The 13th International Conference on
Structural & Geotechnical Engineering
ICSGE-13 December 27-29, 2009
25 YEARS OF CONFERENCES 1984-2009
Ain Shams University, Cairo, EGYPT

المؤتمـــــر الدولـــي الثالث عشـــــر
للهندســــة الإنشـــــائيـــة و الجــــيوتقـــنية
27-29 ديسمبر 2009
جامعة عين شمس – القاهرة
جمهورية مصر العربية

Thirteenth International Conference on Structural and Geotechnical Engineering

Prof. Dr. Emam Soliman
Email:info@ icsge2009.com

To: Eng. Taha Awad Allah ☒ For Your Information

Paper Title: "**BEHAVIOR OF RC BEAMS OF NSC AND HSC EXPOSED TO FLEXURAL LOAD AND ELEVATED TEMPERATURE**"

Paper Ref. : Paper # 47

Sender: Prof. Dr. Emam Soliman Date: December 30th, 2009

RE: Paper Acceptance

Dear Eng., Eng.Taha Awad Allah

We are pleased to inform you that the above mentioned paper has been accepted by the Scientific Committee to be published and presented in the "Thirteenth International Conference on Structural and Geotechnical Engineering, 13th ICSGE".

On behalf of the organizing committee, I would like to thank you for your cooperation. We really appreciate your contribution to this technical event.

Sincerely Yours,

Prof. Dr. Emam Soliman
Conference Secretary General

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RE: Letter for Attending The conference

Dear Eng., Taha Awad Allah

Herewith, we certify that Eng. Taha Awad Allah has attended and presented the above mentioned paper by the "Thirteenth International Conference on Structural and Geotechnical Engineering, 13th ICSGE".

On behalf of the organizing committee, I would like to thank you for your cooperation. We really appreciate your contribution to this technical event.

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Department of Structural Engineering

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BEHAVIOR OF RC BEAMS OF NSC AND HSC EXPOSED TO FLEXURAL LOAD AND ELEVATED TEMPERATURE

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ABSTRACT

This paper discusses the behaviour of normal and high strength concrete beams exposed to elevated temperature. The paper also provides a simple, economical, and reliable technique that can be used to assess the fire resistance of concrete beams exposed to multi-action of external loads and elevated temperature simultaneously. The new technique was verified by testing (36) normal and high strength concrete beams made of concrete mixes of different w/c and s/c ratios. The tested beams comprised simply supported and restrained beams, anti-fire coated beams, and beams cooled by different methods. The results showed that the presented technique is effective and succeeded to distinguish among the different RC beams. The results also indicated that testing RC beams subjected to flexural load and then exposed to elevated temperature provided better understanding to the structural behaviour of the flexural elements in the field. The results also showed that the restrained RC beams exhibited better fire resistance when compared to the simply supported RC beams. Using of anti-fire resisting coating improves the fire resistance of RC beams made of high strength concretes. The results also emphasised on involving the influence of the cooling methods to evaluate the actual behaviour of the flexural elements.

KEYWORDS

NSC (Normal Strength Concrete), HSC (High Strength Concrete), Flexural Load, Silica Fume (S/C), Anti Fire coating, Temperature Development, Techniques of Cooling.

1 INTRODUCTION

The fire resistance of reinforced concrete structures is mainly affected by several factors such as type of concrete, intensity of the external loads, fire duration and severity, the design considerations and construction practices. Design criteria have been based on the results of testing a "standard" fire exposures typically expressed in terms of required reinforcement cover [1]. However, the general applicability and usefulness of this approach may be debated since the heating regimes in real fires may be quite different. In particular, initial heating rates can be more rapid and all real fires have a distinct "cooling phase" [2]. Both of these conditions are recognized as imposing additional stresses on in-situ structures which may be highly restrained. The structure in the field is subjected to a combination of mechanical actions that arise from restrained thermal elongations, degradation of the mechanical properties of the constituents, and transitional thermal creep in concrete. Indeed, under the combined action of temperature and mechanical loads, the microstructure of concrete undergoes physical-chemical changes that result in a degradation of its elastic and inelastic properties, cracking, thermal dilatation, and transient creep [3,4]. Therefore, the understanding of the behavior of reinforced concrete structure when it is exposed to elevated temperature is complex and requires a lot of data and information such as external loading conditions, the temperature gradients according to external heat, and the characteristics of the material at a given temperature condition.

Recently there has been increasing demand on high strength concrete in particular for construction of tall buildings, tunnels, bridges and nuclear vessels [5]. This material typically has considerably higher compressive strength than normal strength concrete, but it is markedly less porous and moisture absorbent. While this generally reduces the water content of the cement, it is also harder for water vapour to escape during heating. It is some times argued that high strength concrete is more prone to spalling, due to its lower porosity and hence the increased likelihood of high pressure developing within the concrete structure [6,7]. However, other recent research has shown that this is not necessarily the case, with some testing showing higher spalling resistance in these materials, attributable to the fact that their improved tensile proper ties can effectively counteract the increase in forces which promote a tendency for spalling[8,9]. Finally, it should be noted that despite severe challenges derived from the complexity of the relevant phenomena, modelling of spalling is beginning to show promise, though with more work still needed [١٠,11].

2 OBJECTIVES

1- Providing a technique that allows testing either flexural or compression elements exposed to load and temperature simultaneously. The technique should be inexpensive, easy to develop, simple to apply, accurate, and simple to interpret.

2- Studying the effect of elevated temperature on the flexural strength of unrestrained and restrained RC beams subjected to combination of flexural load and heat.

3 Studying the effect of cooling methods on the flexural strength of simply supported RC beams subjected to flexural load, heat, and combination of them.

4- Comparing the behaviour of normal and high strength concrete beams when they are exposed to elevated temperature while they are loaded.

