

Resin concretes

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The term 'resin concrete' describes materials in which aggregates are bonded by synthetic resin rather than by Portland cement. Materials of this type are of relatively recent origin but, in a number of countries and especially in the USA, several papers have been published giving details of the nature and engineering properties of epoxide and of polyester resin concretes. Many of the papers also suggest applications for such materials.

In earlier papers,¹⁻⁶ the author has presented information regarding the properties of resin concrete in which the binder is furfural-furfural resin. The most comprehensive publication⁶ deals also with a range of binders including furfural-acetone resin and phenol-formaldehyde resin.

It is difficult, however, to compare published results due to the effect on properties of factors such as differences in the materials used and in the curing conditions, and these are generally not reported with sufficient precision.

A range of tests on the most commonly used forms of resin concrete has therefore been undertaken by the author, using well defined materials and closely controlled conditions. The results of the tests have been compared and typical results are given in this paper together with the general conclusions drawn from the full series of tests. In addition, a study of the influence of the environment during and after hardening is reported for furfural-furfural resin concrete (referred to subsequently as 'berol').

Mix composition and production

Four types of resin have been used in the investigation, as follows: A polymer (polyester resin); a polyadduct (epoxide resin); two polycondensates (furfural-furfural resin and phenol-formaldehyde resin). Details of the individual resins are given in the Appendix.

River aggregate was used for all mixes and the grading was as shown in Table I.

Table I

Sieve size, mm	7.0	4.0	2.0	1.0	0.5	0.2	0.1
Per cent passing	100	91.4	80.7	72.0	41.0	7.4	0.9

The loose bulk density was 1672 kg/m³, the rodded density 1839 kg/m³, the specific weight 2582 kg/m³, and the porosity 35.2 per cent in the loose state and 28.8 per cent in the rodded state.

A range of values for the ratio of sand to the active resin component (*i.e.* excluding the catalyst and the accelerator) was examined for all the resin concretes, as follows: 1:1, 5:1, 10:1, 15:1, 20:1, 30:1 and 40:1, the ratios being by weight.

The quantity of catalyst used was chosen so as to be in the molar relation or as recommended by the manufacturers of individual resins, and similarly for the accelerator. On this basis, the weight proportions chosen for the bonding agents were as follows:

polyester resin: catalyst: accelerator - 10:3:1.5

epoxide resin: catalyst - 10:0.7

furfuryl alcohol: catalyst: accelerator - 10:4:1

phenol-formaldehyde resin: catalyst - 10:2.5

Mixing was by hand and the following sequences shown in Table II were observed:

Table II
Binder

Binder	Mixing Order
polyester	sand + catalyst + resin + accelerator
epoxide	resin + catalyst + sand
furfural-furfural	sand + catalyst + resin + accelerator
phenol-formaldehyde	resin + catalyst + sand

Test specimens were formed using steel moulds, 4 × 4 × 4 cm and 4 × 4 × 16 cm, compaction being by rodding.

The specimens were cured at an elevated temperature, 50°C, and at a relative humidity of 15-18 per cent, in order to ensure that the comparison of properties would be made on fully hardened materials.

The above procedures were selected in order to investigate the effect of filler/active bonding agent ratio on certain mechanical and deformation properties of resin concrete, and the graphs are presented on this basis. In retrospect, however, it is felt that the ratio of the volume of aggregate to that of the total bonding agent (including catalyst and accelerator taking part in forming the molecular structure) is of greater significance and this is referred to elsewhere.^{4,5}

Compressive strength, flexural tensile strength and unit weight

In Fig. 1 the effect of mix composition on the above properties is shown plotted. From the results, it follows that the epoxide, polyester and furfural-furfural resins are equivalent, in principle, from the strength point of view. This fact is particularly clear with mixes leaner than 1:10 and is important since these mixes are most commonly used in practice, due to economic and other reasons.

