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CONCRETE-POLYMER MATERIALS AND ITS WORLDWIDE DEVELOPMENT
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Concrete-Polymer Materials and Its Worldwide Development

By Meyer Steinberg

Synopsis: A wide range of concrete-polymer composite materials is under investigation in a number of laboratories around the world. For this materials development, the older technology of hydraulic cement concrete is combined with the newer technology of polymers to form new and improved materials of construction. Polymer impregnated precast concrete (PIC) is the more developed of the composites and exhibits the highest degree of strength and durability properties improvements. Polymer concrete (PC), an aggregate bound with polymer appears to be a promising material for cast-in-place applications. Numerous applications of PIC are presently under development which indicates a large potential for this material.

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INTRODUCTION

The first sample of polymer impregnated concrete was produced at Brookhaven National Laboratory in 1965 and the first measurements of the physical and durability properties were conducted in 1966 by the U.S. Bureau of Reclamation. The remarkable measurement of 20,000 psi (1410 Kg/cm^2) in compressive strength and the large improvement in freeze-thaw durability becomes in retrospect impressive when considering that in the recorded history of concrete from 2000 BC to 1965 AD, the compressive strength was increased from 800 psi (56 Kg/cm^2) to 5000 psi (353 Kg/cm^2) and durability only in the order of hundreds of freeze-thaw cycles. Thus concrete-polymer materials represents a significant "quantum jump" in the development of concrete and its manufacture. Since 1965 mainly through the efforts of a joint U.S. government agency sponsorship, including the U.S. Atomic Energy Commission, the Bureau of Reclamation, the Office of Saline Water, and the Federal Highway Administration, materials and process information has been developed and is being evaluated for a number of applications in the U.S.

The development of concrete-polymer composite materials is directed at both improved and new concrete materials by combining the ancient technology of hydraulic cement concrete

formation with the more modern technology of polymer chemistry. A wide range of concrete-polymer composites is being investigated.

Material Properties

Polymer impregnated concrete (PIC) is a precast and cured hydrated cement concrete which has been impregnated with a low viscosity monomer and polymerized in-situ. This material is the more developed of the composites. The largest improvement in structural and durability properties have been obtained with PIC. With conventional concrete (28 day water cured), compressive strengths can be increased from 5000 psi (353 Kg/cm²) to as high as 20,000 psi (1410 Kg/cm²). Water absorption is reduced by 99% and the freeze-thaw resistance is enormously improved. With high silica cement, strong basaltic aggregate, and high temperature steam curing strength increases from 12,000 psi (845 Kg/cm²) to 38,000 psi (2680 Kg/cm²) can be obtained. The tensile strength of PIC is essentially one tenth of the compressive strength which is similar to conventional concrete. A maximum of 3500 psi (247 Kg/cm²) tensile strength has been obtained with the steam cured concrete. For steam cured concrete, polymer loadings (i.e. polymethyl methacrylate (PMMA)), of generally around 8% by weight of the dry concrete can be obtained. A photograph of a freeze-thaw test of PIC is shown in Figure 1.

In contrast to conventional concrete, PIC exhibits essentially zero creep properties. Furthermore by polymer impregnating concrete, conventional concrete is transformed from a plastic material to essentially an elastic material with an increase of at least two times in the modulus of elasticity. This is indicated by the linearity of the stress-strain for PIC in Figure 2. The ability to vary the shape of the stress-strain curve presents some interesting possibilities for tailoring desired properties of concrete for particular structural applications.

Methods of Manufacture

PIC is basically formed by drying cured conventional concrete by the most convenient and economical way (hot air,

oven, steam, dielectric heating, etc.) removing or displacing the air in the open cell void volume (vacuum or monomer displacement and pressure), diffusing a low viscosity monomer (< 10 cps) through the open cell structure which saturates the concrete with the monomer and in-situ polymerizing the monomer to form a polymer by the most convenient and economical means (radiation, heat or chemical initiation). A schematic flow sheet of alternate processes is given in Figure 3. Mainly the free-radical vinyl type monomers, i.e. methyl methacrylate, styrene, acrylonitrile, t-butyl styrene, and other thermoplastic monomers are used. Good results are also obtained with crosslinked and thermosetting monomers such as styrene-trimethylol propane trimethacrylate (TMPTMA) and polyester-styrene. The more important criteria are that the monomer should be a relatively low cost, readily available material and have a relatively low viscosity. Much information on the formation and structural and durability properties of PIC have been accumulated over the past four years in the U.S. (1-4) Table I gives a summary classification of the PIC materials and properties. A U.S. patent has also been issued on the production of PIC. (7)

Polymer cement concrete (PCC) is a premixture of cement paste and aggregate to which a monomer is added prior to setting and curing. The introduction of various organic materials to a concrete mix has been tried numerous times in the past by others as well as by BNL. The results obtained are either disappointing or relatively modest in improvement of strength and durability. In many cases materials poorer than concrete are obtained. Under the best conditions compressive strength improvement over conventional concrete of ~ 50% are obtained with relatively high polymer concentrations of ~ 30%. Polyester-styrene, epoxy-styrene, furans and vinylidene chloride have been used in PCC with limited success. This is explained by the fact that organic materials are incompatible with aqueous systems and in many cases, interfere with the alkaline cement hydration process. The incentive to attain improved premix concrete materials is that it can be cast in-place for field applications, whereas PIC requires a precast structure. The answer lies in PC development.

