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Mechanical Properties and Microstructure Characteristics of Self-compacting Concrete with Different Admixtures Exposed to Elevated Temperatures

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ABSTRACT

Self-compacting concrete (SCC) is a high-performance concrete widely used as a building material. The present investigation examines the effects of age and cooling type (air-cooled and water-cooled) of SCC after being exposed to elevated temperatures and compares them to those of normal conventional concrete (NCC). Two types of concrete; i.e., NCC and SCC, were developed and studied for early-age and residual strengths. SCC was developed with three different types of admixtures; namely, fly ash (FA), silica fume (SF) and metakaolin (MK) as binder materials, by replacing the cement. The mechanical characteristics of FA- and SF-blended SCC before heating show similar results, whereas MK-based SCC possesses greater strength than other mixes. In the case of specimens exposed to high temperature of 1000°C, MK-blended SCC produced the lowest residual strength compared to FA- and SF-based mixes. Further microstructural investigation was conducted to examine the internal structure of the specimens exposed to various heating temperatures. From the results, it is concluded that the higher the strength gain upon aging, the greater the strength loss upon temperature rise.

KEYWORDS: Self-compacting concrete, Fly ash, Silica fume, Metakaolin, Residual strength, Microstructure.

INTRODUCTION

The performance and properties of structures may deteriorate due to different exposure conditions during their service life. Among all, fire is considered one of the most serious threats to human life. A significant reduction in strength was noticed when concrete was exposed to a temperature of 400ºC (Liu et al., 2022; Sogbossi, 2020). Further increase in temperature beyond 400 °C causes a drastic strength loss and spalling may occur, which results in decreasing the load-carrying capacity of the structural members (Nuruddin et al., 2014). Strength deterioration of concrete exposed to higher temperatures is attributed to the chemical degradation of the binding medium (Abed and Brito, 2020; Ali, 2012). Further, the reasons for strength degradation of concrete exposed to fire include higher pore water pressure, breakdown of calcium-silicate-hydrate (CSH) gel and thermal incompatibility between the cement paste and the aggregates, leading to a bond strength loss in the interfacial transition zone (ITZ) (Khattab et al., 2021).

The development of SCC is a boon to the construction industry because of its unique properties, such as flow ability, filling ability, resistance against bleeding and segregation, compared to NCC (Mehrdad et al., 2021). SCC can be employed in congested reinforcement areas or structures with complex shapes where concrete compaction is restricted. It also enhances construction efficiency and concrete

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productivity. SCC is considered one of the most appropriate structural materials, because it can flow under its weight without any bleeding or segregation (Ali et al., 2019; Nuruddin et al., 2014). The water-cement (w/c) ratio, binder-filler ratio, aggregate size and dosages of super-plasticizers (SPs) and viscosity-modifying agents (VMAs) all have significant impacts on the flow ability and segregation resistance of SCC (Arslan et al., 2020; Pathak and Siddique, 2012).

Some researchers stated that explosive spalling is observed in the temperature range from 200 to 300°C, resulting in a loss of strength (Andiç-Çakır and Hızal, 2012; Fernandes et al., 2021), which may be experienced by weak microstructures. Compared to CC, SCC has a larger volume of binder material accompanied by SCM, such as FA, MK, SF, … etc., than the filler materials (Li et al., 2012; Pathak and Siddique, 2012), resulting in the concrete being less permeable. Pathak and Siddique (2012) studied the effect of low-calcium FA on the strength properties of SCC under high temperatures in the range between 20 and 300ºC. A significant mass loss was observed, accompanied by a strength loss due to evaporation of pore water. Li et al. (2012) studied the fire performance of high-strength concrete (HSC) in the range from 200ºC to 1000ºC at an interval of 200ºC and found that the strength of the concrete starts following the downward trend and spalling was initiated at the temperature of 200ºC with red and off-white straws. The findings stated by Li et al. (2012) do not match with other research findings. Researchers (Ali, 2012; Arslan et al., 2020; Nuruddin et al., 2014) examined the thermal performance of high-strength concrete at high temperatures in the range 0-1000ºC and stated that carbonate-based aggregates have a better performance than HSC under elevated temperatures, concluding that aggregate type had a direct influence on the fire performance of HSC.

