LABORATORY STUDY OF POROUS CONCRETE FOR ITS USE AS TOP-LAYER OF CONCRETE PAVEMENTS

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SYNOPSIS

Included in the project 'Optimization of the Surface Characteristics of Concrete Roads in Accordance with Environmental Acceptance and Traffic Safety', funded by the European Commission by means of the Brite/Euram project BE-3415, a laboratory program is being carried out by Dutch, German and Spanish institutes in order to study the composition and characteristics of porous concrete for its use as top-layer of concrete pavements.

The main objective of this laboratory work is to optimize the composition of porous concrete with respect to strength, acoustic properties, drainage, durability and costs comparable to porous asphalt. This latter material is now widely used in different European countries due to its noise reducing and drainage properties. These two aspects (noise produced by traffic and drainage) are currently considered very important because of environmental impact and safety matters.

The main parts of the work which is being carried out can be summarized in the following points:

a. Optimization of porous concrete mixtures. In this part three favourite porous concrete mixtures (one in each country) have been selected after studying their flexural, compressive and splitting tensile strength, dry density, accessible porosity, and permeability. The main parameters studied were the grading and maximum size of aggregates, and the type of additives (polymers, silica fume, superplasticizers) to be used. Each selected mixture was adapted to the specific conditions of the corresponding country.
b. Tests on the favourite mixtures. Favourite mixtures have been tested in order to study their static and dynamic modulus of elasticity, noise absorption characteristics, skid resistance, resistance to pulling-out of grains by the action of traffic (mechanical wear) and frost-thaw resistance.
c. Additional tests on the selected mixtures. Several other tests are planned to study several characteristics of porous concrete behaviour as, for instance, fatigue strength, de-icing behaviour and the effect of clogging of the pores.

Results obtained so far have given very useful information on the relationship between porous concrete composition (grading and size of aggregates, type and amount of additives, water/cement ratio, etc.) and porous concrete characteristics (accessible porosity, permeability, flexural tensile strength, compressive strength, splitting tensile strength, modulus of elasticity, frost-thaw resistance, etc.). These relationships were actually used to define the most appropriate mixtures to be used in specific projects.

In this paper the testing program carried out, as well as the results obtained so far and the corresponding practical consequences (in some cases already checked in several experimental stretches) are described.

1. INTRODUCTION

The unceasing growth of road traffic throughout Europe leads to ever greater noise pollution, to overburdening of the road network and to growing accident rates. The affected population is no longer prepared to pay this as a price for mobility. The development of less noise producing and safe road systems and a better utilization of the capacity of the existing road network is consequently one of the main objectives to be accomplished in road construction research.

In comparison with other types of pavements, concrete roads have a long service life. On the other hand, conventional concrete roads with a dense surface texture are being experienced noisier than dense asphalt roads due to their less favorable surface texture [1].

Besides its draining and water storing capacity drainage (porous) asphalt is known to reduce noise emission by traffic, more than other types of pavements due to the absorption of noise [2].

To reduce the noise emission a porous concrete top-layer would therefore be most effective.

Porous concrete has been in use for several years, mainly as a drainage sublayer for pavements or a draining pavement on for instance parking-lots [3]. Up till now, porous concrete has not been used as a noise absorbing and draining road surface.

The requirements concerning mechanical properties and durability for such a porous concrete are more rigid than for the previously mentioned applications. To develop a more durable type of porous concrete a laboratory program is being carried out as part of the project 'Optimization of the Surface Characteristics of Concrete Roads in Accordance with Environmental Acceptance and Traffic Safety', funded by the European Commission by means of the Brite/Euram project BE-3415. The laboratory studies are being carried out by Intron, institute for materials and environmental research, the Technical University of Catalonia (UPC) and the Research Institute of the German Cement Association (VDZ). The other participants on this Brite/Euram project are Hochtief, Technical University of Berlin, BASt (Germany), CUR, Cobeton (the Netherlands), Geocisa, IECA and Dragados (Spain).

This paper presents the first results of the laboratory studies and deals with the basic properties of porous concrete.

The limiting conditions considered for porous concrete are the following:

- noise emission and drainage properties similar to porous asphalt;
- acceptable strength and stiffness;
- adequate surface properties with respect to traffic safety (skid resistance, evenness);
- sufficient service life (bonding to underlaying dense concrete, frost-thaw resistance, effect of de-icing salts, fatigue, etc.);
- construction by means of currently available techniques;
- costs similar to porous asphalt.

Based on previous research in the Netherlands and Spain, the following practical requirements were defined [2, 3, 4, 5, 6, 7]:

- a maximum grain size of the aggregate of about 10 mm;
- a good bond between mortar and the coarse aggregate;
- the use of a gap-graded aggregate material;
- an accessible porosity of 20 to 25% (V/V) (continuous pores which are in connection with open space);
- a workability of the fresh porous concrete mix corresponding with a compaction factor according to DIN 1048 of 1.20 ± 0.02 (with respect to construction of the porous concrete layer with a slip-form paver);
- a flexural tensile strength of minimally 3.0 MPa after 28 days of hardening;
- a splitting tensile strength of minimally 2.0 MPa after 28 days of hardening.

2. RESEARCH PROGRAM

As locally available aggregates must be used, each country had to develop their own porous concrete mixture. The available aggregates are listed in table 1.

This was thought necessary, because experiences from previous tests have learned that the type of aggregate may have a major influence on mix composition and mix properties [3]. The main parameters studied were the grading and maximum size of aggregates, and the type of additives (polymers, silica fume, superplasticizers) to be used. Results from these tests were used to define specific mixtures which were used in experimental stretches. Optimization of the mix composition of porous concrete has been based on:

- workability,
- flexural tensile strength,
- compressive strength,
- splitting tensile strength,
- accessible porosity,
- permeability,
- frost-thaw resistance,
- skid resistance.

The optimum mix composition will be tested for:

- strength development in time,
- direct tensile strength,
- modulus of elasticity,
- fatigue behaviour,
- noise absorption,
- matrix structure,
- permeability (drainage) and the effect of dirt input,
- de-icing behaviour,
- bond strength to dense concrete,
- UV resistance (only polymer modified mixtures),
- moist resistance (only polymer modified mixtures).

Since the research program continues up to 1993, part of this testing program has not yet finished.

3. FRESH POROUS CONCRETE

Mix composition

The basic composition of the porous concrete mixtures is shown in table 2.

Mixing and curing of porous concrete

The materials were mixed in the following order:

1. coarse and fine aggregates
2. cement
3. additives + water

Fresh porous concrete has been produced in a pan mixer. The mixing time (after adding all the materials) equalled 1.5 minutes. After mixing, test samples were made (cubes, prisms and cylinders). The samples were compacted by vibrating.

Mixtures without polymer were cured for one day in the mould at 20°C. Thereupon, the test specimens were stored at 20°C for 6 days in lime saturated water followed by storage at 20°C and 65% R.H. (Germany and the Netherlands). In Spain the test specimens were stored for one day in the mould at 20°C and thereupon, the test specimens were stored at 20°C and 95% R.H.

Mixtures with polymer additive were cured for one day in the mould at 20°C preventing drying out. Thereupon, the test specimens were stored at 20°C and 65% R.H. (Germany and the Netherlands) or at 20°C and 50% R.H. (Spain).

Workability

The workability of fresh porous concrete is characterized by means of the compaction factor (DIN 1048). Based on the results of the Dutch research program, the compaction factor of fresh porous concrete should equal 1.20 ± 0.02, if the porous concrete is to be laid with a slip-form paver. In the case of porous concrete laid by an asphalt paving machine, the compaction factor will be higher. A reference value for this type of paving machine has not yet been established, but from full scale tests the workability did not seem as critical as was found from tests with a slip-form paver [3, 8].

The laboratory tests have shown that in case of polymer modified porous concrete, the time available for transporting and laying the fresh porous concrete must be limited compared to mixtures without polymer addition, especially at higher temperatures and for a higher polymer content. Also, the type of polymer is of importance. The compaction factor is shown in table 3 as a function of the type of polymer, the polymer content, the temperature of the mixture (air temperature) and the time elapsed after mixing.

4. EFFECT OF MIX COMPOSITION ON THE STRENGTH PROPERTIES OF HARDENED POROUS CONCRETE

Aggregates

The effect of the grain size of the coarse and fine aggregates on strength is illustrated in the figures 1 and 2.

From these figures it follows that the grain size of the fine aggregate has a major effect on accessible porosity and strength, while the grain size of the coarse aggregate does not seem to have a significant effect.

It is obvious that a porous concrete mixture requires a gap-graded grain size distribution of the aggregate. Coarse aggregate 5/8 combined with fine aggregate 0/5 gives an almost continuous grain size distribution. The stability of the grain skeleton is poor (no contact between the coarse grains) and therefore, strength is poor.

But when the grain size of the fine aggregate is small compared to the grain size of the coarse aggregate (5/12 combined with 0/3, or 5/8 combined with 0/2), the stability of the grain skeleton is much better and strength increases. On the other hand, the amount of fine aggregate is also important. This amount must be adapted to the size of the pores (grain size of the coarse aggregate), as is shown in reference 3. This factor may have influenced the results shown in figures 1 and 2, since the mixture based on 5/8 and 0/2 contains less sand than the other mixtures.

According to figures 1 to 2 it may be concluded that:

1. Strength nor accessible porosity are significantly influenced by the size of the coarse aggregate.
2. Strength is controlled by the amount of accessible porosity (strength decreases with increasing accessible porosity).
3. Strength and accessible porosity depend on the grain size of the fine aggregate in relation to the grain size of the coarse aggregate and the amount of fine aggregate. A gap-graded grain size distribution of the aggregate is required.

Since the Spanish commercially available aggregates are restricted to 0/5 and 5/12 (continuous grain size distribution), it is necessary to limit the amount of fine aggregate. An amount of fine aggregate of 175 kg/m^3 appeared obvious too much. Further tests were carried out using 100 kg/m^3.

Additives

Polymer

Previous research has shown that polymer additive improves the frost-thaw resistance substantially [3]. Nine types of polymer have been investigated. To compare the influence of the type of polymer on strength, mixtures with 10% polymer solids (by weight of cement) have been compared (see figures 3 to 5). The strength is shown as a function of accessible porosity.

