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Review Article

Effect of Elevated Temperature on Diverse Properties of Concrete Containing Waste Materials

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Among the growing industries around the globe, concrete industry has been contributed significant role to the national economy. The most widely used construction material and the second-most consumed material in the world after water is concrete, which has been employed as insulation in applications involving high temperatures. This extensive review has been highlighted the best possible extracts from the literature on the assessment of thermal effects on various properties of concrete containing various waste products, in particular. Few enhanced performance after being subjected to high temperatures have been reported when industrial by-products are replacing conventional ingredients. Various mechanical properties of concrete after exposure to elevated temperatures have been recapitulated and reviewed. Effect of elevated temperature on many significant physicochemical, mechanical, microstructural changes in concrete made with various materials such as waste slags, recycled coarse and fine aggregates, silica fume, fly ash, crumb rubber, etc. have been vividly summarized and compared. Better performances for concrete incorporating recycled aggregates under exposure to elevated temperature have been reported from the results. Finally, the authors have made an attempt to summarize the short-comings in the specific field of research and discussed on available future scopes on utilization of various industrial by-products in sustainable concrete production under elevated temperature.

Keywords: Elevated temperature, Industrial waste, Mechanical properties, SEM, Sustainable green concrete

1 Introduction

Concrete has most largely been employed construction materials due to its several conveniences like, strength, durability which has been influenced over other construction materials[1]. It has mainly been prepared by blending cement, fine aggregate and coarse aggregate with water, among them, cement is factory manufactured and both the aggregates are natural resources[2]. Aggregate is one of the key materials which has been occupied almost 70% of concrete volume and internationally consumed 8-12 million tons from the natural resources. The natural balance has not been kept preserved due to high consumption of aggregate and become highly demanding. This necessity is the reason for finding alternative resources[3,4]. Sustainability and recycle have been noted as the answer to conquer this requirement. 25% of the wastes have been dumped due to demolishing buildings and roads, from which 90% is recyclable[5]. Sometime concrete has been exposed to fire or high temperature and then the strength of concrete decreases due to contiguity with high temperature. Therefore, these concretes are getting spoiled and turns into undesirable deteriorations. Consequently, the properties of concrete following fire exposure are still significant to bear its strength. Now a day's high strength concrete has extensively been used as it provides better mechanical properties, durability, and plasticity along with superior performances in comparison with normal strength concrete. So, the conviction to exposure of high strength concrete under elevated temperature has to be improved. For high-strength concrete, the addition of silica fume (SF) has been expanded the affectability of concrete subjected to high temperature as far as mechanical properties. Again, spalling sensitivity of high-strength concrete can be controlled by the addition of some polymeric fibers. Few physical and chemical non-reversible changes have been occurred in concrete after exposure to high temperatures. It has been observed that after 750-800°C, concrete loses more than 60% of its initial strength. Therefore, many researchers are interested to prepare a concrete that may have properties to resist the effects of high temperature in several ways. This may be by using some solid wastes

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or industrial by-products as cement and/or aggregates, re-using recycled aggregates, or adding some additives like polypropylene fiber, steel fiber, waste glass powder, etc[6–8]. Crushing concrete aggregate as both fine or coarse aggregate in new concrete have been provided a better clarification. Though, limited research on recycled coarse aggregate (RCA) concrete has been noticed. Increment of both elevated temperature and replacement percentage of RCA have been decreased the residual strength. Higher than 600°C temperature along with utilization of RCA have been decreased almost 20% of strength. But enough experimental researches have been conducted to find the properties of recycled fine aggregate (RFA) concrete at both normal and elevated temperature. Experimental results state that the incorporation of RFA have been improved the residual properties of concrete after thermal exposure. Cumulative results say that a higher replacement by fine and coarse aggregate have been presented 5-40% less compressive strength than normal concrete[9–12]. The main and important effects of high-temperature exposure are dehydration of cement paste, an increase of porosity, thermal expansion, crack formation, strength decrement, etc. It is known as "the thermal incompatibility of concrete components". Thermally induced stresses in the interface transmission zone (ITZ) between cement paste and aggregate have been turned out this divergence. Mainly these slags have been used in road construction but following a suitable treatment, these can be utilized in concrete making process[13–15]. The durability performances of concrete like chloride penetration, sulphate attack, and protection against alkali-silica reaction have been improved by the use of slags such as Ground Granulated Blast Furnace Slag (GGBFS), steel slag (SS), electric arc furnace slag (EAFS) etc. Although lower durability has been provided by the use of higher percentage replacement of raw material in concrete[16,17]. A large amount of fly ash (FA) has been produced in various coal-fired steam power plants and dumped into ash ponds. Almost 7% of total CO_2 emission per annum has been produced by cement industries. So, pollution and solid waste dumping can be reduced by utilizing FA in terms of cement replacement, as it has an economic advantage like pozzolanic material. Fire-resistive assets has been boosted by consuming $Ca(OH)_2$ and forming additional C-S-H gel that provided strength to concrete mixes[18–21]. Heating and cooling rate along with firing duration have been affected the properties of concrete subjected to elevated temperature. Thermal shock have been expected due to accelerated heating and cooling strategies to the concrete which provides surface cracks and internal voids, resulting observable strength decrease happens[19,22]. Additionally, the type and gradation of aggregate have been played significant responsibility on the residual strength of concrete. The experimental result have been presented on the higher imperviousness to fire for carbonate aggregate than siliceous aggregate. Advanced residual strength have been provided for concrete with coarser aggregate than the finer aggregate[23,24]. Crumb rubber (CR) has also been noted as a by-product and utilized as both types of aggregates in concrete. Improved compressive strength just as proficiency to defend against spalling is noted for post-fired rubberized concrete while contrasted with ordinary concrete. In any case, the substitution of aggregate by rubber have been restricted within 5-8% of the total aggregate, more than that may demolish the properties of concrete. Eventually, a higher temperature has been likewise deteriorated the properties of concrete[22,25]. Few studies have been performed on the concrete containing steel spiral fiber or metal spring for advanced mechanical properties of concrete. According to various numerous contemplates, the utilization of an extremely less amount of steel spiral fiber or metal spring has been played an essential role in the mechanical strength, flexibility, and water absorption of concrete. Mechanical strength of the post-fired concrete have been improved by the use of steel spiral fiber or metal spring yet diminished the ductility. Metal spring can prevent the deep and broad cracks for post heated concrete. However, consolidate expansion of steel fiber and metal spring can't perform like the concrete that have been made with metal spring independently after firing at elevated temperature[26]. A deficiency of almost 60% and 55% of compressive strength for air and water cooling techniques on high-density concrete has been stated respectively from 500°C to 750°C. In the event that FA and siliceous aggregate based cement is cooled quickly in water for 5minutes and 20 minutes then almost 35% and 55% of strength diminish has been noted [27].

2 Materials and Methods

Different kinds of waste materials utilized as replacement in concrete reviewed in this article. Utilization of conventional materials in concrete put lots of impacts on the environment that was the motivation of the utilization of different by-products was a trend all through the world to manage down their effect on the environment. RCA, RFA, EAFS, GGBFS, CR, SS, FA SF are the industrial waste products which were utilized as an alternative material in concrete and provided impacts on concrete after submitting to elevated temperature.

The methods which put effect on the properties of concrete submitted to elevated temperature are reviewed as follows: Rate of Heating and Cooling, Firing Duration, Cooling Method, Nature of Aggregate, Size of Aggregate.

3 Results and Discussion

3.1 Factors affecting on the properties of concrete under exposure to elevated temperature

Structural members of concrete used in buildings have to satisfy appropriate fire safety requirements. This is because fire is one of the most expected risks to the construction and structures[1,22]. Concrete is usually identified as high resistance composite material versus elevated temperature[19]. Some factors, which are observed to play chief role in the post-fire properties of concrete, such as the Rate of heating and cooling[7,19,22], firing duration[22,23], cooling method [19,22,24,28], nature of aggregates[19,20,23], size of aggregate[19,20], etc.

3.1.1 Rate of heating and cooling

The rate of heating and cooling of the samples adopted crucial role in the post-heating properties of concrete. It is seen from the experimental results that a higher rate of heating and cooling provided abrupt shock on concrete which brings about the development of wider surface cracks just as a monstrous decrease in mass and mechanical strength of concrete[19]. Critical disintegration isn't noticed for lower temperatures however at a higher temperature, insignificant disintegration is recognized from the surface of the concrete[7]. The samples, cooled rapidly after heated at a higher temperature, showed more extensive crack just as lesser residual mass and strength than typically cooled samples[22]. Time v/s Temperature Curve presented in Fig. 1 is showing heating and cooling rate from different research articles and also compared with ISO:834 curve[29].

