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Research Article

Effect of elevated temperature on strength and durability properties of concrete using nano-silica and alccofine

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Abstract

The strength and durability properties of concrete using nano-silica and alccofine after exposed to higher temperatures were investigated in this study. Concrete with 3% nano-silica and 15% alccofine were prepared and water cured for 28 days. In an electric boogie furnace, concrete specimens with and without nano-silica and alccofine were heated to 400°C and 800°C for 4 hours. The specimens then were allowed to cool until they reached room temperature. The compressive strength test was used to determine strength, whereas the water absorption, porosity, and rapid chloride permeability tests were conducted to check durability properties. SEM images were used to examine the microstructure of concrete specimens at elevated temperatures. According to the test results, the strength and durability properties of concrete using nano-silica and alccofine deteriorated at high temperatures. At room temperature, concretes containing alccofine and nano silica performed better than control mixes. A severe loss in strength and a significant increase in charge pass, water absorption and porosity were observed at 800°C for concrete using alccofine and nano silica. The microstructural analysis using scanning electron microscopy methods also reported that the porosity increased with increase in temperature.

1. Introduction

Fire remains one of the most serious potential hazards, as it affects the structural integrity of concrete structures. [1]. Fire has an adverse and unrecoverable effect on the physical, strength, and serviceability properties of concrete. As a result, it is critical to look into the efficiency of concrete that's been subjected to fire. It has been reported that the duration of exposure will have no or little impact on the concrete's compressive strength when subjected to fires up to 200°C [2-5]. Moreover, regardless of the exposure temperature, growing the exposure duration has been shown to have a negative impact on the residual capacity of concretes, particularly the strength properties [3]. Some supplementary cementitious materials from agricultural and industrial waste shows an unpredictable effect on performance of concrete under fire, and therefore been extensively studied by a number of researchers [6, 7]. Carbonates start to break down at 500-600°C, and are believed to trigger permanent destruction to concrete and they're a key component of the primary binder form of concrete [8]. In particular, temperature over 800°C, almost all contents of concrete degrade, resulting in considerable strength as well as weight loss since the thermal characteristics of aggregates and cement paste differ, this causes residual stress and cracking [9]. Poon et al. [10] compared the compressive strength and durability properties like rapid chloride diffusion, porosity & crack pattern of control mixes and high strength mixes for temperature up to 800°C and concluded that a significant loss in

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durability in terms of permeability occurred than the loss of compressive strength. As such, several advanced laboratory techniques, such as scanning electron microscopy analysis, energy dispersive spectrometer, and X-ray diffraction analysis, are used to reveal concrete degradation mechanisms after exposed to elevated temperatures [11]. Karahan [12] tested experimentally the transport properties after being exposed to elevated temperatures, of high-volume slag or fly ash added concretes and found that according to rapid chloride permeability (RCPT) test results, slag-based concrete binds more chlorine than fly ash-based concrete, and the behavior of slag-based concrete at elevated temperatures was superior to that of fly ash-based concrete. Demez et al. [13] assessed mechanical characteristics of high strength concrete (HSC) using pyrophyllite aggregate after exposed to elevated temperatures and concluded that the loss of compressive strength was much more pronounced in all concrete mixes subjected to temperatures above 600°C. Ercolani et al. [14] investigated the action of concrete when subjected to elevated temperatures and various cooling systems and found that if water is employed as a cooling medium, the rise in temperature affects physical as well as mechanical characteristics causing increase in degradation with development of cracks or microcracks. Mousavimehr et al. [15] stated that in addition to enhancing the mechanical as well as durability properties of rubberized concrete at elevated temperatures, the combined effect of metakaolin and silica fume can indeed create environmentally sustainable mixes by minimizing carbon footprint in comparison to a control mix. Because extreme heat can disintegrate the mechanical characteristics of concrete and potentially harm the entire structure, it's indeed critical to ascertain the impact of elevated temperatures upon on mechanical characteristics of high-performance concrete (HPC) [16]. With increasing elevated temperatures, HPC's thermal expansion dramatically increases. Therefore, from above studies it is self-evident that concrete's high-temperature characteristics are critical for simulating the fire behavior of concrete structures. It was discovered in a prior study that adding nano-silica and alccofine to concrete increased its strength properties [17]. Because nano-silica and alccofine aid in the development of high strength concrete, their use in concrete may expand. As a result, it is critical to determine if concrete manufactured from these ingredients is safe in the event of a fire or high temperatures.

