BOND OF ARAMID COMPOSITE BARS IN CONCRETE AFTER EXPOSURE TO TEMPERATURE CYCLES

VERBUND VON ARAMIDSTÄBEN IN BETON NACH TEMPERATURWECHSELLAGERUNG

ADHERENCE BETON-BARRES D'ARMATURE EN ARAMIDE APRES EXPOSITION A DES CYCLES THERMIQUES

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SUMMARY

Pull-out tests with short embedment length were carried out with 7.5 mm thick aramid composite bars in 60 MPa concrete. Standard climate, natural weathering, and thermal cycles between -20 and +40°C were applied during about one year. Results are reported with respect to maximum bond stress, bond stress-slip relation and bond creep.

ZUSAMMENFASSUNG

Auszugversuche mit kurzer Einbettungslänge wurden an 7,5 mm dicken Aramidbewehrungsstäben in B55 durchgeführt. Normklima, Auslagerung im Freien und Temperaturzyklen zwischen -20 und +40°C wurden angewandt. Ergebnisse hinsichtlich der Verbundfestigkeit, der Verbundspannungs-verschiebungskurve und des Verbundkriechens werden berichtet.

RESUME

Des essais d'arrachement direct avec une courte longueur d'encrage ont été effectués avec des barres d'armature en aramide de 7,5 de diamètre dans un béton d'une résistance de 60 MPa. Les spécimens ont été exposés au climat standard, au climat naturel et à des cycles thermiques allant de -20 à +40°C pendant environ un an. Les résultats concernant la résistance de la liaison d'adhérence, la relation contrainte-glissement et fluage de l'adhérence sont présentés.

KEYWORDS: Prestressed concrete, non-ferrous reinforcement, ceramid, bond, temperature cycles, bond creep

1. MOTIVE

Reinforced and prestressed concrete has proven to be durable in most environments. However, there are some harsh conditions where reinforcing and prestressing steel may suffer from corrosion. Such situations may occur in marine environment with splash water, along traffic areas with deicing salt, or in thin walled elements with rapid carbonation. Under those circumstances fibre polymer composites can replace steel and make a reinforced concrete structure more durable. Besides very high strength of the fibers and corrosion resistance of fibres and polymer there is some concern about the thermal mismatch of concrete and the composite bar. Concrete has a coefficient of thermal expansion which is about $10 \cdot 10^{-6}$ K^{-1} and the aramid composite has a coefficient of thermal expansions of $-2 \cdot 10^{-6}$ K^{-1} along the bar and $70 \cdot 10^{-6}$ K^{-1} normal to the bar. This means that the bar will more expand and contract in transverse direction and less in longitudinal direction than concrete. These differential movements cause stresses and even splitting cracks which may impair bond. That this can happen has already been experienced in [DE SITTER, TOLMAN, 1995] and predicted in [MATTHYS, S. ET AL., 1996]. However, more experimental data is necessary in order to quantify the effect of temperature cycles, time and exposure condition on bond. This paper reports on a series of experimental investigations and will discuss the results. For detailed information see [GOLLAS, 1998].

2. TESTING PROGRAMME AND METHODS

To study the bond behaviour of aramid in concrete 150 mm cubes were cast with an aramid bar embedded in the center over a length of 30 mm. The concrete was a normal weight concrete with a mean cube strength of 55 MPa. The aramid consisted of 200.000 filaments with a diameter of 12 µm embedded in vinylester resin. Matrix and fibres take each about 50% of the bar. The outer circular dimensions of the bar are about 7.5 mm diameter. The surface of the bar was covered with quartzitic sand of 125-250 µm grain size. The tensile strength of the bar amounted to 1520 MPa, Young´s modulus was 60640 MPa, and the ultimate strain 2.5%. Fig 1 shows the cube with the aramid bars.

