High Temperature Performance of Self-Compacting High-Volume Fly Ash Concrete Mixes

Amrutha*, Gopinatha Nayak*, Mattur C. Narasimhan* and S. V. Rajeeva**
*National Institute of Technology Karnataka, Surathkal, Mangalore
**Mahendra Engineering College, Mahendhirapuri, Tamilnadu.
palligopi@rediffmail.com

ABSTRACT

Quite often, concrete in structures is likely to get exposed to high temperatures, including an incident of fire. The strength-retention properties of concrete after such an exposure are of great importance in terms of the serviceability of buildings. This paper presents an experimental study on the strength retention and impermeability aspects of a set of self compacting, high-volume fly ash concrete mixes under elevated temperatures. Five self-compacting concrete mixes with a higher 60% level of cement replacement with fly-ash, are designed and the effects of elevated temperatures, in the range of 200–800°C, on the physical, mechanical and durability properties of these mixes are assessed. The assessment is in terms of the weight losses and the reduction in the compressive strengths of concrete cubes and split tensile strengths of concrete cylinders. The durability characteristics are assessed in terms of RCPT test results on these mixes. Performances of these self compacting concrete mixes (SCC) at elevated temperatures are also compared with two normally-vibrated concrete mixes (NCs) of an equivalent M30 strength grade. Test results indicate that weight of the specimens significantly get reduced with an increase in the level of elevated temperature, with sharp variations beyond 600°C. The experimental results also show that large improvements against chloride-ion penetration and better strength-retention at higher temperatures can be realized with self-compacting high-volume fly-ash concrete mixes additionally admixed with GGBFS and silica fume.

Keywords: Self compacting concrete; large-volume fly ash replacement; chloride permeability, Strength retention, Elevated temperature performance.

1. INTRODUCTION

One major challenge facing the civil engineering community is to execute projects in harmony with nature using the concept of sustainable development. This calls for use of high performance, environment-friendly and economical construction materials. In the context of concrete, which is the most predominant building material, it is necessary to identify less expensive cement-substitutes. In recent years, many researchers have established that the use of supplementary cementitious materials (SCMs) like fly ash, blast furnace slag, silica fume, metakaolin, rice husk ash etc. can not only improve the various properties of concrete, both in its fresh and hardened states of concrete, but also can contribute to reduce the construction costs [1]. However the strength and durability characteristics of concrete mixes with such SCMs have to be ascertained before using them in large infrastructural projects.

Concrete is possibly exposed to elevated temperatures during a fire or when it is performing in walls of furnaces and reactors. The mechanical properties such as strength, modulus of elasticity and volume stability of usual concrete mixes are significantly reduced during sustained exposure to elevated temperatures. This may result in undesirable aesthetic and functional deteriorations to the buildings, often leading to structural failures. Aesthetic damage is generally easy to repair while functional impairments are more profound and may require partial or total repair or replacement, depending on their severity [2, 3]. Therefore, assessment of the mechanical properties and durability characteristics retained in concrete after a fire-exposure is of importance for determining the residual load carrying capacity and for planning for the reinstating of the fire-damaged constructions [4–6].

When exposed to higher temperatures, the chemical composition and physical structure of the hydrated concrete change considerably. The release of chemically bound water from the calcium silicate hydrate (CSH), which is the strength giving compound in a cement paste, becomes significant at about 110°C. The dehydration of the hydrated calcium silicate and the thermal expansion of the aggregate increase the internal stresses and from 300°C, micro-cracks are induced through the material [7, 8]. Calcium hydroxide, ($Ca(OH)_2$), which is one of the important compounds in a hardened cement paste, dissociates at around 530°C resulting in the shrinkage of concrete [9]. The fire is generally extinguished by water and CaO turns into [$Ca(OH)_2$] causing cracking and crumbling of concrete. Therefore, the effects of high temperatures are generally visible in the form of surface cracking and spalling [10]. Some changes in colour may also occur during the exposure [11]. The modifications produced by high temperatures are more evident when the temperature exceeds 500°C. Most changes experienced by concrete beyond this temperature level are considered irreversible [12]. CSH-gel, decomposes further at about 600°C. At about 800°C, concrete is usually crumbled. Above 1150°C, feldspar melts and other minerals of the cement paste turn into a glass phase. As a result, severe micro-structural changes are induced and concrete loses its strength and durability. Large amounts of shrinkage may also start due to the decomposition of $CaCO_3$ into CO_2 and CaO with associated volume changes causing destructions.