3.1.2 Firing duration

The concrete samples are likewise influenced by the duration of firing inside the furnace. Concrete samples which are heated for a lesser time (practically up to 30-60 minutes) may be unable to supply desired strength though the samples which are heated approximately for 2-4 hours fulfill the desired properties. But if the exposure time increased over 6 hours, the post-heated properties may not fulfill its ideal prerequisites. Experimental results showed that lesser time exposure to elevated temperature influenced appropriately for the concrete samples. Again, higher time exposure to high temperature made the specimen brittle. On the off chance that the

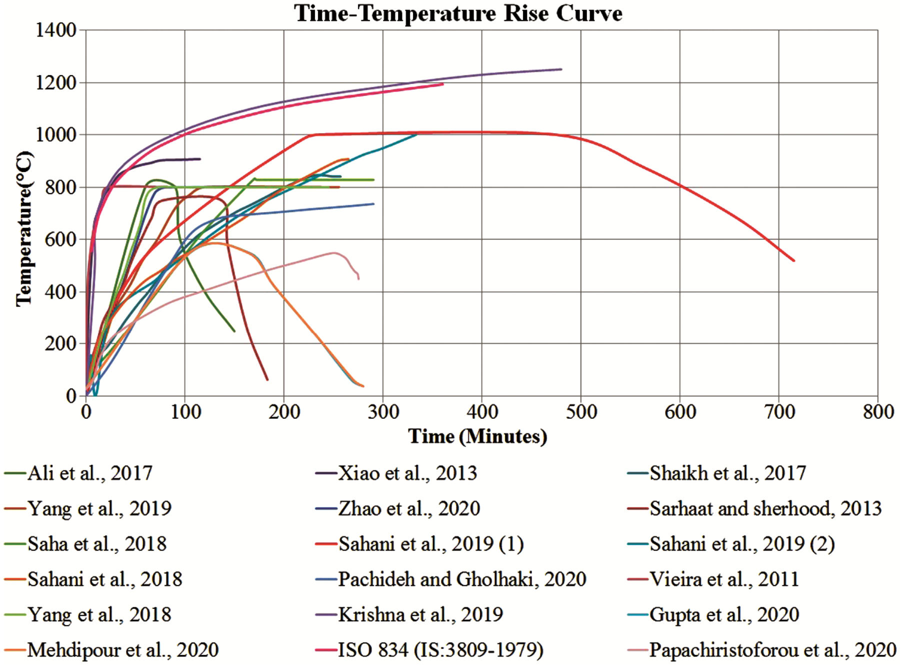


Fig. 1 — Time v/s Temperature Curve.

samples treated at elevated temperature for 2-4 hours, the expected properties of concrete developed. It could be a result of decomposition of C-S-H (Calcium Silicate Hydrate) gels and evaporation of chemically combined water[22,23]. Time v/s Temperature Curve presented in Fig. 1 showing the duration of firing from different research articles.

3.1.3 Cooling method

The way toward cooling the samples after exposure to elevated temperature played a critical function on the residual properties of concrete. Samples after heat treatment cooled by couple of strategies[19]. One was rapid cooling system' in which warmed samples were cooled by submerging in cold water or splashing cold water on the sample surfaces. Another was typical cooling strategy' where samples were simply kept at room temperature for soothing. Accelerated cooling techniques conveyed a thermal shock on the specimens. Consequently, changes in surface color, surface crack, gigantic decreased in residual strength, occurred on the concrete samples though these kinds of failures were viewed as less significant for normal cooling strategy[22,28]. Typical cooled samples showed higher residual mass and strength than the quickly cooled specimens. Air-cooled samples showed nearly 3-16% more residual compressive strength than the water-cooled samples. As the temperature built, the concrete specimens with a fast-cooling system became worse affected[28]. Specimens' exposure to lower temperature showed tiny cracks whereas more extensive and profound surface cracks seen for the specimen's exposure to a higher temperature. Various kinds of surface color changes happened for the two sorts of cooling techniques yet no specific pattern noted[24].

3.1.4 Nature of aggregate

As the aggregates takes about 70-80% of volume, the kind of aggregate considered in concrete showed a significant role in the post-fire properties of concrete. Experimental results from different authors said that carbonate and dolomite aggregates showed evidence of higher imperviousness to fire properties than siliceous aggregate followed by limestone aggregate. Experiments additionally demonstrated that concrete with coarser aggregate had lower strength loss and less spalling as assessed to that of finer aggregate. Lightweight aggregate concrete didn't lose serious strength up to 600°C because of its origination at high temperatures and lower thermal conductivity. The sort of aggregate additionally put an effect on the poison ratio of concrete after submitted to elevated temperature[19,20,23].

3.1.5 Size of aggregate

The maximum size of aggregate utilized in concrete additionally influenced the post-fired properties of concrete. Concrete specimens which are fired up to 300°C, not influenced by the size of aggregate[20]. Experimental outcomes from different authors affirmed that concrete prepared with coarser aggregate had a lesser strength reduction when contrasted with that finer aggregate. Result additionally took attention to that larger aggregate concrete experienced less spalling besides finer aggregate concrete showed explosive spalling later than high-temperature exposure. The larger size of aggregates built concrete less proficient to spalling because of its making of a more extended fracture process region[19]. Particle size distribution of RCA, RFA, CR, EAFS, and GGBFS presented from Figs 2-6 respectively.

3.2 Materials influencing the properties of concrete under elevated temperature

Different kinds of waste materials utilized in concrete as fractional or total aggregate substitution material[5]. Concrete after submitting to elevated temperature, physical and chemical changes took place

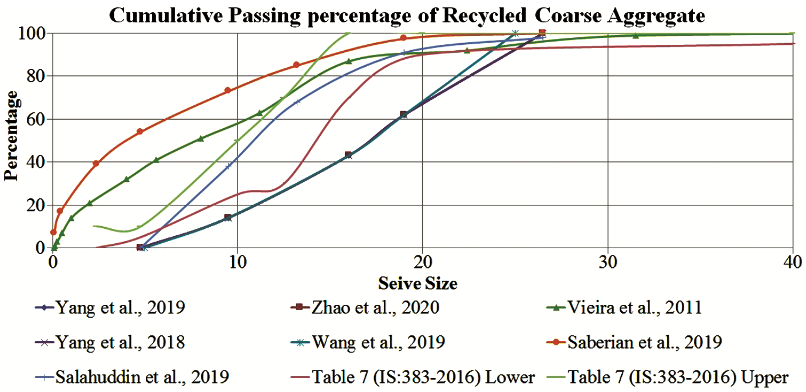


Fig. 2 — Particle Size Distribution of RCA and compared with natural coarse aggregate, Table 7[68].

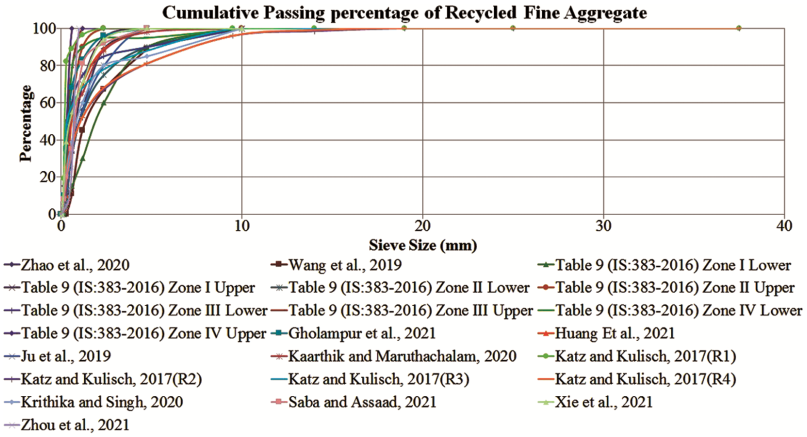


Fig. 3 — Particle Size Distribution of RFA and compared with natural fine aggregate, Table 9[68].

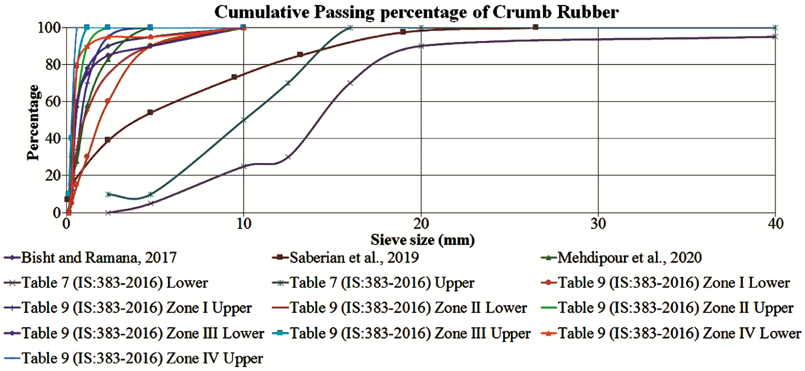


Fig. 4 — Particle Size Distribution of CR and compared with natural aggregate, Table 7 and 9[68].

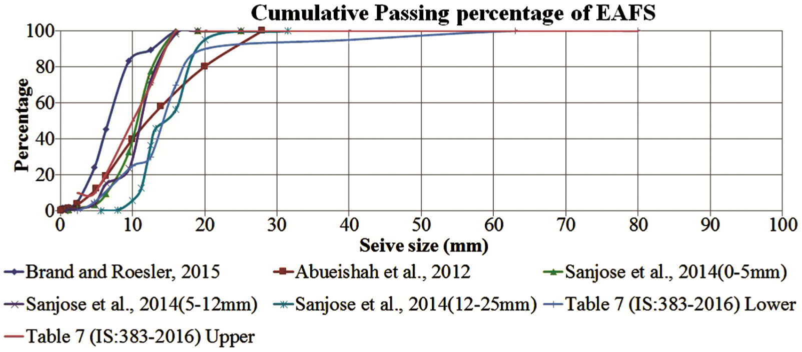


Fig. 5 — Particle Size Distribution of EAFS and compared with natural aggregate, Table 7 and 9[68].

