FRAMEWORK PROGRAMME 1989-92
FIBRE REINFORCED CONCRETE

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ABSTRACT

This article gives a survey of the activities in the Danish Framework Programme 1989-92 about fibre reinforced concrete. The Framework Program covered both research activities and product development. The research activities included characterization of the behaviour of the fresh, the hardening and the hardened fibre reinforced concrete, including - in some areas - modelling based on the underlying mechanisms. Furthermore the research activites covered design principles. The product development covered pipes, reservoirs, pavements, traditional load carrying structural elements and repair methods.

Key words: Fibre reinforced concrete, material characterization, design principles, pipes, containers, pavements, load carrying structural elements, repair methods.

1. INTRODUCTION

The Framework Programme "Cement-based Composite Materials" with the subject fibre reinforced concrete was carried out in Denmark from 1989-92 under the Material Technological Program.

1.1 Objectives

The objectives of the Framework Programme were to:

- improve the competitive power of the building industry by increasing the use - and introduce new applications - of fibre reinforced cement-based composite materials.

- initiate, strengthen and coordinate research work in fibre reinforced cement-based composite materials in order to minimize material consumption through development of stronger and lighter structures.

1.2 Organization

The programme was organized with the objective of obtaining a reasonable level of research as well as a reasonable focus on specific application possibilities. While the product development dealt with specific application possibilities, the inter-disciplinary research dealt with solution of the problems arising during the product development, the aim being to develop general calculation models and testing methods.

1.3 Demarcation

The program mainly treated cement-based composite materials with an amount of fibres from 0.5 -5.0 vol.- %. For these materials, it is characteristic that strain localization appears, see section 3.3.2. The fibre types investigated were primarily steel and polypropylene fibres. Note that the designation fibre reinforced concrete (FRC) will be used in this article for both fibre reinforced cement, fibre reinforced mortar and fibre reinforced concrete.

1.4 Publications

A main report, which has been written as a "state-of-the-art" report, contains all the results obtained in the Framework Programme, /1/. A complete list of publications can be seen in this report. Only selected relevant references are used in this article.

1.5 The participants

A broad combination of Danish industrial companies and institutes were involved in the project.

- Aalborg Portland A/S
- Bekaert A/S
- Concrete Centre, Danish Technological Institute
- Danish Building Research Institute
- The Department of Structural Engineering, Technical University of Denmark
- Danish Railways (DSB)
- Fr. Petersens Maskinfabrik A/S
- The Institute of Product Development, Technical University of Denmark
- Otto Christensen & Kaj Sørensen A/S
- Pedershaab Maskinfabrik A/S

- Rambøll Hannemann & Højlund A/S
- Rasmussen & Schiøtz Øst A/S
- Steensen & Varming, Rådgivende Ingeniører A/S
- Unicon Beton I/S
- Vejdirektoratet
- 4K-Beton A/S

2. A SHORT INTRODUCTION TO FRC

The following is a short introduction to FRC which in a simplified way compares with well known conditions for conventional reinforced concrete. For a more detailed description, the reader is referred to /1/.

Unreinforced concrete is characterized by having a low tensile strength and a low fracture strain, i.e. the material is brittle. When the unreinforced concrete is loaded in tension, the load grows without any crack developement until, suddenly, the concrete breaks completely, see FIG. 1, top.

This is the reason for the present use of reinforcement in the tensile zones of a concrete. When the concrete cracks, the reinforcement takes over the load. The crack width and the distance between the cracks is dependent on the amount of - and the distance between the - reinforcement. The reinforcement possesses yielding properties which results in the load- deformation relation shown at FIG. 1, middle.

FRC can be viewed as concrete reinforced with many small reinforcement bars. This means that the conditions for crack development in FRC is similar to the conditions for crack crack development in conventional reinforced concrete. However, there is also differences, for instance the random orientation and the limited length of the fibres.

The fibres improve the tensile properties of concrete by refining the crack system. In addition, the fibres can transfer stresses in a crack. In the Framework Program these mechanisms were studied through thin section analysis of FRC's loaded in uniaxial tension.

The tensile strength is not necessarily increased by addition of fibres, but the FRC obtains load-carrying capacity, even after the tensile strength is exceeded, see FIG.1, bottom and section 3.3.2. Normally, such a material behaviour is described as ductile.

