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Evaluation of real time fire performance of eco-efficient fly ash blended self-consolidating concrete including granite waste

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Highlights

- Fire performance of fly ash blended SCC including GW was studied.
- Fly ash blended SCC containing GW exhibited superior fire resistance characteristics.
- Sustainability analysis suggested that use of GW up to 40% exhibited better sustainable solution.
- GW up to 40% could be selected as a substitute to fine aggregate where failure due to fire is a problem.

Abstract

Manufacturing of granite products generates enormous amounts of granite waste (GW) worldwide, which triggers environmental pollution on its dumping. On the other hand, the resistivity of concrete structures and the safety of humans are likely to undergo intense threats when exposed to fire attacks. Therefore, an experimental study was conducted to determine the real-time fire attack performance of eco-efficient fly ash blended self-consolidating concrete (SCC) containing up to 60% GW as a replacement for natural fine aggregate. The change in weight, compressive strength, water absorption, and ultrasonic pulse velocity characteristics of SCC were determined after being exposed to varying elevated temperatures of 200±10°C, 400±10°C, 600±10°C, and 800±10°C. Advanced Fourier transform infrared test was done to examine chemical changes in fire-exposed specimens. Test results revealed that FA blended SCC containing GW (up to 60%) exhibits better post-fire properties, with optimum mechanical and durability properties at 30%. Besides, sustainability analysis results revealed that the use of GW up to 40% exhibited better sustainable solutions under the given economic and environmental cost factors. This study concluded that up to 40% GW as a replacement to fine aggregate could be positively incorporated in the production of FA blended SCC, where failure due to fire is a problem.

Previous Next

Keywords

Eco-efficient self consolidating concrete; Fire attack; Granite waste; Compressive strength; Fourier transform infrared analysis

1. Introduction

Fire is considered as one of the critical threats to most structures. The significant usage of concrete as a structural material for making buildings has led to the insistence on thoroughly identifying the impact of fire on it. The resistivity (i.e., stability and serviceability) of the structures and the safety of humans are greatly affected when concrete is subjected to elevated temperature [1]. Physical and chemical alterations in the cement and aggregate phases and pore pressure within concrete composites during fire attack cause the disintegration of concrete performance [[2], [3], [4]]. Physicochemical reactions, such as break down of calcium hydroxide ($Ca(OH)_2$ or portlandite) and calcium silicate hydrate (CSH) gel, occur at 400°C and 500–900°C, respectively, within the concrete matrix as an effect of fire [[5], [6], [7]]. When concrete components reach a critical temperature, they lose their characteristics due to the above-mentioned physicochemical reactions and are severely damaged. Besides, earlier researchers have claimed that the behaviour of self-consolidating concrete (SCC) and high-performance concrete under fire is distinct from normal compacted concrete (NCC) [5,[7], [8], [9]].

SCC is the improved form of ordinary concrete that can be easily placed in a confined structure section with jam-packed reinforcement without mechanical vibration [10,11]. It was invented in the early 1980s by Prof. Okamura [12]. Since then, it has been globally employed as a construction product in many countries to enrich concrete structures quality under diverse conditions. Furthermore, in the past two decades, researchers have emphasized the production of sustainable concrete by deploying industrial waste products. The incorporation of waste products in concrete has been enhancing rapidly due to their cost-effectiveness, eco-efficient, and better structural performance than natural resources [[13], [14], [15]]. However, it is important to determine the suitability of developed sustainable concrete against aggressive situations. With the continuously rising population and infrastructure accompanying the dearth of fire safety machinery, structures, and buildings are confronting massive fire jeopardy [16]. Therefore, the fire performance of concrete structures or concrete containing industrial waste products needs to be assessed.