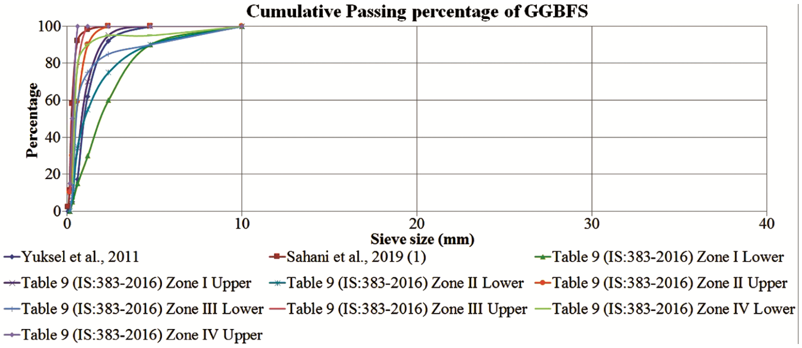


Fig. 6 — Particle Size Distribution of GGBFS and compared with natural fine aggregate, Table 9[68].

Table 1— Physical properties of waste materials

Materials	RCA	FRA	SS	EAFS	GGBFS	CR	FA	SF
Articles Properties	9–12,15,24,28, 30–33,62	12,24,35–41,43,62	13,23, 42,52	44–46,60	14,20,27, 28,44,58–61	22,53,54,57	10,24,25,27, 28,49,60,61	8,18
Dry Density (kg/m^3)	2250-2520	2222-2820	2900-3210	2092	2800-2850	NA	2310-2400	2200-2320
Bulk Density (kg/m^3)	1310-1957	1225-2690	1940	1562-1700	1236-1690	455-545	NA	1002
Water Absorption (%)	1.3-9.25	3.97-10.83	0.8-3.7	0.45-3.35	4-8.3	0.3	NA	NA
Crushing Index (%)	12-15.2	NA	NA	22	NA	NA	NA	NA
Specific Gravity	2.28-2.45	2.29-2.52	3.19	3.01-3.97	2.08-2.91	1.05-1.15	2.05-2.9	2.32
Fineness Modulus	NA	2.4-3.3	NA	NA	NA	NA	NA	NA

Table 2 — Chemical properties of waste materials

Materials	FRA	EAFS	GGBFS	SS	FA	SF
Articles Components	35,37,41,62	44–47,60,67	14,20,27,30,50, 51,58–61,68,69	16,33,58,59	14,24,25,27, 49,50,61,69	44,57,62
SiO2	49.41-68.86	9.6-26.4	21-39.66	14.38-17.08	46-58.75	93.6-98
CaO	4.45-16.96	16.9-39.62	31.6-56.1	24.98-45.23	1.46-10.56	0.35-0.83
Al2O3	0.16-10.65	3.9-11.57	11.63-23.7	4.7-7.19	21.85-33	0.05-0.37
Na2O3	1-2.11	0.11-0.6	0.13-0.46	0.12	0.3-2.3	0.02-0.33
K2O	0.83-3.1	0.03-0.06	0.26-0.65	0.13	0.46-4.8	0.15-0.17
MgO	0.8-2.32	1.9-9.23	1.85-9.8	3.46-10.58	0.89-2.57	1-1.21
Fe2O3	2.76-6.31	23.9-44.8	0.15-3.35	20.34-37	3.31-13.5	0.11-3.08
SO3	0.17	0.1-0.26	0.6-4.58	0.25-0.34	0.08-0.65	0.55-0.9
MnO	0.1	0.7-6.28	0.24	2.9-8.91	0.02	NA
P2O5	0.01	0.2-0.52	0.01-0.02	0.4	0.78-0.98	NA
Cr2O3	0.01	4.1-5.1	NA	NA	NA	NA
TiO2	0.25	0.04-0.65	0.55-1.38	NA	1.54-2.6	NA
LOI	13.3-22.13	NA	0.05-1.08	4.99	0.51-3.5	0.53-2.88

which resulted in some modification in various properties of concrete[27]. As the utilization of regular raw materials in concrete left lots of impacts on the environment, that was the reason of the utilization of different by-products was a trend all through the world to manage down their effect on the atmosphere[30]. RCA[9–12,15,24,25,28,30–33], RFA[12,24,34–43], EAFS[44–47], GGBFS [7,13,14,20,21,23,48–51], CR[22,25,52–57], SS[6,16,33,58–60], FA[17,18,20,21,49–51,59,61], SF[8,17,18,21,62,63] are the industrial waste products which were utilized as an alternative material in concrete and provided impacts on concrete after submitting to elevated temperature. The physical and chemical properties of waste materials from various sources presented in Table 1 and Table 2 respectively. Images of the waste materials presented in Fig. 7.

3.2.1 Effect of recycled coarse aggregate

From visual perception, no critical impact was noticed below 400°C temperature. Then the formation of silly cracks started within the temperature 400-600°C. The cracks became prominent after the exposure to 600°C. Exposure to high temperature, for example, 750-800°C the cracks turned more extensive and more profound too[9,10,12,15,24,28,31]. No spalling was observed for every specimen. This no-spalling tendency was seen to be followed for every sample during heating and after cooling too[9,11,12,15,24,28,32]. Concrete specimens incorporating a very less amount of CR along with RCA had an evidence of spalling at and over 600°C[25]. Different color changes were likewise seen after different temperatures restoring even though no accurate connection was seen for changes of color. However, hardly any shades of dark tone were seen at a lower temperature, and at the exceptionally high-temperature yellowish surface was taken note[9,24,28,31]. Residual compressive strength after heat curing was appeared to be decreased with the addition of temperature for a fixed substitution level. Though just air-cooling samples after exposed within 100-200°C were showing somewhat upgraded result than the unheated samples. However, for a fixed temperature, specimens with half substitution just provided a marginally better residual compressive strength contrasted with different examples. This failure might be because of dehydration and disintegration of hydration items[9–12,15]. It is interesting to see that samples with a higher level of substitution were showing either relatively comparable or marginally higher properties than any remaining examples inside the temperature range 250-500°C. The

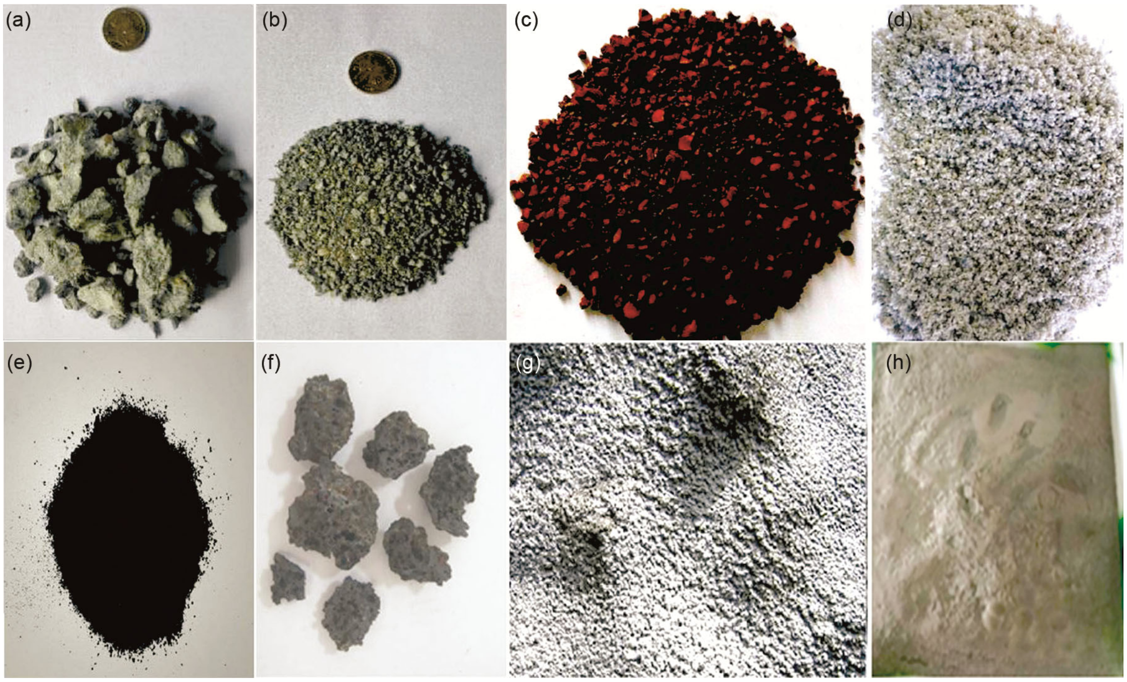


Fig. 7 — Images of waste materials (a) RCA[19], (b) RFA[19], (c) EAFS[67], (d) GGBFS[27], (e) CR[33] (f) SS[56], (g) FA[27], and (h) SF[71].