3 EXPERIMENTAL PROGRAM

3.1 Beams Preparation

The experimental program included testing of 36 RC beams. 18 RC beams were made of normal concrete mixes of w/c ratio 0.45, 0.5 and 0.6. The other 18 RC beams were made of high strength concrete mixes of S/C ratios 12.5%, 20%, and 25%. Table 1 shows the used mixes. Table 2 and Table 3 describe the different loading conditions. Fig. 1 shows the dimensions and reinforcement of the tested simple and restrained RC beams.

3.2 Technique of Rising the Temperature

Photo 1 and Photo 2 show the technique of inducing temperature in the tested RC beams. The technique comprised the following:
1-Confining the RC beams with electrical coil which can withstand temperature up to 2000^{o}C. Fixed pitch of 100 mm is used to obtain regular temperature distribution on the surface of the beam.
2- Covering the RC beam with insulating sheet to prevent heat dissipation.
3- Making a very small hole to measure the temperature with the thermocouple at intervals at fixed locations till reaching the required temperature.
4- Recording the temperature gradient on the surface using the thermocouple to investigate the influence of density of concrete on the heat transfer inside the tested beams. More details about testing conditions are given in Tables 2 and 3

4 RESULTS AND ANALYSIS OF NSCB

4.1 Compressive Strength of Concrete Mixes

The results of the cube compressive strength presented in Table 1 show that increasing the w/c ratio from 0.45 to 0.60 leads to decreasing the average cube compressive strength. The average cube compressive strength of the three mixes M1, M2, and M3 were 20.4 N/mm2, 17.3N/mm2, and 11.1 N/mm2 at 7days, while they were 28.0 N/mm2, 25.1N/mm2, and 18.2 N/mm2 at 28 days respectively. The average tensile strength obtained from the splitting test was 2.72N/mm2, 2.45N/mm2, and 1.98N/mm2 respectively.

4.2 Temperature Development at Surface of Tested Beams

Fig. 2 shows the development of temperature at the surface of the tested beams exposed to heat and/or load. The results show that the beam NSCB16 achieved 432^{o}C at 140 minutes while beams NSBC12, NSCB13, NSCB14, and NSCB15 reached 327^{o}C, 330^{o}C, 329^{o}C, 347^{o}C at 135, 130, 120, and 135 minutes respectively. The results indicated that loading the beam before exposing to heating led to higher resistance to temperature transfer inside the concrete beam. For example, the beam NSCB16 may need about 45 minutes to reach 200^{o}C at the surface while the beam NSCB13 may need about 77.5 minutes to reach the same temperature. Also, at the same time of exposure, NSCB16 reached the highest temperature with respect to the loaded beams NSBC12, NSCB13, NSCB14, and NSCB15. The temperature development of the concrete beams made with the mix M2and M3 and coded by NSCB2 and NSB3 showed similar results as indicated for NSCB1.

The results could also explain the influence of the type of the mix on the temperature rising. Increasing the w/c ratio from 0.45 to 0.60 (ie decreasing the density of concrete) led to increase the surface temperature and decreased the time required to reach this surface temperature. Consequently, an increase of the resistance to temperature transfer inside the beam is expected. In fact this observation postulated that two factors play an important role in the distress of the heated beams. Those two factors are the temperature value and the temperature gradient. Low dense concrete will suffer from the high induced temperature near surface as well as the non-uniform distribution (stepped gradient). On the other hand, high dense concrete will mainly suffer from the uniform distribution through the thickness of the beam. Clearly, the steel reinforcement in low dense concrete will suffer from more distress low dense concrete

4. 3 Flexural Strength Test Results

4.3.1 Initial cracking load [Pcr]

Table 4 shows the influence of loading conditions on the initial cracking load. The initial cracking load of the restrained beam NSCB12 represents 92.73% of the reference beam NSCB11. For normal strength concrete beams made with concrete mix of w/c =0.45, the initial cracking load of the reference beam NSCB11 was 16.5KN while the initial cracking load of the heated beam NSCB16 was 6.0 KN. This result indicates that heating the beam without loading led to a reduction in the initial cracking load by about 63.36%. For the other three beams, NSCB13, NSCB14, and NSCB15, which are subjected to 60% of its ultimate capacity, the percentage of reduction in the initial cracking load was about 29% regardless of the method of cooling.

This observation postulated that exposing the beam to heating caused much severe damage to the initial cracking load if it is compared with the cases of exposing to loading and heating respectively. The same observation was noted for the other two groups of beams made with mixes of w/c ratios 0.5 and 0.6. The difference was in the absolute values. The beams of the second group showed a reduction in the initial cracking load of about 67.37% for the case of heating only (i.e. beam NSCB26), while an average reduction of about 31.25% was noted for the cases of loaded beams (i.e. NSCB23, NSCB24, and NSCB25. Table 4 shows that there was no influence of the cooling method on the initial cracking load of the tested beams. Also increasing the compressive strength of the concrete has a slight influence on the initial cracking load.

4.3.2 The Ultimate Load [P_{ult}]:

Table 3 and Fig. 3 presented the result of the ultimate load of the tested beams exposed to different loading conditions. The ultimate load of the restrained beam NSCB12 represented 87.90% of the reference beam NSCB11. The ultimate load of the reference beam of with the mix M1 NSCB11 was 35.63KN while it was 11.04KN for the heated beam NSCB16. A reduction of about 69.01% was occurred due to heating without loading. For the beams NSCB13, NSCB14, and NSCB15, the ultimate loads represented 75.44%, 57.53%, and 48.44% of the reference beam NSCB11 respectively. Beams of Mixes M2 and M3 showed similar results.

Table 4 shows the effect of cooling methods on the ultimate load of the tested beams. The lowest values for the ultimate loads were obtained for the tested beams which left to cool in air before crushing. The beams NSCB15, NSCB25, and NSCB35 lost about 51.56%, 56.54%, and 51.30% of their original ultimate capacity while beams NSCB14, NSCB24, and NSCB34 lost about 42.47%, 46.46%, and 42.22% of their original ultimate capacity respectively. Similar results were obtained for beams made of mixes M2 and M3.