Since no research has been done on the durability properties of concrete using nano-silica and alccofine after subjected to higher temperatures. Therefore, in this study an attempt has been made to evaluate the residual compressive strength and durability properties like water absorption and porosity, rapid chloride permeability and morphology of concrete mixes using alccofine and nano silica after exposure high temperatures. To relate the strength and durability properties of different concretes mixes at elevated temperatures, they must be prepared and evaluated under identical material and heating regimes.

2. Experimental Studies

2.1. Material Used

OPC of 53 grades confirming to IS 12269-1987 was used in this study with specific gravity 3.15. The physical properties of cement are given in Table 1.

Table 1. Physical properties of cement

Sr. no	Properties	Values	Requirements as per IS: 12269-1987
1.	Soundness (Le Chatelier method)	1.2	< 10mm
2.	Initial setting time	56 min	> 30min
3.	Final setting time	259 min	< 600 min
4.	Fineness	300 (m^2/kg)	> 225 m^2/kg
5.	Standard Consistency	32%	-

Alccofine (Al) which is an ultra-fine slag or ggbs having particle size 4-6µm and specific gravity 2.86. It was procured from local dealers. Nano silica (Ns) having size of 17nm and specific gravity 2.2-2.4 shown in Fig. 2 was used. The properties alccofine and Ns obtained from manufacturer are given below in Table 2. As a fine aggregate, locally accessible river sand with specific gravity 2.65 has been used and coarse aggregates with a size of 20 mm having specific gravity 2.79 were used. Conplast SP430DIS is a high range water reducer superplasticizer that is used to maintain the workability of concrete mix. The laboratory tap water was used.

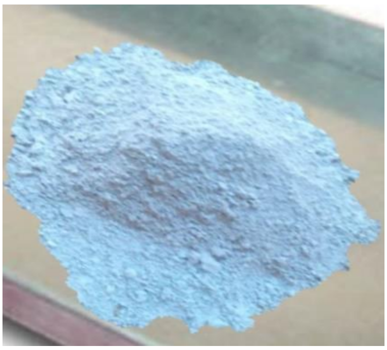


Fig. 1 Alccofine

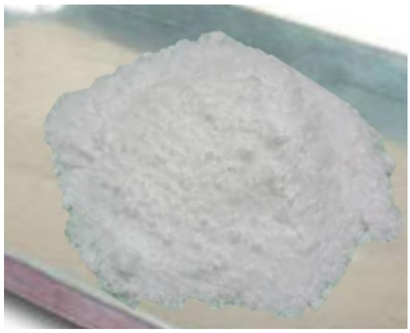


Fig. 2 Nano silica

Table 2. Chemical and physical properties of materials

Item	Calcium oxide	Silicon dioxide	Aluminum oxide	Ferric oxide	Magnesium oxide	Sulfur trioxide	Avg. particle size
Al	32.1-34.3	33-35	18.0-20.0	1.8-2	8.0-10.0	0.30-0.70	4-6µm
Ns	0.060	99.880	0.0050	0.0010	-	-	17nm

2.2. Mix Proportions

Three blends of different concrete M40, M50, and M60 were taken into account to research the characteristics of concrete using nano-silica and alccofine, and mix design has been carried for all concrete grades according the IS10262:2019 and IS 456:2005 with w/c ratios of 0.4, 0.36, and 0.3. Alccofine (15%) and nano silica (3%) were used to replace cement. The mix proportions of the concrete mixes are given in Table 3.

