TEMPERATURE EFFECTS ON BOND BETWEEN CONCRETE AND REINFORCING STEEL

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Summary: *Bond behaviour between concrete and reinforcing bars was observed under elevated temperatures. Five different concrete compositions were used. Hundred five pull-out specimens (Ø120 mm, 100 mm) were prepared. After removing the specimens from the formwork, they were stored in water for seven days then kept at laboratory conditions until testing. The specimens were 28 days old by testing. After heating up the specimens, they were kept for two hours at these maximum temperatures (20 °C, 150 °C, 300 °C, 400 °C, 500 °C, 800 °C). Specimens were then cooled down in laboratory conditions. Finally the specimens were tested at room temperature. In order to check the compressive strength standard cubes were cast, cured, and heat treated, then tested to compressive strength. The results showed reduction in residual compressive strength and considerable changes in steel-concrete bond under high temperatures. Based on test results, a proposal is presented for the modification of MC2010 bond-ship formula in order to consider temperature effect.*

Keywords: *Concrete, reinforcement, bond, elevated temperature*

1. INTRODUCTION

In some areas of bond behaviour (like fatigue and especially high temperatures) limited information is available. The main reasons are complexity of the experiments and the high cost.

During the exposure to high temperatures, concrete undergoes changes in its chemical composition, physical structure and water content. These changes primarily occur in the hardened cement paste. The resulting physical changes and chemical decomposition of major concrete constituents are demonstrated by e. g. cracks, explosive spalling or both [1, 2, 3, 4, 5].

Investigations on the bond strength between concrete and reinforcing steel at room temperature have been carried out over many years however, only few experiments have been carried out to study the effects of high temperature on the bond characteristics. Bažant and Kaplan [5] concluded their results (that is also presented in Figure 1):

Bond strength reduces as temperature increases, and the reduction rate is greater compared that of concrete strength. The percentage reduction of bond strength for ribbed bars at elevated temperatures is less than that for plain round steel bars.

Differences in the diameters of plain bars and deformed bars had little effect on the strength reduction of bond.
The experimental procedure influences the results of bond tests at high temperatures.
The type of aggregate in the concrete affects the bond strength at elevated temperatures.
The smaller the concrete cover, the greater is the reduction in bond strength.

Post heating behaviour of the concrete to steel bond has been investigated over the past 50 years using two types of bond test specimens, specified in ASTM (Annual Book of ASTM Standards, 1993) and RILEM (Bond test for reinforcement bond steel: 2- pull-out test, 1983) test methods [6,7].

The different studies showed significant effects of steel rebar surface characteristics, concrete confinement, concrete basic properties (w/c ratio, cement and aggregate type, additives), maturity and relative humidity, and testing conditions (heating and cooling duration and rate, and testing while hot or cold on concrete to steel bond behaviour under wide range of high temperature) [5, 8, 9, 10].

Due to the complexity of bond characterisation at elevated temperatures, as first order approximation, simplified bi-linear and tri-linear models, as shown in Figure 1 are proposed herein to calculate the bond strengths of deformed and smooth bars at elevated temperatures, respectively.

Based on results by Bazant and Kaplan [5] Huang [11] proposed the following equations:

$$\tau_{max,T} = \tau_{max,20}\left(1.0 - \frac{0.22}{360}(T-20)\right) \quad \text{for } 20\ °C \le T \le 380\ °C$$

$$\tau_{max,T} = \tau_{max,20}\left(0.78 - \frac{0.75}{270}(T-380)\right) \quad \text{for } 380\ °C < T \le 650\ °C$$

$$\tau_{max,T} = 0.03\tau_{max,20} \quad \text{for } 650\ °C < T$$

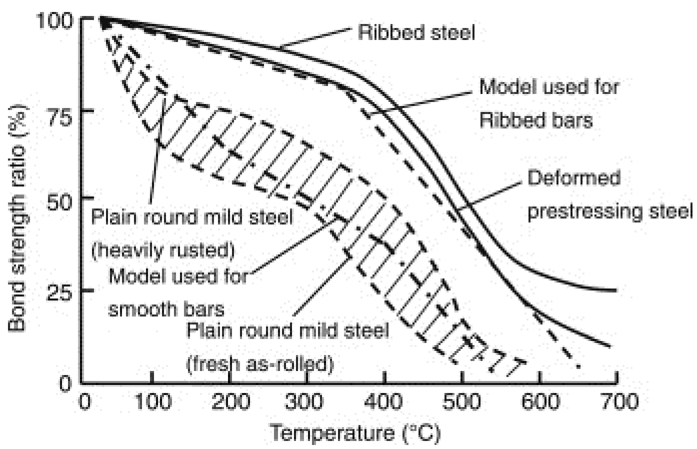

Figure 1: Degradation of bond strength between concrete and reinforcing steel [5]