Permeability of concrete is believed to be the most important characteristic of concrete that affects its durability [13]. It is apparent that for many concrete members, the ability of the concrete to resist chloride penetration is an essential factor in determining its successful performance over an extended period. The principal result of the intrusion of chloride ions into concrete is the corrosion of the reinforcing steel. Once this occurs, the structure will no longer maintain its structural integrity; the lifespan is reduced, and the general safety of the public amenity is severely degraded.

At micro-level, the chloride permeability of a concrete mix is related to the pore structure of the cement-paste matrix. As pore volume increases, the apparent chloride diffusion coefficients increase [14]. The resistance of concrete to chloride penetration is significantly increased with the incorporation of finer fly ash particles [15]. This increase results from the reduced water-to-binder ratio, the reduced average pore-size of the paste and the improved interfacial zone. The incorporation of fly ash may also enhance the workability of the mixes due to the spherical and smooth surface of the fine fly ash particles. Hence the use of higher volumes of fly ash in concrete is advantageous in reducing the permeability of concrete due to their filler as well as pozzolanic effects [16].

In this experimental investigation, the effect of elevated temperatures on the physical, mechanical and durability characteristics properties of a few self compacting concrete mixtures which have high volumes of fly ash admixed to them, is assessed. Further, effect of blending other mineral admixtures like GGBFS and silica fume in such concrete mixes are also examined.

2. EXPERIMENTAL INVESTIGATIONS

2.1. Materials

Ordinary Portland cement (OPC) similar to ASTM Type I[17] conforming to the requirements of 43 grade OPC as per **IS:8112** was used. Fly ash meeting the requirements of ASTM C 618 (Class F) was used. The characteristics of cement, fly ash and other pozzolanic materials used herein and are presented in Table 1. Two fractions of crushed granite metal, with mean aggregate of size of 12.5 and 20 mm, and good quality well graded river sand were used as coarse and fine aggregates, respectively. The coarse and fine aggregates had specific gravities of 2.68 and 2.61, respectively. A commercially available poly-carboxylic-based high-range water reducing admixture has been used as a hyper-plasticizer in the present investigation.

2.2. Mix Design

In this investigation, initially a M_{30} grade conventional normally-vibrated concrete mixes was designed and developed using Indian code of practice. As a follow up, increasing the fines- content in the form of quarry dust (QD), an SCC of same grade was developed, using trials. These base designs were later

Table 1. Chemical Composition of Cementitious Materials

	Cement	FA	SF	MK	GGBFS	RHA
Specific gravity	3.05	2.06	2.20	2.60	2.81	2.43
Lime_Reactivity, N/mm^2	–	4.73	4.10	4.82	5.16	4.48
Oxides	**Percentage contents**					
CaO	60.84	1.79	0.68	0.08	23.28	0.51
SiO_2	16.34	58.87	94.89	52.20	43.63	95.96
Al_2O_3	6.95	32.17	2.20	44.50	14.82	0.27
Fe_2O_3	5.38	2.93	0.18	1.11	5.14	0.57
K_2O	2.73	1.14	0.92	–	1.92	1.06
Na_2O	1.5	0.37	0.19	0.41	2.06	0.01
Na_2O_{eq}	–	1.12	0.80	0.41	–	–
MgO	2.32	0.92	0.46	–	3.40	0.21
Mn_2O_3	–	–	0.48	–	–	–
P_2O_5	1.67	0.56	–	0.65	1.60	0.62
SO_3	1.99	0.49	–	0.32	3.97	0.33
LOI	0.28	0.76	–	0.72	0.19	–

modified to develop five different self compacting fly ash concrete mixes, all with a constant, high-volume fly ash dosage (60%), and admixed with other superpozzolanas. The contents of the additional super-pozzolanas in the various mixes were again based on development of required rheological (flow) properties in the various mixes and cost-implications. **EFNARC** (European guidelines for self compacting concrete) guidelines were used to design the SCC mixes.

