AFDELINGEN FOR

BÆRENDE KONSTRUKTIONER

DANMARKS TEKNISKE HØJSKOLE

STRUCTURAL RESEARCH LABORATORY

TECHNICAL UNIVERSITY OF DENMARK

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RUPTURE CRITERIA FOR FRC-MATERIALS

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From a materials research point of view, the most outstanding characteristics of fibre-reinforced brittle matrix materials compared with fibre-reinforced plastics are: 1) the very low volume fraction of fibre with which we have to work in the former and 2) the fact that, regardless of the type of fibre used - glass, steel, asbestos, cellulose or plastic - the ultimate elongation of the reinforcement is always considerably higher than that of the brittle matrix alone.

For these reasons we can achieve only modest improvements in the strength values of our materials by adding the fibres, but under optimum conditions, it is possible to improve the ductility and fracture toughness of cement and concrete materials substantially, principally by a drastic change in the ultimate strain of the composite compared with that of the unreinforced matrix. However, because of the special mode of failure of these types of two-component materials - characterized by a form of broken stress-strain curve as shown in Figure 1, a rupture criterion must be defined before ultimate stress and strain values and figures for fracture toughness can be usefully discussed.

The real value of the fibre-reinforced brittle matrix material depends more on its behaviour all the way up to final rupture - especially in area 2 - than on the figures for ultimate stress and strain. One material, such as, for instance, a high quality asbestos cement, may be useful for most purposes right up to the ultimate point because of the excellent interaction between fibre and matrix, while another composite may be useless as soon as it has passed the proportional limit, quite independent on the ultimate values measured.

FRC-materials can be divided into two main groups, in the first of which C stands for concrete and mortar etc., and in the second, for cement, gypsum, calcium-silicate etc. In the first group of materials, the reinforcement is normally 3-dimensionally randomized, the fibres being simply mixed together with the other components, with quite a low fibre volume fraction, maximum about 1 to 2%.

In the other group, the fibre orientation is normally 2-dimensional, more or less randomized in plane, and with a somewhat higher fibre volume fraction than in the first group, up to say 5 to 10% - but still very low fibre contents compared with FRP-materials (fibre reinforced plastics), where volume fractions below 20 to 30% are exceptional.

For these reasons, i.e. low fibre content, brittle nature of the matrix and low efficiency of the reinforcement due to its orientation and poor anchorage of the fibres, we will quite often, with these composites, find ourselves near the point at which rupture occurs in the same unpleasant manner as in what we term an under-reinforced concrete beam, where the reinforcement is of practically no use at all as the first crack in the concrete means total collapse of the structure.

We have to be very careful - far more careful than the plastics people need to be - to ensure that we can pass the critical point P in Figure 1, at which the matrix gives up and the fibres have to take over on their own.

However, our troubles do not end there. Even if we are clever enough to put the components together and construct our material in such a way that the fibres survive the passing of this critical point, we can only be satisfied if the cracking -up of the matrix in the tensile zone from that point on occurs in such a manner that the composite is still fully useful even up to much higher strain.

In our opinion, this means that the cracking of the matrix may only occur as micro-cracking. A finely distributed network of invisible micro-cracks throughout the tensile zone will normally do no harm, but once the first discrete, visible crack cuts through the tensile zone, the entire character of the material changes drastically, and we no longer feel safe with the composite, at any rate, not in our laboratory. Our rupture criterion is therefore quite clear: rupture is the point at which the first visible crack occurs. Even if the material were to cohere in some way or other after this visible cracking, with the reinforcement acting as a kind of safety net for the broken pieces of material in-between, we would still not call it a real material any more. A material showing teeth like that in Figure 2, for instance, hardly inspires confidence.

Our task is thus to choose the components and put them together in such a way that, first, the composite will pass the proportional limit without the fibres getting damaged and, secondly, that it will then reach as great a strain as possible during micro-cracking of the matrix before the first visible crack occurs.

According to our experience, the tools at our disposal - the means of attaining this result - can be put in the following six points:

1. High fibre content
2. Ductile fibres
3. Thin fibres
4. Uniform fibre distribution
5. For 2-d orientation: maximum l/d
6. For 3-d orientation: optimum l/d

Re. 1. With a high degree of reinforcement the risk of too early rupture as in an under-reinforced concrete beam will naturally be reduced.

Re. 2. The combination of two brittle materials will always be a delicate problem. It can be done with success under special conditions, but we then have to pay much more attention to the other parameters mentioned.