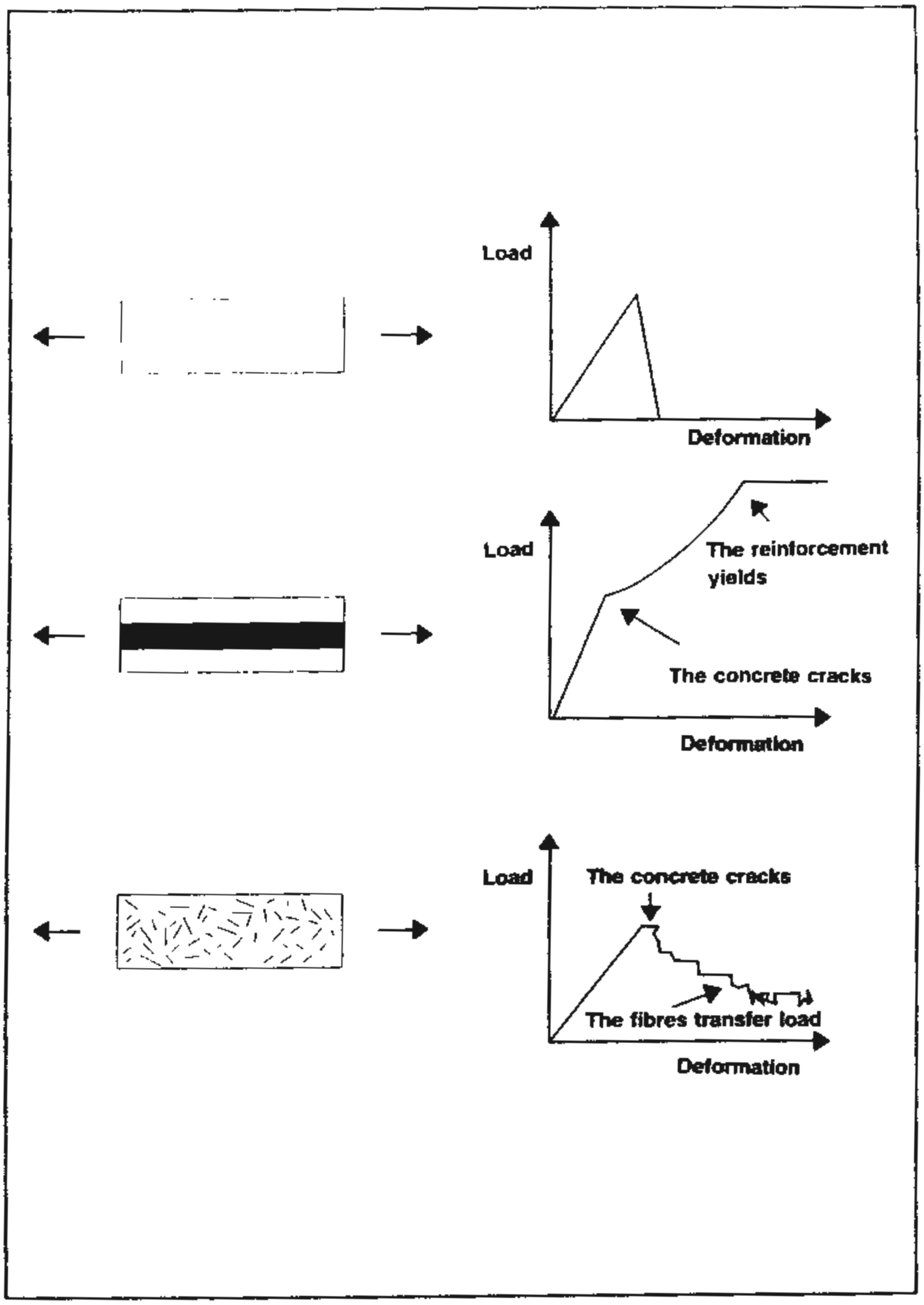

FIG. 1. *Material behaviour of unreinforced concrete, conventionally reinforced concrete and FRC*

The effectiveness of the fibres in improving the tensile properties is controlled by the process which transfers load from the concrete to the fibres. This means that the most desirable properties for the fibres in this respect can be summarized as follows:

- long fibres
- small cross-sectional area
- fibrillated or deformed surface
- high tensile strength
- high E-modulus

3. RESEARCH ACTIVITIES

3.1 The fresh material

The properties of the fresh FRC were investigated in connection with various processing techniques, primarily spraying, extrusion and placing with a paving machine. In these processes standard testing as well as existing models for rheological behaviour was used for characterization of workability.

Generally, when fibres are added, a concrete becomes less workable, more stiff and coherent. The workability of the fresh FRC is controlled by the same parameters which controls the effect of the fibres, as described in section 2. If the workability is reduced significantly, the fibres cannot be evenly distributed and the internal structure of the concrete becomes bad with many defects. The production process also affects this relation. Obviously, a complex interplay exists with respect to fiber effect, workability and production methods, which makes mix design of FRC difficult. However, the following guidelines can be given.

- A high amount of cement paste improves the workability and ensures that all the fibre surfaces are covered with paste.
- Use of a microfiller material ensures a dense paste, and thereby a good adhesion to the fibres as well as a good workability.
- An effective dispersion of the fibres is achieved most efficiently by pre-mixing the fibres and the fine aggregates.
- An increased time of mixing is beneficial.
- When spraying, addition of microsilica increases the adhesiveness of the FRC, so that it can be sprayed at skew planes.
- The maximum amount of fibres when sprayed is approximately 2-3 vol.- % steel- and glass fibres and 1-2 vol.- % polypropylene fibres.
- The packing of the sand and the paste is important with respect to obtaining a clay-like consistence which is necessary when extruding. A densely packed paste with a cement content of minimum 800 kg/m^3 and a sand content at about 1000 kg/m^3 is sufficient with regard to extrusion of geometrically simple products.
- The maximum amount of polypropylene fibres when the FRC has to be extruded is 4 vol.- %.

The above guidelines resulted in suitable mix design for FRC for different applications, see /1/.

3.2 The hardening material

Shrinkage in combination with some kind of restraining effect can result in crack development. This phenomenon is especially important for pavements, where normally it is necessary to cut contraction joints for every approximately 5 m.

It has been shown that addition of fibres can diminish the crack development caused by shrinkage, see for instance /2/. Fibres with a low E-modulus in amounts of less than 0.3 vol.- % is normally sufficient to prevent cracking caused by plastic shrinkage. Elimination of cracks caused by shrinkage under severe climatic conditions demands up to 1.5-2.0 vol.- % of fibres.

The fibres have no influence on the amount of shrinkage, which means that it is not correct to state that fibres prevent cracking. More correctly, they refine the crack system so that many small cracks appear instead of a few large cracks.

Investigations in the Framework Programme indicate that a combination of fibres and a shrinkage reducing additive can be beneficial in relation to avoiding harmful cracking in for instance pavements /3/. However, it has to be remarked that the shrinkage reducing additive can result in side effects in the form of a high air content as well as a retardation of the hardening process.

3.3 The hardened material

3.3.1 Compression

Typically, the compressive strength is unchanged by addition of fibres, though some investigations have shown that addition of fibres with a high E-modulus, for instance steel fibres, increases the compressive strength by up to 40 %. There appears to be an optimum amount of fibres with regard to the compressive strength, because of a competitive process between the fibre resistance against crack development (and thereby a strength increase) and the negative effect of the fibres on the workability which increases the pore- and micro crack density (and thereby a strength decrease). The same conditions are valid with regard to the E-modulus of FRC.

However, the most remarkable change of the mechanical behaviour under compression when fibres are added is that the descending part of the stress-deformation curve becomes less steep, see FIG. 2. It can also be seen in FIG. 2 that the FRC with 1 vol.- % steel fibres and 1 vol.- % polypropylene fibres results in a more ductile behaviour compared to the FRC with 2 vol.- % polypropylene fibres. Furthermore, it can be seen that the fracture strain increases when fibres are added due to a more unlinearly behaviour.

The descending part of the stress-strain curve is strongly dependent on the size and the geometry of the test specimen, the boundary conditions and the testing equipment and can therefore not be used, without correction, as a stress-strain relation.

