

The six working sessions of the Committee have been organized, having the character of microsymposia.

The main approach of the Committee activity has been described as follows:

to generalize the knowledge about relation between the CPC structures /and components/ and its technical properties and thus to afford the engineers the data of C-PC for practical application via from "Material model to application" with positive feedback. There are keywords: Material structure - Material properties - Application.

The Committee TC 105 CPC covers very large area of interest contrary to the regular RILEM custom. At present RILEM Committees deal individually with rather narrow area reflecting needs of the contemporary stage of development of portland cement concrete technology. However, that is not the case of polymers in concrete. Regarding to CPC, the First RILEM Technical Committee founded by dr. L´Hermite in 1949, should serve as a pattern. L´Hermite´s Committee was named "Cements and Concrete", just parallel to our polymers and concrete problems.

The tasks and the final results of the TC 105 C-PC are characterized as follows:

- C-PC state of the art report
- C-PC classification criteria
- C-PC terminology and definitions.

Regarding to the C-PC classification the problem has been focussed on the composite structure types as the main classification criterion including also chemical nature od the materials - component properties.

2. EVOLUTION OF THE C-PC

2.1. History

The prevailing materials used in the history of mankind determined the main civilization phases: Stone Age /until 3500 B.C./, Bronze Age /3500 - 1000 B.C./, Iron Age /since 1000 B.C./ and very recently the Composite Age. The leading materials in building have changed their position during hundreds and hundreds of years.

The present is characterized by the "apogee" of concrete and the constant increase of polymer consumption in the building industry. Constant developments in civil engineering and growing industrial activities create a continual demand for building materials that satisfy increasingly stringent requirements.

The Concrete - Polymer Composites /C-PC have been practical results of that statement and seem to be good answer for these requirements. The basic concept of C-PC is not a new one. History reveals that organic admixtures were used in building constructions in ancient times. These materials were used to make surfaces more durable against different climatic conditions. For instance, asphalt was used for painting the baths of Mohan-jo-daro and Harrapa in India /2300 B.C./. The walls in Ajanta and Ellora caves were prepared for painting by applying different coats containing different natural organic materials like milk from different trees, tree leaves, pulp from fruits, oils, etc. These imparted specific properties. Tung-oil, wheat flour, glutineous rice are known to be used in China. One existing example of this composition is the great China wall. Beside this, animal blood, egg whites, gelatine, milk, casein and glue were also used, espacially in Bohemia, Italy, Greece and Egypt. These natural organic materials used in those days were nothing but a type of polymers like polysaccharides, natural rubber, proteins, resins and wax.

People were not so well versed with the technology of the organic materials. They used natural materials locally available from which different components played their role in imparting their characteristic properties. It will not be an exaggeration to say that the use of polymers in concrete, mortars and plasters is not new. People knew that these admixtures gave good results, without knowing any scientific explanation. Their theoretical approach is not known but they must have had good empirical knowledge about the building materials. Not much work on these additives is documented. Mostly it came through heredity.

The use of synthetic polymers in portland cement concrete is not very new, the available literature data back to 1909. More work in this field has been done in 1920. In the 1930s polymer cement concretes were developed based upon rubber latexes. Several products based on polyvinyl acetate were developed in the 1940s. In the 1960s latexes based on thermo plastic polymers such as acrylics and vinylidene chlorides were introduced. Various latexes like styrene butadiene and acrylic are now widely used.

The cementless polymer concrete has been used firstly in 1953 as an overlay on a highway in Sacramento /California Div. of Highways, USA/. It happened even before the first patent on polymer concretes has been issued /1956/. Since the early sixties large concrete fields have been repaired and protected against corrosion by polymer concrete applications and some years later precast element production has started. Recently polymer concrete - machine castings and - electric insulators were elaborated among others and new non-building application are in development. Polymer Impregnated Concrete has been patented in 1954 in the USSR. In 1967 an extensive research program hase been started in the Brookhaven National Laboratory, USA. This technology is still in progress.

2.2 Current Status of C-PC

The number of papers on polymer-concrete composites has been approximately 4000 /Bibliography on Polymer Concretes by Y. Ohama, Koriyama University, 1986/ and there are about 3000 patents /Fig. 2.1, Fig. 2.2/ till 1985. Several hundreds of papers have been published in the course of last five years.

The RILEM TC 105 C-PC offers the focus and the forum to meet contemporary and future needs. The State-of-the-Art Report is an approach for ongoing technical information on the basis of the theory of composite structures and its scientific backgrounds.

2.3 Future development

Future developments in concrete material will be determined by energy considerations and new requirements. It means that in the future an increase and enlargement of existing polymer concrete applications should be expected rather than quite new applications.

Development of a large market for PC applications in sea and underground structures, machine building and electric insulation is very likely. In all these fields the use of polymer concretes serves energy saving or even serves directly to develop new energy sources /petrochemical sea platform/ and energy transmission /insulators/. Further more, in the case of polymer concrete insulators and machine casting, the consumed processing energy is considerably lower than that of existing materials /during the material production/.

An increase of polymer concrete application in various rehabilitation jobs should be expected. It is involved with the necessity for the renewal of existing engineering infrastructures /bridges, roads, tunnels, dams, sevage systems and so on. / For this type of applications many directions were issued /USA, Japan, France/, the first European standard for presevation and repair of for concrete structures has been worked out in 1990.

Increase of polymer concrete applications in industrial buildings, hydrotechnics structures and sewer systems is predicted due to severe /chemical/ aggressive exposure conditions.

Further polymer concrete development would lead to a new generation of materials suitable to extend requirements, viz. light - weight-, reinforced- and microreinforced-, "all - weather"-, expandable-, high temperature resistance - polymer concretes and others, as well as sandwich type and other complex structure systems.

It is difficult to overestimate the significance of mixing and casting machines for further, particularly polymer concrete development. Not only an increase of productivity but futher improvement of the homogenity of polymer concrete mixes and lower costs of materials /lower resin binder contents are to be expected/.

The problem is how to find the most effective way for the use of a suitable C-PC. There is the problem of proper material design. "Tailor-made" concrete polymer composites for particular application - that is the guiding rule for the present and future. Tis State-of-the-Art Report should serve this idea.

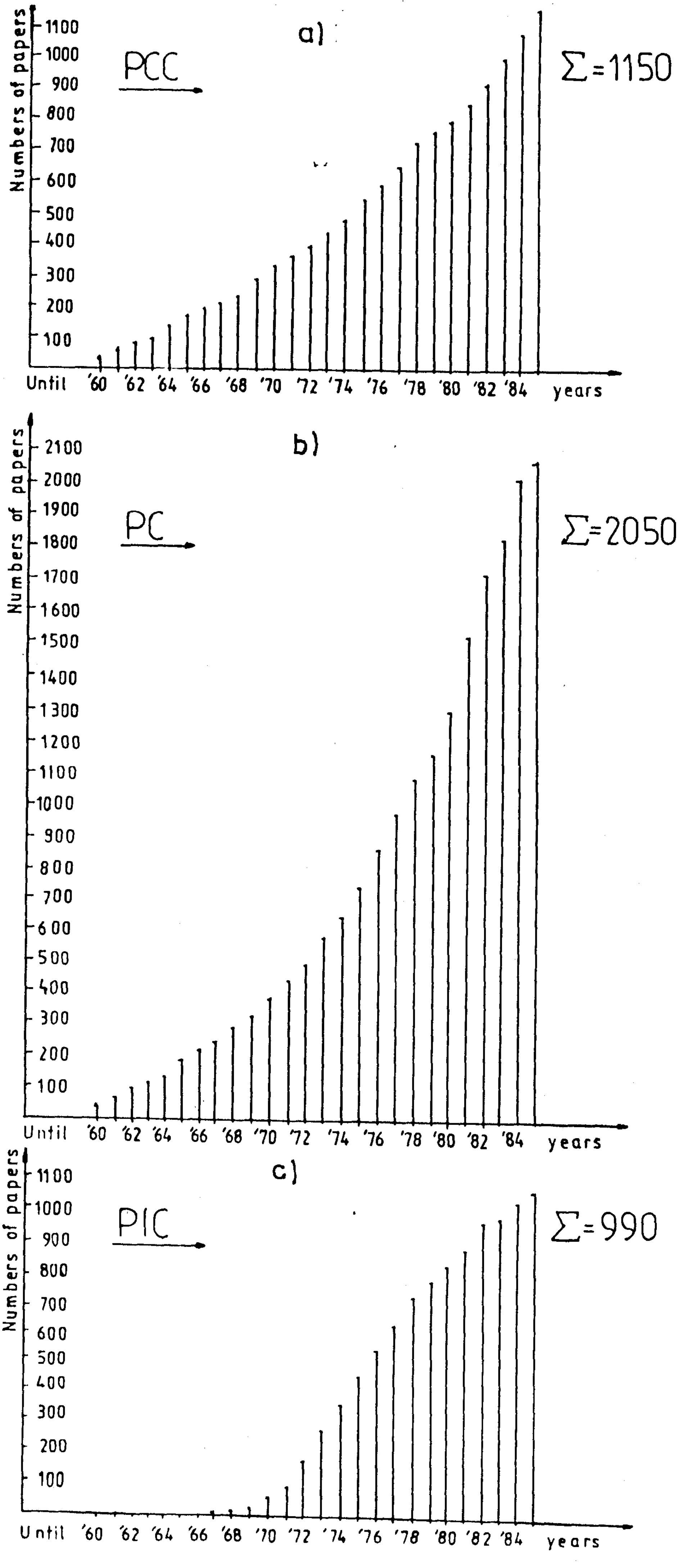

Fig.2.1.

