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Experimental investigation of high temperature effect on Slag based alkali activated concrete and ordinary concrete

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ABSTRACT: Effect of elevated temperature on residual mechanical properties of slag based alkali activated concrete (SAC) was compared with Ordinary Portland cement concrete (OPC) when subjected to temperature up to 900 ° C. SAC was prepared using sodium hydroxide and sodium silicate activators. Residual compressive strength, tensile strength, flexural strength, modulus of elasticity and bond strength was studied at different temperature ranges to evaluate effect of high temperature on both concrete. It was observed that compressive strength for OPC decreased from 32 MPa to 19 MPa while in SAC variation was decrease was found to be from 32 MPa to 25 MPa. Similarly in SAC variation in residual split tensile, residual flexural strength, residual Modulus of Elasticity and residual bond test was much less compared to OPC concrete. Physical changes were much noticeable in case of OPC at high temperature compared to SAC. This indicates that SAC performed better at high temperature as compared to that OPC.

1 INTRODUTION

Today, the progress of any nation is measured by growth in its infrastructure sector and consumption of power for industrial use. The increasing urbanization is leading to a great and rapid expansion of the infrastructure sector which is experiencing an unprecedented growth. Thus, the use of cement as largest consumed building material is no surprise. It is a well-known fact that, manufacturing of cement utilizes a large quantity of natural resources in terms of raw material as well as fuel, this is leading to a tremendous pressure on these resources. Every ton of cement produces approximately 0.7 to 0.9 tons of carbon dioxide, leading to large scale environmental damage (Mehta, 2001; Scrivener & Kirkpatrick, 2008). Cement based concrete achieves good compressive strength only when adequate and proper curing technique is adopted, this is generally done by use of water which is a scarce commodity in developing countries. According to Copenhagen Accord of 2009, signed by more than 120 countries, it was agreed to control the rise in global average temperature to below 2°C (Meyer, 2009). These conditions have led to an urgent need to find solutions to problems which lead to global warming. One such desired solutions is to find an alternative to popular building materials such as cement concrete. The need is of course to establish alternatives which will have similar or higher compressive strength and longer service life and also help in achieving sustainable development (Aïtcin, 2000). One such alternate in field of concrete is alkali activated concrete, which avoids the use of cement altogether for its production.

Alkali activated concrete uses industrial wastes like fly ash, slag, bottom ash, metakaolin, red mud, etc. as source material. Activation is done via alkaline mediums which can be in form of sodium or potassium hydroxide, carbonates or silicates or a combination of these (Torgal *et al.* 2008). Countries like India stand to benefit a lot by use of industrial waste as source, as this will give a huge boast to economy and will help in conserving environment and also address the issues of disposing such wastes by converting them into a useful product. In the era of rapid development and industrialization there is a definite trend of population shift towards urban areas. As land resources cannot be increased in urban areas, vertical development in form of high rise buildings becomes inevitable. Also modern transportation techniques makes underground construction more attractive option. Fire in high rise buildings or underground structures during any stage from construction to service can be very fatal as it causes sudden rise in temperature leading to rapid change in molecular structure. Therefore, it is very important to consider effect of fire on mechanical properties of concrete ordinary concrete. Studies on concrete made from OPC, have shown that, under high temperature the degradation of mechanical properties occurs at various range of temperature and spalling occurs at high temperature range causing the exposure of reinforcement bars in concrete (Xiao & Konig, 2004).

Xiao and Konig (Xiao and Konig, 2004) summarized the investigation conducted on mechanical behavior of Portland cement concrete exposed to high temperatures in China. They observed that when temperature was increased up to 400°C, there was a drop in compressive strength. When temperature reaches 800°C, drastic decrease in the compressive strength was observed. Tensile strength had more degradation as compared to compressive strength at high temperature. It was also observed that cooling regimes had influence on mechanical behavior of concrete. Concrete which was air cooled had higher compressive strength compared to one which is cooled with water. Qianmin *et al.* (Qianmin *et al.* ,2015) reviewed the works carried out on concrete exposed to high temperature and observed that due to physical and chemical changes in concrete, disintegration of hydrated product is likely to take place leading to deterioration and spalling. Addition of mineral admixture like fly ash and slag increases resistance at elevated temperature. Omer (Omer, 2007) studied mechanical properties of concrete prepared from ordinary cement and crushed limestone with gravel and found that sharp reduction in strength beyond 800°C. Ergun *et al.*(Ergun *et al.*,2016) carried out bond test on ordinary concrete subjected to temperature and found that residual bond strength decreased with increase in temperature.

