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THE PREPARATION, PROPERTIES, AND POTENTIAL
APPLICATIONS OF CONCRETE-POLYMER MATERIALS

by

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The Preparation, Properties, and Potential Applications of Concrete-Polymer Materials

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M. Steinberg⁽¹⁾ and J.E. Backstrom⁽²⁾

Summary

Preformed mortar and concrete can be fully impregnated with monomer and polymerized in-situ by either gamma radiation or thermal-catalytic techniques. This latter material hereafter called concrete-polymer has been found to have substantially improved structural and durability properties compared with those of conventional concrete. The improvement in properties appears to be a function of the polymer loading. Maximum increases in strength are obtained by forming and curing the concrete, subsequent drying, evacuating, soaking the concrete in monomer, and initiating polymerizations in situ by Co⁶⁰ gamma radiation. Strength increases of up to four times the control specimens have been obtained. Water permeability, water absorption, and chemical attack by distilled water, sulfate, brines, and hydrochloric acid have been reduced to negligible values compared with severe attack observed on the control specimens. The thermoplastic monomers, methyl methacrylate, styrene, and chlorostyrene are of value for normal temperature applications. Crosslinked and thermosetting monomers such as 60% styrene-

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40% trimethylolpropane trimethacrylate, diallyl phthalate, polyester-styrene, and epoxy-styrene impregnated in concrete allow the maintenance of strength and durability properties up to temperatures in the order of 150°C. Radiation treated concrete-polymer results in strength properties that are from 12 to 38% higher than thermal catalytically treated material. There appears to be little difference between the effect of radiation and thermal treatment on the durability properties of concrete-polymer except that which can be attributed to polymer loading. Polymer impregnation significantly increases the bond strength and flexural strength of steel-reinforced and fiber-reinforced concrete. Polymer impregnated concrete containing light weight aggregate such as expanded volcanic ash is increased in compressive strength by more than a factor of 9. Concrete-polymer is being considered for construction of corrosion resistant sewer pipe, drain pipe, building block, underwater structures, large multi-stage flash desalination plants, highway applications, and underground support systems. A preliminary comparison between concrete-polymer and other materials of construction indicate reasonable economic potential for certain applications.

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INTRODUCTION

Concrete is used in nearly all types of construction throughout the world because of its capacity to be formed into a variety of sizes and shapes, the ready availability of the raw material from which it is made, and its relatively low cost. Although concrete is an excellent building material, certain limitations to its use are recognized. These relate mainly to its relatively low tensile strength, its tendency to crack with changes in temperature and moisture, and its deterioration because of permeability, absorption, chemical and physical (freeze-thaw, abrasion, cavitation, etc.) attack under various environmental conditions. Improvements in strength and durability could significantly extend the usefulness and applications of concrete.

Based on the concept of diffusing a monomer through the porous mass of concrete and in situ polymerization of the monomer with Co⁶⁰ gamma radiation, initial experiments were carried out with methyl methacrylate and styrene impregnated mortar bars. A

hard glossy polymer was formed throughout the cross section of the concrete, and it was found that the compressive strength was improved by as much as a factor of 2.4, the absorption was decreased by 98%, and the hardness was increased by a factor of 1.9. Based on these remarkable preliminary results a cooperative research effort was undertaken by the Brookhaven National Laboratory and the U.S. Bureau of Reclamation, supported jointly by the U.S. Atomic Energy Commission and the U.S. Department of the Interior.¹

The long range objectives of the joint program are the investigation and development of a concrete-polymer composite as a new material of construction. The program includes the development of techniques for the preparation of the concrete-polymer material, the measurement of the physical and chemical properties, the preparation of full-scale concrete products, and the conceptual design and evaluation of various specific applications.

CONCRETE-POLYMER PREPARATION TECHNIQUES

Concrete Formation

Concrete is usually prepared by thoroughly mixing hydraulic cement and water with sand, gravel, crushed rock, or some other aggregates, casting the mixture in a mold, and allowing it to hydrate or cure in a humid atmosphere.² After a 28-day cure the concrete reaches about 80% of its ultimate strength. Concrete at this point

contains ~3.5% by weight of bound or hydrated water and ~3.5% by weight of free water. When an air-entraining agent is used, the total available void volume in the concrete is ~14%. The amount of free water and the void volume in the concrete determine the quantity of monomer and polymer that can be added or loaded into a precast concrete.