Number of published papers on

PCC /a/, PC /b/,

PIC /c/, C-PC /d/

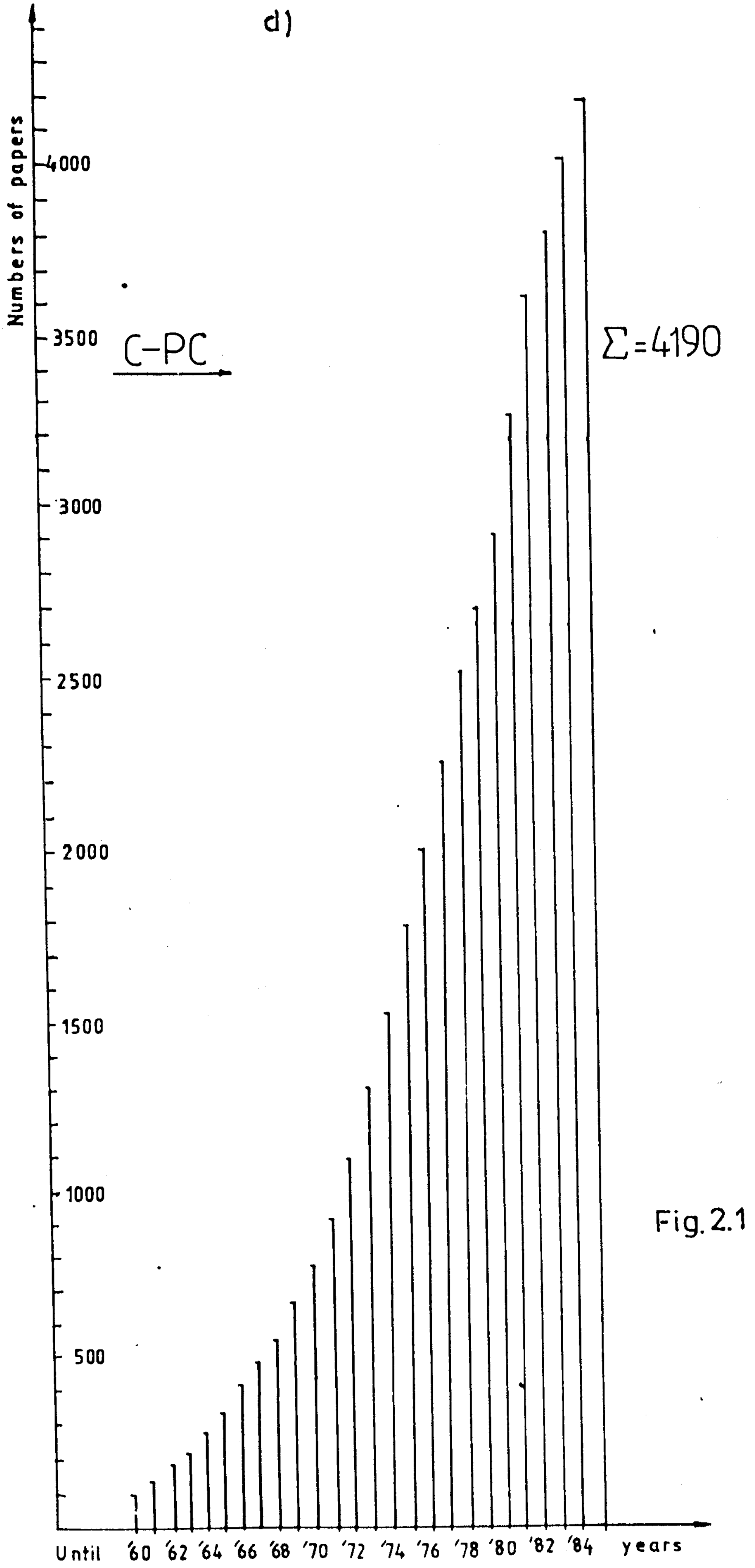
d)
Numbers of papers
4000
3500
3000
2500
2000
1500
1000
500
C-PC
Σ=4190
Until
'60
'62
'64
'66
'68
'70
'72
'74
'76
'78
'80
'82
'84
years

Fig. 2.1

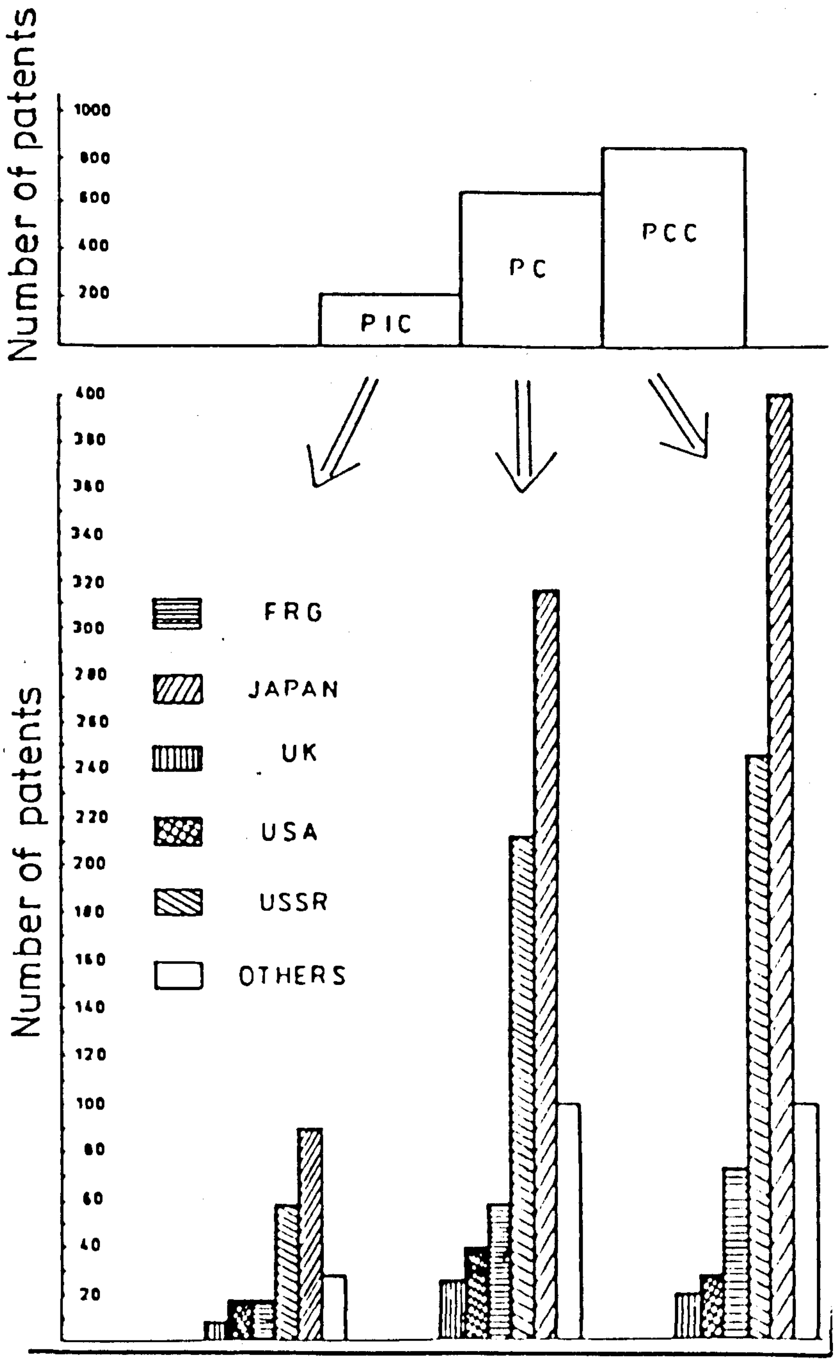

Fig. 2.2. Number of patents on PIC, PC and PCC in total and in particular countries till 1985

3. TYPES OF C-PC

The general concept of a polymer concrete composite - from a technical point of view - involves a process by which chemicals /monomers, oligomers, prepolymers, polymers/ introduced into a concrete mix and in the case of chemical activity are subject to polymerization or polycondensation by thermocalytic or other systems. An infinite number of different mixtures depending on the chemical nature of components, their contents and manufacturing process can be bound this way. However, not each mixture of binder and aggregates is just a concrete composite, although cohesive composite materials are obtained. The main and universal /undependent on the kind of composite components/ criterion /compare chapter 5/ of composite categorization /see code for classification - Appendix I/ is the material structure.

As to the first criterion the inner stress transition could be realized

- by shear flows mechanisms /structure mode I/
- or by direct force flows mechanisms /structural mode II and III/

As the second criterion the material system could be

- poreless /mode I and II/
- with closed porous phase /mode I and II/
- with open porous phase /mode III/

The concrete polymer composites are categorized /Tab. 3.1, see also Classification Code in Appendix I/ in contradiction to a portland cement concrete /marked as CC/.

PMC	polymer modified concrete; low /< 5 % by weight of portland cement/ dosage of polymer to modify concrete; usually polymer affects only the concrete mix rheological properties, before hardening
PCC	polymer cement concrete; dosage of polymer to affect the mix rheological properties as well as some properties after hardening
PC	polymer concrete; cementless /sometimes called as "resin concrete"/

PIC polymer impregnated concrete; subgroups could be recognized: partially - or fully - polymer impregnated concretes, both according to impregnated volume /or depth/ or to degree of fulfilment of pore volume of element, e.g. PIC_s - polymer impregnated concrete on inner surface /the inner pore surface is covered by polymer skin/

Further PIC are possible, e.g.

PIP_C - polymer impregnated polymer concrete. Subgroups as above

PIP_{CC} polymer impregnated polymer cement concrete Subgroups as above

PIM_{CC} polymer impregnated polymer modified concrete. Subgroups as above

POC polymer on concrete - polymer coating, no "real" C-PC

All types of concrete polymer composites can be reinforced. Beside steel or other bars reinforcement various fiber, as steel or polymeric and carbon fibers, are employed for reinforcing.

The main task of using polymer in concrete is always "better" concrete. Concrete polymer composites could bring vastly increased tensile and/or compressive strength and frequently other mechanical properties /e.g. abrasion resistance/ as well as higher water tighness and resistance to frost and chemical attacs. The C-PC as any other materials have shown of course also some disadvantages /compare chapter 7/.

Three main types of concrete polymer composites /C-PC/ are selected as the subject of the state-of-the-art report. They are: polymer cement concrete /PCC/, polymer concrete /PC/ and polymer impregnated concrete /PIC/. The other C-PC types are neglected for vairous reasons:

- in PMC the polymer is only an admixture -a modifier- used mainly for changing the rheological properties of the fresh concrete mix and very rarely effects on the composite properties in the solid state,

- PIP_{cc} and PIP_c can be treated as the second generation /just in progress/ - superposition of the basic C-PC´s selected above /PCC PIC and PC PIC/. Until this moment the PIP_c has been realized with very promising results in Czechoslovakia, but on the laboratory scale only. On the PIP_{cc} no work is documented until now.

The economical effectiveness should be pointed out. The polymer "per se" is usually tens of times more expensive than ordinary portland cement. In the case of impregnation, additional manufacturing process is energy consuming and complicated. Moreover, the full-impregnation process is mostly restricted to the precast concrete elements only.

4. THEORETICAL BEHAVIOUR OF COHESIVE COMPOSITE MATERIALS

Concrete polymer composites /C-PC/ all have characteristics of the generally accepted definition of composite materials: "A solid material system consisting of two or more phases, at least one of which is solid, with macroscopically distinguishable boundaries among phases, which attains properties /or a group of properties/ not attainable by any compound /phase/ either singly or by their simple summation". /See list of terms and definitions of TC 105 C-PC/.

C-PC form part of a longer group of solid /cohesive/ particular composites with polymer or hybrid /organic - inorganic/ matrices, characterized by the fact that their superstructures /structures of the system/ are analogous with those of cement concrete /concrete-like structures/.