4.4 The Ductility

Fig. 7 shows the load-displacement curves of the tested beams and Table 4 shows the ultimate displacement recorded at failure. The reference beams NSCB11, NSCB21, and NSCB31 showed the least values of displacement when compared with the other beams. Slight increase of displacements of restrained beams was recorded. The displacement values of the restrained beams NSCB12, NSCB22, and NSCB32 were 9.770mm, 8.988mm and 4.6741mm respectively. The values of the displacement of the reference beams NSCB11, NSCB21, and NSCB31 were 8.760mm, 8.059mm, and 4.191mm respectively. On the contrary, the beams NSCB16, NSCB26, and NSCB36 showed the highest values of displacements and they were 18.300mm, 16.836mm, and 8.755mm respectively. Similar results were recorded for the beams of mixes M2 and M3.

It is generally accepted that the creep due to temperature change becomes more critical with temperature. Recently it has been reported that the strain components are assumed to be uncoupled and the total strain of concrete at high temperature is assumed as the sum of three different components and can be written as:

$$\varepsilon_{total} = \varepsilon_{th}(T) + \varepsilon_{\sigma}(\sigma, T) + \varepsilon_{cr}(\sigma, T, t)$$

where ε_{th}, ε_{σ}, ε_{cr}, T and t represent free thermal strain, stress-induced strain, thermal creep strain, temperature and time, respectively. The free thermal strain and the thermal creep strain are originated with the temperature change, while the stress-induced strain is generated by the external loads. Inelastic strain change due to moisture in concrete is neglected for the reason that it is so small compared to thermal creep strain at high temperature and its effects are getting disappear at more than 400°C [5].

Cooling the tested beams gradually in air before crushing it causes relatively higher displacement with respect to the beams cooled suddenly with water. The displacement of the beam NSCB15 was mm17.300mm while it was 14.670mm for the beam NSCB14. Similar trend was observed for the beams of mixes M2 and M3.

4.5 Modes of Failure of the Tested Beams

The reference beams such as NSCB11 showed the typical mode of failure under flexural load. The cracks were initiated in the tension zone within the middle third of the beam. The cracks were then propagated along the depth of the beam. For beam NSCB16 exposed to heating before crushing, the cracks were initiated and propagated along the length of the beam. Beams NSCB12, NSCB13, NSCB14, and NSCB15 showed similar mode of failure as the reference beam but the crack intensity was relatively higher.

5 RESULTS AND ANALYSIS OF TESTED HSCB

5.1 Compressive Strength of Concretes Mixes

Table 1 shows the results of the cube compressive strength of the different HSC mixes. The results showed that increasing the S/C ratio from 12.5% to 25.0% led to increase the average cube compressive strength from 31.10 N/mm2 to 38.60 N/mm2 at 7days, while they are increased from 87.50 N/mm2 to 122.70 N/mm2 at 28 days. The tensile strength values were 8.02N/mm2, 9.16N/mm2, and 11.34N/mm2 respectively.

5.2 Temperature Development at Surface of Tested Beams

Fig. 4 showed the development of temperature at the surface of the tested beams. The beam HSCB16 reached 408°C at 60 minutes while beams HSCB12, HSCB13, HSCB14, and HSCB15 achieved 319°C, 328°C, 299°C, 308°C at 70, 75, 90, 90 minutes. This observation indicated that loading the beam before exposing to fire led to higher resistance to temperature transfer inside the concrete beam The temperature development of the concrete beams made with the mix M2and M3 and coded by HSCB2 and HSCB3 indicated similar results as indicated for HSCB1. Increasing the S/C ratio from 12.5% to 25% led to decrease the surface temperature. Consequently, the resistance to heat transfer inside the beam will be decreased. Therefore, the mix M1 is expected to have a steeper temperature gradient when compared to the mix M3. In fact this observation postulated that the beams made with the mix M1 of s/c=12.5% will suffer from elevated temperature near the surface while gradual distribution of temperature through the thickness of the beam is expected for mix M3. Mixes of higher densities will suffer from the vapour pressure of relatively higher temperature while mixes of relatively lower densities will be more sensitive to damage near surface.

5.3 Flexural Strength Test Results

5.3.1 Initial Cracking Load [P_{cr}]

Table 5 shows the results of the loads and displacement of the tested beams. For high strength concrete beams HSCB11 made with concrete mix M1 the initial cracking load was 15.1KN. The unloaded heated beam HSCB16 shows that the initial cracking load was zero. It seems that severe damage was occurred for the beam due to the induction of high tensile stresses in the outer layer all around the beam. The initial cracking load of the restrained beam HSCB12 was 28.30KN and represented 81.46% of the reference beam HSCB11. The initial cracking load of beams HSCB13, HSCB14 and HSCB15 represented 63.58%, 63.58%, and 83.44% of the reference beam HSCB11. Similar behavior could be seen for the beams made of mixes M2 and M3. The only difference is the absolute values.

5.3.2 Ultimate load (P_{ult})

Table 5 and Fig. 5 show the results of the ultimate load of the tested beam. The ultimate loads of reference beams HSBC11, HSCB21, and HSCB31 were 32.10KN, 35.32KN and 39.73KN for the reference beams and HSCB31 respectively. Increasing the S/C ratio from 12.5% to 25% leads to increase the ultimate load by about 23.8%. The ultimate load of the restrained beam HSCB12 represented 88.16% of the reference beam HSCB11. The results of beams HSCB16, HSCB26, and HSCB36 show the severe effect of heating the beams without loading them. The ultimate loads of the beams HSCB16, HSCB26, and HSCB36 represented 1.56%, 0.96%, and 0.28% of the ultimate load of the reference respectively. The results also show the influence of loading the beams HSCB13, HSCB23, and HSCB33 before rising the temperature. The ultimate load of the beams HSCB13, HSCB23, and HSCB33 represented 79.02%, 67.75%, and 63.18% of the reference beams HSCB11, HSCB21, and HSCB31.