Researchers around the globe have utilized different SCMs to enhance the special property of concrete against elevated temperatures. Pathak and Siddique (2012) studied the effect of FA-blended concrete exposed to fire and observed that the concrete has gained strength at the temperature range from 121ºC to 149ºC. Strength degradation was noticed in the concrete with 10% to 40% when subjected to a temperature from 200ºC to 800ºC. Moreover, cracks were initiated at 400ºC-800ºC (Li et al., 2012). In addition, Pathak and Siddique (2012) examined the mechanical properties of concrete exposed to elevated temperatures with a composition of 25% and 40% cement replacement with FA. The study's findings revealed that specimens with 40% FA exposed to 400ºC have the least amount of strength loss when compared to CC exposed to the same temperature. Researchers (Ali et al., 2019; Babalola et al., 2021) studied the effects of FA-and MK-based cement mortar exposed to a temperature range from 27ºC to 800ºC. Zero strength reduction was noticed up to 400ºC and beyond 400ºC, a reduction in strength was noticed. Therefore, 400ºC may be considered a critical temperature. Moreover, FA-blended mortar shows a better resistance against fire than MK-blended mortar.

Mathew and Paul (2012) investigated the strength and durability performance of CC and HSC with different SCMs exposed to elevated temperatures. The results of the investigation showed that samples with GGBS offer a better performance than CC. A study on concrete with binary mixture of pumice powder and SF at high temperatures reported that the inclusion of pumice powder and SF declines the strength and density of concrete beyond 600ºC (Mehrdad et al., 2021). In addition, Hossain and Lachemi (2006) examined the performance of volcanic ash in cement mortar and highlighted that cement replacement with volcanic ash affects the later-age properties of CC and specimens exposed to high temperatures.

The main objective of this study is to provide suitable guidelines for designing concrete structures with suitable binding materials to enhance their fire-resistance property. The scope and outcome of the investigation suggest the use of SCMs to sustain compressive strength when the concrete is exposed to elevated temperatures. Moreover, the data towards the effect of fire on concrete age is limited and the information on early-age fire exposure of SCC with different supplementary cementitious materials (SCM's) is found to be scarce.

MATERIALS AND METHODS

Materials

The present investigation utilizes Ordinary Portland Cement (OPC) of M 20 grade as a binding medium. Locally available river sand of a size less than 4.75 mm, having a specific gravity of 2.62, falling under Zone II of (IS 383, 2016) and crushed granite stones of a size of 10 mm having a specific gravity of 2.71 were employed as fine and coarse aggregates.

SCC Development and Mix Proportioning

Saturated surface dry (SSD) conditioned fine and coarse aggregates were added and allowed to rotate for a period of 1-2 minutes in a rotary-type mixer drum. The binder, water and suitable admixtures are added and the mixer drum is allowed to rotate for further 2-3 minutes to achieve proper consistency. EFNARC (2002) stipulations were followed in the development phase of SCC mixtures to ensure workability properties, such as flow ability, filling ability and segregation resistance, as shown in Fig. 1. The workability tests were performed within 15 minutes of adding water. The flow ability and filling ability of SCC were tested using the slump-flow test, the T_{500} test and the V-funnel test, while the segregation resistance of SCC was evaluated using the J-ring test. The workability properties of the developed mix are given in Table 1.

Figure (1): Workability tests

Table 1. Workability properties

Workability Tests	Workability Properties				
	SCC-SF	SCC-FA	SCC-MK	EFNARC Standards	
				Min.	Max.
Slump Flow (mm)	730	745	715	640	800 (SF 2)
T_{500} Flow Time (sec)	3.00	3.10	2.28	>2 (VS 2)	
J-Ring (mm)	7.93	6.71	6.4	0	10
V-Funnel (sec)	9.32	8.28	7.46	≥7 to ≤ 27 (VF 2)	
V-Funnel T_5 (sec)	10.21	9.63	9.19	±3	

* Note: SF 1: Slump-flow Class 1; VF 2: V-funnel Class 2.

