

An Investigation of the Properties of Polymer Concrete

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Synopsis:

An investigation of various formulations of polymer and aggregate composites was undertaken in order to determine possible applications of these new materials in building construction. A number of polyester-styrene-methyl methacrylate resin systems were mixed with combinations of sand, gypsum, gravel, clay and chopped glass fibers, cast and cured, and the resulting materials were then tested. No portland cement was used. Maximum compressive strength obtained was 21,100 psi (145.6N/mm²) and maximum splitting tensile strength was 2,210 psi (15.2N/mm²); unit weights ranged from 122 to 145 pcf (1,970 - 2,350kg/m³) and modulus of elasticity ranged from 1,460,000 to 3,300,000 psi (10.1 to 22.8kN/mm²). Rapid curing at ambient temperatures was possible. The addition of a chlorendic anhydride improved polymerization at both ambient and elevated temperatures.

Detailed formulations are presented for the most promising systems investigated. These polymer composites cost more than portland cement concretes for equal volumes of material but compare well on a strength-to-cost basis. Specific applications of these new materials will require additional development and testing. However, in many instances, they offer an attractive alternative to conventional concretes with regard to physical properties and architectural aesthetics.

Keywords: aggregates; compressive strength; concretes; curing; fiber reinforced concretes; mix proportioning; modulus of elasticity; polyester resins; polymer concrete; stress-strain relationships; tensile strength.

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I. INTRODUCTION

This work investigates the formulation of various composite materials, consisting of a polymeric matrix with mineral fillers, for application as building materials. Our approach seeks to utilize the higher tensile strength and lower density of polyester and acrylic polymers (as compared to portland cement) and the variety of colors and textures that can be obtained by combining these resins with different mineral fillers, to create new materials for certain structural and architectural applications.

Specifically we sought to optimize the formulation of resin-aggregate systems, capable of curing at ambient temperatures under field conditions, to give materials with high strengths in flexure and compression. Specialty formulations, which achieve certain colors and textures of architectural interest, were also explored. Specimens from the most promising formulations were tested in compression and flexure and compared with respect to physical properties and cost with ordinary concrete.

II. PREVIOUS WORK

The development of polymer-aggregate concretes is relatively recent but is continuously increasing in scope and intensity. One of the main difficulties concerns the adaptation of polymer formulation and curing techniques, developed for controlled temperature and humidity to field applications, where these conditions vary widely. The following paragraphs provide a summary of the investigations to date.

Dennard (1) studied the complete replacement of portland cement in

concrete with a polyester resin. Optimum formulations contained 12% by weight resin and were oven cured at 350° F. They showed flexural strengths of approximately 800 psi and a compressive strength of nearly 16,000 psi. Jejcic (3) compared various epoxy and polyester resins. Epoxy was found superior to polyester chiefly for its moisture tolerance, but its cost was about six times higher. The problem of grading of the aggregate was also recognized in obtaining optimum mechanical properties from the material and minimizing the quantity of resin.

L'Hermite and Jejcic (5) listed the special properties of resin concretes and described their appearance as quite similar to ordinary concrete. Gebauer and Coughlin (2) compared polymer cement and polymer mortar composites based on styrene and methyl methacrylate. Radiation techniques were used to create a prepolymer cement paste and mortar which was cast and polymerized with either thermal-catalytic or gamma radiation means. Methyl methacrylate samples using pure cement powder showed the greatest compressive strengths and the lowest water absorption. Smith and Waling (7) evaluated several resin binders for use with lightweight aggregates.

Kukacka and DePuy (4) reported significant improvements in polymer concretes with the use of various acrylic resins. Strengths up to 17,000 psi at polymer loadings of up to 15% were obtained with conventional aggregates. With Type II portland cement and Number 30-mesh Ottawa sand, specimens with a compressive strength of 23,500 psi were obtained. Ohama (6) reports the first systematic study of resin-mineral proportions of polyester resin concrete. Compressive strength was found to be considerably higher in samples cured at elevated temperatures. The water content of the aggregate was also shown to affect the strength.

Previous work in the Author's laboratories revealed several novel aspects of polymer-aggregate concretes. These were:

1. Methyl methacrylate polymers or copolymers that may be cured at ambient temperatures without irradiation.
2. The compounding of polymer and aggregate materials to achieve aesthetically desirable structures.
3. The casting of highly crystalline mineral aggregate with a clear polymer binder in thin sections to achieve a translucent material for controlling light.

III. EXPERIMENTAL

A. Materials

The following is a comprehensive list of components, from which we selected the various formulations for the composite systems, investigated in this work.

1. Resin System
 - (a) unsaturated polyester resins (Diamond Shamrock Co., Dow Chemical Co.*)
 - (b) styrene (Dow Chemical Co.*)

- (c) methyl methacrylate (Rohm and Haas Co.*)
 - (d) crosslinking agents: Divinylbenzene; Trimethylol Propane
Trimethacrylate
 - (e) fire retardant (also crosslinking agent): Chlorendic
Anhydride
 - (f) silane coupling agent (for aggregate binding):
γ-Methacryloxypropyltrimethoxysilane
 - (g) catalysts: Methyl Ethyl Ketone Peroxide, Azobisisobutyroni-
trile
 - (h) accelerators: N-N-Dimethylaniline; Cobalt Napthenate
2. Aggregates
- (a) natural aggregates (sand and gravel) normally used in or-
dinary concrete
 - (b) sea sand
 - (c) gypsum
 - (d) various clays
 - (e) Ottawa sand
 - (f) chopped glass fibers

B. Procedure

The components of the resin system were premixed in the proper proportions, in the order listed above, just prior to mixing with the prepared aggregates.

The aggregates were air-dried with the exception of the gypsum powder which was heated in a 2-inch layer at 75° for two hours then cooled and stored in a sealed container at room temperature. The glass strands were chopped by hand to approximately 3/8 inch with standard scissors.

Two methods were adopted for mixing the aggregate with the resin. The principal method was to first thoroughly wet the sand, gravel and chopped glass fiber, then manually mix in the gypsum and clay powders. The ratio of resin to the aggregate components was determined by the amount of resin necessary to produce a stiff, workable paste. This paste was cast by placing it into a suitable mold with rodding at appropriate intervals. Several sharp taps were also administered on the mold surface while filling the mold.

The second method was used exclusively when sand fines were the sole aggregate component. The sand was poured directly into the mold and rodded at intervals to compaction. The resin system was then introduced at the base of the mold and allowed to diffuse up through the

*Polymeric materials need to be identified by manufacturer because of variations in formulation

sand under atmospheric pressure until it was saturated.

Samples produced with the second method were placed in an oven and heated to 75° C for twelve hours, then removed from the oven and cooled to room temperature. This was done to speed up the polymerization process without using accelerators with the catalysts which could prematurely polymerize the binder before the aggregate was completely saturated.

Samples produced with the first method were cured at room temperature, 20° C, for twenty-four hours using a combination of catalysts and accelerators.

C. Testing Procedures

All material tests followed standardized ASTM procedures where possible. Any variance from accepted ASTM procedure was undertaken to facilitate screening rather than full scale verification. A listing of material test procedures follows:

1. Flexural Strength; Modulus of Elasticity
 - (a) ASTM* C293-68, using a cylindrical beam
 - (b) Specimen size: 2 in. diameter x 8 in. cylinder
 - (c) Instrumentation: Instron Universal Testing Machine, synchronized chart; load vs. time, deflection vs. time.
2. Compressive Strength
 - (a) ASTM C116-68
 - (b) Specimen size: 2 in. diameter x 4 in. cylinder
3. Splitting Tensile Strength
 - (a) ASTM C496-71
 - (b) Specimen size: 2 in. diameter x 4 in. cylinder

IV. RESULTS AND DISCUSSION

Initially methyl methacrylate alone was used for the resin matrix. It suffered in these ways: the monomer volatility was too high, producing noxious vapors in the mixing phase and excessive evaporation before complete polymerization; also polymerization at ambient temperatures could only be achieved by gamma radiation, considered to be impractical for field application.

Polyester and styrene were then studied as an alternative resin system. They had better handling characteristics and polymerization could be achieved at ambient temperatures with chemical catalysts. However, the composites did not have the high quality finish, strength or weathering characteristics of the composites with methyl methacrylate.

*1973 Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia.

In an effort to optimize the polymerization characteristics and physical properties of our resin, we developed various combinations of polyester-styrene and methyl methacrylate. These are described in Table I, together with the aggregates used in the composite systems.

A. Optimization of Resin Formulations

Using the four resin formulations described in Table I, a number of chemical additives were introduced to accelerate the polymerization process and improve the composite strength. A set of forty samples was prepared with either a fine or coarse sand mixture. The amount of polymer required to produce a workable, mud-like mix was noted, and the mix was cast in glass tubes 0.655 in. in diameter x 6 in. long. They were then cured at either room temperature or in an oven. Following the cure, the forms were removed and the surface quality of the specimens was noted. They were then tested in flexure. Typical results are shown in Table II.

Because of the relatively high viscosity of the unsaturated polyester resin, formulations that were high in this component required greater proportions of resin to aggregate in order to achieve a workable paste. However, only the resin formulations high in polyester (over 40%) were capable of curing at room temperature. The formulations with 20% polyester failed to get an initial set at room temperature and were subsequently placed in an oven to cure (Table II).

Increased use of styrene in the resin mix was found to have a tendency to decrease the flexural modulus and strength of the composite. Thus composites made with Resin Mix C, which contains 25% styrene, develop flexural moduli of 2,250,000 psi (15.5 kN/mm²) and flexural strengths of 5,750 psi (39.7 N/mm²) versus 2,070,000 (14.3 kN/mm²) and 5,250 psi (36.2 N/mm²) respectively for systems with Resin Mix D, which has 60% styrene.

The amount of methyl methacrylate in the Resin Mix was found to contribute most directly to the appearance of the composite. Increases in methyl methacrylate content gave composites with glossier surfaces and reduced darkening of the aggregate.

A chlorendic anhydride was added to the resin mix to promote polymerization and enhance fire resistance of the system. The anhydride did improve the polymerization rate at room temperature. It was also useful in achieving a flaw-free composite, with a tack-free finish on exposed surfaces.