Re. 3. For a given volume fraction of fibre the distribution of cracks in the tensile zone of the matrix will primarily depend on the diameter of the fibres or fibre bundles. A great many thin reinforcement units instead of a few thick ones give the greatest chance of a long area of micro-cracking.

Re. 4. If the distribution of the reinforcement within the composite is poor, with some areas containing very few or no fibres and other areas over-reinforced, the total efficiency of the reinforcement may be very low.

The under-reinforced areas will act as notches from which too early rupture starts up, and the over-reinforced areas will normally be unable to act as crack arrestors when this rupture process begins because, here, the fibres will quite often be poorly anchored in the matrix.

Re. 5. and 6. Low fibre aspect-ratio gives a low overall efficiency of the reinforcement with early rupture as a result.

In the case of 2-d orientation, fibre aspect-ratio and maximum fibre volume fraction are independent parameters, so here we are free to use fibres of as great a length as we can get them.

In the case of 3-d orientation, on the other hand, the two parameters mentioned are inter-related. The balance point giving optimum mechanical properties must therefore be found as shown in the following.

Tests with FRC-materials

During the years we have carried out research into both the groups of FRC-materials mentioned above. In the following a few examples from these investigations will be mentioned.

Tests with 3-d fibre orientation

In the first group, where the matrix is concrete or mortar, we have used steel fibres as reinforcement in the tests mentioned here, and the aim of these investigations has been to find, for a given fibre diameter, the fibre aspect-ratio that gives optimum mechanical properties for the composite in 3-dimensional orientation.

If the fibres are very short the matrix can absorb a large quantity during the mixing, all fibres being well distributed throughout the mass, without any balling-up and with all fibre surfaces fully coated by the cement paste. However, the efficiency of a short-fibred reinforcement is low.

On the other hand, very long fibres, for which the anchorage efficiency is much higher, can only be properly mixed in much smaller quantities. We therefore have to find the balance between fibre aspect-ratio on the one hand and maximum fibre volumen fraction on the other, i.e. the point at which the total effect of the reinforcement is optimum.

The two boxes shown in Figure 3 contain the same quantity of the type of steel fibres used in our investigations. The fibre diameter is .15 mm, 6 mill round fibres, quite thin, but we prefer thin fibres for their good crack distribution, as mentioned above.

There is 1 lb fibre in each box. In the small one, the fibre aspect-ratio is only 20, while in the big one, it is about 250. The small box has a volume of 12 cu.in., and the big one, a volume of 120 cu.in., so the volume fraction of fibres when loosely packed in air, as here, is 30% with the short fibres, and only about 3% with the long fibres.

The diagram in Figure 4 tells the same story in another way; it shows the maximum volume fraction of fibre versus aspect-ratio for the fibres in air, as mentioned above, and for the fibres mixed into different types of matrix materials: cement paste, cement mortar and concrete. With bigger grain size of aggregate, the maximum amount of fibre will naturally be reduced since the fibres cannot be mixed into the aggregate particles, but the tendency of the curves remains unaltered. In the middle of the diagram, at aspect-ratios of about 100, the cement paste can take up only about 60% of the quantity of fibre that could be packed in air; the cement mortar can take 40%, and with the concrete, we get right down to 20%.

For all the points shown in the diagram we have made mortar mixes with the maximum amount of fibre added, and from these mixes we have cast series of test specimens for bending tests and impact tests in order to find the best type of reinforcement.

The impact prisms, 4 x 4 x 16 cm, were tested in an ordinary pendulum machine with 3-point loading, see Figure 5, whereas the bending prisms, 4 x 6 x 40 cm, were tested under 4-point loading, with electric strain gauges glued to the tensile and compressive edges as shown in Figure 6.

From this systematic examination of the different types of steel fibre reinforced mortars we found two regions for the optimum mechanical properties, as shown in Figure 7. An aspect-ratio of about 80-100 and a fibre volume fraction of 2%, as in area 1, gave the best results in the bending tests, whereas the optimum in impact strength was reached in area 2, with half the quantity of fibres, but twice the length of those in area 1.

The diagram in Figure 8 shows the stress-strain curves from the bending tests on the neat cement mortar, i.e. without fibres. It shows bending stress versus edge strain measured directly with the strain gauges, as shown before. A modulus of rupture of 4.8 MN/m^2 and an ultimate edge strain of about 200 micro-strain (.02%) is quite normal for this type of mortar. The fact that the tensile strain gauge was running a little further out than the compressive gauge during the last part of the test shows us that some micro-cracking occurs in the tensile zone just before final rupture, even in this unreinforced material.

