# DURABILITY OF PROPYLENE FIBRES IN CONCRETE

Herbert Krenchel, Dr.techn.
Department of Structural Engineering, ABK,
Technical University of Denmark, DTH, Denmark

Anders Staf Hansen,
Civilingeniør, Erhvervsforsker,
DANAKLON A/S, Varde, Denmark

ABSTRACT

Experimental approach for estimating the long-term durability of high tenacity polypropylene fibres in cement and concrete. For well stabilized pp-fibre material the durability at normal ambient temperatures seems extraordinary good.

Key words: fibre degradation, accelerated weathering tests, Arrhenius plot, antioxydants, activation energy.

## 1. INTRODUCTION

Fibre concrete as structural material has been through different stages of development over the years. Today it seems fully accepted that this composite material - if it is made in the right way - is a high quality type of concrete with a reliable tensile strength and with substantially improved toughness and durability in comparison with ordinary plain concrete.

The use of steel fibres for mixing into concrete started about 1960. Alkali resistant glass fibres - primarily used for spraying-up with a neat Portland cement matrix - were introduced some ten years later and have had great success, for very thin-walled structures first of all. But both these fibres are quite expensive and that has been a limitation, no doubt, to the marketing of such FRC-materials. Furthermore there has been some durability problems with GRC-materials, (glass fibre reinforced cementitious materials).

About 1970, the first types of plastic fibre were introduced on the FRC-market, the "Caricrete"-fibre developed by Zonsveld. It is a heavy cross-section polypropylene fibre or yarn (6.000 to 65.000 Denier, i.e. 0.7 to 7.2 gr/m) primarily mixed into concrete for improving the impact resistance of the material.

Some five years later a so-called high tenacity polypropylene fibre was introduced as replacement fibre for asbestos cement-like material as well as for ordinary fibre concrete, /1/, /2/. Much interest has been focused on this new type of synthetic fibre because of its high specific fibre surface and good mechanical properties in combination with a very reasonable volume price. But what about the durability? We all know that steel fibres will corrode near the surface of the concrete and that even the best types of AR-glass fibres are not fully alkali resistant. Will the synthetic fibres stay better on that point?

It is well known that polypropylene has an extremely good resistance against most types of chemical attack but, on the other hand, it will be attacked over the years by oxydation, especially in combination with ultraviolet light. What will be the result then when the pp-fibres are embedded in a cementitious matrix?

These problems have been examined for about six years now in accelerated tests at elevated temperatures. The first results of these tests will be presented at the end of this paper.

## 2. TESTS AT ELEVATED TEMPERATURES

Synthetic fibres are more sensible to high and low temperatures than steel and glass fibres. At very low temperature most plastic materials become brittle and at high temperatures the elastic modulus of all thermoplastics is drastically reduced.

Series of tests have been carried through with FRC-plate material reinforced with the high tenacity pp-fibre mentioned above (from Danaklon, former Jac. Holm, Varde, Denmark) and with a neat Portland cement matrix. The tests were carried through at different temperatures ranging from $\div 20^{\circ}$ C to $+140^{\circ}/180^{\circ}$ C. (Bending tests at maximum $140^{\circ}$ C, impact tests at maximum $180^{\circ}$ C). The test pieces had a plate thickness of about 6 mm. 12 mm, 30 Denier polypropylene fibres*) were used and the fibre/cement weight-ratio was 4.7%. After thorough mixing with surplus water (and a smearing additive: Methocel 228, 0.3% on the dry weight of cement) the mixture was de-watered on a plane vacuum filter, the filter cake being finally pressed between two platens (Q = 10 MPa) during the setting period of the cement (16 hours at $20^{\circ}$ C). During mixing the water/cement ratio was 1.20, after de-watering and pressing it was between 0.20 and 0.25. The volume concentration $V_f$ of pp-fibres in the plates made in this way was about 10% giving an FRC-material with extraordinary high modulus of rupture and impact strength.

For each series of plates 3 test pieces: $230 \times 45 \times 6$ mm were cut out for bending tests and 6 pieces: $70 \times 20 \times 6$ mm for impact tests. All test pieces for bending were equipped with two electric strain

---

*) KRENIT fibres from Danaklon, Varde, Denmark.