Table 3. Mix proportions and notations of different concrete mixes

Concrete grade	Additives	Notations	Water Kg/m^3	Cement Kg/m^3
M40	0	M4	160	400
	AL+ Ns	M4AlNs	160	328
M50	0	M5	159	440
	AL+ Ns	M5AlNs	159	360.8
M60	0	M6	158	527
	AL+ Ns	M6AlNs	158	400

Table 3 (Con.). Mix proportions and notations of different concrete mixes

Concrete grade	FA Kg/m^3	CA Kg/m^3	Al Kg/m^3	Ns Kg/m^3	w/c
M40	667	1248	-	-	0.4
	667	1248	60	12	0.4
M50	642	1243	-	-	0.36
	642	1243	66	13.2	0.36
M60	596	1218	-	-	0.3
	596	1218	79	15.8	0.3

Fig. 3 Electric bogie for heating specimens

Fig. 4 Rapid chloride permeability test apparatus

Fig. 5 Compression testing apparatus

2.3. Test Methods

Concrete samples of cubic size 150 mm & 100mm and disc sample of 100mm diameter and 50mm height size were casted and cured for 28 days in water. After curing the samples were dried and then placed in electronic bogie furnace shown in Fig. 3. The elevated temperature of 400 and 800 degree Celsius was maintained for 4hours duration. The fire duration of 4hrs is considered because as per National Building Code of India, desirable fire grading of columns and beams is 4 and 3 hrs. The samples were then cooled to room temperature by leaving them out in the open air. 150 mm samples were tested for compressive strength as per IS: 516 – 1959 [18].

Using the ASTM C 642-06 [19] procedure, 100 mm samples were used to determine water absorption and porosity. The ASTM C1202 [20] specification was used as a guide for the rapid chloride permeability assessment using a 50 mm disc samples. After completing the compressive strength test, the specimens were ground into fine powder for microstructural analysis using Scanning Electron Microscopy (SEM) test. Test apparatus for compressive strength test and rapid chloride permeability test shown in the Fig. 3 & 4. The results at room temperature (RT) were compared to those obtained at higher temperatures.

3. Result and Discussion

3.1. Compressive Strength

The Compressive strength results of concrete specimens subjected to elevated temperatures are depicted in the Fig. 6 as the average of the observations. It can be seen from the Fig. 6 that increasing the temperature decreases compressive strength. Compressive strength results of Al+Ns concrete mixes were between 66 to 83 Mpa at RT, 64.9 to 80 MPa at 400°C, and 29 to 41.3 MPa at 800°C, respectively, as shown in Fig. 6. And compressive strength results of control mixes were between 51.1 to 68.5 MPa, 57 to 67.4 MPa and 30.3 to 30.9 MPa at RT, 400°C, and 800°C, respectively. Compressive strength decreased by 0.3 to 1.7% at 400°C, 40 to 48% at 800°C for control mixes, and 1.5 to 3.3% at 400°C, 50 to 56% at 800°C for Al+Ns mixes.

The percentage decrease in compressive strength was greater for Al+Ns concrete mixes M4AlNs, M5AlNs, & M6AlNs compared to control mixes M4, M5 & M6 because of degradation of calcium silicate hydrates [1]. Despite the fact that Al+Ns mixes had higher compressive strength than control mixes at 400°C, the percentage decrease in compressive strength was significantly higher for Al+Ns mixes. Fig. 13 shows that the compressive strength decreases as the porosity increases. Therefore, increase in porosity with temperature is one of reason for decrease in compressive strength at higher temperatures. Cross sections of concrete samples at different temperatures are shown in Fig. 7, 8 & 9. The color of hardened concrete changed after exposed to higher temperatures. Cracks appeared in the aggregate & paste's interfacial transition zone (ITZ), as well as within the aggregate at 800°C from Fig. 9 which is another reason for reduced compressive strength. Because the interfacial transition zone (ITZ) is the weakest connection between cement paste and aggregate, it can enhance crack propagation. As a result, increasing temperature raises internal stresses, which accelerates material cracking, multiplies defects, and thereby lowers strength [21, 22].