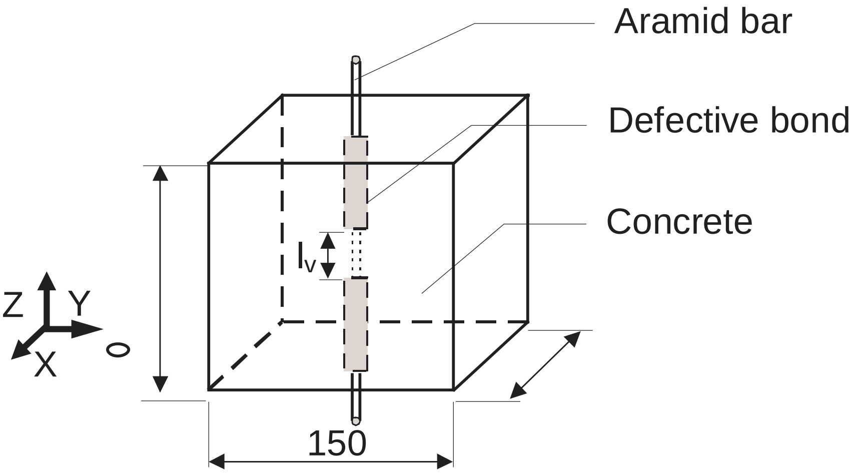

Fig. 1: *Cube with aramid bar used for pull-out tests*

Three exposure conditions were applied: standard climate with 20°C and 65% RH, natural exposure on the roof of the laboratory building (460 m NN), and temperature cycles between -20 and +40°C (1 cycle in 8 hours). Some specimens were continuously loaded, others not. After a certain time of exposure pull-out tests were performed.

The short term pull-out test equipment is shown in Fig. 2. Relative displacements between concrete and aramid were measured at the loaded and non-loaded side of the specimen.