The resin-to-catalyst ratio was important in determining both the rate and extent of the polymerization. Either too much or too little catalyst resulted in flawed materials. Generally, the specimen's shape, size and percentage of resin as well as the cure temperature controlled the catalyst requirements. Less catalyst was required with high resin loadings due to increased polymerization exotherms per unit volume. Less catalyst was also required with larger or more compact sections because of lower heat dissipation rates, due to the lower surface-to-volume ratios of the specimen.

The use of additional accelerators significantly increased the rate of polymerization, making rapid cures at room temperature possible even with small samples. The higher cure rates also reduced evaporation of the resin from the specimen. However, excess accelerator often introduced flaws in the polymeric matrix and surface finish, such as unpolymerized areas and discoloration in the specimen.

As expected, specimens cured in the oven at 75° C developed higher flexural strengths (by 10 to 15%) than those cured at ambient temperature (20° C). However the most dramatic effects of the oven cure were observed in the flexural moduli, which were 35 to 50% higher than those of the same formulations, cured at 20° C.

Resin Mix C was selected as the optimum polymer formulation, and was used as the resin basis for the composite systems, listed in Table III. The addition of an azo catalyst and reduction in the quantity of accelerator in the optimum formulation improved the rate and extent of the polymerization at room temperature. The addition of larger quantities of crosslinking agents and a silane coupling agent improved the physical properties of the polymer matrix, resulting in stronger and stiffer composites. Test results for these materials are shown in Table IV.

B. Aggregate Systems

In the initial testing of the resin binders, two aggregate mixtures were studied. The first combination consisted of the resin mix with conventional concrete sand and gypsum filler. The second combination consisted of the resin binder with sea sand and gypsum filler. The difference between the two aggregate systems was, principally, particle size. The concrete sand was smoothly graded with a maximum particle size of 0.150 inches. The sea sand was smoothly graded with a maximum size of 0.0150 inches.

In these initial tests, specimens with sea sand showed an average polymer content 16% greater than specimens with concrete sand. The specimens showed significant differences in their flexural strengths and moduli of elasticity. Those with sea sand were almost 12% stronger than those with concrete sand. The reverse was true with respect to their moduli of elasticity. Specimens with concrete sand were almost 10% stiffer than specimens with sea sand.

Using the polymer binder shown in Table III, a subsequent test series was conducted. These systems were formulated and tested in order to investigate a wider range of aggregate sizes, to incorporate some new materials, and to clarify the contributions of gypsum to the properties of the composite. A number of aggregate gradings were selected with a range of particle sizes from sand fines to gravels. Chopped glass and Ottawa sand were also studied in separate tests. Clay was added to some formulations. The materials were either premixed or the resin was introduced after placement as described in the Experimental section. Specimen sizes were increased to allow for the coarse materials. With the exception of the specimens that had the resin introduced after placement in the mold, all specimens were cured

at room temperature. A discussion of the results follows.

The influence of particle size on resin loadings was clearly demonstrated in these experiments. The specimen with sand fines and gypsum required twice as much resin to achieve a workable mix as a similar specimen with 50% gravel (Table IV, System II and System V).

Gypsum was used to produce plasticity in the aggregate-resin mix. Handling qualities were similar to conventional concrete when gypsum was added. The gypsum gave a smooth molded finish in the cast materials, and was a desirable medium for enhancing the aggregate colors. The resin absorbency of the gypsum was significantly reduced by heating it in an oven as described.

A sand-and-resin specimen was studied in comparison to a sand-resin gypsum specimen. A special procedure of diffusing the resin through the packed sand (see Experimental section) was adopted to achieve an even distribution of polymer in the specimens without gypsum. This procedure eliminated voids in the material normally incurred with batch techniques. The specimen without gypsum showed an increase in compressive strength of slightly more than 10%, and a decrease in stiffness of more than 50%. The specimen also showed a 20% increase in amount of polymer required over the comparable specimen with gypsum (Table IV, Systems I and II).

Ottawa sand as filler produced a particularly unique material. The highly crystalline Ottawa sand was remarkably translucent when combined with the clear polymer binder. Cast in sections from 1/16 to 1/4 inch thick a number of panels were produced with different degrees of translucence. The fine spherical sand diffused light uniformly, and cast a slightly golden hue because of its faint straw color.

Fiber glass strand was cut into 3/8 in. lengths in an investigation of fiber reinforcement, and added to the material during the mixing phase. The chopped fiber was added in what was considered to be the maximum limit for a good, workable mix. The fiberglass increased the polymer requirements of the material by more than 50% of comparable materials without fiber. The stress-strain curve of this material was unique; it was not perfectly brittle, having some elastic deformation (fiber failure) before rupture (Fig. 1). The compressive strength was lower, by 33% (Table IV, System II and System VI).

Red and grey clay powders were tried in a few material formulations. They were very effective in imparting a natural earth color to the polymer-aggregate materials. Adding 5% clay (by aggregate weight) during the mixing produced materials with an especially attractive appearance.

V. ECONOMICS

The polymer binder represents a considerable increase in material costs when compared with conventional portland cement binder. However, an "inplace" cost analysis of several polymer concrete formulations, summarized in Table V, indicates that in certain cases they might well

be competitive with conventional concrete in terms of the total cost of field-constructed structures.

For lack of better information, this analysis assumes similar placing and forming costs for the polymeric and conventional concrete, based on average figures for cast-in-place column, beam and slab costs for a reinforced concrete building. In Table V one column of data shows the cost of that amount of polymer concrete equivalent to one cubic yard of portland cement concrete, assuming the volume is reduced in proportion to the increase in compressive strength. This assumption is valid if the size of the structural member is based on compressive strength. If the size of the member is based on the concrete strength in tension, the volume reduction would be even greater. If the size of the member is based on stability considerations or on strength of reinforcement, then of course the volume reduction would be less. We arrive thus at estimated total costs for equivalent structures, using the various polymer formulations under development, which compare favorably with the corresponding cost of portland cement concrete.

Table V also shows the equivalent structure weight of the various concrete systems. The weight of the polymer concrete structures ranged from only 24 to 46% of that of the portland cement structure. Consequently, in design, the cost of the polymer concrete structure could be reduced even further to reflect reduction in the structure's dead load with a corresponding reduction of frame and foundation requirements.

This rough estimate does not take into account other advantages of polymer concrete, such as its faster curing time (1 day versus 28 days) for faster construction and recycling of formwork, or its various aesthetic aspects, which may eliminate finishing or decorative operations necessary with conventional concrete.

VII CONCLUSIONS

On the basis of this investigation, a number of conclusions appear valid:

1. Maximum individual values of strength obtained were as follows:

Compressive strength	21,100 psi	(145.6 N/mm ²)
Flexural tensile strength	6,000 psi	(41.4 N/mm ²)
Splitting tensile strength	2,210 psi	(15.2 N/mm ²)
2. Modulus of elasticity ranged from 1,460,000 psi (10.1 kN/mm²) to 3,300,000 psi (22.8 kN/mm²).
3. Unit weights ranged from 122 to 145 pcf (1,970-2,350 kg/m³).
4. Rapid curing at ambient temperatures was possible. The addition of a chlorendic anhydride improved polymerization at both ambient and elevated temperatures.
5. The addition of methyl methacrylate monomer to a polyester-styrene resin improved the resin for use in polymer aggregate systems by imparting a hard clear mirror finish to the cast

materials. It reduced the viscosity of the polyester-styrene resin for a workable mix with less resin without reducing the strength. It also formed a co-polymer with enhanced weathering characteristics.

6. The selected proportions of polyester-styrene-methyl methacrylate gave resin systems, suitable for making casting pastes with low resin requirements or diffusing through compacted sands under atmospheric pressure. These systems cure quickly, with negligible monomer evaporation.
7. The aggregate particle size and distribution affected the strength and resin requirements of the composite system. Fine sands produced a more workable mix which may be cast in relatively thin sections and sawn and sanded with hand power tools. The addition of coarser sands and gravels produced the most economical mix but with a corresponding reduction in strength and homogeneity.
8. A pre-heated gypsum powder was instrumental in obtaining an economical, workable mix for casting with equipment and procedures similar to those of conventional concrete construction.
9. The polymer concretes investigated cost more than conventional concretes for equal volumes of material but compare well with conventional concretes on a cost-to-strength basis.

Specific applications of these new materials will require additional testing, but there would appear to be a wide range of potential applications for these materials.

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TABLE I
Resin Formulations and Aggregate Systems Tested
 (All quantities are parts by weight)

<u>Resin Mix A</u>		<u>Resin Mix B</u>	
Polyester	40	Polyester	20
Styrene	40	Styrene	30
Methyl methacrylate	20	Methyl methacrylate	50
Hexachloro-1,3-butadiene	2	Hexachloro-1,3-butadiene	2
Divinyl benzene	.6	Divinyl benzene	.6
Methyl ethyl ketone peroxide	1.6	Methyl ethyl ketone peroxide	1.5
2,2'-azobisisobutyronitrile	.04	2,2'-azobisisobutyronitrile	.1
 <u>Resin Mix C</u>		 <u>Resin Mix D</u>	
Polyester	45	Polyester	20
Styrene	25	Styrene	60
Methyl methacrylate	30	Methyl methacrylate	20
Methyl ethyl ketone peroxide	1.4	Hexachloro-1,3-butadiene	5
2,2'-azobisisobutyronitrile	.06	Divinyl benzene	1.5
		Methyl ethyl ketone peroxide	2.4
		2,2'-azobisisobutyronitrile	.04
 <u>System 1</u>		 <u>System 2</u>	
Resin Mix	15-20	Resin Mix	20-25
Concrete sand	67	Sea sand	67
Molding plaster	33	Molding plaster	33