No standardized test method exists which can be used to determine the complete compressive stress-strain curve. Therefore, a test set-up was developed with closed-loop control by a combination of axial and circumferential deformation.

A more detailed description, including simple models, of the compressive behaviour of FRC can be seen in /4/. Furthermore, a detailed description of the test method is given in that publication.

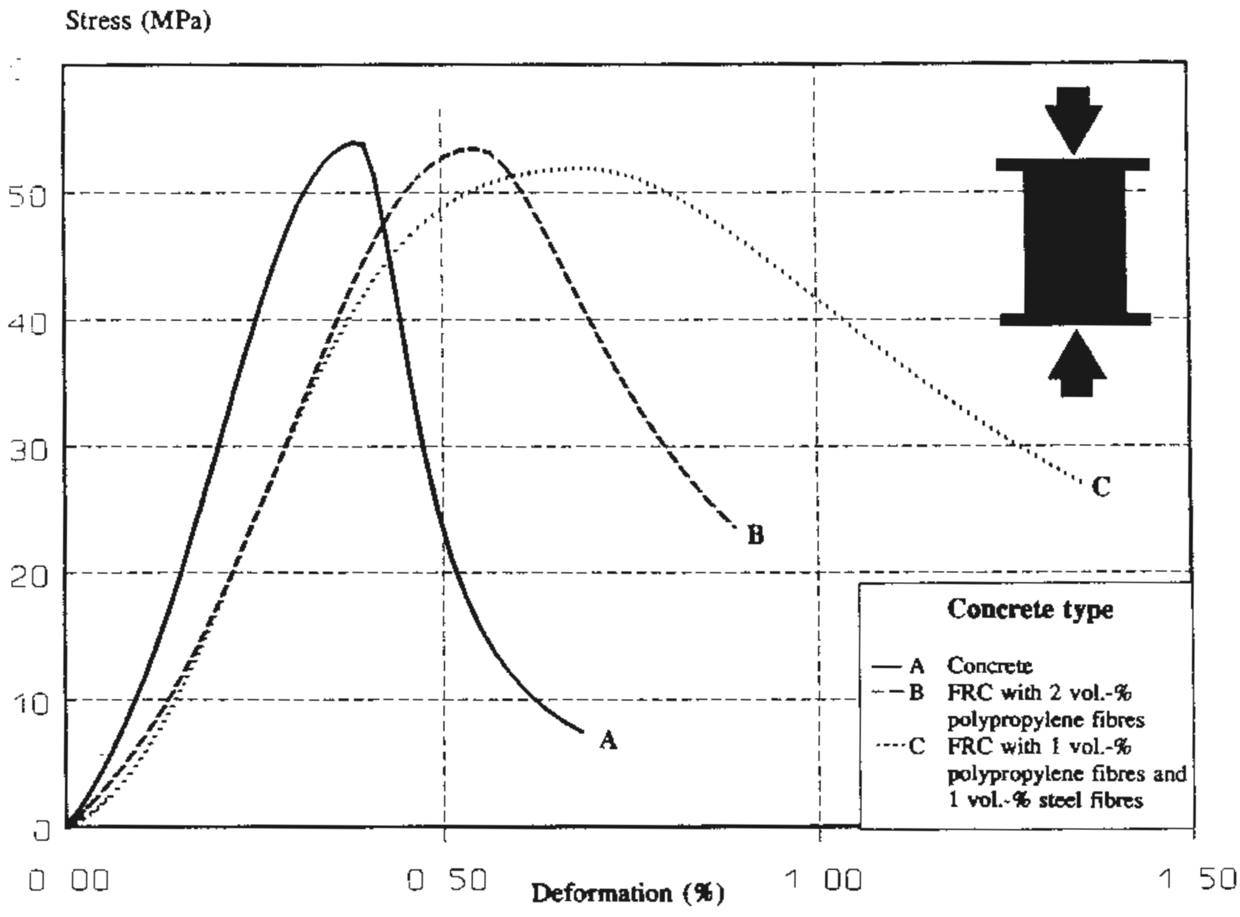

FIG.2. *Compressive stress-strain curves*

3.3.2 Tension

The strain in an FRC which is loaded in tension localizes in a macroscopic crack when the tensile strength is exceeded. After that, the deformation takes place in this crack while the material outside the crack unloads. Therefore, it was found most convenient in the Framework Programme to characterize the tensile load-deformation behaviour in a stress-strain curve for strains less than the fracture strain, and a stress crack width curve for strains larger than the fracture strain. This material description was originally suggested by Hillerborg /5/.

In FIG. 3 stress-crack width curves can be seen for the same FRC's as shown at FIG. 2. Again, the FRC's are more ductile, characterized by the area under the stress-crack width curve, compared with the unreinforced concrete and the FRC with both steel- and polypropylene fibres is more ductile compared with the FRC with polypropylene fibres only.