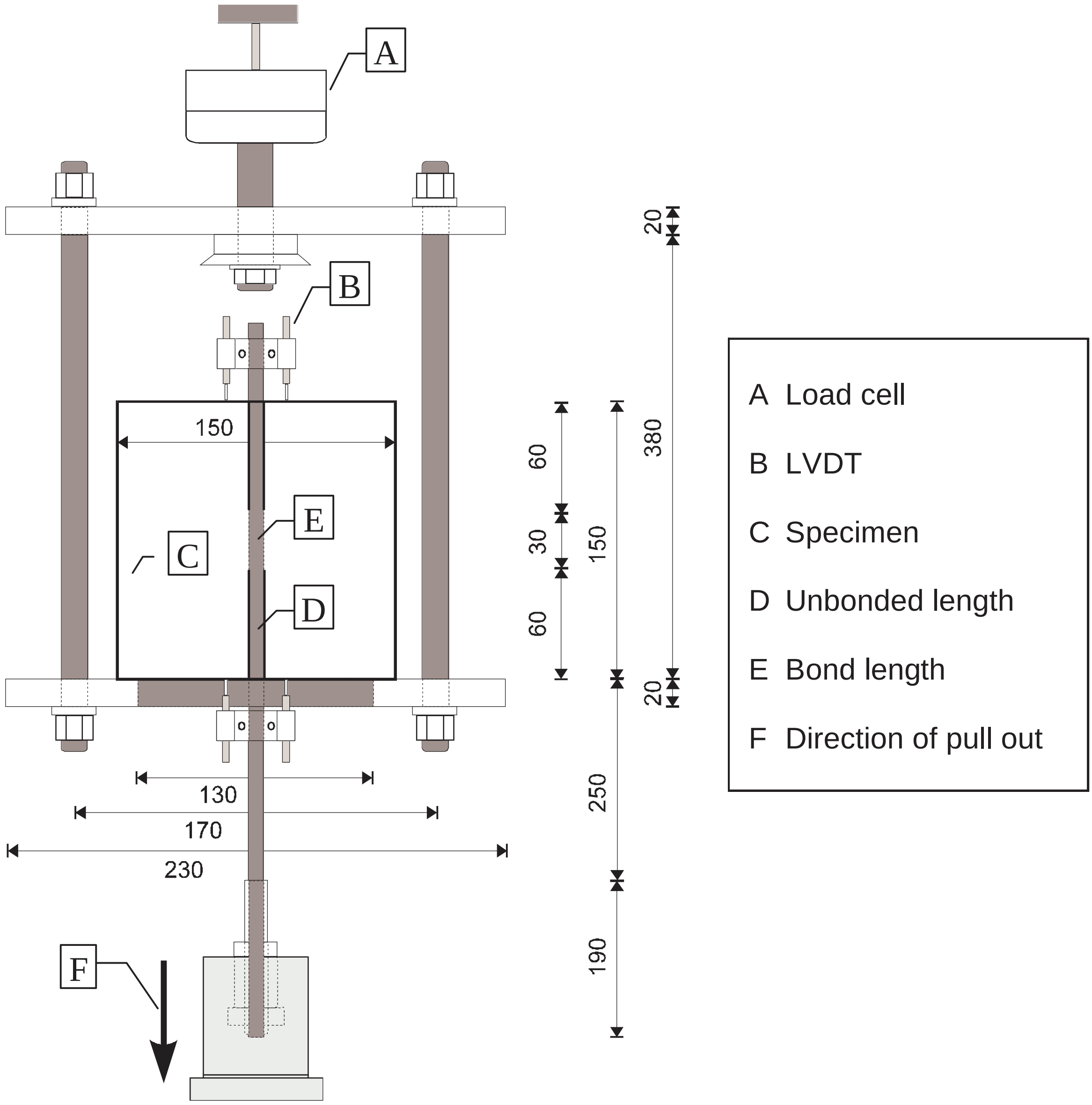

Fig. 2: *Pull-out test equipment for short term test*

Several specimens were kept under load while exposed either to standard environment or thermal cycles. Fig. 3 shows the long term loading equipment which consists of a series of plate springs and displacement gauges.

This equipment allowed to measure the relative displacement as function of time, i. e. bond creep. After sustained loading, the specimens were subjected to short term loading in order to measure the residual bond stress-displacement relation.

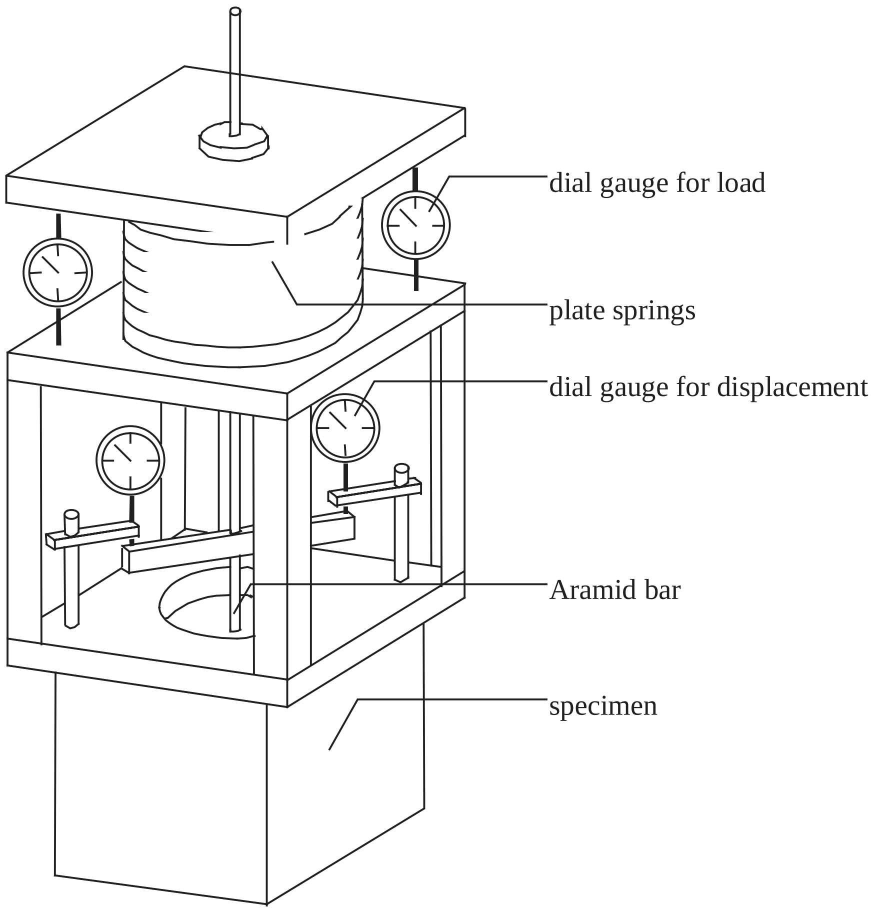

Fig. 3: *Long term loading equipment*

3. TEST RESULTS

Test results of short term loading are mainly received as pull-out force vs. displacement relation. Fig. 4 shows the bond stress as function of relative displacement.