2. EXPERIMENTAL STUDY

We carried out an experimental study to analyze the bond characteristics after high temperatures. Test variables were:

- maximal temperature (20°C, 50°C, 150°C, 300°C, 400°C, 500°C, 600°C, 800°C)
- type of aggregate (quartz gravel, expanded clay)
- type of fibres (polypropylene fibers, hocked-end steel fibers).

The water cement ratio was constant: w/c=0.43. The amount of cement, water, aggregate, fibres and plasticizer are given in Table 1. The consistency of concrete was measured by flow table tests and resulted 450 to 500 mm.

Table 1 Experimental concrete mixes (polypropylene fibers, **hocked-end steel fibers)*

	Mix 0	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
cement (kg/m^3)	350	350	350	386	386	350
water(kg/m^3)	151	151	151	181	181	151
aggregate (kg/m^3) 0-4 mm	912 quartz sand	912 quartz sand	912 quartz sand	1024 quartz sand	1015 quartz sand	912 quartz sand
aggregate (kg/m^3) 4-8 mm	485 quartz gravel	485 quartz gravel	485 expanded clay	302 expanded clay	390 quartz gravel	485 quartz gravel
aggregate (kg/m^3) 8-16 mm	544	544	544	-	-	544
plasticizer kg/m^3)	1.4	1.4	1.4	5	5	1.4
fibres (kg/m^3)	-	1*	1*	-	-	35**

By the preparation of specimens special casting forms were used (Figure 2). The pull-out specimens had a diameter of 120 mm and height of 100 mm. Details of pull-out specimens are presented in Figure 3. Slip was measured with two LVDT's at the unloaded side (Figure 3).

Figure 2: The casting forms to the measurements of bond strength

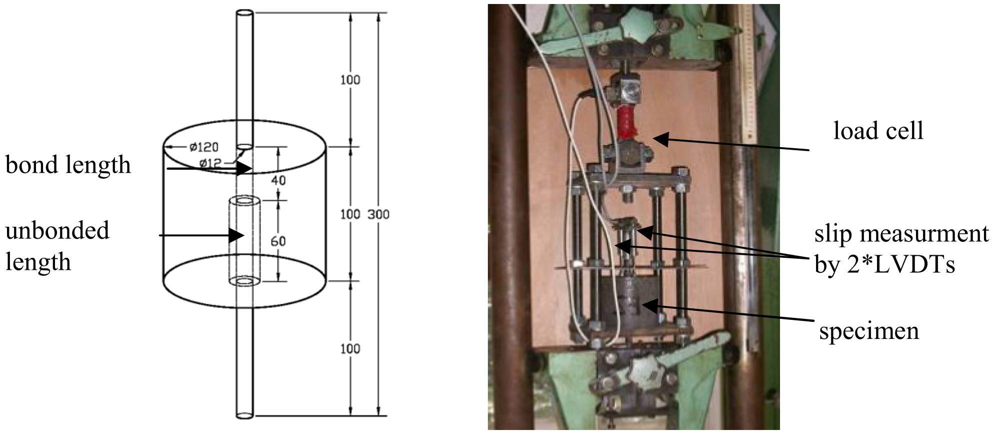

Figure 3: Pull-out tests
a) Specimen b) test setup

3. TEST RESULTS

3.1 Compressive strength

The compressive strength was measured after the heating process on concrete cubes of 150 mm sides. Figure 4 indicates the measured relative residual compressive strength values of concrete as a function of maximal temperatures up to 800 °C.

