Magazine of Concrete Research
Volume 65 Issue 7

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Magazine of Concrete Research, 2013, **65**(7), 415–421
http://dx.doi.org/10.1680/macr.12.00108
Paper 1200108
Received 03/07/2012; revised 04/10/2012; accepted 7/11/2012
Published online ahead of print 14/02/2013

Study on compressive strength behaviour of normal concrete and self-compacting concrete subjected to elevated temperatures

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Self-compacting concrete (SCC) is a form of high-performance concrete that flows and fills the form without segregation. This paper presents the behaviour of concrete when it is subjected to elevated temperatures. The investigation reports the loss in compressive strength and risk of spalling of SCC. The effects of elevated temperature on the properties of normal concrete (NC) and SCC are summarised. The compressive strength of NC and SCC was determined at different temperatures, thus providing scope of determining loss/gain in strength. In addition, modes of cooling and variation in different grades of concrete were studied. Non-destructive testing using a rebound hammer was also conducted to study the changes in surface hardness of concrete specimens subjected to elevated temperatures. The test results indicate that SCC is more sensitive to elevated temperatures, compared to NC.

Introduction

Fire causes significant personal, capital and production loss in most countries of the world each year. Hence, the provision of appropriate fire safety measures for structural members is a major requirement in building design. Concrete is widely used as structural material in building construction where fire resistance is one of the key considerations in design. Concrete is a non-homogenous material whose fire performance is controlled by its constituent materials such as aggregate, cement paste and other ingredients. Over the last three decades, there has been significant research and development activity in concrete technology and this has led to improved concrete mixes known as high-performance concrete (HPC). These HPC mixes include high-strength concrete, self-compacting concrete (SCC), fibre reinforced concrete and fly ash concrete, which offer superior strength, durability and cost advantages.

SCC is a form of HPC that flows to a virtually uniform level under the influence of gravity without segregation, during which it de-aerates and completely fills the form work and the spaces between the reinforcement, without any need for induced compaction. SCC is obtained by limiting the water–cement ratio and adding effective plasticisers, increasing sand–aggregate ratio and adding some viscosity enhancing admixtures.

The study on concrete subjected to elevated temperatures is increasing in significance. Study of the literature has revealed changes in mechanical properties of concrete when it is subjected to high temperatures (Phan and Carino, 2000). Furthermore, the new concretes that are being developed, such as SCC, require the characterisation when it is subjected to elevated temperatures (Sri Ravindrarajah *et al.*, 2002). This is needed because of the changes in the composition of the material such as the differences in the paste phase and aggregate phase between the normal concrete (NC) and new concretes (Nassif *et al.*, 1999). Such a study is very necessary to establish the durability of new concrete.

The present investigation focuses on the study of the compressive strength behaviour of NC and SCC subjected to elevated temperatures following different cooling regimes. It is assumed that 400°C, 600°C and 800°C represent the sort of temperatures that concrete would be exposed to in a fire. The cooling regimes such as quenching and air cooling may represent what happens when the fire is either put out with water or goes out slowly.

Present investigation

The experimental programme was designed to investigate the compressive strength behaviour of NC and SCC subjected to elevated temperatures. The primary aim of the experimental study is to compare the compressive strengths of NC and SCC of M20 and M40 grades with different cooling regimes. The compressive strengths of concrete (20 and 40 MPa) adopted in the present investigation represent the ordinary and standard concrete as per the Indian standards (IS456-2000) (BIS, 2000) and these strengths are most widely used. The programme consists of casting and testing a total number of 120 cubes of 100 × 100 × 100 mm size each. Of these 120 cubes, 60 cubes were cast with M20 and M40 NC and the remaining 60 cubes were cast with the same grades of SCC. Different sets of cubes were tested for different sets of temperatures, for a time interval of 60 min, with different modes of cooling, which are as tabulated below in Table 1.