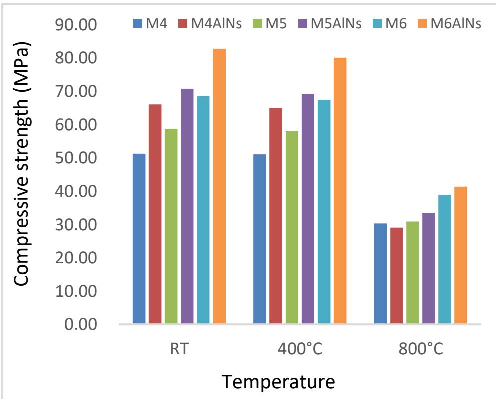


Fig. 6 Compressive strength values at elevated temperatures

Fig. 7 Cross section of a hardened concrete at room temperature.

Fig. 8 Cross section of a hardened concrete at 400°C.

Fig. 9 Cross section of a hardened concrete at 800°C.

3.2. Water Absorption and Porosity

Water absorption and porosity values of concrete with and without Al and Ns were calculated using test procedure given in ASTM C642 for all the concrete grades. The water absorption of concrete specimens subjected to elevated temperatures are depicted in the Fig. 10 as the average of the observations.

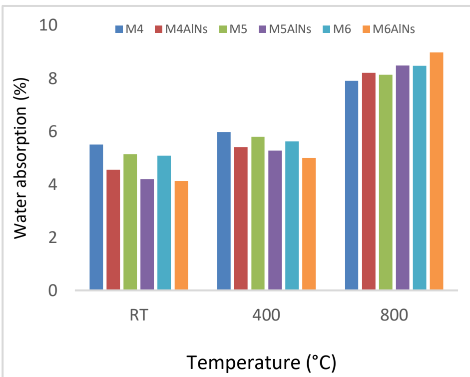


Fig. 10 Water absorption values at elevated temperatures

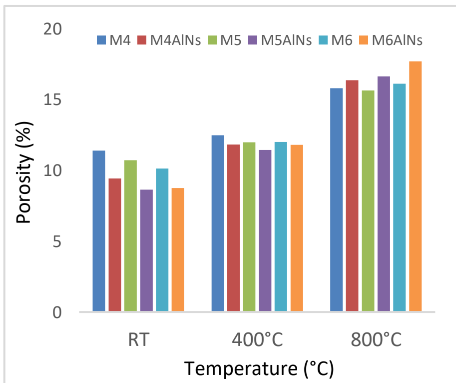


Fig. 11 Porosity values at elevated temperatures

It can be seen from the Fig. 10 that increasing the temperature increases water absorption due to internal cracking. The three major reasons of such an internal cracking could be the breakdown of crystalline calcium hydrate particles, development of steam pressure, and degradation of C-S-H [7].

Concrete with a water absorption value of less than 5% is considered to be of high quality [23]. Water absorption of Al+Ns concrete mixes ranged from 4.1 to 4.6 %, 5.4 to 5.8 %, and 8.2 to 9% at RT, 400°C, and 800°C, respectively, as shown in Fig. 10. And water absorption of control mixes ranged from 5 to 5.5 %, 5.6 to 6%, and 7.8 to 8.5 % at RT, 400°C, and 800°C, respectively. At RT, concretes mixes containing Al+Ns showed less than 5% water absorption. At 400°C and 800°C, all the concrete mixes showed water absorption greater than 5%. The percentage increase in water absorption of control mixes is 8 to 13% at 400°C, 43 to 67% at 800°C and for Al+Ns mixes is 18 to 26% at 400°C, 80 to 118% at 800°C. The percentage increase in water absorption was greater for mixes M4AlNs, M5AlNs, & M6AlNs mixes at 800°C compared to M4, M5 & M6 mixes.