Drying

To obtain maximum loading of the concrete with the monomer the free water is removed by drying. This can be done by various techniques, such as oven drying, vacuum drying in a heated air stream, or infrared or microwave heating. To thermally dry 3-in.-diam. x 6-in.-long cylindrical concrete specimens to constant weight in a muffle furnace at 221°F (105°C), a drying time of 100 hr is required. The drying time is considerably decreased at higher temperatures; e.g., 8 hr at 302°F (150°C). For undried specimens the monomer loadings were usually <3.5 weight % and for dried specimens, >3.5 weight % of the unimpregnated specimen.

Evacuation, Soaking, and Pressurizing

The impregnation of concrete with monomer is essentially a displacement of the air in the void volume of the concrete. This can be accomplished by slowly lowering the specimen into the liquid monomer and allowing the liquid pressure and capillary forces to displace the air volume. The air can also be displaced by forcing

the monomer through the concrete under a differential pressure. Another method is to evacuate the air and submerge the specimen in the liquid monomer. This eliminates the possibility of entrapment of air toward the center of the specimen, which would prevent full loading. It was also found that evacuation of specimens significantly decreased the subsequent soaking time required for obtaining comparable monomer loading. The application of pressure during soaking in monomer is another technique that can be used to further reduce loading time.

Table I indicates the effect of evacuation, soaking, and pressure on the time required to impregnate a 3-in.-diam x 6-in.-long cylinder of concrete and the polymer loadings achieved with use of a monomer of relatively low viscosity, such as methyl methacrylate. It can be seen that, for similar soaking times, the polymer loading values were 20% to 30% higher for evacuated than for non evacuated samples. The effect of 5 psig nitrogen gas pressure over the monomer in which the sample was soaking indicates that for the nonevacuated specimens there is little change in polymer loading. However, for evacuated samples the soaking time required to reach a loading of 6.5% was reduced from 5 to 1 hr (compare specimens No. 8 and 12).

Monomer Selection

The selection of a monomer to form a concrete-polymer material depends on the end application of the material, which in turn dictates the properties of the polymer desired, the process requirements, and properties of the monomer. Cost must also be considered.

For ambient or low temperature application, thermoplastic polymers can be used. Low-cost monomers that have been used in this category include ethylene, ethylene-SO₂, vinyl acetate, methyl methacrylate, styrene, styrene-acrylonitrile, and chlorostyrene. Others awaiting test are vinyl chloride, vinylidene chloride, and t-butyl styrene. These monomers are limited for use at temperatures below ~100°C because of the relatively low softening points.

For higher temperature applications thermosetting monomers can be used and cross-linking agents can be added to the thermoplastic-type monomers. Monomers selected for studying high temperature properties of concrete-polymer materials include 90% methyl methacrylate-10% trimethylolpropane trimethylacrylate (the latter, TMPTMA, is a polyfunctional cross-linking agent), 60% styrene-40% TMPTMA, acrylonitrile, diallyl phthalate, polyester-styrene mixtures, and epoxy-styrene mixture. These polymers have softening temperatures that permit them to be used above ~150°C.

For processing purposes the monomer should have a relatively high boiling point or low vapor pressure under polymerization conditions to limit vaporization losses between the time the concrete specimen is impregnated and the time it is fully polymerized.

To prevent evaporation, polymerization can be carried out in a closed system such as an enclosed vessel or the concrete can be wrapped in polyethylene sheet. Another possibility is carrying out the polymerization under water, which is especially attractive for decreasing monomer loss. The monomer in the specimen is usually not miscible with water so that it has little effect on the properties of the concrete-polymer.

Gaseous and higher vapor pressure liquid monomers are more difficult to handle in process. Closed pressurized containers are needed and excess monomer surrounding the specimen is wasted and must be removed after polymerization. For many applications a hard glassy polymer is required to produce a strong bond and provide resistance to chemical attack. The polymers of ethylene formed below their melting

point from the gaseous phase yield a powdery material in the interstices of the concrete which does not seem to adhere to the concrete. Methacrylate when polymerized forms a hard glassy material which tends to line the voids and capillary structure of the cured concrete.