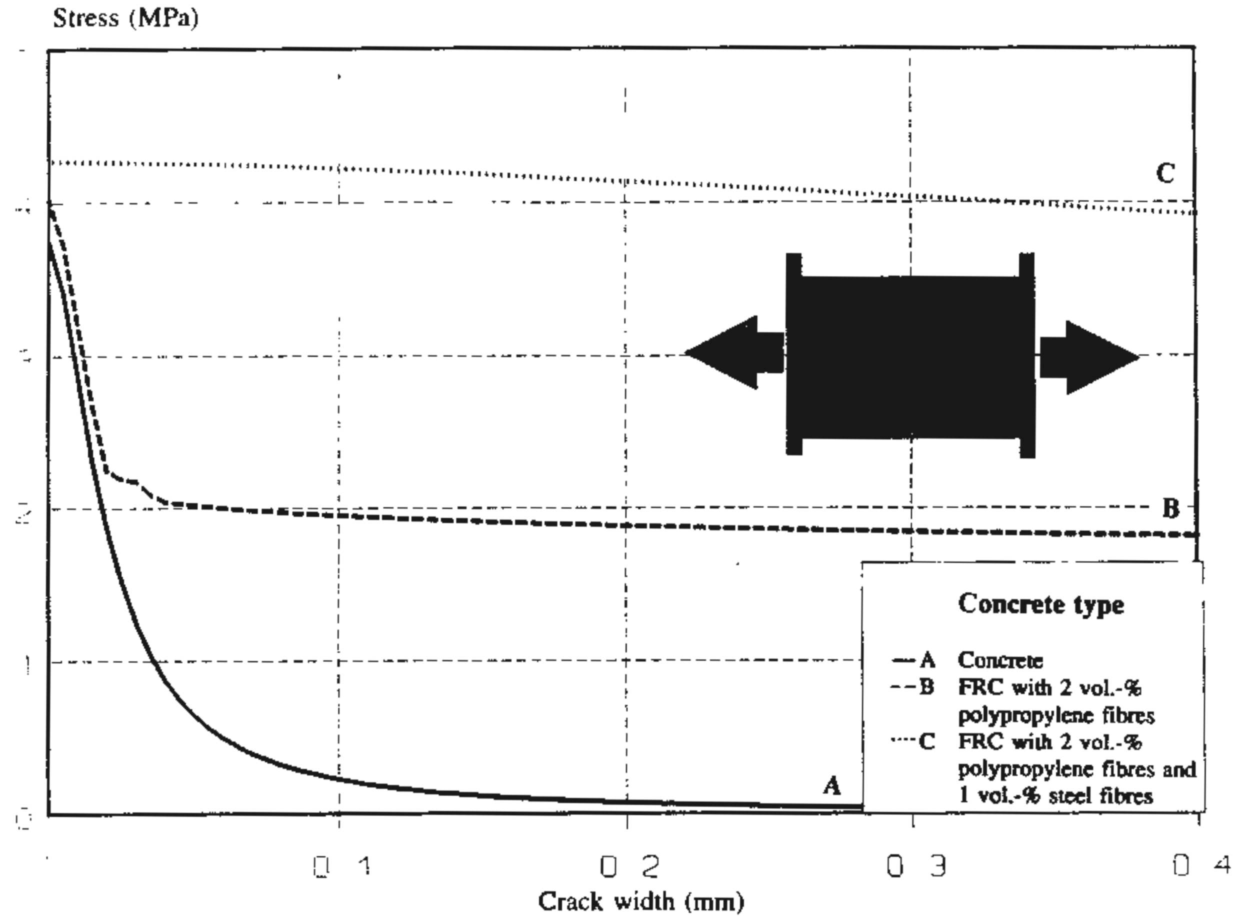

FIG. 3. *Stress-crack width curves*

Several advanced models to describe the stress-crack width relation have been suggested, see for instance /6/. However, these models are too complicated to be used in practice for width calculations of FRC structures. The following simple, empirical expression has been found to produce a good description of the stress-crack width relation and can be used in calculation models:

$$\sigma(\omega) = \frac{f_t}{1+(\omega/\omega_o)^p} \qquad (1)$$

$\sigma(\omega)$ is the stress transferred in the crack, f_t is the tensile strength of the FRC, ω the crack width, ω_0 the characteristic crack width corresponding to a stress of 50 % of the tensile strength and p is a form parameter. The expression is suggested by Stang /7/.

No standardized test methods to determine the uniaxial tensile properties exist. Therefore, a test method was developed in which the test specimen is glued in between the loading fixtures in the test set-up. The test is closed-loop controlled by the displacements at the middle of the specimen. To determine the stress-strain relation, an unnotched specimen is used whereas the stress-crack width relation is determined with notched specimens. For a more detailed description of the test set-up see /8/.

In /9/ experimental uniaxial tensile testing of a large number of FRC's is reported - both stress-strain curves and stress-crack width curves interpreted according to equation (1).

3.3.3 Bending

Bending tests are easy to perform and often ductility is defined from the area under the bending load-deformation curve, for instance according to ASTM C1018-85, /10/. However, bendings tests cannot be used as an indirect determination of the tensile properties (because of the unlinear behaviour) and cannot be used for - dimensioning of other flexurally loaded elements (because of the size effect). It was therefore decided in the Framework Programme to concentrate on material properties determined under uniaxial conditions, though some FRC's have been tested in bending in order to allow comparence with other tests reported in the literature, see /9/.

3.4 Durability

3.4.1 Service life prediction

In a large test programme, different kinds of FRC's were investigated. The overall conclusion of the test programme was as follows.

- FRC's with natural fibres and glass fibres (also alkali resistent) lose strength and ductility when aged, though alkali resistent fibres have a better durability than non-alkali resistent fibres. On the basis of a hot water test, the ductility of FRC with alkali resistent glass fibres is predicted to be approximately 1/3 of its initial value at 28 days after 35 years of natural weathering.
- FRC with steel and polypropylene fibres gain strength and ductility when aged. The increase in ductility is predicted to be 40 % after 10 to 40 years of ageing, unaffected by the ageing process. This is explained by a better fiber-matrix adhesion caused by continued hydration.
- Autoclaved cellulose fibre FRC show a reduction of 1/3 of

the initial ductility at 28 days after 40 years, predicted on the basis of natural weathering.

- At crack widths less than 0.13-0.25 mm corrosion of steel fibres is prevented. Normally, corrosion of steel fibres does not lead to damages.
- There are two mechanisms responsible for the degradation of glass fibres and natural fibres: 1) alkali corrosion (chemical degradation) 2) precipitation of hydration products either in the glass fibre bundles or in the cavities in the natural fibres.
- Natural fibres, including cellulose fibres, are not dimensionally stable, i.e. they can absorb and liberate moisture. This can lead to delamination of the FRC.

The above conclusions are determined on the basis of primarily flexural testing after natural and accelerated ageing. A more detailed description of the tests can be seen in /11/. In /11/, a discussion of the use, including limitation, of accelerated testing can be seen too.

3.4.2 Frost resistance

Tests carried out in the Framework Programme indicate that the frost resistance of an FRC is similar to the frost resistance of an unreinforced concrete. An air content of approximately 6 % measured on the fresh FRC is sufficient to obtain an acceptable frost resitance, /12/. It has to be remarked that it can be difficult to obtain a satisfactory air void system in an FRC.

The frost resistance is measured according to SS 137244, /13/. It must be underlined that some FRC structures where the frost resistance determined according to SS 137244 was characterized as unacceptable, did not show any sign of degradation after several years of outdoor exposure.

3.4.3 Permeability

The permeability has been measured on cracked FRC's and compared with the permeability of cracked concrete without fibres, /1/. The test has shown that the speed of flow is lower in an FRC compared with unreinforced concrete. This confirms the fact that the fibres refine the crack system (and thereby the permeability).