explanation for addition and decrement of the compressive strength after exposure to different temperature was related with the proper and improper thermal coordinating respectively between binder material and aggregate. High-strength concrete specimens with lesser water-cement proportion had faced a higher reduction in compressive strength after exposure to elevated temperature[28,30–33]. Concrete, with minimally added CR and waste steel wires, showed enhancement in residual compressive strength after temperature treatment [25,32]. An equivalent pattern of diminishing in split tensile strength was noted for all types of samples with the ascent of elevated temperature. Diminishing in split tensile strength following exposure to elevated temperature was somewhat higher than the reduction in compressive strength. Improvement after the formation of micro-cracks occurred because of crack concurrence after submitted to elevated temperature. Within an exposure to 600-800°C temperature split tensile strength of recycled aggregate concrete developed to be more conspicuous which suggested a higher physical and chemical decay inside its microstructure[15,28,30,31]. The utilization of RCA decreased the flexural strength of concrete. These declination increased with the increment in the amount of RCA in concrete. But, for a fixed substitution level residual flexural strength diminished with the increment of temperature. Eventually, it turned out to be right around zero at a high temperature. A comparable pattern of higher reduction in compressive strength at low water-cement proportion was seen for flexural strength too[9,33]. The proportion of modulus of elasticity between typical concrete and the replaced specimens was appeared to be comparable for a fixed temperature. The diminishing propensity of elastic modulus was noticed for the RCA with the increment of both substitution proportion and temperature. An immense drop in residual modulus of elasticity was numbered within the temperature 400°C. Sometime this decrease in modulus of elasticity was more significant than the declination in residual compressive or split tensile strength of concrete. For this situation, the water-cement proportion didn't influence the modulus of elasticity[10,11,15,31,33]. Mechanical properties of fire exposed RCA concrete mixes shown in Fig. 8.

3.2.2 Effect of recycled fine aggregate

RFA put significance for the density of fresh and hardened concrete. Both the densities were accounted for as diminishing order with the increment of the amount of RFA[36]. The impact of RFA on the formation of surface cracks was similar like the impacts of RCA with the exception of few issues. Prominent cracks didn't remain critical after the temperature arrived at 800°C[12,24]. The use of RFA did not provide any tendency of spalling in concrete. Color changes were not significant until the

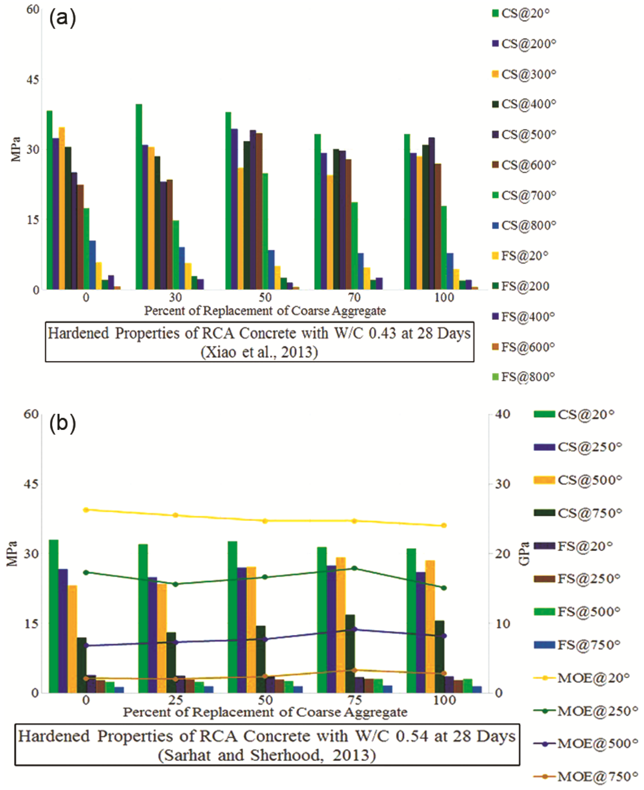


Fig. 8 — Hardened Properties of RCA Concrete After Exposure to Elevated Temperature, (a) W/c 0.43 at 28 days, and (b) W/c 0.54 at 28 days.

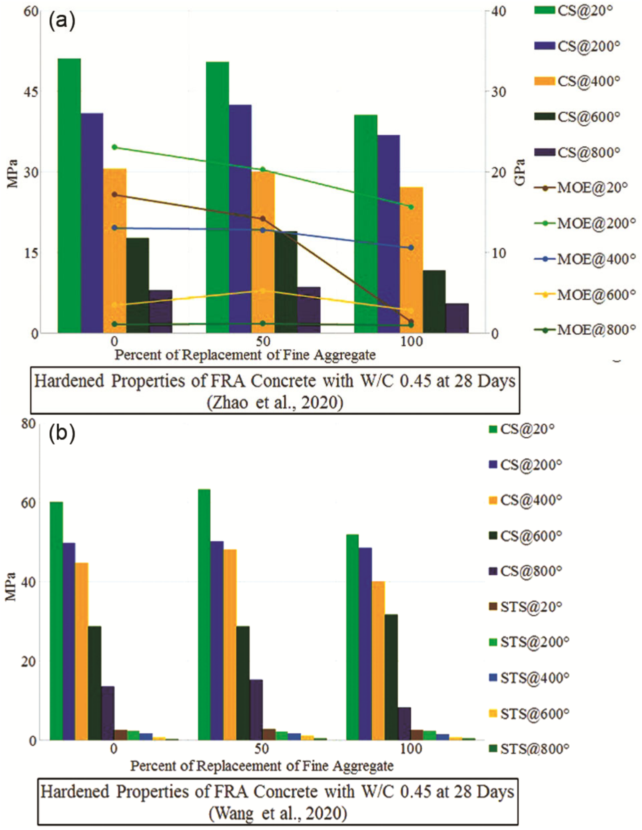


Fig. 9 — Hardened Properties of RFA Concrete After Exposure to Elevated Temperature.

temperature arrived at 400°C. However, the surface color of concrete samples changed to yellowish-grey at 800°C from whitish-grey at 600°C. Finally, almost light-yellow shaded concrete was seen after 800°C[24]. RFA improved the residual compressive strength of concrete when presented to a lower temperature. Equivalent distribution between regular and RFA improved the compressive strength of concrete subsequent submitting to 200-400°C. A higher amount of RFA at a higher temperature additionally improved the residual compressive strength in concrete. This improvement might be a direct result of comparable thermal development among old and new mortar[12,24]. Diminishing pattern in modulus of elasticity of RFA concrete was seen as the temperature increments. A slight increment or basically no decrease was noticed for the samples with 50% substitution within 400-600°C temperature. The residual elastic modulus of all types of examples turned out to be practically similar on or after the temperature of 800°C[12]. RFA affected split tensile strength when submitted to a similar temperature. A reduced pattern was seen for split tensile strength when the temperature increased however change was notified when the substitution rate increased. So essentially any unmistakable relationship wasn't found for the changes of split tensile strength at elevated temperature[24]. Mechanical properties of RFA concrete samples exposed to elevated temperature displayed in Fig. 9.

3.2.3 Effect of ground granulated blast furnace slag

Utilization of GGBFS took more consideration for improving the properties of typical and post-fired concrete. Optical inspection of the specimens showed the basic grey color that implied no color change happened up to 400°C. The light reddish-grey tone at 600°C followed by whitish pink tone at 800°C was noticed. The reddish tone was looked after exposure to 1000°C temperature. These changes of shading were affected by the sorts of aggregates utilized in the concrete[20,21,23]. The crack pattern of post-fired concrete samples containing GGBFS was very not the same as post-fired typical ones. No cracks were found on the sample surface till 200°C temperature. Micro-cracks were found on surface within the temperature of 200-500°C. After that temperature, less but more extensive cracks were found on the surface of the concrete while the specimens had a higher substitution proportion. This explanation potentially might be because of divergent extension between aggregates[7,14,20,23]. No explosive spalling was noticed all through the absolute heat treatment method and assuming occurs, that was irrelevant. However, unstable corner and additionally surface spalling was noted uniquely at high temperature if either heating rate or duration of heating was more. This might be expected to escape of evaporable water or chemically bounded water[7,14,20,23]. Changes in compressive strength of concrete before and after exposure to elevated temperature were huge with the augmentation of GGBFS. A slight yet unimportant addition in compressive strength was seen before heat relieving when 20-40% substitution of fine aggregate happens by GGBFS. Minor addition or similar strength was additionally noticed for the samples with 0-20% cement alternation by GGBFS within 200-400°C[7,13,14]. 10-30% alternation of fine aggregate by GGBFS provided better residual strength at all temperatures than other replacement level. The distinction in strength at a fixed lower temperature wasn't huge for all types of samples. After treatment at a very high temperature, an extreme decrement was noticed for all types of samples. The decrement pattern was higher when the substitution proportion is higher. This significant loss in compressive strength might be because of dehydration and decomposition of C-S-H gel at extremely high temperature[20,21,23]. Utilization of 10-50% of GGBFS as an elective material in concrete built split tensile strength at room temperature. A slight unexpected decrement of split tensile strength up to 200°C temperature subsequently slow decrement with the increment of temperature was seen for all types of examples. Split tensile strength diminished strongly while contrasted with compressive strength. That might be because split tensile strength was more sensitive to cracks. Specimens tend to untie under tensile loading which took into consideration crack opening[14,21,23]. Flexural strength at room temperature was appeared to be in increase mode up to 30% utilization of GGBFS followed by a decrement pattern was seen. The flexural strength of concrete was upgraded by the utilization of GGBFS while compared with ordinary concrete at all temperatures. The tendency of flexural strength after exposure to elevated temperature was appeared to be diminished while compared with the strength at room temperature. Residual flexural strength proportion was lower up to 200°C yet from that point onward, it turned out to be superior to ordinary concrete[21,23]. The modulus of elasticity before heat exposure didn't fluctuate with the increment of replacement. A steady diminishing approach at a fixed temperature was seen with the addition of GGBFS in the concrete. Additionally, continuous decrement was likewise seen with the increment of temperature for a fixed replaced level. GGBFS displayed a gigantic loss for modulus of elasticity between the least and highest elevated highest temperature[7,13,14]. Hardened properties of post fired GGBFS concrete specimens shown in Fig. 10.