Materials used

Cement used in the investigation was 53 grade ordinary Portland cement conforming to IS 12269 (BIS, 1987a). The fine aggregate conforming to zone 2 according to IS 383 (BIS, 1987b) was used. Crushed granite aggregate of size 20 mm, 16 mm and 10 mm well-graded aggregate according to IS 383 was used in this investigation. Fly ash conforming to IS 3812:1981 (BIS, 1981) was used as a mineral admixture. High-range water-reducing admixtures known as superplasticisers were used for improving the flow or workability for decreased water–cement ratio without sacrificing the compressive strength. Conplast SP430 was used, which combines the properties of water reduction and workability retention.

The mix proportions for M20 and M40 grades of NC and SCC used are given in Table 2. The mixes adopted were determined by trial. The water binder ratio of these mixes was kept nearly constant and the self-compacting properties were achieved. The new properties of SCC are presented in Table 3.

Casting and testing of specimens

The standard moulds of size 100 × 100 × 100 mm were fitted such that there were no gaps between the plates of the moulds.

S. no.	Grade of concrete	Temperature	No. of specimens cast 100 × 100 × 100 mm (hot state)	No. of specimens cast 100 × 100 × 100 mm (air cooling)	No. of specimens cast 100 × 100 × 100 mm (water quenching)	No. of specimens cast 100 × 100 × 100 mm
1.	M20	—	—	—	—	3
	(NC)	400°C	3	3	3	—
		600°C	3	3	3	—
		800°C	3	3	3	—
2.	M40	—	—	—	—	3
	(NC)	400°C	3	3	3	—
		600°C	3	3	3	—
		800°C	3	3	3	—
3.	M20	—	—	—	—	3
	(SCC)	400°C	3	3	3	
		600°C	3	3	3	
		800°C	3	3	3	
4.	M40	—	—	—	—	3
	(SCC)	400°C	3	3	3	—
		600°C	3	3	3	—
		800°C	3	3	3	—
Total no. of specimens cast			36	36	36	12

Table 1. Details of specimens cast

Material: per m^3	Unit	M20		M40	
		NC	SCC	NC	SCC
Cement	kg	360	270	450	320
Fly ash	kg	—	200	—	185
Fine aggregate	kg	668	1155	464	1132
Coarse aggregate	kg	1137	696	1319	682
Water	Lt.	162	202	202	229
Superplasticiser (SP430)	Lt.	—	33·2	—	31·8

Table 2. Mix proportions for M20 and M40 grades of NC

S no.	Test	M20	M40	European Federation for Specialist Construction Chemicals and Concrete Systems specification
1.	Slump flow by Abrams cone: mm	680	700	650–800
2.	T50 cm slump flow: s	5	4	2–5
3	J-ring: cm	4	2	0–10
4.	V-funnel: s	6	7	6–12
5.	V-funnel at T5 minutes: s	6	5	+3

Table 3: Fresh properties of self-compacting concrete

The entire casting was done in two stages, each corresponding to M20 and M40 grades of NC and SCC. In case of SCC of M20 and M40 grades, super plasticiser was used for workability purposes as per the specifications and calculations. The entire mix was mixed in a pan mixer for about 3–5 min and then poured into moulds. At the end of casting, the top surface was made plane using a trowel and a hacksaw blade to ensure a top uniform surface. After 24 h of casting, the specimens were kept for wet curing for 28 days before testing. After 28 days of curing, each of the specimens was heated with the help of an electrical furnace at temperatures of 400°C, 600°C and 800°C for 60 min and with different cooling regimes: that is, air cooling, water quenching, and hot state. All the specimens, after being subjected to the required temperature, were tested for destructive and non-destructive tests. The strength results and rebound values are tabulated in Table 4 and Table 5, respectively.

Discussion of test results

In this investigation the specimens, which are subjected to elevated temperatures of different magnitude, are tested following various cooling regimes. These testing states are referred to as cooling regimes. The various cooling regimes considered are

- room temperature (< 40°C): testing the unheated specimens (reference specimens)
- hot state: testing the heated specimens at hot condition – that is, testing immediately after removing from the electrical furnace
- after water quenching: testing the heated specimens after quenching them in water for 20 min
- air cooling: testing the heated specimens after cooling them in air to room temperature.