TABLE II
Initial Testing of Polyester Resin Systems
Selected Results

Sample	%Resin in System	%HET in Resin	%Accelerator in Resin		System	Remarks	Flexural Strength		Modulus of Elasticity	
			DMA	C.N.			psi	N/mm ²	psi x 10 ⁶	kN/mm ²
1	A,20	5	---	---	1	evaporation	4,960	34.2	2.39	16.5
2	A,25	5	---	---	2	evaporation	6,020	41.5	2.05	14.1
4	A,25	10	---	---	2	evaporation	5,630	38.8	1.61	11.1
*6	A,22	20	---	---	2	OK	5,330	36.8	1.21	8.3
7	A,20	10	.25	.25	1	evaporation	4,260	29.3	2.51	17.3
8	A,22	10	.25	.25	2	evaporation	5,750	39.7	2.14	14.8
10	A,25	10	.25	.25	2	OK	7,400	51.1	2.13	14.7
11	B,18	5	---	---	1	evaporation	5,710	39.4	2.52	17.4
14	B,22	10	---	---	2	OK	5,070	35.0	1.74	12.0
16	B,20	20	---	---	2	evaporation	5,980	41.3	2.20	15.2
17	B,18	10	.25	.25	1	evaporation	5,230	36.1	2.12	14.6
18	B,22	10	.25	.25	2	evaporation	5,400	37.3	1.97	13.6
22	C,25	5	---	---	2	evaporation	5,670	39.1	2.07	14.3
24	C,25	10	---	---	2	OK	6,310	43.5	2.14	14.8
*26	C,24	20	---	---	2	OK	5,450	37.6	1.31	9.0
*28	C,23	10	.25	.25	2	glossy	4,180	28.8	1.58	10.9
*29	C,22	10	.25	.25	1	glossy	3,200	22.1	1.77	12.2

PC Properties

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TABLE II (cont'd)
Initial Testing of Polyester Resin Systems
Selected Results

Sample	%Resin in System	%HET in Resin	%Accelerator in Resin		System	Remarks	Flexural Strength		Modulus of Elasticity	
			DMA	C.N.			psi	N/mm ²	psi x 10 ⁶	kN/mm ²
32	D,22	5	---	---	2	evaporation	6,320	43.6	1.95	13.5
33	D,17	10	---	---	1	evaporation	5,230	36.1	2.13	14.7
36	D,20	20	---	---	2	evaporation	5,520	38.1	1.93	13.3
37	D,18	10	.25	.25	1	x-evapor.	4,990	34.4	1.93	13.3
38	D,20	10	.25	.25	2	x-evapor.	4,920	33.9	1.56	10.8

*All samples were cured for 12 hours at 75°C, except those marked with an asterisk, which were cured for 19 days at 20°C.

TABLE III

Selected Material Formulations and Costs*

	Parts by Weight	Unit Cost per lb., \$	Cost per 100 lbs., \$
<u>Resin Mix</u>			
Polyester	400	0.46	17.0
Styrene	235	.30	7.0
Methyl methacrylate	235	.38	8.0
Chlorendic Anhydride	130	.71	8.6
<u>Additives:</u>			
TMPTMA	25	50.00	0†
HCB	25	2.40	5.0
Silane Coupling Agent	10	2.97	2.8
MEK Peroxide	10	1.97	1.8
ABIBN	2	15.30	3.0
DMA	0-2	2.15	0.4
C.N.	0.2	1.93	~ 0

Cost per 100 lbs. resin mix.....\$53.6

System I

Resin Mix	200	0.536	10.72
Fine Sand	800	0.0016	0.13
Cost per 100 lbs. System I.....			\$10.85
Density = 127 pcf;			
Cost per cu.yd.: \$372.04			

System II

Resin Mix	166	0.536	8.89
Fine Sand	556	0.0016	0.09
Gypsum Plaster	278	0.0239	0.66
Cost per 100 lbs. System II.....			\$ 9.64
Density = 130 pcf;			
Cost per cu.yd.: \$338.36			

System III

Polymer Binder	145	0.536	7.72
Medium Sand	305	0.0016	0.05
Fine Sand	305	0.0016	0.05
Gypsum Plaster	245	0.0239	0.58
Cost per 100 lbs. System III.....			\$ 8.40
Density = 134 pcf;			
Cost per cu.yd.: \$303.91			

*Bulk price, f.o.b. the manufacturer, effective June, 1976

†Calculations omit TMPTMA. If included, price per lb. of polymer is \$1.70

TABLE III (Cont'd)

Selected Material Formulations and Costs

	Parts by Weight	Unit Cost per lb., \$	Cost per 100 lbs., \$
<u>System IV</u>			
Resin Mix	120	0.536	6.43
Coarse Sand	440	0.0016	0.07
Fine Sand	220	0.0016	0.04
Gypsum Plaster	220	0.0239	0.52
Cost per 100 lbs. System IV.....			\$ 7.06
Density = 140 pcf;			
Cost per cu.yd.: \$266.86			

<u>System V</u>			
Resin Mix	83	0.536	4.44
Gravel	610	0.231	0.14
Fine Sand	305	0.0016	0.05
Gypsum Plaster	152	0.0239	0.036
Cost per 100 lbs. System V.....			\$ 4.666
Density = 145 pcf;			
Cost per cu.yd.: \$182.67			

<u>System VI</u>			
Resin Mix	263	0.536	14.10
Fine Sand	465	0.0016	0.07
Gypsum Plaster	233	0.0239	0.55
Chopped Glass Fiber	39	0.63	2.45
Cost per 100 lbs. System VI.....			\$17.17
Density = 122 pcf;			
Cost per cu.yd.: \$565.57			

<u>System VII</u>			
Resin Mix	200	0.536	10.72
Ottawa Sand	800	0.02	1.6
Cost per 100 lbs. System VII.....			\$12.32
Density = 127 pcf;			
Cost per cu.yd.: \$422.45			

TMPTMA:	Trimethylol Propane Trimethacrylate		
HCB:	Hexachloro-1, 3-Butadiene		
Silane Coupling Agent:	3-Methacryloxypropyltrimethoxysilane		
MEK Peroxide:	Methyl Ethyl Ketone Peroxide		
ABIBN:	2,2'-Azobisisobutyronitrile		
DMA:	N,N-Dimethylaniline		
C.N.:	Cobalt Napthenate		
Fine Sand:	0.0027 - 0.0150 in.	Coarse Sand:	0.930 - 0.250 in.
Medium Sand:	0.0469 - 0.0930 in.	Gravel:	0.250 - 0.500 in.

Table IV. Material Properties Constructed from Experimental Data for Several Polymer-Aggregate Systems, and Conventional Concrete

Material Properties	Polymer-Aggregate System ¹						Fairly High Strength Conventional Concrete ²
	I	II	III	IV	V	VI	
Density, Lb./Cu. Ft.	127	134	134	140	145	122	150
Density, kg/m ³	2,050	2,170	2,170	2,260	2,350	1,970	2,430
Compressive Strength, psi	21,100	18,750	18,300	15,060	10,750	12,600	5,000
Compressive Strength, N/mm ²	145.6	129.4	126.3	103.9	74.2	86.9	34.5
Flexural Strength, psi	4,730	5,600	5,100	2,940	2,160	6,000	675
Flexural Strength, N/mm ²	32.6	38.6	35.2	20.3	14.9	41.4	4.7
Splitting Tensile Str., psi	1,932	1,865	2,210	1,653	1,560	2,200	500
Splitting Tensile Str., N/mm ²	13.3	12.9	15.2	11.4	10.8	15.2	3.4
Modulus of Elasticity, ksi	1,460	3,260	3,200	3,300	2,760	1,630	3,400
Modulus of Elasticity, kN/mm ²	10.1	22.5	22.1	22.8	19.0	11.2	23.5
Polymer, %	20	16.7	14.5	12.0	8.3	26.3	-
Max. Size of Aggregate, In.	0.0150	0.0150	0.093	0.250	0.50	0.0150	0.50
Max. Size of Aggregate, mm	0.38	0.38	2.4	6.4	12.7	0.38	12.7

¹See Table III for mix proportions and polymer formulation.

²Properties of Concrete, A.M. Neville, 1963, John Wiley & Sons, N.Y.

PC Properties

TABLE V
Cost and Weight Comparison of
Equivalent Structures of Polymer Composites Versus Portland Cement Concrete¹

Concrete System	Density lb./cu.ft.	Mat'l Cost, \$/cu.yd.	Placing & Forming Cost, \$/cu.yd.	In-Place Cost, \$/cu.yd. ²	Compressive Strength, psi	Cost of Material Equivalent to One cu.yd. of P.C. Concrete.\$ ³	Weight of Material Equivalent to One cu.ft. of P.C. Concrete.lb ⁴
II	130	338	123	461	18,750	123	34.7
III	134	304	123	427	18,300	117	36.6
IV	140	267	123	390	15,060	129	46.5
V	145	182	123	305	10,750	142	67.4
Portland Cement Concrete	145	26	123	149	5,000	149	145

¹All costs effective June, 1976.

²Cost without reinforcing or prestressing steel

³In-Place Cost X $\frac{\text{Compressive Strength of Portland Cement Concrete}}{\text{Compressive Strength of Concrete System}}$

⁴Density X $\frac{\text{Compressive Strength of Portland Cement Concrete}}{\text{Compressive Strength of Concrete System}}$

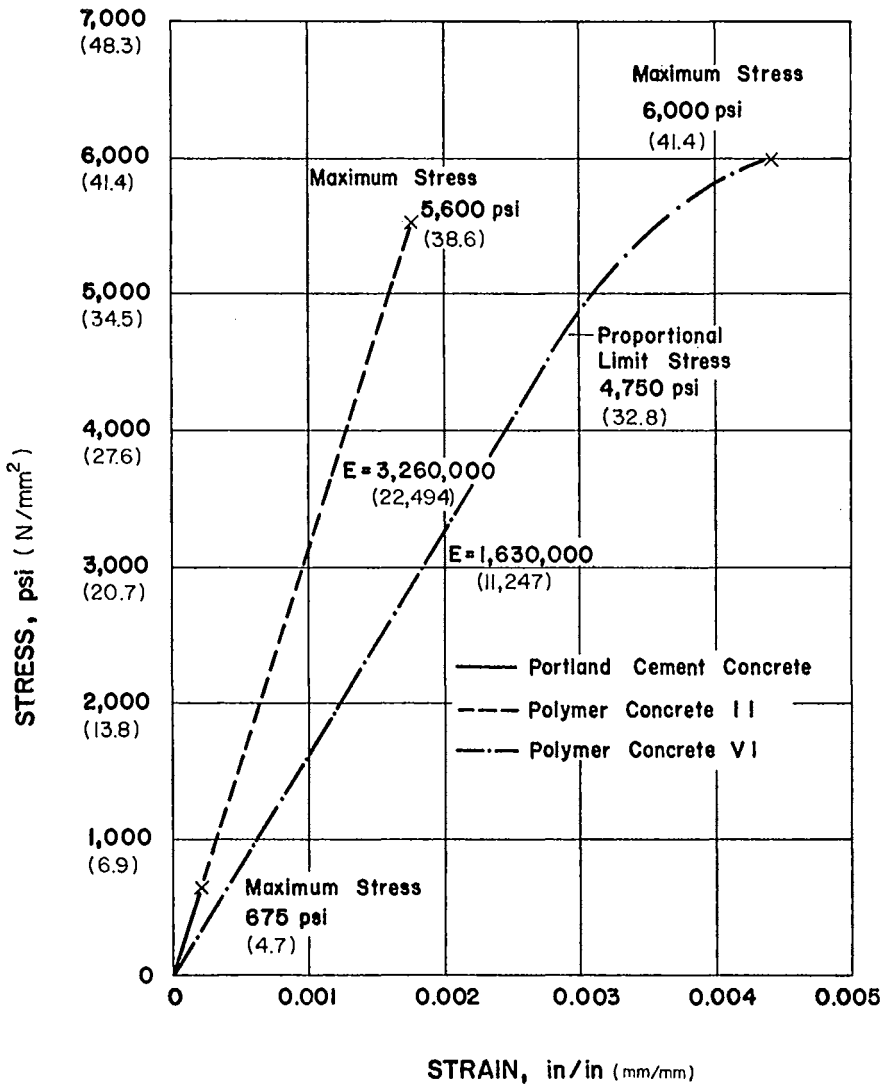


Fig. 1--Stress-strain diagrams for flexure of polymer concretes II and VI and portland cement concrete