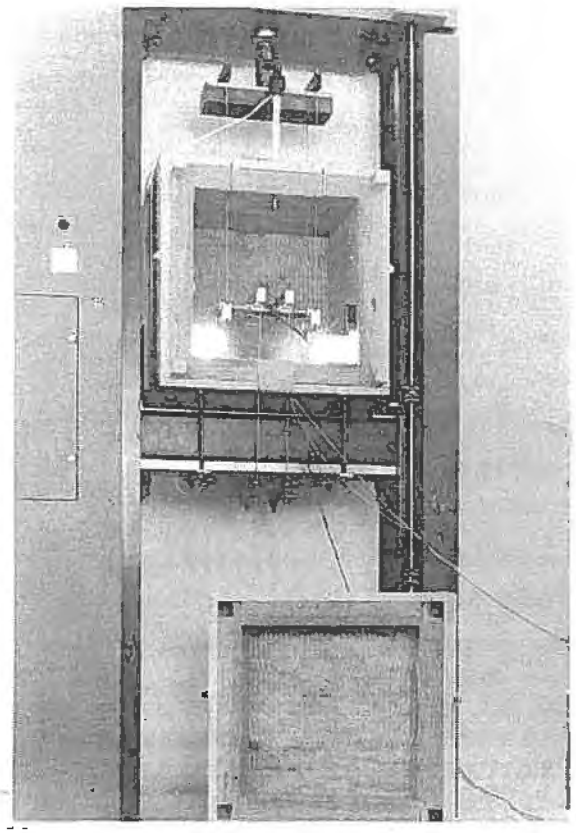

Fig. 1 10 tons Instron testing machine with cooling and heating equipment for making bending tests at constant temperatures in the range: $\div 20^{o}$ C to $+140^{o}$ C.

gauges (Type ABK, 17 mm) in the mid-span for determining the edge strain in tension and in compression during the test.

## 2.1 Bending tests

The testing machine (10 tons Instron) was equipped with a special well insulated constant temperature box with coils for heating and cooling and with a thermostate for keeping the temperature constant, see Fig. 1. After the test piece had been fixed correctly in the machine for four point bending the box was closed and the heating or cooling system was put on. Within approximately one hour the testing temperature was reached, and this was then kept constant "over night" (min. 16 hours) before the bending test was carried through. In these bending tests the full stress/strain curves were registered on a 2-pen x/y-recorder. The test results are shown on the diagram Fig. 2. It will be seen that the modulus of rupture, $\sigma_b^u$, is only slightly decreasing in the temperature range from $\div 20^{o}$ to $120^{o}$ C (approximately 20% strength reduction at $120^{o}$ C). At higher temperatures the strength drops dramatically. No doubt the fibres are now rapidly loosing strength and elastic modulus.

The elastic modulus of the FRC-material also decreases with increasing temperature (35-40% reduction from $\div 20^{o}$ to $120^{o}$ C) but this material property is stabilized for higher temperatures.

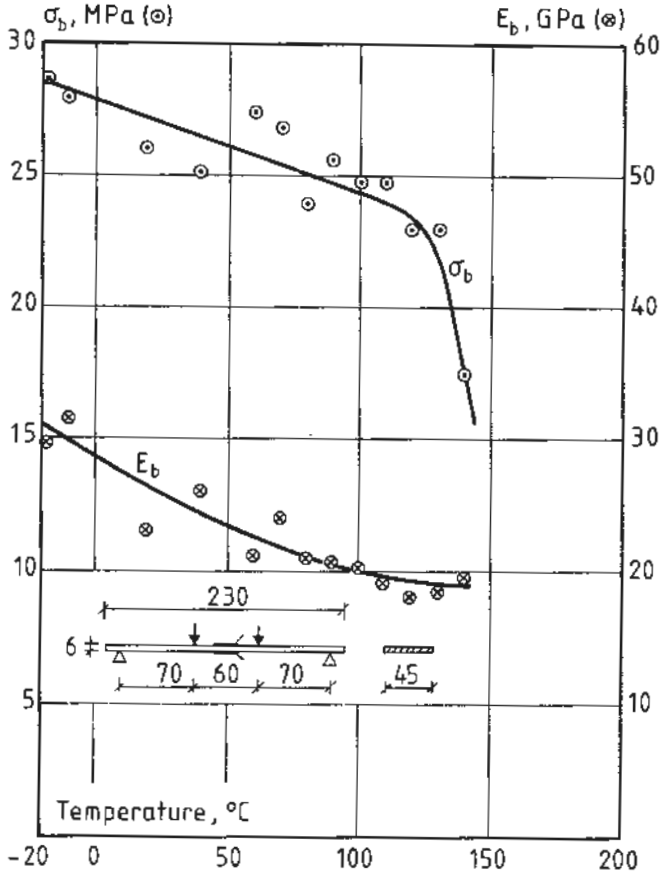


Fig. 2 Modulus of rupture, $\sigma_b$ (= M/W), and elastic modulus in bending, $E_b$, for 6 mm FRC-plate material tested at different temperatures. Polypropylene fibre reinforcement: $V_f \sim 10$ vol-%. (Dimensions in mm).