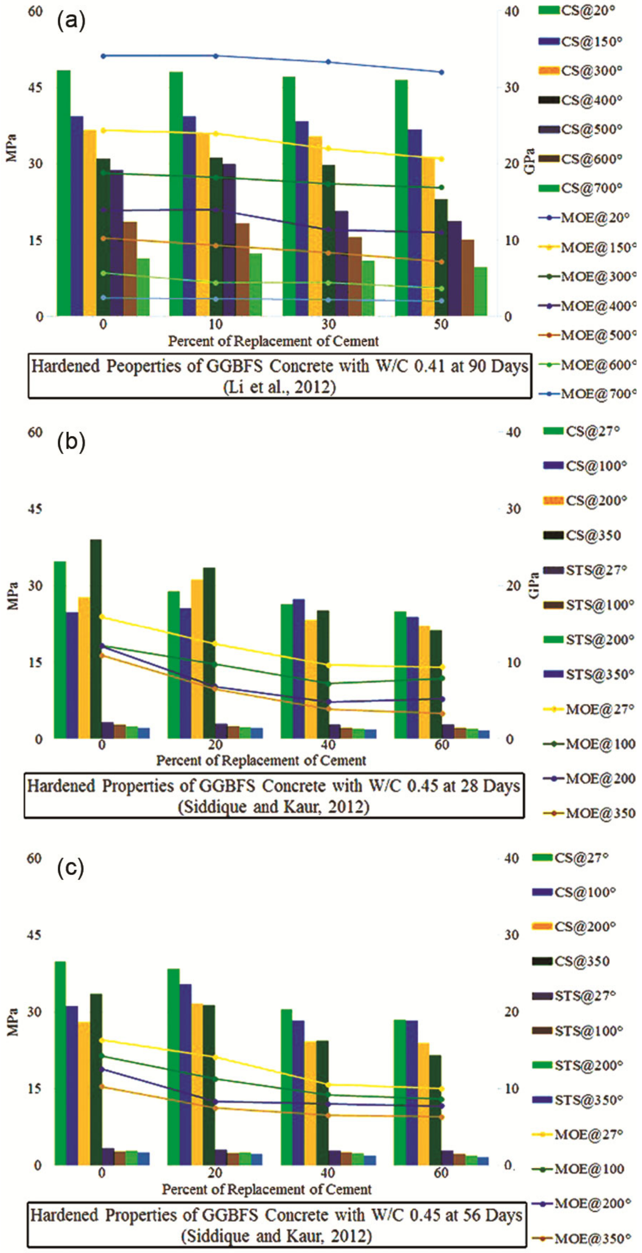


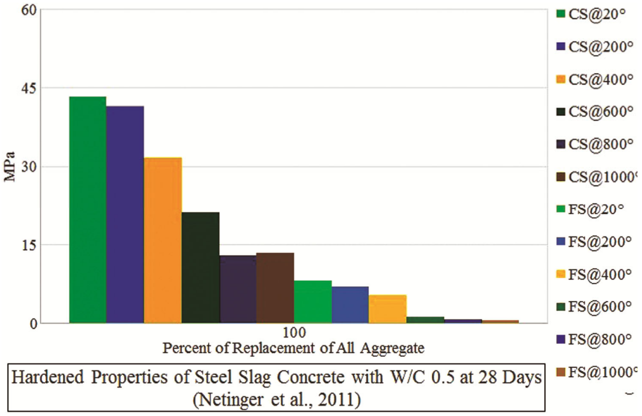
Fig. 10 — Hardened Properties of GGBFS Concrete After Exposure to Elevated Temperature.

3.2.4 Effect of steel slag

The imperviousness to fire properties of concrete prepared with SS as alternative raw material focused around this segment. No micro cracks were seen at a lower temperature. Advancement of micro cracks was observed after a high range of thermal treatment. Concrete prepared with SS as a raw material didn’t show spalling mechanism at any temperature if the heating rate is 1-2°C/min[16,58]. Residual compressive strength of concrete increments as the water-cement ratio diminished. At lower temperature SS didn’t fulfill much as it fulfills at higher temperature as far as residual compressive strength. Below 400°C residual compressive strength was lower for the typical concrete however much improvement is seen while the temperature was 400°C or above it. Performance of SS concrete turned out to be low after 800-1000°C temperature while correlation with typical concrete. It was likewise noticed that high volume SS in concrete might diminish the performance at any condition[6,16,33,58,59]. As to flexural strength, SS concrete showed fundamentally prevalent performance through entire temperature range[6]. For a particular specimen, the modulus of elasticity was either higher or similar within 100-200°C yet from that point forward, it went down. Within 800-1000°C territory modulus of elasticity turned out to be extremely low while contrasted with ordinary concrete. A similar inclination was noted for all experimental cases. At higher age, thermally treated SS concrete showed a quite a close modulus of elasticity[16,58,59]. Figure 11 showed the hardened properties of post fired SS concrete specimens.

3.2.5 Effect of crumb rubber

Rubberized concrete samples were showing few surface cracks subsequently submitting to high temperature. Incorporation of a higher amount of rubber and exposure to high temperature made extra voids to the sample which developed additional surface breaks. This incident happened might be because of the transformation of calcium hydroxide from calcium oxide at an elevated temperature which aimed enhancement in volume and eventual outcome significant cracks in concrete[22,54,56]. At lower temperatures, rubber concrete samples didn’t affirm such spalling from its surface. In any case, the combination of a higher quantity of rubber and temperature made a propensity of spalling in concrete. The specimens begun to spall when the temperature was more than 500-550°C. It superbly might be because of the decomposition of higher rubber content at higher temperatures[22,25,56]. The compressive strength of concrete was straightforwardly impacted by the utilization of CR. At room temperature, lessening in compressive strength of concrete at any period was transparently relative to the amount of rubber added aside from 10-20% addition[53,54]. The compressive strength of concrete appeared to be in higher-order at any temperature when the level of CR existed within 5%. Yet, as the amount was over 5% then a minor development in strength was seen after exposure up to 150°C and after this temperature compressive strength begun to diminish. This increment in strength might be confirmed because of a fall in calcium hydroxide and an un-hydrated spot which was positive for microstructure. Compressive strength of concrete was noticed to be diminished with the addition of exposure timing for a fixed specimen[22,25,56]. Prior to heating, lower substitution of aggregates by CR outcome in quite similar split tensile strength like the ordinary samples though decrement propensity was noticed for a higher level of replacement. Decrement of split tensile strength seen with the increment of temperature. In any case, decrement in split tensile strength was more conspicuous within the temperature range 450-600°C. After 600°C split tensile strength of rubberize concrete appeared to be a poor circumstance[53,56]. The flexural strength of rubberize concrete specimens constantly decreased with the increment of replacement proportion[53,54]. Before fire exposure, a similar tendency of decrement like compressive strength also noticed for modulus of elasticity. After exposition to exalted temperature, the decreasing propensity was notified for all types of specimens. Up to 300°C, this decrement reached almost 50% when the specimen having incorporation of more than 25% CR. Discharge of water vapor and extension of cracks right through the



Hardened Properties of Steel Slag Concrete with W/C 0.5 at 28 Days (Netinger et al., 2011)

Fig. 11 — Hardened properties of ss concrete after exposure to elevated temperature.

voids guided the diminution of modulus of elasticity[22,53]. Post fired mechanical properties of concrete incorporating CR displayed in Fig. 12.

3.2.6 Effect of fly ash

No color change was seen for the specimens incorporating FA concerning normal concrete up to 400°C. FA samples turned their surface color to reddish black at 600°C temperature and it became reddish or brownish-white after exposure to 800°C temperature. Finally, surface became reddish after submitting to 1000°C. From the visual examination, no surface cracks were witnessed within the temperature of 400°C. Few hairline cracks were detected after exposure to 600°C temperature. Those cracks became prominent after exposure to 800°C or more temperature. No spalling was detected almost up to 800°C temperature exposure. But the samples had a minor tendency of a corner and/or surface spalling after curing at 1000°C temperature[20,21]. The compressive strength of the normal specimen provided better results at any temperature than every specimen incorporating FA. Residual compressive strength of concrete diminished with the increment of FA percentage at a specific temperature. Among all the specimens only 10-20% replaced specimens provided better results at any temperature. But at very high temperatures i.e., 800°C, the residual compressive strength of FA concrete samples was almost similar to each other. More than 30% replacement of raw material by FA showed poor results at any temperature. The decrement of compressive strength at any temperature was very large if high volume FA was used. It happened due to the slow pozzolanic reaction rate of FA. FA based samples showed improved result at longer age due to the mutual effect of cement hydration and pozzolanic action of FA in the growth of long-term strength due to the supplementary CSH gel development at a later age[17,18,59,61]. The split tensile strength was always higher for the samples incorporating FA than the normal concrete samples. This trend followed through the whole experiment even after incrementing of elevated temperature. But if the temperature increased for a specific FA-based sample, then the split tensile strength seemed to be diminished with the increment of temperature. The decrement ratio was less up to 200°C temperature and beyond that, the ratio was noted to be increased[21,59]. In the case of flexural strength, a similar tendency like split tensile strength was noted for the FA-based concrete samples. Percentage of residual flexural strength appeared more for FA-based samples while compared to the normal concrete samples[21]. Figure 13 presented the residual compressive strength of concrete with FA.