Time-Dependent Properties of Concrete Members Bonded by Polymer Mortar

By H. Schorn

Synopsis: This paper presents results of experiments and a theoretical concept of composite systems consisting of Portland cement concrete bonded by polymer mortars. Criteria for time-dependent shear failure are given. The criteria are based on the different deformation behaviour of Portland cement mortar and polymer mortar.

Keywords: bonding; epoxy resins; mortars (material); plastics, polymers and resins; strength; stress-strain relationships.

Dr.-Ing. H. Schorn is chief engineer at the Building Research Institute of the Technical University at Aachen. He is working in the various fields on the application of polymers in concrete.

There are many requirements in civil engineering to assemble individual elements in a force-locking way, to monolithic constructions. First of all, the prestressed bridges made of precast elements are most usual. Besides, there are other applications in the planning, for example, effects of plane load-bearing structures. It seems to be suitable to begin with the classification of the applications according to the effective load cases schematically (fig. 1).

Classification, Definitions

Case 1 shows pure shear stress by an external loading directly on the joint edge resulting across the adhesive joint length in the known nonuniform stress distribution depending on the stiffness of the materials. In this case we are actually speaking of an adhesive joint - in the second case, however, it is better, not to use the criterion of the adhesive tests. Here, a bond system exists which becomes effective between cement and resin bound materials. Due to the loading under compression, a uniformly distributed shear stress is setting up on the joint at not too large angles. The stress is decreasing to zero at the external edges only. The influence of this decrease in stress at the edges is negligible even with relatively small specimens of 4 x 4 x 16 cm which are used here. A photo-elastic checking /1/ resulted in an approximately uniaxial stress state of these specimens under compression.

Case 2 can be classified in two parts a and b. In Case 2a the shear stress is low with reference to the normal stress. The angle is shown about 10 degrees. For instance, such a joint loading is possible with prestressed constructions. Practically the joint mortar is acting only as a filler between the units having a sufficient compressive strength. In Case 2b, the combined loading is represented more precisely, when the angle α is exceeding approximately 30 degrees. Although stress states, occurring actually rarely, are registered thereby, this Case is the most far-reaching and most suitable for investigations since, by this method, the references in literature may be resumed and conclusions may also be possible for Case 1 and 2a.

The essential factors for a joint for a long-term loading may be classified into physico-chemical conversions, thermal factors causing changes in mechanical properties, and of course, as third factor, the time. Physico-chemical conversions may occur if water molecules reach the bonding area by the capillary system of the hardened cement paste. Investigations made on these

phenomenae belong to the concrete corrosion tests. They have not been superimposed to the tests on the long-term behaviour on which is reported here. They have been carried out on specimens which were dry enough.

In this context, it seems to be necessary to refer to the temperature behaviour of polymer mortars. The effects of this relationship referring to the polymer mortars are occasionally overestimated.

Temperature

In fig. 2, the stress-strain curves of epoxy mortars having a mix composition of 1 : 4.4 by weight are represented at various temperatures. The whole curves in the left diagramme show an epoxy resin mortar being only a little temperature-dependent. It is tested up to temperatures of 112 °C. They represent the decreasing modulus of elasticity, the decreasing strength and approximately the same values of the ultimate strain. In the right diagramme, the strength is plotted against the temperature. The absolute values of the strengths are still in the range of the compressive strength of a normal cement concrete at temperatures of about 80 degrees. The strength decreases in a critical extent only when using a highly temperature-dependent resin. These are the dotted curves in the left diagramme and the lower curve respectively in the right diagramme of fig. 2. It should be mentioned that the polyester resins used generally in civil engineering may also give similar curves.

Types of Failure

Although the influences of temperature and time cannot be really compared, both factors produce changes in strength as well as in deformation. In doing so, the differences in deformation of concrete and epoxy bound together have to be taken into account. From the differences in deformation destruction causing stress states may occur. The type of destruction should be always distinguished whether it is a compression failure or shear failure. At compression failure the pattern of the fracture is the same as those of pure cement concrete and mortars, respectively. The shear failure is, however, defined as a type of failure in which the influence of the joint in the fracture pattern will become clearly recognizable. This may be either a sliding in the bond area or even a fracture in the concrete along the joint. This is illustrated in fig. 3. The right side of which shows prisms 4 x 4 x 16 cm failing under compression, the left side shows the shear failure.

It follows that it is only logical to define the time-dependent critical failure in the following way: The critical failure is the appearance of the time-dependent or the temperature-dependent shear failure in these bonding systems failing by compression failure at the short-term test. In other words, the typical case is that short-term loading produces a compressive failure while

long-term loading produces a shear failure. This definition is not in agreement with publications giving only the conditions for compression failures and shear failures at short-term tests, for example /2, 3/. Today we may rightly assume that systems having shear failures at short-term tests generally should be excluded from technical applications.

The type of failure is further demonstrated in fig.3a. The strength is plotted against the logarithm of time. Curve A represents the strength under high sustained load against the time for the Portland cement concrete. Shear failure against the time curve would be curve B. Point C is the point of the transition to the shear failure.

Time

In order to have an idea of the stress inducing deformation changes in the joint, we will follow up some of the deformation curves in fig. 4. The prisms have been loaded for about two years. On the ordinate the logarithm of the modulus of elasticity is plotted as secant modulus through the zero point of the stress-strain coordinate. The abscissa indicates the logarithm of time given in hours. The upper curve (A) shows the total deformation of the cement mortar used for tests - thus, it is not distinguished between deformations by creep and shrinkage. This is the reason why actually the total deformations - and not the load-dependent deformations alone - are giving the stress inducing deformation differences between polymer mortar and Portland cement mortar.

The lower curve (B) has been plotted from measuring values of an epoxy mortar having approximately the same volume of the aggregate as that of the cement mortar. The similar courses of the two curves are remarkable. The curves (C) and (D) represent the actually used joint mortar which had a lower grain component than (B) in order to assure a better workability. These curves have also a similar course. When the stress reached the value of about 42 N/mm^2 , the epoxy mortar with the lower grain component could no longer be measured since, at this stress value considerable nonuniform deformations occurred on the specimen's cross-section.

It is noted that the materials Portland cement mortar and resin mortar bound together show approximately the same deformation behaviour (upper diagramme in fig. 4). Thus, from the time-dependent investigation on cement mortar and polymer mortar only, a criterion cannot be obtained for the time-dependent transition from compression failure to shear failure. Extrapolations from tests on compound specimens do not provide a basis for such a criterion either. In fig. 4 it is to be seen the change in the modulus of elasticity of four similar test specimens at different loadings. These values on the three lower curves have been measured up to fracture. The linear extrapolation of the deformations in the logarithmic coordinate system, commonly used

with plastics, should be used with discretion since it contains the physically irrelevant extreme case of infinitely large deformations. Therefore, it should be developed a theoretical conception of the failure behaviour giving a criterion of the time-dependent transition from compression failure to shear failure.

This criterion should be derived from experiments concerning the time-dependent deformations of cement mortar and polymer mortar. The thesis is presented: There exists a definite lower limit for the deformation difference between the cement-mortar and the resin-mortar. Deformation differences above this will cause shear failure. This limit is a function of the factors: loading, time, and eventually temperature. This is represented in fig. 5. The attained shear strengths at the time of 36 seconds at a shear failure are taken as 100 per cent. The deformation difference between the materials bound together will increase with the time at constant loading. If a constant deformation difference is required, the sustained loading should be less than 100 per cent. This can be seen from the hypothetic curve (A) corresponding to the time-depending deformation behaviour. However, the deformation difference will also decrease at sustained loads of less than 100 per cent corresponding to the decreased sustained load. The hypothetic curve converts to the set of curves shown in the smaller range in fig. 5 according to the loading. Only one point of each of these curves is a real one, namely the point of intersection, points of intersection as shown in fig. 5. In this way, the shear failure curve is formed point by point. In this figure, the curve is approximately plotted as straight line. The round points show the measuring results. The small points are taken from tests carried out by Mr. Franke of the Technical University of Stuttgart /4/ who used the same materials in his experiments. The shear failure had been produced by reduction of the joint area. Also this test series gives results for the comparison with the calculated curve.

It should not be concealed that there are several tests which have not shown at a certain time compression failures nor shear failures in contrast to the expected results. It is assumed that this happened to specimens which are at the upper limit of the unavoidable scatter of their material properties (corresponding to the dotted curve). This refers both to cement mortars as well as polymer mortars. A definite explanation could be given only after removing the specimens from the loading equipment. However, this will not happen for one more year.

The shear failure curve is represented by the following equation:

$$\frac{\tau}{\tau_c} = \frac{1}{1 + \varphi(t)}$$

$\varphi(t)$ is the curve of the deformation difference which may be determined separately from the time-dependent mortars. In the chosen coordinate system, φ can only achieve values between 0 and - in extreme cases - 1.

