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Prestressed Concrete Structures with High Strength Fibres

Ouvrages en béton précontraint, avec des fibres à haute résistance

Vorgespannte Bauwerke mit hochfesten Chemiefasein

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SUMMARY

Tendons of man-made high strength fibres – in this case aramids – are appreciated in environments which are aggressive to prestressing steel. The main advantages are : non-corrosive, insensitive to chlorides and to electro-magnetic currents. Characteristics and structure of the material as such differ from steel experience. Understanding of material behaviour, especially in alkaline environment and under stress is essential. Emphasis is laid on the differences in relaxation behaviour between steel and Arapree tendons.

RÉSUMÉ

Les éléments de précontrainte en fibres chimiques haute performance – ici en aramide – peuvent être utilisés avantageusement dans des environnements agressifs pour les aciers de précontrainte. Les avantages principaux sont les suivants : inoxydabilité, résistance aux chlorures, non-conductibilité électrique. La connaissance du comportement du matériau, notamment dans un environnement alcalin et sous contrainte est un facteur essentiel pour son application. Les différences de comportement en relaxation seront traitées particulièrement.

ZUSAMMENFASSUNG

Zugelemente aus hochfesten Chemiefasern – hier Aramiden – können bevorzugt eingesetzt werden in Umgebungen, die Bewehrungsstähle angreifen. Hauptvorteile sind : nichtrostend, unempfindlich gegen Chloride, elektrisch nichtleitend. Voraussetzung für den Einsatz ist die Kenntnis des Materialverhaltens, insbesondere in alkalischer Umgebung und unter Spannung. Vertieft werden die Unterschiede im Relaxationsverhalten.

1. INTRODUCTION

The properties generating the interest in the use of high-strength man-made fibres as an alternative to steel in reinforced and presstressed concrete structures are:
- high strength; up to 3000 N/mm^2 (fig. 1).
- non-corrosive; not attacked in carbonated concrete
- resistant to aggressive environments like chlorides
- insensitive to electro-magnetic currents

Practical use, however, is still restricted by:
- lack of experience and hesitation to use non-proven materials;
- relative low E-modulus; therefore preferably to be used in prestressing;
- brittleness; no deformation due to yield;

Not withstanding these restrictions it seems to be worthwhile to investigate the advantageous properties in view of the improvement of the durability of concrete structures in "exposed" conditions. Several developments of tendons based on high-strength man-made fibres have recently been made public [1] to [4]

For practical use as a prestressing tendon in concrete structures at least the following (very) long term aspects must be considered:
- creep/relaxation behaviour
- behaviour in different environments (e.g. alkaline and carbonated)
- stress rupture/stress corrosion behaviour
- residual strength under sustained loading.

For each of these the different nature of polymer materials (long chains of molecules) versus steel (atom-rostrum) could lead to significant and even surprising differences. This paper will extend the information given in [1] and [2] with special emphasis on current investigations about creep and relaxation of Arapree*). With respect to the other items only short indications are given.

2. NON-CORROSIVE TENDONS

2.1 Continuous tensile elements for structural application

In general polymer fibres are excluded owing to their low modulus of elasticity (fig. 1), high creep and temperature sensitivity.

Carbon fibres are very insensitive to aggressive environments. They may in general be disregarded on account of their low strain at failure (insufficient warning behaviour). Low E-modulus carbon fibres (pitch based types) may become a possibility in the future. As yet they are not considered. That leaves glass fibres and aramid fibres.

2.2 Glass-fibres

The first development which found its way into actual service is "Polystal", which consists of circular rods of E-glass bonded by a polyester resin. [3].

2.3 Aramid fibres

Aramid is an organic man-made fibre with a high degree of crystallinity. Two grades of stiffness are generally available; E-moduli in the range of 70 kN/mm^2 and 130 kN/mm^2. In the case of Twaron they are denoted Twaron and Twaron-High Modulus (HM). At the Imperial College of London Parafil ropes containing aramids to be used in unbonded tendons are being investigated (4). Enka and HBG jointly develop Twaron based tendons and stressing devices suitable to prestressed concrete. These tendons are named Arapree.®

*) Arapree®: a composite of Twaron® fibres and epoxy resin.
Twaron® : the aramid fibre produced by Aramide Maatschappij v.o.f.