Polymer-concrete (PC) is an aggregate bound with a polymer binder. This material can be cast and formed in the field. It is called a concrete because by the general definition, concrete consists of any aggregate bound with a binder. The cheapest binder is portland cement, which costs in the U.S. about 1¢/lb. Polymer can also be a binder, however, it is more costly than hydrated cement, varying from 5¢/lb upwards to 30¢/lb for the majority of the polymer of commerce. Polymer filled with aggregate, for example, powdered walnut shells in plastics for table tops and furniture products has been known for a long time. What is referred to with PC is an aggregate filled with a polymer. The polymer acts as a binder for the aggregate. The main technique in producing PC is to minimize void volume in the aggregate mass so as to reduce the quantity of the relatively expensive polymer needed for binding the aggregate. This is accomplished by grading and mixing the aggregates to minimize void volume. For example to obtain less than 20% by volume voids, a stone aggregate mix of 3/8-1/2 in. stone (60.7% by wt.), 20-30 mesh sand (23.0%), 40-60 mesh sand (10.2%) and 170-270 sand (6.1%) are mixed and vibrated together in a form. Monomer is then diffused up through the mixed aggregate and the polymerization is initiated by either radiation or chemical means. There is also another reason for looking forward with interest to the development of this new class of PC materials. The problem with conventional concrete is the alkaline portland hydraulic cement which on curing, forms internal voids. Water can be entrapped which on freezing can readily crack the concrete. Furthermore the alkaline cement can be chemically attacked by acidic materials and concrete rapidly deteriorates under this condition. With polymer as a binder, most of these difficulties are overcome. The polymer can be made compact with a minimum of open voids and most polymers are hydrophobic and resistant to chemical attack. As shown in summary Table 1, PC compressive strengths can be obtained as high as with PIC (~20,000 psi (1410 Kg/cm²)). A silane coupling agent is added to the monomer to improve the bond strength between the polymer and the aggregate. The main problems arise from the viscoelastic properties of the polymer. Polymer usually has a low modulus of elasticity which means it is flexible and exhibits creep properties. This is mainly why plastics are not used alone in structural members. By using polymer

as a binder with aggregates, some of these difficulties are overcome and there is much hope for developing an important new class of high benefit to cost ratio materials. It is interesting to note, from the open literature, that investigators in the USSR (6) have advanced the development of PC to a greater extent than in the U.S., whereas PIC is much more advanced in the U.S. than in the USSR. Much more investigation and experience is required with PC to make it a reliably acceptable material of construction.

Consideration can be given to the aggregate in the binder-aggregate concretes or composites. The definition of an aggregate is any readily available bulk material. The cheapest and most readily available aggregates are natural stone and sand and that is why they are used all over the world. There are many kinds of stone aggregates which basically relate to igneous (granite), metamorphic (slate) and sedimentary (sandstone) stone. Aggregates are also classified as standard weight, structural lightweight and insulating lightweight. Among the various lightweight polymer impregnated concrete materials, perlite and expanded shale which have poor structural properties, has been used to produce a material which is lighter than wood and compressively as strong as concrete. This opens up possibilities for producing lightweight structurally strong mortars and concretes which are buoyant and have a high strength-to-weight ratio. Table 1 briefly summarizes the properties of concrete-polymer materials produced to date including surface coated (SC) and partially penetrated PIC referred to as coated in-depth concrete (CID). An attempt at rating the improvement in strength and durability properties in relation to a cost of manufacture is indicated in the table as a relative benefit to cost ratio for each of the materials. The factors taken into account include cost of monomer, cost of manufacture, the degree of improvement of both strength and durability, and the weight.

Applications Development

A number of applications of concrete-polymers are being investigated in the U.S. For the U.S. Federal Highway Administration (FHWA) advanced prestressed-post tensioned bridge deck designs are being investigated. The U.S. Office

of Saline Water (OSW) is investigating corrosion resistant PIC for constructing economical distillation vessels used in producing fresh water from the sea. The U.S. Bureau of Mines (USBM) is investigating the chemical stabilization of coal mine roof supports by impregnation of rock (5) with monomers followed by in-situ polymerization and also in developing a pumpable roof bolt. Segmental PIC tunnel linings is another application under development by the U.S. Bureau of Reclamation (USBR). The U.S. Navy has been interested in the use of PIC for underwater buoys and habitats. PIC is also being investigated for beams and building blocks for durable housing. The American Concrete Pipe Association (ACPA) in cooperation with the U.S. Atomic Energy Commission (USAEC) and the USBR is investigating the use of PIC for sewer and pressure pipe. There is also interest in PIC for railroad crossties.

