RESIDUAL BOND STRESS OF SELF-COMPACTING CONCRETE SPECIMENS AFTER HIGH TEMPERATURE TREATMENT

Konstantinos G. Trezos, Ioannis P. Sfikas*

Laboratory of Reinforced Concrete, National Technical University of Athens, GREECE.

*: corresponding author. gsfikas@teemail.gr

ABSTRACT

Wide research on bond under ambient temperatures has been previously conducted, building confidence in Self-Compacting Concrete (SCC) over Normally Vibrated Concrete (NVC). Yet, the effect of high temperatures on SCC bond has not been sufficiently investigated.

The present study is evaluating the effect of high temperatures (300, 650 and 900 °C) on bond characteristics (average bond stress, maximum bond stress and corresponding slip). Eight SCC mixtures with various water to binder ratios and silica fume levels of cement replacement and four NVC mixtures have been tested by performing pull-out tests.

It has been found that silica fume concretes are more prone to explosive spalling, but their bond stress levels are not affected for temperatures of up to 300 °C. This temperature appears to affect the bond stresses for all other mixtures. The bond characteristics are significantly deteriorated for even higher temperatures, this effect being slightly stronger for SCC.

Keywords: bond; high temperatures; water-to-binder; silica fume

INTRODUCTION

Concrete bond to steel reinforcement is considered to be one of the most significant mechanical properties, as it determines the ability of reinforced concrete to ideally perform as a uniform structural material. A wide number of recent studies have provided sufficient data to give confidence in the bond behaviour of Self-Compacting Concrete (SCC), by proving that it can develop remarkably high bond strength. Most researchers [1-3] have mainly focused on the effect of reinforcement bars on bond strength (significance of bar diameter, effective bond length, position of bars (top-bar effect or cover thickness), whilst less studies [1; 3-5] are oriented to concrete properties (compressive strength, age, constituent materials origin and properties). Still, there are some more specialized aspects of bond strength that need to be investigated in contrast to Normally Vibrated Concrete (NVC). Heat treatment is considered to be amongst one of the influencing parameters of bond. Due to its dense microstructure (smaller and discontinued pores), SCC may be more sensitive to high temperatures than NVC [6]. Various studies [6-9] have been conducted on the residual mechanical behaviour of heat treated SCC, which are mainly oriented at the compressive and the tensile strength, as well as at the corresponding stress-strain curves and the severity of concrete spalling. Some durability indicators (porosity, permeability), have also been limitedly investigated. The scope of this study is to investigate the behaviour of SCC, which has been heat treated under medium-high and high temperatures, and to compare the resulting bond strength with NVC mixtures, which have received the same treatment. The results of previously published work [4], concerning the same mixtures treated exclusively under ambient temperatures, have been used as reference.

MATERIALS AND MIXTURE PROPORTIONS

Eight SCC and four NVC mixtures (Cf. Tab. 1) were cast and tested. Three SCC mixtures had different water-to-binder ratios, i.e. w/b=0.36, 0.51 and 0.56, whilst the other five SCC mixtures had a varying silica fume level of cement replacement, i.e. sf/b= 4.9, 6.9, 8.9, 12.3 and 14.0 % (by mass of total binder). The NVC mixtures differed in the incorporated superplasticizer quantity.

Cement (c). A typical Portland composite cement (CEM II / B-M (P-W-L) 42,5 N) was used. Its grading is shown in Fig. 1a, in contrast to silica fume and limestone powder.

Silica fume (sf). The incorporated silica fume (Cf. Tab. 2) is a highly active pozzolan in the form of fine powder. Its grading (Cf. Fig. 1a) is finer than cement by approximately one order of magnitude.