Table 5 and Fig. 5 also show the influence of coating the beams HSCB14, HSCB15, HSCB24, HSCB25, HSCB34, and HSCB35 with anti-fire coat. An increase was observed due to the use of the anti-fire coat. The ultimate load of beams HSCB14 and HSCB15 represented 109.1% and 103.1% with respect to the ultimate load of the uncoated beam HSCB13 respectively. Similarly, the ultimate load of beams HSCB24, and HSCB25 represented 111.8% and 100.9% of the ultimate load of beam HSCB23 respectively. The results postulated that cooling the beams suddenly with water may lead to less damage if it is cooled gradually in air. Beams HSCB14, and HSCB15 represented 79.02% and 74.71% of the reference. The ultimate load of beam HSCB14 represented 1.058 of the beam HSCB15. Fig. 6 illustrated comparison among the ultimate loads of NSCB and HSCB However more extensive research work should be implemented specifically the results of beams made of mixes M2 and M3 indicated that significant differences may be existed.

5.4 Displacement at Initial Cracking [Δcr]

Table 5 shows the displacement recorded at the initiation of the cracks. The displacement values of the reference beams HSCB11, HSCB21, and HSCB31 were 0.368 mm, 0.435 mm, and 0.512mm respectively. The displacement values of the restrained beams HSCB12, HSCB22, and HSCB32 were 5.120mm, 4.726mm and 4.126mm. The loaded beams HSCB13, HSCB14, and HSCB15 showed displacement values 0.405mm, 0.972mm, and 627mm respectively which were relatively higher than those of the reference beam HSCB11. Cooling the tested beams gradually in air before crushing it causes relatively higher displacement with respect to the beams cooled suddenly with water. The displacement of the beam NSCB15 was mm19.00mm while it was 17.00mm for the beam HSCB14. Similar trend was observed for the beams of mixes M2 and M3.

5.5 The Ductility

Fig. 8 shows the load-displacement curves of the tested beams and Table 5 shows the ultimate displacement recorded at failure.. The reference beams HSCB11, HSCB21, and HSCB31 showed the least values of displacement which are 6.340mm, 5.852mm, and 5.109mm respectively. A slight decrease of the displacement of the restrained beam was recorded. The displacement values of the restrained beams HSCB12, HSCB22, and HSCB32 were 5.120mm, 4.726mm and 4.126mm. On the contrary, the beams HSCB16, HSCB26, and HSCB36 showed the highest values of displacements and they were 23.000mm, 21.229mm respectively. The loaded beams HSCB13, HSCB14, and HSCB15 showed displacement values 18.00mm, 17.00mm, and 19.00mm respectively. Cooling the tested beams gradually in air before crushing it causes relatively higher displacement with respect to the beams cooled suddenly with water. The displacement of the beam NSCB15 was mm19.00mm while it was 17.00mm for the beam HSCB14. Similar trend was observed for the beams of mixes M2 and M3.

5.6 Modes of Failure of the Tested Beams

The reference beams such as HSCB11 showed the typical mode of failure under flexural load. The cracks were initiated in the tension zone within the middle third of the beam. The cracks were then propagated along the depth of the beam. The beam NSCB12 exposed to heating before crushing it showed that cracks were initiated and propagated along the length of the beam. Spalling of concrete at different location was observed. The beam exerted upon by flexural load before heating showed that the cracks were firstly initiated in the tension zone, propagated along the depth of the beam. The cracks were accompanied by the spalling of the concrete.

6 CONCLUSIONS

1- The presented fire technique proved to be easy to develop, practical to use and inexpensive.
2- The restrained concrete beams exposed to elevated temperature show better behaviour when compared to the simply supported beams while concrete beams exposed to fire only exhibited the lowest value of ultimate loads. It should be noted that using this case of loading will not predict the actual behavior of the flexural element in the field.
3- Using the anti-fire coating improves the ultimate load with respect to the uncoated beams.
4- The gradual cooling in air in the case of the flexural elements exposed to fire may not provide the best results. This should be attributed to the propagation of the cracks while the beam is still loaded. However, more research work to investigate the effect of cooling methods is needed.

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Table 1: Compressive strength of concrete mixes

Concrete Type	Cement	Aggregate	ID	W/C	S/C	f_t (N/mm2)	f_c (N/mm2) 7 days	f_c (N/mm2) 28days
NSC	OPC	Dolomite	M1	0.45	-	2.72	20.4	28.0
			M2	0.50	-	2.45	17.3	27.1
			M3	0.60	-	1.98	11.1	18.2
HSC			M1	0.30	12.5%	8.02	31.1	87.5
			M2	0.29	20.0%	9.16	33.3	107.3
			M3	0.28	25.0%	11.34	38.6	122.7

W/C: Water/Cement ratio **S/C: Silica/Cement ratio**

Table 2: Description of tested beams NSCB

Notation	Description
NSCB11	A beam tested in the flexural test facility at ambient temperature and taken as reference.
NSCB12	A beam restrained in the longitudinal direction, loaded by 60% of the ultimate load, heated up to the initiation of the first crack and tested in the flexural test facility.
NSCB13	A beam loaded by 60% of the ultimate load, heated to the initiation of the first crack, and then loaded till crushing.
NSCB14	A beam loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled suddenly by water, and then loaded till crushing.
NSCB15	A beam loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled gradually in air, and then loaded till crushing.
NSCB16	A beam heated up to the initiation of the first crack and tested in the flexural test facility.
NSCB21	A beam tested in the flexural test facility at ambient temperature and taken as reference
NSCB22	A beam restrained in the longitudinal direction, loaded by 60% of the ultimate load, heated up to the initiation of the first crack and tested in the flexural test facility.
NSCB23	A beam loaded by 60% of the ultimate load, heated to the initiation of the first crack, and then loaded till crushing.
NSCB24	A beam coated by anti fire coat, loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled suddenly by water, and then loaded till crushing.
NSCB25	A beam coated by anti fire coat, loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled gradually in air, and then loaded till crushing.
NSCB26	A beam heated up to the initiation of the first crack and tested in the flexural test facility.
NSCB31	A beam tested in the flexural test facility at ambient temperature and taken as reference
NSCB32	A beam restrained in the longitudinal direction, loaded by 60% of the ultimate load, heated up to the initiation of the first crack and tested in the flexural test facility.
NSCB33	A beam loaded by 60% of the ultimate load, heated to the initiation of the first crack, and then loaded till crushing.
NSCB34	A beam coated by anti fire coat, loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled suddenly by water, and then loaded till crushing.
NSCB35	A beam coated by anti fire coat, loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled gradually in air, and then loaded till crushing.
NSCB36	A beam heated up to the initiation of the first crack and tested in the flexural test facility.