Bakharev (Bakharev, 2006) studied thermal stability of Class F fly ash paste and found that it had low stability when activated with sodium based activators due to occurrence of change in microstructure, while when fly ash was activated with potassium based activators it had good thermal stability up to 1000°C. Kong & Sanjayan (Kong & Sanjayan, 2008) tested geopolymer paste activated with potassium hydroxide and sodium silicate solution with class F fly ash. It was observed that there was decrease in strength due to inclusion of aggregates, as there was differential thermal expansion between aggregates and geopolymer paste. Kong & Sanjayan (Kong & Sanjayan, 2010) studied effects of elevated temperature up to 800°C on geopolymer paste, mortar and concrete prepared from fly ash. It was observed that concrete with 10mm size aggregate had better strength at ambient and high temperature. Size of specimen played an important role for evaluation of thermal stability for geopolymer paste. Kong *et al.* (Kong *et al.*, 2007) observed that strength of fly ash paste increased as compared to metakaolin based geopolymer paste at elevated temperature of 800°C, indicating difference in pore structure between two materials. Cheng & Chiu (Cheng & Chiu, 2003) used combination of metakaolin and ground granulated slag in geopolymer concrete and exposed it to elevated temperature. It was observed that a 10mm thick panel when exposed to 1100 °C flame reached a temperature less than 350°C when measured on reversed side, showing that it has great potential to be used for industrial application. Guerrieri *et al.* (Guerrieri *et al.*, 2009) compared residual compressive strength of alkali activated slag concrete with sodium based activators and lime at elevated temperature up to 1200°C. It was observed that strength loss in alkali activated slag concrete was due to higher thermal shrinkage in binder.

Lot of studies have been carried out on determination of durability properties of alkali activated concrete. It is found that alkali activated concrete has excellent resistance to acid attack (Bakharev, 2005), sulfate attack (Bakharev *et al.*, 2002), lower sorptivity (Adam *et al.*, 2010) compared to Portland cement concrete. Limited studies are available for effect of high temperature on mechanical properties of SAC cured under ambient curing condition. In ambient curing, no external heat is applied and hence it is more readily applicable in field.

2 EXPERIMENTAL PROGRAM

2.1 *Materials*

Ground Granulated Blast Furnace Slag (GGBFS) used as source material, was obtained from JSW cement works and it contained 37% silica, 34% calcium oxide and confirmed to IS :12089 -1987. Table 1 shows properties of GGBFS.

Table 1. Properties of Ground Granulated Blast Furnace Slag

Sr. No.	Characteristic	Results	Requirement as per IS 12089-1987
1.	Colour	White	-
2.	Specific surface area (m^2 / kg)	379	275 min.
3.	Loss of ignition(%)	0.6	-
4.	SiO_2	36.8	
5.	Al_2O_3	17.12	-
6.	CaO	34.4	-
7.	Fe_2O_3	0.92	-
8.	Glass Content	92.5	85 min
9.	Specific Gravity	2.91	-

Pozzolanic activity index was found to be 90.9%. Wet sieve analysis conducted on GGBFS found 89% particles below 45 micron sieve and 11% above 45 micron sieve. Alkaline solution consisted of mixture of sodium hydroxide and sodium silicate. Sodium hydroxide was obtained in form of flakes with 98% purity and was dissolved in tap water depending on the concentration of solution, expressed in terms of Molarity (M) (Hardjito *et al.*, 2004). Sodium silicate was in liquid form with 15.5 % of Na_2O, 35.4% of SiO_2 and 49.1% of water. Sodium silicate had ratio of SiO_2/Na_2O as 2.23 and specific gravity of 1.58. Naphthalene based superplasticizer was used for increasing the workability of alkali activated concrete. In experimental studies Ordinary Portland cement of Grade 53 conforming to IS: 12269 - 1987 standard was used to produce OPC. Locally available coarse aggregate of 10mm and 20mm size was used to prepare both concrete. Fineness Modulus of 20mm aggregate was 7.3 while for 10mm aggregate it was 6.03. Specific gravity was 2.7 and it confirmed to IS: 2386- 1963. Locally available river sand conforming to IS: 383 – 1970 was used as fine aggregate in both concrete. Specific gravity of fine aggregate was 2.6, conforming to Zone II with fineness modulus of 3.5.