It is obvious that an asymptotic value is attained at $\tau/\tau_o = 0.5$. The use of an equation with defined strength under high sustained load does not disagree with known measured values with regard to the shear failure. It should be mentioned, however, that no strength values obtained from sustained loadings have been reported in the literature, contrary to pertinent results on Portland cement concretes.

Conclusions

The presented investigation concerning the fracture of the system consisting of Portland cement concrete members bonded by polymer mortars has determined that long-term loadings result in shear failure, while short-term loadings result in compression failure. The dividing point between the so-called "short-term" and "long-term" time periods is calculated from the shear failure curve of the composite system. This failure curve approaches asymptotically a definite strength value. Test results given so far, indicate that it is possible to estimate a more reliable value of the strengths of the composite system under high sustained load than it has been given until now.

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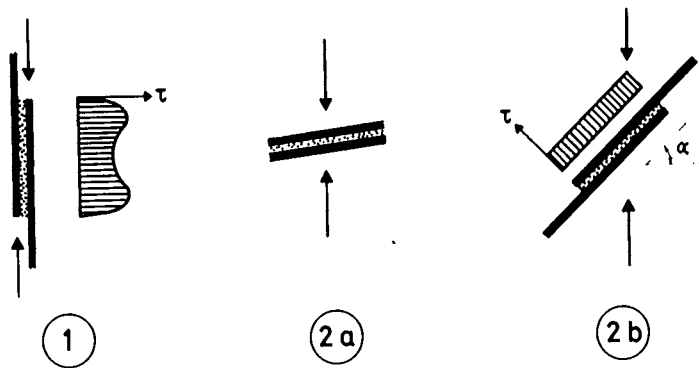


Fig. 1: Classification of loadings

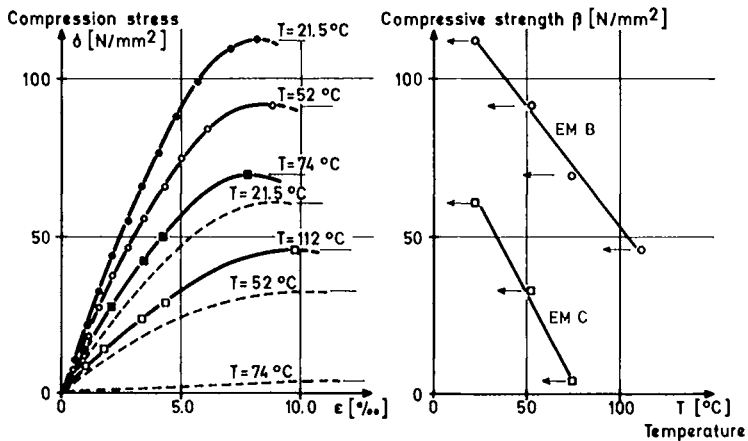


Fig. 2: Stress-strain curves of epoxy mortars (Prisms 4x4x16 cm)



Fig. 3 : Compression and shear failure of composite systems

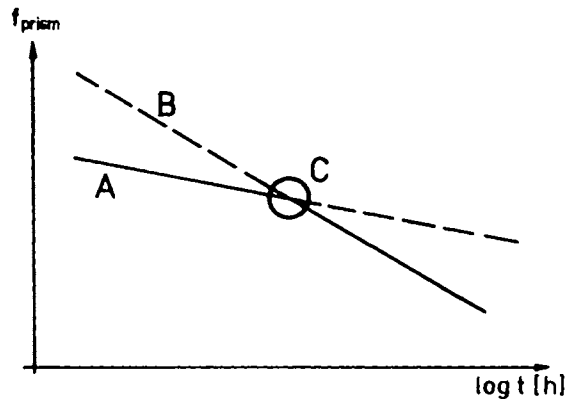


Fig. 3a : Compression failure and shear failure curves

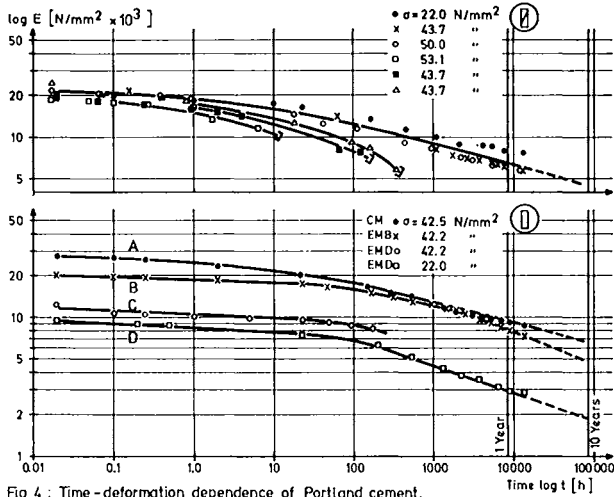


Fig. 4 : Time-deformation dependence of Portland cement, mortar (CM), epoxy mortar (EM) and bond systems

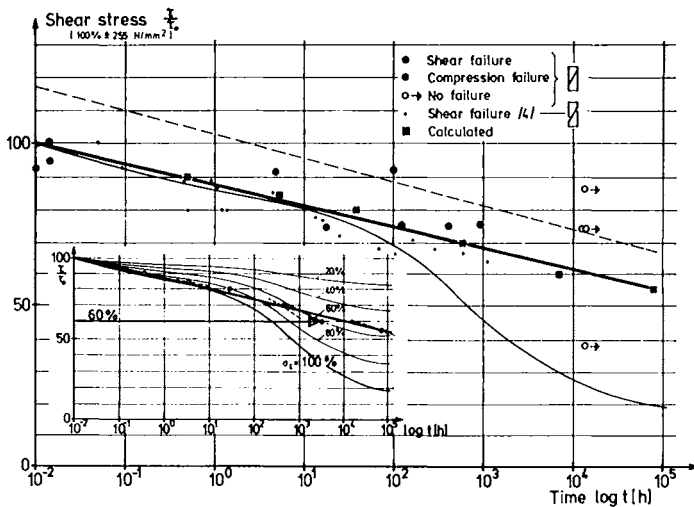


Fig.5: Shear stress-time relationship, measured and calculated

Determination Methods for Working Life of Polyester Resin Concrete

By Y. Ohama

Synopsis: The objective of this study is to find out appropriate methods of determining the working life of fresh polyester resin concrete. Three types of methods tentatively specified to establish a standard test method of working life determination for it are given and their applicability to fresh polyester resin concrete prepared with various mix proportions and working life is discussed. The tentative methods are outlined as follows:

- (1) Penetration method--Based on penetration depth of steel rod into fresh resin concrete.
- (2) Pull-out resistance method--Based on pull-out resistance (measured by spring balance) of steel rod embedded, from fresh resin concrete.
- (3) Finger-touching method--Based on the sense of touching through polyethylene film on fresh resin concrete by fingers.

It is concluded that penetration, pull-out resistance and finger-touching methods are satisfactorily applicable to the determination.

Keywords: binders (materials); consistency tests; plastics, polymers and resins; polyester resins; resin concrete; workability.

Y. Ohama is an associate professor at Department of Architecture, College of Engineering, Nihon University, Koriyama, Fukushima, Japan. He received a B.S. in chemistry from Yamaguchi University in 1959 and Ph. D. in architecture from Tokyo Institute of Technology in 1974. He has worked in the field of resin concrete, polymer-modified concrete, polymer-impregnated concrete, etc. for the past 17 years. Currently he is active in the technical committee work of plastics concrete in Architectural Institute of Japan and the Society of Materials Science, Japan.

INTRODUCTION

Recently, polyester resin concrete (abbreviated as REC) has been applied extensively in the field of construction works, but determination methods for working life of fresh polyester resin concrete have not been proposed until now. Determination of the working life is most important for both applications of precast and cast-in-place polyester resin concrete. The objective of this study is to find out the adequate methods of determining the working life of fresh polyester resin concrete.

In this paper, a few methods tentatively specified to establish a standard test method (for JIS, Japanese Industrial Standard) of working life determination for polyester resin concrete are given and their applicability to polyester resin concrete prepared with various mix proportions and working life is examined. Working life in this study is defined as "Period of time during which a polyester resin concrete, after mixing (strictly speaking, after adding catalyst to unsaturated polyester resin), remains suitable for casting or placing by vibrator, etc., or retains suitable consistency for use".

TENTATIVE DETERMINATION METHODS FOR WORKING LIFE OF POLYESTER RESIN CONCRETE

Tentative determination methods for working life of polyester resin concrete are outlined as follows (These determinations shall be conducted at $20 \pm 2^{\circ}\text{C}$, 70% or less R.H.) :

Penetration method--A steel rod (size, $\phi 16 \times 500$ mm; weight, 760 ± 5 g) shall be penetrated into fresh polyester resin concrete by its own weight and its penetration depth shall

be measured, observing the presence of visual penetration hole or mark. Total time elapsing from adding catalyst to unsaturated polyester resin to obtain 90 mm or less of penetration depth and observe visual penetration hole or mark, shall be reported as working life.

Pull-out resistance method--A steel rod (size, $\phi 16 \times 250\text{mm}$, weight, $370 \pm 5 \text{ g}$) embedded beforehand in fresh polyester resin concrete shall be pulled out from it and the pull-out resistance shall be measured as a load by spring balance. Total time elapsing from adding catalyst to unsaturated polyester resin to obtain 2.0 Kg or more of pull-out resistance, shall be reported as working life.

Finger-touching method--About 200 cm^3 of fresh polyester resin concrete shall be packed and sealed in polyethylene film bag, and then the sense of touching through polyethylene film on it by fingers shall be inspected. Total time elapsing from adding catalyst to unsaturated polyester resin to feel stiff for caking or gelling, shall be reported as working life.

MATERIALS

Liquid Resins, Catalyst and Accelerator--Four types of commercial orthophthalate-type unsaturated polyester resins denoted as UP-1, UP-2, UP-3 and UP-4, shown in Table 1, were used as liquid resins together with, 55 % DMP(dimethyl phthalate) solution of methyl ethyl ketone peroxide (MEKPO) as a catalyst and 6 % xylene solution of cobalt naphthanate (Co.Na.) as an accelerator.