1. Most considerable reduction of compressive strength took place between 400 °C and 800 °C in all cases within our temperature range.
2. The residual compressive strength values at the maximal temperature of 800 °C were between 20 % to 30 % of the strength at 20 °C for concretes with polypropylene fibers (Mix 1) and for concrete without fibres (Mix 0). Our test results indicated the advantageous influence of polymeric fibres in concrete subjected to high temperatures.
3. The residual compressive strength values of quartz gravel aggregate at the maximal temperature of 800 °C was 20 % of the strength at 20 °C for concretes with steel fibers. Between 50 °C and 400 °C the highest strength reductions were in case of specimens with steel fibers. That can be explained by the similar forms of fibers.
4. The relative residual compressive strength of lightweight aggregate concrete with expanded clay (Mix 2 and Mix 3) was higher after heating the specimens up to 400 °C and then cooled down to room temperature as in the case of concrete with quartz gravel aggregate. The relative residual compressive strength values were lower in case of concrete with quartz gravel aggregate by 10 to 20%.

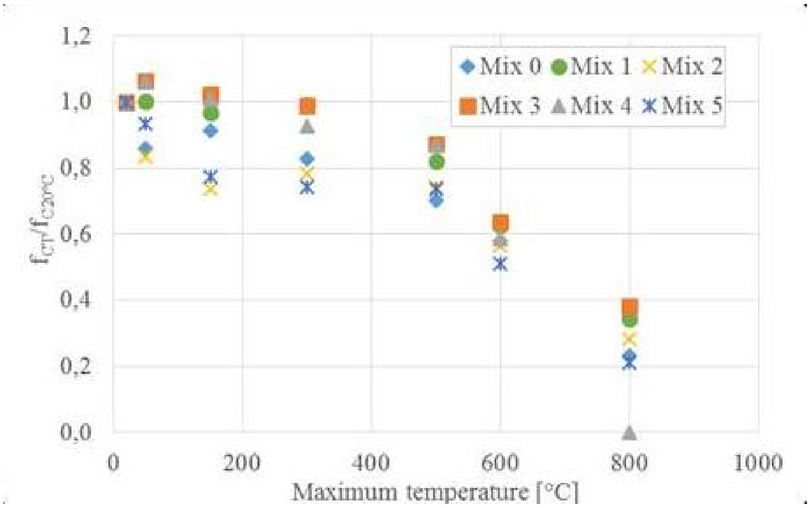

Figure 4: Relative residual compressive strength (every point gives the average of 3 measurements)

3.2 Bond strength

Figure 5 indicates the measured relative residual bond strength values of concrete as a function of maximal temperatures up to 800 °C. Pull-out test were carried out at room temperature after heating and cooling the specimens. The following conclusions can be drawn:

1. The relative bond strength reduction was higher than the relative compressive strength reduction in all cases.
2. Most considerable reduction of bond strength took place between 400 °C and 500 °C. This reduction can be explained by the decomposition of portlandite at 450 °C.
3. The relative bond strength of lightweight concrete with expanded clay (Mix 2 and Mix 3) was higher to 400 °C but lower above 500 °C compared to concrete with quartz gravel aggregate.
4. The relative bond strength of fibre reinforced concrete (Mix 1 and Mix 2) was lower to 400 °C but higher to 500 °C and higher temperatures as in the case of concrete with quartz gravel aggregate.

In Figure 6 are presented the force –slip diagrams for Mix 0 in function of temperature. The following conclusions can be drawn:

1. With increase of temperature the bond stress decrease and the slip values increases.
2. After temperature loading with 20 °C, 50 °C and 150°C the force slip diagrams has the same tendencies. The strength reduction is not more as 20 %.
3. After the temperature loading with 600°C and 800 °C the tendencies of force slip diagram change. That could be explain with the missing of chemical bond (decomposition of portlandite). The strength reduction is 80 % after

temperature loading with 600 °C, and 93 % after temperature loading with 800 °C.

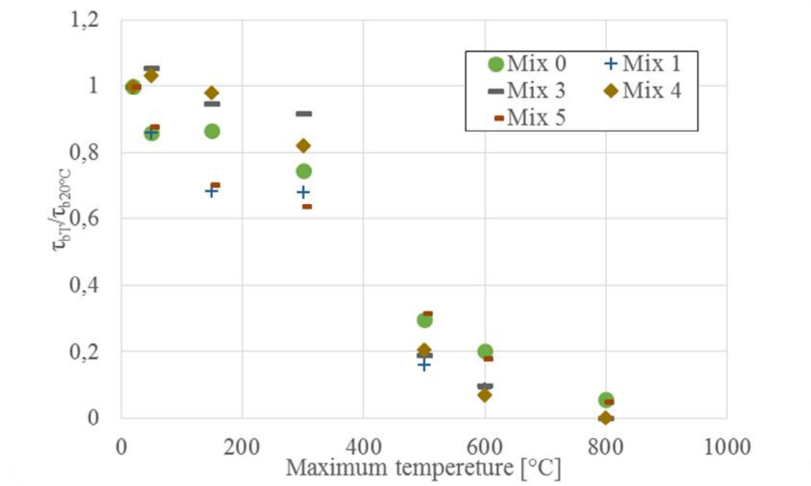

Figure 5: Test result on bond strength measured on ribbed reinforcement (every point gives the average of 3 measurements)