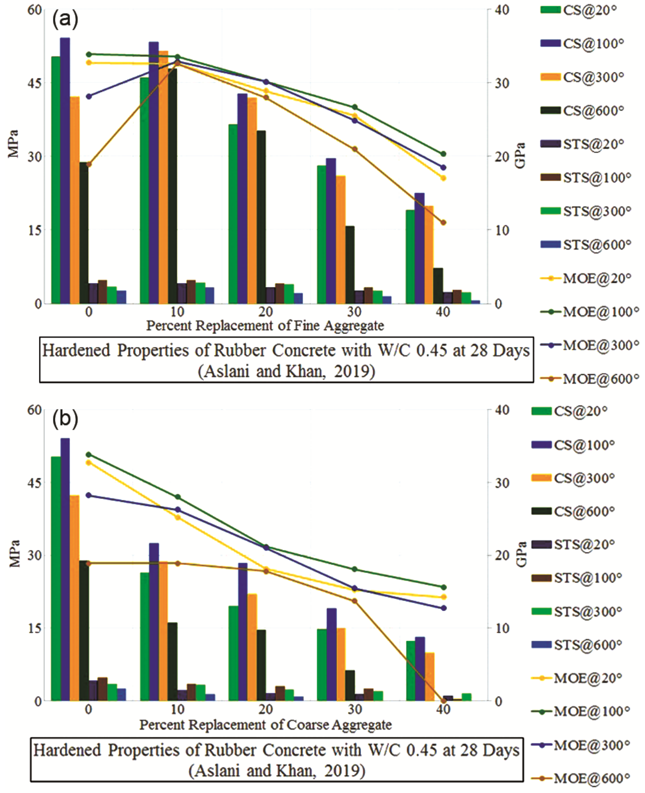


Fig. 12 — Hardened properties of rubber concrete after exposure to elevated temperature.

3.2.7 Effect of silica fume

Concrete specimens up to 300°C temperature showed no spalling by any means. Within the range of 300-500°C temperature concrete specimens displayed fractional spalling from its corner or surface. In any case, beyond the temperature of 600°C, the spalling

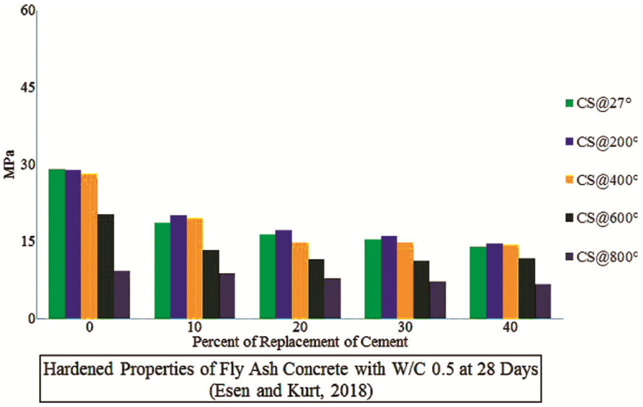


Fig. 13 — Hardened properties of fa concrete after exposure to elevated temperature.

inclination was excessive. Sometimes the samples crumbled inside the furnace[8]. Compressive strength of concrete consolidating 10-20% SF showed comparative outcomes while contrasted with control specimens. In any case, at lower temperature for example within 400°C, samples with 10-20% substitution by SF showed an increment in compressive strength concerning typical samples. That was on the grounds that it filled the micro voids of the concrete resulting the development in strength. After 400°C, no particular pattern of decrement seen for the samples incorporating SF. At very high temperatures residual compressive strength diminished radically. This value was almost zero when the temperature was on or above 800°C[8,17,18]. On account of flexural strength, the value could be perceived by three zones. In the first zone, the flexural strength dropped somewhat higher up to 200°C. At that point up to 400°C decrement propensity was lower than the past one. Finally, it again dropped up to 600°C temperature and beyond that temperature, the flexural strength went almost zero like compressive strength[8]. Residual compressive strength of concrete mixes incorporating SF after exposed to elevated temperature showed in Fig. 14.

3.3 Microstructural study

Calcium Silicate Hydrate (CSH), Ca(OH)2 (CH) were the most important hydrated stages existing in the concrete. The variable quantities which affected the mechanical behavior of CSH phases were the shape, size, concentration, spreading, orientation of grains and pore structure. Scanning Electron Microscope (SEM) clarified the establishment of appropriate and clear CSH gel in several steps[5,12]. Microstructural studies of concrete incorporating various waste materials under elevated temperature were reviewed as follows:

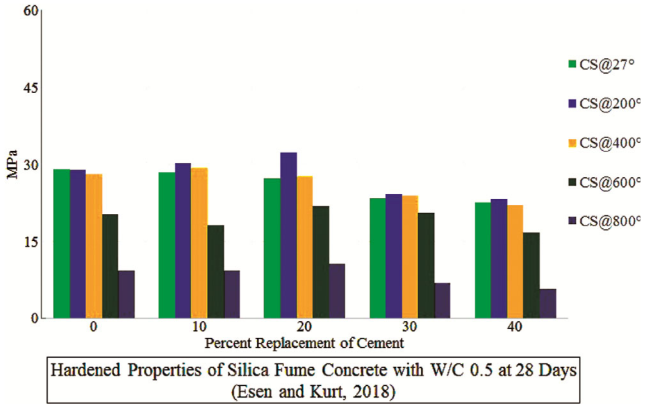


Fig. 14 — Hardened properties of sf concrete after exposure to elevated temperature.

**Note:* *CS@200°; STS@200°; FS@200° and MOE@200° indicate the Compressive Strength; Split Tensile Strength; Flexural Strength and Modulus of Elasticity of concrete specimens after exposure to 200°C temperature. Compressive Strength; Split Tensile Strength & Flexural Strength are shown in primary vertical axis and Modulus of Elasticity is shown in secondary vertical axis.*

3.3.1 Recycled coarse aggregate concrete

SEM images exposed the upshot of elevated temperature on the degree of porosity and morphological variations in RCA concrete accompanying with the increase in temperature. Slackly packing, large crystalline but equitably filled microstructural graphs were observed in RCA concrete. It confirmed the RCA concrete as porous in nature. SEM images also revealed the chemical and morphological changes with the increment of temperature. Crystallinity in microstructure developed with the rise in temperature and loss of CSH and Calcium Sulfoaluminate hydrate (CASH) gel due to dehydration[31]. Figure 15 displayed the SEM images of RCA concrete after exposed to various temperature.

3.3.2 Recycled fine aggregate concrete

From the micro-structural study, it has been observed that the internal structural of samples with FRA was compact at lower temperature up to 200°C and alternation occurred when subjected to higher temperature than 400°C. Decrease in CH crystal content begun due to the loss of crystal water, along with the dehydration and decomposition of CSH gel emerged which caused the concrete to make porous. This might be the reason for the deterioration in the compressive strength of FRA concrete. After exposure to same temperature, similar kind of morphological changes were observed in the concrete containing different FRA content[12]. Figure. 16 showed the SEM images of FRA concrete.

3.3.3 Ground granulated blast furnace slag concrete

SEM study on GGBFS concrete showed some basic hydrated products like CSH gel, ettringite and CH gel in additional with some pores, cracks were observed. Poros and disorganized CSH gel was noticed in GGBFS concrete which may result insufficient compaction of newly made concrete. It might be due to the smooth, angular shape and rapid soaking of water from newish concrete as GGBFS has high water absorption tendency. At 800°C detachment of CSH gel aroused which caused internal cracking and coarsening results enormously degradation in the microstructural concrete[20]. Figure 17 displayed the SEM images of GGBFS concrete.