Thorough mixing and adequate curing are most essential for achieving a good self compacting concrete. In the laboratory the concrete was mixed in a special horizontal shaft ribbon mixer of 125 L capacity. The mixing time was kept to about 3–4 min for normal concretes. It was increased to about 5–6 min for self compacting concretes made with hyper-plasticizers for realizing the complete potential of the hyper-plasticizer. The Mix-designations for the various mixes evaluated herein are shown below. The details of the mix-proportions for the various mixes and their flow properties satisfying the EFNARC guide-lines are given in Table 2. Standard cube and cylindrical moulds are then cast using these mixes. The demoulding of specimens was generally done by 24 h of casting.

Table 2. Mix Proportions for various fly ash admixed SCC mixes - M30 Grade

Mix Designation		CC1	CC2	SCFA	SCSF	SCMK	SCGGBS	SCRHA
Cement	**(Kg/m^3)**	410	405	240	222	168	120	198
Fly Ash	**(Kg/m^3)**	–	–	360	360	360	360	360
Silica Fume (SF)	**(Kg/m^3)**	–	–	–	18	–	–	–
Metakaolin (MK)	**(Kg/m^3)**	–	–	–	–	72	–	–
GGBFS	**(Kg/m^3)**	–	–	–	–	–	120	–
Rice Husk Ash (RHA)	**(Kg/m^3)**	–	–	–	–	–	–	42
Water	**(Kg/m^3)**	175	172	168	168	168	168	168
Coarse Aggregate	**(Kg/m^3)**	1134	1130	720	720	720	720	720
Fine Aggregate	**(Kg/m^3)**	612	612	765	731	735	754	727
w/p		0.43	0.41	0.28	0.28	0.28	0.28	0.28
HP	**(Kg/m^3)**		3.0	3.0	3.0	3.0	3.0	3.0
Slump/Slump flow	**(mm)**	90	700	760	700	785	730	735
V funnel	**(seconds)**	–	–	9	11	9	10.5	10.5
Compressive Strength	**7 days**	33.65	33.88	34.2	21.5	27	34	18
(N/mm^2)	**28 days**	43.65	48	55.33	38	45	42	37.5

CC1	Control concrete of grade M_{30}	M_{30}
CC2	50% QD and 50% cement, Control SCC	
SCFA	60% fly ash, 40% cement.	
SCSF	60% fly ash, 3% SF and 37% cement.	
SCMK	60% fly ash, 12% MK and 28% cement.	
SCGGBS	60% fly ash, 20% GGBS and 20% cement.	
SCRHA	60% fly ash, 7% RHA and 33% cement.	

3. RESULTS

3.1. Physical Properties of Specimens

Experimental investigations were carried out on all seven concrete mixes indicated in Table 2. The specimens of 100 mm-size cubes and 100 mm ∅ × 200 mm long cylinders were cast. The specimens were conventionally cured in water tanks for 28 days. The initial weights of all the specimens were taken. The cubes were then exposed to designated elevated temperatures at the age of 28 days in a temperature-controlled electric oven. Specimens were heated to temperatures of 200°C, 400°C, 600°C and 800°C and were soaked at those temperatures for a retention period of 3 hours after which the oven is switched-off. The specimens were cooled to room temperature, within the oven. Typical time-temperature curves for heating and cooling in the oven are shown in figures 1 and 2 respectively (for

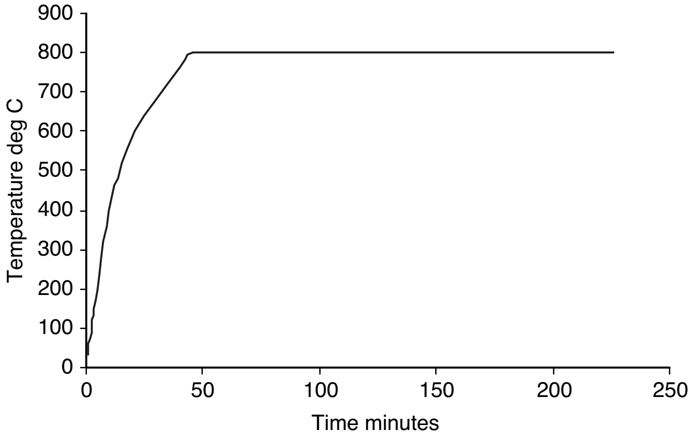

Figure 1. Rate of heating the specimens.