2.2 *Mix proportioning of SAC and OPC concrete*

Alkali activated concrete was prepared from ground granulated blast furnace slag as source material. As there is no code available for mix design of slag based alkali activated concrete, mix design was carried out by assuming its density as 2400 kg/m^3. Variation was done in parameters affecting the mix design and guidelines of Hardjito et al. (Hardjito et al., 2004) were followed to obtain the characteristic compressive strength of 25 MPa for comparison with the control concrete. In this investigation ambient curing was adopted as in practical application it is difficult to apply high temperature. One day rest period was given to all specimen after casting and then demoulding was carried out. Mix design of OPC was carried out according to IS: 10262-2009 for M 25 grade of concrete. Mix design for OPC and SAC is given in Table 2.

Table 2. Mix Proportions for OPC and SAC concrete

Type of concrete	SAC	OPC
Source Material	GGBFS	Cement
Quantity kg/m^3	428.6	365
Coarse aggregate kg/m^3	1170	1218
Fine aggregate kg/m^3	630	689
Water kg/m^3	42.9	164
Sodium Hydroxide kg/m^3	68.6	-
Sodium Silicate kg/m^3	102.9	-
Super plastizer kg/m^3	4.3	2.5

2.3 *Specimen Preparation*

Cubes of 150 × 150 × 150 mm were prepared to measure residual compressive strength. Residual flexural strength was measured on beams of 100 × 100 × 500 mm, residual split tensile strength and modulus of elasticity was evaluated on cylinders of 150 mm diameter and 300 mm length. Bond strength was evaluated using 150 × 150 × 150 mm cube with 12 mm diameter bar embedded according to IS: 2770 -1997 as shown in Figure 1. In this test, load was recorded at a relative slip of 0.002 mm at free end of the specimen using Universal Testing Machine. Bond strength was calculated by value obtained from failure load divided by the surface area of the embedded length of the bar.

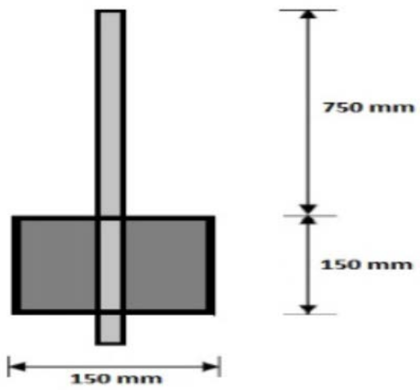

Figure 1. Bond test specimen

2.4 *Heating and test procedure*

Automatic gas fired furnace having temperature range up to 1000 °C was used to apply heat in which K-type of thermocouples were inserted from the top to measure the temperature of furnace. Terra-wool coating was provided throughout the furnace to have heat insulation. In the furnace auto cut off system was installed. In this system as shown in Figure 2, after setting a target temperature by controller on panel board, burners were sparked and flame was ignited and there was increase in furnace temperature. When target temperature was reached in the furnace, burners had automatic cut off and temperature inside the furnace had gradual reduction and again at one point burners automatically ignited and thus the heating was continued. Temperature in the furnace was set by establishment of time temperature relationship. Comparative graph of IS: 3809 - 1979 standard curve and experimental curve is represented in Figure 3.