The variation in the strength of NC and SCC specimens subjected to elevated temperatures and testing following different cooling regimes is shown in Figures 1 to 4. The variation in rebound values of NC and SCC specimens is represented in Figures 5 to 8.

Effect of elevated temperatures on type of concrete

The compressive strength results of NC and SCC subjected to different exposures of temperature are presented in Table 4. These results clearly indicate that there is a reduction in compressive strength with temperatures of exposure. The reduction in compressive strength with temperature occurred both in NC and SCC. The loss of strength may be attributed to the occurrence of micro cracking in concretes heated to high temperatures.

The average percentage loss of strength with temperature given in column nos 7 and 14 of Table 4 reveals that the SCC has suffered more loss of strength with temperature compared to the NC. The average loss in strength in NC is about 16·6%, 25·5% and 45% at 400°C, 600°C and 800°C, respectively. In the case of SCC the average compressive strength loss presented in Table 4 is observed to be 29·2%, 45·6% and 71·4% at 400°C, 600°C and 800°C, respectively.

In general the SCC mixers normally have high paste to aggregate content compared to NC; hence more loss of strength in SCC may be attributed to the fact that the concrete with high compaction such as SCC can develop high internal stresses when heated. These stresses are caused by the evaporation of moisture and can result in cracking leading to the higher loss of strength.

Effect of elevated temperature on grade of concrete

The compressive strength test results presented in Table 4 show that percentage loss of strength with elevated temperatures has increased with increasing grade of concrete. The M40 grade concrete (both NC and SCC) shows higher percentage of strength loss than M20 grade concrete. In M20 grade NC, the percentage of strength loss is about 16·6%, 25·5% and 45% at 400°C, 600°C and 800°C, respectively, whereas similar concrete of M40 grade has shown a percentage loss in strength of 28%, 50·6% and 69·4% at 400°C, 600°C and 800°C respectively.

In the case of SCC of M20 grade, the percentage loss in strength is 29·1%, 45·6% and 71·4% at 400°C, 600°C and 800°C, respectively, whereas in the case of SCC of M40 grade, the percentage of strength loss is observed to be 52·9%, 57% and 74%, respectively at 400°C, 600°C and 800°C. Hence high-strength concretes have higher percentage of strength loss than lower strength concretes; however, this difference becomes somewhat less significant at temperatures above 600ºC.

In the case of M20 grade concrete, the increase in strength was observed at 400°C. This may be either a freak result or there may be intensifying hydration with temperatures up to 400°C. This

Temp. ↓	M20													
	NC							SCC						
	1 f_{ch}: MPa	2 Pl_{sh}: %	3 f_{cw}: MPa	4 Pl_{sw}: %	5 f_{ca}: MPa	6 Pl_{sa}: %	7 Pl_{sav}: %	8 f_{ch}: MPa	9 Pl_{sh}: %	10 f_{cw}: MPa	11 Pl_{sw}: %	12 f_{ca}: MPa	13 Pl_{sa}: %	14 Pl_{sav}: %
<40°C (room temp)	26	—	26	—	26	—	—	27·56	—	27·56	—	27·56	—	—
400°C	27	—	21·66	16·6	26·33	—	16·6	18·77	31·8	22·27	19·2	17·71	36·4	29·1
600°C	17·63	32	21·03	19·1	26·8	—	25·5	18·18	34	17·12	37	9·12	66	45·6
800°C	15	42	16·36	37	11·36	56	45	10·75	60	6·54	76·2	6·05	78	71·4
	M40													
	NC							SCC						
<40°C (room temp)	49·75	—	49·75	—	49·75	—	—	50·6	—	50·6	—	50·6	—	—
400°C	48·18	3·0	31·36	36·9	27·72	44·2	28	29·66	41	23·18	54·1	18·41	63·6	52·9
600°C	33·18	33	23·5	52·7	16·81	66·2	50·6	30	40	17·95	64·5	16·8	66·7	57·6
800°C	16·9	66	13·8	72·1	14·8	70·2	60·4	15·6	68	12	76·2	10·9	78	74