Most monomers have a low enough viscosity so that they can be easily diffused through relatively thick layers (6 in.) of concrete at reasonable rates. Monomers such as styrene and methyl methacrylate with viscosities <1 centipoise are typical examples. Other monomers such as polyesters and epoxies have viscosities several hundred times higher, which makes it difficult for them to diffuse through concrete. However, dilution with comonomers of low viscosities can reduce the viscosity sufficiently to allow penetration through the concrete. Viscosity effects are also important in partially impregnating a concrete material. With low viscosity monomers it is difficult to form sharply defined partially impregnated layers because of capillary diffusion through the concrete.

POLYMERIZATION TECHNIQUE

Polymerization of monomer impregnated concrete was

initially carried out with Co⁶⁰ gamma radiation. A principal advantage of using radiation is that free-radical chain reactions can be induced at ambient temperature. This limits vaporization loss and may produce a better concrete-polymer bond. The disadvantages are the dose requirements and the relatively high initial investment required for the radiation source and facility.

In the thermal-catalytic method a peroxide catalyst is usually used to initiate the free-radical chain reaction. The main disadvantages are the higher temperatures required for carrying out the polymerizations, the potential hazard of explosion on addition of catalyst to the monomer, and disposal of excess catalyzed monomer after the impregnating operation. Combinations of heat, radiation, and catalyst have been experimented with in attempts to reduce the radiation and catalyst requirements and increase the rate of polymerization. In the case of thermal polymerization a muffle furnace, infrared heating, and microwave heating can be used to provide the thermal energy.

Promoters have been used to reduce the temperature at which the catalyst normally decomposes and to effect polymerization at ambient temperature. The use of a combination of monomer, catalyst, and promoter may have some advantage for field

impregnation of cast-in-place concrete.

To provide improved control over the polymerization and additional safety, it is possible to add the catalyst to the concrete mix prior to curing and to add the promoter to the monomer used for impregnating. It has been found that benzoyl peroxide when incorporated in premixed concrete will initiate polymerization of methyl methacrylate at room temperature when cobalt naphthenate is added to the monomer used for impregnation.

Some typical Co^{60} gamma radiation dose requirements for fully polymerizing several concrete-polymer systems are given in Table II. There is some evidence¹ that a lower dose is required to polymerize monomer in concrete than monomer alone. This may be attributed to energy transfer effects in the heterogeneous concrete-monomer system.

For thermal-catalytic treatment, benzoyl peroxide was used as a free radical initiator in concentrations varying between 0.2 and 5 wt %. For methyl methacrylate, at a

temperature of 75°C, polymerization is complete in about 30 min. with 5 wt % catalyst and in about 70 min. when 1% catalyst is present.

For impregnation of concrete specimens the following standard procedure was generally followed.

1. The dried or undried concrete is evacuated to a pressure of <80 mm Hg. Drying of concrete is usually accomplished by heating to temperatures of 105° or 150°C to constant weight.
2. The concrete is soaked in monomer with a nitrogen blanket pressure of 5 psig.
3. The monomer is drained.
4. The specimen is then wrapped in polyethylene sheeting to reduce evaporation losses.
5. Polymerization is then carried out to completion using either radiation or thermal-catalytic means.

STRENGTH AND DURABILITY OF CONCRETE-POLYMER

Normal Temperature

Wherever possible, standard procedures were used in performing strength and durability tests.^{1,2} A summary of the properties for methyl methacrylate impregnated concrete is given in Table III.

Notable improvements in properties compared with those of control specimens of untreated concrete have been obtained as follows:

- (a) Compressive strength increases of 285%, or a factor of almost four.
- (b) Tensile strength increases of 292%.
- (c) Modulus of rupture increases of 256%.
- (d) Flexural modulus of elasticity increases of 44%.
- (e) Freezing and thawing improved by more than 300%.
- (f) Hardness-impact ("L" hammer) increases of 73%.
- (g) Water permeability decreases to negligible values.
- (h) Water absorption decreases of as much as 95%.
- (i) Corrosion by distilled water and sulfate brines decreases to negligible values.

Methyl methacrylate impregnated concrete-polymer specimens subjected to creep tests exhibited expansion under sustained load (negative creep), in contrast to contraction in length (positive creep) shown by ordinary concrete. If confirmed, this property could significantly influence the design of concrete-polymer structural and prefabricated members.

In Figure 1 concrete-polymer shows resistance to chemical attack by 15% HCl. The unimpregnated control specimens shows severe attack by the HCl on the cement phase.