Increase in temperature leads to the formation of large number of air voids due to evaporation of free water, accompanied by capillary water, and then physically bound water [24]. Porosity of Al+Ns concrete mixes ranged from 8.6 to 9.5 %, 11.4 to 11.8 %, and 16.3 to 17.7 % at RT, 400°C, and 800°C, respectively, as shown in Fig. 11. And porosity of control mixes ranged from 10.1 to 11.4 %, 11.9 to 12.5 %, and 15.6 to 16.1 % at RT, 400°C, and 800°C, respectively. The percentage increase in porosity of control mixes is 9 to 18% at 400°C, 38 to 59% at 800°C and for Al+Ns mixes is 25 to 35% at 400°C, 73 to 102% at 800°C. The percentage increase in porosity was greater for Al+Ns concrete mixes M4AlNs, M5AlNs, & M6AlNs at 800°C compared to control mixes M4, M5 & M6. Because at high temperature as water evaporates, the internal pore pressure increases, which causes significant internal pressures upon on solid skeleton of concrete due to the compact structure and lower permeability of Al+Ns concrete mixes. And thereby increases no. of micro cracks leading to increase in no. of voids in concrete matrix [24].

The graph of water absorption versus porosity is plotted considering all concrete mix at all temperatures as shown in Fig.12. The porosity of concrete is linearly proportional to water absorption [25]. Therefore, increase in porosity increases water absorption due to increase in total pore volume of concrete. Similar results were reported by Karahan et al. [12] for concrete using slag with the porosity values varying between 9.3–11.0% at 20°C, 10.4–11.7% at 400°C, and 16.2–17.4%, at 800°C, and water absorption varied between 4–4.5% at 20°C, 4.5–5.5% at 400°C, and 7.5–8.5%, at 800°C, respectively.

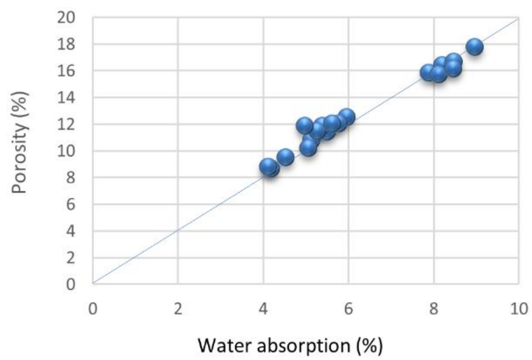


Fig. 12 Water absorption vs. Porosity

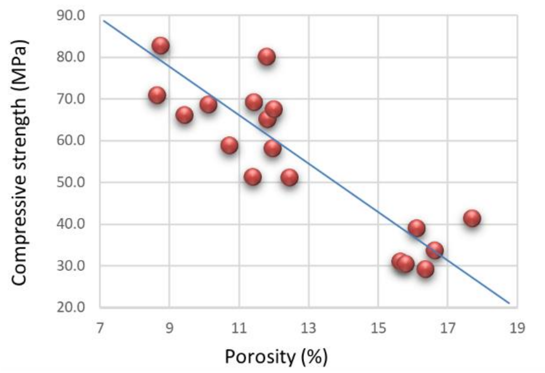


Fig. 13 Porosity vs. compressive strength

3.3. Rapid Chloride Permeability

The RCPT test, that is used to measure concrete's durability in terms of chloride-ion permeability, is easy to perform and can be completed in just 6 hours. Before exposing to high temperatures all the concrete mixes showed very low permeability s per ASTM 1202. As when the temperature was elevated, there was a substantial loss of permeability. If the charge moving through the concrete specimen is greater than 4000 C, then as per ASTM 1202 it is categorized as highly permeable [10, 25]. Since more current flows into a highly permeable concrete its chloride-ion resistance is an indirect indicator of its permeability and internal pore structure [7]. RCPT values of Al+Ns concrete mixes ranged from 700 to 940 C at RT, 1170 to 1590 C at 400°C, and 4920 to 6990 C at 800°C, respectively, as shown in Table 4.