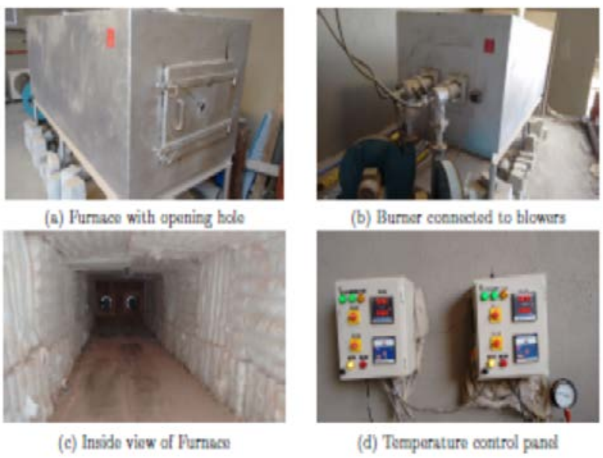

Figure 2. Furnace used for application of high temperature

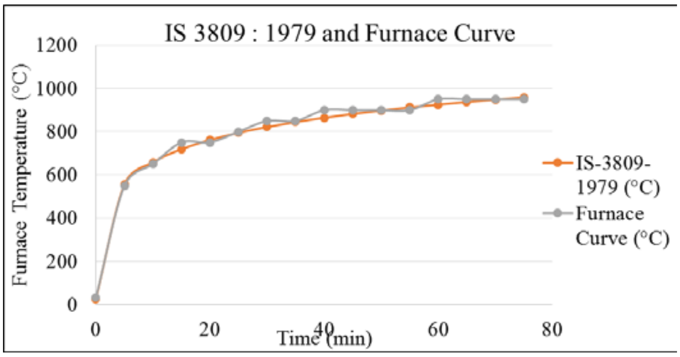

Figure 3. Comparison of IS: 3809:1979 recommended curve & Experimental curve

Duration of fire exposure at target temperature was 1 hour. Rise in temperature of specimen along heating regime of furnace for different elevated temperature was measured with use of infrared laser beam gun.

3 RESULTS AND DISCUSSIONS

3.1 *Physical changes after high temperature exposure*

OPC did not experience any visual color change up to 500°C, but at 900 °C cubes were observed to be whitish in color which may be due to higher reduction of moisture in OPC specimens. No visible color change was seen on SAC.

In both OPC and SAC concrete, hairline cracks were visible when they were exposed to temperature higher than 700°C. The cracks were spread throughout the specimen. At temperature of 500°C width of crack was less than 0.1 while it increased to 0.2 mm when temperature is was raised to 900°C. In SAC crack width (Figure 4 a), was found to be from 0.1 mm to 0.2 mm while higher crack width was observed in OPC. In OPC specimen, due to high temperature difference between surface and inside of specimen rapid reduction of moisture took place. Due to this there is rapid rise in pore pressure in concrete, which created tensile stress. When pore pressure exceeded, the tensile stress it caused

Figure 4. a) Cracks in SAC 4 b) Spalling in OPC

spalling (Sarkar *et. al.*, 2014). Spalling was more prominent in OPC specimens and it increased with increase in temperature. As observed in Figure 4(b) OPC experienced severe spalling between 700°C and 900°C while in SAC no spalling was observed.

3.2 *Residual Compressive strength*

OPC cubes were water cured and SAC were cured at ambient temperature for 28 days. Set of three specimens were exposed to temperature of 500°C, 700°C and 900°C each for 1 hour and tested in compression as per IS:516 -1959. Values of residual compressive strength after exposure of OPC specimens were 26.7 MPa, 21.17 MPa and 19.3 MPa, while SAC were 30.6 MPa, 29.0 MPa and 27.2 MPa at 500°C, 700°C and 900°C temperature respectively. As observed from Figure 5, there was reduction in residual compressive strength due to high temperature exposure for both type of concrete. OPC and SAC graphs have value of R^2 greater than 0.9 indicating linear regression analysis can be used for measuring residual compressive strength. It was observed that loss of compressive strength for OPC was very high and decrease was more as temperature increased which may be due to loss of water from internal pores of concrete. In SAC, reduction in compressive strength was observed, which could be due to stress development in dense microstructure at elevated temperature. This equation can be used to find residual compressive strength in OPC and SAC at any temperature between 27°C to 900°C in both type of concrete.

Figure 6, shows that in OPC, the reduction in strength was 17.5%, 34.6% and 40.4% with increase in temperature from room temperature to 500°C, 700°C and 900°C. In case of SAC, the reduction in strength was found to be 12.2%, 16.7% and 21.9% from room temperature to 500°C, 700°C and 900°C. The loss of strength in case of OPC was 40% at 900°C while 22% in SAC at same temperature. This shows very less loss of compressive strength in SAC with increase in temperature compared to OPC. Thus, in can be observed that SAC exhibits better behaviour over OPC with increase in temperature.