The effect of polymer loading on compressive strength is shown in Figure 2. The strength was found generally to increase with polymer loading. It should be noted that it is difficult to obtain uniform partial loading of dried concrete so that the partially loaded samples may also show the effect of water content. Attempts to explain the effect of polymer loading on strength can be made by using the theory of particulate filled composite systems and the additive strength rule

$$S_c = S_m V_m + A B S_d V_d$$

S_c is the strength of the concrete-polymer composite, S_m is the cement strength, V_m is the cement volume, S_d is the aggregate strength, V_d is the aggregate volume, A is a theoretically and experimentally determined constant, and B is a factor relating to the bonding between phases. The experimental results on compressive strength correlate well with this theory^{3 4,5}.

High Temperature

The effect of temperature on compressive strength for several concrete-polymer systems is shown in Figure 3.

Best results were obtained with the 60% styrene-40% TMPTMA monomer mix which gave a 175% increase in strength over the control (high-strength concrete containing fly ash and type V cement, 8000 psi) at 25°C. The strength was maintained, decreasing by only 16% up to a temperature of 143°C. The methyl methacrylate +10% TMPTMA lost about 35% strength on increasing the temperature to 143°C. This is probably due to using an insufficient amount of the TMPTMA cross-linking agent needed to increase the softening point.

Radiation versus Thermal Polymerization

Table IV gives a comparison of the compressive strengths of several concrete-polymer systems for each of two methods of polymerization. Generally, the radiation polymerized material gave higher strengths than the thermally polymerized material.

In the case of methyl methacrylate plus 10% TMPTMA the strengths were only 12% higher for radiation treatment. This difference increased to 38% for styrene. Other structural properties such as tensile strength and modulus of elasticity showed similar trends. A higher bond strength between the

polymer and the concrete in the case of radiation treatment may account for this result.

Table V shows the differences in the freeze-thaw durability of concrete-polymer specimens receiving radiation and thermal treatment. The data indicate that the thermally treated specimens have either the same or slightly better durability than the radiation treated material. The generally higher durability, however, may be related to the higher polymer loading present in the thermal samples for this series of tests.

Reinforced Concrete

Because of the low tensile strength of concrete, steel reinforcing bars are usually incorporated in structures when concrete is stressed in tension. Although the tensile strength of concrete-polymer is higher by a factor of 4 than that of concrete, it is still relatively low compared to that of steel. Standard tests on reinforcing bars in which a 1-in.-diam steel rod is pulled out of a 6 in. diam concrete cylinder indicated that the force needed to pull the bar from a concrete-polymer cylinder was 700 psi or almost 3 times the force required for a cylinder of

ordinary concrete (238 psi). This greatly improved bond strength between concrete-polymer and steel is of significance in concrete structural design.

Steel fiber has been used to reinforce concrete. When 10 mil square bar fiber 2 in. long is incorporated into concrete to the extent of 2% by volume the modulus of rupture (flexural strength) increases by a factor of 2 (from 580 psi to 1135 psi). When impregnated with polymer the fiber reinforced concrete-polymer increases the modulus of rupture by another factor of 2.5 (from 1135 to 2852 psi). Thus an overall increase by a factor of 5 in the flexural strength is achieved for a polymer-impregnated fiber-reinforced concrete as compared with standard concrete.

LIGHT WEIGHT CONCRETE-POLYMER

Low density aggregate such as slag, shale, and pumice is used in concrete to reduce its weight. For structural purpose, the density of light weight concrete is usually about 90 to 110 lbs/ft³ and the compressive strength is in the order of 2000 to 3000 psi. However, very light weight aggregate, such as foamed glass, vermiculite (expanded mica);

mearlcrete (foamed cement) and perlite (expanded volcanic ash) is used for producing extra light weight concrete which has low structural strength and is used mainly for insulation purposes. The density of these extra light weight concretes is usually less than 60 lb/ft^3 and can be as low as 20 lbs/ft^3 . The compressive strengths are usually less than 300 psi. Several types of light weight concrete were impregnated with polymer and tested for compressive strength. The results are shown in Table VI. Because of the high porosity of these concretes the polymer loading was greater than 100% so that the density of the concrete more than doubled. The compressive strength increased by more than nine times. In the case of perlite concrete the compressive strength increased from 125 psi to as high as 4200 psi. Polymer impregnated insulating type concretes may now have some potential for structural applications. Much additional work is required in developing light weight concrete-polymer especially in investigating the possibility of lowering the polymer loading.