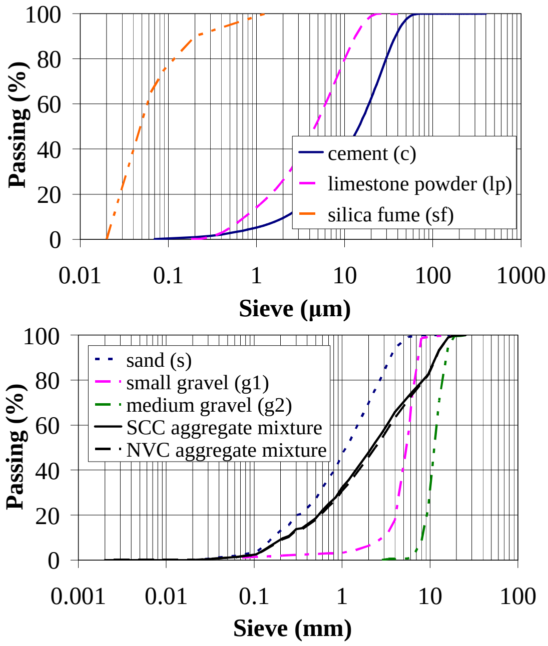
Table 1. Mixture proportions (kg/m^3) and compressive strength, f_{cc} (N/mm^2)

description		SCC1	SCC2	SCC3	SCC4	SCC5	SCC6	SCC7	SCC8	NVC1	NVC2	NVC3	NVC4
cement	c	350	350	350	333	326	319	307	301	400	400	400	400
effective water	w	126	178.5	196	158	158	158	158	158	204	204	204	204
limestone powder	lp	175	175	175	175	175	175	175	175	-	-	-	-
silica fume	sf	-	-	-	17	24	31	43	49	-	-	-	-
medium gravel 8/20	g2	350	350	350	350	350	350	350	350	375	375	375	375
small gravel 4/10	g1	150	150	150	150	150	150	150	150	200	200	200	200
sand 0/4	s	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050
PCE superplasticizer	pce	11.7	3.8	3.2	7.3	5.1	5.2	6.1	8.8	0.0	0.5	1.0	2.0
total mass	W	2213	2257	2274	2240	2238	2238	2239	2241	2229	2230	2230	2231
w/b ratio	w/b	0.36	0.51	0.56	0.45	0.45	0.45	0.45	0.45	0.51	0.51	0.51	0.51
sf/b ratio	sf/b	-	-	-	4.9	6.9	8.9	12.3	14.0	-	-	-	-
compr. strength	f_{cc}	61.3	49.5	43.0	52.9	54.3	58.4	59.1	65.5	49.7	50.7	45.2	48.6

Table 2. Physical properties and chemical analysis (%w/w) of silica fume (sf)

physical properties		chemical analysis (%w/w)								
density (t/m^3)	specific surface (BET)	SiO_2	Al_2O_3	CaO	SO_3	Cl	Fe_2O_3	K_2O	Na_2O	L.O.I. (1000°C)
2.20	24.2	96.40	0.75	0.35	0.05	0.01	0.56	0.43	0.04	3.01

Figure 1. Grading curves of: (a) fine materials: cement, limestone powder and silica fume (b) sand 0/4, small gravel 4/8, medium gravel 8/16 and SCC and NVC aggregate mixtures



Aggregates. Three nominal gradings of locally available crushed calcareous limestone aggregates (Cf. Tab. 3 & Fig. 1b) were used: sand (s) 0/4mm, small gravel (g1) 4/8mm and medium gravel (g2) 8/20mm. All suitable corrections were adopted for the aggregates to reach the saturated-surface-dry (SSD) state.

Limestone powder (lp). The enhancement of the plastic viscosity characteristics and the required stability were achieved by the incorporation of high purity and high fineness limestone powder (Cf. Tab. 5 and Fig. 1a).

Superplasticizer (pce). Suitable dosages of polycarboxylic ether superplasticizer were introduced to all mixtures, in order to reach the required fluidity.

Steel bars. Deformed steel bars of grade B500C were used, which originated from the same batch and had a nominal diameter, d_{nom}, of 16 mm.