The bahviour of C-PC composites in respect of their short-term properties /mechanical, physical and chemical/, internal stress states /primary and secondary/, microfailure modes and performance, is the function primarily of:

- the properties of the phases, namely the property of the geometrically continuous matrix /matrices/ /bounding agent/;
- the volume representation of the matrix /matrices/ in the system;
- the porosity /void volume/ of the dispersed phase and the volume representation of the fluid phase / voids and pores/ in the system;
- the mechanical /physical/ and chemical interaction between the matrix /matrices/ and the dispersed phase /also dependent on the conditions of the origin of the material which determines the primary state of internal stresses in the system; and
- the mechanical /physical/ and possibly chemical interaction of the system with ambient envitonment /loading, humidity, temperature, etc./ responsible for the secondary state of internal stresses

The structural organization of the matrix /the continuous phase/ of the individual C-PC types may be considerably different:

- in the PCC the basic structure of the hydrates /cement/ is influenced by the polymer and a joint /mixed, hybrid/ structure of polymer and hydrate is formed,
- in the PC the matrix consists of a single polymer structure,
- in the PIC two mutually independent structures originate successively in the system, viz. the hydrate structure and the polymer structure, and
- in the PIPc two mutually independent polymer structures originate successively in the system x/

Although there is a number of mechanisms of the generation and application of the C-PC which mutually permeate, some of which act synergically and are difficult to separate, the relative weights of the individual functions depend primarily on the structural organization of the system /or superstructure/. In accordance with their superstructure the individual C-PC types may be classified as one of the three basic composite types /Type I, II, III composites/ /Fig. 5.1/, or shown in the diagram in Fig. 5.2/.

The number of Type I composites includes filled bonding agents /filler binder or filled polymer/, i.e. the systems in which the particles f are loosely dispersed /segregated/ in the matrix m. With the exception of the cases in which the matrix is porous the system may be considered as compact or when it fully fills the given volume v_c, where $v_c = v_f + v_m$ /Fig. 5.3/. To this group also the PC are sometimes erroneously included.

The dominant portion of stress transfer in these systems is effected in dependence on geometrical and physical parameters, by the shear flow of the interparticles regions

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x/ In other C-PC types not considered here, for instance in PMC, the hydrate structure is influenced only slightly and indirectly; in PICs the hydrate structure is only closed /overcoated/ on its inner surface, etc.

/including the interphase interfaces/ in which mechanical energy is dissipated into thermal energy or the origin of new surfaces /crazes, microcracks or cracks/. A typical example of the stress transfer in the matrix following primarily the indirect, namely shear flow mechanisms along the interphase boundaries, is shown in Fig. 5.4 for the Type I composite model made of bronze circular inclusions in epoxy matrix investigated by the photoelastic method.

Practically all C-PC systems as typical bonded fillers are Type II and Type III composites, in which the closely dispersed particles form a skeleton, the parts of which are connected by solid matrix bridges only. Moreover, in Type II composites, there are closed pores, p_c, forming an integral part of the system superstructure, so that $v_c = v_f + v_m + v_{pc}$ /Fig. 5.5/. This porosity may vary from zero to a value which is a function of many variables.. In type III composites, there are also open, continuous pores p_o, and $v_c = v_f + v_m + v_{pc} + v_{po}$ /Fig. 5.6/.

In both these composite types the dominant portion of stress transfer is performed by direct force flow among the dispersed particles resulting in the generation of force configuration in the structure which is particularly dependent on interphase properties. Mechanical energy is equal for the deformation of the internal skeleton /incl. the interphase region/, for the failure of the skeleton and the failure of the individual skeleton particles. The results of photoelastic investigation of the analogic model with the same geometric arrangement as former but differing in the spacing of the individual inclusions given in Fig.5.7 show near the direct force transfer from grain to grain.

The origin of closed pores improves the inner stress state /primary and secondary/ similarly as in the Type I composite; from the mechanical point of view, therefore, their presence in the superstructure could be advantageous.

If the volume of continuous pores /Type III composites/ is sufficiently filled with the binder /e.g. by impregnation/ /Fig.5.8/, a bistructural system originates in which a new independent infrastructure, geometrically organized in fibre form, combines effectively with the initial superstructure system by means of a great number of interfaces. This interaction results in a significant synergistic effect /Fig 5.9/, differing from all other benefits accompanying the impregnation of the continuously porous superstructure system, such as the improvement of phase adhesion, chemical influence on the primary matrix, and the increase of the density of the system. In the case of total /perfect/ impregnation the unit volume is defined as $v_c = v_f + v_{m_2} + v_p$; in the case of partial impregnation it is $v_c = v_f + v_{m_1} + v_{p_c} + v_{m_2} + v_{/p_o - m_2/}$.

Various properties important for the use of the same superstructure system may be also significantly influenced by the type of polymer matrix /or polymer admixture/, the type of dispersed phase /including the microfiller/ and the selection /or influencing/ of the interphase. The mechanical - structural effect of the chemical composition of the matrix is negligible; of great importance in this respect is the viscosity and surface tension of the uncured binder, which influence significantly the workability, the volume of occluded air pores and thus, indirectly, also the mechanical properties of the hardened system. The behaviour of the superstructure, however, is influenced by the deformation, strength and time-dependent matrix parameters, in accordance with their relationship to analogous parameters of the second part of the composite. The significatnt /more pronounced/ viscoelastic behaviour of the matrix increases the toughness of the system, but simultaneously decreases its service life under high frequency fatigue due to internal heating. Of similar significant influence is the kind of bonding between matrix and filler /adhesive or cohesive/ as well as the relative magnitude of thermal and humidity expansion /or contraction/ of the individual system components.

The influence of considerably different phase properties /sometimes favourable, other times unfavourable/ may be modified by changing interphase properties /by the increase or decrease of interphase bonds/ or by the creation of a transition layer or, if it already exists, by changing its thickness. For instance, weaker interphase bonds increase the toughness, because the increase of dissipated energy of the interface joints. On the other hand, strong interface bonds provide the system high strength and simultaneously brittleness, due to the lack of inner barriers to defect /crack/ propagation.

It is important that the individual phases be chemically compatible and/or mutually inert /over long period of time/. The chemical composition of the matrices /as well as other phases present in the system/ exercises direct influence on the chemical resistance of the system /chemical corrosion/. On the other side,the physical corrosion /e.g. due to crystallization pressure in the pores/ and physical-mechanical corrosion /e.g. due to the cleavage of the phases/ are primarily the function of the properties of the whole superstructure system /e.g. the degree of continuity of its porosity and the type of interphase bonds/, although the diffusion resistance of the phases present in the system may also play a certain role.

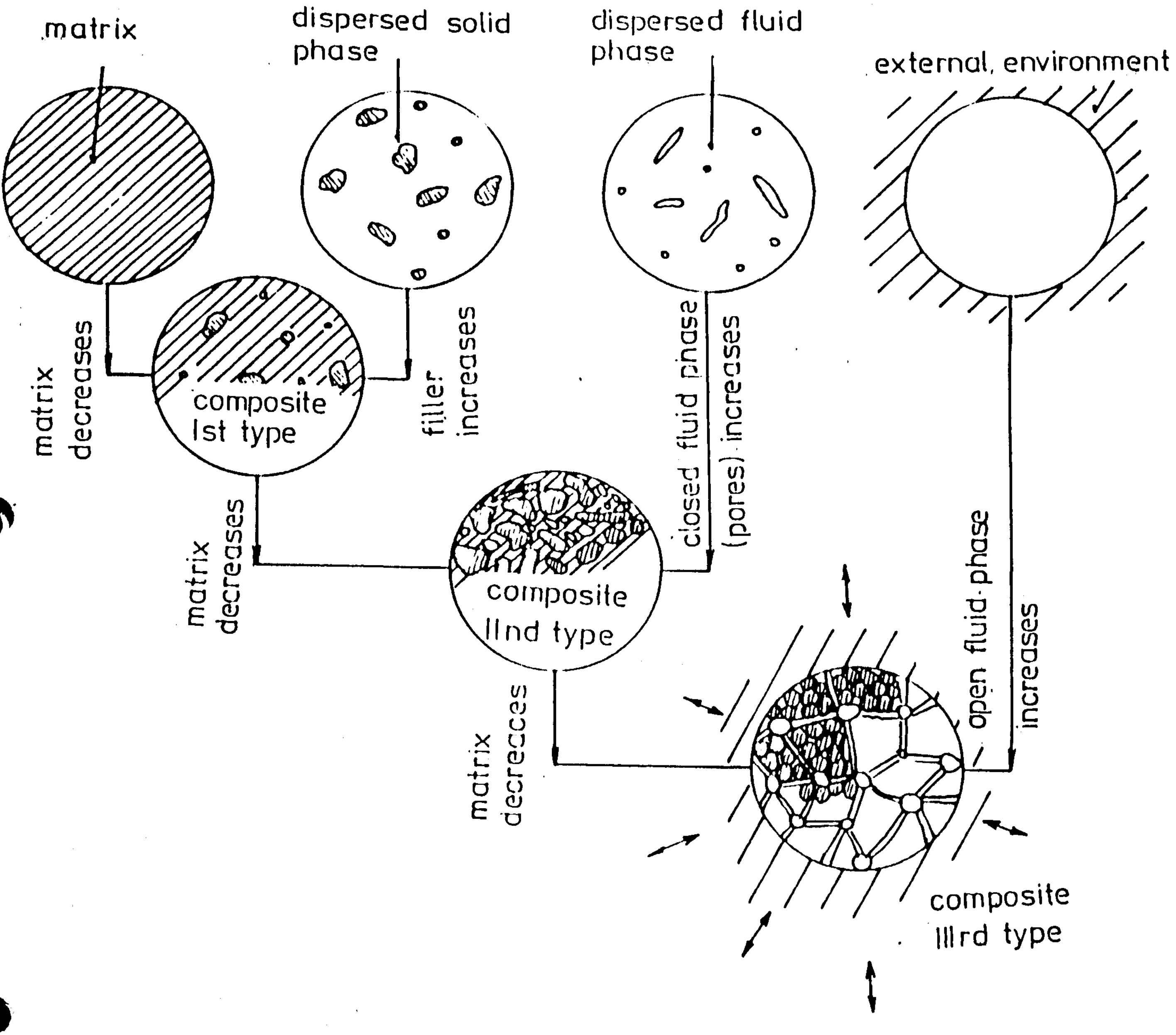


Fig. 4.1. Schematic classification of composites according to their (macro) structural arrangement.