The similar strength of all three resin concretes proves that, from the point of view of the strength of the composite material, the strength of the bonding agent alone is not especially critical. Other factors are considered to be more decisive, such as the internal distribution and the proportion of the individual phases, *i.e.* the state of internal stress in the system concerned, determined by the porosity of the filler, by the relative quantity of the bonding agent and by the quantity of voids.

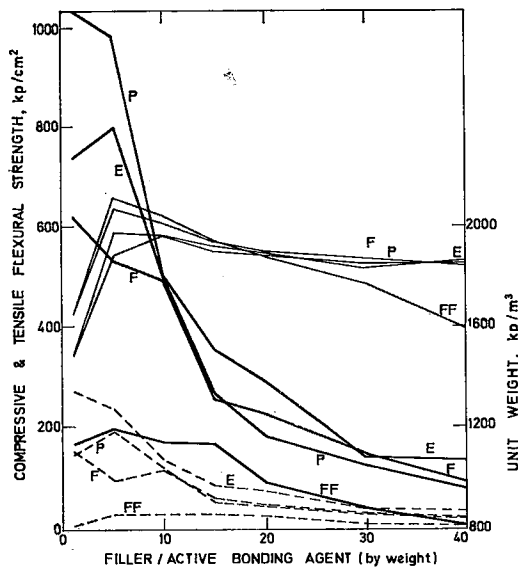


Fig. 1 The effect of filler/active bonding agent ratio on compressive strength, flexural tensile strength and unit weight of resin concretes hardening at elevated temperatures

— compression
 — unit weight
 --- flexural tension
 E = epoxide resin concrete
 FF = phenol formaldehyde resin concrete
 P = polyester resin concrete
 F = furfural-furfural resin concrete
 temperature in hardening 50°C
 humidity in hardening 18 per cent RH

In the first range (a discontinuously porous system, up to weight ratios of 1:5–1:7), a greater strength is attained with the polyester resin than with the epoxide resin, and this is attributed principally to the low workability of the highly viscous epoxide resin, as apparent also from the effect on the respective values of unit weight. The furfural-furfural resin shows a characteristic behaviour, with strength increasing beyond the ratio producing maximum density.³

In the comprehensive study³⁻⁶ the influence of the catalyst and accelerator dose was examined. In the first range (*i.e.* resin concrete with a small relative quantity of aggregate) increasing the catalyst dose reduced the strength. However, the strength increased proportionally in the second range (also called the intermediate range, *i.e.* the region containing voids but not necessarily fully continuous) and in the third range (a continuously porous system, approximately for ratios greater than 1:10–1:12). In the case of the furfural-furfural resin concrete, increasing the accelerator content decreases, in some measure, the strength. An examination of the unit weight of all the resin concretes showed clearly that the mixture with the maximum relative density was obtained in the vicinity of an aggregate: active bonding agent ratio of 5, which formed the boundary between the first and the second ranges considered.

All these results make it clear that one cannot speak about a simple relationship between strength and the bonding agent content.

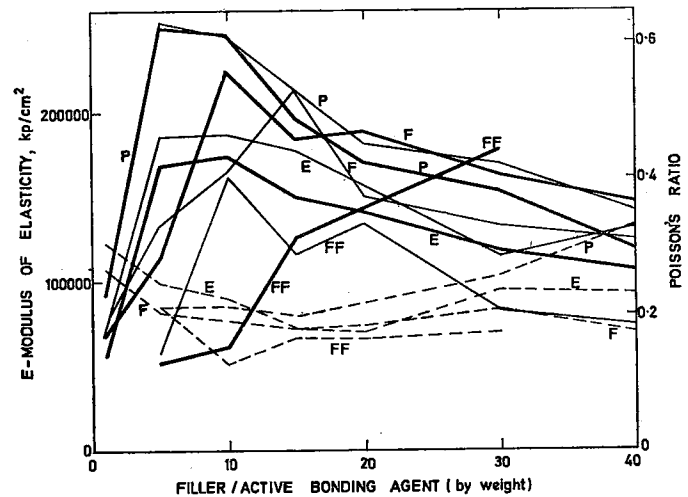


Fig. 2 The effect of filler/active bonding agent ratio on the elastic moduli and Poisson's ratio of resin concretes hardening at elevated temperatures

— dynamic modulus of elasticity
 --- average modulus of elasticity } corresponding to $\frac{H}{3}$
 - - - average Poisson's ratio

Static modulus of elasticity, dynamic modulus of elasticity, modulus of elasticity in shear and Poisson's ratio

In the same way as in the previous section, the effect of mix composition on the above properties is shown plotted in Fig. 2.