Table 3. Physical properties of aggregates

type	symbol	apparent density on an oven dried basis (t/m^3)	water absorption (%)
sand	s	2.66	0.9
small gravel	g1	2.66	1.1
medium gravel	g2	2.65	1.0

Table 4. Physical properties and mineralogical composition (%w/w) of limestone powder

physical properties			mineralogical composition (%w/w)				
density (t/m^3)	specific surface area* (m^2/g)	moisture (%)	$CaCO_3$	SiO_2	MgO	Fe_2O_3	Mn_2O_3
2.70	1.09	0.21	97.60	0.83	0.76	0.09	0.001

*calculated from the grain size analysis

TESTING AND ANALYSIS PROCEDURES

Concrete classification. For SCC, the workability (unconfined flowability), the viscosity and the passing ability were assessed by the Slump-flow, the V-Funnel and the L-Box tests, respectively. The Slump test was performed to assess the workability for NVC. Considering that fresh properties of the same mixtures have been previously discussed [4], only the final classification is listed here (Cf. Tab. 5) for reasons of completeness.

Table 5. Rheological classification of mixtures

description	SCC1	SCC2	SCC3	SCC4	SCC5	SCC6	SCC7	SCC8	NVC1	NVC2	NVC3	NVC4
slump class									S1	S2	S4	S4
slump-flow class	SF3	SF1	SF1	SF1	SF2	SF2	SF2	SF2				
viscosity class	VS1	VS1	VS1	VS1	VS1	VS1	VS1	VS1				
V-funnel viscosity class	VF1	VF1	VF1	VF1	VF1	VF1	VF1	VF1				
L-box	PA2	PA2	PA2	PA1	PA2	PA2	PA2	PA2				

Description of specimens. For each mixture, four 150 mm edge cubes and two 200 mm edge cubes (Cf. Fig. 2a) with an effective bond length of $5 \times d_{nom}$= 80 mm were cast.

Curing and treatment. All specimens were air cured at ambient temperature for 28 days. Then, both specimens (#1, #2) of each mixture were heated (Cf. Fig. 3) in a high temperatures oven up to a temperature of 300 ^oC, at which they were maintained for 30 min. Specimen #1 was exported from the oven, whereas specimen #2 was further heated up to 650 ^oC or 900 ^oC (Cf. Tab. 6). The specimens were then left in the oven to naturally cool down for 24 h. Two of the specimens (SCC6, SCC8) were destroyed by explosion, before the test's finish, a fact that is attributed to the high heating rate (6.2 ^oC/min). As it has been previously reported [8], silica fume concretes may present an explosive spalling tendency at low heating rates (1 ^oC/min), whilst other concretes may not have a similar effect for heating rates of even 10 ^oC/min. The behaviour of concrete during heat treatment is extensively described in literature [7; 9].

Figure 2. Bond specimen setup and testing equipment [4]