3.5 Design Principles

3.5.1 Serviceability limit state design

In a number of conventional reinforced concrete structures, a large part of the reinforcement is placed only to reduce and to control the crack widths, for instance structures in aggressive environments. This crack controlling reinforcement is often difficult and expensive to place and tie. Furthermore, it is difficult to cast and vibrate the concrete around the very compact crack controlling reinforcement. Fibre reinforcement is an attractive alternative to conventional reinforcement in this situation.

A model was developed in the Framework Programme to predict crack widths in FRC structures with conventional concrete. In the model, the FRC is assumed to behave linearly elastic until the tensile strength is exceeded. After that, the material is characterized by the stress-crack width relation described in section 3.3.2. Due to considerations of space, an exhaustive description of the model cannot be given here, and the reader is referred to /8/.

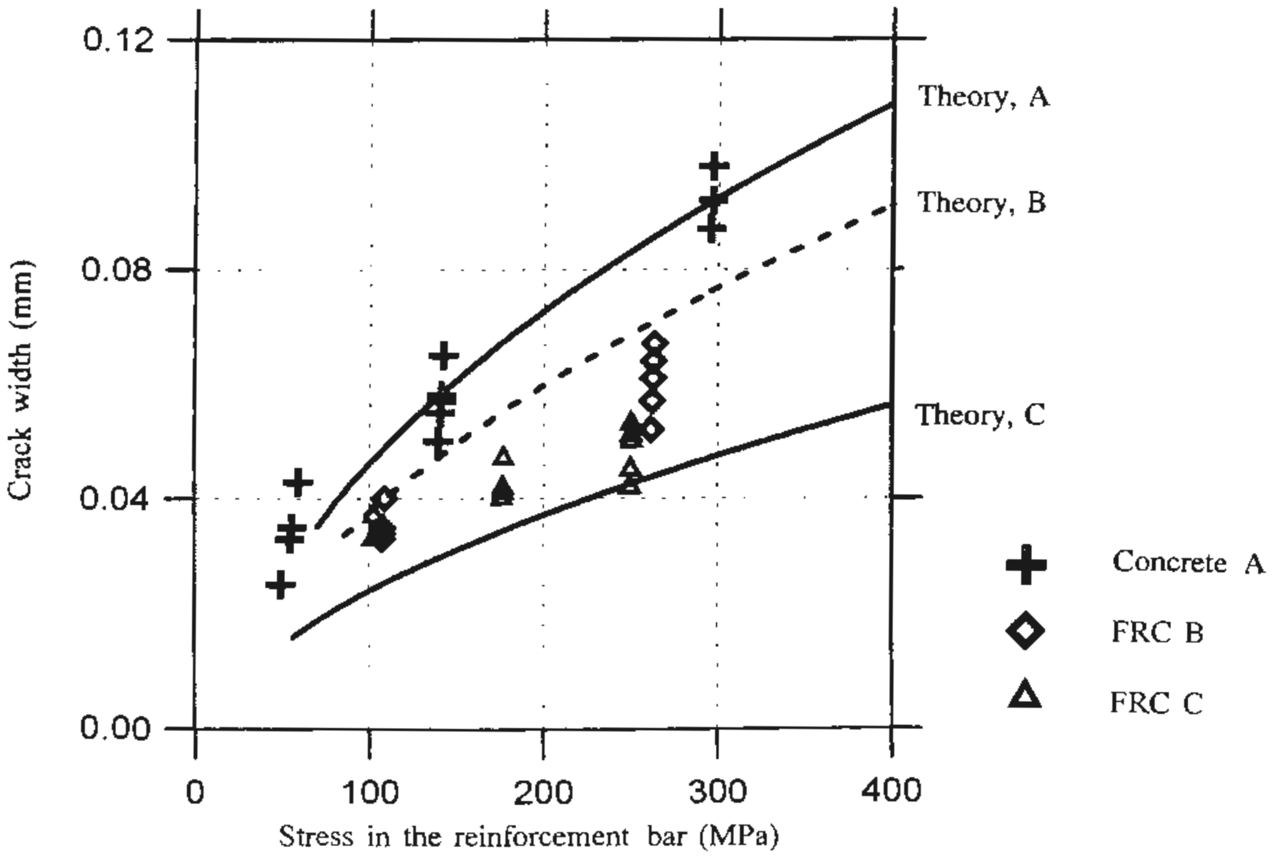

FIG. 4. *Experimental and theoretical results for crack widths in the prisms.*

In order to verify the crack width model, prisms loaded in uniaxial tension were investigated, among other things. The prisms were reinforced with a single reinforcing bar. The crack widths and the distance between the cracks were recorded with a video camera and the results treated with an advanced image analysis system. Further information about the test programme can be seen in /14/. FIG.4 shows experimentally determined, and theoretically calculated, crack widths as a function of the stress in the reinforcing bar. The concretes (A, B and C) are the same as shown in FIG. 2 and FIG. 3. It can be seen from FIG. 4 that the model describes the influence of fibre reinforcement very well.

The structural crack width model constitutes together with an experimental material characterization a complete design tool which can be used when designing FRC structures where fibre reinforcement is used as a crack controlling reinforcement, while the conventional reinforcement has a load carrying function. Tests have shown that the tensile strength and the stress-crack width parameters, ω_o and p from equation (1), can be assumed to be dependent on the volume fraction of fibres. By introducing these relations in equation (1), corresponding values of the degree of reinforcement for a beam loaded in bending and the fibre volume fraction can be obtained. This is shown in FIG. 5 for different values of M/b, where M is the bending moment and b is the width of the beam. The example assumes a maximum crack width of 0.1 mm and an effective beam height of 0.3 m. The FRC is reinforced with steel fibres, see /8/ and /15/.