The data shown in the figures 3 to 5 cannot be compared without considering the differences in strength due to differences in grain size distribution of the mixtures. Since the relationship between accessible porosity and strength is well defined when only one mixture is considered (see solid lines in figures 1 and 2), dotted lines have been drawn in the figures 3 to 5 having a slope equal to the slope of the lines in figures 1 and 2. The slope of the lines in figure 4 are based on the results from the test section at Texel [8]. Taking into account the fact that the mixtures with coarse aggregate 5/12 and fine aggregate 0/5 have a somewhat lower strength than the mixtures based on aggregate 4/8 or 5/8 and fine sand, it was found that the polymer emulsions A, C, E, F and H gave the best results regarding strength. The lowest strength has been obtained for polymer emulsion G, while polymer emulsions B, D and I take an intermediate position.

For polymer emulsion E, the effect of polymer content on strength has been investigated. Taken into account the difference in accessible porosity, which has an important influence on strength, it seems that the polymer content has no significant effect on compressive strength (see figure 6) nor on splitting tensile strength (see figure 7).

In general the addition of a polymer emulsion gives rise to an increase in flexural tensile strength (see figure 9), while compressive strength and splitting tensile strength remain more or less the same.

Silica fume

To determine the effect of silica fume, two mixtures have been tested. First a mixture with silica fume only and second a mixture with both silica fume and 10% polymer solids (by weight of cement). In both mixtures silica fume has been added as a suspension consisting of 50% water and 50% silica solids together with a superplasticizer. The results are compared to mixtures without silica fume (see figures 8 to 10).

According to these figures it can be seen that the addition of silica fume has no significant effect on the strength properties of porous concrete after 28 days of hardening.

Superplasticizer

The addition of polymer to a porous concrete mixture reduces the amount of water needed to fulfil workability requirements. In the case of 10% polymer solids (by weight of cement) this reduction is sufficient. But if only 5% polymer solids (by weight of cement) are added, still a relatively large amount of water is required. This will have a negative effect on strength properties and durability. To reduce the water content furthermore, a superplasticizer is added.

For one type of mix, the influence of the type of superplasticizer on strength has been determined. This porous concrete mix contained 5% of polymer solids (by weight of cement, polymer emulsion E). The results of the tests are shown in figures 11 and 12. These figures show compressive strength and flexural tensile strength as a function of the dry density, which is strongly related to (accessible) porosity.

It has been shown that the type of superplasticizer has no influence on strength properties of polymer modified porous concrete, except for superplasticizer B which gives a somewhat lower strength after 7 days of hardening [8]. This is caused by the addition of a retarding agent to the superplasticizer. After 28 days of hardening no difference in strength between the several types of superplasticizer occurred.

Because the addition of a retarding agent can cause problems related to insufficient strength development when curing is poor, only additives that have no effect on early strength are acceptable [8].

5. DRAINAGE PROPERTIES OF POROUS CONCRETE

Drainage characteristics of porous concrete are determined by its permeability, which is closely related to the accessible porosity (see figure 13).

For an accessible porosity of 25% (V/V) the coefficient of permeability equals about 0.01 m/s. The results gave the impression that not the grain size of the coarse aggregate determines the permeability of porous concrete, but the grain size of the fine aggregate. This may be caused by the enlarging of the distance between the coarse grains when the grains of the fine aggregate do not fit into the pores of the coarse aggregate grain skeleton. Thus, more continuous pores, which control the permeability, may be formed. Of course, the amount of mortar also has a major effect on permeability.

6. SOME MECHANICAL PROPERTIES OF POROUS CONCRETE

Compressive strength

As shown in the previous chapter, strength of porous concrete depends on the grain size distribution of the aggregate, (accessible) porosity and the type of additive. In reference 1 it has been stated that an acceptable noise reduction comparable to drainage asphalt requires an accessible porosity of at least 25% (V/V). In case of an accessible porosity of 25% (V/V) the compressive strength that can be reached will be about 18 MPa. This seems to be the maximum compressive strength of porous concrete at this porosity (see figures 1 and 3).

Flexural tensile strength

According to figure 4 the maximum flexural tensile strength at 25% (V/V) accessible porosity will be about 4 MPa (German mixture without silica fume). This fulfills the stated requirement of at least 3.0 MPa. Comparing the flexural tensile strength of porous concrete with and without polymer additive, it appears that porous concrete without polymer additive cannot fulfil the stated minimum flexural tensile strength. According to figure 4 both mixtures with 5 and 10% polymer solids (by weight of cement) seem to fulfil strength requirements. Therefore, the necessity of adding 10% polymer solids (by weight of cement) may be questionable, especially since the difference in flexural tensile strength between mixtures with 5 and 10% polymer solids is small (see figure 14).

Splitting tensile strength

The effect of polymer addition on splitting tensile strength seems minimal, like compressive strength (see figure 7). For an accessible porosity of 25% (V/V), the maximum splitting tensile strength will be about 2 MPa. This meets the stated design criterion of at least 2.0 MPa after 28 days of hardening.

Modulus of elasticity

The dynamic modulus of elasticity has been measured by means of ultra sonic testing. It was assumed that the Poisson constant equalled 0.20. The effect of accessible porosity and compressive strength on the dynamic modulus of elasticity is shown in figures 15 and 16, respectively.

According to figures 15 and 16 it appears that addition of polymer decreases the modulus of elasticity. For an accessible porosity of 25% (V/V), the dynamic modulus of elasticity equals about 20 to 25 GPa.

7. MATRIX STRUCTURE OF POROUS CONCRETE

The structure of the polymer-cement matrix of porous concrete has been studied with a scanning electron microscope (SEM). Samples of the porous concrete were put in acid in order to dissolve the cement and make the structure of the polymer particles (threads) visible. Porous concrete with 10% (m/m) of polymer solids (by weight of cement) is shown in figure 17. The polymer is distributed homogeneously throughout the matrix and a continuous mesh of polymer threads has formed that strengthens the cement stone matrix.

Porous concrete with 5% (m/m) of polymer solids (with respect to the weight of cement), the polymer is not distributed homogeneously any more. At some spots more polymer can be found than at other spots, while the polymer has formed threads only to a lesser extent, or not at all.

8. DURABILITY OF POROUS CONCRETE

Frost-thaw resistance

Especially in northern countries the destructive mechanism of freezing and thawing has a major effect on the life of road materials, particularly when de-icing salts are involved. Since porous concrete forms the top layer of the pavement, it is exposed to the most severe conditions. Therefore high demands are made upon the durability of porous concrete. In the case of frost-thaw resistance it has been shown that a polymer additive is needed to improve durability [3].

In order to optimize the type of polymer in relation to frost-thaw resistance, tests have been carried out with different types of polymer.

In the Netherlands test specimens were used which have been obtained by drilling cores ∅ 100 mm from cubes after about 14 days of hardening. The top and bottom part of each core was sawn off. The test specimens were then stored at 20°C and 65% R.H. After 28 days of hardening the test specimens were cleaned and all loose particles were removed. In Germany cubes ⌑100 mm were used which were stored at 20°C and 65% R.H. After 28 days of hardening testing started.

Before subjecting the test specimens to freezing and thawing, the test specimens were placed under water in a 3% solution of sodium chloride during 24 hours followed by a draining period of ½ hour.

Each cycle of freezing and thawing consisted of:

1. freezing at 20°C during 16 hours by which the test specimens were stored at about 95% R.H., followed by
2. thawing at +20°C during 7½ hours by which the test specimens were stored under water in a 3% solution of sodium chloride, followed by
3. draining during ½ hour.

After each tenth cycle, the loss of weight of each test specimens has been determined by collecting the loose particles and to dry and weigh them. For each mixture five test specimens were tested. It was not possible to determine compressive strength, because the test specimens were destroyed or damaged too much at the end of the testing period.

In order to make the differences in frost-thaw susceptibility of polymer modified porous concrete visible, the number of cycles after which the loss of weight equals about 10% (m/m) is given in table . From the results it followed that in general frost-thaw susceptibility improves when the polymer content is increased. On the other hand the type of polymer emulsion is critical. According to table 4 porous concrete with polymer A, C, E or F shows a better result with respect to freeze-thaw resistance than porous concrete with polymer B or I.

Besides the standard way of testing (freezing in air and thawing under water), porous concrete has also been tested while the lower part (1 cm) of the test specimen being submerged in a 3% solution of sodium chloride. This way of testing seems realistic, as it is likely that the lower part of the porous concrete layer may become saturated with water. In winter times (thawing during the day and freezing at night), the porous concrete may become heavily attacked by the action of frost and thaw this way. This second test method appeared more destructive than the first test method. The results of these tests indicated that polymer E gives a better freeze-thaw resistance to porous concrete than polymer C or F.

The addition of silica fume improves the resistance to freezing and thawing further more.

Wear of porous concrete and resistance to mechanical impact

In order to test the resistance of porous concrete to impact forces, test specimens of porous concrete have been subjected to impact forces according to the Cantabro test. The Cantabro test is a modified Los Angeles test, but without the steel balls. This modified test was originally developed to study mixtures of porous asphaltic concrete. In the case of asphaltic concrete this test is useful in showing a relationship between the loss of weight and the resistance of the drainage asphalt to impact forces by traffic under real conditions.

For porous concrete several tests have been performed, the results of which are shown in figure 18.

The loss of weight of porous concrete after 300 cycles is comparable to the loss of weight of drainage asphalt. The Cantabro test gives an impression of the coherence of the porous concrete in relation to pulling out of grains from the matrix. A good correlation has been found between the loss of weight and the compressive strength of porous concrete.

For drainage asphaltic concrete the limiting value for the loss of weight equals 30%. It has not been possible yet to set a limiting value for this test for porous concrete. According to figure 18 this criterion is fulfilled when the compressive strength of porous concrete is at least 10 MPa. Thus, for 'normal' porous concrete the results of the Cantabro test are comparable to drainage asphalt. On the other hand it is not known if the criterion of a maximum loss of weight of 30% may be applicable to porous concrete. Also, the suitability of this test for porous concrete is not known yet. From figure 18 it appears that the addition of polymer has no significant effect on the loss of weight.

Resistance to wetting and drying

Since the polymer in practice might degrade due to alternating wetting and drying out, so that porous concrete may loose (tensile) strength and durability in time, test are being carried out in order to determine the durability of polymer in porous concrete.

Test prisms of the porous concrete have been subjected to cycles of alternating wetting and drying, starting after 28 days of hardening. Each cycle consisted of storing the prisms for 2 days under water followed by 12 days drying in air at 20°C and 65% R.H. After a given number of cycles the flexural tensile strength of three prisms has been measured. Also, the flexural strength of three reference test specimens (continuously stored at 20°C and 65% R.H.) has been measured. According to the results so far no deterioration of porous concrete can be observed after 5 cycles.