So far as values for the elastic modulus are concerned, the mixes at the end of the second range (*i.e.* with mix ratios of 1:10–1:15) are the most advantageous for constructional practice and this applies to all the resin concretes tested. A more favourable state of internal stress is thought to exist in this range, in spite of the fact that the quantity of the bonding agent is less than the value leading to the greatest relative density. The static modulus of elasticity, based on the average of a number of determinations at stresses between zero and one third of the ultimate strength, attains a maximum value at a mix ratio of 1:10 in the case of polyester resin concrete, furfural-furfural concrete and the epoxide resin concrete, the relative values being in the order listed. The same conclusion essentially applies for the modulus of shear also.

By increasing the quantity of catalyst used,^{3,6} the modulus is affected in the same general way as is strength.

Poisson's ratio has its most advantageous value from the viewpoint of building construction for mixes in the second and the beginning of the third range, *i.e.* mixes with an aggregate/active bonding agent of about 15.

The values of elastic modulus of polyester and of furfural-furfural resin concretes are high enough, generally, for constructional exploitation, but particular attention should be paid to the high creep characteristics and this point is discussed in a forthcoming publication.

Porosity, shrinkage and thermal coefficient of expansion

Fig. 3 provides details of some further physical properties of resin concretes. With the exception of phenolformaldehyde resin concrete, the low porosity (or absorptivity)

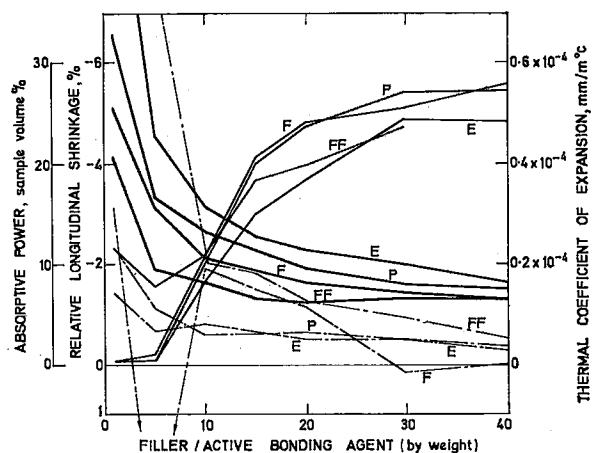


Fig. 3 The effect of filler/active bonding agent ratio on absorptive power, longitudinal shrinkage and thermal coefficient of expansion of resin concretes hardening at elevated temperature

absorptive power —
 average thermal coefficient of expansion — +20 — +80°C
 shrinkage - - -

in the first range indicates the discontinuity in the porosity characteristics of all resin concretes. The porosity increases from the mix ratio producing the greatest unit weight (see Fig. 1). The phenol-formaldehyde resin, on the contrary, has a considerable porosity when used in mixes rich in bonding agent, the lowest absorptivity being with the most dense mix (according to the unit weight).

The absolute value of porosity is the same, approximately, with all the resin concretes examined. Increasing the quantity of catalyst^{3,6} tends to reduce porosity initially but it then increases it and thereby decreases the durability of resin concretes. A small catalyst increase, up to about 50 per cent, in comparison with the quantities used for pure resin is, however, profitable.

Curing at elevated temperatures generally tends to increase the absorptivity and, probably due to the more severe state of internal stresses resulting from rapid polymerisation, to higher shrinkage and greater pore volume. Results of shrinkage tests show conclusively that increased temperature during hardening always causes an increase in the final shrinkage value. The data concerning shrinkage are, of course, inexact since shrinkage measurements are started some 24 h after producing the mix. In the case of epoxide and polyester resin concretes, a substantial part of the total shrinkage value has already occurred during this time, especially with mixes rich in bonding agent. The results of shrinkage are therefore given merely as an approximate guide.