Bond stress is defined as pull-out force divided by embedment length times perimeter of the aramid bar. The embedment length was 30 mm, the bar diameter 7.5 mm. The specimens A1 and A4 were stored in natural weather not sheltered from rain during one year. Specimens K3 and K10 were stored in a room with standard climate 20°C/65% RH until the age of 187 days. Finally, specimens K7 and K12 were subject to 350 temperature cycles prior to testing. It should be mentioned that these six individual results were selected such that each couple represents the highest and the lowest maximum bond stress of one exposure condition. The results which are not shown were lying between them.

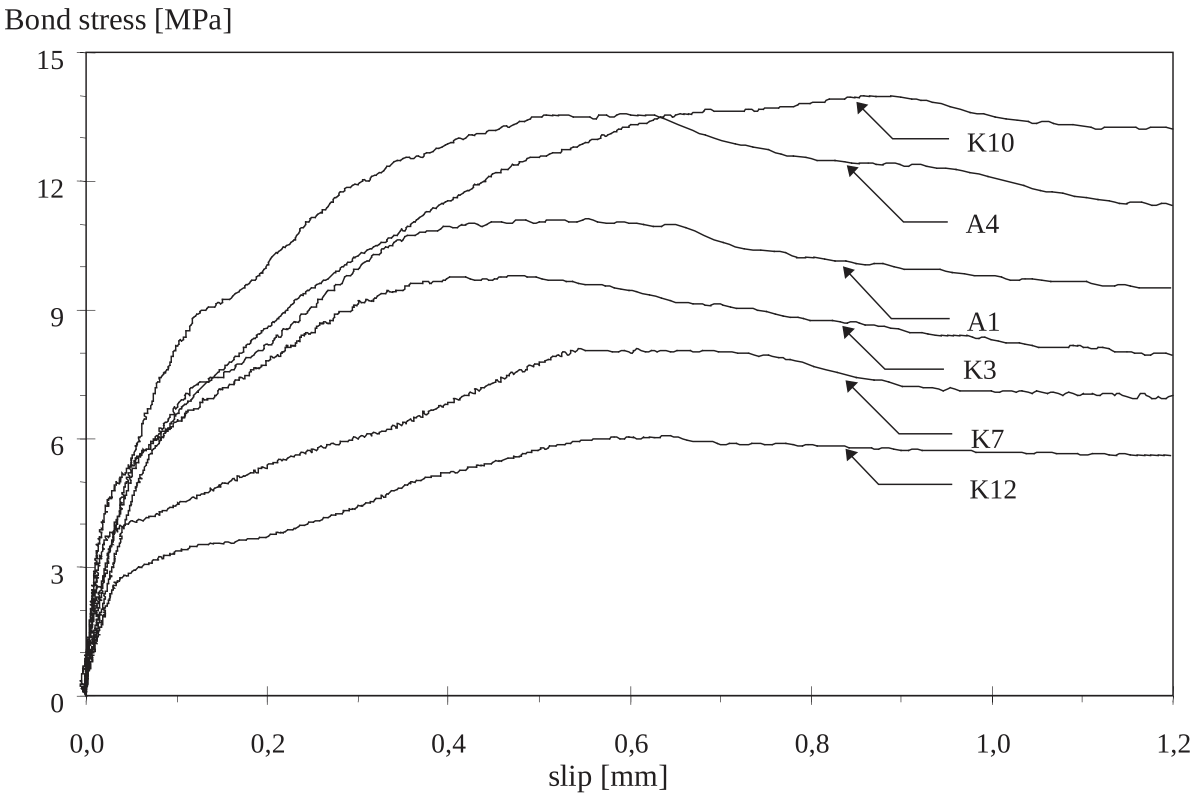

Fig. 4: *Bond stress vs. relative displacement as result of pull-out test*

The concrete compressive strength was measured on three 150 mm cubes which were stored in the same way. The results were 61.4 MPa for cubes in natural weather, 59.0 MPa in standard climate, and 61.5 MPa after the temperature cycles. These results show no significant difference between the storage conditions. This means that concrete strength cannot explain the considerable differences of the lines of Fig. 4.