Researchers have assessed the fire performance of concrete composites containing different industrial wastes. Rajawat et al. [17] evaluated the fire performance of waste ceramic NCC at distinct temperatures of 200, 500, and 800°C. They reported that the utilization of ceramic waste as sand enhances the resistance against fire attack. Sudarshan and Vyas [18] studied the effect of marble aggregate as an alternative of about 75% of coarse aggregate by weight on NCC subjected to elevated temperature. They reported that marble-based NCC performed better than the conventional NCC when subjected to elevated temperature. Tiwary et al. [19] reported that NCC containing up to 10% of marble and foundry waste as a cement and sand replacement performed better than the control mix, respectively. They also reported that compressive strength enhanced for incorporating up to 10% of marble and foundry waste in NCC when subjected to up to 400°C elevated temperature. Santos and Rodrigues [20] studied the impact of fire attack on the mechanical attributes of calcareous-based and granite-based aggregate. They reported that granite-based NCC showed more residual mechanical strength than the calcareous-based NCC when subjected to elevated temperature. Nuaklong et al. [21] reported that granite modified geopolymer composite had lower resistance against fire than the geopolymer composite made with fine aggregate. Thomas and Harilal [22] found about 32% compressive strength loss for quarry dust aggregate-based NCC at 400°C. Hachemi and Ounis [4] determined the influence of fire attack on NCC, including recycled brick aggregate, as a substitution of about 30% of coarse aggregate (by weight). They reported that recycled brick-based NCC showed similar or better resistance after being subjected to elevated temperatures than the conventional NCC. Nadeem et al. [9] examined the effect of fly ash (FA) and metakaolin on NCC at elevated temperatures and reported that FA-based NCC performed better than metakaolin based NCC. They also reported that both the FA and metakaolin based mixes showed significant strength loss after being subjected to 400°C. Xu et al. [23] reported that NCC containing 25–50% FA showed about 4–15% compressive strength loss at 450°C temperature, while NCC made without FA showed 20% compressive strength loss. Anand et al. [7] utilized different mineral admixtures (i.e., FA, silica fume, and metakaolin) to produce SCC and evaluated their efficacy against the elevated temperature. They detected that the mechanical characteristics of SCC diminished due to the decomposition of cement hydrates and the formation of pores at elevated temperatures. They also reported that FA and silica fume-based SCC showed better resistance to fire attack than the metakaolin-based SCC. Aydin and Baradan [24] found the effect of fire on the pumice aggregate-based composites prepared with FA. They reported that the inclusion of FA as an alternative to cement enhances the resistance of pumice aggregate-based composites against elevated temperatures.

According to the available study, the fire performance of cement-based composites containing granite waste (GW) has not been thoroughly investigated. Granite waste (GW) is a by-product of granite stone industries, produced in massive quantities during the cutting and polishing of granite blocks. According to the world natural stone association (WONASA) report [25], India is the third biggest country of granite block production in the world after China and Brazil. It has been reported that about 20–25% amount is resulted in GW during different production stages of the granite industry. This waste is disposed of in the open environment, and the non-biodegradable nature of this waste negatively affects the environment and human health. The continuous stockpiling of GW has reduced the useful land area [26]. It has a substantial environmental impact due to its adverse effect on soil permeability. It hinders water seepage to the lower layers, affecting aquifer recovery and plant life. If inhaled, it also risks human health due to the small percentage of crystalline silica in the granite fines [27]. To minimize the piling of GW and provide an alternative to natural resources, researchers have utilized GW in the development of green concrete composites [[28], [29], [30], [31], [32]].

Previous literature shows superior mechanical and durability (other than fire) attributes on employing GW in concrete composites [29,33,34]. Earlier, the authors of this study observed superior fresh and hardened performance of granite-based SCC [35,36]. However, the previous investigation on GW-based SCC lacks detailed research on fire safety, which may present a challenge to field application. Several authors have also reported a huge deterioration in concrete properties containing industrial waste after being subjected to high temperatures [[17], [18], [19],22]. Therefore, to ensure the safe and sustainable application of GW, it is crucial to understand the performance of FA blended SCC containing GW after exposure to elevated temperatures.

The study, for the first time, presents an experimental investigation of the real-time fire behaviour of FA blended SCC, including GW as a substitution of natural fine aggregate. During the real time fire case, the degree of heating is fluctuating [2,18]. The structural performance of concrete is determined after application of real time fire conditions [37]. Compressive strength, ultrasonic pulse velocity (UPV), and water absorption tests were conducted to measure the fire performance of developed SCC mixtures. The advanced Fourier transform infrared spectroscopy (FTIR) technique was utilized to determine chemical changes in developed SCC mixtures. FA blended SCC including GW was also investigated for cost, carbon emissions, and embodied energy. The study's results will help to understand the effect of GW on the fire safety of concrete and identify a robust (fire-safe) and sustainable application of GW in FA blended SCC for the construction industry.