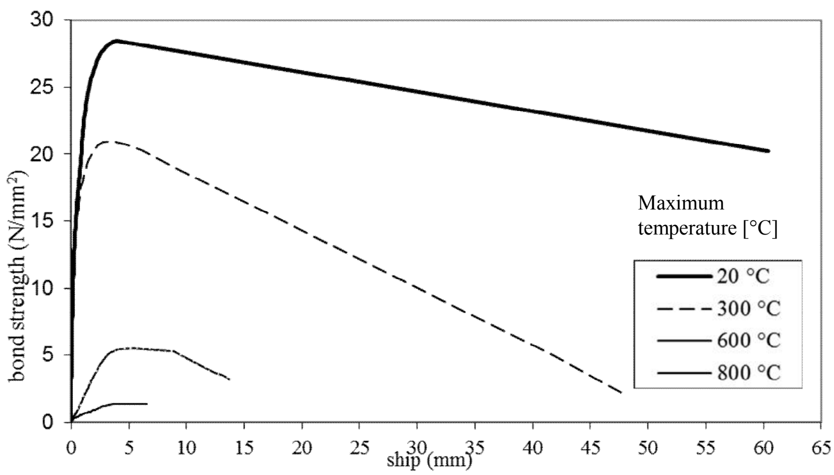

Figure 6: The τ_b- slip diagram as a function of temperature (for Mix 0)

3.3 Relationship between bond strength and compressive strength

Figure 7 presents the compressive strength and bond strength of tested concretes with different composition stored at 20°C (reinforcement S500, deformed bar, f_{yk}=500 N/mm^2).

According to the figure the following conclusions can be drawn:

(1) The compressive strength of concrete with quartz gravel aggregate and expanded clay aggregate measured at 20 °C was less than the concrete.

(2) The bond strength in concrete with steel fibers at 20 °C was higher than the concrete with quartz gravel aggregate without fibres.

(3) The bond strength of concrete with polypropylene fibres and lightweight concrete at 20 °C is less than the concrete with quartz gravel aggregate without fibres.

Figure 8 indicated the ratio of the bond strength to compressive strength of concrete as a function of the maximum temperature. In the temperature ranges 20 °C to 400 °C as well as 500 °C to 800 °C the strength ratio decreased approximately linear. Between 400-500 °C a significant strength reduction took place. The significant strength reduction can be explained by the decomposition of portlandite (at about 450 °C).

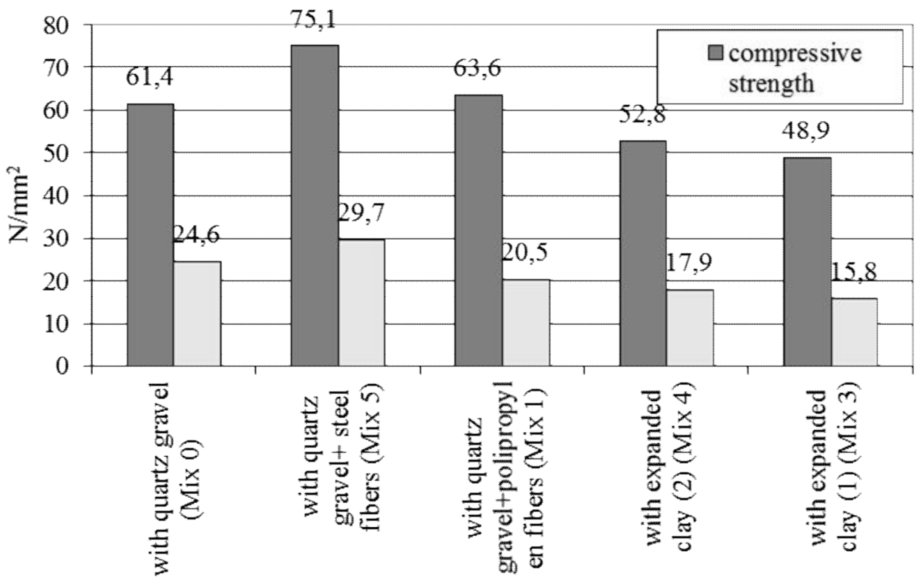

Figure 7: Concrete compressive strength and bond strength with various mixes at 20 °C