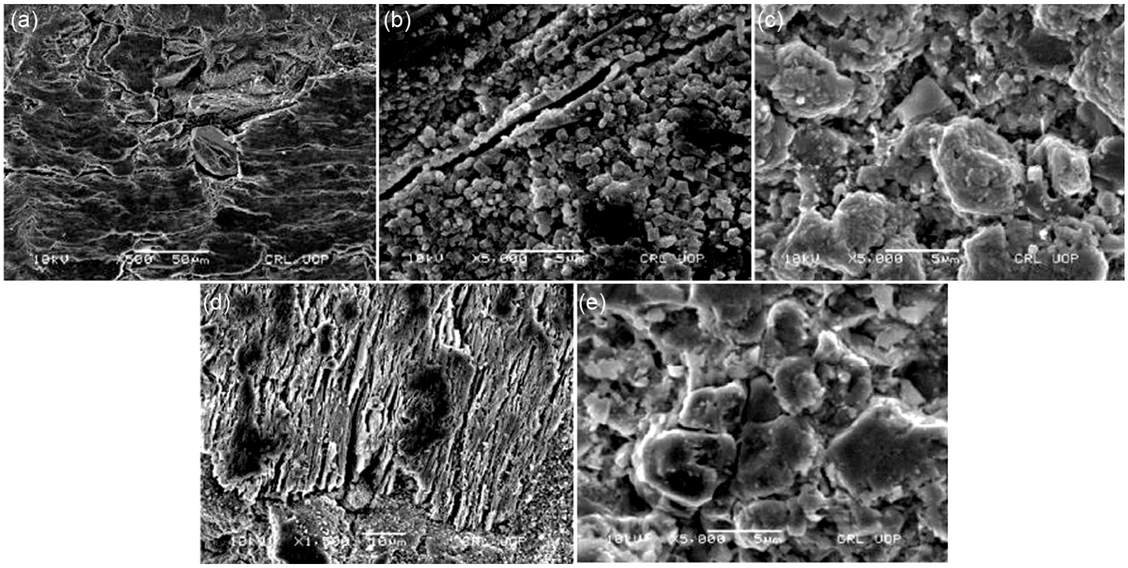


Fig. 15 — SEM images of RCA concrete at (a) 100°C, (b) 200°C, (c) 400°C, (d) 600°C, and (e) 800°C [31].

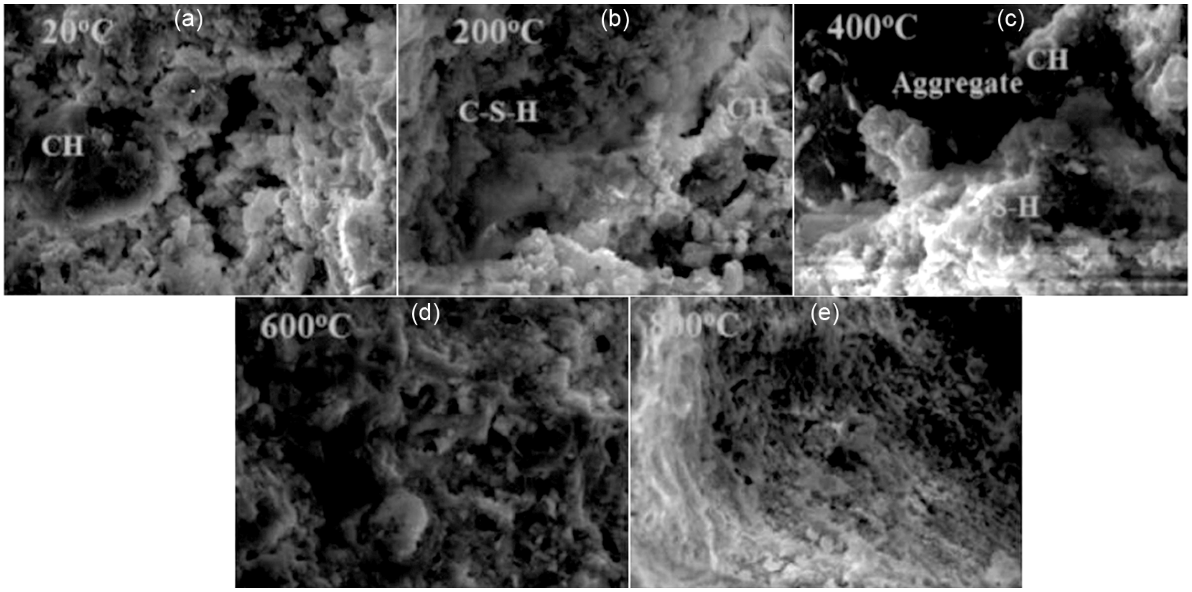


Fig. 16 — SEM images of FRA concrete at (a) normal temperature, (b) 200°C, (c) 400°C, (d) 600°C, and (e) 800°C [12].

3.3.4 Steel slag concrete

The mix was categorized by a compressed interfacial transition zone (ITZ) which contained of CH content about SS aggregates. From the microstructural performance, it looked the SS aggregates were partially hydrous because of the existence of reactive minerals, even though the degree of reaction may differ from grain to grain. The poor performance of slag-based mixes above 200°C temperature could be due to the dense ITZ as the dense ITZ might not accommodate the variances between the thermal enlargement of SS and the contraction of cement paste. Upto 200°C temperature no microstructural changes were seemed but above that, tiny cracks were noticed and after 400°C wider cracks were observed in the ITZ between coarse aggregate and cement paste. At and after 600°C normal aggregates were not affected whereas wider cracks and deteriorations were detected in few extents around SS aggregates. After 800°C temperature total decomposition of CSH is noticed and locally restructuring of CH content was recognized during the cooling process[16,58]. SEM images of SS concrete samples after exposed to elevated temperatures have been displayed in Fig. 18.

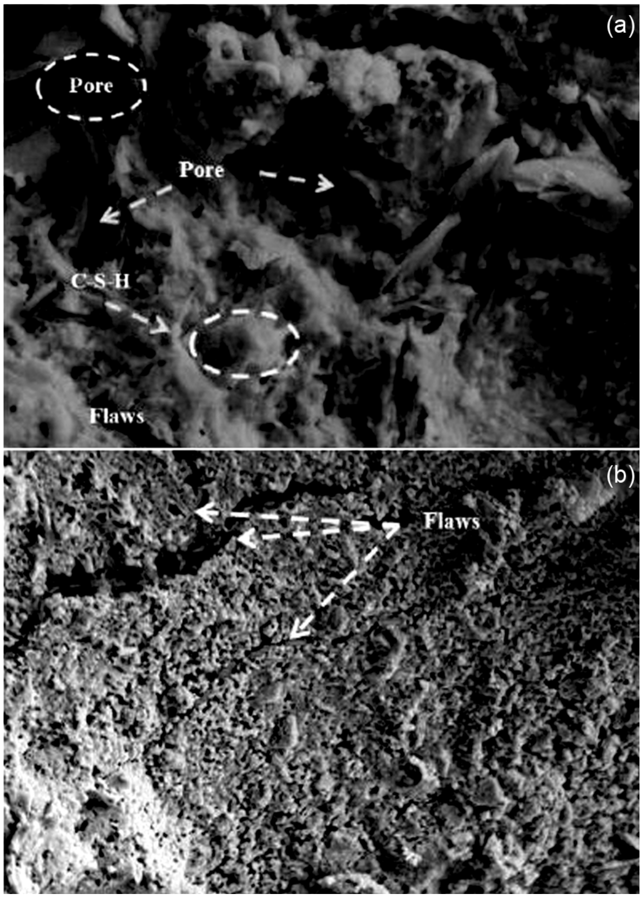


Fig. 17 — SEM images if GGBFS concrete at (a) normal temperature, and (b) 800°C [20].

3.3.5 Rubberized concrete

Microscopic images on rubberized (CR) concrete showed gaps in between rubber aggregate and cement paste, which empowered weaker bond in the sample. These gaps developed with the rise in temperature, consequently, degradation in compressive strength occurred at elevated temperature[22]. SEM images of rubberized concrete samples have been presented in Fig. 19.

3.3.6 *Fly ash concrete*

The microstructure of high-volume FA concrete after exposure to various ranges of temperatures having some partly reacted and unreacted FA particles coated with CSH and CH products which evidenced about the slow reactive properties of FA. These unreacted FA particles caused huge reduction in mechanical strength. But after exposure to low range of temperature, transformation of more reacted grains with enhanced densification was noticed, consequently, development in mechanical strength was observed[18]. At very high temperature, immense deviations in morphology of concrete were detected and so no evidence of unreacted FA particles was realized which demonstrates broad pozzolonic reaction of FA has developed[20,61]. SEM images of FA concrete samples exhibited in Fig. 20.