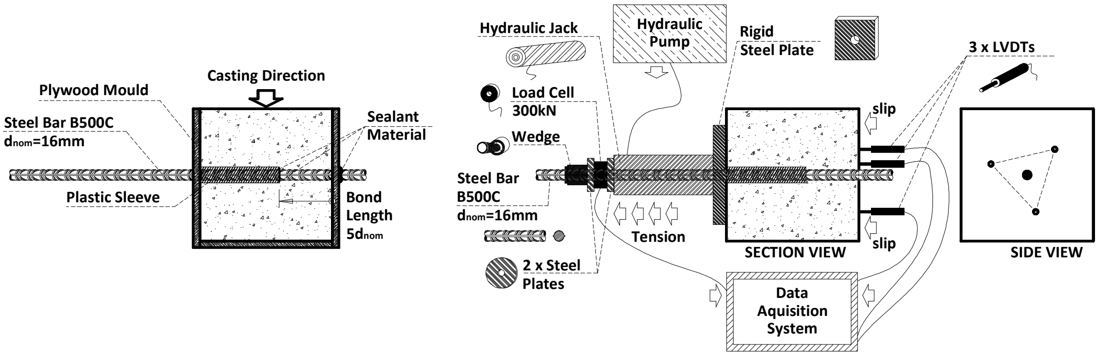


Figure 3. Heat treatment profiles

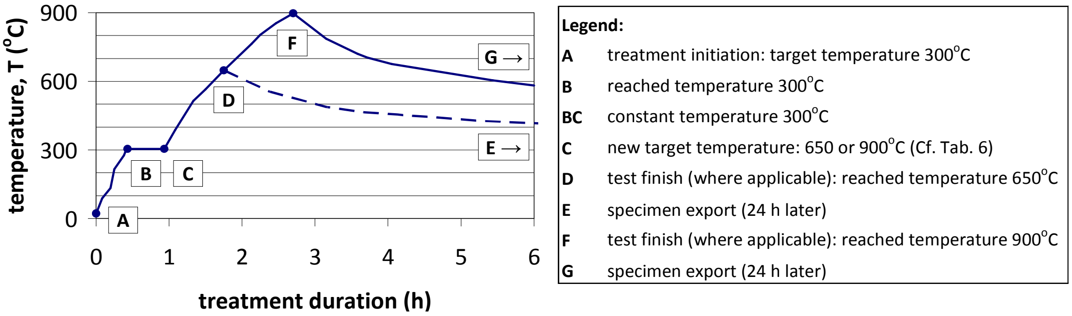


Table 6. Maximum temperatures during heat treatment for each mixture (Cf. Fig. 3)

bond specimen	SCC1	SCC2	SCC3	SCC4	SCC5	SCC6	SCC7	SCC8	NVC1	NVC2	NVC3	NVC4
#1	300	300	300	300	300	300	300	300	300	300	300	300
#2	900	650	650	650	900	615*	650	450*	900	650	900	650

*temperature, at which the specimen was destroyed by explosion (before reaching the target temperature)

Compressive strength (f_{cc}). At 28 days, the four 150 mm edge cubes were tested on a compression frame to determine the compressive strength, f_{cc} (N/mm^2) (Cf. Tab. 1).

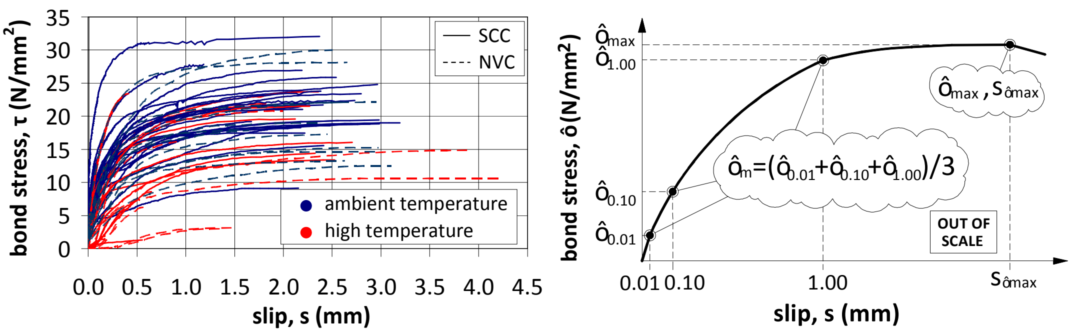
Bond characteristics. The bond characteristics of each mixture were determined by pull-out tests (Cf. Fig. 2b). A pull-out force, F (N), was progressively applied up to bond failure. The rebar slip, s (mm), was recorded using three Linear Variable Differential Transformers (LVDTs). The bond stress, τ (N/mm^2), at every different moment was calculated using Eqn. (1), where F (N) the applied pull-out force, d_{nom} (= 16 mm) the steel bar nominal diameter and L (= 80 mm) the nominal bond length, and plotted as a function of the corresponding average slip, s (mm), of the LVDTs (Cf. Fig. 4a).

$$\tau = F / \pi \, d_{nom} \, L \qquad (1)$$

For the evaluation of the bond behaviour three representative values were selected

(Cf. Fig. 4b): (a) the maximum (or ultimate) bond stress, τ_{max}, at the time of the bond failure and (b) the corresponding slip, $s_{\tau max}$, as well as (c) the arithmetic mean, τ_m, of bond stresses $\tau_{0.01}$, $\tau_{0.10}$ and $\tau_{1.00}$, which is known as the 'average' bond stress. The acquired values were compared to the corresponding values from previously published work [4], in which specimens were exclusively treated under ambient temperatures.