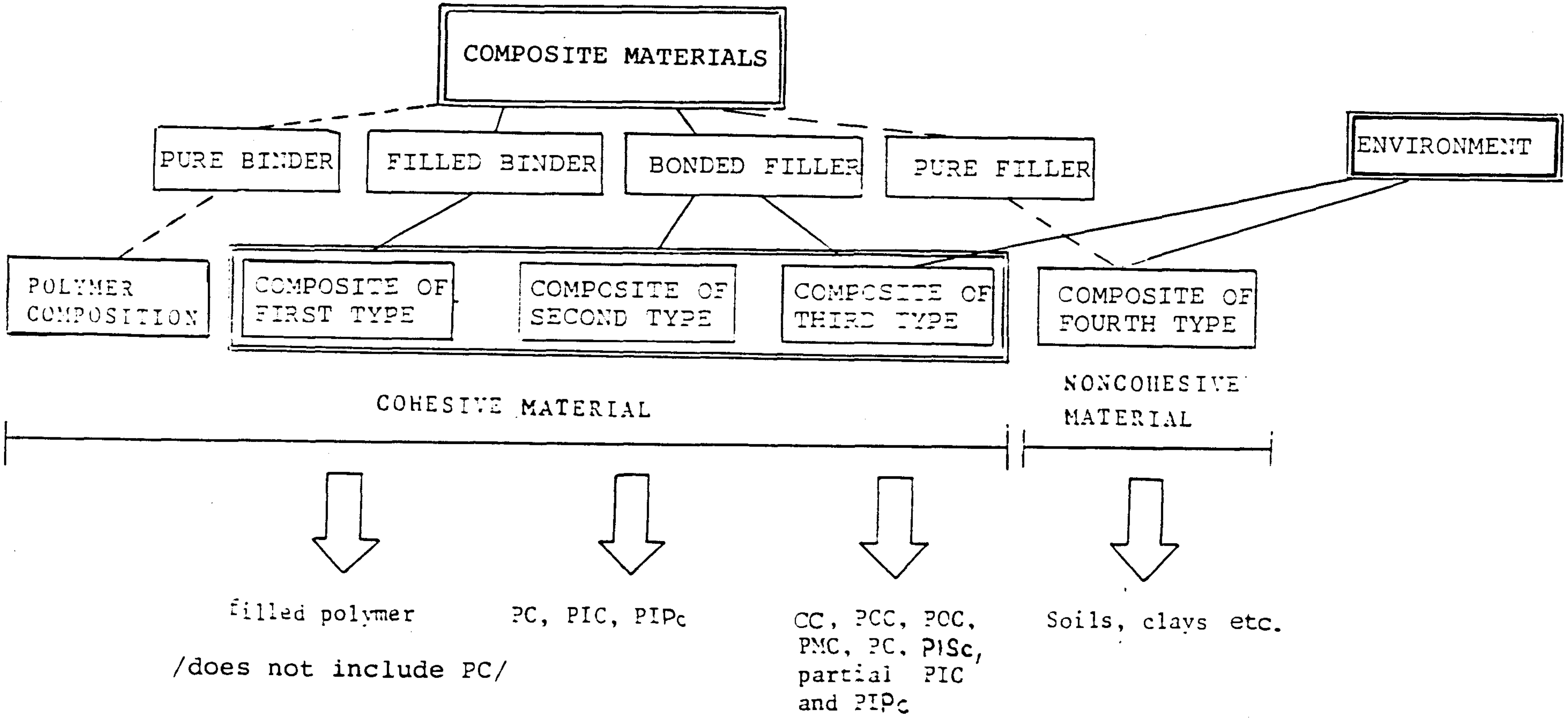
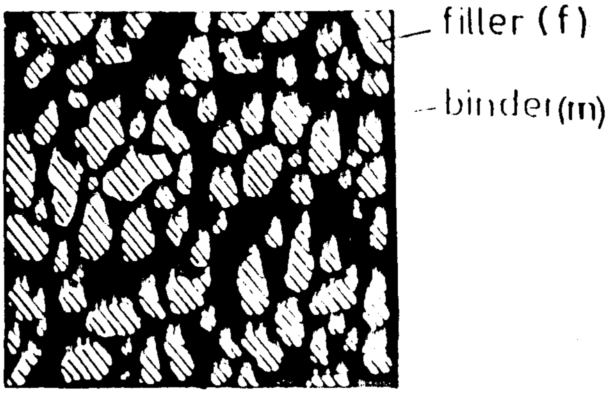


Fig. 4.2. Fundamental Types of Composite Materials

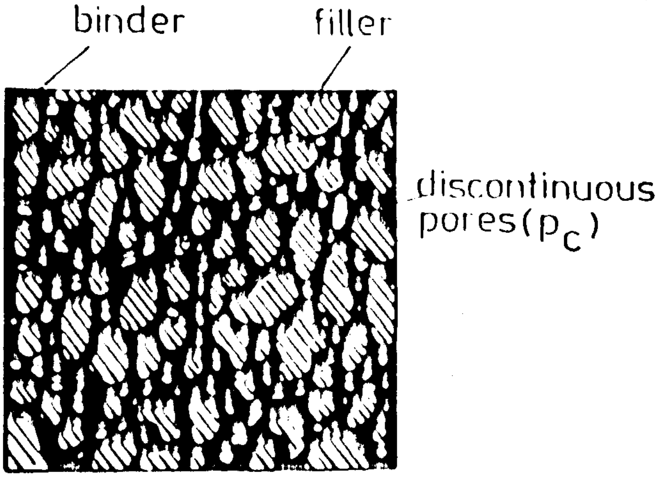


filled polymer

Does not include

CC, PCC, POC, PMC, PIC, PIPc

Fig.4.3. Composite material of first type



Includes
All

PIC, PIPc
Include
Most
PC

Does not include

CC, PCC, POC, PMC

Fig. 4.5. Composite material of the second type

Fig.4.4.

The shear flow mechanisms along the interphase boundaries in the Type I composite model

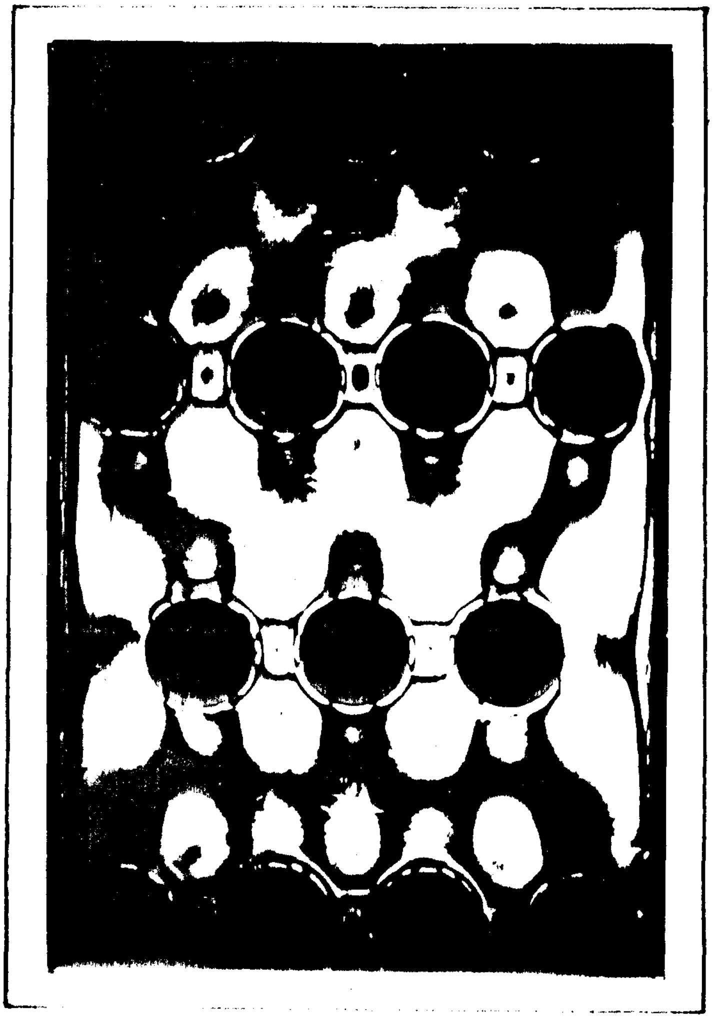
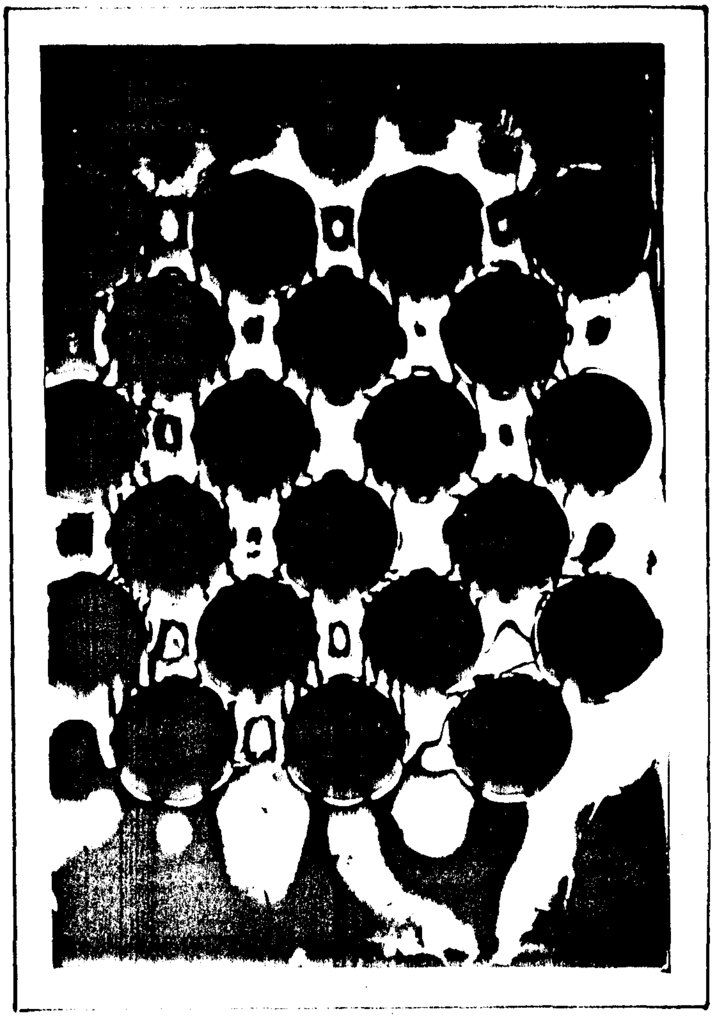
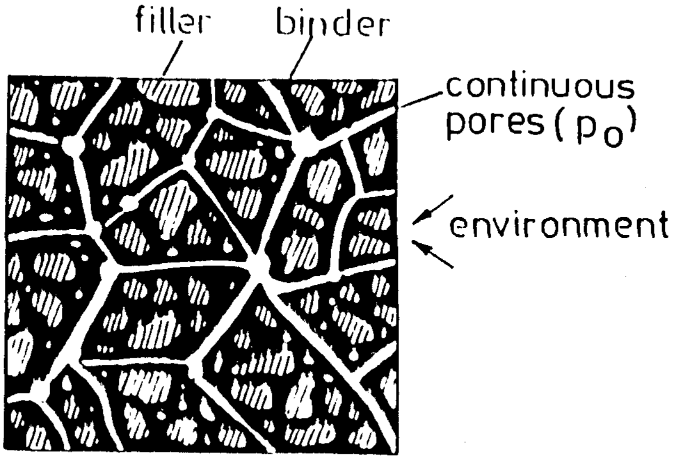