The next diagram, Figure 9, shows the corresponding stress-strain curves - to another scale - for the fibre-reinforced material in area 1 of Figure 7 - the material with the best bending properties. For the purposes of comparison, the curves from the foregoing diagram for the unreinforced matrix material are shown here to the same scale.

It will be seen that the bending strength of the steel fibre reinforced material is 2½ times that of the unreinforced mortar and that the ultimate elongation in the tensile zone has increased tenfold as a result of the 2% by volume of fibres mixed in.

Up to the point of proportionality, the two sets of curves look very much alike, which is quite natural, but after that, the strain gauge in the tensile zone of the reinforced material speeds up, running three to four times as fast as the compressive gauge, which means that the neutral axis is now moving upwards in the prism, and this - in turn - means that some kind of cracking is taking place in the tensile zone all the way from the point of proportionality to the point of final rupture.

However, this cracking can only be registered indirectly by studying these two curves. No cracks are visible on the prism itself and no cracking can be heard during the test. All the way up, the material behaves as though it were still homogeneous, until the ultimate point is reached at which the first visible crack cuts through the tensile zone and through the tensile strain gauge as well - a so-called strain gauge killer.

What happens after this point is of little interest to us. When the tensile strain gauge has been killed, the load falls, and the material, although still cohering to some extent, no longer seems good enough for practical use. So the peak of the curve is the ultimate point according to the rupture criterion formulated earlier, and the last part of the diagram, from point P to point U , represents the real output from mixing fibres into the brittle matrix.

The finding of two different optima in the diagram in Figure 7, one for bending properties and another for impact properties, as measured in the pendulum machine, naturally has something to do with this rupture criterion.

From the ultimate point in the bending test and out to total separation of the broken prism some energy is absorbed, and this is part of the total impact energy measured in the pendulum machine. With greater fibre aspect-ratio this last part of the total impact energy represents a substantial part of the total impact strength measured, and so the impact optimum must be found to the right of the bending optimum in the diagram.

Tests with 2-d fibre orientation

Our research on the other group of brittle matrix materials with 2-dimensional fibre orientation started about 25 years ago. In this field, our main aim - as in so many other laboratories around the world - has been to try to find a suitable synthetic fibre to replace asbestos as reinforcement for neat Portland cement etc.

Here, our interest centres particularly on the cheapest types of synthetic mineral fibres, the glass-wool and rock-wool fibres, but the problem seems to be not so much that of finding a suitable type of fibre as the far more complicated problem of finding the right way to put the components together to obtain the same excellent interaction between matrix and reinforcement as in asbestos-cement, with a long area of micro -cracking right up to the ultimate point and a high total efficiency for the reinforcement.

As far as we can see to-day, there are two major problems here that account for nearly all the disappointment and negative results that have plagued our research in this field for so many years. First, there is the problem of opening-up the mineral wool, defiberizing the material completely, without reducing the fibre length, and, secondly, the problem of fixing the fibres in correct position in relation to each other during the building-up of the composite, so that the variation in fibre volume fraction from point to point in the finished product is kept at an absolute minimum.

With these two problems under control, and it seems that we control them quite well to-day, we are getting really good results, even with the cheaper types of mineral fibres, achieving strength values and ultimate elongations that are practically the same as for ordinary asbestos cement.

However, we are not satisfied yet because we know that the efficiency of the reinforcement we put into our material is still far below its optimum. The elongation at rupture of the composite we make is at present considerably lower than the ultimate strain of the fibres alone, but we believe that this can be improved.

The method applied for defiberizing the mineral wool, keeping a maximum of fibre length even after the wool has been fully opened, and - in the next stage - fixing the individual fibres in the right position in relation to each other during the building-up of the composite, is, in fact, quite simple.

In a wet process, it is possible, with a suitable dispersing agent, to wash out and separate the wool fibres without any fibre cutting, even in the case of a material with a very big fibre aspect-ratio, and the resultant slurry of single fibres in water can then be used without further treatment to make a very thin, uniform and open paper of the synthetic mineral fibres, see Figure 10.

By the use of a suitable glue or size, the paper can be given sufficient water-strength, with the fibres fixed to each other at their points of intersection, and this paper can then be used as a reinforcing material in the same way as the so-called surfacing mats or non-woven glass fabric was used for the same purpose in the tests described in the author's thesis, published in 1964 [1]. The composite is built up as a laminate of several layers of this reinforcing paper after each layer has been filled up with a smear of cement paste simply scraped into its pores - quite parallel, in fact, to the way in which so-called ferro-cement is built up, but to another scale, see Figure 11, [2].