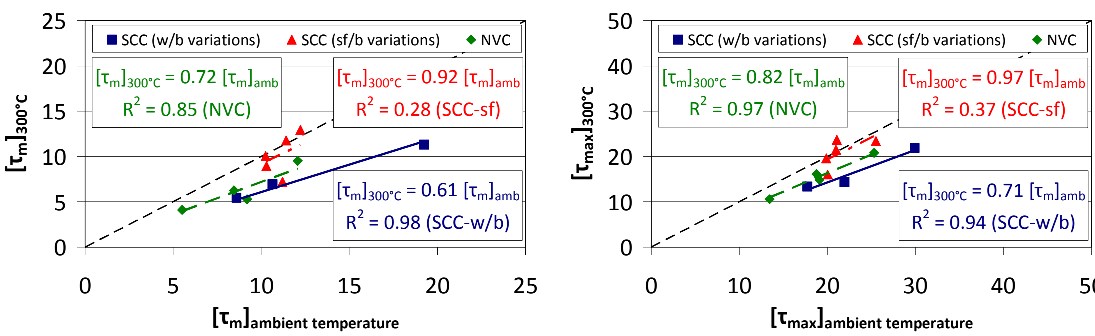
Figure 4. (a) Bond stress, τ (N/mm²), as a function of slip, s (mm), for all mixtures and for the different treatment temperatures and (b) definition of values retained by each τ vs. s curve.



RESULTS AND DISCUSSION

Medium-high temperatures (up to 300 °C). The residual bond stresses, τ_m or τ_{max} (N/mm²), are correlated with the corresponding reference bond stresses [4]. The coincidence with the diagonal would imply an insignificant bond stress reduction. It appears that τ_m (Cf. Fig. 5a) is reduced by approximately 40 % for mixtures with varying w/b ratios, whilst for NVC mixtures the reduction reaches about 28 %.

Figure 5. Correlation between bond stress,τ (N/mm²), calculated for specimens treated at ambient temperature or at 300 °C, for (a) τ_m and (b) τ_{max}.



The reduction is smaller for τ_{max} (Cf. Fig 5b), reaching 29 % and 18 %, respectively. The correlation coefficients of the linear regressions are considerably high (R^2=0.85 to 0.98). For both stresses, mixtures with varying sf content appear to stay almost unaffected by the heat treatment. As shown in Fig. 6a, $s_{\tau max}$ appears to be almost constant after heat treatment for the varying w/b ratios, whilst there is a non-constant but evident reduction for higher sf levels. An unclear behaviour is observed for NVC.

Figure 6. Slip corresponding to the maximum bond stress, $s_{\tau max}$ (mm), of specimens treated at 300 °C, normalized to the corresponding slip of specimens treated at ambient temperature.

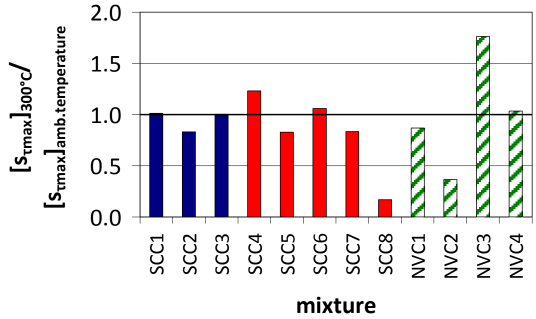
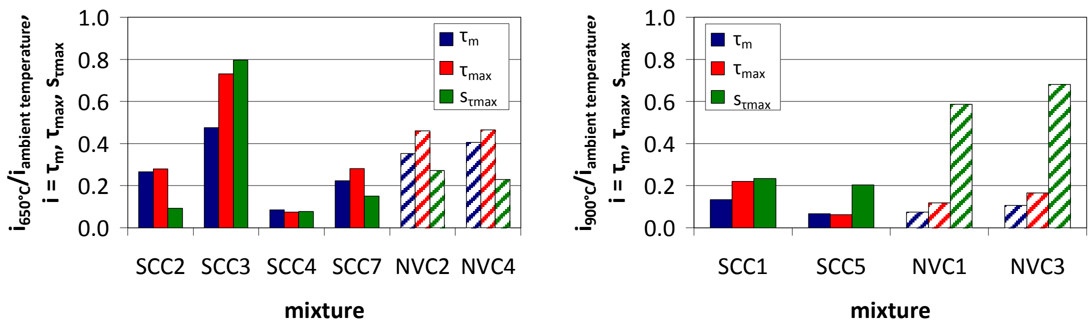


Figure 7. Bond characteristics (τ_m, τ_{max} and $s_{\tau max}$), calculated for high temperatures, normalized to the corresponding characteristics at ambient temperatures, for (a) 650 °C and (b) 900 °C.