## 2.2 Impact tests

These tests were carried out in a somewhat different and simpler manner. As each test only takes a few seconds each test piece was just taken out from the insulated box (with a metal grip), quickly placed in the impact machine and tested.

The impact test results are shown in the diagram Fig. 3. It will be seen that this material property is kept practically constant up to about 110°-120° C. After that it also drops dramatically when approaching the melting point of the fibre, (approximately 165° C).

## 3. ACCELERATED DURABILITY TESTS

Weathering degradation of a plastic material as polypropylene is primarily caused by oxidation. The process is UV-catalyzed but it could also be drastically slowed down by mixing into the polyolefin raw material, moderate amounts of UV-stabilizers and anti-oxydants.

The rate of reaction of these degradation processes is strongly affected by the temperature, following the Arrhenius equation: rate = constant $\times e^{E/RT}$, in which E is the activation energy

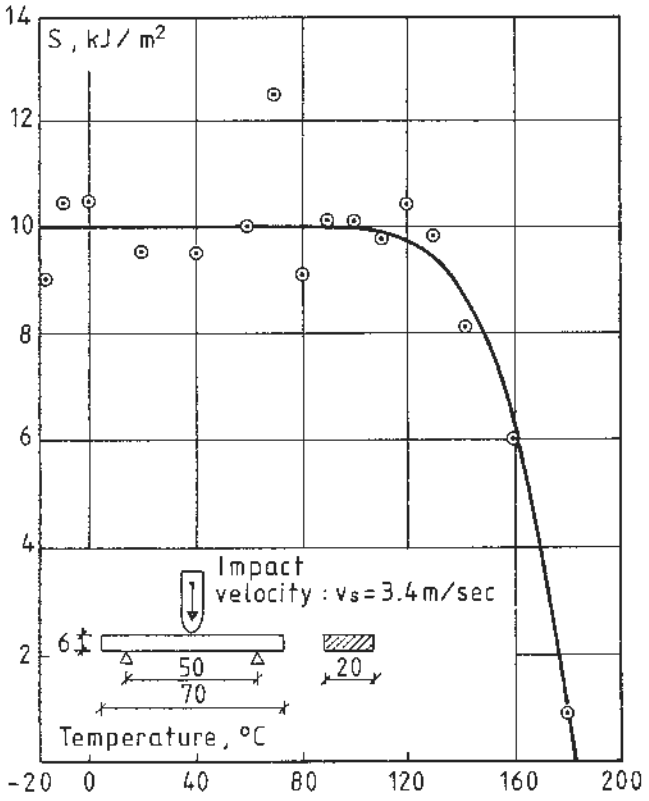


Fig. 3 Izod impact strength, S , for 6 mm polypropylene fibre reinforced plate material tested at different temperatures. (Dimensions in mm).

(Calories per Mol), and R is the gas constant (1.98 Cal/Mol/$^{o}$K). The rate constant is temperature independent as long as no temperature discontinuity point is passed (as the melting point or glass point f.inst. of the material examined).

So the process can be analyzed at elevated temperatures (within the range of discontinuity points mentioned) and when the magnitude of the activation energy E for the system is established the rate of degradation at normal ambient temperatures could be predicted by extrapolation.

Two series of accelerated tests at elevated temperatures have been carried through with polypropylene fibre raw material containing different types and different amounts of antioxydants and UV-stabilizers.

The first series were carried out at the laboratories of Ciba-Geigy, Switzerland, some twelve years ago. These tests were made at rather high temperatures: 90$^{o}$-120$^{o}$ C and so they were finished within quite a short period (less than a year).