Filler and Aggregate--Commercial calcium carbonate ("heavy" grade ; size, 2.5μ or less) was used as a filler, Isawa crushed andesite (size, $5 \sim 10$ and $10 \sim 20 \text{ mm}$) as coarse aggregate and Fujigawa river sand (size, $1.2 \sim 5$ and 1.2 mm or less) as fine aggregate. Their water content was controlled to be less than 0.1 %. The properties of the filler and aggregate are listed in Table 2.

TESTING PROCEDURES

Determination of Working Life of Binder

Binder for polyester resin concrete was prepared by mixing unsaturated polyester resin with 0.5, 1.0 % (by weight) of catalyst and accelerator respectively, and tested for working life according to JIS K 6804 (Measuring Method for Working Life of Adhesives) at 20°C . Spinning, gelling and caking of binder were observed as the end point

of this test.

Determination of Working Life of Polyester Resin Concrete

The polyester resin concrete for testing was mixed by using Eirich-type intensive counter-current mixer, in conformity with the same binder formulations as described above and the mix proportions given in Table 3, at 20°C, 50 % R.H. The fresh polyester resin concrete is tested for working life in accordance with the penetration, pull-out resistance and finger-touching methods as mentioned above. Also total time elapsing from adding catalyst to unsaturated polyester resin to the time to be unable to cast by vibrating table (number of vibration, 9000 vpm), was determined as working life.

TEST RESULTS AND DISCUSSION

The test results are shown in Table 4 and Fig. 1.

As a matter of course, the working life of both binder and fresh polyester resin concrete becomes shortened with a rise in contents of Co.Na. and MEKPO, regardless of the type of unsaturated polyester resin and binder content.

In working life determination of fresh polyester resin concrete having good consistency at 11 to 13 % of binder content, the penetration, pull-out resistance and finger-touching methods are applicable regardless of the type of unsaturated polyester resin and the difference in the working life obtained by these methods is rarely recognized. At binder content less than 11 %, only finger-touching method is applicable because of the bad consistency. Besides, in case that suitable consistency for working life determination is obtained, the working life values determined by three tentative methods become nearly equal to those determined by the method based on suitability of vibrating compaction.

Also if gelling is observed as the end point in working life determination of binder, then the working life of binder, i.e. unsaturated polyester resin, often coincides with that of fresh polyester resin concrete with the binder, determined by the tentatively-specified methods e.g. finger-touching method, as shown in Fig. 1. In this case, the relation between working life values of polyester resin concrete and its binder can be expressed as empirical formula, $y = x$ (where y and x are working life of polyester resin concrete and its binder, respectively).

CONCLUSIONS

The conclusions obtained from the above-mentioned test

results are summerized as follows :

- (1) In case that suitable consistency for the determination is obtained, penetration, pull-out resistance and finger-touching methods given in this paper are applicable to the working life determination of fresh polyester resin concrete. However, at lower binder content (less than 11 %), only finger-touching method is applicable.
- (2) If gelling is observed as the end point in working life determination of binder, the working life of binder often coincides with that of fresh polyester resin concrete prepared with the binder, regardless of the type of unsaturated polyester resin.
- (3) The effect of binder content on working life of fresh polyester resin concrete is hardly recognized.

Table 1. Properties of Unsaturated Polyester Resins for Testing

Type of Resin	Acid Value	Specific Gravity (20°C)	Viscosity (20°C, cP)	Styrene Content (%)
UP - 1	19.6	1.050	340	38.3
UP - 2	17.0	1.120	445	39.3
UP - 3	25.4	1.122	430	38.0
UP - 4	19.5	1.171	48	50.0

Table 2. Properties of Filler and Aggregate for Testing

Type of Filler and Aggregate	Grading (mm)	Specific Gravity (20°C)	Water Content (%)	Organic Impurities
Calcium Carbonate Heavy	$< 2.5 \times 10^{-3}$	2.70	0.08	No
Isawa Crushed	10~20	2.58	0.03	No
Andesite	5~10	2.58	0.04	No
Fujigawa	1.2~5	2.56	0.06	No
River Sand	< 1.2	2.55	0.08	No

Table 3. Mix Proportions of Polyester Resin Concrete

Materials			Weight Percent (%)		
			Binder Content 9.00	11.25	13.00
Binder, Unsaturated Polyester Resin			9.00	11.25	13.00
Filler, Calcium Carbonate			9.00	11.25	13.00
Aggregate	Crushed	Size, 10~20	15.39	14.55	13.89
	Ardesite	(mm) 5~10	15.39	14.55	13.89
	River Sand	Size, 1.2~5	10.16	9.60	9.17
		(mm) < 1.2	41.06	38.80	37.05

Table 4. Working Life of Polyester Resin Concrete and Its Binder

No.	Type of Unsaturated Polyester Resin or Resin Concrete	Co.Na. Content (phr)*	MEKPO Content (phr)	Binder Content (Wt.%)	Working Life of Binder (min)			Working Life of Resin Concrete(min)			
					(End Point) Spinning	Gelling	Caking	Penetration Method	Pull-Out Resistance Method	Finger-Touching Method	Method Based on Suitability of Vibrating Compaction
1	UP - 1	0.5	0.5	9.00	42	47	62	8	15	45	40
2				11.25				47	45	45	45
3				13.00				40	45	45	45
4		0.5	1.0	11.25	16	19	27	19	20	18	19
5				13.00				21	21	21	21
6		1.0	0.5	11.25	27	32	48	33	32	30	33
7				13.00				35	33	36	35
8		1.0	1.0	9.00	14	16	23	8	15	16	15
9				11.25				14	15	18	16
10				13.00				15	16	15	15

Table 4 Cont.

No.	Type of Unsaturated Polyester Resin or Resin Concrete	Co.Na. Content (phr)*	MEKPO Content (phr)	Binder Content (Wt.%)	Working Life of Binder (min)			Working Life of Resin Concrete(min)			
					(End Point) Spinning	Gelling	Caking	Penetration Method	Pull-Out Resistance Method	Finger-Touching Method	Method Based on Suitability of Vibrating Compaction
11	UP - 2	0.5	0.5	11.25	52	56	87	48	48	48	48
12		1.0	1.0	11.25	17	19	31	16	17	16	16
13	UP - 3	0.5	0.5	11.25	95	99	135	80	95	90	93
14		1.0	1.0	11.25	23	26	37	27	28	27	27
15	UP - 4	0.5	0.5	11.25	58	60	78	60	65	60	65
16		1.0	1.0	11.25	30	32	40	35	35	29	35

*phr; parts per hundred parts of resin,

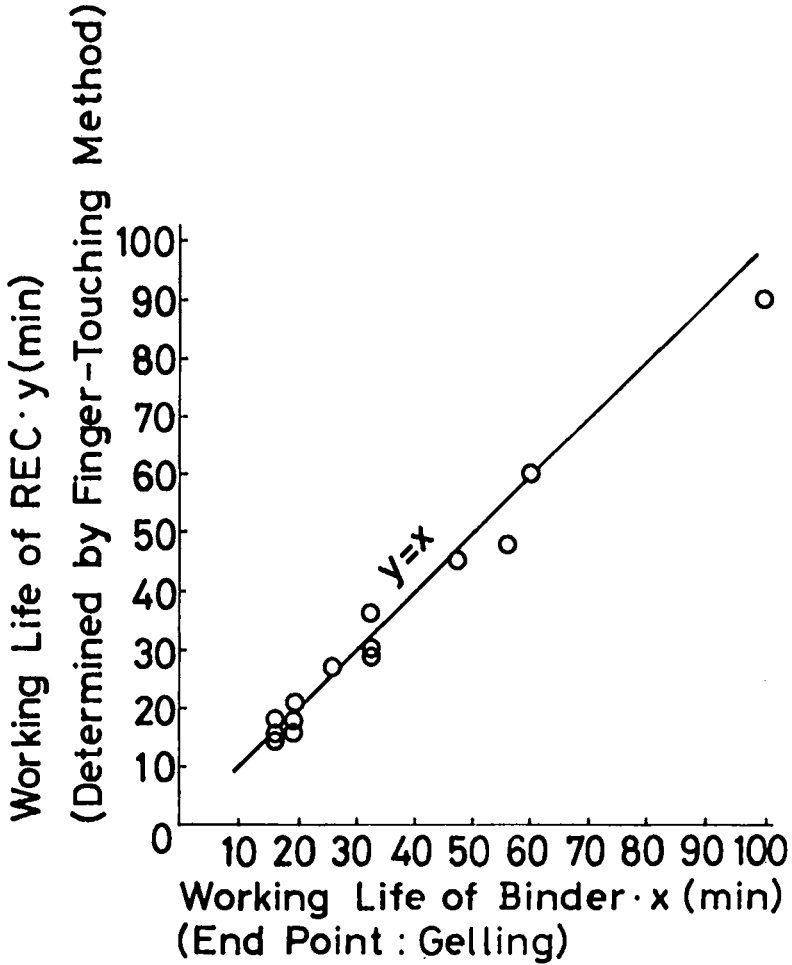


Fig. 1. Relation between Working Life Values of Polyester Resin Concrete and Its Binder

Furane Resin Concrete and Its Application to Large Diameter Sewer Pipes

By Richard A. Bareš

Synopsis: Some research results of the investigations of the properties of the various types of resin concrete were described. Particular attention was afforded to furane resin concrete which is cheap, based on continuously available raw materials, of equivalent mechanical properties and superior chemical resistance to all other types of resin concrete used.

Experimental research results were used as a basis of a generalization of some relations generally valid for composite materials of granular type.

Several examples of practical application of furane resin concrete to the construction of underground works in Czechoslovakia were described.

Keywords: furan resins; pipe linings; pipes (tubes); plastics, polymers and resins; resin concrete; sewer pipes.

R.A. Bareš has been closely associated with structural mechanics as well as nonhomogeneous materials for more than two and a half decades, and deeply interested in the utilization of plastics in building for a number of years. Now Chief Research Scientist of Institute of Theoretical and Applied Mechanics of the Czechoslovak Academy of Sciences in Prague he is concerned with both research problems and the technical assistance to the building development.