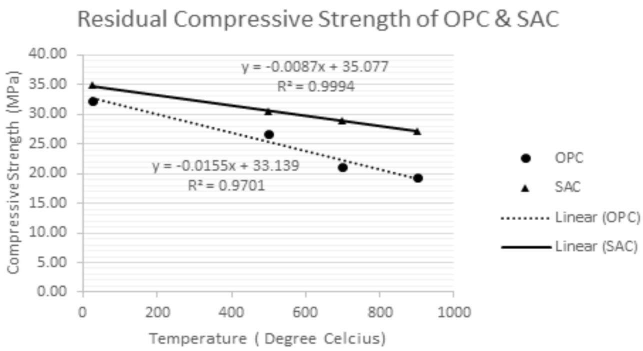

Figure 5. Change in compressive strength at different temp ranges.

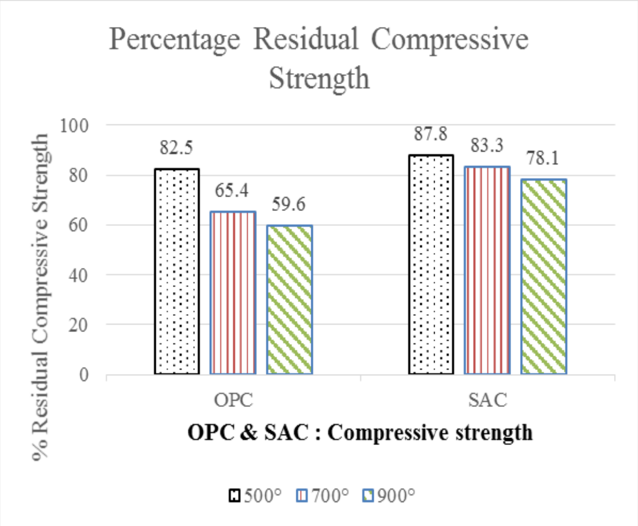

Figure 6. Percentage residual Compressive strength

3.3 *Residual Flexural strength*

Three beams of 100 mm × 100 mm × 500 mm were tested in flexural testing machine as per IS: 516 -1959 after applying temperature of 500°C, 700°C and 900°C for 1 hour and subsequent cooling of specimen at room temperature. All specimens were cured for 28 days before application of high temperature. Residual flexural strength observed in OPC specimen were 3.74 MPa, 3.3 MPa and 2.68 MPa, while in SAC, 3.66 MPa, 3.27 MPa and 2.96 MPa was observed at 500°C , 700°C and 900°C temperature respectively. As observed from Figure 7, up to 700°C, average flexural strength for OPC and SAC was nearly same but at 900 °C, the decrease was more in case of OPC compared to SAC. Strength reduction occurs due to cracks formation at higher temperature as concrete is weak in tension, therefore when load is applied on the specimen, widening of flexural cracks takes place. Regression analysis for both OPC and SAC have R^2 value greater than 0.9 indicating linear analysis can be applied.

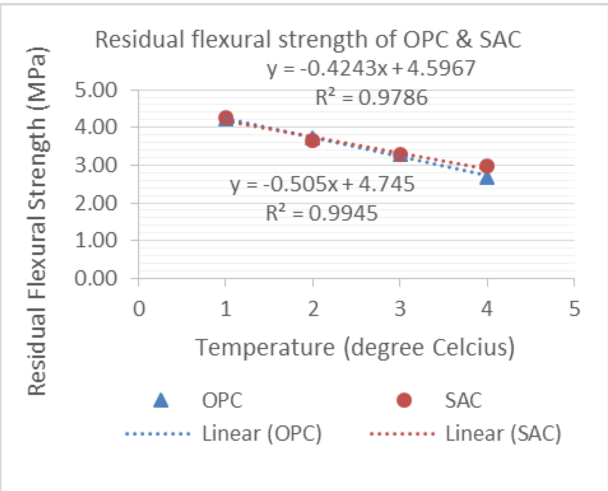

Figure 7. Reduction in Flexural Strength for OPC and SAC

Figure 8, show that highest loss in OPC was 36.4% reduction when exposed to 900°C, while in SAC this reduction was 30.2% at same temperature.