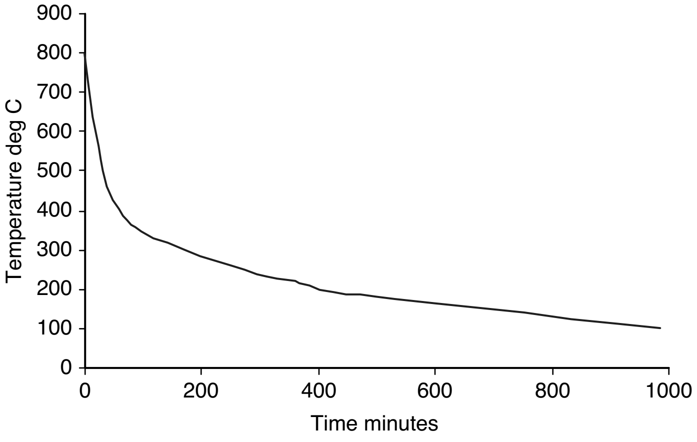

Figure 2. Rate of cooling the specimens.

Maximum Temperature = 800°C). Some physical observations were initially made like change in colour, surface cracking, amount of surface spalled, and presence of surface voids. The cube specimens were then subjected to compressive strength test and the cylinders to split tensile strength test.

3.2. Surface Colour and Cracking

The damage to the concrete after being subjected to high temperatures can be roughly detected by observing the concrete surface. Thus, assessment of fire-damaged concrete usually starts with visual observation of the colour changes, cracking and spalling of concrete surface. The change of concrete colour can be attributed to the change in texture, composition, and expansion and crystal destruction during a fire. The variation of the colour under rising temperature could be identified under three main categories. Below 200°C, the concrete colour did not change noticeably. When temperatures were increased to 400°C & 600°C, the colour of the concrete slightly changed to dust colour or greyish. At 800°C temperature, the specimens were observed to be pinkish red or fully dust (white) in colour. Explosive spalling occurred at temperatures of 600°C and above, in a few specimens of mixes admixed with metakaolin or rice husk ash as shown in Figure 3.

There were no visible effects observed on the surface of the specimens heated up to 400°C. The concrete specimens started to crack when the temperature was increased to 600°C but the effect was not significant at that temperature level. The cracking became quite pronounced at 600°C and became extensive by 800°C. The cube specimens of **SCMK** mix were completely decomposed at 800°C when, due to excessive cracking with spalling of the concrete. This was attributed to continuous crack formation. Formation of large cracks, parallel to the hot surfaces leads to degradation of the strength of the fire-exposed concrete and pressurization of concrete pores. At ultimate stages, the thermal spalling of the concrete may be characterized by explosive breaking of concrete into pieces, often without any advance notice.

3.3. Residual Weights and Compressive Strengths of the Specimens

Cubes of 100 × 100 × 100 mm were cast using the candidate concrete mixes and were cured in water for 28 days. Then, after an initial air-drying, the specimens were weighed and then subjected to elevated temperatures ranging from 200 to 800°C in an electrically controlled laboratory oven. The temperature in the oven was built-up to the designated temperature and the specimens were soaked at that temperature sustained for 3 hr. After heating, the specimens were allowed to cool to lab temperature. The specimens were then stored in dry condition at room temperature for 2 hr until testing. The loss in weight, compressive strength and the split tensile strength of the various specimens were tested for [18]. The average percentage residual weights, ie. the ratio of weight of the specimen after exposure to elevated temperature to the original weight at ambient temperature of specimens of all the mixes are presented in the Fig. 5. It is clear from the values that weight-loss increases with an increase in the temperature of exposure. While for most of the mixes, the reduction in weight gradually increased up to 800°C, there is a sharp jump in weight-loss beyond 400°C in the SCMK mix. It can also be observed