Table3: Description of tested beams HSCB

Notation	Description
HSCB11	A beam tested in the flexural test facility at ambient temperature and taken as reference.
HSCB12	A beam restrained in the longitudinal direction, loaded by 60% of the ultimate load, heated up to the initiation of the first crack and tested in the flexural test facility.
HSCB13	A beam loaded by 60% of the ultimate load, heated to the initiation of the first crack, and then loaded till crushing.
HSCB14	A beam coated by anti fire coat, loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled suddenly by water, and then loaded till crushing.
HSCB15	A beam coated by anti fire coat, loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled gradually in air, and then loaded till crushing.
HSCB16	A beam heated up to the initiation of the first crack and tested in the flexural test facility.
HSCB21	A beam tested in the flexural test facility at ambient temperature and taken as reference.
HSCB22	A beam restrained in the longitudinal direction, loaded by 60% of the ultimate load, heated up to the initiation of the first crack and tested in the flexural test facility.
HSCB23	A beam loaded by 60% of the ultimate load, heated to the initiation of the first crack, and then loaded till crushing.
HSCB24	A beam coated by anti fire coat, loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled suddenly by water, and then loaded till crushing.
HSCB25	A beam coated by anti fire coat, loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled gradually in air, and then loaded till crushing.
HSCB26	A beam heated up to the initiation of the first crack and tested in the flexural test facility.
HSCB31	A beam tested in the flexural test facility at ambient temperature and taken as reference.
HSCB32	A beam restrained in the longitudinal direction, loaded by 60% of the ultimate load, heated up to the initiation of the first crack and tested in the flexural test facility.
HSCB33	A beam loaded by 60% of the ultimate load, heated to the initiation of the first crack, and then loaded till crushing.
HSCB34	A beam coated by anti fire coat, loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled suddenly by water, and then loaded till crushing.
HSCB35	A beam coated by anti fire coat, loaded by 60% of the ultimate load, heated to the initiation of the first crack, cooled gradually in air, and then loaded till crushing.
HSCB36	A beam heated up to the initiation of the first crack and tested in the flexural test facility.

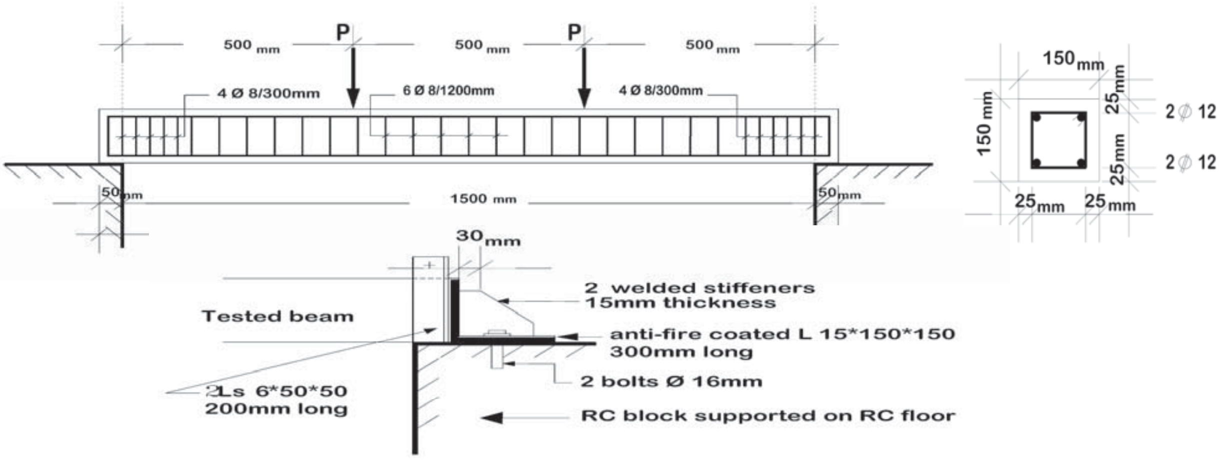

Fig. 1: Concrete dimensions and details of reinforcement of tested beams

Table 4: Recorded Loads and displacements of beams NSCB

Beam I`D	P cracking (KN)	Δ cracking (mm)	P ultimate (KN)	Δ ultimate (mm)	$P_{cr}/P_{cr.r.}$ (%)	$P_{cr}/P_{ult.}$ (%)	$P_{ult}/P_{ult.r.}$ (%)
NSCB11	16.50	0.367	35.63	8.760	100.00	46.31	100.00
NSCB12	15.30	0.234	31.32	9.770	92.73	48.85	87.90
NSCB13	11.70	3.248	26.88	14.310	70.91	43.52	75.44
NSCB14	11.70	2.470	20.5	14.670	70.91	57.07	57.53
NSCB15	11.70	2.703	17.26	17.300	70.91	67.87	48.44
NSCB16	6.00	1.400	11.04	18.300	36.36	54.35	30.99
NSCB21	16.00	0.338	27.52	8.059	100.00	58.10	100.00
NSCB22	14.50	0.215	23.19	8.988	90.63	62.53	84.27
NSCB23	11.00	2.988	19.85	13.165	68.75	55.42	72.13
NSCB24	11.00	2.272	14.73	13.496	68.75	74.86	53.52
NSCB25	11.00	2.487	11.96	15.916	68.75	91.98	43.46
NSCB26	4.10	1.288	7.4	16.836	25.63	55.41	26.89
NSCB31	11.70	0.176	23.00	4.191	100.00	45.22	100.00
NSCB32	10.80	0.112	19.01	4.674	92.31	56.81	82.65
NSCB33	10.00	1.554	16.10	6.846	96.15	62.11	70.00
NSCB34	10.00	1.182	13.29	7.018	96.15	75.24	57.78
NSCB35	10.00	1.293	11.20	8.276	96.15	86.96	48.70
NSCB36	2.40	0.670	7.20	8.755	23.08	33.33	31.30