It will be realized that this system of building-up can give a very uniform distribution of the thin-fibred reinforcement throughout the material. The fibres we use are only about 5μ thick (0.2 mill) and the maximum aspect-ratio is about 1500-2000, but there are naturally many fibres shorter that in the reinforcing paper. At present we are working with a fibre volume fraction of 4-6% in the fibre-cement plates, but it seems possible to bring this up to about 8-10%, which should give better strength and, at the same time, a greater ultimate strain of the composite, approaching that of the fibre alone.

[1] Krenchel, H.: "Fibre Reinforcement", Dissertation, Technical University, Copenhagen, Akademisk Forlag, Copenhagen 1964.

[2] Whitener, J.R.: "Ferro-Cement Boat Construction", Cornell Maritime Press.Inc., Cambridge, Maryland 1971.

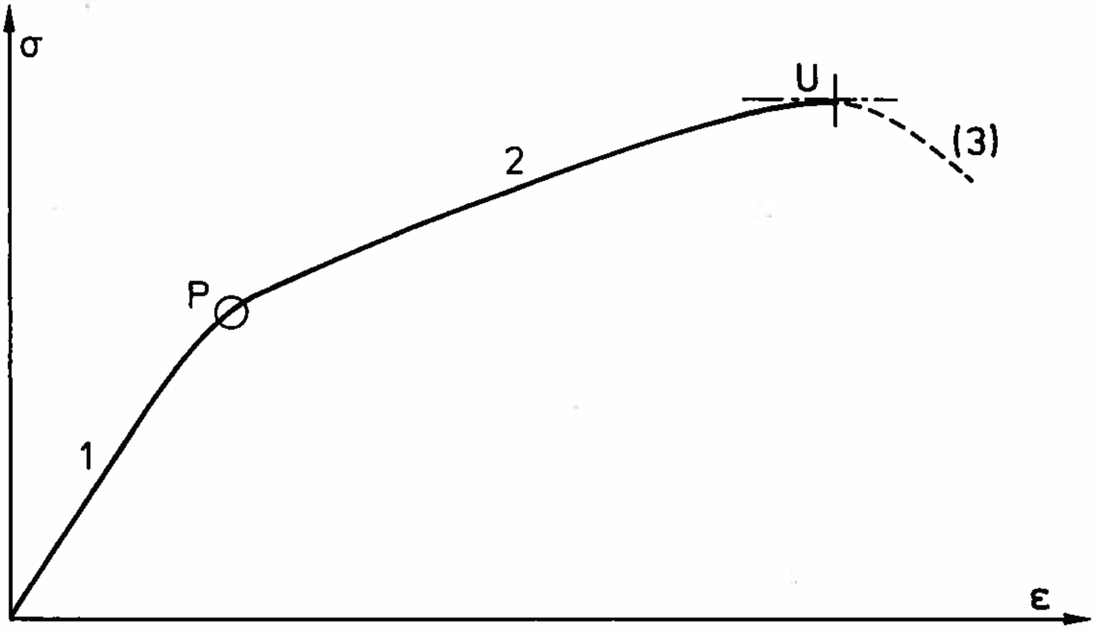

Fig.10

Characteristic stress-strain curve for tensile or bending tests on FRC-materials

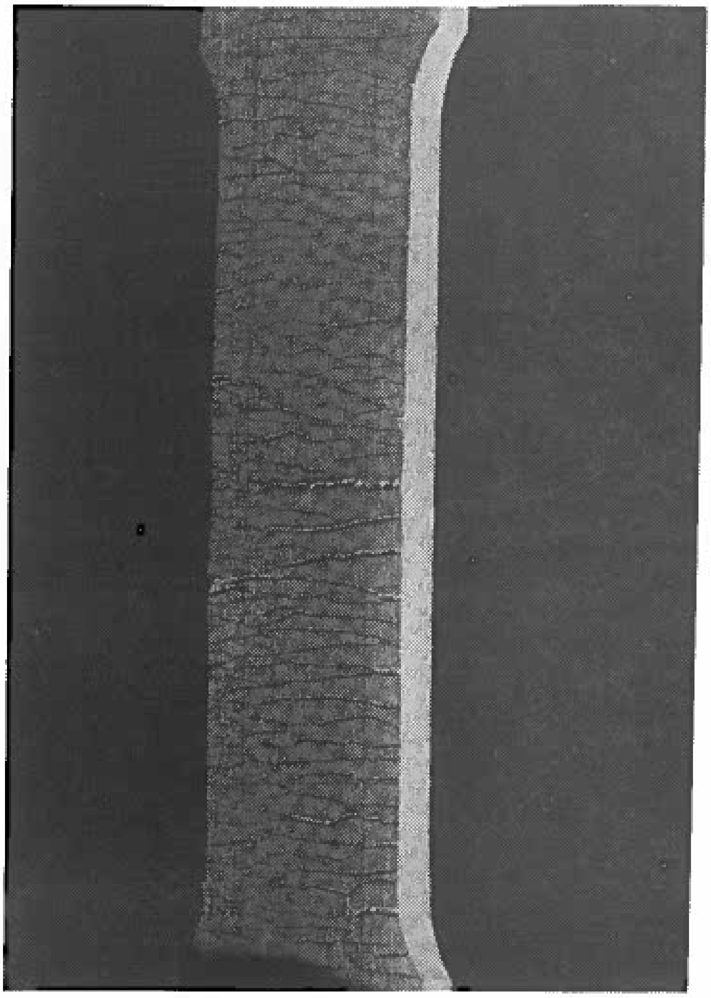

Fig.2

Tensile test specimen of polypropylene fibre reinforced Portland cement (2-d fibre orientation, $V_f = 0.18$).