MONOMER ADDITION TO PREMIX CONCRETE

Attempts have been made to add monomers to the concrete mix prior to curing. Radiation was used to polymerize the mass after 1 day of curing. In many of the tests the concrete did not harden, and for those specimens that did harden the compressive strength was no higher than that of the control without monomer.

In one notable case, in which 8% acrylonitrile was added to a standard concrete mix and radiation polymerized, an 87% increase in strength was obtained. Numerous attempts to add various organic constituents to premixed concrete have been made in the past. In most cases the strengths were increased by a relatively small factor, the increase usually being much less than 50%, and improvements in durability were also very limited. These results are not unexpected, since organic monomers could interfere with the hydration process of cement. Furthermore, concrete shrinks on setting and a void volume is formed in the concrete mass. The unique feature of impregnating precast concrete is that a large part of the void volume in the capillaries and pores is filled with polymer and forms a continuous internal reinforcing structure which appears to be the basis for the remarkable improvements in strength and durability.

VALUE OF CONCRETE-POLYMERS AND POTENTIAL APPLICATIONS

A comparison of the properties of concrete-polymer with those of other more common materials used in construction is shown in Table VII. The tensile strength for concrete-polymer lies between that of the concrete and the polymer alone, while the compressive strength and modulus of elasticity are greater than those of either of these materials. Based on preliminary estimates,

the cost of prefabricated concrete polymer sewer pipe produced by radiation treatment (6¢/lb) is roughly double the cost of ordinary concrete pipe (3¢/lb). For a 6% methyl methacrylate loading at 20¢/lb of monomer, the cost of monomer is 1.2¢/lb of finished concrete-polymer or about 40% of the cost of manufacturing the impregnated pipe. The structural properties are related to volume of the material; thus, if the compressive strength for concrete-polymer increases by a factor of 4 over that for ordinary concrete and the cost increases by a factor of only 2, then the cost to volume strength ratio decreases by a factor of 2. The cost to volume strength index is shown in the last column of Table VII. In terms of compressive strength the economic value of concrete-polymer is superior to that of all the other materials with the exception of glass which is not considered a reliable material of construction. Concrete and concrete-polymer are much better than the other materials in terms of modulus of elasticity. However, for tensile strength, steel is the leader, and it is for this reason that concrete is reinforced with steel. The general conclusion is that the use of concrete-polymer for structural purposes appears economically reasonable.

Several possible applications of concrete-polymer material includes sewer and pressure pipe, building material for housing, underwater structures, railroad ties, and chemically resistant material of construction for large desalination plants. The incorporation of colored dyes with the monomer allows concrete-polymer material to be considered for a variety of aesthetic applications, such as in decorative wall and floor tile.

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Table I

Techniques for Monomer Impregnation of Concrete

Sample No. ^a	Evacuation time, hr ^b	Soak time in monomer, ^c hr	Nitrogen pressure, psig	Polymer loading, % weight
1 ^d	0	3	0	1.89
2	0	3	0	4.61
3	0	1	5	3.62
4	0	3	5	4.62
5	0	5	5	4.81
6	2	1	0	4.54
7	2	3	0	5.44
8	2	5	0	6.32
9	2	1	5	6.64
10	2	2	5	6.15
11	2	3	5	6.43
12	1	1	5	6.51

^aAll samples are 3-in.-diam x 6-in.-long cylinders.

^bVacuum pump to $\approx$ 1 in. Hg.

^cMethyl methacrylate monomer.

^dAll samples except No.1 were dried to equilibrium prior to soaking.

TABLE II

Radiation Requirements for Concrete-PolymerCo⁶⁰ Gamma Radiation

Monomer (a)	Radiation intensity rads/hr	Radiation dose rads
Methyl methacrylate	1.6×10^5	1.2×10^6
	3.4×10^5	1.8×10^6
Methyl methacrylate + 10% TMPTMA	2.5×10^5	1.0×10^6
Acrylonitrile	1.9×10^5	1.3×10^6
Styrene	2.6×10^5	2.5×10^7
60% styrene + 40% TMPTMA	5.0×10^5	1.0×10^6
Chlorostyrene	2.5×10^5	6.0×10^6

a) Monomers contain inhibitor.

TABLE III

Concrete-Polymer Materials - Summary of Properties of Methyl-Methacrylate Impregnated Concrete
(Dried concrete specimens containing 4.6 to 6.7 wt % PMMA.)