Table 5: Recorded loads and displacements of beams HSCB

HSCB11	15.1	0.368	32.10	6.340	100.00	47.04	100.00
HSCB12	12.3	0.488	28.30	5.120	81.46	43.46	88.16
HSCB13	9.6	0.405	23.25	18.000	63.58	41.28	72.44
HSCB14	12.6	0.972	25.37	17.000	83.44	49.67	79.02
HSCB15	12.6	0.627	23.98	19.000	83.44	52.54	74.71
HSCB16	0.0	0.000	0.51	23.000	0.00	0.00	1.59
HSCB21	15.2	0.435	35.32	5.852	100.66	43.04	100.00
HSCB22	13.1	0.577	30.70	4.726	86.18	42.67	86.92
HSCB23	10.3	0.479	23.93	16.614	67.76	43.04	67.75
HSCB24	12.7	1.150	26.77	15.691	83.55	47.44	75.79
HSCB25	12.7	0.742	24.14	17.537	83.55	52.61	68.35
HSCB26	0.0	0.000	0.34	21.229	100.00	0.00	0.96
HSCB31	15.3	0.512	39.73	5.109	100.66	38.51	100.00
HSCB32	13.9	0.679	32.80	4.126	90.85	42.38	82.56
HSCB33	10.4	0.563	25.10	14.504	67.97	41.43	63.18
HSCB34	10.8	1.352	29.11	13.698	83.66	37.10	73.27
HSCB35	10.8	0.872	26.19	15.310	83.66	41.24	65.92
HSCB36	0.0	0.000	0.11	18.533	100.00	0.00	0.28

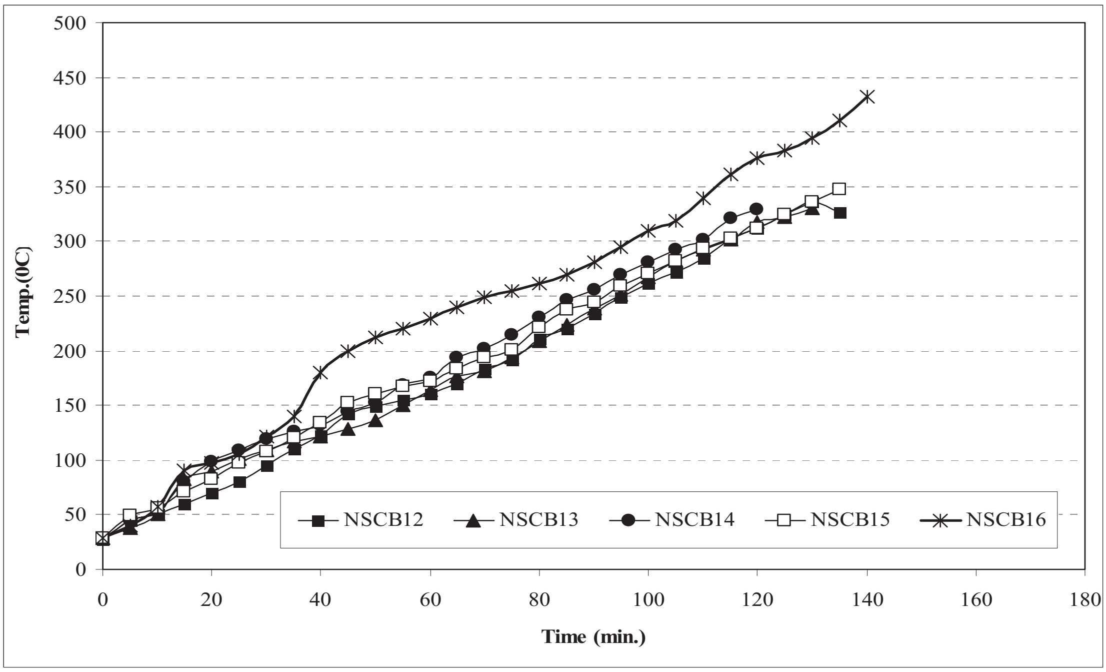

Fig. 2: Temperature development at surface of tested beams (NSCB)