Fig 4.7

The direct force flow mechanism among the dispersed particles in the Typa I/II composite model



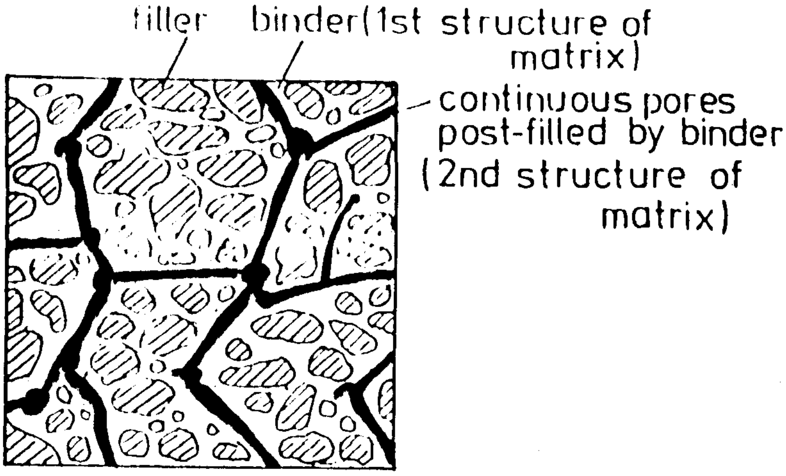


Includes
All
CC, PC, POC, PMC,
partial PIC
partial PIPc

Includes Some

PC

Fig. 4.6. Composite material of third type



PIC

PIPc

Fig. 4.8. Bistructural composite system

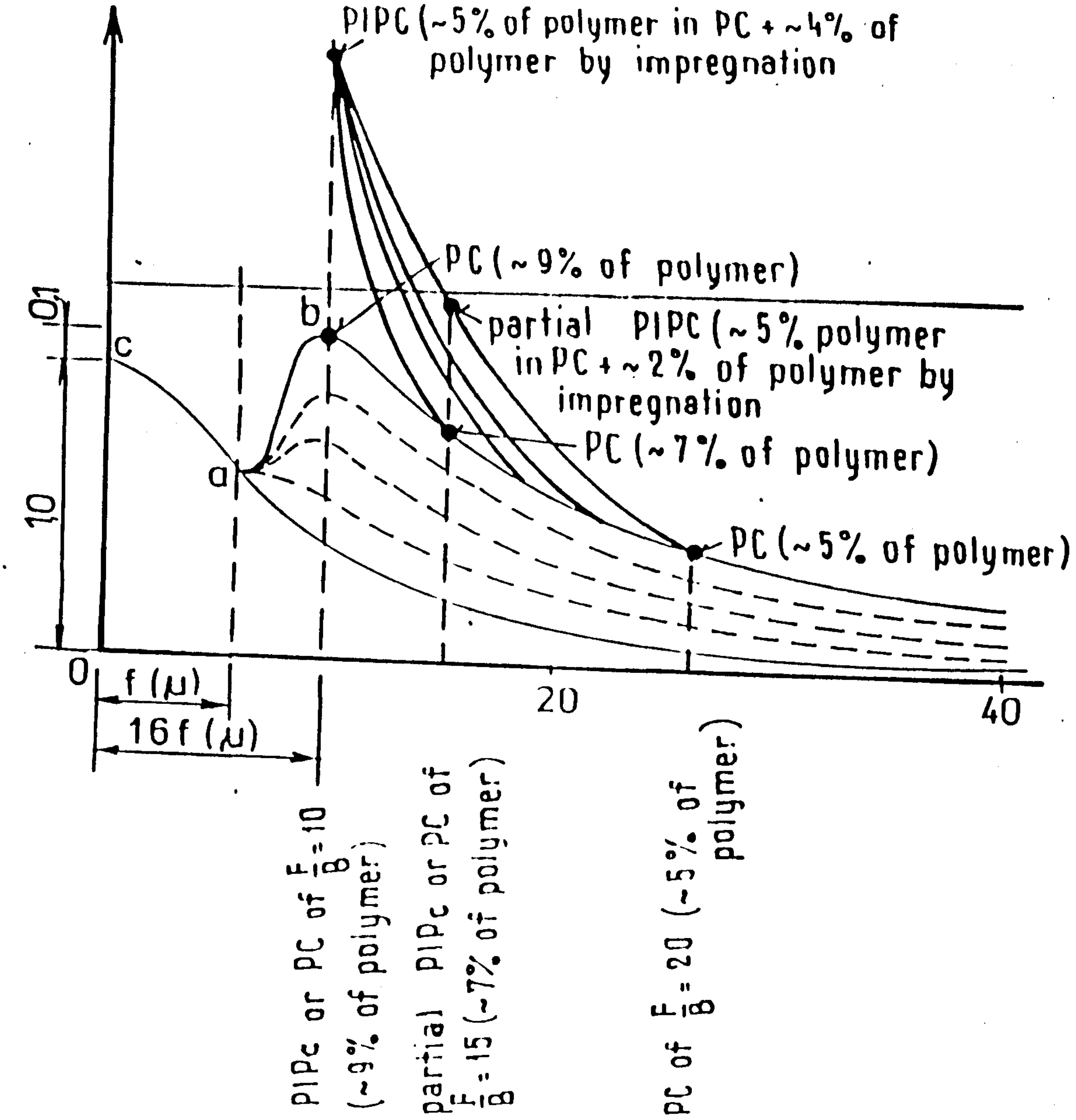


Fig. 4.9. Change of strength of PC after impregnation by the same polymer (PIPc) plotted against the ratio /by weight/ of solid phases
μ = pore volume of compacted filler system

5. PREPARATION OF CONCRETE POLYMER COMPOSITES

5.1. Polymer cement concretes /PCC/

Polymer cement concretes differ in the chemical composition of the polymer concrete. It is possible to recognize basically two types of such compositions: relatively chemically inert /elastomers and thermoplastics/ and chemically reactive /thermosetting/ resins or prepolymers and monomers. More precisely such type modifications and their results could be described as shown in tabl.6.1:

- premix polymerization and premix polymer cement concrete in which the modifying material is added to the fresh concrete in the form of complete polymer, that is, the polymerization of the modifying material has taken place before addition to the concrete
- postmix polymerization and postmix polymer cement concrete in which polymerizable components of a system are mixed with the fresh concrete and the polymerization is obtained by chemical means inside the concrete along with hydration of the cement.

The type of the chemical reaction during the postmix polymerization /thermosetting/ is very important. It is possible to recognize the thermosetting process as polycondensation with liberation of water /or other small molecules/ as a by-product, and polymerization or polyaddition with no by-product at all.

5.2. Polymer concrete /PC/

5.2.1 Aggregates

Usually, well-graded aggregates similar to those used in ordinary concrete determine the quality of PC materials. The maximum density of the dry mixture should be achieved. This requires addition of fine filler, 0 to 0,2 mm, as a prerequisite. This is important for both the mechanical and the chemical characteristics. Where structural components of PC are to be subjected to static or dynamic loading, only unbroken and screened aggregates may be used.

Gravel, sand and powders of natural stones like quartz, granite and basalt are suitable for a strong and chemical resistant PC. For low density applications lightweight aggregates like expanded clay or glass and micro spheres are available. If pigments are to be added to the compound, they should be weather- and UV-resistant. Normally metal oxide pigments are used.

Aggregates must be free of moisture. Even small amounts of moisture in the mix could alter the mechanical characteristics of the PC.

5.2.2 Binder

PC contains organic binder only. The following reactive resins are generally used:

- epoxy resins /E/
- methylmethacrylate resins /MMA/
- unsaturated polyester resins /UP/
- polyurethane resins /PU/
- furan resins /F/

The curing is started by adding a curing agent or initiator appropriately specified for the resin; once initiated the reaction cannot be stopped. An accelerator is often used to increase the curing rate.

Each irganic chemical reaction is dependent upon temperature. This is true for polyaddition /E, PU/, polycondensation /F/, as well as for radical polymerization /MMA, UP/ curing systems.

5.2.3 Proportions

Generally, mix proportions are different from those of ordinary portland cement concrete. In concrete technology, proportions are given in terms of weight of aggregate to weight of binder.

The larger the aggregate the less binder is necessary; the less binder the more PC behaves like stone, and the more binder the more PC must be considered as a fille plastic.

A binder-aggregate ratio of 1:7 approximately equals a binder volume of a concrete with a usual content of cement paste /25 Vol. %/.Mix proportions with very small resin contents /e.g. 1/20/ are often used. In these cases the material will be continuously.

5.2.4 Mixing and Workability

PC can be prepared batchwise in batch mixers /kneading machines/ or continuously in casting machines. Preparing means metering the single components precisely and mix them thoroughly and homogeneously in the desired quantities. Both batchwise and continuous mixing have advantages and disadvantages. The decision depends on the goal as well as on economy.

The workability is determined by content and viscosity of the binder and by type and grading of aggregates. The viscosity range at 20 °C begins with 2 to 150 mPas for methyl-methacrylate /e.i. the specific surface area/ and reaches 40 000 mPas for epoxy-tar. The viscosities for UP, F and PU resins of 100 and 10 000 mPas, respectively. line within the above range.

5.2.5 Moulds and Compaction

The moulds can be made of many different materials including steel, aluminium, silicone and polyethylene. The materials differ in price and in life. Therefore, it is necessary to choose the right mould material according to the product to be cast. Moulds for single parts or for small productions runs can be made from the cheapest material; for mass production, steel or aluminium are more suitable due to the longer life.

The surface of the PC product is an exact reproduction of the mould. Brilliant surfaces of products can be only obtained by using moulds with very fine surfaces.

Frequences and amplitudes for compaction must be reconciled with the mould to be filled. The dimensions and weight of the mould determine if the vibrators maybe attached directly to the mould or if the compaction should be done on a vibrating table. The vibration energy must be so applied to the PC that separation is prevented. The best results are usually obtained by application of vibration with high frequency and low amplitude /250 - 300 Hz, 0.0 - 0,3 mm/. For an application in situ mobile batching machines are available which can be adapted to the particular requirements. In case of overlays the substrate material should be dry, clean, and primed. The PC can be applied manually or by means of machines, e.g. paving machines. The equipment should correspond to the job size and to the consistency of the PC mix which can range from a self-flowing mix in a thin layer to a high viscosity PC in a thicker layer.