All lines in Fig. 4 show a linear part at low stresses which is followed by displacement hardening until the maximum stress is reached, and finally a gradual decay of stress with increasing slip. The slope of the linear part scatters by a factor of about two, however there is no systematic influence of the exposure condition. The maximum bond stress and the slip which occurs at maximum stress as measured at the free end of the bar is given in Table 1.

Table 1: *Maximum bond stress τ_{max} and accompanying slip Δ*

Specimen	Exposure condition	τ_{max} MPa	Δ mm	Mean values τ_{max}	Mean values Δ
A1	Natural weather	11.1	0.56		
A4		13.6	0.62	12.4	0.59
K3	Standard climate	9.8	0.50		
K10		14.0	0.88	11.9	0.69
K7	Thermal cycles	8.1	0.62		
K12		6.1	0.64	7.1	0.63

The mean values of τ_{max} and Δ show that natural weather caused the largest value of τ_{max} and the smallest of Δ, i. e. the pull-out resistance is greatest. Standard climate is a little less, and thermal cycles clearly reduced the pull-out resistance to half compared to natural weathering. Since compressive strength of concrete is the same, it must be concluded that the mismatch of thermal expansion of aramid and concrete has had a rather detrimental effect. It can also be concluded that thermal cycling between -20 and +40°C is much more detrimental than natural weathering. In contrary, natural weathering over one year has caused an improvement of bond which is probably due to the moderate climate with high humidity (about 70% RH) and not extreme temperatures.

Sustained loading has been performed in standard climate and under thermal cycles. Table 2 shows the loading regime of the specimens. To determine the strength level of the specimen there were companion specimens which were loaded after a certain time of exposure in standard climate (159 or 74 days) or under thermal cycles (222 to 465 cycles).

Table 2: *Loading regime of sustained loading*

Specimen	τ_{max} [MPa]	Stress level τ_{sust}/τ_{max}	Sustained stress MPa	Exposure during sustained loading
A15	10.2	85	8.67	Standard climate
A6	10.2	85	8.67	
A7	10.2	75	7.65	
A5	10.2	75		
K4	10.6	80	7.65	
K1	9.2	80	7.36	Thermal cycles
K9	9.2	80	7.36	
K11	9.2	80	7.36	
A22	8.5	50	4.25	
A27	8.5	50	4.25	
A25	8.5	30	2.55	
A26	8.5	30	2.55	

Short term loading led to τ_{max} in Table 2. The sustained stress is 30 to 85% of τ_{max}. The load duration in the standard climate was confirmed to 10 months, while the specimens subject to thermal cycles were removed when the slip increased drastically. Fig. 5 shows the results of sustained pull-out tests in standard climate in double logarithmic scale.

The slip is measured on the loaded side of the bar and contains the initial displacement due to loading and the time dependent displacements due to sustained loading. It should be noted that there was no bond failure at the end of test (max. duration 9288 hours).