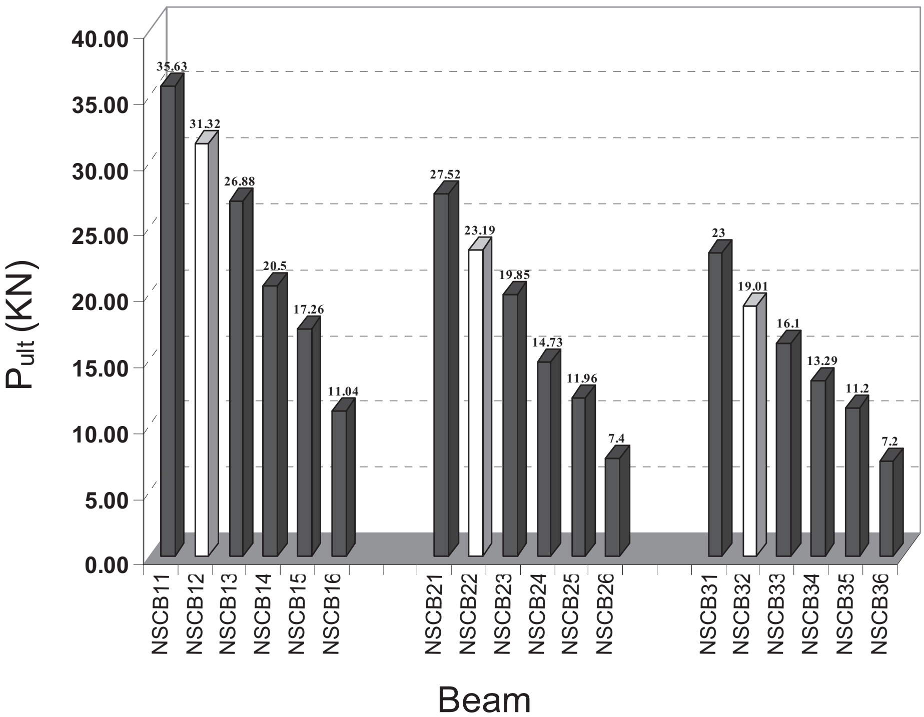

Fig. 3: Influence of loading condition and mix type on the ultimate load of NSCB

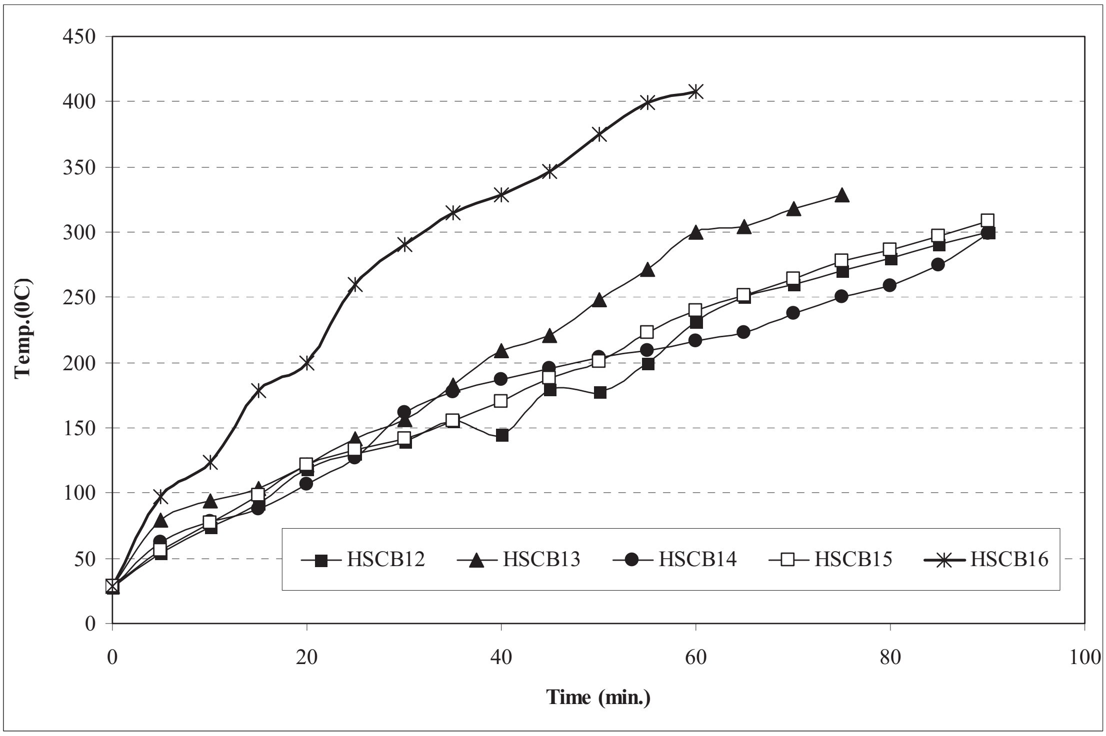

Fig. 4: Temperature development at surface of tested beams (HSCB)