2.4 Arapree tendons

For practical reasons like handling, good adherence, stability and resistance to many chemicals, epoxy resin was selected as the bonding matrix to produce tensile elements. A strip-like shape proved to be effective in continious bond with the cement matrix, using pretensioning and avoiding the need to insert permanent ducts or (metallic) terminations. In this approach effective use of the non-corrosive character can be made. A cover of only a few millimetres is sufficient. In addition, the strip-like shape enabled simple anchorage devices to be developed. The characteristics determining the use of EP impregnated Twaron HM as tendons in prestressed concrete are given in table 1.

3. DURABILITY

To simulate ageing, investigations are carried out at elevated temperatures to evaluate the retention of properties over 50 to 100 years. The results available, from accelerated testing [1], give a number of preliminary conclusions:

- chemical resistance: outstanding with regard to practically all hazards that can be assumed to exist in or around concrete structures; for instance:
- alkaline attack: lifetime predictions from extrapolations based on Arrhenius plots are fully satisfactory. As a preliminary guidance strength retention of over 80% after 180 days in a saturated $Ca(OH)_2$ solution of 80°C is assumed to be adequate.
- chlorides: no problem at all, which clearly indicates suitability for use in exposed concrete structures (marine environments);

4. CREEP AND RELAXATION

4.1 General

Relaxation and creep are interrelated material properties. Both describe a relation between stress, strain and time. Creep describes change in strain as a function of time at constant stress. Relaxation describes the change in stress as a function of time at a constant length. The former usually expressed in direct strain figures indicating the increase and the latter in percentages of initial stress.
The reaction of the structure of the materials on being stretched is specific. No general law gives a fixed relation between creep and relaxation. A significant difference between prestressing steel and polymeric materials becomes apparent from tests at different stresses.

4.2 Comparison between creep and relaxation of steel and aramid

Three possible relationships between creep and relaxation can be assumed. If relaxation is simulated by a creep test whereby, after a certain time interval, the measured creep is compensated by a decrease in load, then the obtained relaxation will be according to a, b, or c in fig. 2.
From steel it is known,[8][9] that a higher choice of the initial stress-level gives a more than proportional increase in creep strain. ($\varepsilon_{cr2}/\varepsilon_{cr1} > \sigma_2/\sigma_1$; fig. 3a.) Relaxation data show comparable results.[10]
Investigations on Aramids however show a different behaviour. With an increase of stress -as a percentage of ultimate strength- creep strain increases proportionally or even less than proportionally, from ε_{cr1} to ε_{cr2}
It can be concluded that -contrary to prestressing steel- increase of initial stress produces constant or even decreasing relaxation percentages for aramids for the same time interval. $\Delta\sigma_2/\Delta\sigma_1 \leq \sigma_2/\sigma_1$; fig. 3 b/c.
In the following discussion a constant relaxation percentage is assumed to be valid (fig. 3b). Consequently relaxation at t_x can be obtained from any creep test in the practical stress range. The apparent long term modulus E_{tx} giving the relation.

Even at a higher initial stress Arapree shows losses in stress, which are significantly less than prestressing steel type I and in the same range as type II.

5. LONG TERM BEHAVIOUR/SAFETY PROGNOSES.

5.1 Long term behaviour under stress

Practical use in concrete and in the building industry requires reliable long term behaviour under continuously stressed conditions. Creep is one of the properties investigated (see 4). Others, still under investigation, will deserve a -more extensive- future discussion ot the results. Also in these cases differences, due to the inherent behaviour of these fibres, from steel experience do occur.

5.2 Safety prognosis

Based on the above given indications from preliminary results and on [12] a safety prognosis on longterm behaviour under prestress in alkaline environment is given in fig 7.