INTRODUCTION

The quota of plastics used in the building industry is increasing every year. This trend is participated in considerably by the structural application of heavily filled plastics to screeds and cast floorings, protective coatings, plastering, etc. and the application of resin concretes or resin mortars. The latter - bonded filler - are granular materials whose filler acts as skeleton structure /aggregate/ and the bonding agent fills entirely or partly the remaining space in contrast to a filled bonding agent /filled plastics/ in which the solid particles are only dispersed /segregated/ in the bonding agent /matrix/. The reason for the ever increasing application of these materials does not rest only in the increasing knowledge /also with regard to the mechanics of materials/ and in the decreasing price of plastics due to their increasing production, but also in the increase of the assortment of plastics enabling the satisfaction of the most varied users' requirements.

Resin concretes have been investigated in the Czechoslovak Academy of Sciences since 1959. During this period valuable theoretical as well as practical knowledge and experience has been obtained. Apart from the epoxy or polyester resin concretes widely used in the U.S.A., lately supplemented with polyurethane concretes, attention in Czechoslovakia was afforded particularly to resin concretes with furane bonding agent, especially the furfural-furfural copolycondensate. The reason for the use of furane resins was not only their high chemical resistance and durability, but also - and primarily - the fact that the source of the initial materials for their manufacture, timber and agricultural wastes, is very cheap and continuously reproducible by the natural process.

RESEARCH RESULTS

Properties of Furane Concrete

The optimum properties of furane resin concrete /similarly as the resin concretes with different bonding agents/ are obtained by the mixing of a well granulated filler with the bonding agent in the ratio of 1 : 7 to 1 : 12 by weight /in accordance with the filler particle size, the percentage of its porosity and the character of its surface, intensity of working, etc./

The filler is mixed first with pulverized catalyst /or catalyst on an inert carrier/ of acid reaction; afterwards the furfural /or partial pre-condensate of this monomer/ is added and finally the furfural as a copolycondensating diluter and accelerator. A slightly elevated temperature /35 - 40°C/ for a period of 3 days ensures complete hardening; after three hours of this temperature, however, more than 50% of the final values are obtained and the further hardening proceeds, with only slight deceleration, at normal temperatures. The filler must be dry, acid-resistant and devoid of any free carbonates. The outer manifestation for polycondensation is a change of colour from light brown to black. Furane resin concrete cannot be prepared in any other colour.

The change of the density of furane resin concrete in accordance with its composition, as compared with epoxy resin and polyester resin concretes, is illustrated in Fig. 1. The maximum relative density of all resin concretes is attained, if the bonding agent represents approximately 0.3 of the volume of the solids /filler/. Beyond this maximum the porosity begins to increase rapidly /see Fig. 2/.

The changes of compressive and flexural tensile strengths with the changes of the bonding agent: filler ratio are shown in Fig. 3 and Fig. 4. For the bonding agent contents of the order of 0.2 of the volume of solids /which corresponds approximately with the bonding agent: filler ratio of 1 : 10 by weight/ the strengths of all three compared resin concretes are identical.

The change of the modulus of elasticity corresponding with the change of the bonding agent content is illustrated in Fig. 5, while Fig. 6 illustrates the comparison of coefficients of temperature expansion and linear shrinkage during hardening.

For long-term structural application small creep and long term strength are of primary importance. Fig. 7 shows the changes of flexural tensile strength with the length of period of load application: long term strength does not exceed 50% of the short term one /curve A/. At the same the short term strength /curve B/ does not change with time /no self-induced ageing occurs/. However, the creep is reduced to an acceptable magnitude only for the stresses inferior to 30% of the short-term strength.

For structural application also the shape of the stress /strain diagram of various mixes, the value of the Poisson's ratio and the value of ultimate strain are of importance. A comparison of these working diagrams and Poisson's ratios the three resin concrete is shown in Fig. 8; Fig. 9 illustrates the changes of ultimate strain due to the changes of the bonding agent: filler ratio /on the same scale as in. Fig. 1 - 6/.

The influence of temperature on prism strength and the ultimate volume deformation for various mix compositions /different bonding agent: filler ratios/ are shown in Fig. 10 and 11.

The adhesion of furane resin concrete to cement concrete /or vice versa/ is lower than in the case of epoxy resin or polyester resin concrete, and attains maximally 5 kpf/cm² in tension. However, it can be increased considerably by a simple treatment of contact surfaces /roughening, provision of the fresh surface with sand or stone grit, coating with epoxy resin prior to concreting, etc./; to ensure the bond strength of the order of 10 - 25 kpf/cm² is no practical problem.

Furane resin concrete has good resistance to strong acids and lyes /unless they have an oxidation effect/, aliphatic carbohydrates and a number of other agents, its universality in this respect making it superior to all other resin concretes subjected to tests.

Generalization

The generalization of test results proves the justification of the hypothesis of different physical behaviour of materials of this type /non-homogeneous materials with very different properties of solid phases/ according to the type of their porosity as well as the necessity of investigating them in three separate regions: in the first region with discontinuous /closed/ porosity, in the second region which is an intermediate /transition/ region, and in the third region characterized by continuous /open/ porosity.

The general presentation of some properties of the composite systems under investigation in Fig. 12 illustrates the qualitative change of the properties in the narrow transition /second/ region manifesting itself by the quantitative change of practically all investigated relations: density, strength and modulus of elasticity have their extremes in the second region, the ultimate strain, shrinkage and coefficient of thermal expansion suddenly change their gradients, while the coefficient of moisture expansion, porosity and absorptivity grow in this region from almost zero to their final values in the third region. The properties of the filled bonding agent /filled plastics/ differ substantially from the properties of bonded aggregate /resin concrete/, the disadvantage resting with the former, regardless of the type of bonding agent /in the experiments described in Fig. 8 the boundary between both systems lies between the mix with the bonding agent; filler ratio of 1 : 5 and 1 : 10/. For the majority of building purposes the bonded aggregates are, therefore, more advantageous, notwithstanding their economic advantages due to the lower requirements of the more expensive component /bonding agent/ in the system.

Principles of Mix Preparation

Filler-- One of the principal factors influencing the quantity of bonding agent required /and - consequently - all resulting properties/ is the correct selection of the filler.

The principles of this selection include:

- filler must consist of /at least/ three gradings incl. the microfiller in accordance with the so-called discrete granulometric curve /gap-grading/ so as to ensure its minimum porosity;
- the gaps between the individual gradings must be at least two to four times as large as the diameter of the particle of the lower grade;
- the extent of every grade should lie within the limits of $d_{\max} = 2 - 2.5 d_{\min}$;
- the maximum particle size of the filler should be maximally one third of the minimum thickness of the layer applied;
- before the mixing with the bonding agent the filler must be dry /the moisture content of the filler should not exceed 0.2% of its weight/;
- river-dredged gravel-sand, clean dug sand and gravel

or crushed stone or artificial aggregates /incl. expanded/ can be used as the filler; the type of filler used determines particularly the hardness, toughness, modulus of elasticity, wear resistance, thermally insulating capacity, chemical resistance, etc. of the resin concrete;

- in the capacity of microfiller ground quartz sand, fly-ash, crushed stone powder, non-expanded perlite, micro-asbestos, graphite, coconut powder, etc. may be used; apart from the reduction of the porosity of the filler every microfiller affords the system further specific properties;

- the particle size of the microfiller should equal or be inferior to the thickness of the layer of the bonding agent enveloping the particles of the basic filler grade; the observation of this rule ensures the most effective compaction of the system, the maximum reduction of the necessary amount of the bonding agent required and the best workability of the mix. However, since the results of the determination of the thicknesses of particle envelopes are far from explicit /and depend on a number of factors concerning both the bonding agent and the filler/, it is recommended to select the mean particle diameter of the microfiller within the limits of 10 and 50 micrones.

Bonding Agent--The basic factor affording the resulting material its characteristic features is, naturally, the type or modification of the bonding agent which influences also the workability and, consequently, the minimum quantity required in the system. The correct selection of the bonding agent is dictated by the future exploitation of the material /resin concrete/, i. e. the requirements imposed on its various physical properties /adhesion to the filler, relaxation, chemical resistance to UV radiation, ec./.

It holds that

- on the basis of its viscosity the mixing equipment as well as the equipment for the working of the placed material /according to the type of resin either microvibration, heating or a combination of both methods, etc. /must be selected;

- solvents may be used in exceptional cases only and only such solvents may be used as become an integral part of the resulting matrix;

- for batching purposes the individual components of the bonding agent must be so prepared as the ensure that their quotas in the overall volume of the bonding agent may exceed 5% of weight; in the opposite case it is not possible to maintain the necessary homogeneity of the bonding agent

in practice;

- the batching of the individual components of the bonding agent must ensure the life of the mix of at least 30 minutes; the setting should proceed slowly, particularly in its first phase.

APPLICATIONS OF FURANE RESIN CONCRETE

Adequate mechanical properties, high chemical resistance and durability had relatively low price predetermine the fields of application of furane resin concrete: pipe lines for aggressive liquids, protection of tanks, reservoirs and other structures exposed to chemical attack, etc. Some applications, particularly to the pipe lines of various purposes in Czechoslovakia are described further on.

Resin Concrete Pipes /Pipe Cores/

For the removal of heavily aggressive /alternately acid and alkali/ waste water from a big chemical works beside traditional concrete sewer protected by several layers of plastics foils and coatings and a lining of acid-resistant bricks /Fig. 13/ also dia 135 cm resin concrete pipes with a wall thickness of 4 cm were used in the period of 1963 - 1964. These pipes of furane resin concrete were produced in vertical position in a dual mould provided with effective vibrators. The length of the pipes was 300 cm /Fig. 14/. The pipes were transported to the building site, placed on concrete foundations and clad with concrete. In this operation they served as self-supporting interior shuttering for the freshly placed concrete mix /Fig. 15/. After the joints were filled with furane resin mortar /from inside, after the setting of concrete/ the furane resin concrete core afforded effective and continuous protection against the effects of aggressive waste water to the concrete of the pipe.

The inspections of this work, where the conventional and the modern parts serve the same purpose in the same conditions next to each other, were made after two, five and ten years of exploitation. So far the furane resin concrete part has shown no defects, while the brick-lined part was slightly disturbed after five years and failed entirely after ten years and required full reconstruction.

Concrete Pipes with Inner Lining of Resin Concrete

In another part of the same work furane resin concrete was used for the removal of chemically aggressive waste water in a different manner. Concrete pipes produced by spinning by the TUBECO system were provided with an inner lining of furane resin concrete 2 - 3 cm thick applied to the inside of the pipes in the process of spinning under simultaneous rolling. The joints between the individual pipes were sealed with rubber rings /Fig. 16/. This method of production is under further consideration.