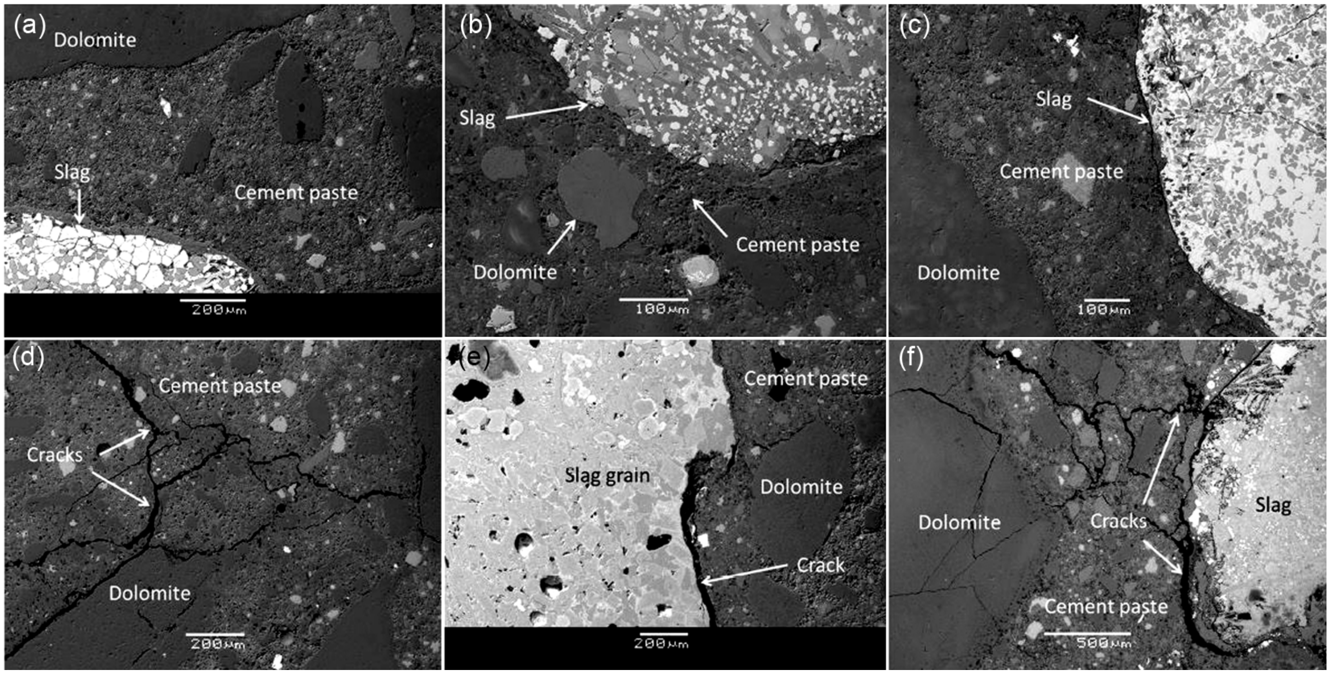


Fig. 18 — SEM images of SS concrete at (a) normal temperature, (b) 100°C, (c) 200°C, (d) 400°C, (e) 600°C, and (f) 800°C [16].

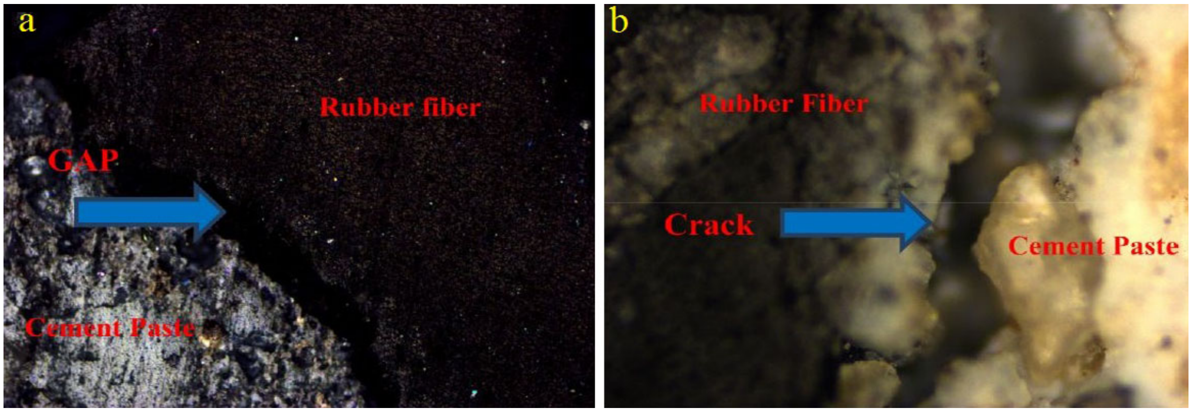


Fig. 19 — SEM Images of Rubberized Concrete at (a) normal temperature, and (b) 300°C [22].

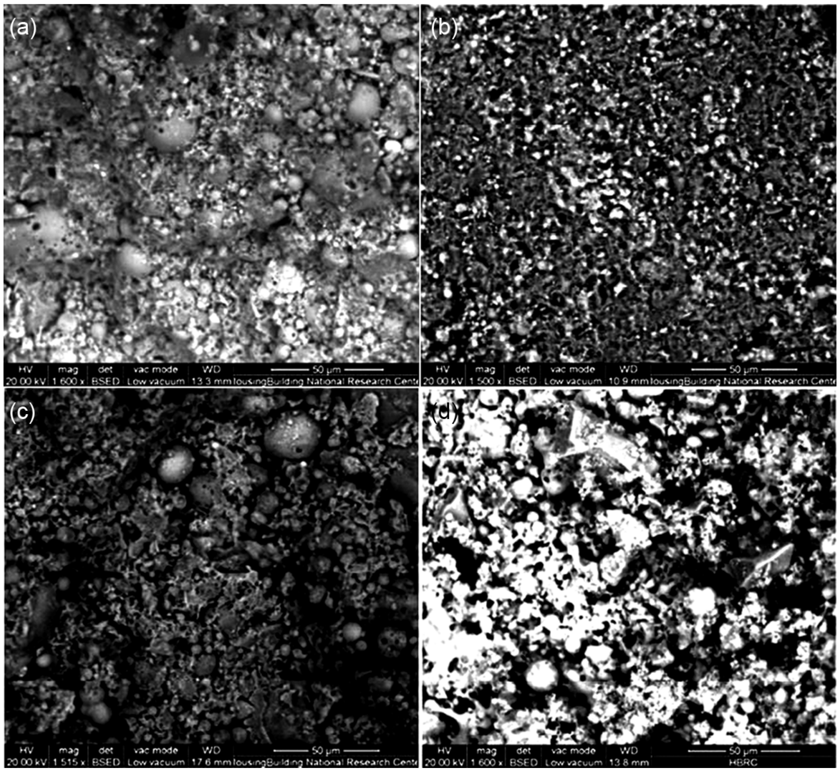


Fig. 20 — SEM images of FA concrete at (a) normal temperature, (b) 400°C, (c) 800°C, and (d) 1000°C [18].

4 Conclusion

Various industrial by-products as utilization of natural aggregates in sustainable concrete under elevated temperature have been reviewed in this article. Many factors affecting the properties of post heated concrete have also been discussed here. These metrics have also been compared with the requirements outlined in the BIS Code of Practices. Many significant physicochemical transforms have been affected properties to get worse at elevated temperatures and set up additional complexities, like crack on the surface and spalling in concrete. Moreover, some of the properties are conditional to temperature and sensorial to few testing parameters like heating and cooling rate, duration of firing, temperature gradient, etc. Depending on the review, few conclusions have been drawn and enumerated below:

- The physical properties of waste materials have been presented almost similar to the natural coarse and fine aggregates whereas both the dry and bulk density of SS is slightly higher than others. Water absorption percentages of both the recycled aggregates are comparatively higher than other waste materials. (Also, bulk density and water absorption percentage of CR are somewhat lower than the other ones. / Maximum physical properties shown for CR are somewhat lower than other ones.)

- Various studies have been employed different temperature curve relating to time. In few cases, the heating and cooling rate is higher and in few other cases, the samples have been taken out from the furnace without being kept for a constant period inside it. For that reason, few post-heated properties like surface crack and spalling have been presented different results for different samples. Speedy heated and cooled samples have mostly been showed different results than the samples almost maintaining ISO 834 curve.
- In visual observation, few color changes have been noted with the increment of temperature above 400°C.The samples with grey color like normal concrete up to 400°C to partial red at 600-800°C and finally a color like pale red after 800°C temperature have been noticed. This color change is almost similar for maximum cases. Also formation of surface cracks have been detected at almost 600°C and the cracks become more prominent at on or after 800°C. These surface cracks have been extended the extreme after exposure to 1000°C.
- With the increment of temperature, the weight of samples have been reduced significantly. Concrete samples exposure up to 800°C temperature have been presented gradual weight reduction and sharp reduction have been noticed after that. After exposure to 1000-1200°C, specimens have been noticed to be entirely perverted. But in terms of weight loss, w/c ratio has been evidenced insignificant importance.
- Concrete specimens with a lower replacement ratio have been presented better residual strength after exposure to temperature. Lesser residual strength has been provided higher replaced samples. Better performances have been accomplished for the specimen with replacement up to 35% compared to normal concrete samples. Above that range, similar performance like normal concrete samples has been noticed. After exposure up to 500-600°C, the residual compressive strength of samples have been performed better. At very high-temperature, samples have exhibited very low residual compressive strength.
- Concrete specimens have shown similar residual flexural strength just like compressive strength after exposure to elevated temperature. For split tensile strength, up to 50% replacement level has been presented better residual properties. Post heated replaced samples have been afforded satisfactory residual split tensile strength while compared with normal concrete samples. Sometimes the samples have not been maintained sufficient bonding to remain un broken after heating at 1200°C temperature.
- The modulus of elasticity of concrete samples has been noticed to decrease as the temperature increases gradually. This decrement of modulus of elasticity has even been started at a very low temperature from 200-400°C. The degeneration of modulus of elasticity is faster than that of compressive strength. But normal concrete specimens has been shown a better modulus of elasticity than the replaced ones.
- Apart from all the surveys, both the coarse and fine recycled aggregates have been presented better performance than all other waste materials after exposure to elevated temperature. Better residual performances have been presented by the specimens incorporated with recycled coarse and fine aggregate.
- Although very few experiments have been worked out above the temperature range 1000°C, so it is felt that few more detailed experimental investigations are essential to get a proper and brief idea of the effect of very high temperature on the properties of concrete.

Finally, the authors conclude that industrial by-products can be utilized as alternative aggregate in concrete innovations. But usage for the concrete structures working at a higher temperature, need more research at higher amount of replacement.

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