The second series is carried out at the laboratories of Danaklon (former Jacob Holm, Varde) and DEF (Dansk Eternit-Fabrik, Aalborg) in collaboration with ABK (Afdelingen for Bærende Konstruktioner, DTH, Lyngby). These tests were started up in December 1980 as part of an industrial Ph.D.-study (Dansk erhvervsforskerprojekt EF 108, Anders Staf Hansen). They are carried out at a somewhat lower temperature level than the above-mentioned tests: 60$^{o}$-90$^{o}$ C, and they will most likely have to run ten or twenty years more

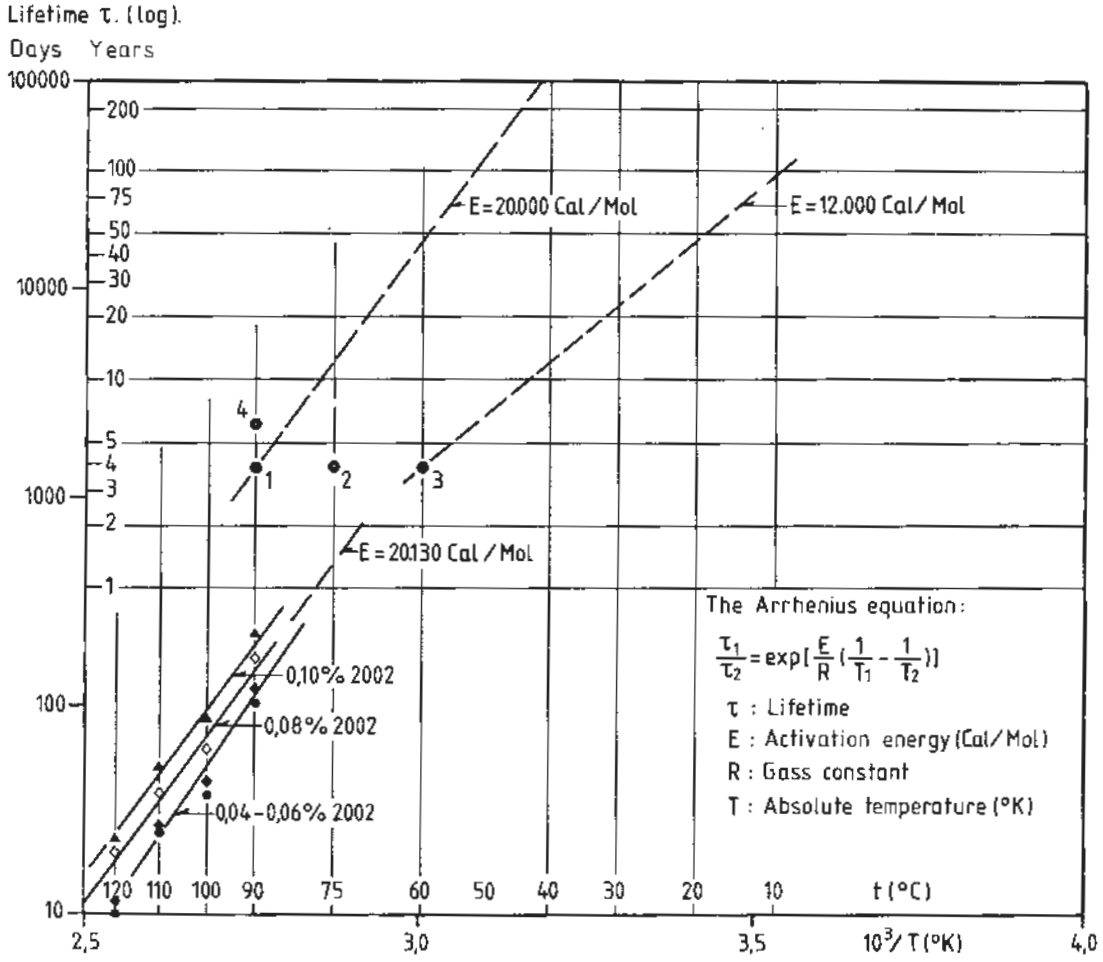


Fig. 4 Arrhenius diagram showing results from accelerated tests at elevated temperatures for estimating the durability of polypropylene fibres at ordinary ambient temperatures.

before the loss in material properties (tensile strength and ultimate elongation at rupture) is of the same order of magnitude at the lowest temperature as it was after four to six years at the highest temperature.