Strain: appr.17%

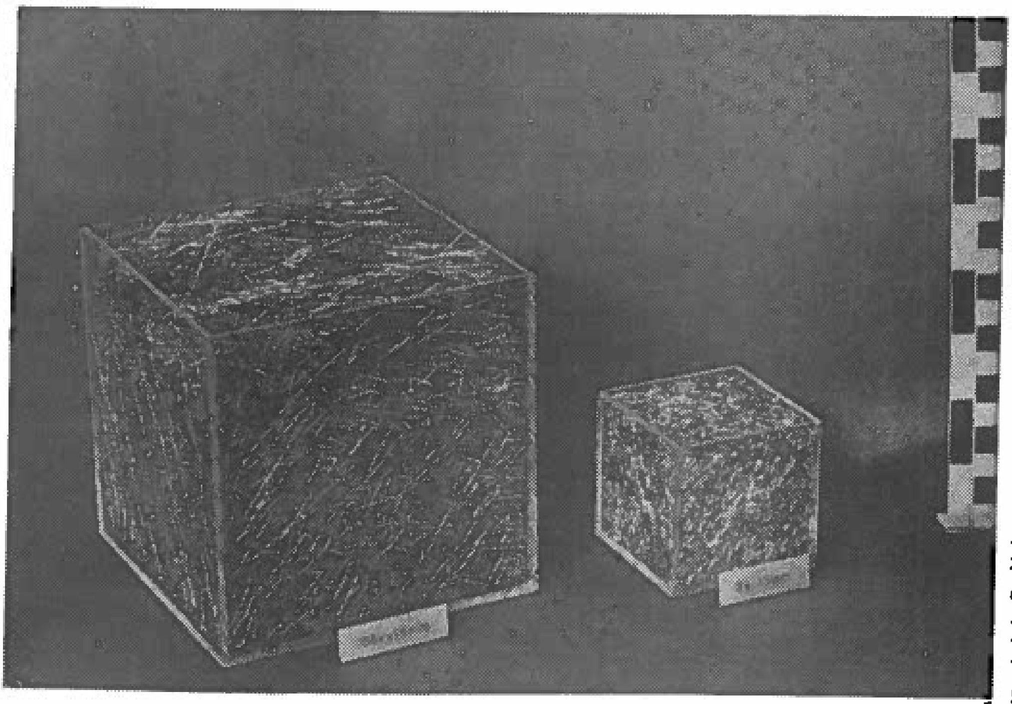

Fig.3

Two acrylic boxes, each containing 1 lb of steel fibres

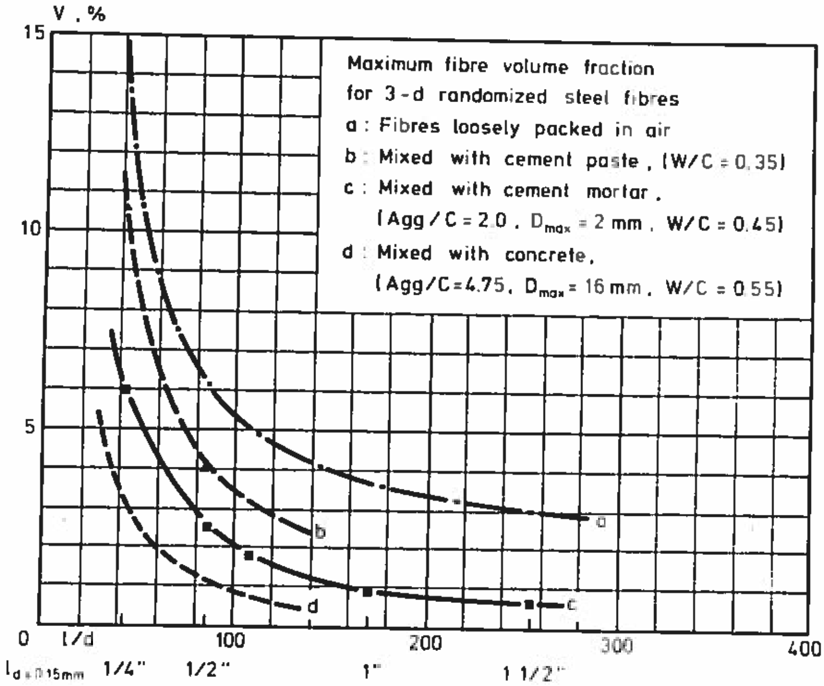

Fig.4

Maximum fibre volume fraction versus fibre aspect ratio