The SCC mix proportions adopted for the present investigation are illustrated in Table 2. Four different mix proportions; namely, normal concrete mix (NCC) and three self-compacting concrete (SCC) mixes were developed. The SCC mixes were prepared using admixtures, such as silica fume (SCC-SF), fly ash (SCC-FA) and metakaolin (SCC-MK). In the case of SCC mixes, the cement and water contents were kept constant, whereas the fine aggregates and coarse aggregates were replaced with SF, FA and MK in different proportions based on trials. The SP and VMA dosages were calculated by the percentage mass of cementitious material as per the latest Indian code (IS 10262, 2019), quoted (Ref. Annex. E (E-8) of (IS 10262, 2019)) that the admixture dosage was made by the percentage weight of cementitious materials.

Elevated-temperature Test

After curing, the specimens are heated in a muffle furnace, which has a size of 500 x 500 x 500 mm. Figure 2 shows a typical example of an SCC specimen exposed to elevated temperatures. The heating temperatures adopted in the present investigation were 500, 750 and 1000°C. The specimens are heated for 1 hour to maintain a uniform distribution of heat throughout the specimen. After attaining the required temperature, the specimens are removed from the furnace and allowed to cool. Two types of cooling regimes were employed; namely, air cooling and water cooling. In the case of air cooling (AC), the specimens are allowed to cool at room temperature, whereas in the case of water cooling (WC), the specimens are immediately taken out of the furnace and water is allowed to spray on the concrete surfaces till they reach room temperature. Initially, all the specimens were weighed at room temperature before being heated. After being exposed to elevated temperatures, the specimens are again weighed. The change in mass before and after heating reveals the mass loss. Moreover, specimens exposed to elevated temperatures undergo colour change and crack formation, which are some of the examples of visual inspection.

Table 2. Mix proportions

Mix ID	Cement (kg/m^3)	Sand (kg/m^3)	CA (kg/m^3)	SF/FA/MK (kg/m^3)	W/C ratio	SP (lit/m^3)
NCC	360	607.00	1214.00	-	0.50	-
SCC-SF	324	961.17	932.14	36	0.49	4.67
SCC-FA	252	911.63	885.58	108	0.49	5.43
SCC-MK	306	941.35	903.21	54	0.49	4.37

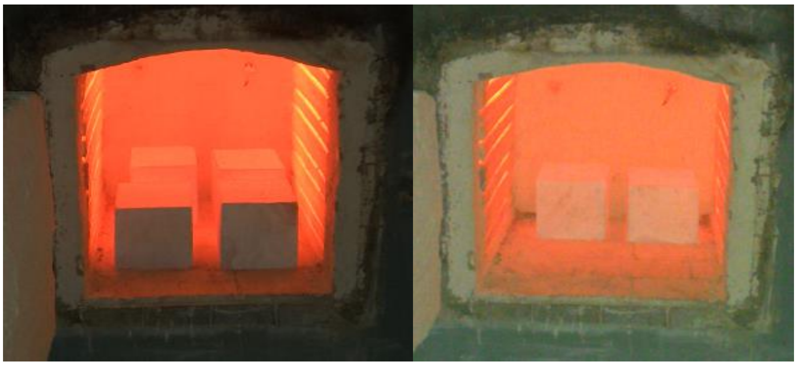

Figure (2): Heating of specimens

RESULTS AND DISCUSSION

Hardened Properties

The specimens were heated and tested to determine the mechanical properties of concrete at three different curing periods; namely, 7, 14 and 28 days. The study investigated the influence of curing on the strength development of fire-affected concrete. All the specimens were heated and cooled to reach room temperature using the air-cooling and water-cooling methods. Compressive strength was found for the cooled specimens using a digitalized compression testing machine (CTM) with a capacity of 2000 kN. The testing procedure adopted to examine the compressive strength of the specimens is in accordance with the Indian standard 516 (2004). Strength test results are taken as an average of three concrete specimens tested at a particular temperature. From Fig 3, it is clear that an increase in temperature shows a downward trend in compressive strength and an increase in the curing period shows an upward trend in compressive strength.

The strength loss of NCC due to the effect of curing with respect to temperature for various curing days is shown in Figs. 3(a) and 3(b), respectively. Fig 3(a) represents the strength results of heat-exposed NCC specimens cooled under AC, whereas Fig 3(b) shows the strength results of NCC specimens exposed to elevated temperatures and cooled under WC. Temperature-exposed specimens cooled under AC retained a higher strength than that of WC-cooled specimens (Husem, 2006). Marginal variations in strength were noticed for both AC and WC, whereas WC specimens suffered a higher percentage of strength loss during all the curing duration. This may be attributed to the quenching effect (Anagnostopoulos et al., 2009).