When furfural-furfural resin concrete is caused to harden at an elevated temperature, an anomaly happens with mixes in the region between the first and the second ranges. The anomaly is thought to be due to the difference between the expansion of the unhardened material as a result of the temperature rise and the contraction of the hardened material after the drop in temperature. The last phenomenon causes a state of considerable internal stress in the system, which manifests itself through a reduction in strength and elastic modulus (see Figs 1 and 2) in that region.

In comparison with Portland cement concrete, the shrinkage of resin concrete is always greater and it is necessary, therefore, to take this into account in design of elements and of structures as a whole.

The values of the coefficient of thermal expansion are within acceptable limits with systems of the second and third range where the coefficient is of the same order as that of Portland cement concrete. With phenol-formaldehyde resin concrete, however, the coefficient for temperatures lower than 20°C is of an unacceptable magnitude and may be attributed to the marked porosity and the influence of humidity rather than to the effect of temperature alone.

Influence of environmental humidity during the hardening of berol (furfural-furfural resin concrete)

The author has referred in a number of earlier publications to the unfavourable influence of humidity on the mechanical properties of berol. The moisture content of the aggregate is important and especially under a greater environmental humidity during hardening, as illustrated in Fig. 4. But even with the use of dry aggregate, the humidity of the environment, in which the berol hardening takes place, exerts a substantial influence on the resulting strength. The decrease of compressive strength with increase of environmental humidity at a constant temperature of 20°C is indicated in Fig. 5. The values being expressed as a percentage of the strength of fully hardened berol (at 50°C, 10 per cent RH). It is obvious from these results that a strength of 100 per cent (*i.e.* complete hardening)

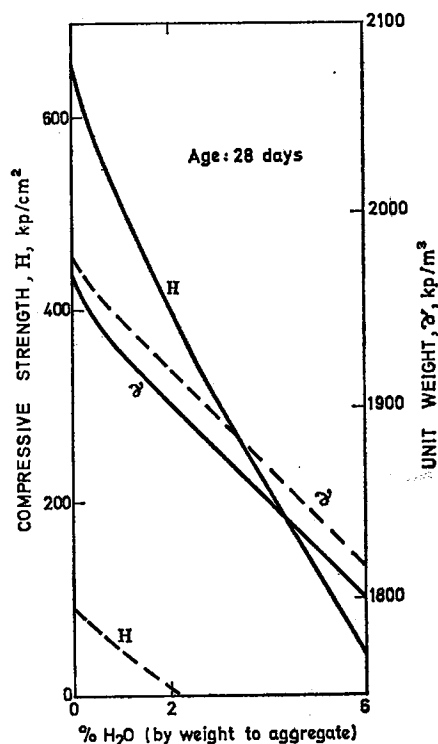


Fig. 4 Influence of aggregate humidity on berol strength (Filler: bonding agent = 15:1)

curing: 50°C, 18% RH
 18°C, 93% RH

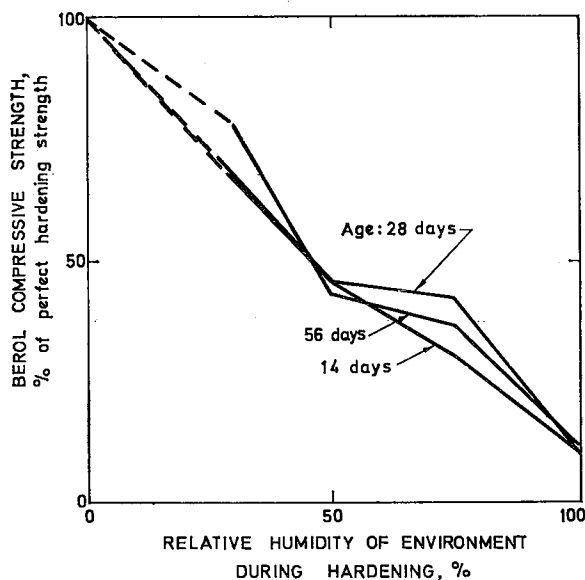


Fig. 5 The effect of environmental humidity during hardening on the compressive strength of berol. (Filler: bonding agent = 15:1, temperature 20°C)