	Control	Irradiation	Difference, % ^b	Thermal- catalytic	Difference, % ^c	Difference, % ^d
Compressive strength, psi	5267	20,255	285	18,161	244	-10
Modulus of elasticity, 10 ⁶ psi	3.5	6.3	80	6.2	77	-2
Tensile strength, psi	416	1,627	292	1,508	262	-7
Modulus of rupture, psi	739	2,637	256	2,287	210	-13
Flexural modulus of elasticity, 10 ⁶ psi	4.3	6.2	44	7.1	65	15
Water absorption, %	5.3 ^a	0.29 ^a	-95	3.58 ^a	-33	1130
	6.4	1.08	-83	0.34	-95	-69
Abrasion, in.	0.0497	0.0163	-67	0.0147	-70	-10
g	14	4	-71	4	-71	0
Cavitation, in.	0.32	0.064	-80	0.020	-94	-69
Water permeability, 10 ⁻⁴ ft/yr	6.2 ^a	0 ^a	-100	—	—	—
	5.3	0.8	-85	1.4	-73	75
Thermal conductivity at 73°F (23°C), Btu/ft-hr-°F	1.332	1.306	-2	1.265	-5	-3
Diffusivity at 73°F (23°C), ft ² /hr	0.0387	0.0409	6	0.0385	0	-6
Coefficient of expansion, in./in.-°F	4.02 × 10 ⁻⁶	5.36 × 10 ⁻⁶	33	5.25 × 10 ⁻⁶	31	-2
Creep for 800 psi load after 30 days, 10 ⁻⁶ in./in.	-95	+38	neg. creep	+56	neg. creep	—
Freeze-thaw durability, cycles, % wt loss	590; 26.5 ^a	2,420; 0.5 ^a	>310	—	—	—
	490; 25.0	750; 4.0	>53	750; 0.5	>53	-88
Hardness-impact ("L" hammer)	32.0	55.3	73	52.0	62	-6
Corrosion by sulfate solution, 300-day exposure, % expansion	0.144 ^a	0 ^a	-100	—	—	—
Acid corrosion in 15% HCl, 84-day exposure, % wt loss	10.4	3.64	-65	3.49	-66	-4
Corrosion by distilled H ₂ O, 120-day exposure at 206°F (97°C)	Severe attack	No attack	-100	—	—	—

^aFrom survey PLIC series; all other data from CP-1 test series. Results based on averages of 1 to 3 test measurements for each property.

$$^b\text{Difference, \%} = \frac{\text{radiation} - \text{control}}{\text{control}} (100).$$

$$^c\text{Difference, \%} = \frac{\text{thermal} - \text{control}}{\text{control}} (100).$$

$$^d\text{Difference, \%} = \frac{\text{thermal} - \text{radiation}}{\text{radiation}} (100).$$

Table IV
COMPRESSIVE STRENGTHS FOR RADIATION AND THERMALLY
POLYMERIZED CONCRETE-POLYMER

<u>Monomer in concrete</u>	<u>Initiation</u>	<u>Av. polymer content,^(a) %</u>	<u>Av. compressive strength,^(a) psi</u>	<u>Concrete-polymer vs control,^(b) %</u>	<u>Thermal vs radiation,^(c) %</u>
Control	none	0	5,270	--	--
Methyl methacrylate + 10% TMPTMA (CP-4)	R	6.3	21,593	310	--
	T	7.3	19,000	260	-12
Methyl methacrylate (CP-1)	R	6.3	19,800	276	--
	T	5.8	16,596	215	-16
Chlorostyrene (CP-6)	R	6.1	16,087	205	--
	T	6.2	14,387	173	-10
Acrylonitrile (CP-5)	R	5.4	14,410	173	--
	T	5.5	10,753	104	-25
Styrene (CP-2)	R	5.0	14,135	168	--
	T	4.7	8,788	67	-38

(a) Average of three specimens.

(b) % Difference = $\frac{\text{test-control}}{\text{control}} = (100)$

R = radiation polymerized.

T = thermally polymerized.