The RCPT values of control mixes ranged from 1518 to 1740 C at RT, 2000 to 2420 C at 400°C, and 5380 to 6000 C at 800°C, respectively. At room temperature (RT), concretes mixes containing Al+Ns showed very low chloride ion penetrability compared to control mixes. Chloride ion penetration at 400°C was moderate for M4, M5 & M6 mixes and low for M4AlNs, M5AlNs, & M6AlNs mixes. The percentage of chloride ion entry into the concrete specimens largely depends on the structure of the internal pores and micro cracks. From Fig. 7, 8, & 9 it can be seen that with the increase in temperature the bond between aggregates and cement paste deteriorated and number of microcracks increased. The increase in rapid chloride permeability at elevated temperature is calculated by comparing it to the values at room temperature. The increase in rapid chloride permeability of control mixes is 1.3 to 1.4 times at 400°C, 3 to 4 times at 800°C to that of rapid chloride permeability at room temperature. The increase in rapid chloride permeability of Al+Ns mixes is 1.6 to 1.7 times at 400°C, 5 to 10 times at 800°C to that of rapid chloride permeability at room temperature. The relationship between porosity and RCPT is shown in Fig. 14, and it was observed that RCPT increases as porosity increases. Therefore, RCPT values of all the concrete mixes after subjected to high temperature of 800°C were greater than 4000 C due to excessive cracking and increased porosity from Fig 11, hence regarded as not durable [26]. As a reason, concrete using alccofine and nano-silica is considered as not durable, and also its utilization should be thoroughly considered for structures that are frequently subjected to heating and cooling cycles. Nadeem et al. [1] noticed an increase in rapid chloride permeability of concrete with fly ash and metakaolin by 3 to 15 times at 400℃ and 20 to 40 times at 800℃ when compared to rapid chloride permeability at room temperature. Poon et al. [7] noticed an increase in rapid chloride permeability of concrete with fly ash and silica fume by 5 to 20 times at 800℃ when compared to rapid chloride permeability at room temperature.

Table 4. RCPT Values at elevated temperatures

Admixtures	RT	400°C	800°C
M4	1732.5	2418.3	5639.4
M4AlNs	934.2	1584.9	4927.5
M5	1557	2035.8	5383.8
M5AlNs	758.7	1309.5	5647.5
M6	1518.3	2007	5996.7
M6AlNs	706.5	1170	6990.3

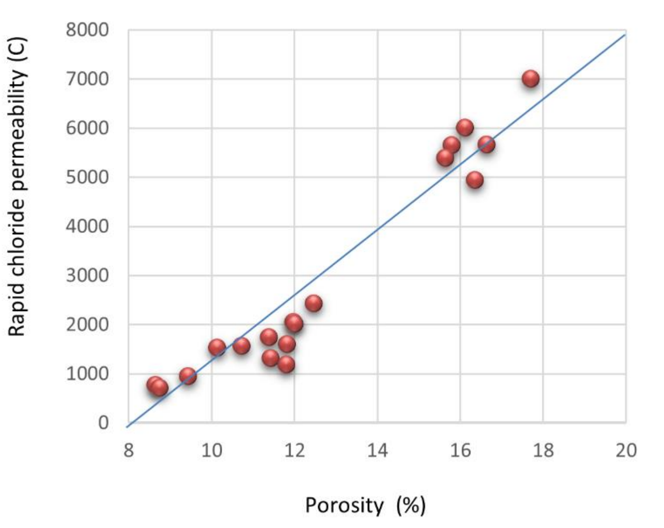


Fig. 14 Porosity vs. rapid chloride permeability

3.4. Microstructural Analysis

Microstructural analysis using SEM examinations of concrete specimens revealed distinct morphological changes as a result of exposure to high temperatures [27]. At 400°C, the concrete matrix appeared coarser and no ettringite was detected [28]. On concrete specimens heated to 400°C & 800°C, microcracks and voids are identified as shown in Table 5. The CH disintegrated at 800°C, resulting in a porous concrete matrix [28]. The microstructure seemed to be very porous in comparison to specimens heated to 400 °C, and porosity increased with concrete grade. Wide voids were noticeable in many areas of the M6AlNs mix concrete specimens as shown in Table 5. The number of voids in Al + NS mixes was higher than control mixes which is consistent with the strength characteristics and durability test results provided above. Due to voids, microcracks, and partially deteriorated CSH, concrete specimens subjected to 800°C showed substantial modifications in the micro - structural of the concrete [29]. As a result, the microstructure of the concrete deteriorated, affecting its strength and durability. Arioz et al. [29] and Handoo et al. [27] investigated the microstructures of concrete specimens exposed to 800°C and found similar results.