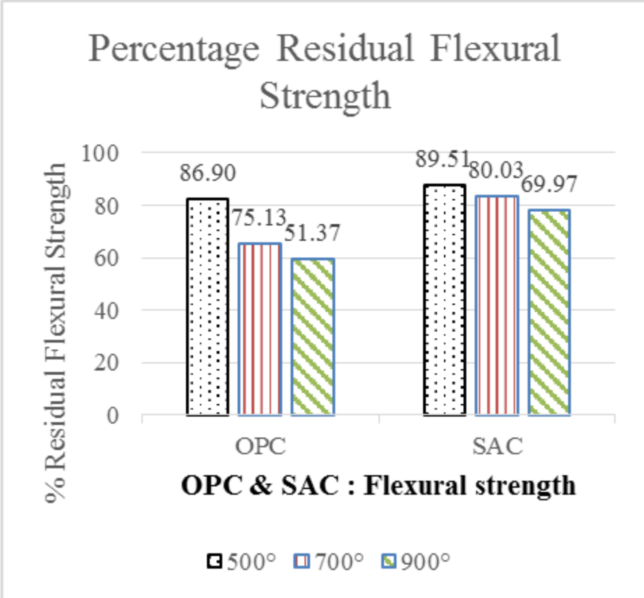

Figure 8. Percentage Residual Flexural Strength of OPC and SAC.

3.4 *Split Tensile Strength*

Average of three cylinder specimens was taken after 28 days of curing and after one hour of heating at temperature of 500°C, 700°C and 900°C respectively and tested as per IS: 516 -1959. Residual split tensile strength was observed to be 2.85 MPa, 2.47 MPa and 1.6 MPa for OPC specimen and 3.56 MPa, 3.18 MPa and 2.78 MPa for SAC specimen at 500°C, 700°C and 900°C temperature respectively. As observed in Figure 9, reduction in split tensile strength occurred due to formation of micro cracks at higher temperature. As concrete is weak in tension when load was applied on the specimen micro cracks were widened and stress capacity of specimen was reduced. As R^2 value for both concrete is greater than 0.9, linear regression analysis can be done and interpolation can be achieved. Figure 10, shows residual spilt tensile strength where in OPC, strength reduction for split tensile test was 13%, 25% and 48.6% at 500°C, 700°C and 900°C while in case of SAC it was observed to be 10.5%, 20% and 30% for same temperature range. Results clearly indicate superiority of SAC over OPC in split tensile test.

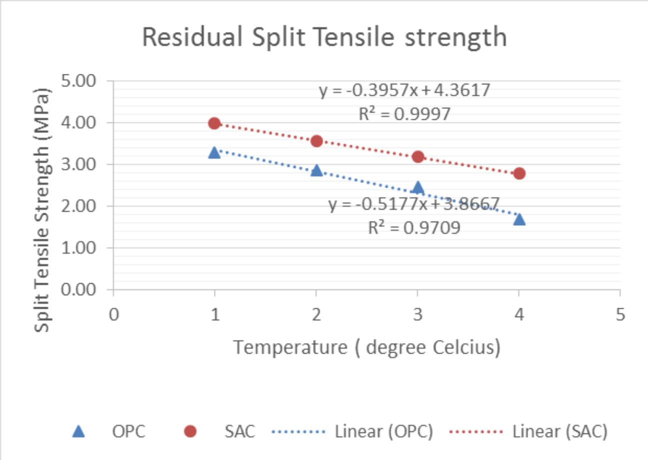

Figure 9: Reduction in split tensile strength.