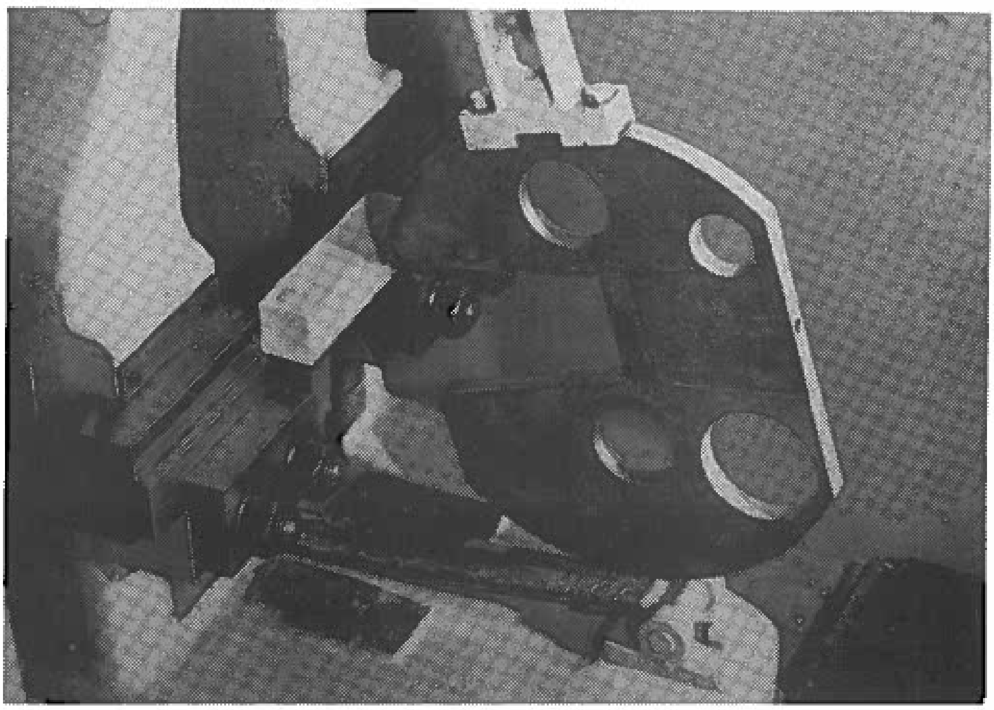

Fig.5

Impact testing of 4 x 4 x 16 cm prisms

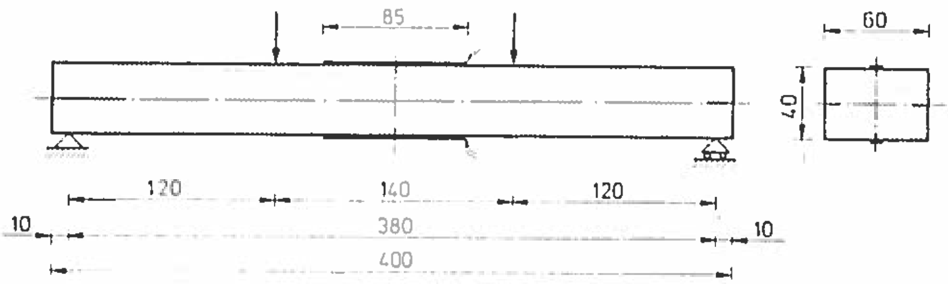

Fig.6

Bending tests on 4 x 6 x 40 cm prisms

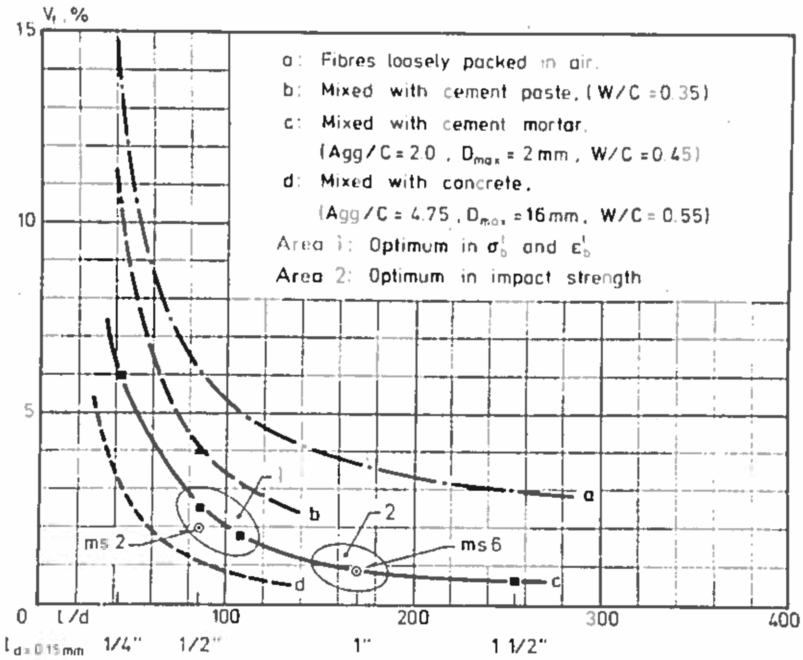

Fig.7