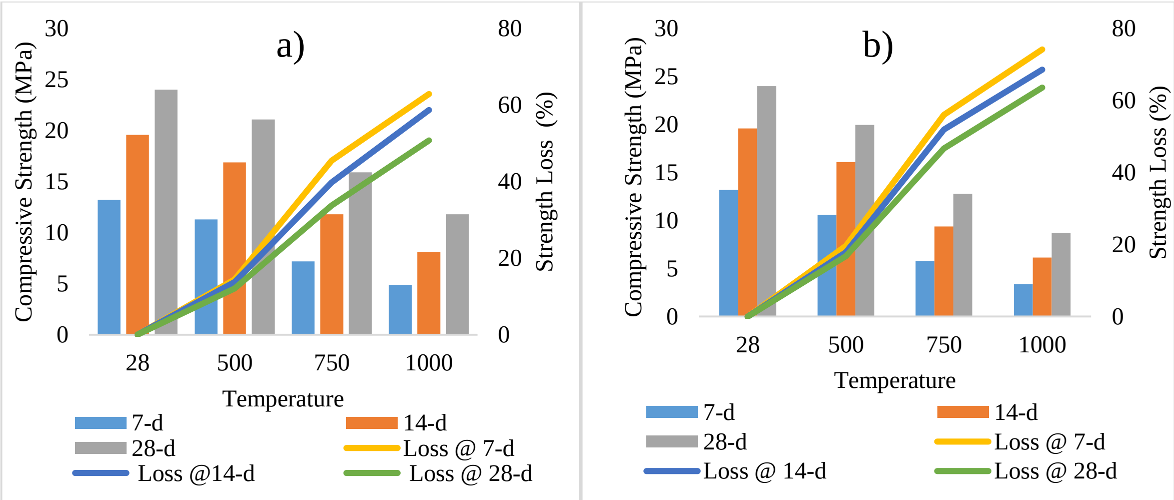

Figure (3): Strength loss of NCC- a) Air-cooled specimens and b) Water-cooled specimens

The initial and residual compressive strengths of FA-blended SCC are shown in Fig 4. From the figure, it is clear that an increase in the curing period (from 7 to 28 days) increases the strength gain, whereas an increase in temperature exposure decreases the compressive strength of the mix. 70%-80% strength loss is observed in 7-, 14- and 28-day water-cured specimens exposed to elevated temperatures and cooled under WC (Fig 4(a)). The AC-cooled mix loses 55%–75% of its strength, while the air-cooled specimens retain the mix's strength (Fig 4(b)).

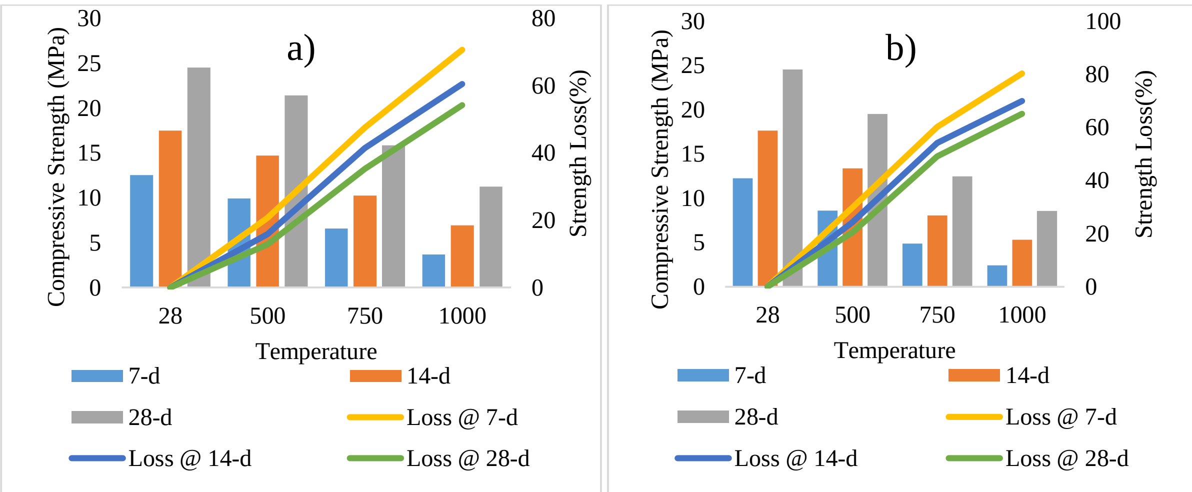

Figure (4): Strength loss of SCC-FA- a) Air-cooled specimens and b) Water-cooled specimens