tensile strength of a perfectly hardened berol (at 50°C, 15% RH):
 14 days 592 Kp/cm²
 28 " 629 "
 56 " 624 "
 test specimens: 4 × 4 × 4 cm

can only be achieved at normal temperature in an absolutely dry environment. With usual values of humidity (50 to 75 per cent) and at a typical temperature of 20°C, only some 50 per cent of the possible strength can be achieved. When specimens are stored in water, hardening does not occur to any significant extent.

The relative humidity of the environment, in which the samples are produced and kept until removal from the moulds, over a period of some 24 h during which stiffening and early hardening takes place, influences the resulting strength even if subsequent hardening occurs at an increased temperature.

In the production of resin concrete of this type, the relative humidity of the environment should not, therefore, exceed some 50-60 per cent otherwise disproportionate reduction in strength takes place.

Influence on hardened berol of saturation with water

The humidity of the environment, in which berol is kept after having been hardened, also has a great influence upon its instant strength* and depends, in particular, on the proportion of the bonding agent to the aggregate. As far as a mix with discontinuous porosity is concerned, the strength reduction resulting from the humidity increase is small. But with mixes with continuous porosity, an apparent reduction in strength takes place. This suggests that increased humidity has no influence upon the properties of the bonding agent itself but that the strength reduction is physical and is caused by an unfavourable state of internal stress in the structure of the material after partial or complete filling of voids by water. Fig. 6

* 'Instant strength' is the strength stated in a certain storage environment.

shows the change of compressive and flexural tensile strengths expressed as percentages of the corresponding value after 28 days at 50°C and 15 per cent RH, that take place with environmental humidity change after the hardening. It is of interest that in the range between 60-70 per cent RH, the humidity at which sample production took place, a reduction of strength is detected for all mixes examined and of approximately the same percentage value. There is the possibility, obviously, of interaction between the bonding agent and the aggregate which may depend on the hardening conditions (primary internal stress), and between the material and the environment (secondary internal stress). The explanation and the separation of these phenomena does not represent a simple matter, and requires further detailed study from the point of view of physicochemical mechanics.

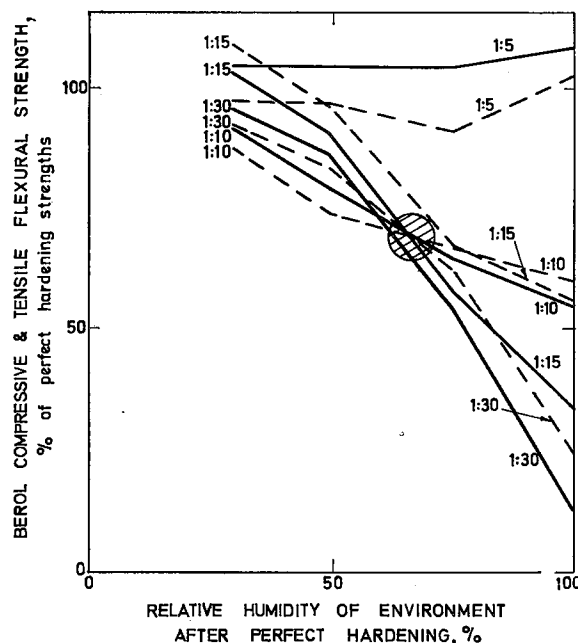


Fig. 6 The compressive strength and flexural tensile strength of a fully hardened berol of various compositions in an environment with various values of humidity related to the strength of berol kept at 55-60°C and 15 per cent RH. (Filler: bonding agent = 5:1, 10:1, 15:1, 30:1, temperature 20°C)

storage after removal of moulds
 14 days at 55-60°C, 15% RH
 14 days at 20°C and various humidity degrees
 test specimens: 4 × 4 × 16 cm
 --- compression
 — tension

From these comparisons the most advantageous state of secondary internal stress (due to saturation of hardened berol with water) from the strength point of view appears to occur in the vicinity of the 1:15 mix (active bonding agent volume: filler volume = 0.242:0.758). The most advantageous state of primary internal stress takes place in an environment close to the one in which the material was produced and allowed to harden initially.