9. CONCLUSIONS

From the results so far, the following conclusions can be drawn:

1. During the first hour after mixing, the workability noticeably decreases in time. The measure of decrease in time depends on the type of polymer, temperature and polymer content.
2. The grain size of the coarse aggregate has no significant influence on strength or accessible porosity. On the contrary, the grain size distribution and the amount of the fine aggregate have a major effect on strength and accessible porosity. Strength and accessible porosity are directly related. The mixture of fine and coarse aggregate should have a gap-graded grain size distribution (not continuous).
3. The type of polymer emulsion affects the strength properties of porous concrete. The addition of polymer gives rise to an increase in flexural tensile strength. Compressive strength does not change, but the dynamic modulus of elasticity decreases. The addition of at least 5% of polymer (solids by weight of cement) is necessary in order to obtain an acceptable resistance to freezing and thawing. The type of polymer is very important in relation to frost-thaw resistance. The addition of polymer does not seem to improve the resistance to mechanical impact.
4. The addition of silica fume has no significant effect on the strength properties of porous concrete after 28 days of hardening, but improves the frost-thaw resistance of porous concrete.

5. Porous concrete with an accessible porosity of 25% (V/V) will have a maximum compressive strength of about 18 MPa and a splitting tensile strength of about 2 MPa. If polymer is added the flexural tensile strength may be increased to about 4 MPa. The dynamic modulus of elasticity will be about 20 to 25 GPa.
6. Among others, the permeability of porous concrete seems to be affected by the grain size of the fine aggregate.

10. REFERENCES

1. Onstenk, H.J.C.M., 'Tire noise and road surface characteristics, report No. 91175 by order of CUR, interim report subtask 1.1, BRITE/EURAM project BE-3415, Intron, Sittard, June 1991.
2. Rosell, J.J., Aguado, A., Josa A., 'Porous Concrete for Urban Pavements', 6th International Symposium on Concrete Roads, Madrid, 1990.
3. Eerland, D.W., Onstenk, H.J.C.M. Ubachs, W.G.M., 'Betonwegdekken met verminderde geluidsemissie (Concrete roads with reduced noise emission)', report No. 90510 by order of CUR, Intron, Sittard, April 1991 (in Dutch).
4. Aguado, A., Rosell, J.J., Josa, A., 'Aplicaciones del hormigón poroso en pavimentos urbanos', Cemento-Hormigón No. 694, 1991, p. 611-625.
5. Eerland, D.W., Grob, Th.S., Onstenk, H.J.C.M., 'Developments in noise reduction of concrete roads in the Netherlands', Proceedings of 6th International Symposium on Concrete Roads, Theme A, Volume III, Madrid, 1990, p. 55-64.
6. Rosell, J.J., Aguado A., 'Teoría, práctica y aplicaciones del hormigón poroso de cemento', Simposio sobre el Agua y el Terreno en las Infraestructuras Viarias, Comunicación No. 1.09, Torremolinos, 1988.
7. Rosell, J.J., Aguado, A., Dolz, J., 'From theory to practice of porous cement concrete', 1st International Congress, R.I.L.E.M. ' De la Science des materiaux au genie des materiaux de construction', Paris, 1987.
8. Onstenk, H.J.C.M., 'Porous concrete - Test section Texel', report No. 91185 by order of CUR, Interim report subtask 3.3, BRITE/EURAM project BE-3415, Intron, Sittard, September 1991.

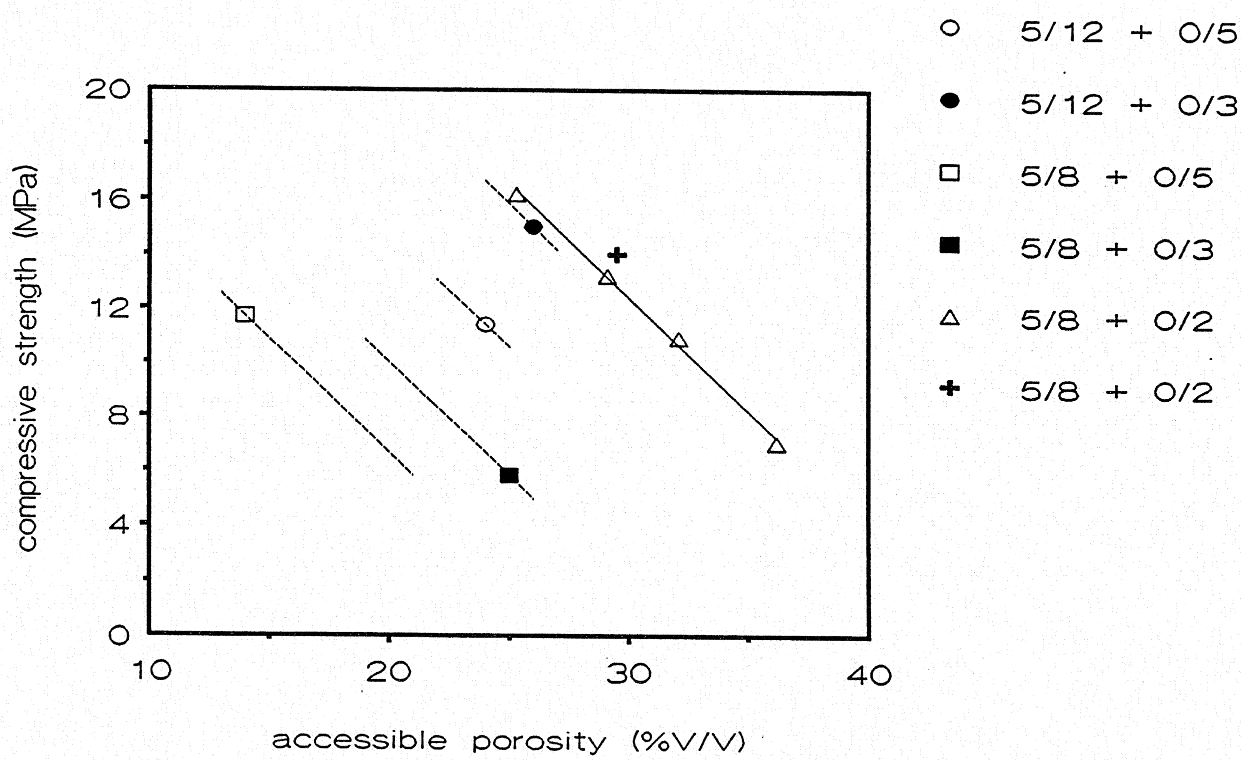

Figure 1. Effect of aggregates on compressive strength after 28 days (no additives).

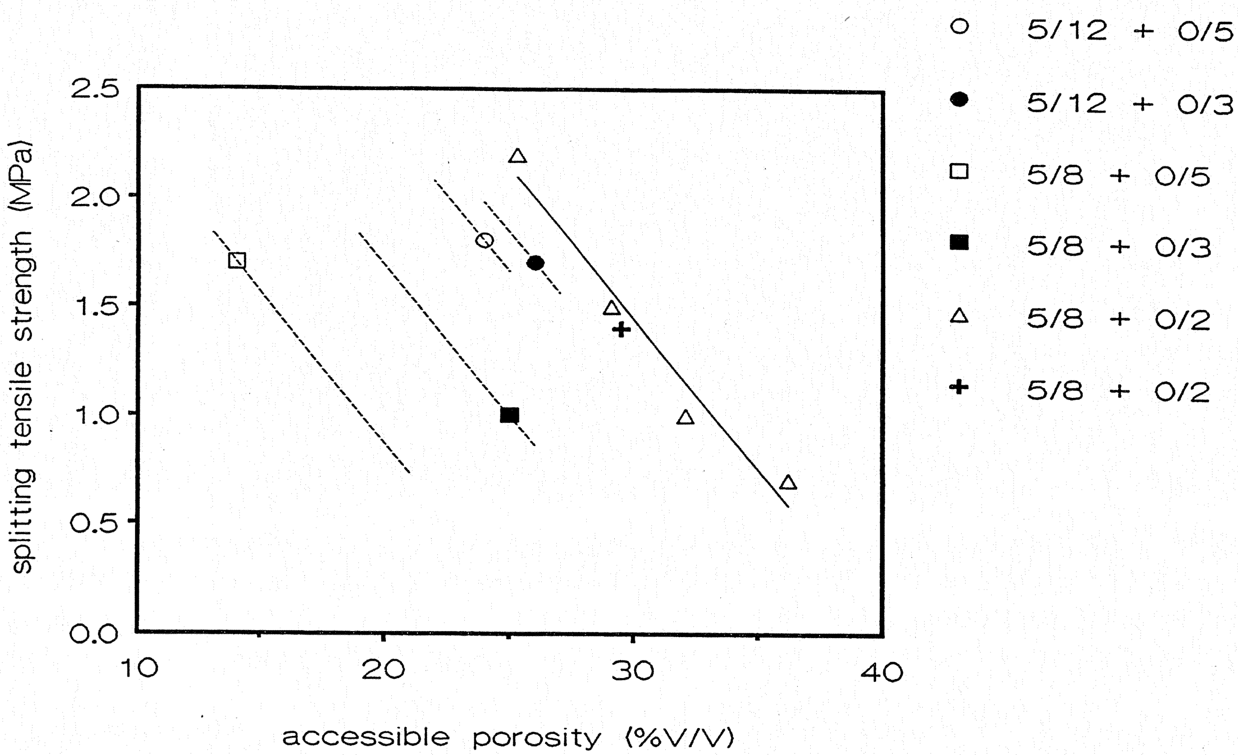

Figure 2. Effect of aggregates on splitting tensile strength after 28 days (no additives).