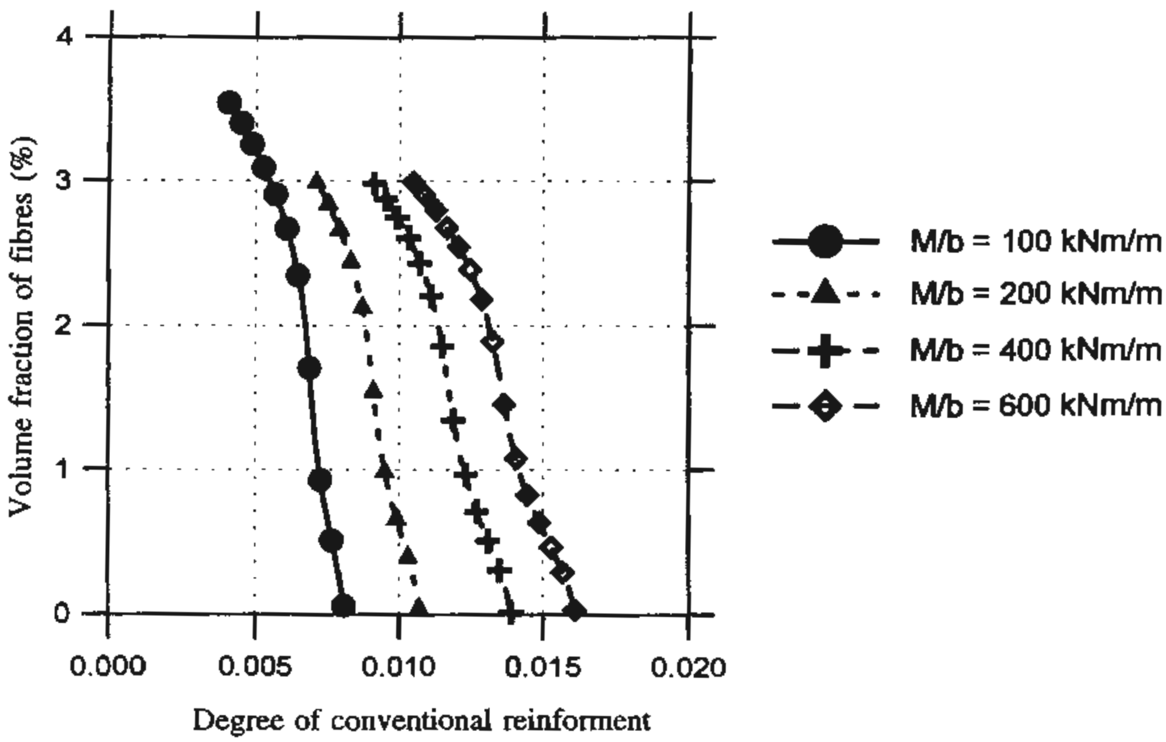

FIG. 5. *Corresponding values of the volume fraction of fibres and the degree of reinforcement for a beam loaded in bending.*

The total material costs for the fibres and the conventional reinforcement for a beam can then be calculated under assumptions about the price ratio between the fibres and the conventional reinforcement. This is shown in FIG. 6 for M/b=200 kNm/m. The figure shows that a reduction in the costs can be obtained by substituting part of the conventional reinforcement with fibre reinforcement. Unfortunately, no detailed experimental results are available to confirm the predictions presented here. A more detailed description of the test series can be seen in /15/.

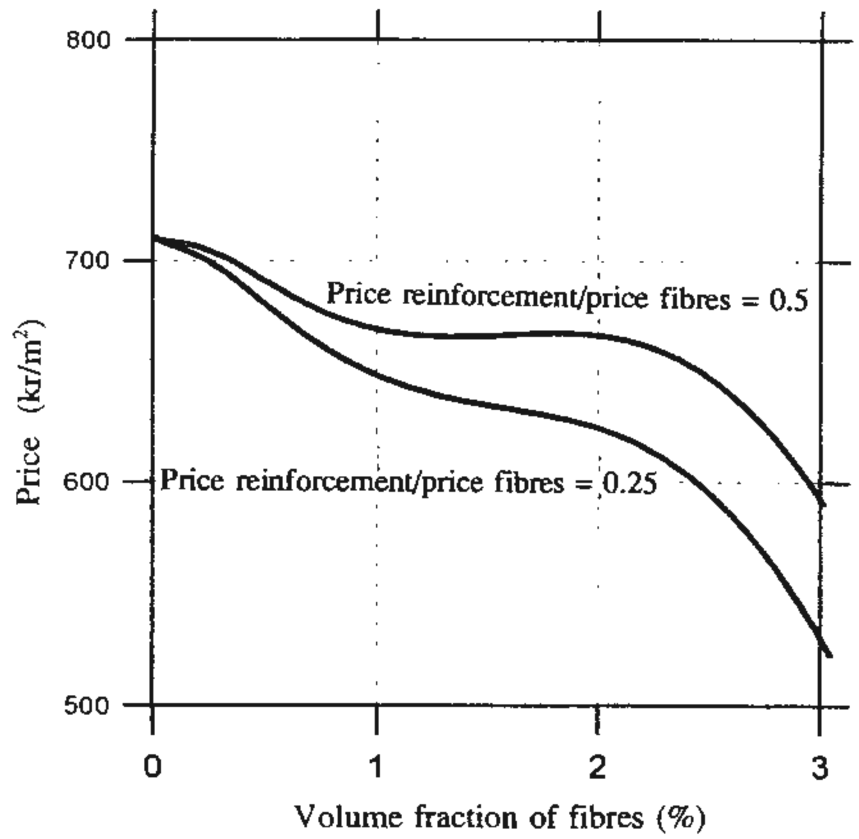

FIG. 6. *Material costs (fibres and conventional reinforcement) for different volume fractions of fibres and for M/b=200 kNm/m.*

3.5.2 Ultimate limit state design

Finite element (FEM) calculations were carried out with an advanced program called LUSAS, which takes into account the stress-crack width relation. The calculations have been carried out for FRC pipes where the material data have been determined from test specimens cut from the pipes. FIG. 7 shows comparison between FEM calculations and experimental results for the load carrying capacity for FRC pipes. It can be seen that good agreement is obtained between experimental and theoretical results. Also calculations of the maximum load in bending tests with FRC beams have been carried out. However, comparisons with experimental results show deviations up to 40-95 %. For a more detailed description of the FEM calculations for FRC, see /16/. Conditions about FRC pipes are mentioned in section 4.1 too.