NC = normal concrete
Pl_{sh} = percentage loss in strength at hot state
SCC = self-compacting concrete
Pl_{sw} = percentage loss in strength after water quenching
f_{ch} = compressive strength at hot state
Pl_{sa} = percentage loss in strength after air cooling
f_{cw} = compressive strength after water quenching
Pl_{sav} = average percentage loss in strength at hot state
f_{ca} = compressive strength after air cooling

Table 4. Compressive strength of M20 and M40 grade NC and SCC concrete subjected to elevated temperatures

process is similar to the strength increase behaviour normally observed in steam curing. The increasing content of hydration products occurring in the temperature range 100–300°C (note that the bound water starts to be released at 180°C) leads to an increase of compressive strength.

Effect of cooling regime on compressive strength of concrete

The compressive strength results presented in Table 4 reveal that the testing after air cooling of specimens resulted in more loss of strength followed by testing after water quenching and testing at hot conditions. In the case of NC (M40) subjected to 600°C, the percentage loss in strength was observed to be 33%, 52·7% and 66·2% for the cooling regimes 2, 3 and 4, respectively. In the case of SCC (M40) subjected to 600°C the percentage loss in strength was observed to be 40%, 64·5% and 66·7% for the cooling regimes 2, 3 and 4, respectively; however, again at high temperatures of exposure the difference in percentage loss in strength between different cooling regimes reduces – for example, for NC of M40 grade subjected to 800°C has shown percentage strength loss to be 66%, 72·1% and 70·1% for the cooling regimes 2, 3 and 4, respectively, whereas in the case of SCC of M40 grade subjected to 800°C loss of strength obtained was 68%, 76·2% and 78%.

Effect of elevated temperature on hardness of the surface of the concrete

In general the surface hardness as represented by the rebound number value in non-destructive testing indirectly represents the likely spalling or loosening of surface of concrete. The rebound number values presented in Table 5 indicate that the rebound number values decrease with elevated temperatures both in NC and SCC. This gives an indication that there may be increased risk of spalling in concretes with elevated temperature.

The non-destructive testing test results indicated that more loss of hardness (or increased risk of spalling) was observed in the case of SCC than NC at elevated temperatures. The rebound number against compressive strength as represented in Figure 9 for NC and Figure 10 for SCC indicates less correlation in the case of SCC. This behaviour may be attributed to the fact that the SCC

Temp. ↓	M20					
	NC			SCC		
	RHC	RWQ	RAC	RHC	RWQ	RAC
Room temperature (<40°C)	26	26	26	28	28	28
400°C	21	21	23	10	13	12
600°C	19	20	21	10	10	11
800°C	12	14	12	10	10	10
	M40					
	NC			SCC		
	RHC	RWQ	RAC	RHC	RWQ	RAC
Room temperature (<40°C)	45	45	45	40	40	40
400°C	22	20	25	10	12	13
600°C	14	16	13	10	10	11
800°C	20	10	10	10	10	10

NC = normal concrete
SCC = self-compacting concrete
RHC = rebound value at hot state
RWQ = rebound value after water quenching
RAC = rebound value after air cooling