The initial compressive strength and strength loss of SF- and MK-blended SCC exposed to elevated temperatures are shown in Figs. 5 and 6. Similar to FA-blended SCC, SF and MK specimens experience strength gain upon curing age and strength loss upon temperature rise. SF-blended mix possesses a strength loss of 55%-75% (Fig 5(a)) in case of AC condition and for WC condition, the strength loss was found to be 60%-80% (Fig 5(b)). MK-blended mix possesses a strength loss of 65%-80% (Fig 6(a)) in the case of AC condition and for WC condition, the strength loss was found to be 80%-85% (Fig 6 (b)). The MK-blended mix obtained the maximum compressive strength upon ageing among all other mixes and experienced a severer strength loss than other mixes (Anand N, 2016).

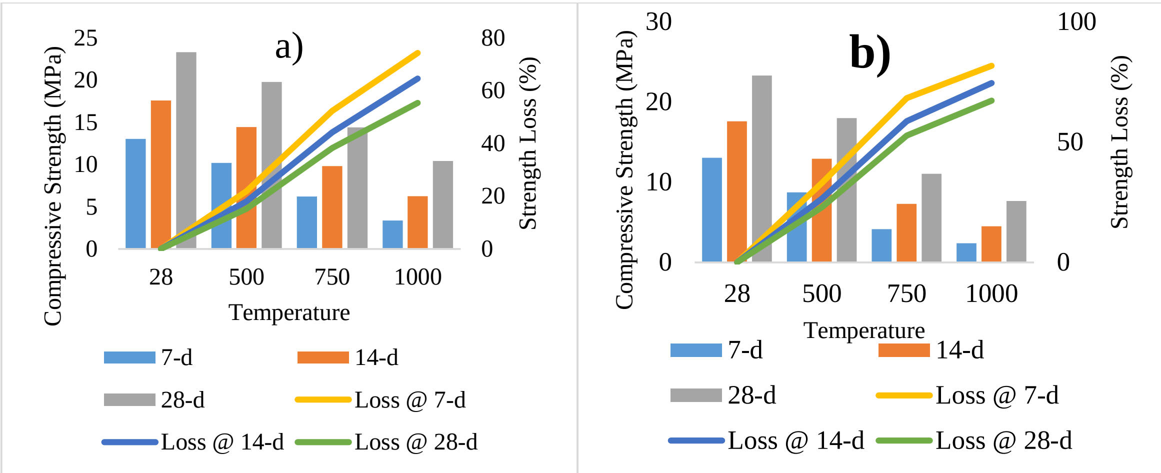

Figure (5): Strength loss of SCC-SF- a) Air-cooled specimens and b) Water-cooled specimens