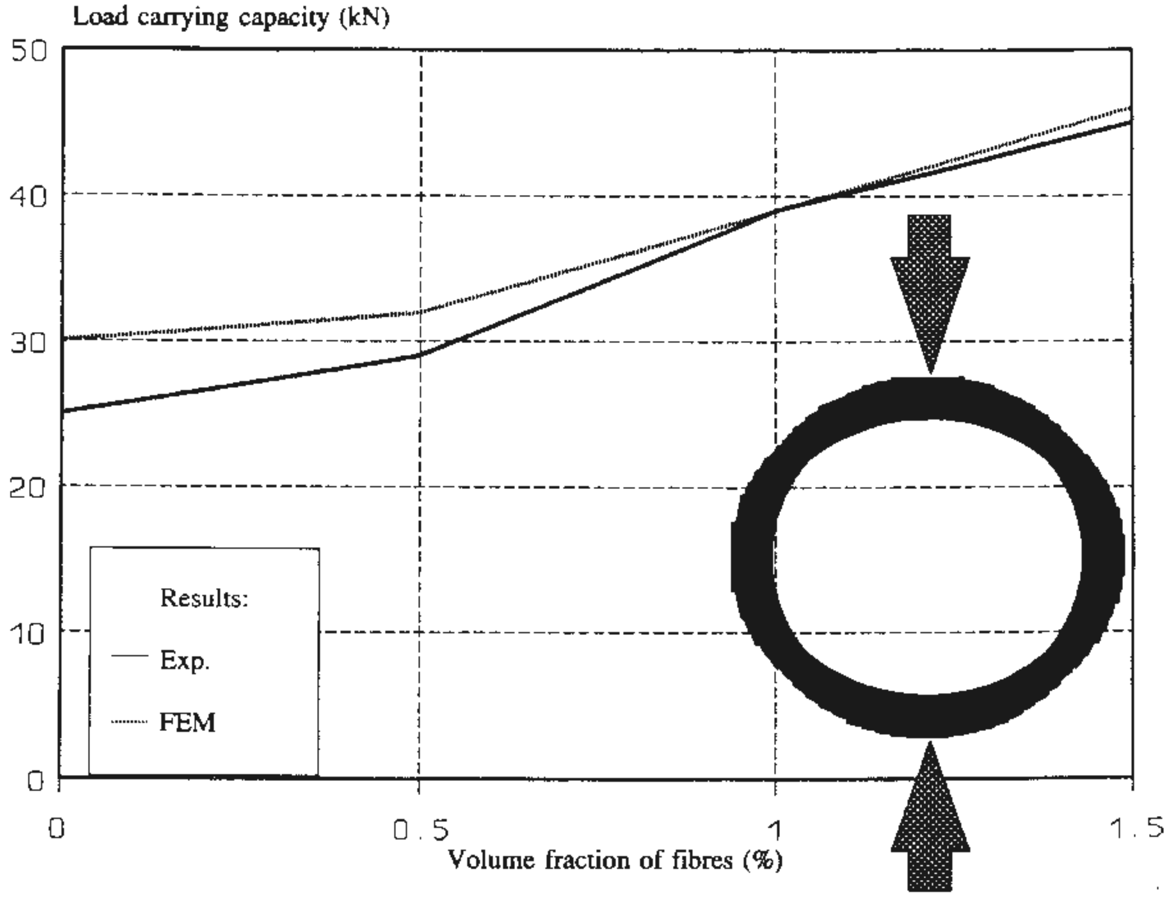

FIG. 7. *Comparison between FEM calculations of - and experiments with - FRC pipes.*

4. PRODUCT DEVELOPMENT

4.1 Pipes

It has been documented by laboratory testing that it is technically and economically possible to produce FRC pipes which can be an alternative to similar pipes made of steel or plastic. The developed pipe is made of a very dense FRC (with 1.75 vol.- % steel fibres) with an inner PVC tube. The inner tube provides the required smooth surface and the corrosion resistance. The economic profit is due to a reduction in the thickness of the pipes to 1/3 of a similar pipe made of concrete without fibres. The above conclusions are verified by calculations using the theory of plasticity for the FRC material and the fracture mechanics for the unreinforced material. As mentioned in section 3.5.2, calculation of the load-carrying capacity of the FRC pipes have also been carried out by the use of an advanced finite element program.

The investigation also covered development of a special production technique (special form and special mixing and vibration technique) which makes it possible to produce the composite pipe. However, further development will be necessary in a future industrial production, see /17/.

An alternative production technique for pipes - namely extrusion - was also investigated by both laboratory testing and full scale testing. The investigation showed that it is only possible to extrude products with a simple geometry, not pipes. However, the investigation resulted in a general knowledge about the relation between the composition and the properties of the fresh FRC, see section 3.1 and /18/.

4.2 Reservoirs

Reservoirs are one of the application possibilities which are commercially produced - as sprayed FRC without conventional reinforcement - by a group of participants in the Framework Programme. This concept constitutes an economically attractive alternative to reservoirs made of traditional reinforced concrete elements. The advantage by using FRC is that the container can be produced in one piece and sprayed directly - with an arbitrary geometry - against the ground. Furthermore, no conventional reinforcement is needed. The cost of the FRC is approximately double the cost of an unreinforced concrete. In return, the thickness of the reservoir can be reduced and it is not necessary to buy and place conventional reinforcement and to cut contraction joints. FIG. 8 shows a trial reservoir produced in 1989 with two different mix designs. 1) with 2 vol.- % polypropylene fibres and 2) with 1 vol.- % polypropylene fibres and 1 vol.- % steel fibres.

FIG. 8. *Trial reservoir made with FRC*

A considerable amount of material data was collected from this full scale test regarding frost resistance, permeability, long term durability and mechanical parameters. After 4 years of outdoor exposure, the reservoir shows no sign of degradation. Furthermore, the reservoir seems to be water proof.

Today, for commercial production, a mix design with only polypropylene fibres is used, because it is cheaper than the mix design with steel fibres. In addition, the obtained properties are acceptable, although inferiour to FRC with steel fibres.

4.3 Pavements

The Framework Programme demonstrated full scale use of FRC to continuous load-carrying pavements using different production methods: Ordinary casting, placing with an asphalt paving machine, or a specially designed paving machine.

2000 m^2 pavements were conventionally cast in 1990, using an FRC with 1 vol.- % polypropylene fibres. The thickness of the pavements was varied between 6 and 10 cm. Contraction joints were cut at varying spacings. The pavements show no sign of degradation after 3 years even if the result of a frost resistance test (according to SS 137244) was that the frost resistance is unacceptable, see section 3.4.2.