Table 5. Rebound numbers of M20 and M40 grade NC and SCC

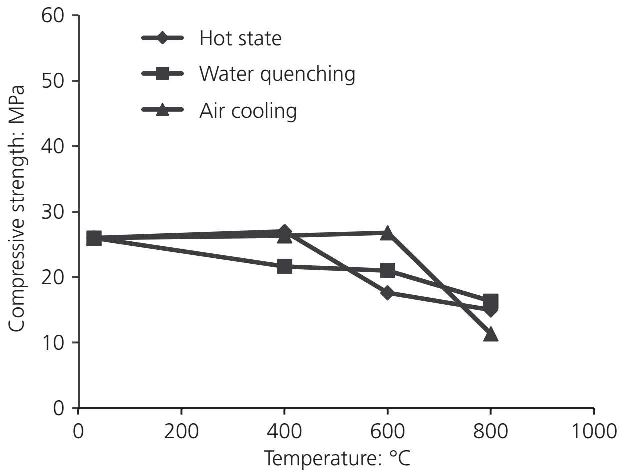

Figure 1. Compressive strength plotted against temperature for M20 grade NC

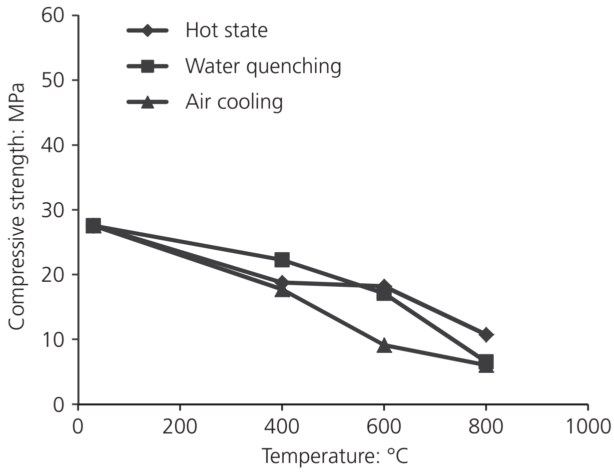

Figure 2. Compressive strength plotted against temperature for M20 grade SCC

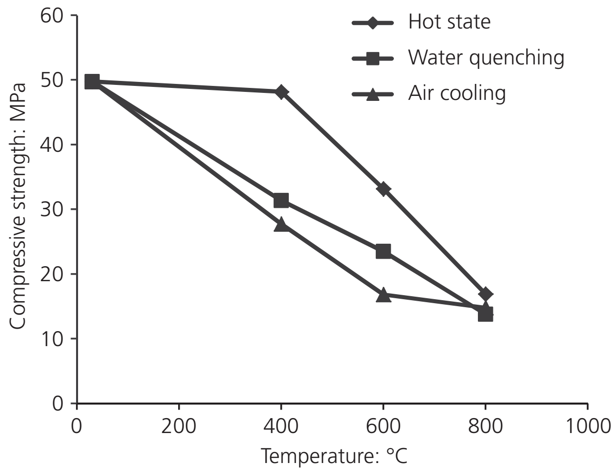

Figure 3. Compressive strength temperature for M40 grade NC

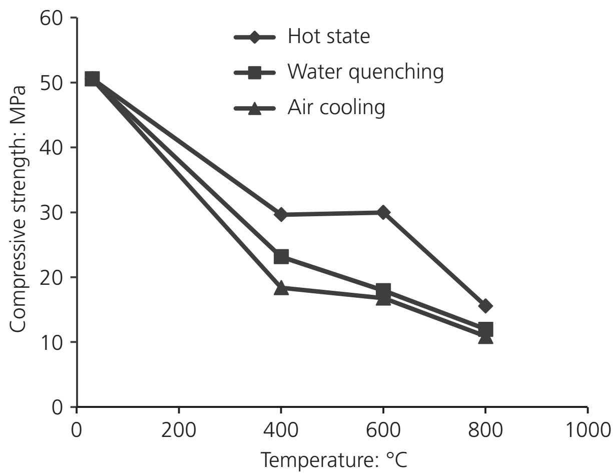

Figure 4. Compressive strength plotted against temperature for M40 grade SCC

suffers more surface disturbance owing to the development of high internal stresses leading to cracking when heated.