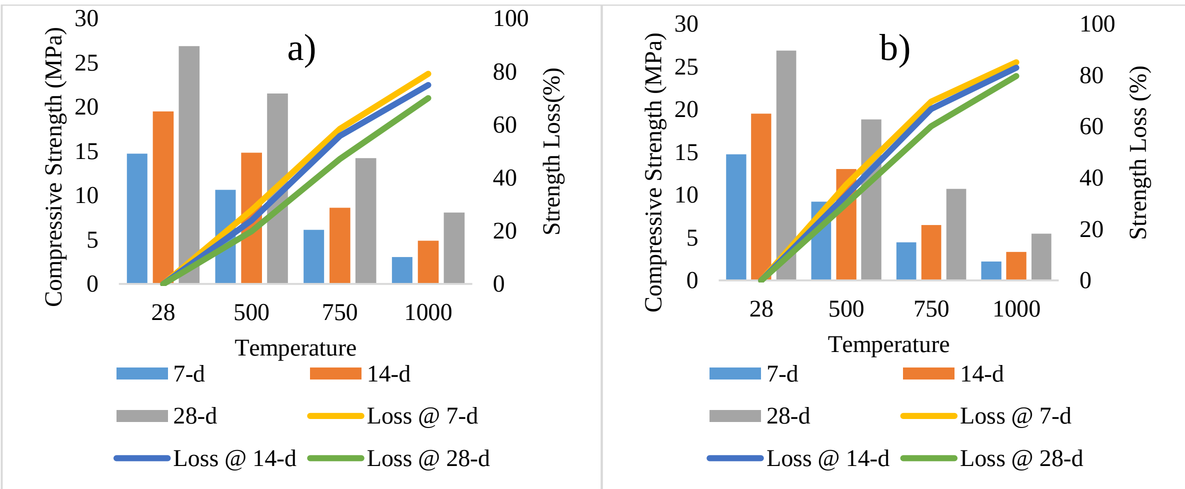

Figure (6): Strength loss of SCC-MK- a) Air-cooled specimens and b) Water-cooled specimens

From the experimental investigation, it is found that the strength loss is found to be high for NCC specimens cured for 7 days and decreases with an increase in curing days. This may be due to the availability of higher moisture content in the concrete at 7 days. This moisture content has been lost at a higher temperature, which resulted in a significant weight loss. Higher moisture content creates higher internal pore pressure within the concrete. It is understood that higher moisture content at 7 days developed higher strength loss as compared to later stages. An increase in strength loss is directly associated with temperature rise.

Mass Loss

Mass loss was evaluated based on the difference between the masses of the specimen before and after heat exposure. Mass loss is a common phenomenon that takes place when the concrete is exposed to elevated temperatures and this may be due to evaporation of pore water followed by the decomposition of the binder medium (Reinhardt and Stegmaier, 2006). It may result in crack formation and even lead to an explosive spalling behaviour. Fig. 7 represents the mass loss of differently-aged concrete specimens exposed to different temperatures. At 28°C, all the concrete mixes attained maximum strength and the same is used to compare the results of higher-temperature exposure. A significant mass loss was found for the specimens exposed to 500ºC, while further increase in temperature results in a drastic increase in mass loss. MK-blended mix shows a severe mass loss, followed by SF- and FA-blended mixes. Mass and strength losses are found to be higher for water-cooled specimens at different curing ages.

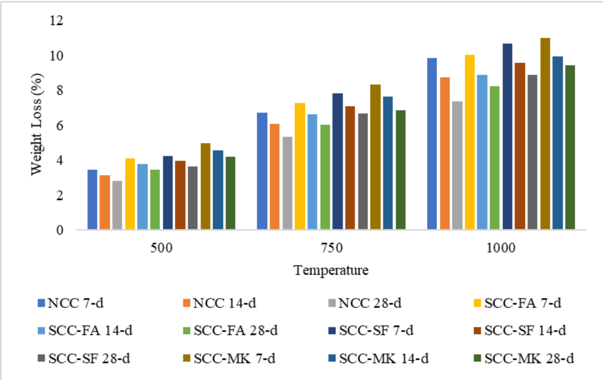

Figure (7): Mass loss of concrete exposed to elevated temperatures

Microstructural Analysis

Scanning electron microscope (SEM) analysis was conducted on specimens of SCC-FA, SCC-SF and SCC-MK exposed to various temperatures. Fig. 8 shows the SEM micrographs of SCC samples that were exposed to 500°C, 750°C and 1000°C. Figs. 8a, 8b and 8c show the microstructure of SCC-FA samples at 500°C, 750°C and 1000°C, respectively. Figures 8d, 8e and 8f as well as Figures 8g, 8h and 8i show the SEM images of SCC-SF and SCC-MK mixes, respectively. Higher damages, such as pores and micro-cracks, were observed for the higher temperature-exposed samples. It can be noticed that all the three mixes (SF, FA and MK) experienced notable cracks at 500 °C.

At 750°C, the SEM images revealed changes in the microstructure such as pores and wider micro-cracks in the SCC matrix and these changes are more pronounced in SCC-SF and SCC-MK mixes than in the SCC-FA mix. In addition, dehydrated amorphous C-S-H gel transformed into phases, while chemically bound water was released from C-S-H gel and the long chain in the C-S-H gel was broken (Sadrmomtazi et al., 2020; Ye et al., 2007). The formation of micro-cracks, pores and newly developed phases from the C-S-H gel and the release of chemically bound water are responsible for the reduction in compressive strength at 1000 °C as compared to the compressive strength of unheated specimens (Uysal, 2012; Uysal et al., 2012).