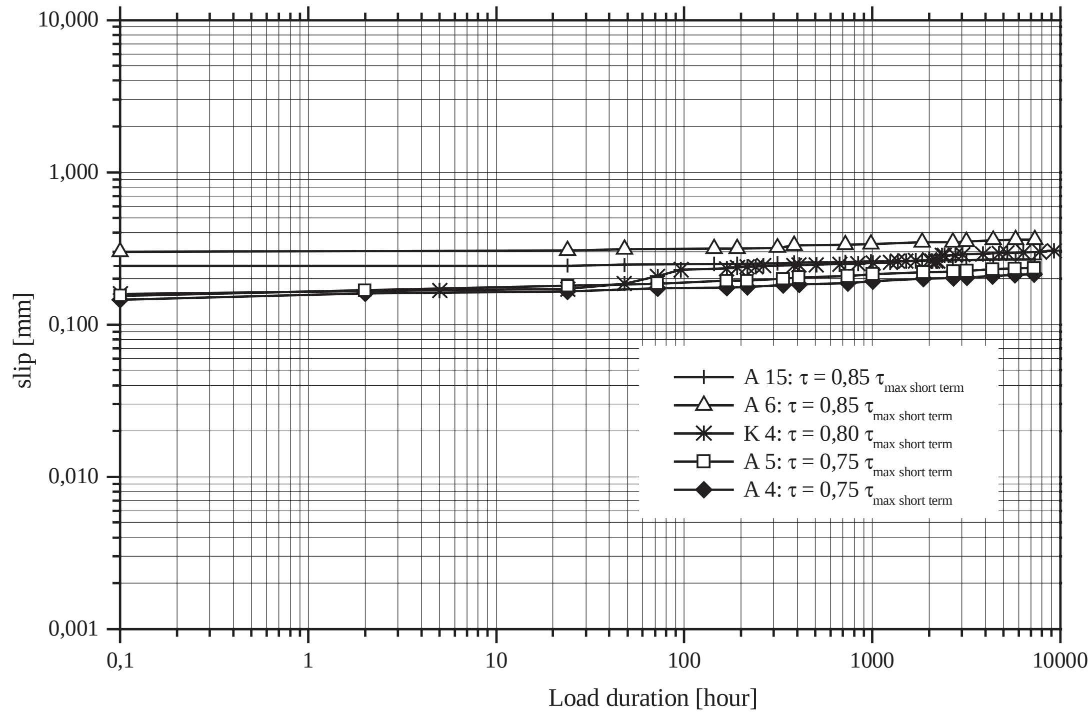

Fig. 5: *Results of sustained pull-out tests in standard climate*

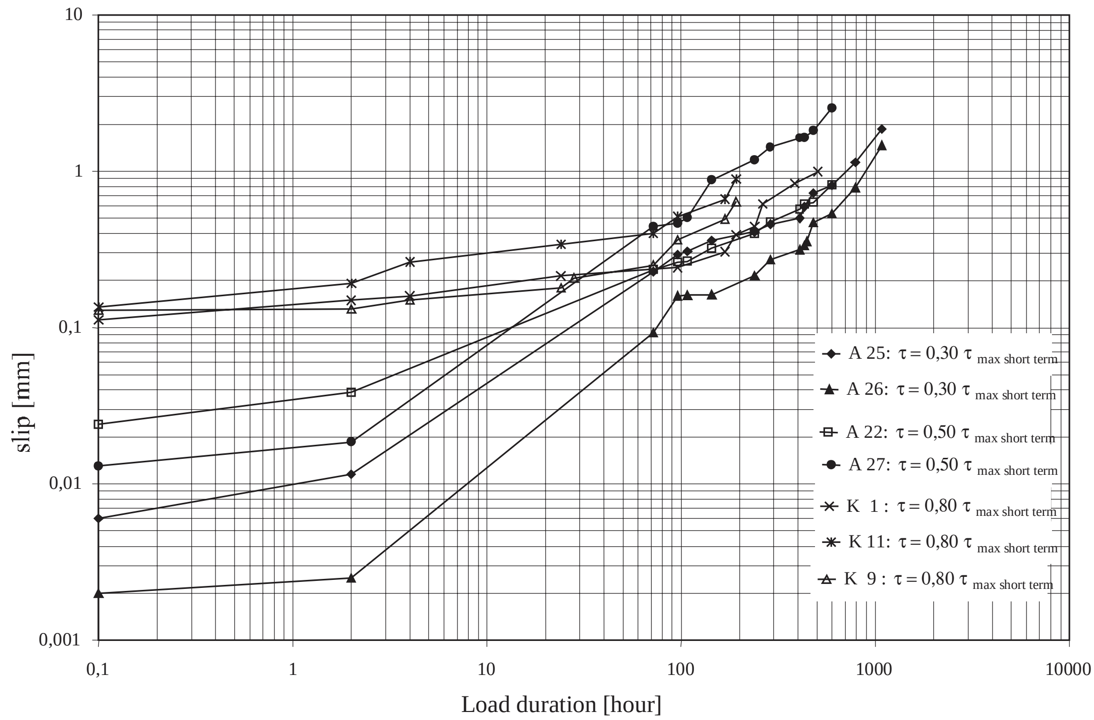

Fig. 6: *Results of sustained pull-out tests with simultaneous thermal cycles.*

Fig. 6. shows the slip-time relation of the specimens which were also subject to thermal cycles. It is obvious that the initial slip depends clearly on the stress level and that a large slip increase occurs as function of time. All specimens failed (failure is defined as showing tertiary creep) after a certain time depending on the stress level: at the highest level after 200 h, at the lowest level after about 1000 h, or in terms of thermal cycles, after 25 cycles and 125 cycles, resp.