Areas of optimum bending properties and impact properties

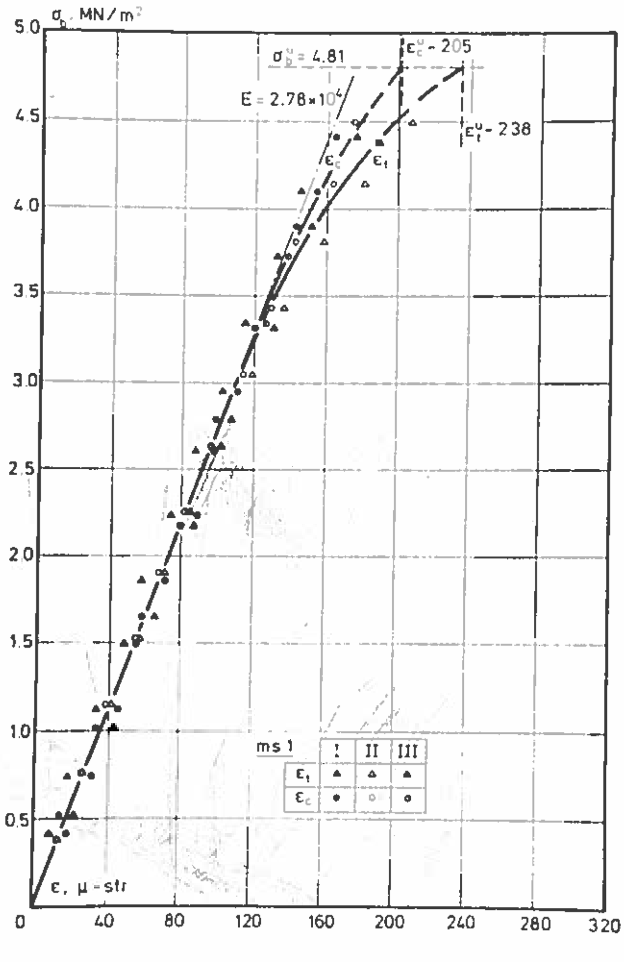

Fig.8

Stress-strain curves from bending tests on neat cement mortar

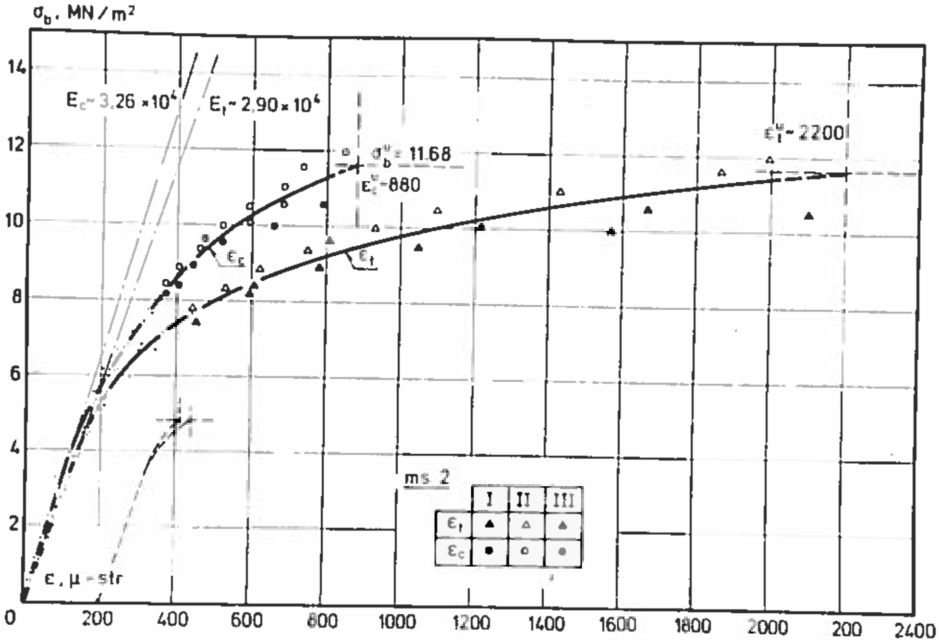

Fig.9