6. APPLICATION

6.1 Experiments

To investigate the behaviour in actual practice experiments are being conducted on concrete elements. One of which is shown in fig.8. [14]

6.2 Fields of application

Notwithstanding the present price level -as compared to steel- an effective and economic long term use of these aramid/epoxy tendons for reinforcement or prestressing may be expected where:

- concrete is exposed to aggressive atmospheric attack;
- aggressive liquids and gases are to be stored;
- chlorides are present (seawater/de-icing salts);
- use of $CaCl_2$ can increase productivity;
- thin and light elements are required;
- large deformation capacity is required (impact, explosions, earthquakes).
- high fatigue requirements are to be met;
- electro-magnetic currents must be prevented.

Table 1: Comparison of properties (based on cross-sectional area of the fibres)

Properties	Units	Prestressing Steel	Glass (Polystal)	Arapree (Twaron HM)
Density	kg/m³	7850	2650	1450
(in resin)			(2000)	(1250)
Youngs Modulus	kN/mm²	200	70	130
Tensile Strength	N/mm²	1750	>2000	>3000
Initial level of prestress	N/mm²	1300	1000	1500
Elongation of break	%	>3.5	3	2.4
Relaxation (0.1-1000h)	%	(type II) 2-3	4	7-9
Chemical Resistance:				
pH>12		++	-	+
pH<10		--	+	++
Cl-ions		-	-	+
Temp.high	°C	400	500*)	300*)
low		+	-	++
Fatigue $2x10^6$		+	-	++