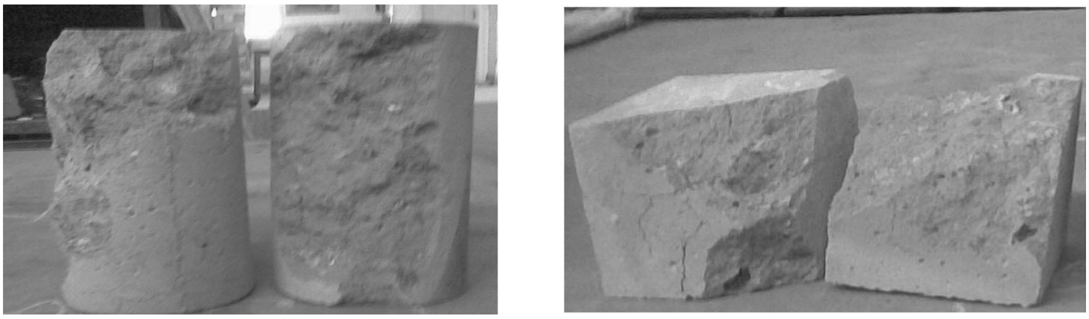

Figure 3. Cylinders and cubes of metakoalin-admixed SCC mixes exposed to 800°C.

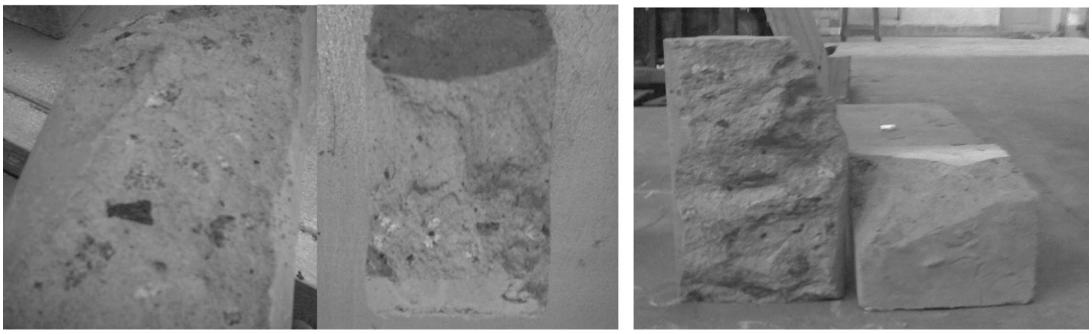

Figure 4. Cylinders and cubes of RHA-admixed SCC mixes at 600°C and 800°C.

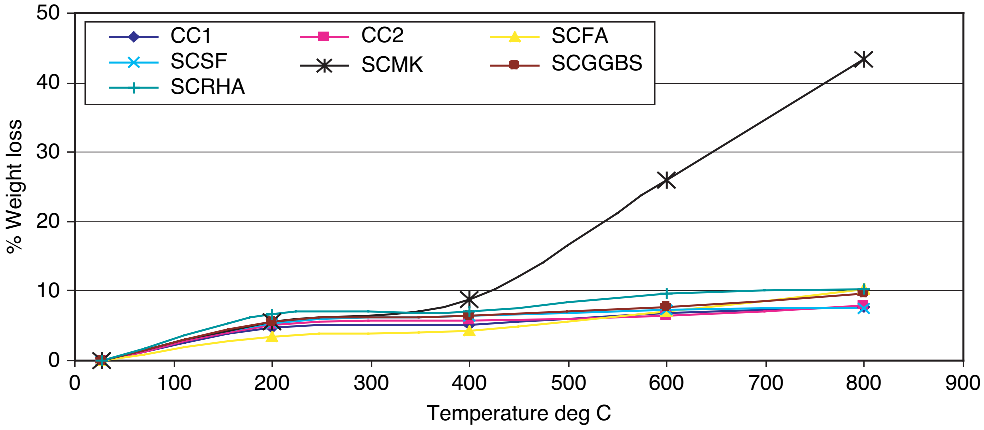

Figure 5. Percentage Weight loss of the SCC mixes subjected to elevated temperatures.

that, of the mixes tested herein, the SCMK and SCRHA mixes had more weight losses when compared with the other mixes. The weight loss in concrete during exposure to elevated temperatures can be related to the change in the mechanical properties of the concrete and the cement paste loses its binding property due to the evaporation of water in the **C–S–H** structure.

The compressive strength and splitting tensile strength results after exposed to high temperature are given in Fig. 6 to Fig. 8. The test results indicated that each temperature range had a distinct pattern of strength loss and compressive strength decreased with the increase of temperature. The reduction in compressive strength can be attributed to the driving out of free water and fraction of the water of hydration of concrete due to higher temperatures or fire. Dehydration of concrete causes a decrease in its strength, elastic modulus, coefficient of thermal expansion and thermal conductivity. Only **SCFA** concrete retained its strength upto 400°C due to the formation of tobermorite Figure 6.