The hardness of surface as indicated by the rebound number was

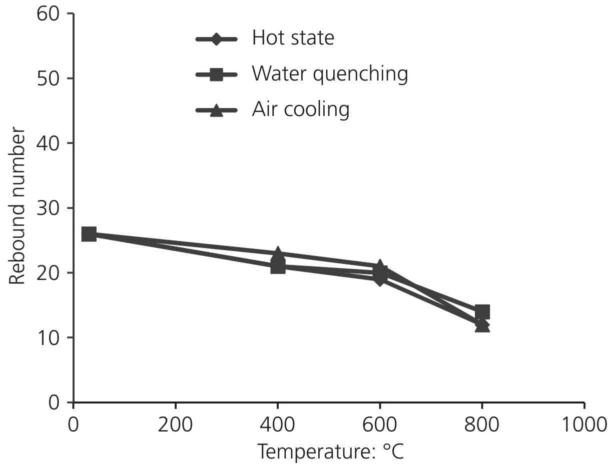

Figure 5. Rebound number plotted against temperature for M20 grade NC

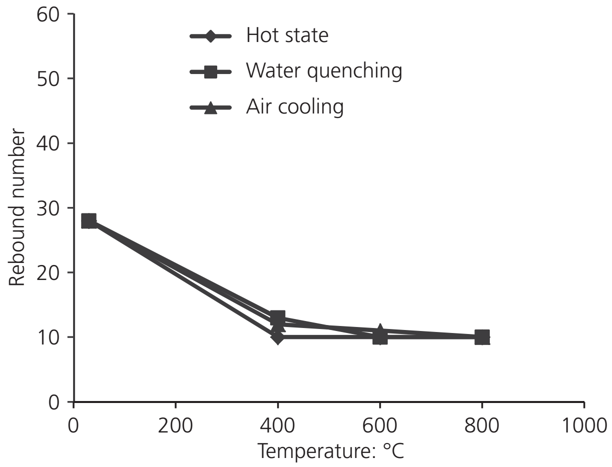

Figure 6. Rebound number plotted against temperature for M20 grade SCC

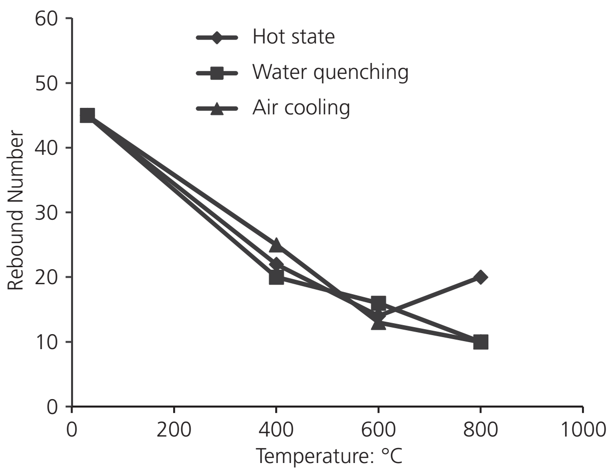

Figure 7. Rebound number plotted against temperature for M40 grade NC

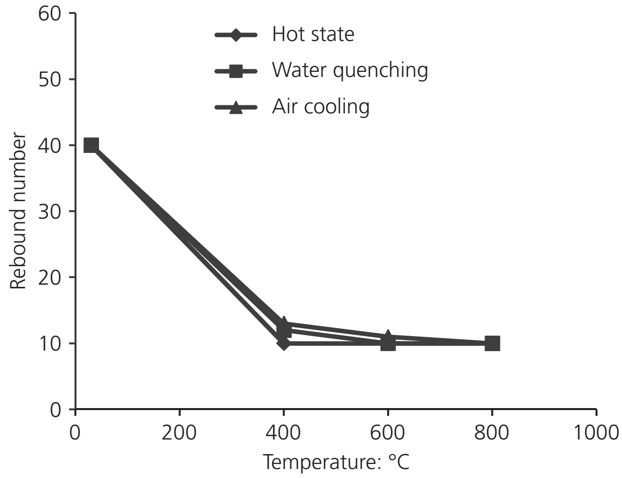

Figure 8. Rebound number plotted against temperature for M20 grade SCC

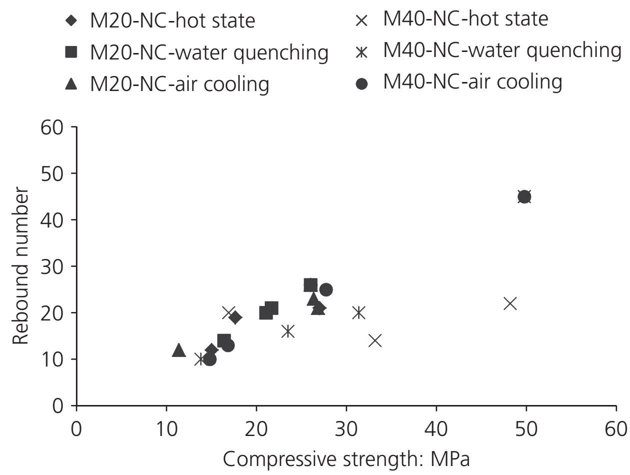

Figure 9. Rebound number plotted against compressive strength for NC

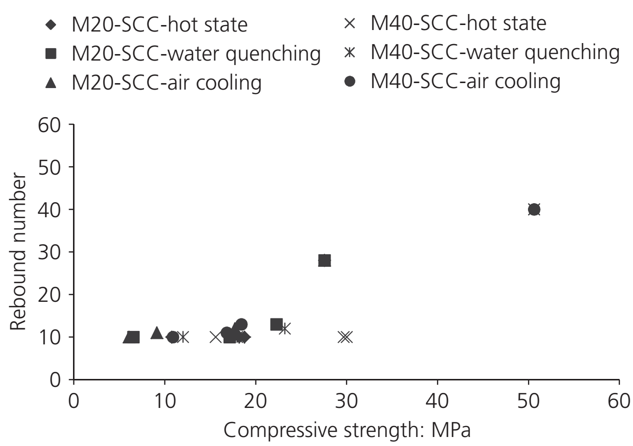

Figure 10. Rebound number plotted against compressive strength for SCC

low for concrete specimens tested at hot condition; however, there was an increase of rebound number of the concretes tested after subjecting the heated specimens to water quenching or air cooling. This means that water quenching and air cooling of heated concrete resulted in an increase of its surface hardness.

Conclusions

From the experimentation the following conclusions can be drawn.

- In general the compressive strength of concrete is decreased when the concrete is subjected to elevated temperatures.
- The decrease in compressive strength with elevated temperature is higher in SCCs compared to NCs, irrespective of cooling regimes.
- In the case of NCs, the average strength decrease is observed to be 16·6%, 25·5% and 45% at 400°C, 600°C and 800°C, respectively, whereas in the case of SCC, the compressive strength decrease is observed to be 29·1%, 45·6% and 71·4% at 400°C, 600°C and 800°C, respectively.
- In general the percentage decrease in strength with elevated temperatures increases with increase in grade of concrete – that is, higher strength concretes have higher percentage loss in strength than lower strength concretes. However, the difference becomes less significant at temperatures greater than 400°C.
- Of the three states of ‘testing of specimens’ – testing after air cooling, testing after water quenching and testing in hot state – a higher percentage decrease in strength is observed in the case of ‘testing after air cooling’ in both NC and SCC.
- Testing after water quenching results in a higher loss in strength compared to the strength obtained in testing at hot condition.
- Rebound number represents the hardness of the surface and indirectly represents the likely spalling or loosening of surface of concrete.
- In general more loss in hardness (or increased risk of spalling) is observed in the case of the SCC compared to NC at elevated temperatures.
- The hardness of surface was low for the specimen at hot state, followed by the other states – that is, water quenching and air cooling.

Acknowledgements

The authors acknowledge with due respect the suggestions received from Dr Venkatesh Kodur, Professor and Director, Center on Structural Fire Engineering and Diagnostics, Michigan State University, USA and the support of the National Institute of Technology, Warangal, India for permitting the experimental investigation.

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