Table 5. SEM images of different concrete mixes

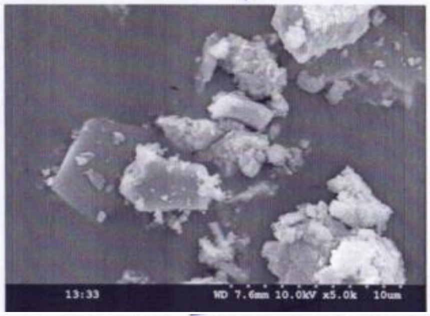
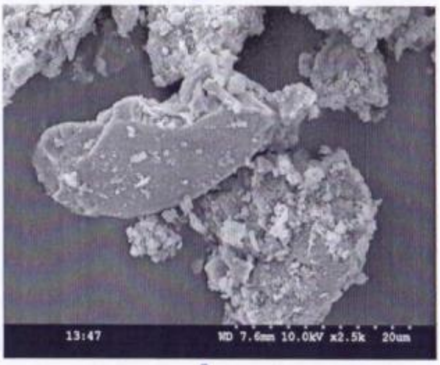
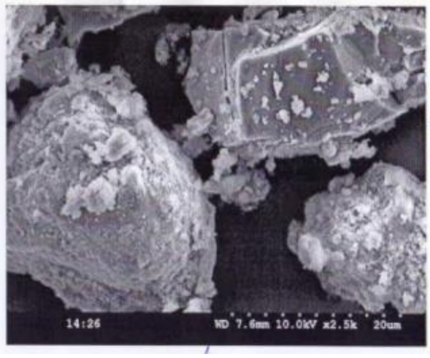
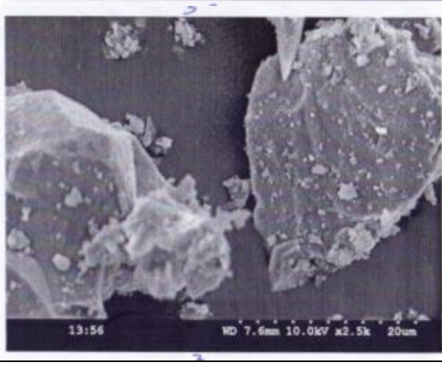
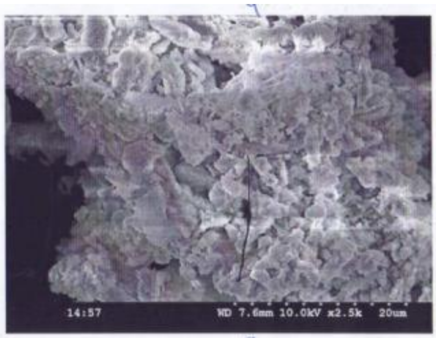
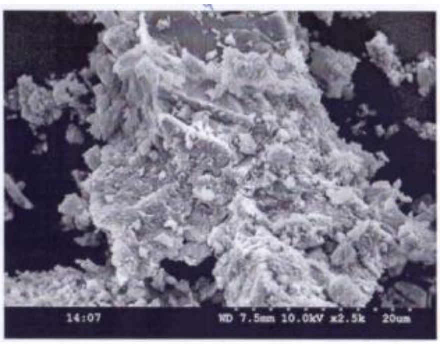
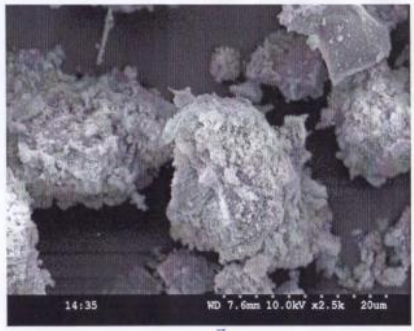
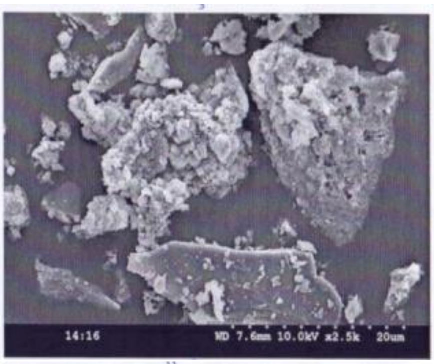
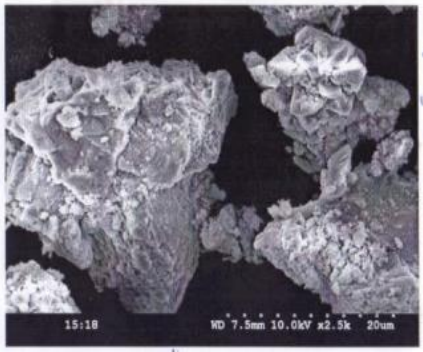
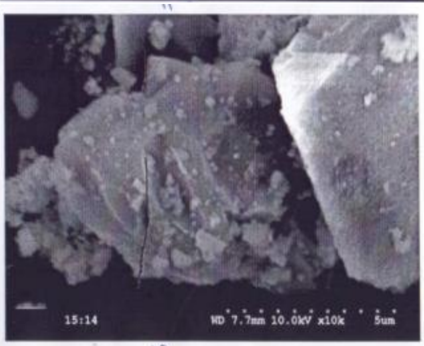
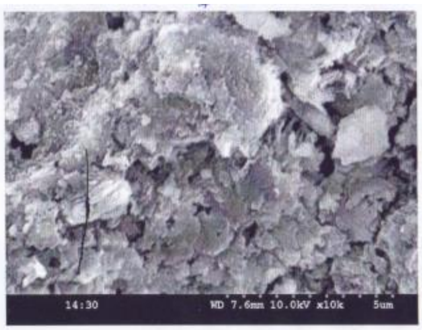
Concrete mixes	Temperature	
	400°C	800°C
M4		
M4AlNs		
M5		