In Japan an industrial construction company together with a chemical company is reported to have constructed a 15 ton/day pilot plant for experimental production of PIC using thermal-catalytic initiation. The material is called powercrete and beams, panels, and pipe have been produced, and a number of structural and durability tests have been performed.

A firm in the Union of South Africa is reported to have constructed a pilot plant for the thermal-catalytic production of PIC using a special type of concrete with smooth surfaces called mirror concrete. In addition to pipe and building concrete, a market for domestic sanitaryware (i.e. wash basins, bathtubs, sinks, etc.) is being explored.

A cement association in Italy and the University of Rome is collaborating in developing a PIC using a high silica cement in high strength concrete. High pressure steam cured concrete using underwater polymer curing is being used. Possibilities for construction of ship plate, sewer pipe and building facings are being explored.

Investigators in Norway, Denmark, Belgium, France, Spain, and Israel are known to be exploring PIC applications.

Extensive work has been conducted in the USSR on developing and applying polymer-concrete (PC) which is aggregate bound

with a polymer binder. The Russian literature (6) indicates significant advances in a number of applications including tunnel supports. PC is also being investigated in the U.S. however to a much less extent than PIC. Interestingly enough, the Russian literature indicates little work on PIC in the USSR.

A number of universities around the world have initiated studies on concrete-polymer materials.

In addition to conventional design procedures sophisticated three-dimensional finite element computer code structural analysis has been developed at Brookhaven National Laboratory (BNL) (8) and is being applied to aid in the design and analysis of structures utilizing these new concrete-polymer materials.

Preliminary cost estimates indicate that PIC materials cost could be competitive with other conventional materials of construction. The feeling is that concrete-polymer which mates an ancient materials technology (concrete) with a new materials technology (polymer) is a growing and exciting one. Given the opportunity of additional investigation, demonstration and experience it is believed that concrete-polymers can become an important class of construction materials.

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List of Figures and Tables

Figure 1 Freeze thaw test on Polymer Impregnated Concrete PIC (contains 6% by wt. PMMA) lost 0.5% by weight. Control conventional concrete lost 26.5% by weight.

Figure 2 Compressive stress-strain curve for PMMA-impregnated concrete. Impregnated shows elastic behavior, Unimpregnated shows plastic behavior.

Figure 3 Schematic of PIC process.

Table 1 Classification of concrete polymer materials and properties.

CONCRETE - POLYMER
3,650 - CYCLES

CONTROL
690 - CYCLES

FREEZE - THAW RESISTANCE

Figure 2

THERMAL PROCESS (WITH OPTIONAL MONOMER
IRRADIATION TREATMENT OR CATALYST ADDITION)
FOR PRODUCTION OF POLYMER IMPREGNATED CONCRETE
(PIC)

Figure 3

Table 1

Classification of Concrete-Polymer Materials

	Polymer loading, wt % PMMA	Density lbs/ft ³	Compressive strength, lbs/in. ²	Strength weight ratio	Durability	Benefit cost index
		(gm/cc)	(Kg/cm ²)			
1. Conventional concrete control	0.0	150 (2.40)	5,000 (353)	33	Poor	1.0
2. Surface Coating (SC) paint or overlay	0.0	150 (2.40)	5,000 (353)	33	Limited	1.1
3. Coating in Depth (CID)	1.0	150 (2.40)	6,000 (423)	40	Good	1.3
4. Polymer Cement Concrete (PCC) premix	35.0	130 (2.08)	7,500 (528)	58	Fair	0.4
5. Polymer Impregnated Con- crete (PIC)						
Standard aggregate						
a. Undried-dipped	2.0	153 (2.45)	10,000 (705)	49	Fair	1.4
b. Dried-evac.-filled	6.0	159 (2.55)	20,000 (1410)	126	Very good	2.0
c. Hi-Silica steam cured	8.0	159 (2.55)	38,000 (2680)	240	Very good	3.0
Lightweight aggregate						
a. Struct. lt. wt. concr.	15.0	130 (2.08)	25,000 (1760)	193	Very good	2.5
b. Insul. lt. wt. concr.	65.0	60 (0.96)	5,000 (353)	84	Very good	2.5
6. Polymer Concrete (PC) cementless	6.0	150 (2.40)	20,000 (1410)	133	Excellent	4.0