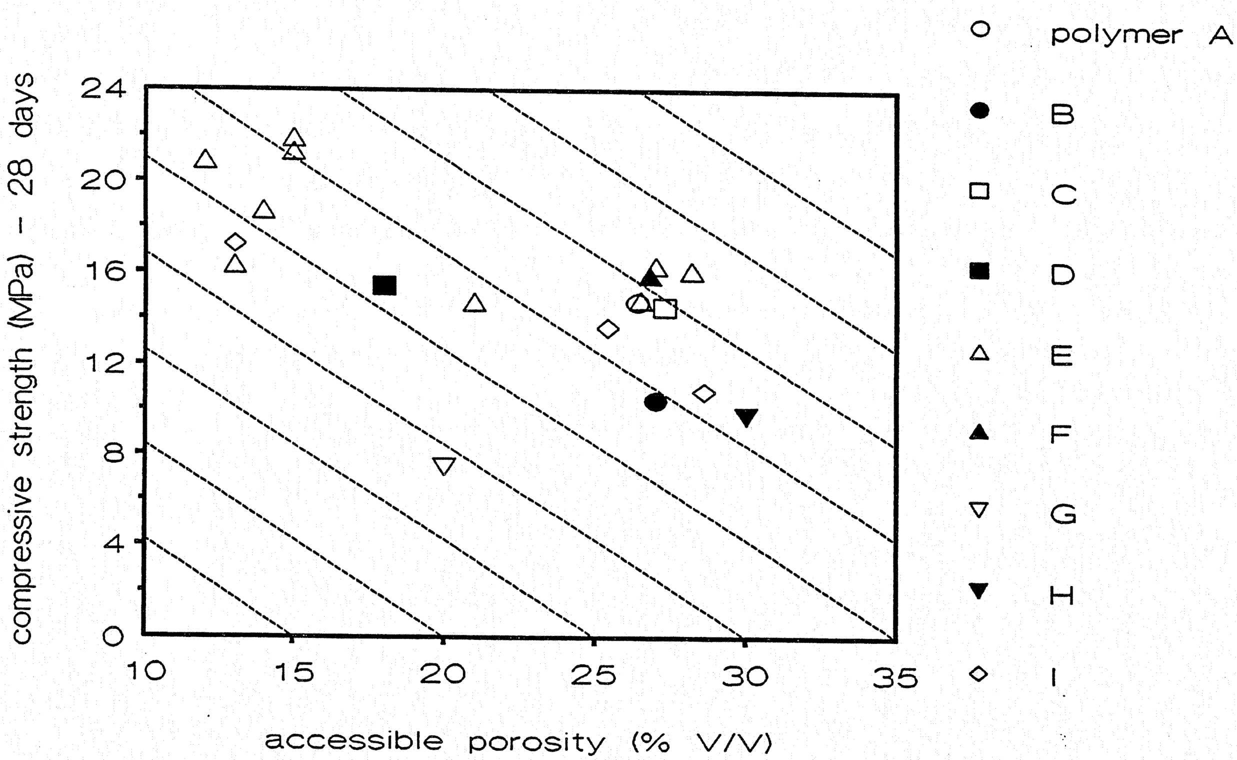

Figure 3. Compressive strength (polymer additive).

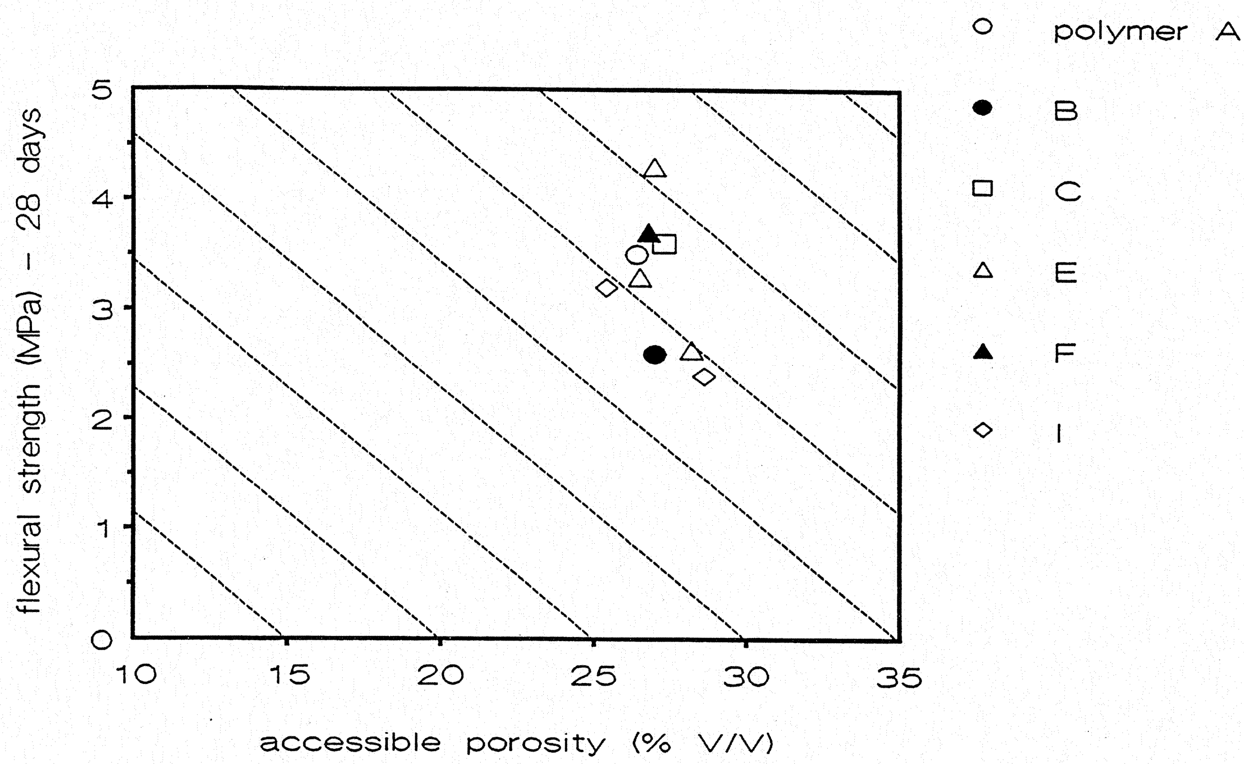

Figure 4. Flexural tensile strength (polymer additive).

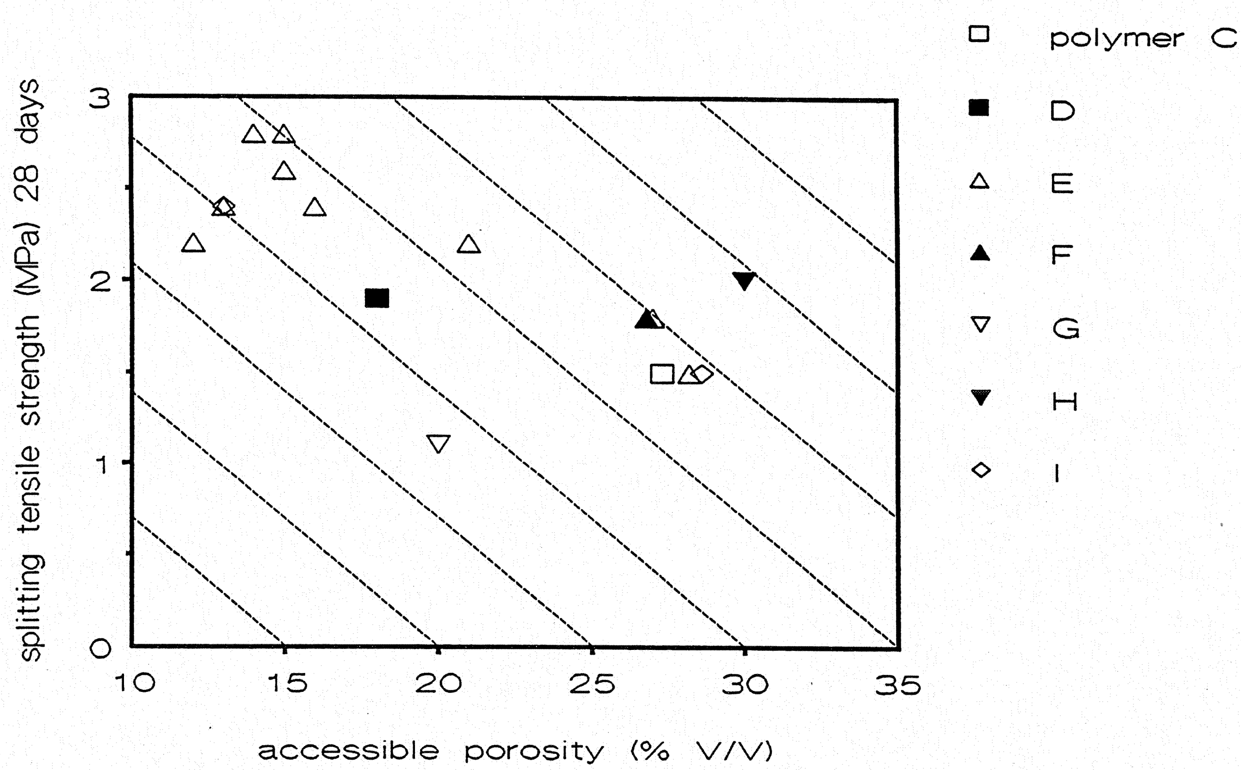

Figure 5. Splitting tensile strength (polymer additive).

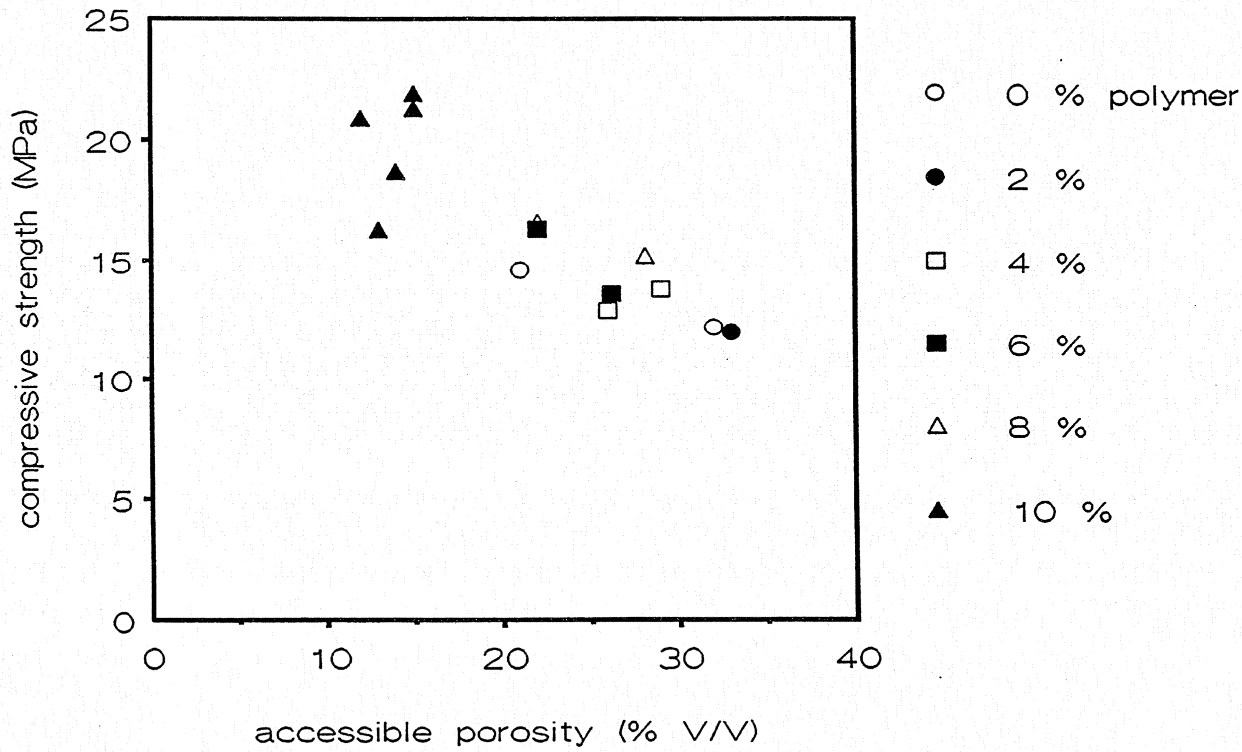

Figure 6. Compressive strength and polymer content (polymer emulsion E, aggregates 5/12 and 0/5).