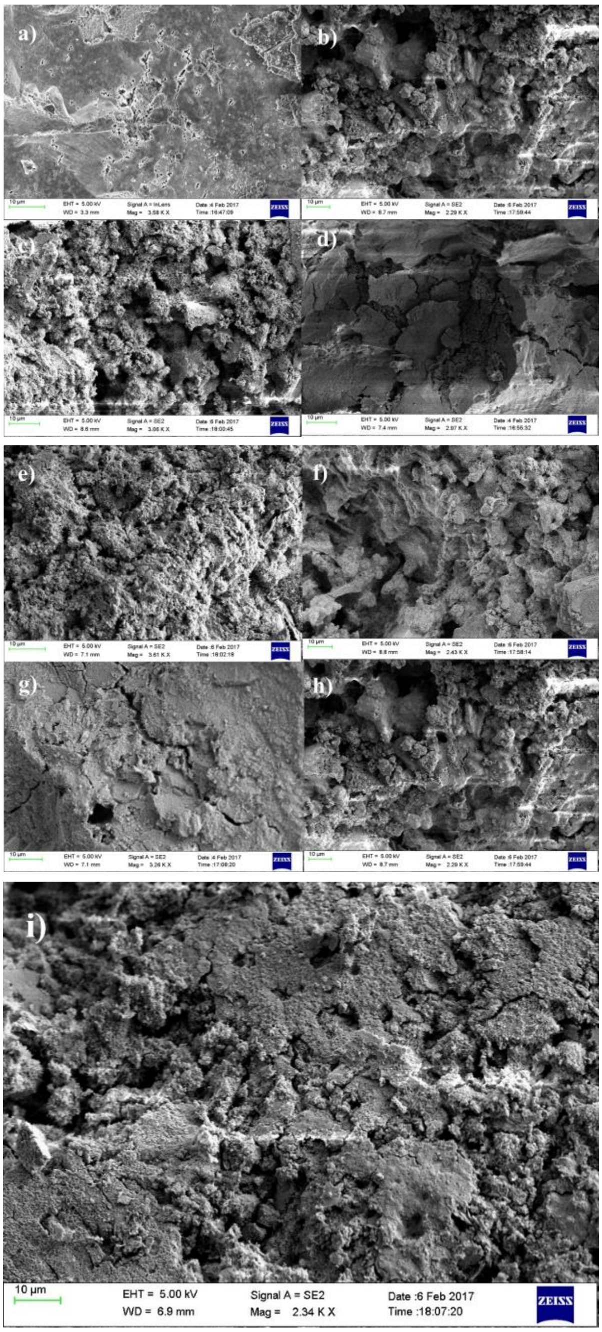

Figure (8): SEM analysis of (a-c) SCC-FA; (d-f) SCC-SF and (g-i) SCC-MK

CONCLUSIONS

From the experimental results, it is evident that an increase in the curing period increases the compressive strength of NCC and SCC. An increase in the temperature of the specimens that were exposed results in a decline in strength. SCC with different admixtures exhibits higher weight and strength losses as compared to NCC. A higher strength retention was noticed upon ageing under temperature exposure for all the mixes.

The use of FA and SF in SCC mixes shows a similar performance to that of normal-concrete mix before heating. The strength gained in terms of curing ages and the strength loss in terms of heating exposure are the same as those of the NCC mix. At early curing ages, the MK-based SCC mix attained maximum strength.

Weight loss is found to be higher for specimens cured for 7days as compared to those cured for 14 and 28 days. It is understood from the experimental investigation that the weight and strength losses of SCC with MK are found to be higher as compared to SCC with FA and SF. In addition to that the moisture content has a similar effect on SCC as that, on NCC. Powder content also has a significant effect on the weight and strength losses of SCC. SEM analysis confirms that hydration produces notable cracks with rise in temperature. At 500°C, micro-cracks were observed for all the SCC mixes. MK-based mix experiences a severe damage with the increase in temperature as compared to FA- and SF-based mixes.

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