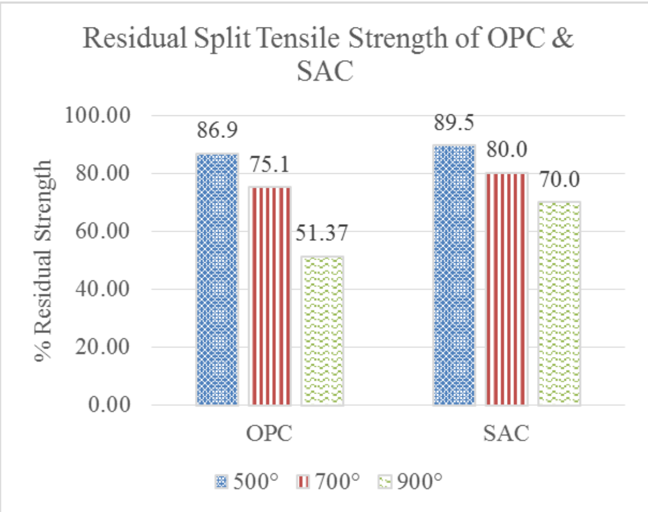

Figure 10. Percentage Residual Split Tensile Strength

3.5 *Modulus of Elasticity*

The Modulus of Elasticity for both mixes was measured for three specimens each, after exposure to elevated temperature for 1 hr after 28 days of curing. Evaluation was done by plotting stress v/s strain graph and initial tangent method was used to evaluate Modulus of Elasticity before and after heating at various temperature. Table 3 shows value of Modulus of Elasticity for OPC and SAC. Figure 11 shows comparison of residual Modulus of Elasticity of OPC and SAC. It can be observed that OPC experienced rapid decrease in Elasticity value with increase in temperature. OPC decreased up to 42.3% at 900°C while SAC 29.8% decrease was observed at 900°C. Due to expansion of concrete at higher temperature hair line cracks are formed in concrete. Due to these cracks, stress carrying capacity of concrete is reduced, which leads to reduction in Modulus of Elasticity. In case of SAC, cracks formed are less and thus, it was observed that SAC has lesser decrease in Modulus of Elasticity compared to OPC.

Table 3. Modulus of Elasticity for OPC and SAC

Temperature	OPC MoE (N/mm^2)	OPC Average MoE (N/mm^2)	SAC MoE (N/mm^2)	SAC Average MoE (N/mm^2)
Unheated	22364 24230 23076	23223	25736 24984 25093	25271
500°	20865 18314 17512	18897	21757 20994 21274	21342
700°	18678 15345 16120	16714	20417 19319 18325	19354
900°	13540 14785 12578	13634	18592 17315 18106	18004

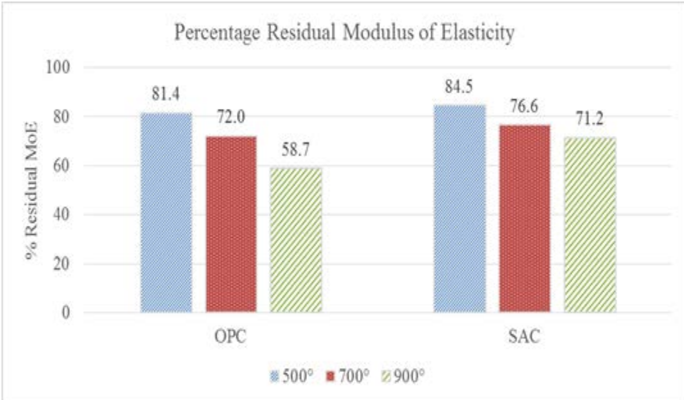

Figure 11: Residual Modulus of Elasticity for OPC and SAC

3.6 *Bond Strength*

Bond strength of both OPC and SAC was measured after 28 days of curing and 1 hour of heating. Heating was done for 500°C, 700°C and 900°C for one hour and subsequent cooling. Load v/s slip graph was plotted as shown in Figure 12 for SAC. It was observed that except for ultimate load graph of OPC and SAC were of similar nature.

$$\text{Bond strength (MPa)} = \text{Load (P)} / (\pi L D) \quad (1)$$

Where P is utlimate load in kN, L is bond length in mm and D is diameter of bar in mm.

Observation from Table 4 suggests that bond strength of OPC decreases rapidly with increase in temperature. Reduction in bond strength signifies creation of expansion cracks in concrete and due to difference in co-efficient of expansion between steel and concrete. It was observed from the graph of Figure 13, residual bond strength that OPC showed 33.88% reduction in bond strength, while in SAC showed 28.6% reduction in bond strength. This indicates superiority of alkali concrete in terms of bond strength over ordinary concrete.