## 3.1 Tests in the temperature range: 90° - 120° C

The test pieces consisted of 30 µm thick and 20 mm wide extruded polypropylene tape material. Each test piece was 200 mm long. All pieces were fixed with one end in the top of a heating oven hanging free with a weight of a few grammes fixed to the other end. All test pieces in one series were placed in this way in the same oven. The temperature in the different ovens was kept constant at 90°, 100°, 110° and 120° C, respectively, and there was a constant, slow air circulation in all ovens to keep similar conditions to oxidation for all test pieces in the total test set-up.

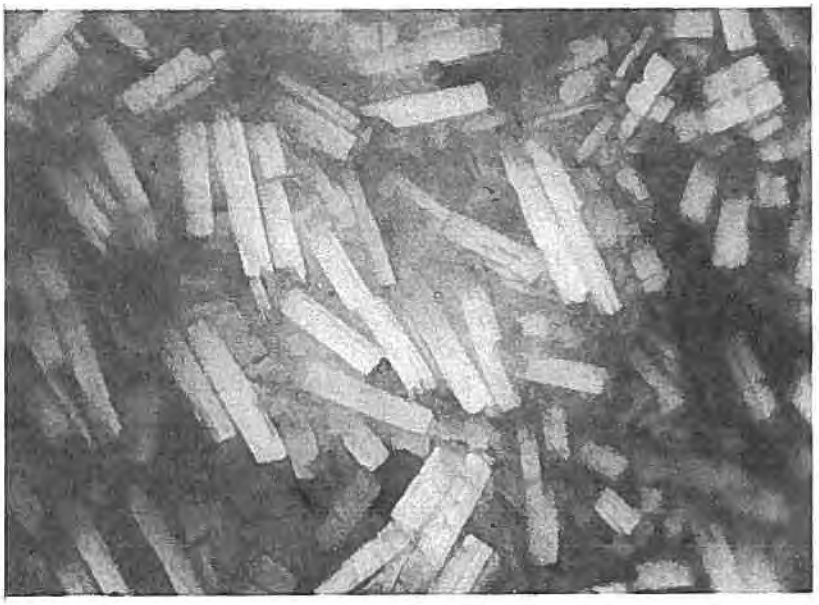

Fig. 5 Micro-photo of cross section in a fibre bundle of high tenacity polypropylene split fibres (100 ×).

Lifetime for the material at a certain temperature level was defined as the time from start until the test piece broke ("burned over") so that part of it was falling down.

In these tests only polypropylene raw material containing stabilizing additive was used (IRGASTAB 2002, produced by CG, Basel). Four different levels of this additive were tried (weight-% of additive: 0.04%, 0.06%, 0.08% and 0.10%).

The lifetime at 90° C ranged from 102 to 223 days and at 120° C from 10 to 23 days as appears from the diagram Fig. 4, lower left hand corner . (For pure polypropylene with no stabilizing additive the degradation process would have been some 20-40 times faster. Lifetime at 120° C would presumeably have been between 6 and 12 hours only). As the diagram gives the lifetime in log-scale on the y-axis and is linear in $\frac{1}{T}$ on the x-axis the experimental plots will fall on straight lines provided the reaction follows the Arrhenius law. It will further be seen that the activation energy E of the process is given directly as the slope of this straight line.

As appears from the diagram the degredation process seems to follow the Arrhenius equation and the activation energy for the system is of the order of 20.000 Cal/Mol. (This value has also been estimated by other specialists on the field).

## 3.2 Tests in the temperature range: 60° - 90° C

These tests are carried out on high-tenacity fibre material from the polypropylene fibre production at Danaklon, Varde. Each test

piece is a rowing of fibre bundle taken from the production line after stretching and fibrillating the extruded pp-tape just before the final chopping into short fibres. The rowing material is weighing 2.3 gr/m (23,000 dtex) and consists of approximately 600 individual fibres from the fibrillation process. (The fibres have a rectangular cross section as they are made by fibrillating the stretched tape with fast rotating needle rollers. Tape thickness ~ 30 µm , fibre width varying between approximately 40 µm and 400 µm with an average width of about 140 µm , see Fig. 5).

The fibre rowings are hanging down in bassins where they are immersed in concentrated Portland cement substrate, saturated with oxygen from a stream of finely dispersed air bubbles (atmospheric air) constantly pumped through the liquid. The liquid in the different bassins is kept at a constant temperature of 60° , 75° and 90° C, respectively, for the three different series. At different time intervals samples of the roving material are taken up, washed and dried and then tested for tensile strength and ultimate tensile straining at rupture. These material properties are then compared with the same properties for the roving material at start of the test before any ageing had taken place (zero-tests).