5.3 Polymer impregnated concrete /PIC/

Distinct from other cement polymer-composites, only PIC is made from ordinary hardened cement concrete. A low viscosity monomer is used to partially fill the capillary pores of the hardened concrete, and, after polymerization, the PIC exhibits extremely high impermeability although the large pores are not fully filled. The smaller capillaries are sufficiently filled to prevent intrusion of water.

There are two types of PIC: partial-depth and full-depth impregnation. Full-depth impregnation utilizes drying temperatures in excess of 100 °C, evacuation, pressurized impregnation and heat. Full-depth impregnation is practical only in the laboratory or in a plant. Partial-depth impregnation is most commonly used for bridges, floors such as parking garages, and hydraulic structures. To achieve partial-depth impregnation, the surface is heated to above 100 °C for several hours, cooled, monomer is applied usually to a thin sand cover and permitted to soak for several hours, and heat is applied to cure the monomer. The depth of impregnation ranges from 15 to 35 mm; the underlying concrete is unimpregnated.

6. PROPERTIES OF CONCRETE POLYMER COMPOSITES

The decision for the use of a CPC should be justified on the basis of desired material properties in the fresh, curing /Table 6.1/ and hardened /Table 6.2/ state. The material properties are relative, i.e. in comparison with ordinary concrete /CC/. Advantages are listed /+/ and disadvantages /-/. Table 6.3 gives an overview of C-PC types convenient for the most frequent current applications, based on the properties given in the previous tables.

The rather limited use of CPC compared with CC mainly due to the expensive polymers /mostly refined products/, which implies that the use has to be justified through a much improved service performance /e.g. durability/ or highly increased productivity /e.g. curing time/. However, the use of CPC may very well be economical if the increased service life of the structure in an aggressive environment and the high cost of otherwise needed repair are taken into account.

6.1 Polymer Concrete PC

Epoxies, polyurethanes, acrylates, unsaturated polyesters and furane resins are binder for polymer concretes. Some polymer concretes have compressive and tensile strength several times greater than CC. The modulus can range from twice to one-twentieth than of normal CC. The water absorption permeability and wear are much less than for normal concrete. The bond to CC is usually quite good, although some resins, e.g. furan, are not compatible and require a primer. The acid resistance varies from good to excellent.

The primary uses of PC are for bridges and floor overlays /screeds/, repair of CC, and precast products. Single gradation aggregates /approximately 3 mm/ are used for decorative screeds in showrooms and other areas with limited exposure to traffic. The use of different colored procoated aggregate permit the use of art designs in the screeds.

PC with well-graded fine aggregates are widely used in screeds. Generally the binder/aggregate ratio is high enough to completely fill the voidspace between the aggregates. Such mortars are strong, impervious, resistant against chemical attack and wear. They are widely used for industrial floors in the chemical and food industry, where the ease of cleaning is also an important factor. The thin PC screeds are generally applied by using self leveling mortars. Thin, e.g. 12 to 15 mm, screeds are used on bridges to provide a good skid resistance, low permeability surface, For bridges where large fluctuations can occur, a resin with a low modulus and high elongation /20 to 30 %/ should be used. Some epoxies and polyesters are available for this purpose.

Strong impervious mortars are also used to repair reinforced concrete because of their strength combined with rapid hardening, good bond to the substrate, absence of drying shrinkage and protection of steel.

PC can be used as a mortar for thin repairs or as a concrete /with large aggregates/ for larger or deeper repairs. Reinforcing steel in the repair helps to offset shrinkage and larger thermal movements.

Precast PC is becoming a large industry. Underground vaults, junction boxes for electrical and telephone lines, and floor drains for aggressive media have been made of PC for many years. Single skin and sandwich wall panels for buildings are produced in several countries. Floor tile, facade panels, and synthetic marble wash basins and bathtubs are widely used. Hollow PC median barriers, located between opposing lanes of traffic, are brought to the site and filled with PC. Structural panels made of PC are placed between the steel rails in railroad traffic crossings.
Due to its excellent dielectric properties. PC is being increasingly used for high voltage electric insulators.
Due to its excellent resistance to aggressive media. PC is used in sewer pipe. Some PC with very high thermal resistance is used as a coating inside of geothermal well pipes.

One of the fastest growing uses of PC is for machine structures and machine bases as a replacement for the cast iron. The high stiffness-to-weight ratio, excellent damping characteristics, low thermal conductors, and ease and speed of fabrication make PC an ideal material for this application.

The use of polymers in mortars or concretes is not restricted to the examples given in this chapter. For the near future a growth in volume as well as in types of applications has to be expected, brought about by better understanding of Concrete Polymer Composites.

6.2. Polymer Cement Concrete PCC

To the cementitious binding agent resinous materials may advantageously be added. A wide variety of dispersions, redispersible powders and special epoxy systems can be used. In the fresh state the advantages are: improved workability, stability and water retention capacity. In the hardened state the improvements are: higher ratio of tensile to compressive strength, higher elongation at break, improved bond to CC, greater impermeability which results in less intrusion of water and chloride, and, hence, less corrosion of steel and lower rate of carbonation; together with a lower drying shrinkage mostly a lower susceptibility for cracking is obtained. These improvements added to the still high alkalinity make PCC an excellent repair material for reinforced concrete for which they are extensively used. They arealso widely used for overlays 1 to 3 cm in thickness for bridge and parking garage floor. Improved bond and flexibility are the reason for the use of PCC as a glue for ceramic and other types of tiles. Usually the glue is a premix of fine sand, cement and a redispersible powder.

Certain dispersions /e.g. SBR/ added in a high concentration to very fine CC make such flexible mortars that they have crack bridging properties when applied in at least two layers of 1,5 mm each.

Strong, wear resistent and good bonding self leveling thin screeds can be made with so-called epoxy-cement systems.

6.3. Polymer-Impregnated Concrete PIC

Impregnation can also be the final treatment of a CC. Silanes and siloxanes in solvents are used to penetrate into the CC to a limited depth. After evaporation of the solvent the pore surface is finally covered with a silicon which makes the concrete surface water repellent. Treated CC surfaces show improved resistance against deicing salts and algae growth is restricted. Impregnated surfaces of CC /e.g. with epoxy/ improve the surface with respect to both wear resistance and chemical resistance.

Deeper impregnations can only be obtained in dry concrete with monomers of very low viscosity. For such applications, acrylates are used and polymerization is obtained by thermal or radiation treatment. It goes without saying that this operation generally takes place in a plant.

The mechanical properties of PIC increase dramatically compared to the unimpregnated concrete. Compression, tensil and flexural strengths are increased 3 to 5 times. The modulus of elasticity is nearly doubled. Creep is reduced by a factor of 10 or more. The absorption and permeability are reduced to essentially zero in some cases. Wear and abrasion resistance are increased by a factor of 10 or more.

table 6.2 ADVANTAGES AND DISADVANTAGES IN THE HARDENED STATE

Properties	PCC			PIC	PC					
	Latex 1)	Epoxy	Ester		A	E	UP	VE	F	PU
Flexural strength	+	+	+	+	+	+	+	+	+	+
Compressive str.	0	0	0	+	+	+	+	+	+	+
Tensile strength	+	+	+	+	+	+	+	+	+	+
Thermal expansion	0	0	0	0	-	-	-	-	-	-
Thermal resistance	0	0	0	0	-	-	-	-	-	-
Aquous salt resist.	+	0	0	+	+	+	+	+	+	+
Acid resistance	0	0	0	+	+	+	+	+	+	+
Alkali resistance	0	0	0	+	-	+	-	-	-	-
Organic solvent resistance	0	0	0	0,-	-[1]	-	-	-	-	-
Carbonation resist.	+	+	+	+	*	*	*	*	*	*
Vibration damping	0	0	0	+	+	+	+	+	+	+
Electrical resist.	0	0	0	0,+	+	+	+	+	+	+
Abrasion resistance	+	+	+	+	+	+	+	+	+	+
Adhesion	+	+	+	*	+	+	+	+	+	+
Hydrolysis, i.e. consuming hydroxyl	0,-[2]	0	-	0	_	*	_	*	*	*
Free chloride gen.	0,-[3]	0	0	0	0	0	0	0	0	0
Fire resistance	0	0	0	0	-	-	-	-		-
Wet properties	0,-[4]	0	0	x	x	x	x	x	x	x

* - the property is not relevant. ? - uncertain value.

[1] e.g. acetone.

[2] polymers containing vinyl acetate, vinyl chloride, vinylidene chloride and <u>lower</u> acrylic monomers.

[3] polymers containing vinyl chloride and vinylidene chloride monomers.

[4] some of the positive properties may be partly lost when wet, but regained when drying out again.

table 63 APPLICATIONS OF CPC

Application	PCC			PIC	PC					
	Latex	Epoxy	Ester		A	E	UP	VE	F	PU
Rapid repair mortar (e.g. patching)	0	x	x	0	x	x	x	x	x	x
Repair mortars for structures	x	x	x	0	x	x	x	x	x	x
Overlays/impregnat.	x	x	0	x	x	x	x	x	O,x	O,x
Storage tanks for aggressives	0	0	0	0	x	x	x	x	x	0
Machine beds and structures	0	0	0	0	x	x	x	x	x	0
Electrical insulat.	0	0	0	0	x	x	x	x	x	0
Prefabricated elements and details	0	0	0	x	x	x	x	x	x	x
Shotcrete	0	x	x	0	0	x	x	x	0	x
CC admixture	x	0	0	0	0	0	0	0	0	0
Crack injection	0	0	0	0	x	x	0	x	O	x
Structural gluing	x	0	0	0	0	x	0	0	0	0

7.0 APPLICATIONS OF CONCRETE-POLYMER COMPOSITES (C-PC)

7.1. POSSIBILITIES OF C-PC APPLICATION

So far there is neither a standardized solution nor unified recommendations for any field of application of C-PC. There exists a lot of materials available and for most of them there are more or less accurate specifications and descriptions of application procedures.

In spite of this, there are many important applications of C-PC in different domains. The most important and usual applications are in concrete engineering and finishing works in building, while less frequent but also very important are applications in machine construction, electrical and chemical industries.

With regard to the primary role of C-PC in any application and nature of the dominant state stresses which appear in C-PC or joint C-PC/substrate, the applications can be devided into structural and non-structural ones.

In the first case, the C-PC or joint C-PC/substrate are subjected to complex multiaxial state of stresses which should be taken into account in design of their bearing capacity, while in the second case they are mainly subjected to simple uniaxial state of stress which appears on interface between the new layer and substrate. Therefore many authors consider that for structural applications,mechanical properties of C-PC or joints are more important, such as:

- compressive, tensile and shear strength
- pull-off strength between C-PC and substrate
- fatigue strength, etc,

but for non-structural applications the properties which ensure durability of the C-PC or joint are as follows:

- porosity, both C-PC and joints,
- gas permeability, both C-PC and joints,.
- watertightness, both C-PC and joints,
- diffusion, both C-PC and joints, etc.