Table 5 (Con.). SEM images of different concrete mixes

Concrete mixes	Temperature	
	400°C	800°C
M5AlNs		
M6		
M6AlNs		

4. Conclusions

The following conclusions can be drawn from the findings of this study:

- The compressive strength of all concrete mixes decreased with increase in temperature, a slight loss of strength was noticed between room temperature and 400 °C and the percentage reduction of Al+ Ns mixes was grater at 800°C. Compressive strength decreased by 0.3 to 1.7% at 400°C, 40 to 48% at 800°C for control mixes, and 1.5 to 3.3% at 400°C, 50 to 56% at 800°C for Al+Ns mixes.
- Cracks appeared in the aggregate & paste's interfacial transition zone (ITZ), as well as within the aggregate and also color of hardened concrete changed with temperature.

- The water absorption and porosity increased with increase in temperature. The percentage increase in water absorption and porosity was greater for Al+Ns concrete mixes M4AlNs, M5AlNs, & M6AlNs at 800°C compared to control mixes M4, M5 & M6.
- The percentage increase in water absorption of control mixes is 8 to 13% at 400°C, 43 to 67% at 800°C and for Al+Ns mixes is 18 to 26% at 400°C, 80 to 118% at 800°C.
- The percentage increase in porosity of control mixes is 9 to 18% at 400°C, 38 to 59% at 800°C and for Al+Ns mixes is 25 to 35% at 400°C, 73 to 102% at 800°C
- At room temperature and 400°C, Al and Ns reduced RCPT values compared to control mixes, but at 800°C, it increased due to increase in porosity.
- For control mixes, rapid chloride permeability increased by 1.3 to 1.4 times at 400°C, 3 to 4 times at 800°C, and for Al+Ns mixes 1.6 to 1.7 times at 400°C, 5 to 10 times at 800°C, compared to rapid chloride permeability at room temperature.
- According to microstructural analysis, the percentage of voids increased and became wider as the temperature rose. As a result, the microstructure of the concrete deteriorated, affecting its strength and durability.

Acknowledgement

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