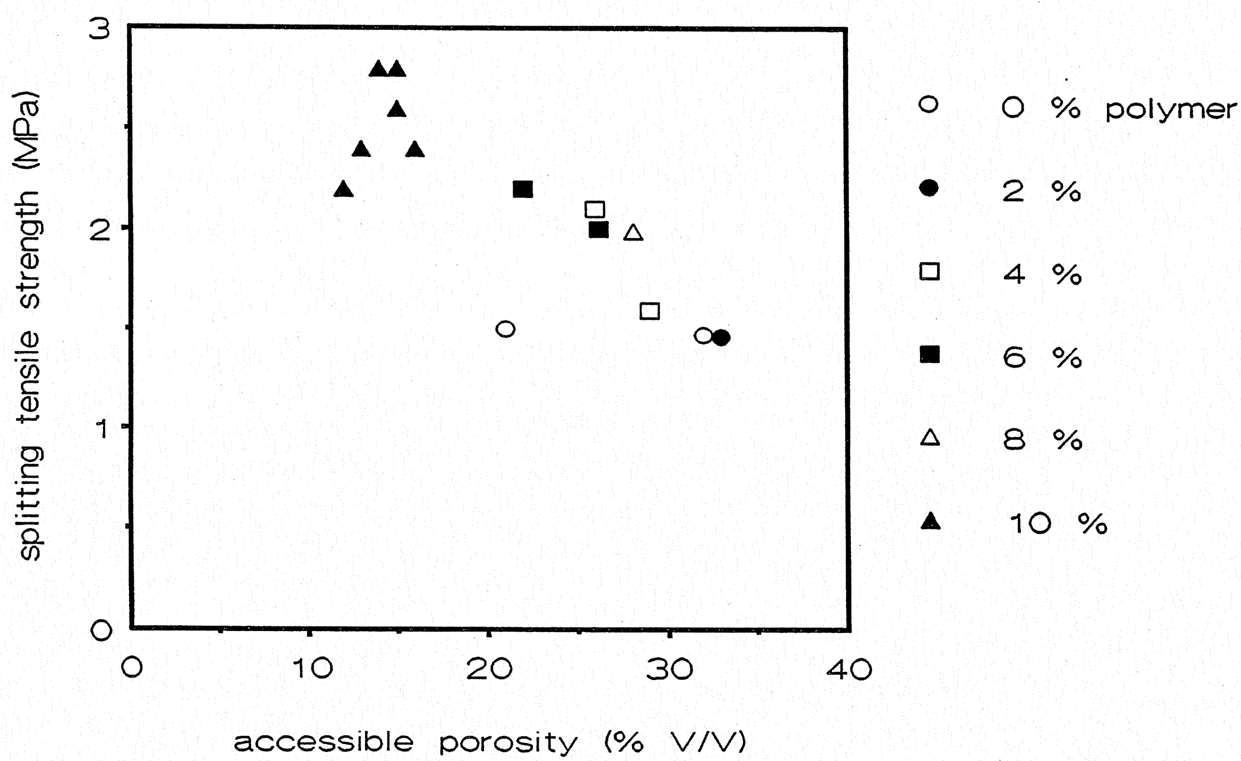

Figure 7. Splitting tensile strength and polymer content (polymer emulsion E, aggregates 5/12 and 0/5).

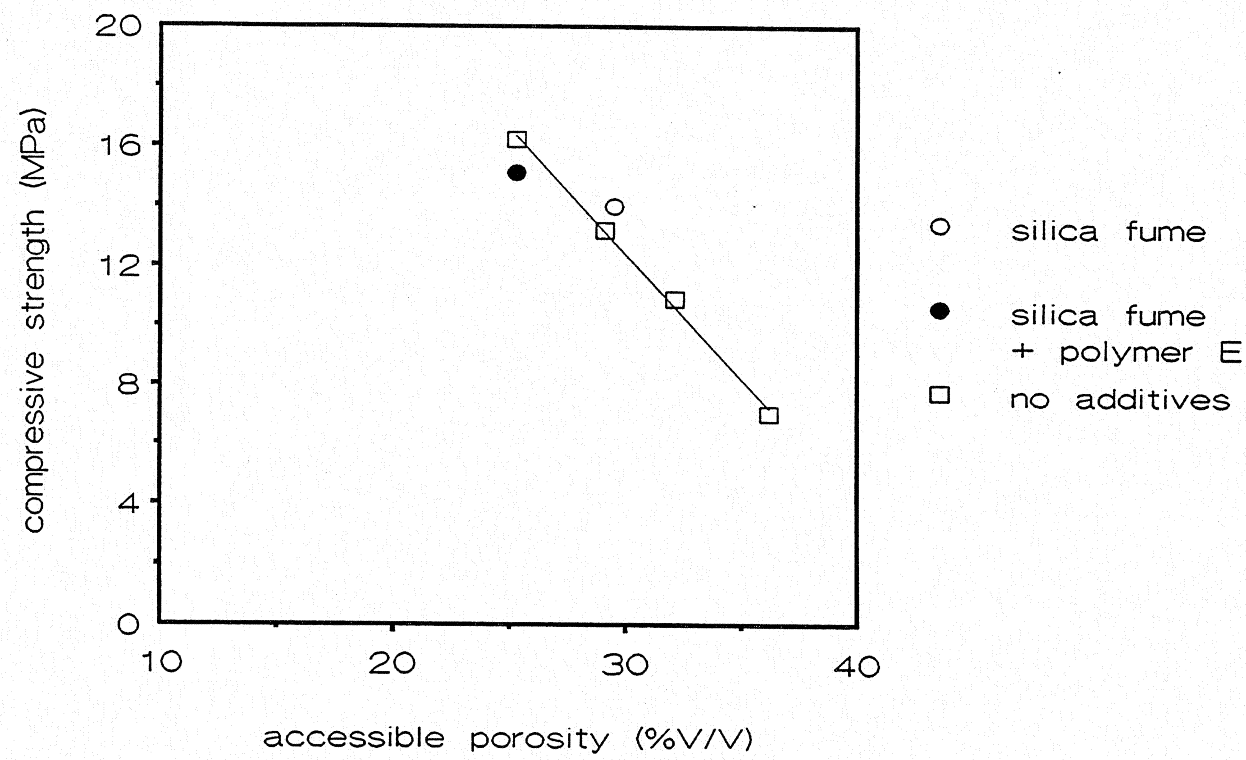

Figure 8. Compressive strength - 28 days of hardening (silica fume, aggregates 5/8 and 0/2).

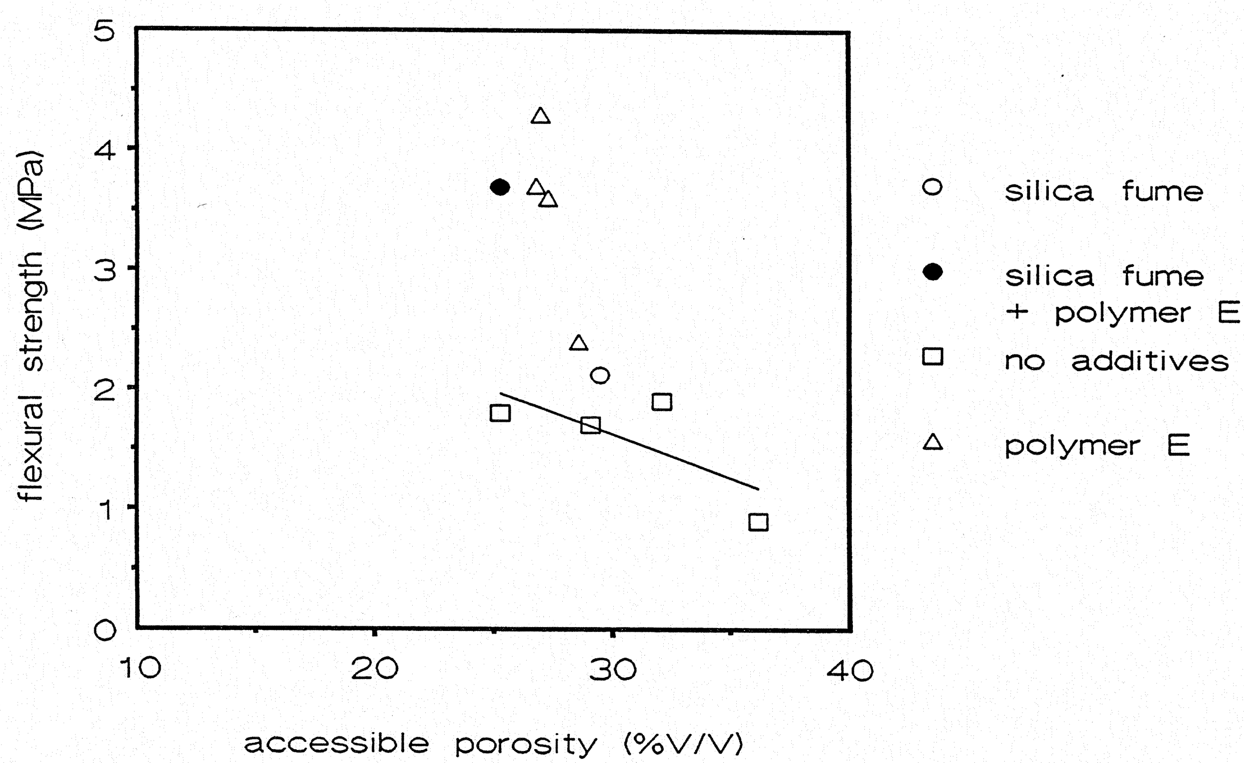

Figure 9. Flexural tensile strength - 28 days of hardening (silica fume, aggregates 5/8 and 0/2).