*) Not valid for resin

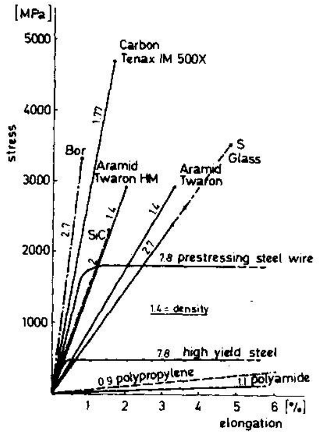

Fig.1 Stress-strain diagram of reinforcing materials

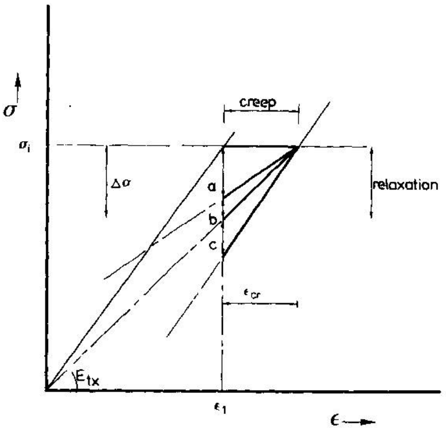

Fig.2 Possible relations between creep and relaxation at a chosen level

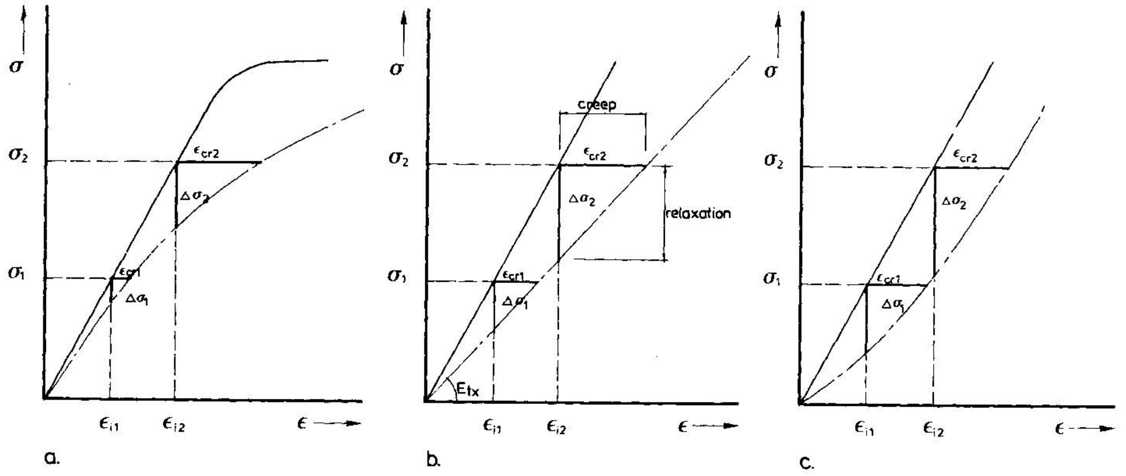

Fig.3 Schematic creep/relaxation behaviour at different initial stress-levels

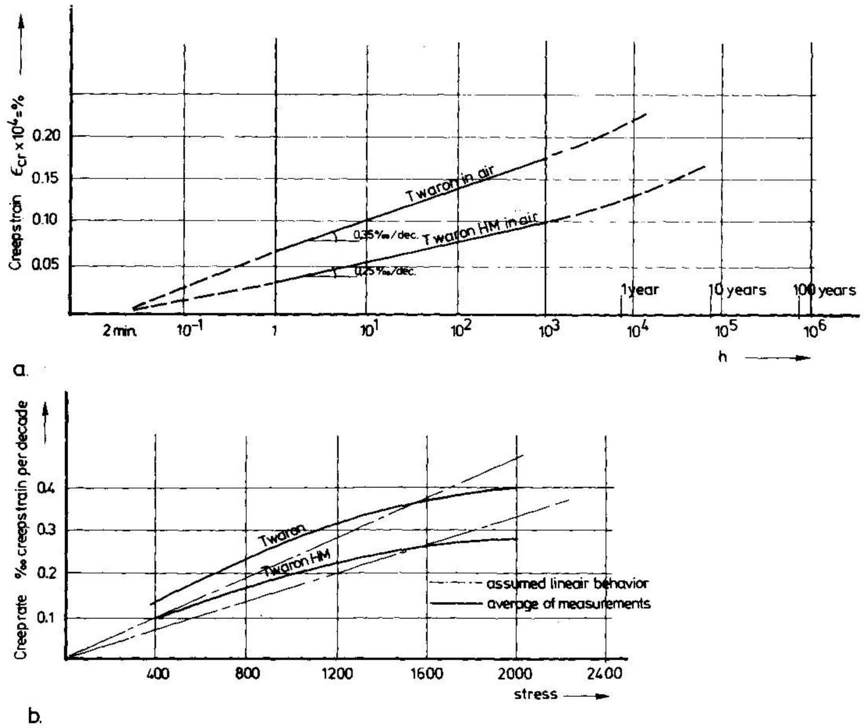

Fig.4 a Creep data of Arapree based on Twaron HM and Twaron in air, measured at $0.5 f_u$ (ca. 1500 N/mm^2)

b Literature survey of average creep rates at increasing stresses

Preliminary data indicate a creepstrain in air of about 0,025% per decade at 50% of f_u (1500 N/mm²) for Arapree based on Twaron HM and about 0,035% per decade for Twaron based Arapree. These figures do increase slightly above 10^3 h. (fig. 4). From [5] corresponding data can be derived, as well as from [6] and [7] The former gives measurements even up to 1000 days. Fig 4b gives a survey of test results described in more than 20 sources [13].

4.3 Relation Creep/Relaxation

For HM: $\Delta\sigma$ per decade $\cong 0{,}025 \times 10^{-2} \times 130 \times 10^{3} \cong 33$ N/mm² $\cong$ 2.1% of 1500 N/mm². Starting at 2 min after stressing this leads to a relaxation of about 10% up to 1000 h; independent of stress level (< 5 decades). For Twaron based Arapree a relaxation of about 8% at 1000 h can be calculated accordingly. Ongoing tests roughly confirm these calculations (fig. 5). The important difference with the behaviour of prestressing steel can also be derived from fig. 5. Final relaxation of prestressing steel is commonly calculated from the 1000 h results multiplying it by a factor of 3 (factor n in formula (1), see 4.4) to accommodate for the time from 10^3 to 10^6 h. This corresponds to a strong upward trend on the log/lin plot. Relaxation of Arapree starts at a higher rate per decade but remains more or less constant although a slight upward trend has to be considered. It seems that for final relaxation of Arapree a multiplication n = 2 will do. In fig. 6a an indicative comparison of relaxation at increasing stresses is given. Fig. 6b gives an extrapolation for 10^6 h. An essential difference in behaviour becomes apparent.

4.4 Example of losses in prestressed concrete

An example may provide indications on the implications of the above.