From the previous facts the findings are summarised as in Fig. 7 as follows:

From completely saturated with water up to a fully

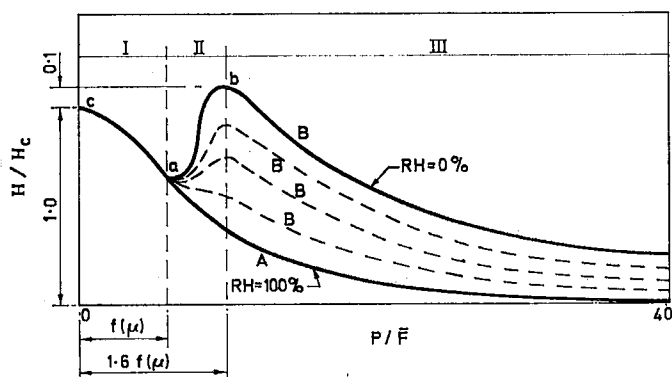


Fig. 7 Effect of degree of saturation with water on the strength of berol of various filler/active bonding agent ratios

III continuous porosity region
 II intermediate region
 I discontinuous porosity region

dried condition, the mechanical properties remain the same in the region of the discontinuous porosity (from the origin up to point a) although they are changing, depending on the filler: bonding agent ratio, according to the curve A. The first region is not a constant one and depends, in particular, on the filler porosity. The system humidity begins to influence the mechanical properties in the continuous porosity region. In a state of complete saturation with water the change of berol strength for various values of the filler: bonding agent ratio is given by the same continuous curve, A, decreasing continuously with decreasing quantity of bonding agent. We may suppose that the curve indicates the minimum strength obtainable for various filler: bonding agent ratios. Filling the voids with water causes a deterioration in the state of internal stress and this occurs in an unloaded material due to the influence of interfacial stress and, in a material under load, due to the influence of water incompressibility and of the unfavourable stress distribution. A reduction in the relative humidity increases the system strength. With perfect drying the system strength is the highest and follows curve B. It may be supposed that this curve indicates the maximum obtainable strength for a certain filler: bonding agent ratio. For systems with a humidity value between the extremes considered, the relationship will be of the same form but will fall between curve B and curve A. With increasing humidity, the peak b declines and ultimately joins curve A when complete saturation is attained.

Application of furane resin concrete

In the CSSR, berol has already been used in the production of large diameter pipes up to 140 cm, for the discharge of highly aggressive effluent at chemical plants⁸ (Fig. 8). The inspection shafts in these pipe-lines have also been constructed with large dimension barrels made of berol.⁷ At present, experimental acid-resistant paving tile floors, made of berol, are being used in a large chemical plant under construction.

These and other industrial uses confirm the properties of berol deduced from the laboratory results, and indicate its suitability and economic advantage for use especially in highly aggressive chemical plants.