For conventionally vibrated concrete mix (CC1), the weight loss is about 4.64% from room temperature to 200°C. The weight loss is attributed loss of free water at lower temperature and loss of chemically combined water from the Calcium Hydrate at higher temperatures. There is a negligible weight loss from 200°C to 400°C. Further rise in temperature from 400°C to 800°C has resulted in weight losses in the range of 4.6% to 7.7%. The decrease in compressive strength of CC1 was higher for increase in temperature from room temperature to 400°C. From 400°C to 600°C there was small decrease in compressive strength. The decrease in compressive strength was much higher above 600°C. This may be attributed to change in chemical composition & physical structure of the concrete. C-S-H gel usually decomposes around 600°C which is the strength giving compound of the cement paste. The conventional concrete with hyper-pasticizer recorded slightly more weight loss at higher temperature

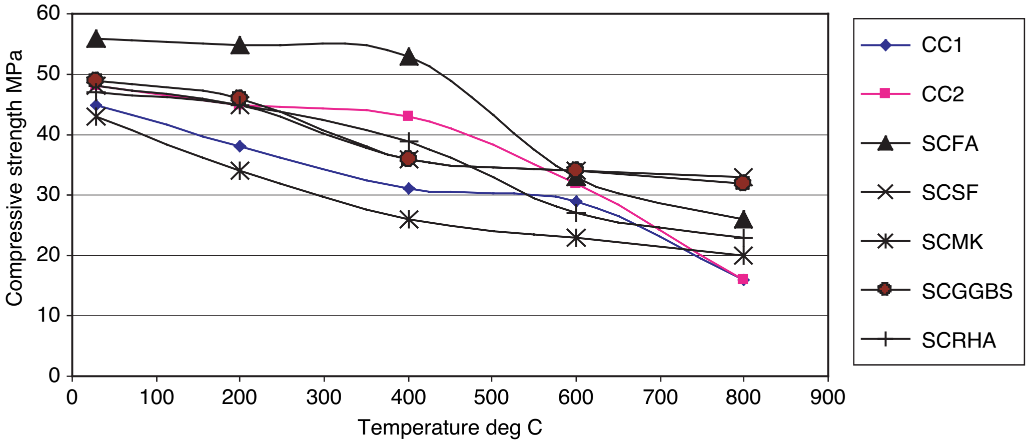

Figure 6. Compressive Strength of the concrete mixes after exposure to elevated temperatures.

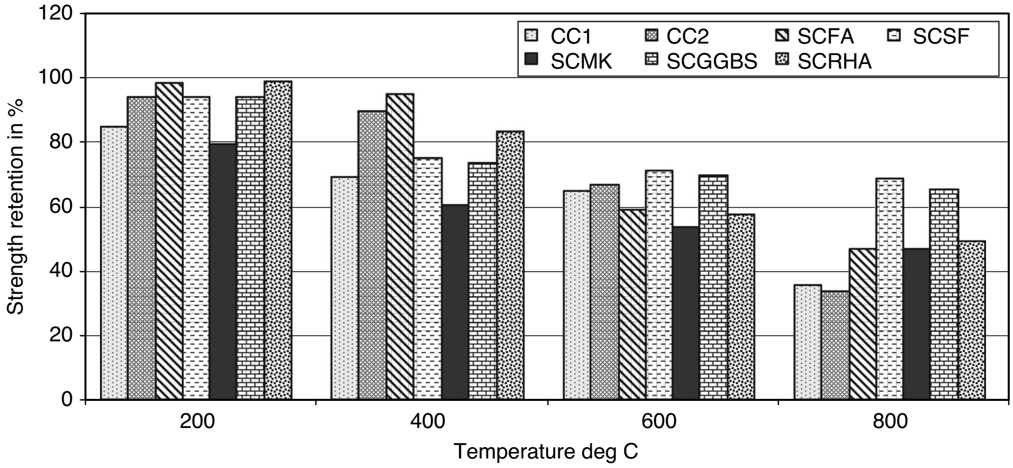

Figure 7. Strength retention of the concrete mixes after exposure to elevated temperatures.