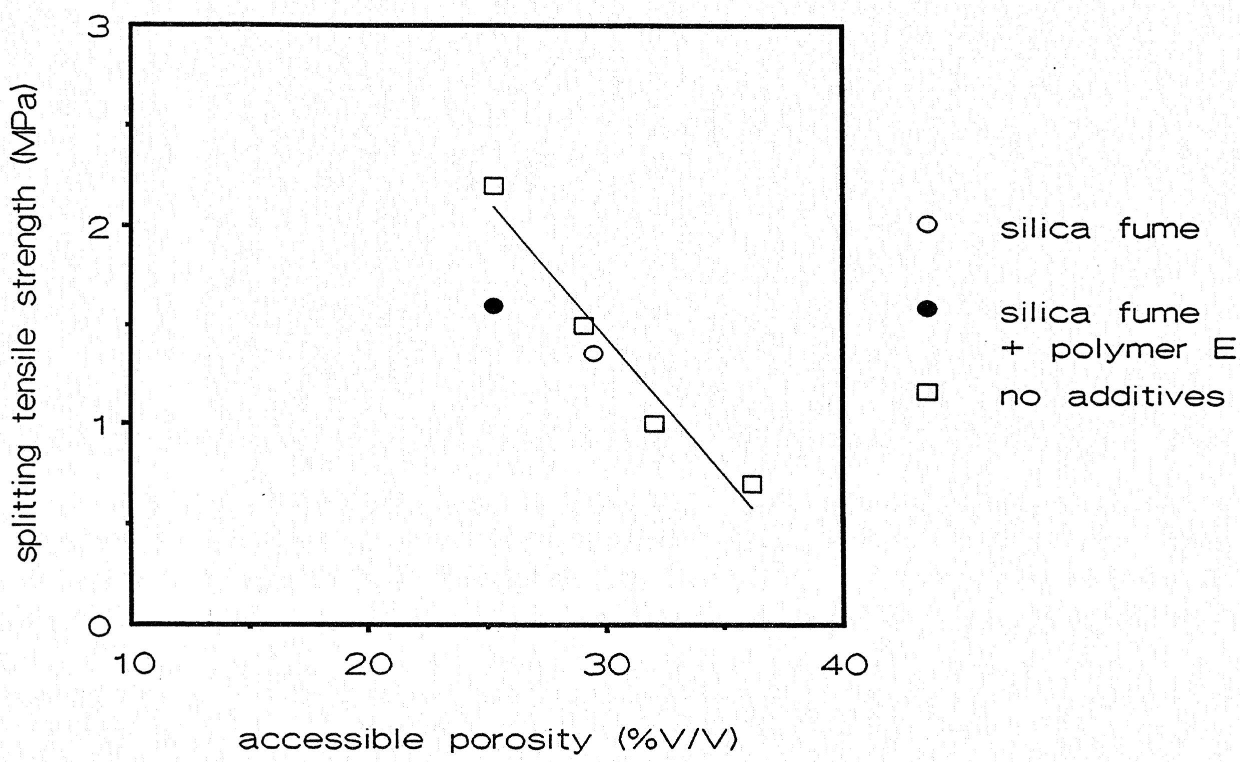

Figure 10. Splitting tensile strength - 28 days of hardening (silica fume, aggregates 5/8 and 0/2).

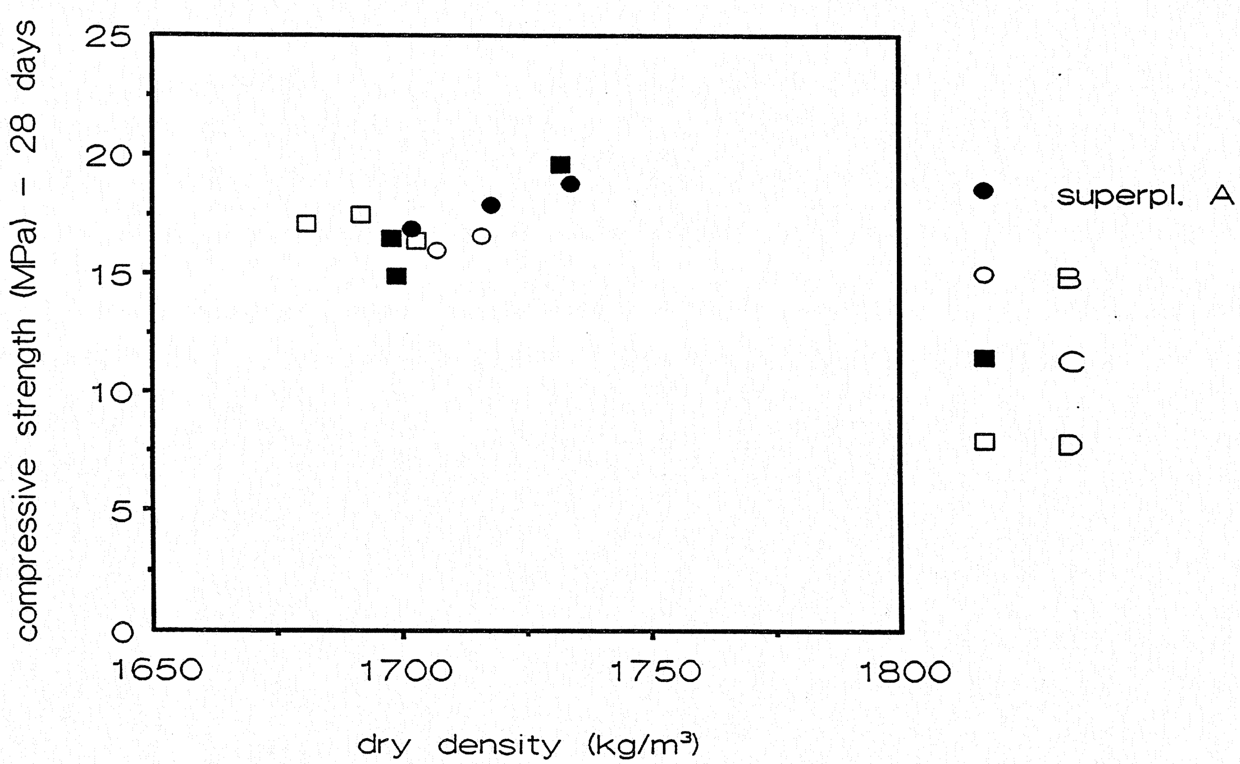

Figure 11. Compressive strength - 28 days of hardening (superplasticizer, aggregates 4/8 and 0/1).

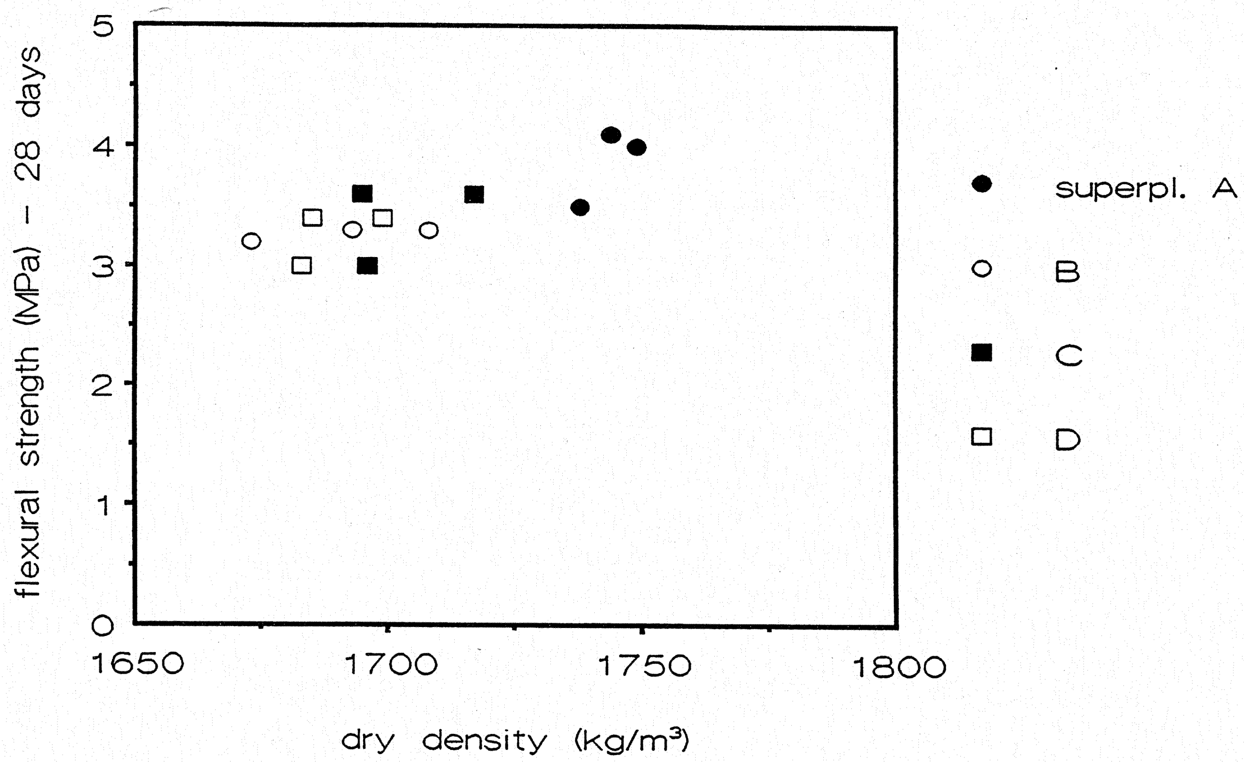

Figure 12. Flexural tensile strength - 28 days of hardening (superplasticizer, aggregates 4/8 and 0/1).