The total test set-up consists of twelve series of roving material of different types, six made from pure polypropylene raw material without any AO-additive and six made from pp-raw material with antioxydant additive (totally 0.4 weight-% of a two-component mixture of commercial antioxydants and UV-stabilizers. The composition and amount of this additive has been chosen by

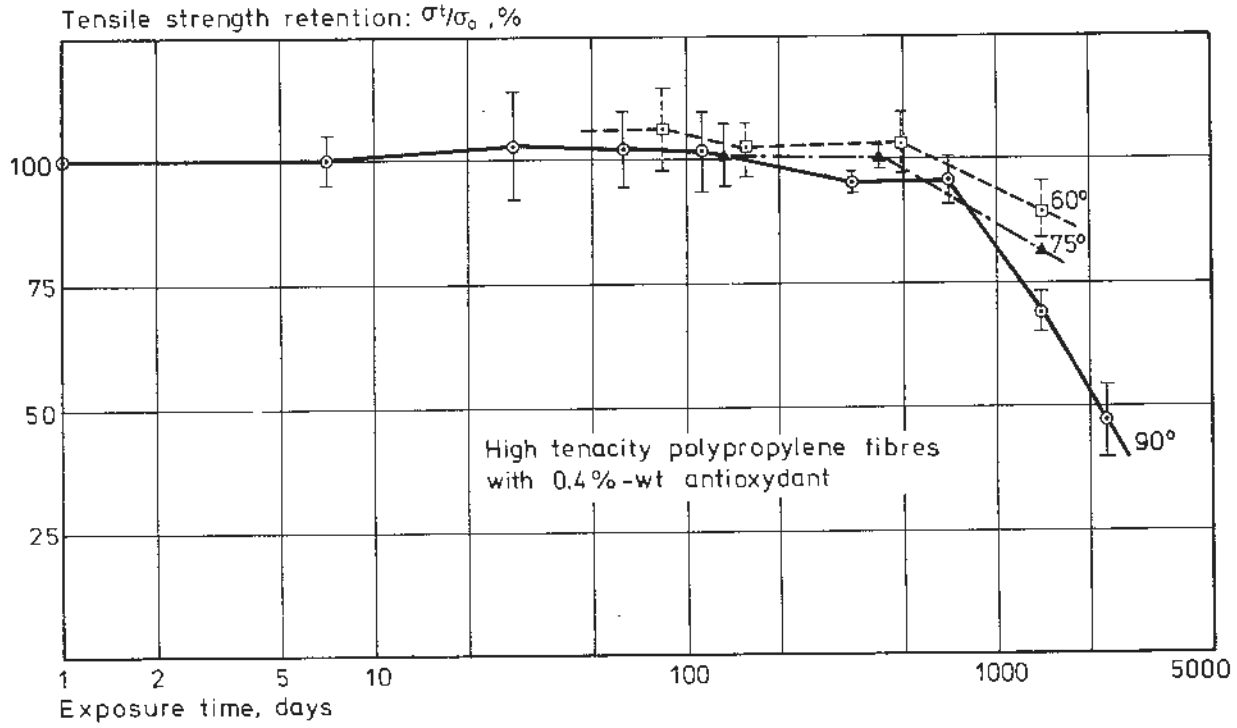


Fig. 6 Development of the tensile strength of plastic fibre rovings in accelerated tests at elevated temperatures (60° , 75° and 90° C). Fibre material: Polypropylene containing 0.4% antioxydant additive.