In 1992, two 75 m trial pavements were placed with both FRC and an unreinforced concrete using an asphalt paving machine and a special designed paving machine. The latter was designed primarily with regard to the transport of the FRC, see /19/. The paving machine is able to both place, vibrate and smoothen the surface of the FRC pavement, see FIG. 9.

The FRC with 0.75 vol.- % polypropylene fibres and 0.75 vol.- % steel fibres was placed with a thickness of 10 cm while the unreinforced concrete was placed (in two operations) with a total thickness of 20 cm. The overall conclusion from this trial test, was that the FRC pavement is in all respects superior to the unreinforced pavement. No cracks have appeared in the FRC pavement, though the length is 35 m and no contraction joints were cut. A more detailed description of the pilot test can be seen in /20/.

The fact that it is possible to reduce the thickness of the pavement made with FRC compared to unreinforced pavements which normally have a thickness of 20 cm, and that it apparantly is possible to increase the distance between the contraction joints combined with the more flexible behaviour of FRC and a possible better durability, makes FRC pavements an economic and technically attractive alternative to asphalt pavements and pavements made with unreinforced concrete. A suitable placing technique favours the use of FRC pavements further. Widespread use of FRC for load carrying pavements implies, however, that the FRC under tensile loading developes a fine system of small cracks instead of a few macroscopic cracks, so-called pseudo-strain behaviour.

FIG. 9. *Placing FRC with a specially designed paving machine.*

4.4 Traditional load-carrying structural elements

It has already been mentioned that fibres constitute an attractive alternative to secondary reinforcement in traditional load carrying structural elements. Simplified calculations on the basis of existing standards, modified by taking into account the tensile strength of the FRC (on the basis of the stress-crack width relation), showed that the following application possibilities are relevant with regard to FRC, see /20/.

- Substitution of secondary reinforcement in beams.
- For traditional prestressed hollow core slabs in order to avoid damage during transport and building-in.
- For walls which are not heavily loaded.
- Substitution of stirrup reinforcement in columns.

The analysis also shows that due to economic considerations the volume fraction of fibres should not exceed 1.5 vol.- %. Generally, substitution of primary reinforcement is not suitable. On the contrary, secondary reinforcement compensates for the missing or very low - not direction specific - tensile strength. Therefore, substitution with 3-dimensional distributed fibres is suitable.

The above calculations have not been confirmed experimentally. Note that the crack width model described in section 3.5.1 confirms the above conclusions.

4.5 Repair

The advantage of using FRC for repair is that it is very flexible, can be made in thin layers and has a good durability because of the resistance of the fibres to crack development. The latter property protects against failure of the adhesion between the old concrete and the repair material caused by shrinkage of the repair material. Furthermore, conventional shrinkage reinforcement can be omitted, which leads to a reduction of the thickness of the repair.

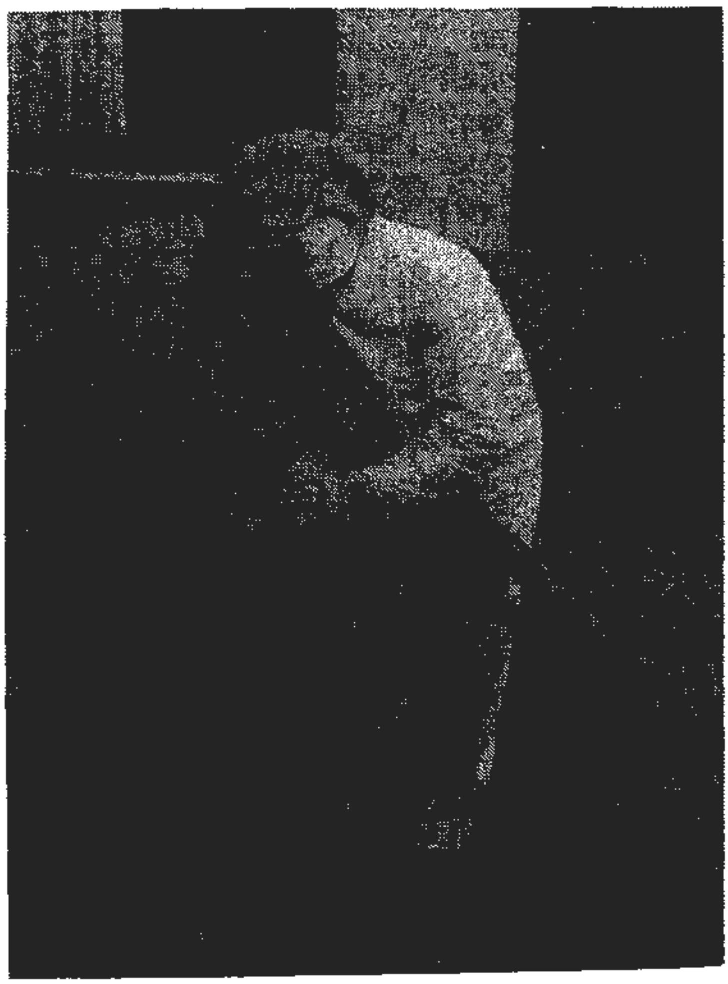

FIG. 10. *Spraying FRC*

The disadvantages by using FRC for repair is that the labour work by mixing and performing is larger, and so is the material cost. However, the full scale tests carried out in the Framework Program indicate that the advantages exceed the disadvantages.

Three different repair methods were thoroughly documented by laboratory testing and full scale repair at different bridges: Conventionally cast and sprayed FRC, fibre membrane and a sandwich build-up consisting of a fibre membrane and FRC. FIG. 10 shows spraying of FRC for repair.

A complete description of the developed mix designs and processing techniques can be seen in /21/. One of the problems still remaining is to obtain a satisfactory air void system to ensure an acceptable frost resistance.

5. CONCLUSION AND FUTURE DEVELOPMENT

From the results of the Framework Project, the following areas can be pointed out as being especially promising.

- Substituion of some of the conventional secondary reinforcement in traditional load carrying structural elements with fibres.
- Use of FRC to pipes and containers.
- Use of FRC to load carrying pavements.

However, further theoretical and practical documentation will be necessary for the preparation of codes of practice or standards in order to implement all the mentioned application possibilities.

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