The specimens which were loaded in standard climate were removed from the sustained loading rig and then loaded in a short-term test in order to determine the residual strength. Fig. 7 shows the results of five specimens. Four of them are rather similar while specimen A15 shows an unexplainable high bond strength.

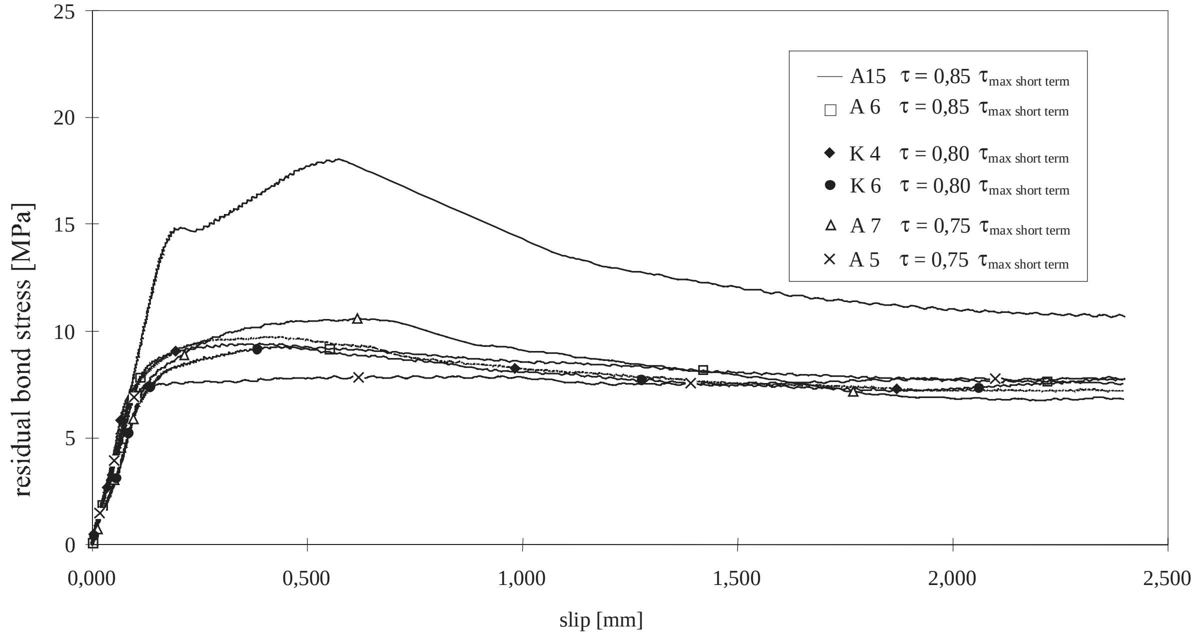

Fig. 7: *Residual bond stress vs. slip relation of specimens from standard climate*

The four similar specimens showed a residual bond strength of 7.8 to 10.6 MPa without a significant dependance on the level of previous sustained loading. However there is some degradation with respect to the strength before loading (10.2 MPa acc. to Table 2.). The specimens which were subject to thermal cycles were not tested for residual strength since they have failed already under sustained loading.

4. DISCUSSION OF RESULTS

4.1 General

Bond of prestressing bars is essential for pretensioned members with direct bond. Good bond means a short anchorage length (transmission length) and, thus, full loading capacity also at the end of a structural member. If bond is affected by environmental effects means that the transmission length increases. It could also mean in a most detrimental situation that splitting cracks occur and bond is reduced to a small percentage of the original value.