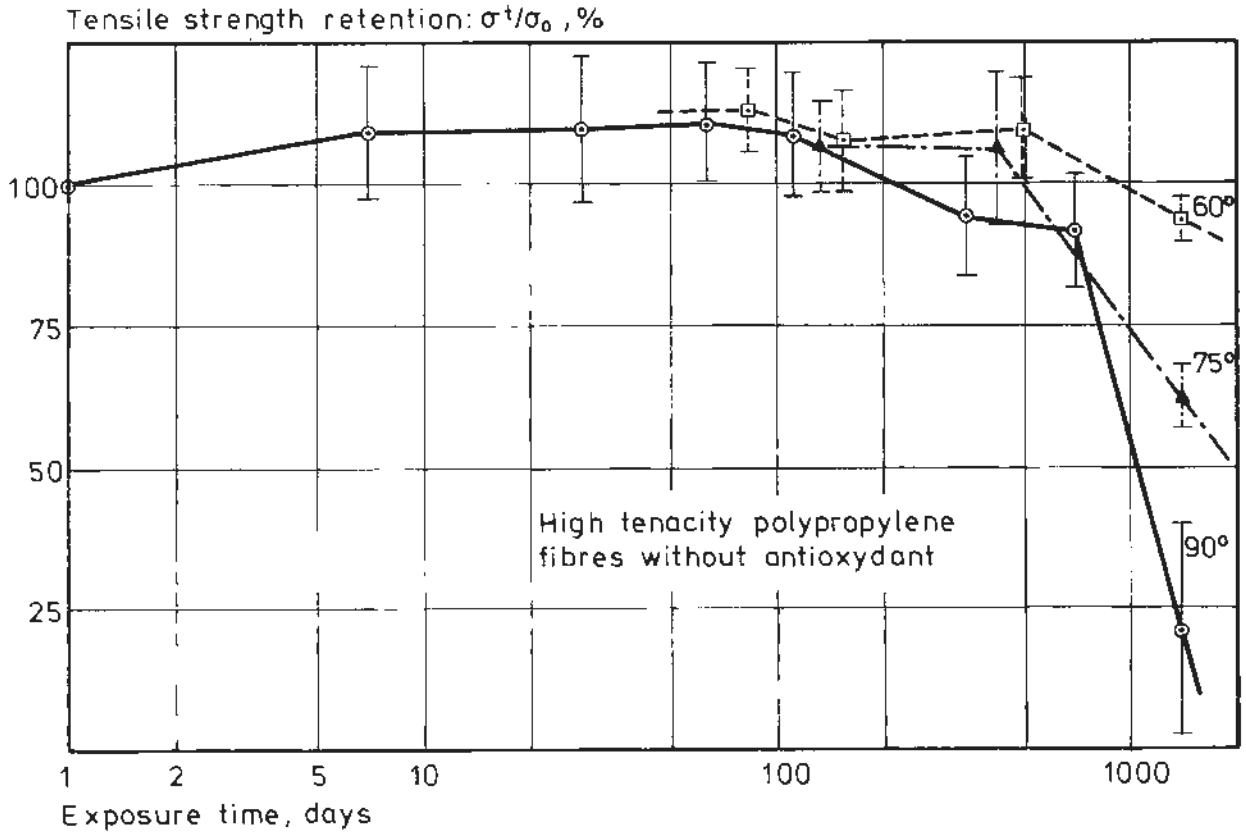


Fig. 7 Development of the tensile strength of plastic fibre rovings in accelerated tests at elevated temperatures (60° C, 75° C and 90° C). Fibre material: Polypropylene without antioxydant additive.

the producers). The tests were started up in December 1980 and so they have been running now for totally 7 years. The time intervals at which samples of the different types of roving have been taken up and tested have been the following, all taken from the day of starting: 1:7 days, 2:28, 3:63, 4:112, 5:343, 6:700, 7:1400 and 8:2251 days. (Last mentioned only at 90° C and only for material containing antioxydants).

The test results are shown in the diagrams Fig. 6 and Fig. 7. It will be seen that for the first 1-2 years of exposure the tensile strength of the fibre material was practically unchanged. After that the tensile strength has dropped, but still after four years (1400 days) the strength reduction, for material with AO-additive, was only about 10% at 60° C, 18% at 75° C and 31% at 90° C. For polypropylene fibres without AO-additive the strength reduction, especially at higher temperatures, was more dramatic: 38% reduction at 75° C and 79% at 90° C.

Fig. 8 SEM-photo of polypropylene fibres with antioxydant additive after 1400 days immersion at 90° C in concentrated Portland cement substrate saturated with oxygen, (1.430 ×) . (Residual tensile strength: $\sigma^t/\sigma_o = 0.70$).

## 4. CONCLUSION

A comparison between the two research series in chapter 3.1 and 3.2 gives us a first possibility for predicting the lifetime of the high-tenacity polypropylene fibres at normal ambient temperatures when used as reinforcement in a cementitious matrix. For this purpose four points from the last-mentioned tests have been plotted in the diagram Fig. 4. Point 1, 2 and 3 are showing the average test results at the three different temperatures after four years exposure (1400 days), representing an average tensile strength reduction of 31% (point 1), 18% (point 2) and 10% (point 3) for polypropylene roving material containing AO-additive. Point 4 is representing an average strength reduction of 53% for the same material after 2251 days exposure, see diagram Fig. 6.