(c) % Difference = $\frac{\text{thermal-radiation}}{\text{radiation}} = (100)$

Table V

**FREEZE-THAW DURABILITY FOR RADIATION AND THERMALLY
POLYMERIZED CONCRETE-POLYMER**

<u>Monomer in concrete</u>	<u>Initiation</u>	<u>Av. polymer^(a) content, %</u>	<u>No. of^(a) freeze thaw cycles</u>	<u>Wt.loss,^(a) % (d)</u>	<u>Concrete-polymer vs control^(b) difference, %</u>	<u>Thermal vs radiation^(c) difference, %</u>
Control	none	0	740	25	--	--
Methyl methacrylate (CP-1)	R	5.9	3,450	6.7	>366	--
	T	6.8	3,450	1.5	>366	-78
Methyl methacrylate +10% TMPTMA (CP-4)	R	6.2	2,560	11.5	>246	--
	T	7.2	2,560	0.2	>246	-98
Styrene (CP-2)	R	4.9	2,635	25	256	--
	T	4.4	3,340	10.5	>352	-67
Acrylonitrile (CP-5)	R	5.1	1,690	25	128	--
	T	5.5	2,020	2.2	>173	-93

(a) Average of two specimens.

$$(b) \% \text{ Difference} = \frac{\text{Test cycles-control}}{\text{control}} (100)$$

R = Radiation polymerized.

T = Thermally polymerized.

$$(c) \% \text{ Difference} = \frac{\text{Wt loss thermal/cycle-weight loss rad/cycle}}{\text{Wt loss radiation/cycle}} (100)$$

(d) Weight loss of less than 25% is considered durable concrete.

Table VI

LIGHT WEIGHT CONCRETE-POLYMER

<u>Concrete aggregate type</u>	<u>Initial density, lb/ft³</u>	<u>% PMMA (a) wt loading</u>	<u>Final density, lb/ft³</u>	<u>Compressive strength, psi</u>	<u>% Increase (d)</u>
Foamed glass	31	130	65	3570	1150
control	31	0	31	286	--
Mearlcrete (b)	38	108	65	1000	833
control	38	0	38	107	--
Perlite (c)	23	170	49	4200	3260
control	23	0	23	125	--

a) Polymethyl methacrylate loading based on dried unimpregnated weight

b) Foamed cement

c) Expanded volcanic ash

d) $\% \text{ Increase} = \frac{\text{Test-control}}{\text{control}} (100)$

Table VII

Comparison of Basic Construction Materials With Concrete-Polymer Material

Material	Strength property (S), psi	Density (W), lb/ft ³	Strength to weight ratio (S/W), psi-ft ³ /lb	Unit cost of material in finished product (C), ¢/lb	Cost to volume strength ratio (C/S/W), ¢/psi-ft ³
<u>Tensile Strength, psi</u>					
Concrete	400	156	2.6	3	1.2
Concrete-polymer (6% PMMA)	1,600	165	9.7	6	0.6
Polymer (PMMA)	7,000	62	112	125	1.1
Steel	70,000	490	143	15	0.1
Aluminum	30,000	165	182	60	0.3
Glass	7,000	137	51	55	1.1
<u>Compressive Strength</u>					
Concrete	5,000	156	32	3	0.09
Concrete-polymer (6% PMMA)	20,000	165	121	6	0.05
Polymer (PMMA)	15,000	62	241	125	0.5
Steel	42,000	490	86	15	0.2
Aluminum	25,000	165	152	60	0.4
Glass	300,000	137	2200	55	0.03
<u>Modulus of Elasticity, E, psi</u>					
			E/W		
Concrete	3.5×10^6	156	1.9×10^4	3	1.6×10^{-4}
Concrete-polymer (6% PMMA)	6.3×10^6	165	3.8×10^4	6	1.6×10^{-4}
Polymer	0.4×10^6	62	0.6×10^4	125	200×10^{-4}
Steel	30×10^6	490	6.1×10^4	15	4.0×10^{-4}
Aluminum	10×10^6	165	6.1×10^4	60	10×10^{-4}

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Glass	10×10^6	137	7.3×10^4	55	7.5×10^{-4}

Figure 1

CONCRETE - POLYMER
497 DAYS

CONTROL
105 DAYS

RESISTANCE TO 15% HCL

Resistance to chemical attack by 15% HCl. Control specimen (right) lost 26% by weight in 105 days.

Concrete-Polymer (left) - containing 6.4% weight loading polymethyl methacrylate lost 7.6% by weight in 497 days.

FIG. 2

CONCRETE-POLYMER MATERIAL
COMPRESSIVE STRENGTH vs POLYMER LOADING

FIGURE 3

CONCRETE - POLYMER MATERIALS
COMPRESSIVE STRENGTH vs TEMPERATURE
OSW - TYPE CONCRETE