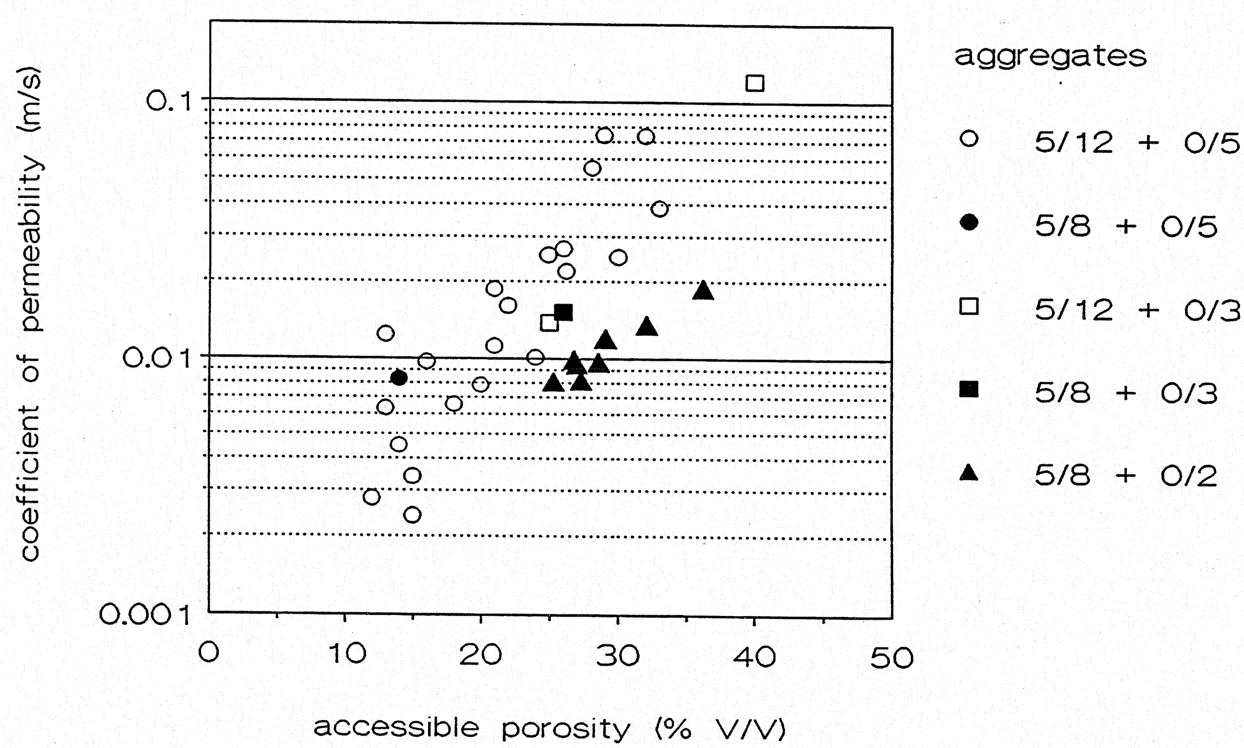

Figure 13. Permeability of porous concrete.

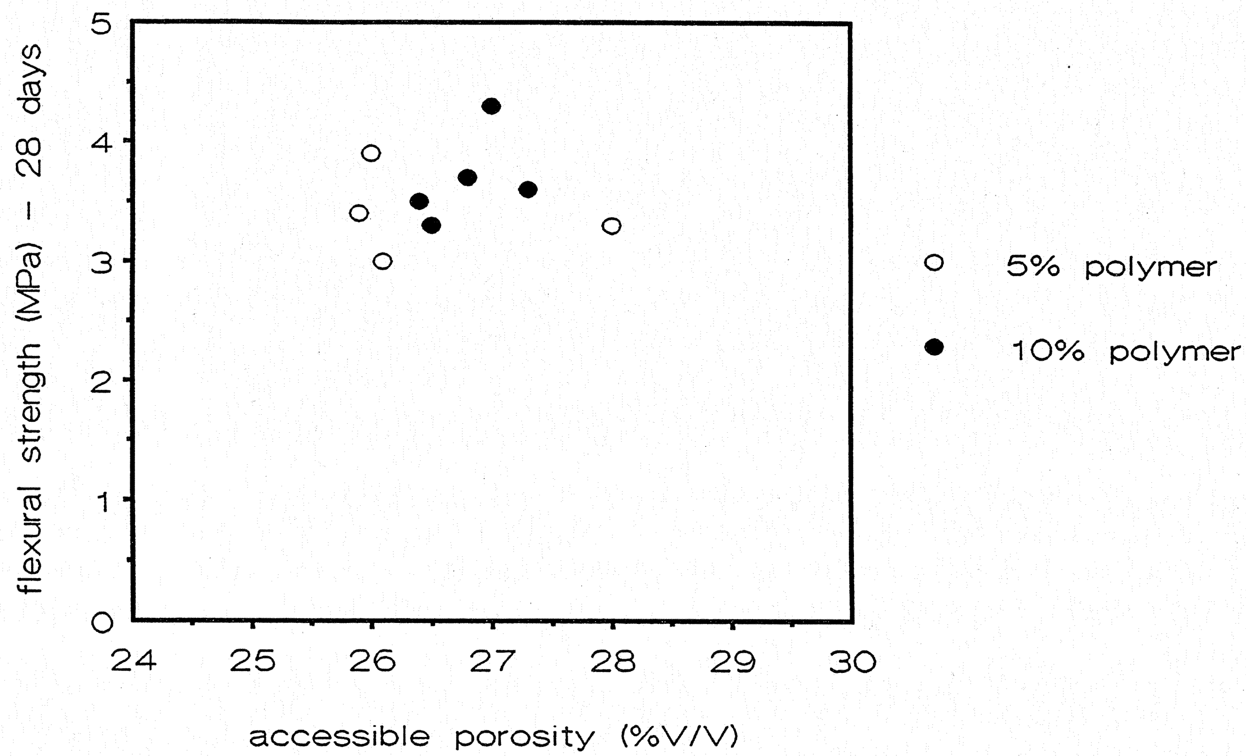

Figure 14. Flexural tensile strength of polymer modified porous concrete (polymer emulsion E, aggregates 4/8 and 0/1).

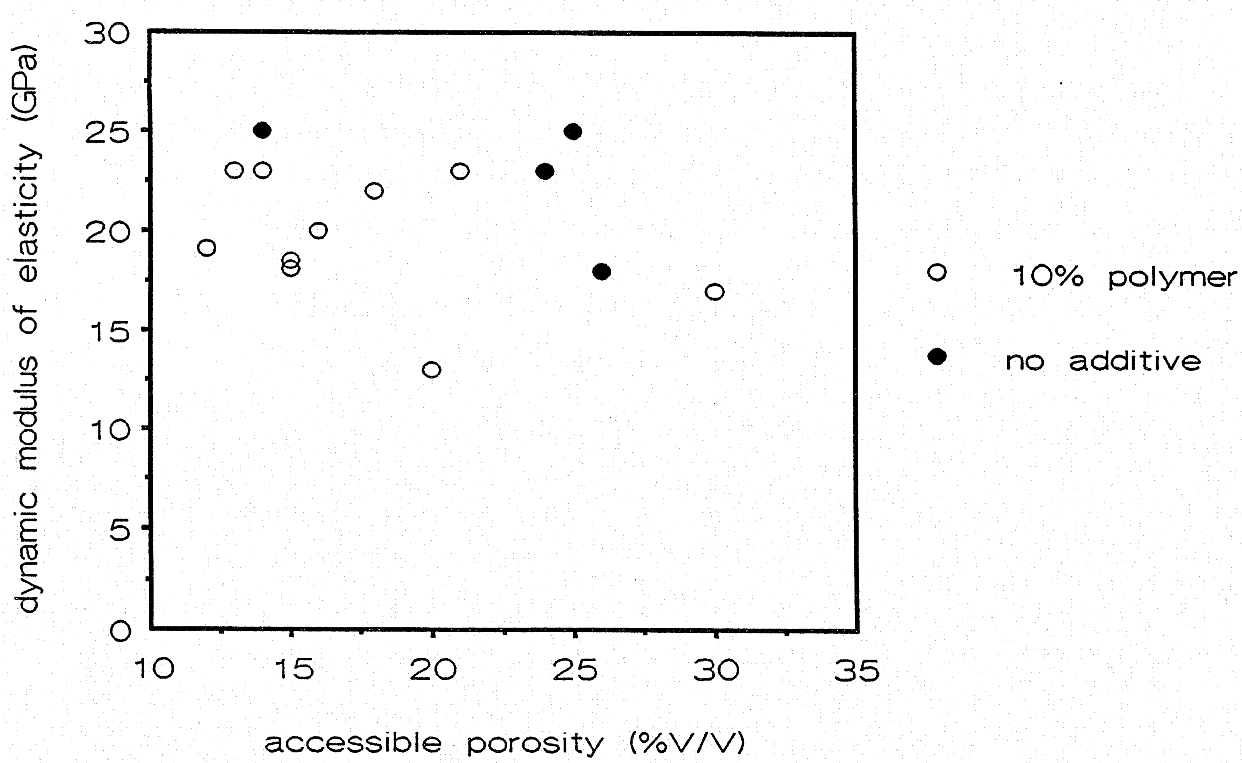

Figure 15. Dynamic modulus of elasticity versus accessible porosity (polymer emulsion E, aggregates 5/12 and 0/5).