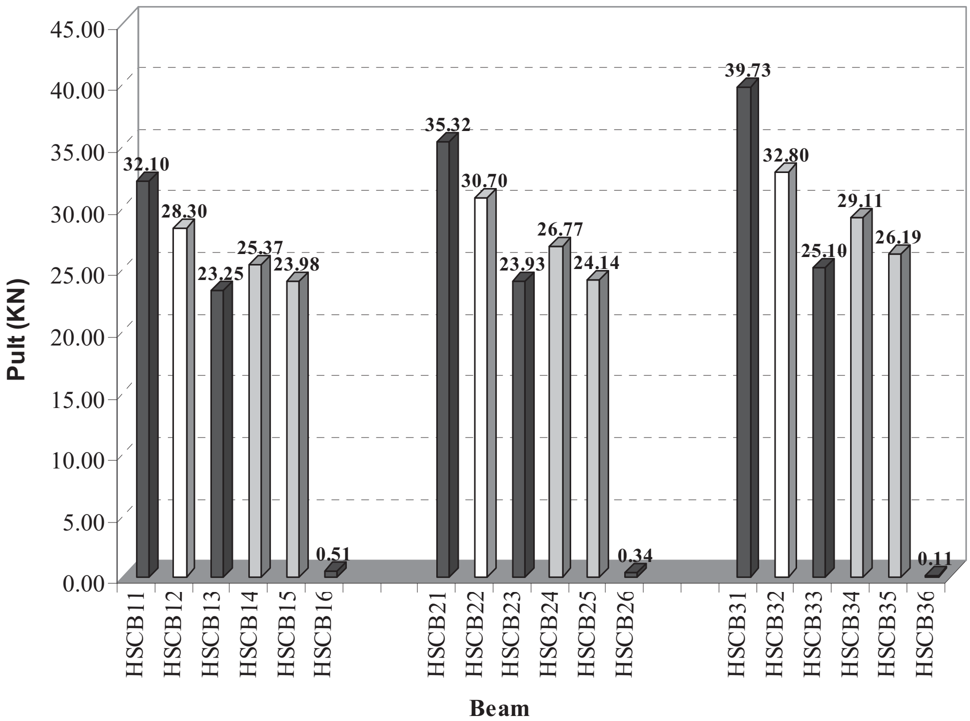

Fig. 5: Influence of loading condition and mix type on the ultimate load of HSCB

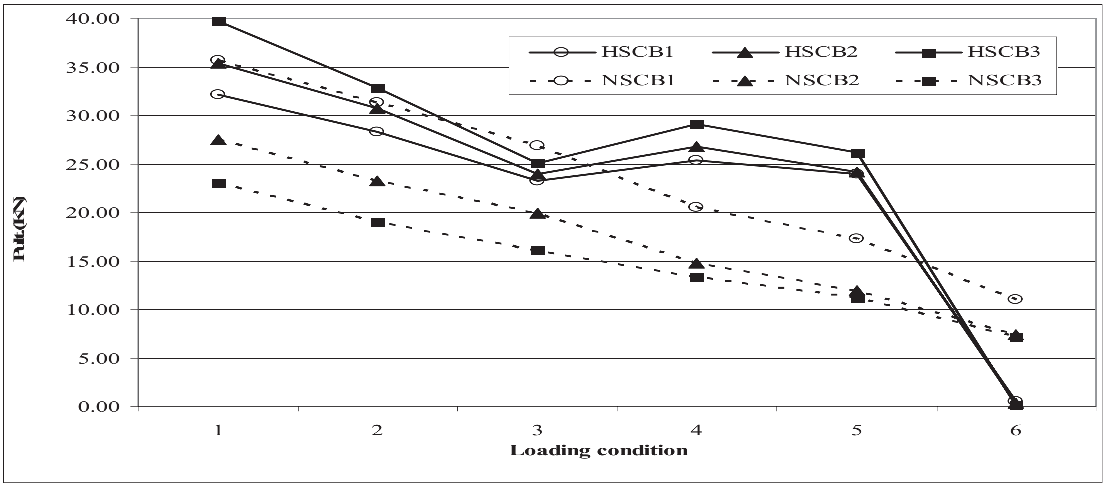

Fig. 6: The ultimate loads of NSCB&HSCB

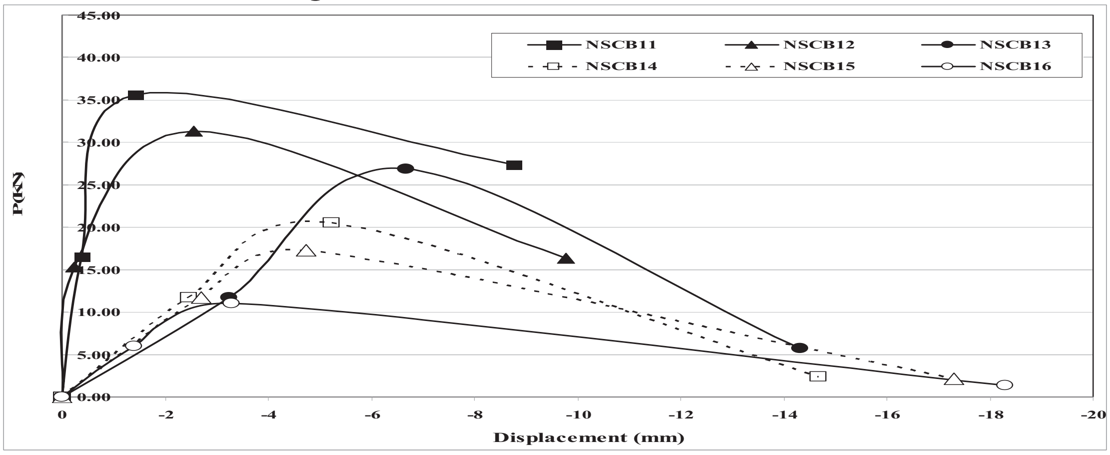

Fig. 7: Load-displacement of NSCB

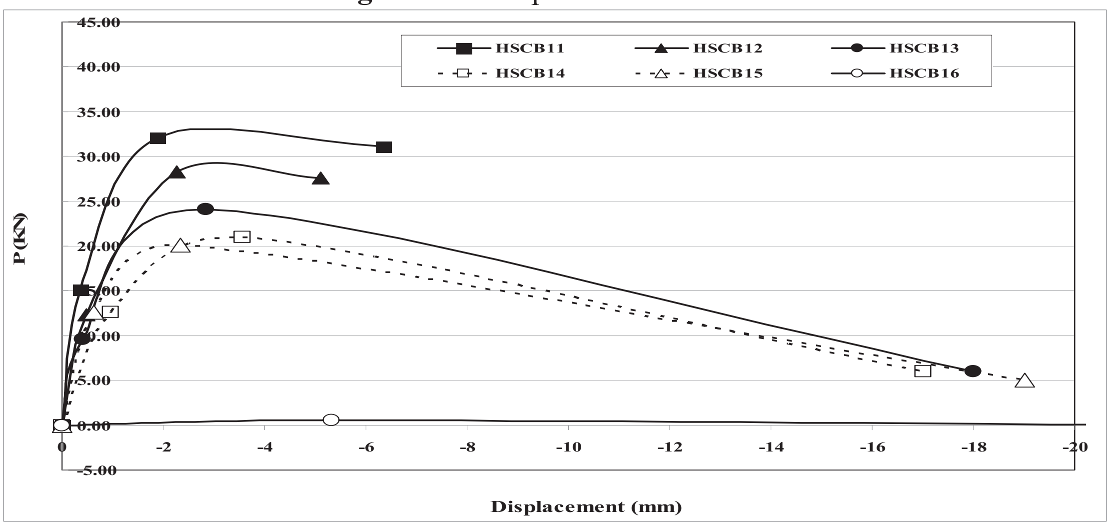

Fig. 8: Load-displacement of HSCB

Photo 1: Technique of heating the RC beam and measuring displacement using LVDT

Photo 2: The heated beam upon reaching 397ºC