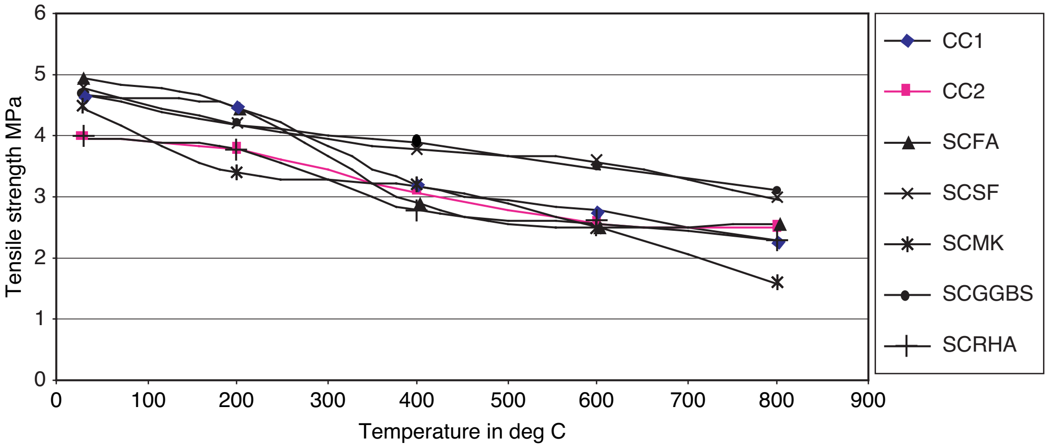

Figure 8. Tensile Strength of the concrete mixtures after exposure to elevated temperatures.

compared to CC1. Compressive strength of CC2 mix up to 400°C is higher but equal strength retention found at still higher temperature zones.

All the SCC mixes except SCMK show similar weight changes at higher temperatures from 5.5% to 10.4%. For SCMK concrete mix the weight loss is about 6.11% from room temperature to 200°C. There was a further percentage weight loss from 6.11% to 12.97% for the rise in temperature from 200°C to 400°C. With further increase in temperature above 600°C, there was huge loss in weight of about 26.5% which is critical for this mix. SCFA has retained same strength upto 400°C. Above 400°C, however, there is a rapid decrease in the compressive strength upto 600°C, which again started decreasing moderately up to 800°C (Figure 7). On blending with silica fume and GGBS in mixes SCSF and SCGGBS, strength retained is above 60% even at 800°C. It is clear from the graph that for small changes in the weights cause decrease in strength of the concrete. Use of Rice husk ash does not show much improvement in the strength giving a indication of poor performance at high temperature. It is clear that loss in strength increases with increase in the weight-losses. The reduction in strength is very sharp until about 10% loss in weight. Almost 70% of the strength is lost as the weight losses reach to just about 10%. When the losses in weight are more than 30%, almost 90% of the strength is lost. Cement paste plays an important role on the relative strength of concrete subjected to elevated temperatures.

3.4. Split Tensile Strength

The tensile strengths of all the heated cylinders (measured in cool state) have been plotted against the temperature for all the concrete mixes shown, for any given oven temperature there is a considerable variation in the strength for concrete mixes using admixtures. The specimens which were exposed to sustained temperatures (200°C–800°C), each for 3 hours, showed a clear decrease in the tensile strength of concrete after such an exposure. Even though strength of fly ash admixed SCC is higher at lower temperature, it suddenly decreases at higher temperature. In figure 8, it is observed that decrease can be controlled by adding GGBS or Silica fume to the SCFA mix. The SCGGBS and SCSF concrete mixes recorded smaller decreases in tensile strength, on heating from room temperature to 200°C while faster degradation in tensile strength on further heating upto 400°C. However, further increase in temperature above 400°C had marginal decrease in tensile strength upto 800°C, leaving these two mixes recording higher split tensile strengths at higher temperatures. Among all the mixes SCMK concrete mix recorded lowest tensile strength clearly indicating the poor performance of the metakaolin under elevated temperature. Above 600°C, there is a huge decrease in tensile strength which is critical for the SCMK mix. For SCRHA concrete mix there is a small decrease in tensile strength from room temperature to 200°C. Above 200°C, the tensile strength started decreasing at a faster rate upto 400°C. Further increase in temperature upto 800°C led to a linear decrease in the tensile strength.