For a successful application of both kinds, an adequate design has to be made, which will include the following: environmental conditions, material properties and details of execution.

A systematization according to the kinds of actual application, materials and location of works in the present state is given in Tables 1, 2 and 3 below.

7.2. SPECIFIC FEATURES AND EXAMPLES OF SOME APPLICATIONS

7.2.1. Structural applications of C-PC in concrete engineering

The so-called structural joints in concrete engineering appear in:

- bonding of fresh to old concrete
- gluing of precast elements
- gluing of steel to concrete.

In the first case these joints are usually called working joints because through them reinforcement is not interrupted in execution. It is defined as an interface on which two consecutively poured concretes are monolythically and permanently joined.

Working joints appear in:

- predictable and unpredictable interruptions of concreting, especially in case of mass concrete structures,
- mixed construction (connection of precast elements with cast in-situ elements), and
- subsequent additional concreting or repair of concrete structures.

Typical examples of working joints between column and beam in buildings are given in Fig. 1.

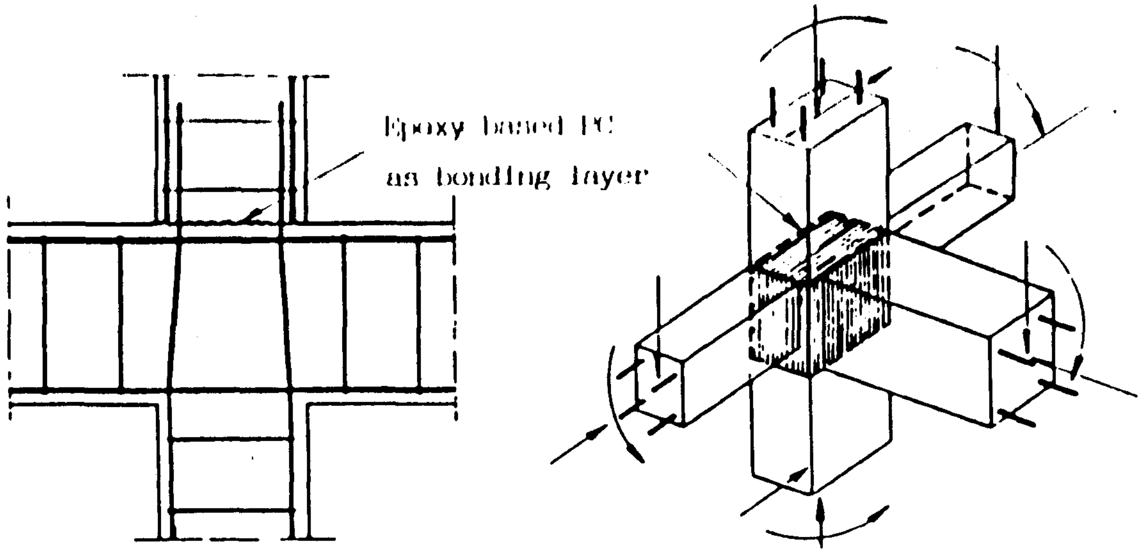


Fig. 1 Column to beam joint in monolythic and precast execution

Gluing of precast elements virtually means assembling of precast elements into a load-bearing structure. The joint in this case may cause only a negligible discontinuance in behavior of the rest of the structure. The difference between these and working joints is in the fact that non-prestresses reinforcement is always interrupted in the joint. Prestressed reinforcement may, but need not exist in the joint, which depends on the type of the structure.

All elements glued have to be over-compressed or loaded during hardening of the glue (adhesive). This will simultaneously affect the final thickness of the glue in the joint (the most appropriate one ranging from 1 to 2 mm), which has a considerable influence on the rigidity of the joint. These kinds of structural joints are most often used in bridge super-structure, Fig. 2.

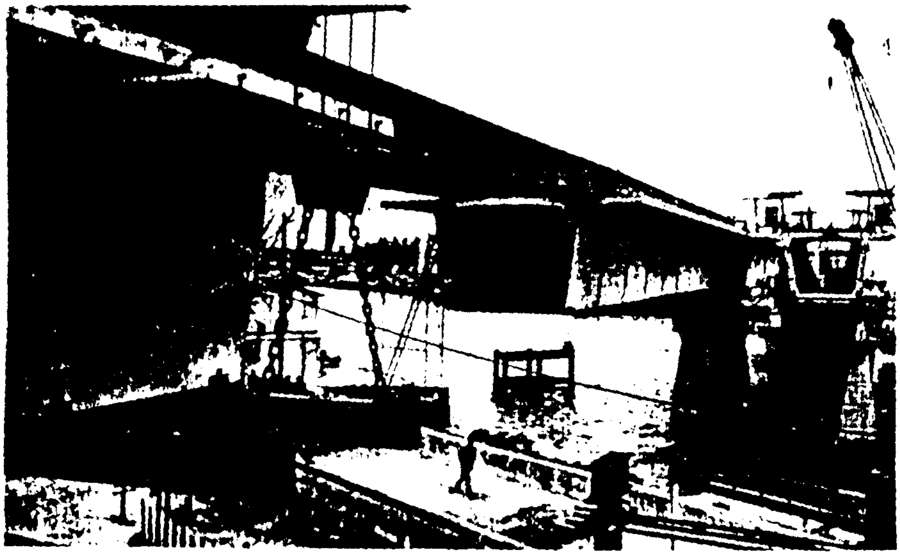


Fig. 2 - Construction of precast concrete box girder bridge

The need for gluing additional external reinforcement or steel ribbons upon the concrete arises mainly from strengthening of concrete structures in the following cases:

- damage to concrete structures (due to overloading, fire, explosion etc.)
- change of loading in service, which may be increased or distributed otherwise,
- change of structural system by elimination or shifting of bearing elements.

Thereby the following limitations are met in application:

- a structure that has to be strengthened must not be in such an unfavourable condition that it would undergo failure unless environment strengthened,
- higher ambient temperatures (over 50°C) may have adverse effect on the glue, so the glue manufacturer should be consulted about the possibilities of application,
- the glued reinforcement can generally not influence the existing deformations and cracks in the structure.

In all the above mentioned cases the requirements on integrity and durability of the joints are expressed in terms of:

- minimum strength of the connection or minimum bearing capacity,
- specified permeability (for gases and liquids),
- desired durability (expressed in terms of decreased physical and mechanical properties of the joints).

The mentioned requirements should be designed in advance on the basis of specific conditions of the structure, service use and environmental influences. In practical execution of these joints, the following C-PCs are most frequently used:

PCC - They are used in working joints of large area, primarily due to their favourable price. If there is a possibility that the joint might come in contact with water, application of PCC is reduced to the polymeric admixtures which do not soften in contact with water. In application of PCC it is important to test its tensile strength and resistance to alternating freeze and thaw cycles.

PC - They are used in working joints of smaller area and in structural joints of the former two cases. For their application the standard specifications ACI-503.2 mainly apply, which comprise the following:

- environmental conditions in application and service, the PC being sensitive to temperature, moisture and outside water influences,
- substratum characteristics, expressed in terms of minimum pull-out strength, purity and moisture content, and
- degree of applicability which generally depends on roughness and texture of the surface as well as on the viscosity of the PC.

7.2.2. Non-structural applications of C-PC in concrete engineering

These applications include the following:

- coating and impregnating of concrete surfaces,
- repair of concrete surfaces, and
- crack injection.

For the application of polymers for repair of concrete the standard specifications /Sasse, Pailere/ are valid since 1991.

Under coating and impregnating we understand additional treatment of concrete surface by producing thin layers 5 mm thick or deep, although there are no limitations regarding thickness or depth of layers respectively.

The reasons for an additional surface treatment of even high-quality concrete may be:

- strong chemical and physical environmental impact (gases, liquids and mechanical loadings),
- simple and efficient cleaning, e.g. swimming pools, waste water treatment facilities etc., and
- aesthetic reasons.

For execution of these protection layers all kinds of polymer and polymer-cement mortars, as well as impregnating means may be considered.
The most important impacts acting upon a new layer which significantly influence its durability and must be adjusted in the design are as follows:

- temperature effects as e.g. temperature variations, alternation of drying/moistening or freezing/defreezing, and
- pressures in interface attributable to fluidopermeability of the system (diffusion, absorption, permeability) if presence of water in the concrete is inevitable.

Repairing of concrete surfaces always means replacing the deteriorated concrete parts and layers by new ones. Concrete damage can be continuous on its skin by water, acids or frost action, and local by reinforcement corrosion which is manifested in the form of cracks and delaminations.
The reinforcement corrosion can start if pH value of concrete, due to carbonation, falls below 9.5, as well as if free chlorides content in the concrete exceeds the critical value. Both appearances are the consequence of penetration of agressive media into concrete, which is closely connected to the rate of flow into the concrete which depends on the pore distribution system and consists of three processes: absorption, diffusion and permeability. Each of the three mentioned processes can be described by means of well-known physical laws and a corelation can be made between the concentration of agressive media per concrete depth and possible service life of the structure. On the basis of the same relations it is possible to design the reinforcement protection e.g. new layers on the concrete.

Four typical tasks may be solved:

1. Diagnosis of the condition of the existing reinforced concrete structure. By chemical analyses of samples taken from the structure the rate of flow of agressive media (Cl, CO_2, etc.) per cover depth and around the reinforcement is obtained. This and the actual age of the structure (t) serve as a basis to calculate the diffusion coefficient (D), absorption (A), permeability coefficient (k) and to forecast the structure service life (t),
2. Calculation of concrete cover permeability parameters D, A, k for the expected structure service life and the given dimensions of the cover (c),
3. Designing the concrete cover depth (c) for the expected structure service life and the given parameters D, A, k.
4. Parameters D, A, k and the cover depth (c) (or protected layer) are optimized for a given service life (t).

In solving the above tasks a good alternative for protecting cover (c) are PCC and PC mortars, since these materials have excellent adhesion to concrete and ten times lower permeability than that of ordinary concrete. The proper choice of the repair material is always determined by specific requirements e.g. if the repair material must resist the chemical action on the concrete and influence of humidity in the concrete it must consist of:

- matrix material for good bonding strength,
- slightly permeable continuous pores for corrosion protection, but still allowing for vapour pressures,
- filler to adopt thermal properties.

Crack injection is always connected to repairing of concrete surface, because the first sign of concrete surface damage is in the form of cracks. Which material shall be used for filling of cracks (pure polymer resins or PC) depends on their width and state (whether active or stable).

Typical examples of concrete surfaces repair are given in Fig. 3 and 4.