High temperatures (650 or 900 °C). For heat treatment in high temperatures (Cf. Tab. 6), the results are presented according to the maximum applied temperature. Values closer to 1.0 would imply a coincidence with the corresponding values for ambient temperatures [4]. For 650 °C (Cf. Fig. 7a), the bond characteristics (τ_m, τ_{max} and $s_{\tau max}$) appear significantly deteriorated for all mixtures, this deterioration being slightly lower for NVC mixtures. For SCC mixtures, a higher reduction is observed for $s_{\tau max}$, followed consecutively by τ_m and τ_{max}. The composition properties (w/b or sf/b variations) seem to have an effect on the resulting bond characteristics, which is more significant for the case of varying w/b ratio. Still, further investigation is needed to confirm this observation and verify any correlation trend. On the other hand, the bond characteristics are not affected by the different workability classes of NVC mixtures (achieved by different pce levels). The same finding is evident for 900 °C (Cf. Fig. 7b). In this case, the highest reduction is observed for τ_m, followed consecutively by τ_{max} and $s_{\tau max}$. A significantly lower reduction is observed for $s_{\tau max}$ of NVC mixtures.

CONCLUSIONS

Explosive spalling was observed for some of the silica fume concretes, a fact that was attributed to the high heating rate (6.2 ^{o}C/min). Temperatures up to 300 ^{o}C have a more significant effect on τ_m than on τ_{max}, for SCC mixtures with varying w/b ratio or NVC mixtures. The corresponding stresses for silica fume concretes are not affected, whilst higher sf contents reduce $s_{\tau max}$. Temperatures up to 900 ^{o}C reduce τ_m, τ_{max} and $s_{\tau max}$, this effect being slightly stronger for SCC. Further investigation is needed to confirm a possible effect of SCC composition variations on the residual bond, whilst different pce levels of NVC mixtures are not reflected in the results.

LIST OF REFERENCES

1. Zhu, W., Sonebi, M., Bartos, P.J.M., Bond and interfacial properties of reinforcement in SCC, Materials & Structures, Vol. 37, 2004, pp. 442-448.

2. Valcuende, M., Parra, C., Bond behaviour of reinforcement in self-compacting concretes, Construction & Building Materials, Vol. 23, 2009, pp. 162-170.

3. Esfahani, M.R., Lachemi, M., Kianoush, M.R., Top-bar effect of steel bars in self-consolidating concrete, Cement & Concrete Composites, Vol. 30, 2008, pp. 52-60.

4. Sfikas, I.P., Trezos, K.G., Effect of composition variations on bond properties of Self-Compacting Concrete specimens, Construction & Building Materials, Vol. 41, 2013, pp. 252-262.

5. Sfikas, I.P., Kanellopoulos, A., Trezos, K.G., Petrou, M.F., Comparison of bond properties of similar Self-Compacting Concrete mixtures cast in two different EU laboratories, 5th North American Conference on the Design and Use of Self-Consolidating Concrete: Innovation, Application and Production, 2013, Chicago, IL, USA.

6. Bamonte, P., Gambarova, P.G., A study on the mechanical properties of SCC at high temperature and after cooling, Materials & Structures, Vol. 45, 2012, pp. 1375–1387.

7. Sideris, K.K., Manita, P., Residual mechanical characteristics and spalling resistance of fiber reinforced self-compacting concretes exposed to elevated temperatures, Construction & Building Materials, Vol. 41, 2013, pp. 296–302.

8. Hertz, K.D., Danish Investigations on Silica Fume Concretes at Elevated Temperatures, ACI Materials Journal, Vol. 89, No. 4, 1992, pp. 345-347.

9. *Al-Sibahy, A., Edwards, R., Thermal behaviour of novel lightweight concrete at ambient and elevated temperatures: Experimental, modelling and parametric studies, Construction & Building Materials, Vol. 31, 2012, pp. 174–187.*