4.2 Short-term loading after various exposure

To model bond the bond-slip relation was introduced by [REHM, 1961] which is measured on a short embedment length and which can be used in the appropriate differential equation. To handle the differential equation it is advantageous to describe the bond slip equation by an equation which can be integrated in a closed form. [NOAKOWSKI, 1978] used a power function which has further been evaluated by [KRIPS, 1984] and [BRUGGELING, 1991]. The function reads

$$\tau = C \cdot \Delta^N \tag{1}$$

with τ the bond stress as averaged over the short embedment length of about 3 times the diameter of the bar, Δ the slip, and C and N constants. To determine the constants C and N, at least two points of the measured τ-Δ curve are selected. Usually the maximum bond stress and the accompanying slip are used and a point between zero and maximum bond stress. After having evaluated the curves of Fig. 4 the results of Table 3 were received.

Compared to reinforcing bars in normal strength concrete, the values of C and N are rather high which means that the bars with sand covered surface have good bond in the 55 MPa concrete.

Table 3: *Material constants C and N for results of Fig. 4*

Specimen	Exposure condition	C [1)]	N [1)]	l_{pt} [mm]
A1	Natural weather	13.1	0.28	208
A4		15.5	0.27	179
K3	Standard climate	12.1	0.28	221
K10		14.7	0.36	224
K7	Thermal cycles	9.5	0.32	287
K12		7.2	0.39	400

[1)] Constants apply for τ in MPa and Δ in mm.

It can also be seen that thermal cycles have decreased bond which is mainly manifested by the multiplying factor C. It should be noted that eq. (1) is fitting only the ascending branch of the τ-Δ curve.

A good indication of bond is the transmission length of a pretensioned bar in concrete. Making use of eq. (1) the transmission length is given by the following equation [BRUGGELING, 1991]

$$l_{pt} = \left[\frac{1+N}{2} \frac{d_p}{4} \frac{\sigma_{pR}}{C} \frac{\sigma_{po}}{E_p} \right]^{\frac{1}{1+N}} \cdot \frac{2\,E_p}{(1-N)\,\sigma_{pR}} \tag{2}$$

with d_p = diameter of pretensioned bar, σ_{pR} = pretensioning stress in the bar, σ_{po} = pretensioning stress after demoulding, E_p = Young´s modulus of bar, and C and N material constants. Inserting the values of the aramid bar into eq. (2) the transmission length takes the values as given in column 5 of Table 3. There, it can be seen that the rather short transmission length is considerably increased due to thermal cycles but there is only little effect due to natural weather.

4.3 Bond creep

The increase of slip in a pull-out test at sustained loading is called bond creep. It can be described by the power function [FRANKE, 1976]

$$\varphi(t) = (1 + 10\,t)^{a} - 1 \tag{3}$$

with φ (t) the creep coefficient which is the ratio of time dependent slip and short-term slip at loading, t the time in hours, and "a" a constant. If the curves of Fig. 5 are evaluated the values of Table 4 are received. There is a tendancy that a lower stress ratio (0.75) loads to larger creep than a high stress ratio (0.85).

Table 4: *Constant a for results of Fig. 5*

Specimen	A5	A6	A7	A15	K4	Average
Constant a	0.035	0.013	0.030	0.008	0.051	0.027
τ_{sust}/τ_{max}	0.75	0.85	0.75	0.85	0.80	-

However, the intermediate stress ratio (0.80) does not fit into this row. But this may be due to the different pre-exposure (K4 only 74 days compared to all other specimens with 159 days).

Evaluating eq. (3) with a = 0.027 leads to a creep coefficient after 15 years (10^5 h) equal to 0.45, i. e. the total slip is 1.45 times the instant slip at the time of loading.

5. CONCLUSIONS

The investigation leads to several conclusions:

- bond between a sand covered aramid composite bar in concrete shows a bond strength of about 12 MPa

- natural weathering during one year did not impair bond strength
- 350 thermal cycles between -20 and +40°C reduced bond strength to about 7 MPa
- transmission length as determined from bond stress-slip relation increased by about 50% after 350 thermal cycles
- bond creep coefficient amounts to 0.45 in standard climate after 15 years
- thermal cycles between -20 and +40°C cause bond failure also at low stresses.

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