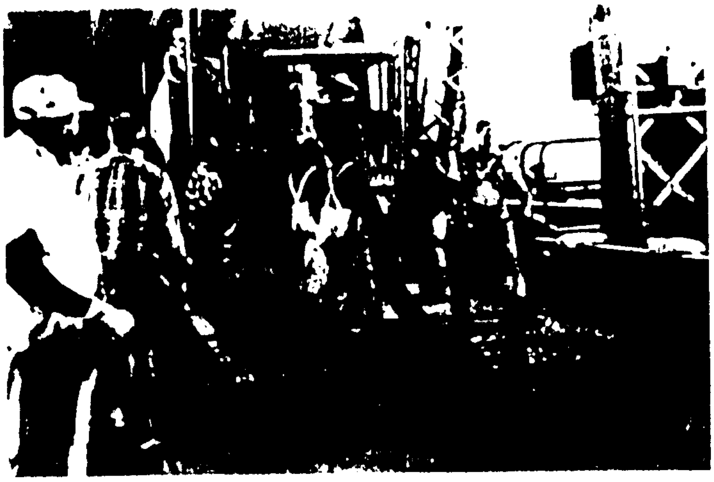


Fig.3. Placement of a bridge epoxy PC overlay

Fig.4. Water tower before and after restoration work with acrylic PCC

7.2.3. Applications of C-PC in finishing works in building

More frequent than others are applications in floorings, pavings and anti-corrosive linings.

Traffic-bearing surfaces such as roadways, bridge and parking garage decks, factory, warehouse and shopping floors and others are required to withstand a variety of environmental conditions. They can be exposed to mechanical damage caused by heavy or high-speed traffic, as well as chemical attack caused by action of water, salt solutions, acids and other chemicals.

The primary materials used for construction of such surfaces are concrete, steel and sometimes wood. Since the above mentioned loadings and actions tend to damage these surfaces, the use of protective measures is required in order to extend their useful life.

Protection overlayers of PC and PCC, thickness dependent on the kind and intensity of loadings and actions, have been increasingly used for this purpose. They belong to three main polymeric families: epoxies, polyesters and methacrylates.

The following basic properties are necessary and common to all overlay systems, independent of the nature of their polymeric binder:

Working life		15-60 min
Compressive strength	min.	28 N/mm²
Bond strength	min.	5 N/mm²
Flexural strength	min.	7 N/mm²
Resistance to water and salt solutions		good
Radiation and heat resistance		good

In more specialized applications, such as in food and chemical processing plants, PC with specific properties shall be used. In addition to the basic properties in the above case, PC must have good resistance to organic and inorganic acids. An example of an anticorrosive C - PC floor in food factory is shown on Fig.5 below.

Fig.5 Anticorrosive PMMA based PC floor in food factory

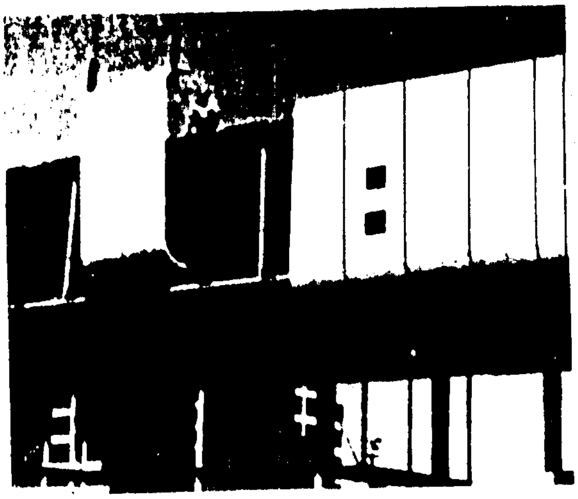
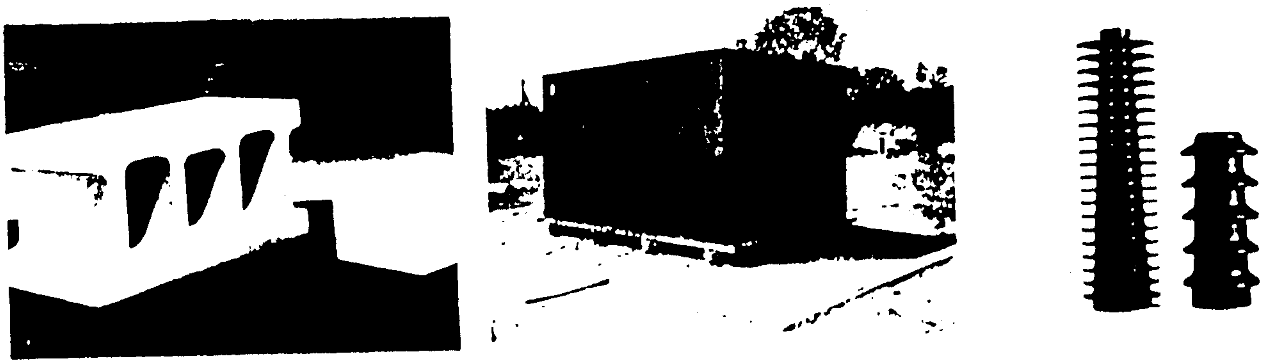


Fig. 10 PC cladding panels

Other products were introduced later on, at the beginning of 1980's. Their further development has brought new products with extraordinary properties (Fig. 11):

a) Insulating PC building blocks, made of light-weight PC, with 480-960 kg/m^3 volumetric mass, 95-200 Joules thermal conductivity and 7-41 MPa compressive strength
b) Acid tank made of furan resin PC which has excellent chemical resistance
c) Support insulators with bell-shaped screens, made of epoxy resin PC in a vacuum pressing process.



a) Building blocks made of insulating PC
b) Acid tanks made of furan resin
c) Support insulators made of epoxy resin PC

Fig. 11

Many new successful application of C-PC can be expected in the future.

Well-proved durability of furan PC cores for waste water piping of a chemical plant, executed in 1964, is shown on Fig. 8. Cores are overcoated with concrete after having been put into place and monolythicized with furanic polymer mortar. Core wall thickness is 4 cm, diameter 140 cm and length of core sections is 300 cm.
Fibrous reinforced FR-PC pipe with 5.2 m diameter for the first time manufactured in the world, as shown on Fig. 9.

Fig. 8 Furan PC piping 8 km long

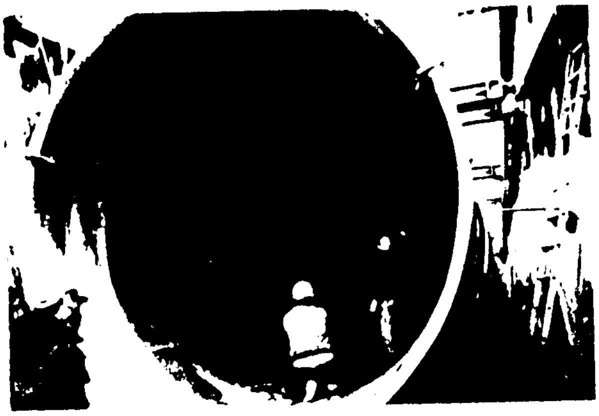


Fig. 9 FR-PC pipe 5.2 m diameter

Strengthening of a concrete floor structure (plain concrete between steel I beams) in a weaving plant can be mentioned as a successful application of PIC. The structure was subjected to high dynamic stresses. Impregnation of the structure was performed by a styrene TMPTMA system in 9:1 ratio (by weight). It was impregnation without vacuum treatment or pressure and with polymerization by heat. Polymer loading was applied at the rate of approx. 6% of the weight on concrete. Concrete strength was increased for 240% and floor structure bearing capacity for 80%.

7.2.5. Non-structural application of C-PC in other domains

One of the fastest growing uses of PC is for precast elements. For years the only precast PC products were building panels, so they developed in many variants and many kinds of finish, e.g. as rough polymer-textured finish (Fig. 10).

A fibrous reinforced PCC consisting of cement, butadiene styrene latex and sand should be mentioned here as a special kind of hydraulic tunnel lining. The content of latex in a PCC mix varies between 1% and 5% on cement mass. Water-cement ratio is 0.28 - 0.40. Applied as shotcrete this material has the following properties:

- Module E 2-3 times lower than ordinary concrete,
- Water impermeability 2-3 times higher than ordinary concrete,
- Tensile strength 5-10 MPa,
- Adhesion to rock and old concrete 0.5-1.6 Mpa,
- Cavitation resistance and mechanical abrasion resistance is 10-15 times as high as for ordinary concrete,
- Higher acid and alkali resistance.

Applications of C-PC in water-proofings and adhesives are also in form of new layers and they here have protective tasks too. The same principle in selection of materials can be applied here, as mentioned formerly.

7.2.4. Structural applications of C-PC in other domains

One of the newest structural application of PC, based on polymethylmethacrylate (PMMA), epoxy resin (EP) and unsaturated polyester resin (UP), is in machine-tool industry i.e. as a non-metallic casting material.

Mixing and placing of this material is very easy because it consists of only two or three components. After compacting in a mould or a metal construction, the hardening process is very fast (a few days) and the machine part is ready. Compared to the same part made of grey cast iron, this part has similar mechanical, but better dynamic properties. Therefore PC is a real alternative to cast iron and steel for machine tool parts (Fig. 6 and 7).

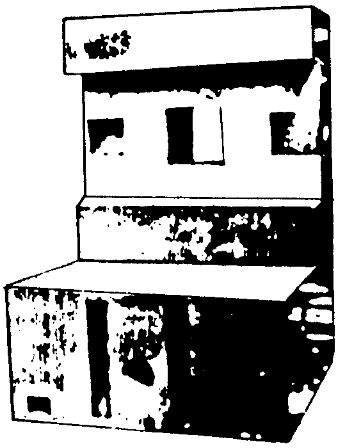


Fig. 6 Frame of a high-speed milling machine made of PMMA polymer concrete

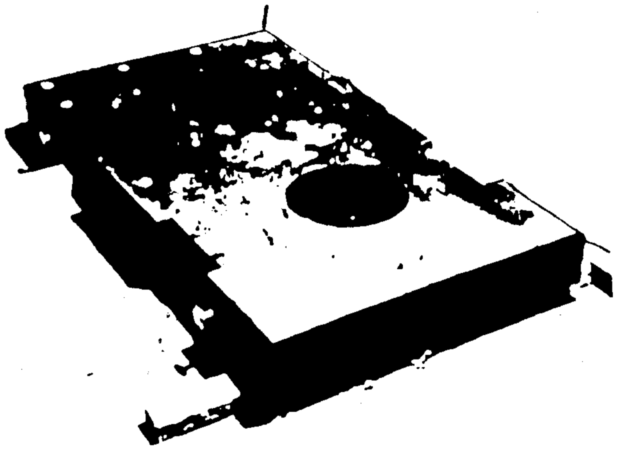


Fig. 7 Plate of a machine frame table made of EP polymer concrete