Reinforced Concrete Pipes with Resin Concrete Cores

In the construction of one of the main sewers serving a new housing estate in Prague dia. 180 cm reinforced concrete pipes 200 cm long with furane resin concrete cores were used /Fig. 17/, which were produced as follows. First a resin concrete core of 2 cm wall thickness was cast in a vertical mould /by means of vibration/; after its setting the exterior mould was removed, reinforcement was fixed and the space between the resin concrete core and a new exterior mould /of 18 cm thickness/ was filled with cement concrete /once again in vertical position/. The pipes were placed on concrete foundation blocks with laser control of position /Fig. 18/. Their joints were pointed with resin concrete mastic from inside and the whole pipe line was grouted with thin concrete to a height of about one third of the pipe diameter. In this project also the method of assembly of resin concrete cores from prefabricated segments and their subsequent cladding with concrete was tried. This method proved slightly more advantageous from the economic point of view.

Large - Diameter Sewers Protected with Prefabricated Resin Concrete Linings

The greatest extent of application of furane resin concrete effected in Czechoslovakia so far has been its use in the construction of the new main sewer leading from the south to the north of Prague. The sewer which is under construction is scheduled for completion in 1978 when it will serve 562,000 people with a specific run-off of 420 litres per head and day, which will increase to 730 litres per head and day for 840,000 people in the year of 2000. The sewer is designed for a flow of 20,44 cu.m per sec., its clearance varying from dia. 200 cm to dia. 360 cm over a length of 11,300 m. Of this overall length 5.5 km pass

in a tunnel driven in rick, 1 km in a tunnel driven in water-logged made-up ground and gravel-sand, and 4 km in an open trench. Apart from that the sewer siphons under the water courses. The required life expectancy is 80 - 100 years. The construction began in 1972. It is a highly exacting project both technically and in time.

The original design considered a concrete /or reinforced concrete/ structure protected with a lining of acid-resistant bricks 15 cm thick /Fig. 19/, i.e. a system used successfully in Prague sewerage system for the past 70 years. However, considerable labour requirements and a shortage of specialists proved a stumbling stone of this process. From the number of other methods available it was decided to accept the alternative replacing the brick lining with a lining of resin concrete 2 cm thick used as "lost" shuttering of the concrete sewer /Fig. 20/.

The alternative enables a continuous concreting of the sewer. Prefabricated steel cages 3 m long /Figs. 21, 22, 23/ are lined with resin concrete segments prefabricated in a special plant. The segments 149 cm long and 90 - 100 cm wide are produced by vibropressing in the curvatures required by the cage cross section. Their weight varies between 60 and 70 kg. In the case of dia. 200 cm sewer six segments are required, while twelve segments are used in the case of dia. 320 cm and dia. 360 cm sewer cross sections. The joints between the segments are sealed with temporary rubber inserts /Fig. 24/. The whole assembly is secured with wire.

The shuttering cages with resin concrete sewer lining are placed by the crane /Fig. 25/, if the sewer is concreted in an open trench. In tunnels they are transported on bogies /Fig. 26/. The cages are fastened to the preceding cage by two pins /Fig. 27/. After placing they are set on four adjustment screws /Fig. 23/ which are used for their accurate alignment. In the tunnels they are fixed by means of another four screws against the vault to secure them against the uplift during concreting. The concrete is cast in sectors comprising 2 - 3 cages /6 - 9 m long/. In tunnels the concrete is placed by means of compressed air pumps and compacted by type CIFA pneumatic surface vibrators mounted on the frames of the shuttering cages. The concrete is thus compacted by means of the vibrations of the resin concrete lining /Fig. 28/.

The shuttering cages are so designed as to fold on a special transport car after the completion of concrete compaction /Fig. 29/.

When the concrete has hardened, the rubber inserts are removed from the joints and the joints are sealed with epoxy resin mortar. This also ensures perfect monolithicization

of the resin concrete pipe /Fig. 30/.

To ensure good bond between cement concrete and resin concrete /in excess of 10 kpf/cm²/ the rear /external/ face of the segments is provided with stone grit pressed into the not entirely hardened resin concrete during the production of the segments.

In tunnels this method ensured an output of as many as 193 m of sewer per month. In a trench a maximum output of 110 m per month was achieved, since - with regard to the uplift of fresh concrete - the whole sewer cross section had to be concreted in three layers. In comparison with the originally considered traditional method the construction was accelerated, on the average, 3 times in the tunnels and 6 times in the trenches. The brick lining in a tunnel required 98.1 manhours/m, while the resin concrete lining required only 29.4 manhours/m. The economy of labour requirements due to the introduction of the new method amounted to 70%. The same economy was achieved also in the trenches.

In spite of the high price of resin concrete the overall costs per 1 m run of the sewer is lower by several per cent, as a result of a lower volume of enveloping concrete and a smaller volume of carthworks required. /Fig. 19 and 20/.

The furane resin concrete was used also for additional structures /inspection chambers, branch-off pipes, etc./. In actual construction no difficulties have arisen so far and the construction proceeds according to schedule.

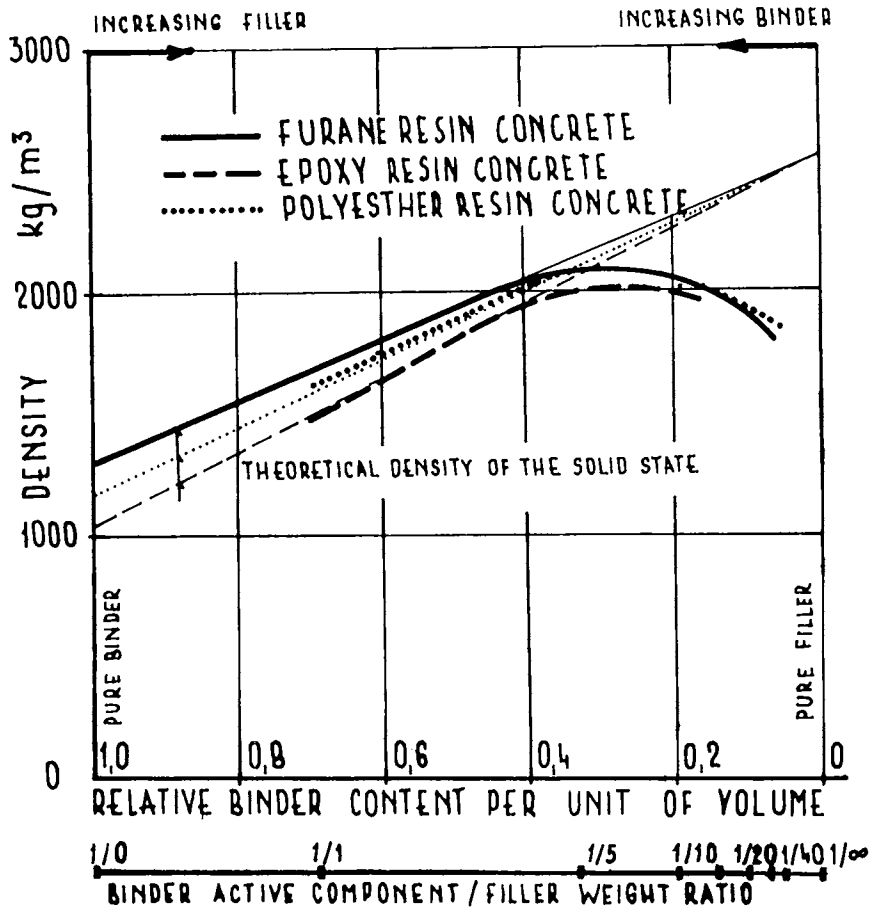


Fig. 1--Density of resin concretes plotted against concrete mix composition

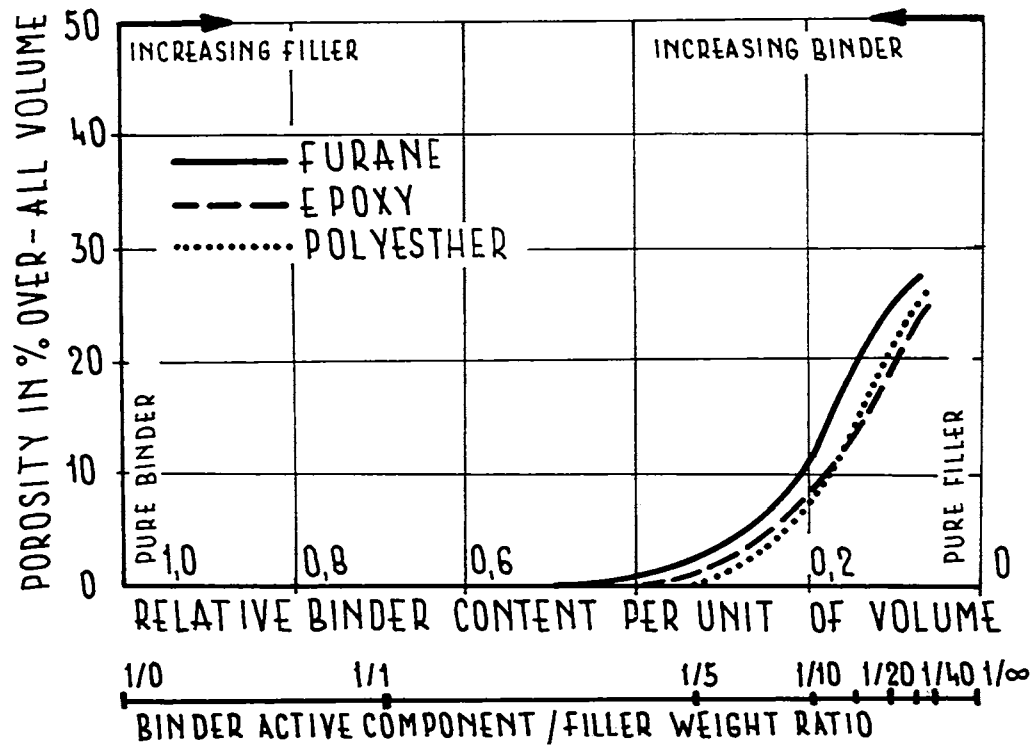


Fig. 2--Porosity of resin concretes plotted against mix composition