Losses du to relaxation $\Delta\sigma_{p,1} = n\cdot\Delta\sigma_{p.1000}\ (1 - m\ \frac{\Delta\sigma_{p,r+\phi}}{\sigma_{po}})$ (1)

A pretensioned prestressed column 220 mm square ($A_c = 484\text{x}10^2$ mm²) is subjected to a uniform initial prestress of 10 N/mm² (484 kN).
Initial stress level in Arapree 1500 N/mm² $\cong 0{,}5\ f_u$.
and in prestressing steel 1350 N/mm² $\cong 0{,}8\ f_u$.
$f_{ck} = 35$ [N/mm²] → E-mod = $33{,}5\text{x}10^3$ N/mm² → $\varepsilon_{\text{elast.}} = \frac{10}{33.5 \times 10^3} = 0.33\text{x}10^{-3}$
assume ϕ creep = 2 → $\varepsilon_\phi = 0.66\text{x}10^{-3}$
assume shrinkage $\varepsilon_{cs} = 0.25\text{x}10^{-3}$ $\underline{0.91\text{x}10^{-3}}$
Concrete deformation: $1.24\text{x}10^{-3}$

$\Delta\sigma_{p,r+\phi}$ becomes: Twaron HM → $0.91\text{x}10^{-3}\text{x}130\text{x}10^3 = 118$ N/mm²
Twaron → $0.91\text{x}10^{-3}\text{x}\ 70\text{x}10^3 = 64$ N/mm²
Steel → $0.91\text{x}10^{-3}\text{x}200\text{x}10^3 = 182$ N/mm²

Losses due to relaxation:

Twaron HM	$\Delta\sigma_{p,1} = 2\text{x}10(1-2 \text{ x } \frac{118}{1500}) =$	16.6				%
Twaron	" $= 2\text{x}\ 8(1-2 \text{ x } \frac{64}{1500}) =$		14.5			%
Steel (type I)	" $= 3\text{x}\ 8(1-2 \text{ x } \frac{182}{1350}) =$			17.3		%
Steel (type II)	" $= 3\text{x}\ 3(1-2 \text{ x } \frac{182}{1350}) =$				6.5	%
Losses due to concrete deformations						
Twaron HM	$\Delta\sigma_{p,2} = 1.24\text{x}10^{-3}\text{x}130\text{x}10^3 = 161$ N/mm²	11.5				%
Twaron	" $= 1.24\text{x}10^{-3}\text{x}\ 70\text{x}10^3 = 87$ N/mm²		6.2			%
Steel	" $= 1.24\text{x}10^{-3}\text{x}200\text{x}10^3 = 248$ N/mm²			18.2	18.2	%
Total losses	Twaron HM	28.1				%
	Twaron		20.7			%
	Steel (type I)			35.5		%
	Steel (type II)				24.7	%

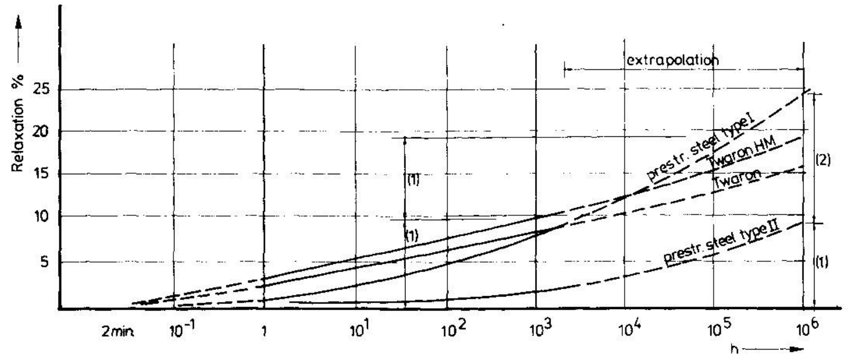

Fig.5 Relaxation behaviour

- Arapree (based on Twaron HM and Twaron), independent of initial stress
- Prestressing steel (type I and II), initial stress ca. $0.7f_u$