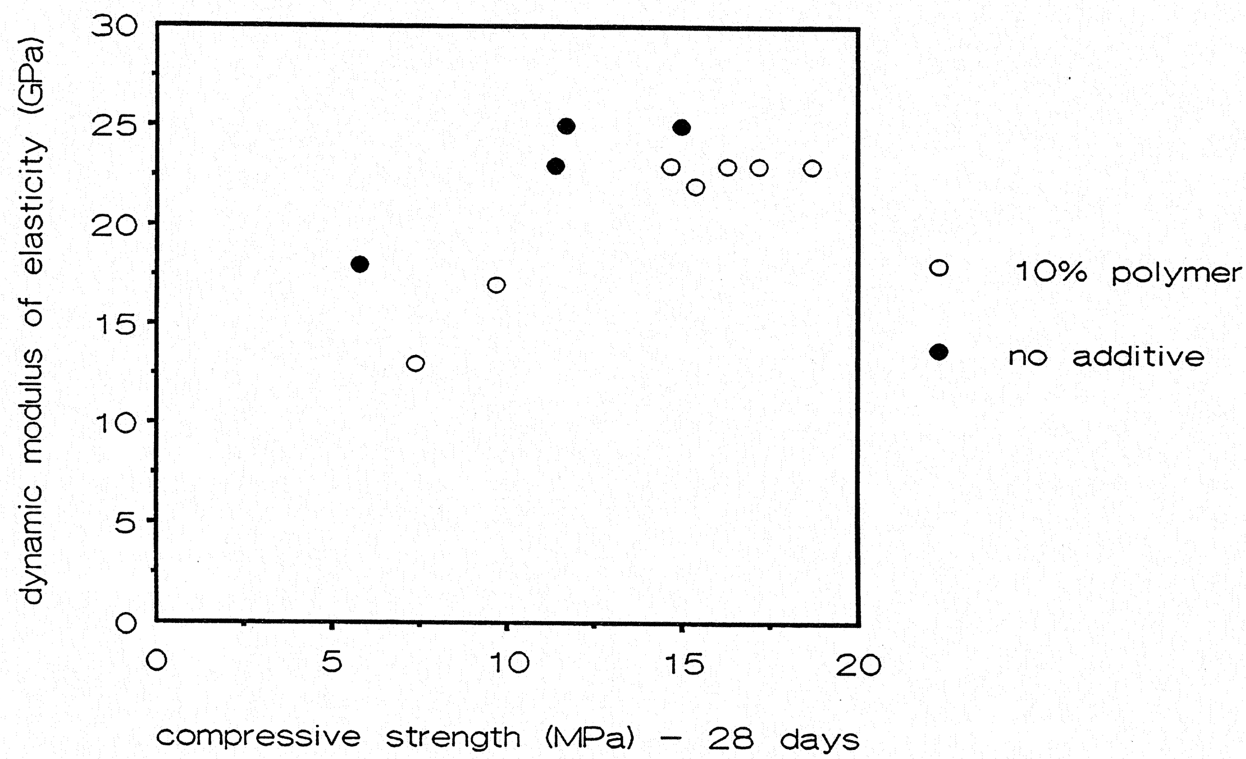

Figure 16. Dynamic modulus of elasticity versus compressive strength (polymer emulsion E, aggregates 5/12 and 0/5).

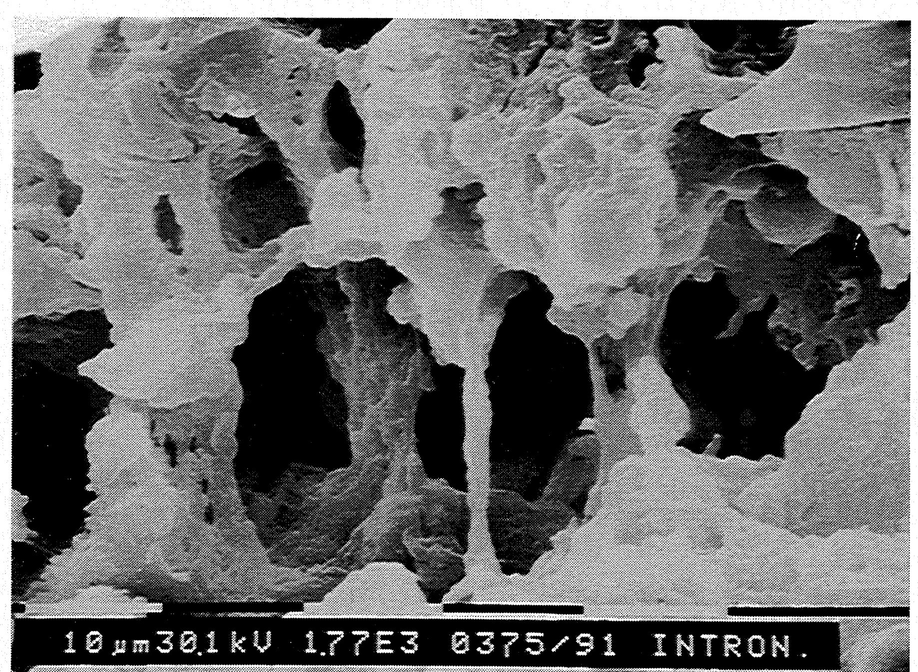

Figure 17. Polymer matrix (10 % polymer solids by weight of cement) of porous concrete [1770×].

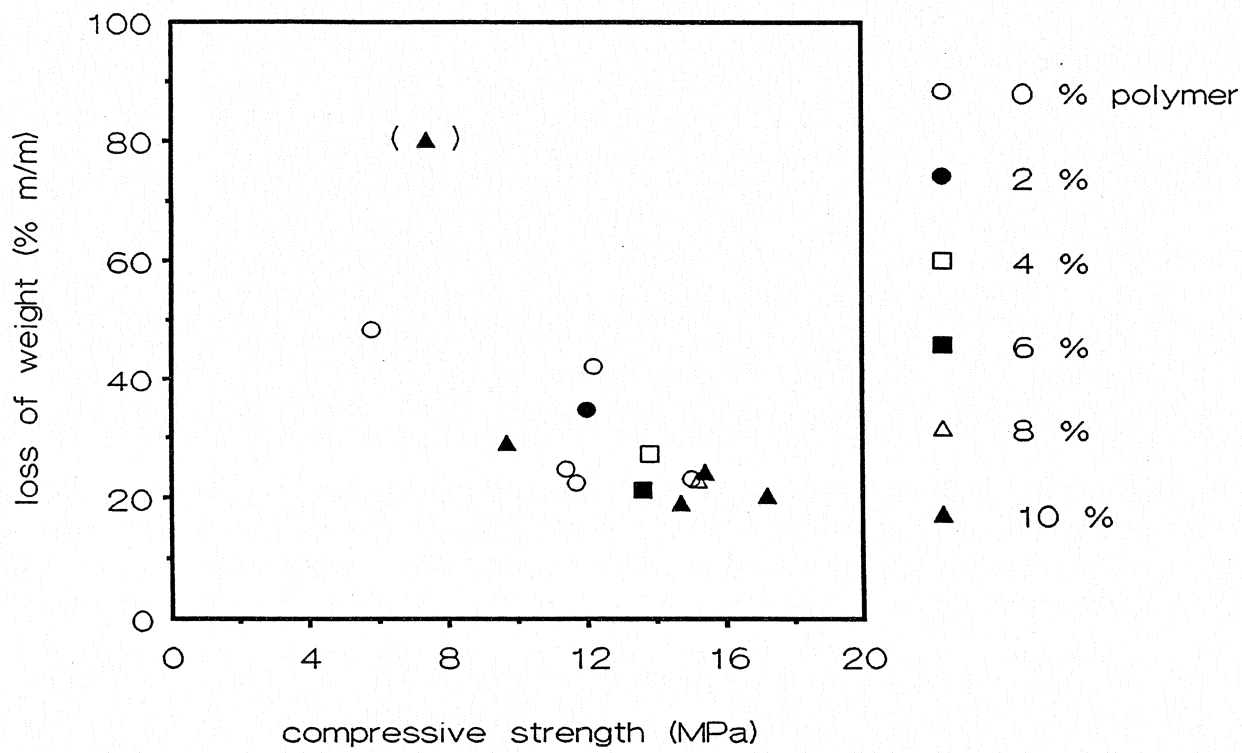

Figure 18. Loss of weight of porous concrete - Cantabro test (polymer emulsion E, aggregates 5/12 and 0/5).

Table 1. Aggregates (crushed material).

	Germany		The Netherlands		Spain			
grain size (mm)	0/2	5/8	0/1	4/8	0/3 [1]	0/5	5/8 [1]	5/12
rock material	river sand	basalt	river sand	river gravel	limestone	limestone	granite	granite
density (kg/m³)	2650	3030	2650	2650	2700	2700	2650	2650
sieve (mm)								
16								0
11		0		0			0	32
8		5		3			22	68
5	0	83	0	90	0	0	63	97
2	5	100	1	100	13	37	100	100
1	20		3		42	58		
0.5	52		18		59	71		
0.25	92		73		68	78		
0.125	99		97		77	84		
0.063	99				86	89		

[1] difficult to obtain in Spain (no commercial grain size)

Table 2. Basic mix composition.

material	Germany	the Netherlands	Spain
coarse aggregate:			
5/12 mm	-	-	1400 kg/m³
5/8 mm	1534 kg/m³	-	-
4/8 mm	-	1389 kg/m³	-
fine aggregate:			
0/5 mm	-	-	100 kg/m³
0/2 mm	77 kg/m³	-	-
0/1 mm	-	66 kg/m³	-
cement	282 kg/m³ [1)]	207 kg/m³ [2)]	250 kg/m³ [3)]
water (emulsion water included)	71 kg/m³	72 kg/m³	75 kg/m³
additives:			
polymer (solids), Forton VF 774	28 kg/m³	16 kg/m³	25 kg/m³
silica fume	28 kg/m³	-	-

[1)] ordinary portland cement PC 35 F
[2)] portland fly-ash cement PCFA (± 25 % fly-ash)
[3)] portland fly-ash cement PCFA 35 (± 40 % fly-ash)

Table 3. Compaction of fresh porous concrete.

polymer content (%) [1)]	polymer emulsion	compaction factor (DIN 1048)								
		8 °C			21 °C			33 °C		
		5 min.	35 min.	65 min.	5 min.	35 min.	65 min.	5 min.	35 min.	65 min.
5	B	1.18	1.25	1.25	1.19	1.22	1.23	1.19	1.21	1.22
5	A	1.18	1.23	1.26	1.20	1.28	1.30	1.19	1.21	1.22
5	E	1.19	1.23	1.25	1.20	1.24	1.27	1.19	1.20	1.22
10	A	1.19	1.21	1.22	1.20	1.22	1.25	1.19	1.28	1.29
10	B	1.20	1.26	1.27	1.20	1.22	1.24	1.28	1.28	1.25
10	E	1.16	1.20	1.21	1.22	1.24	1.25	1.20	1.26	1.29
10	I	1.20	1.22	1.22	1.20	1.22	1.23	1.20	1.24	1.25

[1)] percentage polymer solids by weight of cement

Table 4. Frost-thaw susceptibility.

polymer emulsion	number of cycles at 10 % loss of weight	
	5 % polymer solids	10 % polymer solids
A	41	54
B	- [1)]	33
C	36	54
E	46 / 54 [2)]	67 / 54 [2)]
F	42	47
I	39	26 / 26 [2)]

[1)] not measured
[2)] VDZ / Intron