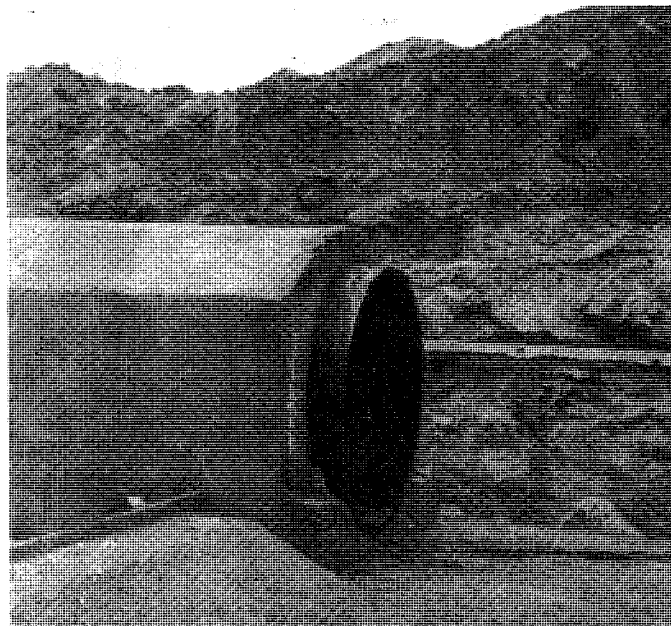


Fig. 8 Large dimension pipelines, with berol cores, for waste water

Summary

By means of laboratory tests, it was possible to obtain information and to establish a pattern of behaviour for various resin concretes. In summing up the findings relating to general character, it is concluded that all properties of resin concrete are a function of:

- bonding agent properties* – each property of resin concrete is limited by the corresponding property of the bonding agent. It can only be exceeded when an especially favourable state of internal stress is induced in the material.
- the amount of binding agent in the mix* – the bonding agent volume fraction determines the influence of the bonding agent properties on the property of the resin concrete.
- filler porosity* – the ratio of the bonding agent volume to the volume of filler voids in the material determines the degree of cohesion and the density achieved. The macro-structural state of stress under load also depends on the filler porosity.
- the effect of the hardening conditions on the mechanical interaction between the bonding agent and the aggregate* – the conditions under which the resin concrete is allowed to harden govern the combination of the properties attributable to given volume fractions of bonding agent and filler and they determine the state of primary internal stress in the material.
- mechanical interaction of the material and the environment* – the properties of the environment have a decisive influence on resin concrete and govern the development of the state of secondary internal stress in the material.

From the point of view of chemical resistance, furfural-furfural resin concrete is superior to the other resin concretes examined and it resists practically all non-oxidisable acids and bases. Because particularly high strength is not necessary for use in practice the author considers that furfural-furfural resin concrete is the most

suitable for industrial exploitation even from the economical viewpoint.

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Appendix: details of resins used

Polyester resin: ChS - polyester 104 with a content of about 70 per cent of unsaturated polyester, the remainder being styrene

Catalyst - methylcyclohexanene-peroxide

Accelerator - cobalt-naphthenate in solution with styrene, the proportion being 1:40

Epoxide resin: ChS - epoxide 1200, in which the equivalent of the epoxide groups -OH-CH in 100g of resin is approximately



0.3, containing 5 per cent by weight of dibutyl phthalate

Catalyst - diethylene - triamine

Furfural-furfural resin: technical furfuryl alcohol (about 80 per cent by weight) and technical furfuryl aldehyde

Catalyst - sodium nitrate

Accelerator - furfuryl aldehyde

Phenol-formaldehyde resin: phenol-formaldehyde polycondensate Umacol B in acetone solution with an average content of resin components (dry matter) of 72 per cent

Catalyst - a 50 per cent solution of P-toluene sulphonic acid in water

References

¹ Bares, R., Hosek, J., *Stavebnicky casopis SAV*, IX, no 7 1963,

² *Idem*, *Technical Digest*, no 6, 1962, (Czechoslovak)

³ *Idem*, *Bulletin RILEM*, no 28 1965,

⁴ Bares, R., Navratil, J., Berka, L., Javornicky, J., 'Symposium on the research and reception tests of synthetic materials for construction RILEM,' Final Report, Liege, 1964

⁵ *Idem*, *Bulletin RILEM*, no 28 1965,

⁶ Bares, R., 'Set of Final Reports UTAM-CSAV,' 1964-7

⁷ Cermak VI Final Report n.p. Doprastav-Bratislava, Czechoslovakia Feb. 1964

⁸ *Ibid.* Dec. 1964.