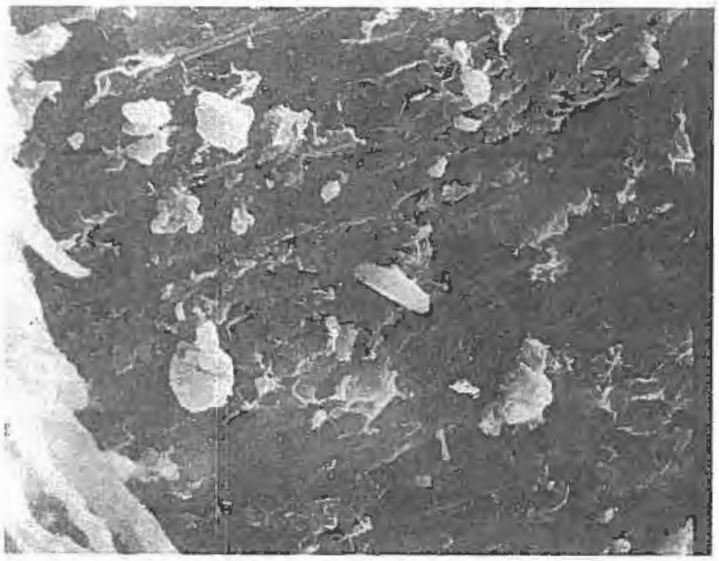

Fig. 9 SEM-photo of polypropylene fibres without antioxydant additive after 1400 days immersion at 90° C in concentrated Portland cement substrate saturated with oxygen, (1.430 ×) . (Residual tensile strength: $\sigma^t/\sigma_o = 0.09$).

From this it is possible now to make a first estimate of the strength reduction of polypropylene fibres in a cementitious matrix at ordinary ambient temperatures, say an average temperature over the year being 20° C.

For this purpose two Arrhenius-lines are shown in the diagram with two different values for the activation energy: E = 20.000 Cal/Mol (which is the most probable value for this reaction system) and an absolute lowest value for such reactions: $E_{min}$ = 12.000 Cal/Mol. (Suggested by the polyolefin specialists at Ciba-Geigy, Switzerland).

It will be seen that for pp-fibres with AO-additive the most pessimistic estimate is about 50 years lifetime for a first significant strength reduction of about 7-10%. Even after 100-200 years the strength reduction should not be more than some 30-50% for material with the type and amount of additive used in the production of these pp-fibres.

REFERENCES

/1/ Krenchel, H. and Jensen, H.W.: Organic Reinforcing Fibres for Cement and Concrete, ACI: Concrete International 1980. Fibrous Concrete. The Construction Press Ltd., Lancaster, England, 1980, pp. 87-98.

/2/ Krenchel, H. and Shah, S.P.: Applications of polypropylene Fibres in Scandinavia, ACI: Concrete International, March 1985, pp. 32-34.

/3/ Evans, M.E.: The Influence of Additives on Processing and Properties of Polypropylene Film Fibres, The Plastics Institute, London: Textiles from Film, II Conference, Paper No. 2, 6-7 July 1971, pp. 13-23.

/4/ Baum, B.: The Weathering Degradation of Polyolefins, Polymer Engineering and Science, Vol. 14, No. 3, March 1974, pp. 206-211.

/5/ Sysling, H.: Antioxidanten und UV-Stabilisatoren, Kunststoffe 66(1976)10, pp. 670-674.

/6/ IRGASTAB 2002 - a stabilizer for polyolefins, CIBA-GEIGY Studies, 1977, pp. 4.

/7/ Sitek, F., Linhart, H. und Müller, H.: Neure Entwicklungen auf dem Gebiete der Lichtstabilisierung von Polypropylenfasern, III Internationales Faser-Symposium, Kalinin, Mai 1981, pp. 18.

/8/ Galloway, J.W., Williams, R.I.T., and Raithby, K.D.: Mechanical Properties of Polyolefin-Reinforced Cement Sheet for Crack Control in Reinforced Concrete, Transport and Road Research Laboratory, TRRL Supplementary Report 658, Crowthorne, Berkshire, 1981, pp. 19.