3.5. Rapid Chloride Penetration Test

Accelerated chloride permeability tests were conducted on standard cylindrical specimens (100 mm dia, 50 mm thick) of all the candidate large volume fly-ash admixed self-compacting concrete mixes (figure 9), after their exposures to different levels of elevated temperatures. Tests are performed at after constant 28-days of curing, as per **ASTM C1202**. It can be seen that, at room temperature, all the self compacting fly ash concrete mixes assessed herein show a total charge passing at less than 1000 Coulombs and these can be categorized as having **very low** chloride permeability, at 28-days of curing, as per assessment criteria [**19**]. Correspondingly the two normally vibrated concrete mixes have RCPT values falling in the range of mixes with **low to moderate** chloride permeability. Amongst the SCC mixes SCGGBS mix has exhibited the best impermeability performance, at room temperature.

With the exposure of the specimens of the different mixes to elevated temperatures, at the same 28-days of age, the RCPT values are continuously growing for all the large volume fly-ash admixed SCC mixes tested herein, Fig. 10. The exposure to higher elevated temperatures upto 600°C, bringing complex changes, both in physical and chemical attributes, result in large increases in the porosity and permeability of the void-system of the micro-structures of all the concrete mixes. leading to increased RCPT values. While, among the SCC mixes tested here, the SCGGBS mix continues to record the

Figure 9. RCPT Test Apparatus.

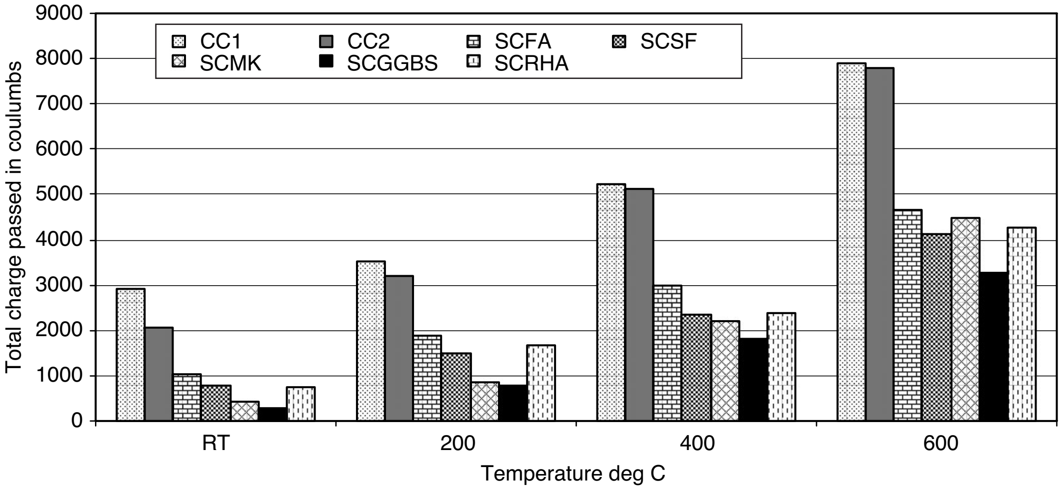

Figure 10. Chloride Ion Penetration in Various SCC Mixes at Elevated Temperatures (28 days of curing).

lowest RCPT values at successively higher temperature of exposure, larger increases in the RCPT values are observed with the SCMK mix. Larger increases in the permeability values are also the characteristic of the conventionally vibrated normal concrete mixes.

4. CONCLUSIONS

Blending of fly ash with GGBS and Silica fume in SCC mixes has prevented the decrease of concrete strength at higher temperatures. It shows that fly ash contributes to the interfacial properties mainly by the pozzolanic effect at higher powder contents. Color changes were observed on concrete surface because of the effect of high temperatures. Most of the surface cracks became visible when the temperature reached 600°C. Therefore, we can have some ideas about the change in the concrete strength. The weight of the concrete specimens reduced significantly as the temperature increased. A sharp reduction in weight was observed beyond 400°C in metakaolin blended concrete. The relative strength of concrete reduced with increase in exposure temperature. **SCSF** and **SCGGBS** mixes showed much lower reduction in compressive strengths compared to all the mixes. All the SCC mixes show RCPT values less than 1000 Coulombs at 28-days and at higher temperatures show lesser chloride penetration compared to ordinary concrete.

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