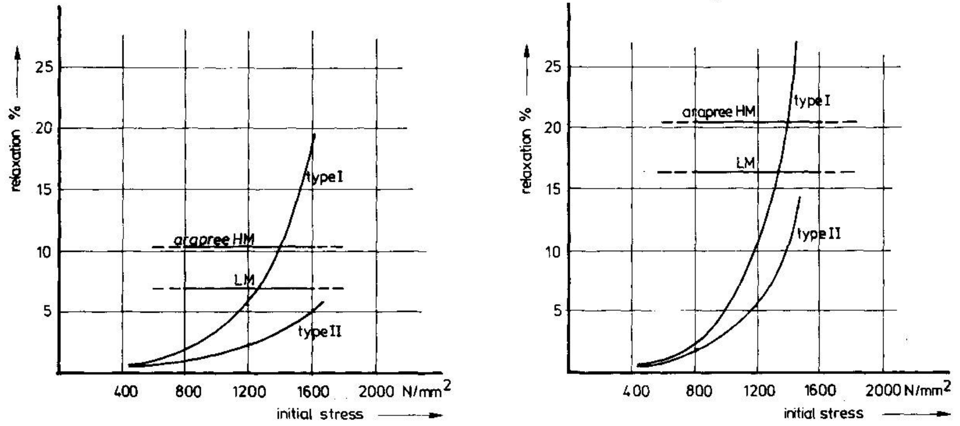

Fig.6 Comparative relaxation behaviour at different initial stress-levels

a Measured at 10^3 h b Expected at 10^6 h

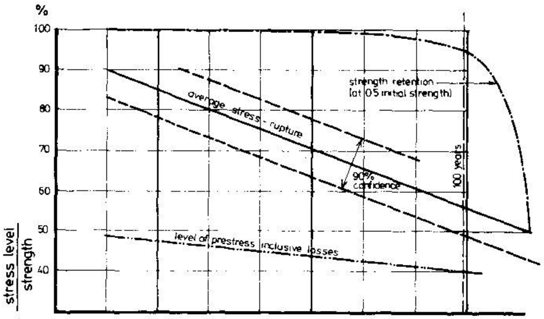

Fig.7 Safety prognosis

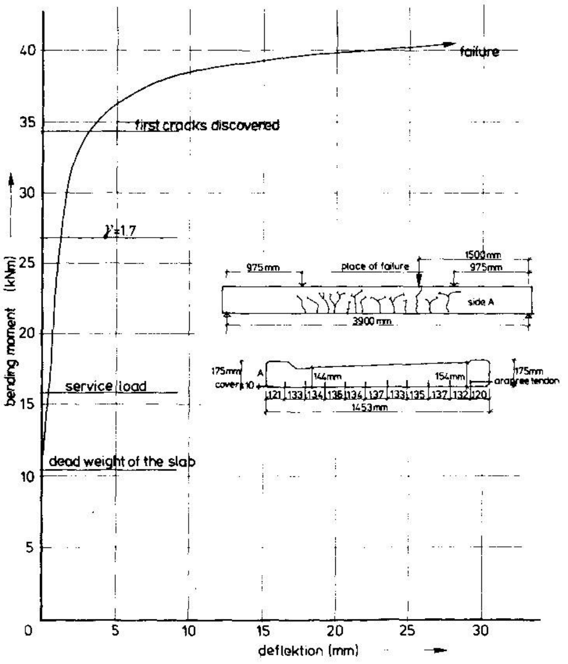

Fig.8 Graphical representation of a load-test on a balcony slab

7. CONCLUSIONS

1. High strength man-made fibres in general and especially Arapree can be assumed to be a valid and satisfactory alternative for longterm use under stressed conditions in structural concrete.
2. With Arapree the final losses of stress to take into account for relaxation and concrete shortening have the same order -or even less- then those of prestressing steel.
3. With prestressing steel stress relaxation increases progressively at higher levels. Arapree shows a relaxation behaviour, which is roughly independent of the stress level applied.
4. The multiplication factor n -to calculate final relaxation losses from 1000 h measurents can be chosen equal to $n = 2$ (prestressing steel $n = 3$).
5. Arapree based on Twaron HM (with the higher E modulus) exhibits a lower creep rate than the type based on Twaron, but the relaxation of the Twaron based type is lower as a result of the different modulus of elasticity.

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