Stress-strain curves for fibre -reinforced cement mortar

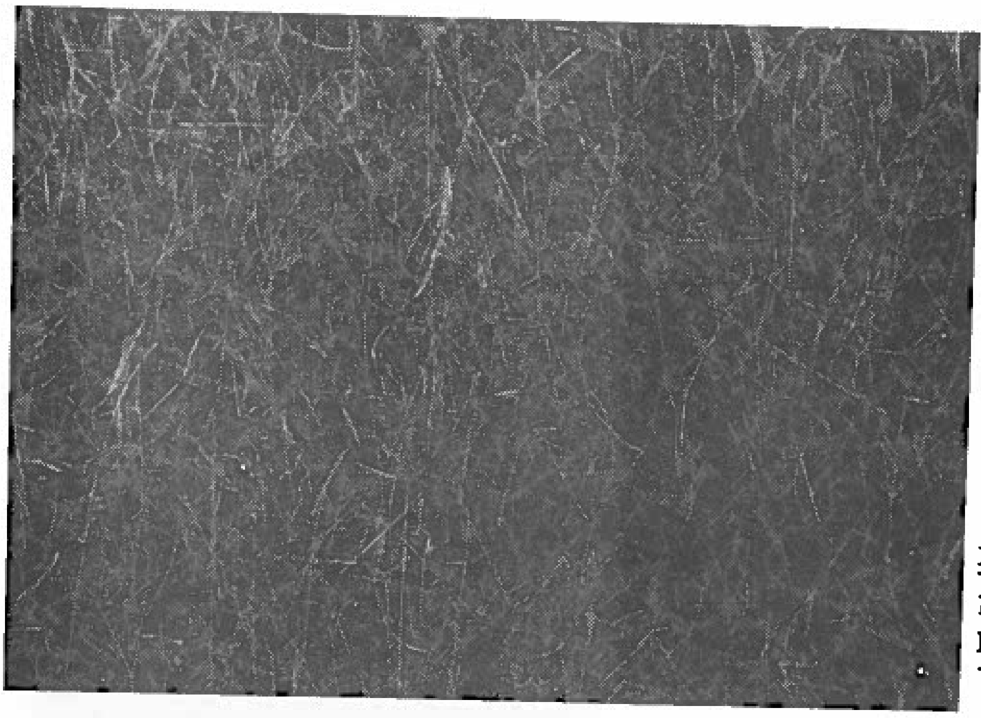

Fig.10

Reinforcing paper of glass -wool fibres (x 10)

Fig.11

Building-up of ferro-cement

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