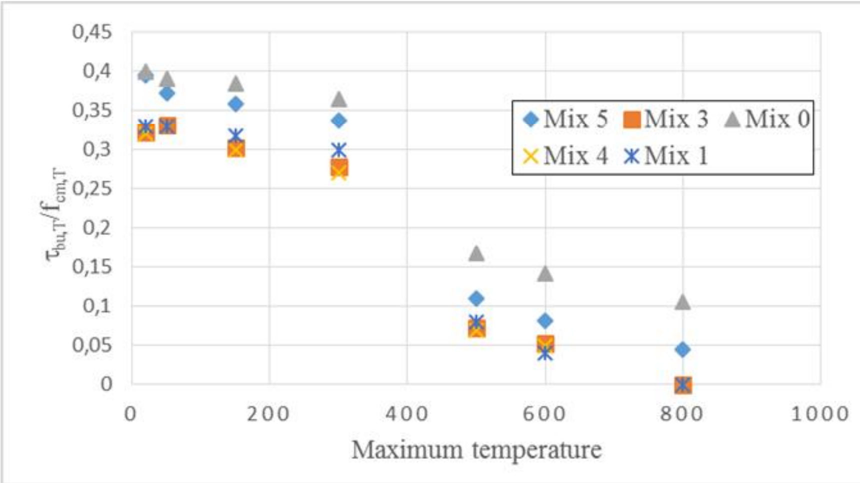

Figure 8: τbu,T /fcm,T as a function of maximum temperature in case of ribbed reinforcement

4. CALCULATION OF BOND STERNGTH VS. TEMPERATURE

The bond strength in case of concrete with quartz gravel aggregate could be calculated for confined concrete:

$$\tau_{bmax}=2.5f_{ck}^{0.5} \qquad [12]$$

Based on test results, a proposal is presented for the modification of MC2010 bond-ship formula as a function of temperature and concrete composition:

For concrete with quartz gravel:

Between	20 °C and 400 °C	$\tau_{bmax,T}=2.5f_{ck}^{0.5}$
	400 °C and 800 °C	$\tau_{bmax,T}$=fck0.4

The calculated correlation coefficients were: for R^2= 0.96 for Mix 0 and R^2= 0.93 for Mix 5.

For concrete with expanded clay:

Between	20 °C and 400 °C	$\tau_{bmax,T}=2.0f_{ck}^{0.5}$
	500 °C and 700 °C	$\tau_{bmax,T}=fck^{0.4}$
	above 800°C	$\tau_{bmax,T}=0$

The calculated correlation coefficients were: R^2= 0.98 for Mix 3 and R^2= 0.98 for Mix 4.

5. CONCLUSIONS

The following conclusions can be drawn from our experimental study on the influence of high temperatures to the residual bond characteristic. Pull-out specimens tested at cold state after heated up to (20 °C, 150 °C, 300 °C, 400 °C, 500 °C, 600 °C and 800 °C). The types of concrete were: C, SFRC, PPRC, LWAC1, LWAC2. Type of steel reinforcement was deformed rebar.

Most considerable reduction of bond strength took place between 400°C and 500°C in all cases. This reduction can be explained by the decomposition of portlandite by 450°C. This was valid for all tested concrete types (C, SFRC, PPRC, LWAC1, LWAC2) with all tested reinforcements (deformed rebar).

Reduction of bond strength both below 400°C and above 500°C are close to linear on different levels.

Based on test results, a proposal is presented for the modification of MC2010 bond-ship formula as a function of temperature and concrete composition:

For concrete with quartz gravel:

Between	20 °C and 400 °C	$\tau_1=2.5f_{ck}^{0.5}$
	400 °C and 800 °C	$\tau_1=f_{ck}^{0.4}$

For concrete with expanded clay:

Between	20 °C and 400 °C	$\tau_1=2.0f_{ck}^{0.5}$
	500 °C and 700 °C	$\tau_1=f_{ck}^{0.4}$
	above 800°C	$\tau^1=0$

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