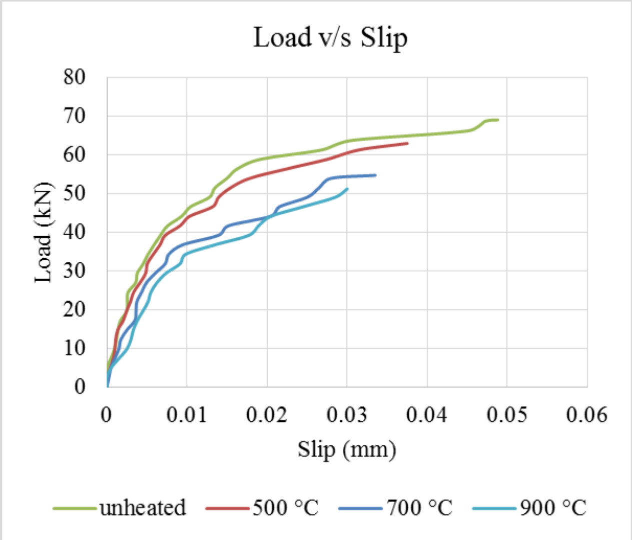

Figure 12: Load v/s Slip graph for SAC

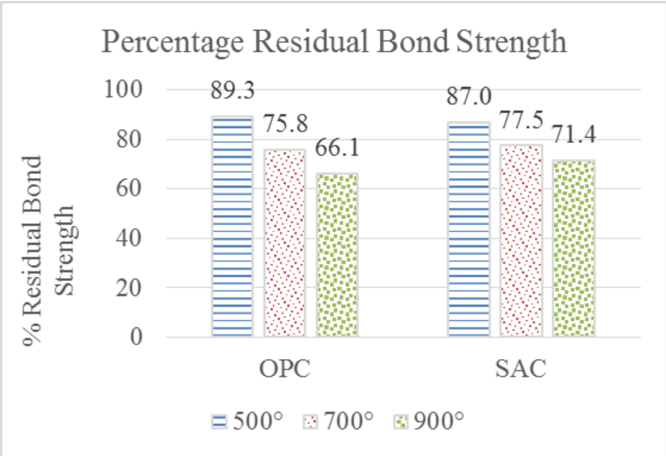

Figure 13: Residual bond strength in SAC and OPC

Table 4. Bond Strength of OPC and SAC

	OPC		SAC	
Temperature	Bond Strength (N/mm2)	Average	Bond Strength (N/mm2)	Average
	11.50		13.17	
27°	11.75	11.83	12.87	12.63
	12.23		11.84	
	11.10		11.48	
500°	10.82	10.57	10.69	10.98
	9.78		10.78	
	9.25		10.33	
700°	8.10	8.97	9.42	9.78
	9.55		9.60	
	8.12		9.27	
900°	8.32	7.82	9.08	9.01
	7.02		8.68	

4 CONCLUDING REMARKS

Investigation of OPC and SAC at various temperatures leads us to following conclusions:

•In OPC concrete, compressive strength decreased by 17%, 35% and 40% ,while in SAC 12%, 17%, 22% decrease in compressive strength was observed at temperature of 500°C , 700°C and 900°C compared to 27°C . Also, maximum decrease in compressive strength was observed at 900°C was approximately twice than that of SAC.

• In OPC concrete higher degradation occurred with increase in temperature, which is reflected in higher loss of strength at high temperature. In case of SAC, loss of strength was linear. This shows that SAC has better compressive strength compared to OPC at high temperature.

•In case of flexural strength, reduction of almost 36% occurred in OPC while in SAC reduction was 30% at 900°C. Thus, though decrease in flexural strength occurs in both concrete, it was observed to be more in OPC compared to SAC.

•In Split tensile test, decrease in OPC strength at 900°C compared to room temperature was reduced almost to half, while it was 30% in SAC for same temperature. This shows better resistance to thermal stress by SAC compared to OPC.

•Reduction in Modulus of Elasticity was observed at 900°C temperature in OPC was almost 40% compared to room temperature while in SAC concrete it was 29%, indicating more stress carrying capacity by SAC at high temperature.

•Bond strength of OPC was reduced by 34 % while SAC experienced reduction of 29 % at 900°C, indicating a strong bond between concrete and steel at high temperature in SAC compared to OPC.

Evaluation of mechanical properties of both OPC and SAC shows that slag based alkali activated concrete has much better resistance to temperature at all high temperature range. This study paves a way for slag based alkali activated concrete to be applied and exploited for use in structures exposed to high temperature where normal concrete often fails. Since slag constitutes as source material, problems related to industrial waste disposal can also be addressed. Further, due to use of ambient curing technique, pitfall of requirement of temperature curing for obtaining strength in alkali activated concrete can be negated. Thus, slag based concrete can be ideal for use as sustainable concrete when subjected to high temperature and has high potential in ceramic based application.

5 ACKNOWLEDGMENTS

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