2. Experimental program

2.1. Materials

Cement, fly ash (FA), fine aggregate, and coarse aggregate utilized in this study were Ordinary Portland cement (OPC) 43 grade, class-F fly ash, river sand, and basalt stone (10mm size) confirming with relevant codes [[38], [39], [40]], respectively. Chemical compositions of raw materials, as examined by X-ray fluorescence (XRF) technique, are shown in Table 1. Granite waste (GW) was utilized in dried conditions. GW mostly consists of quartz (SiO_2), albite ($NaAlSi_3O_8$), and microcline ($KAlSi_3O_8$) crystalline phases as obtained by X-ray diffraction technique [31], which are accorded with the chemical composition of GW as obtained by XRF (Table 1). The physical properties of raw materials are shown in Table 2. Sieve analysis results (Fig. 1) indicated that particles of GW are smaller than fine aggregate. The fine aggregate and GW surface morphology was obtained using the scanning electron microscope (SEM) technique. Nova Nano SEM-450 apparatus was utilized for SEM analysis. SEM images of fine aggregate and GW particles, shown in Fig. 2(a) and (b), respectively, indicate that the particles of GW are relatively more rough and angular than fine aggregate particles. GW and fine aggregate's thermal attributes were obtained using thermogravimetric analysis (TGA). The material sample in the TGA system was heated from 30°C to 800°C with a heating rate of 10°C/min. TGA pattern (as shown in Fig. 3) indicates that GW has a comparatively smaller weight loss than fine aggregate on exposure to elevated temperature.

Table 1. Chemical composition of raw materials (%).

Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	MgO	P_2O_5	MnO
Cement	45.88	31.30	3.49	3.30	0.22	0.69	5.21	0.05	0.05
FA	0.90	58.19	26.93	4.27	0.07	1.10	0.69	0.21	0.06
Fine aggregate	2.51	77.25	6.14	1.12	1.08	4.28	0.34	0.05	0.04
GW	0.89	69.77	10.74	1.80	3.13	4.84	0.54	0.05	0.03

Table 2. Physical properties of raw materials.

Materials	Specific gravity	Water absorption (%)	Fineness modulus	Specific surface area (m^2/kg)	28 days compressive strength (MPa)
Cement	3.16	–	–	297	45.8
FA	2.28	–	–	353	–
Fine aggregate	2.64	1.00	2.50	–	–
Coarse aggregate	2.71	0.40	5.99	–	–
GW	2.57	4.49	1.40	–	–

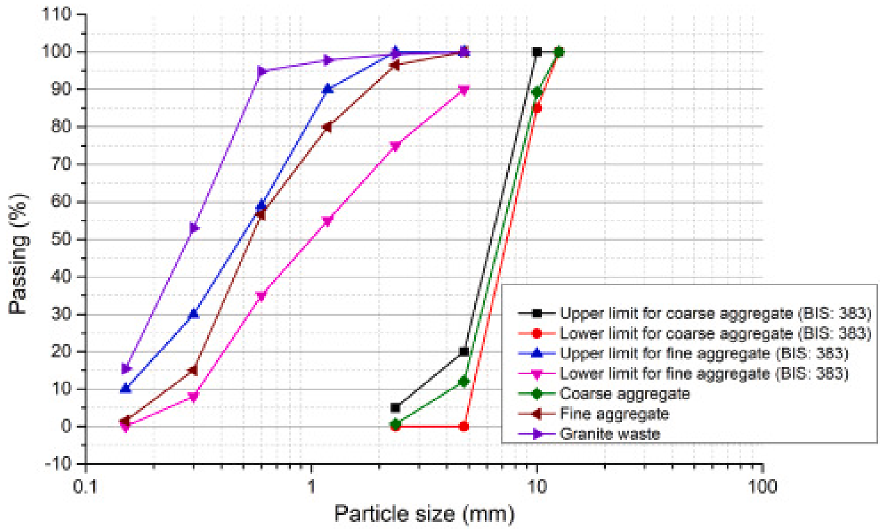

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Fig. 1. Gradation of aggregate and GW [35].

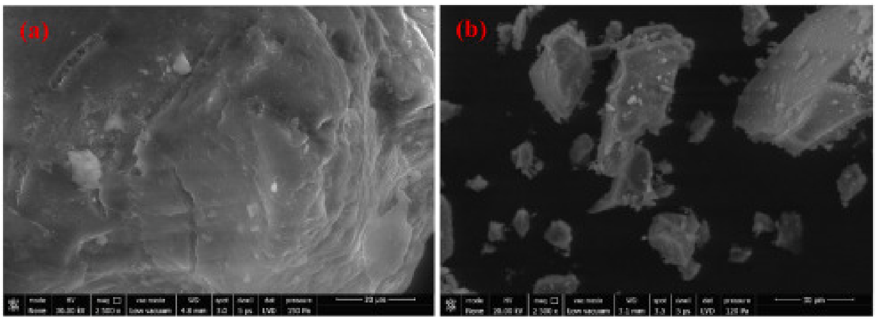

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Fig. 2. Microscopic images of (a) fine aggregate; (b) GW.

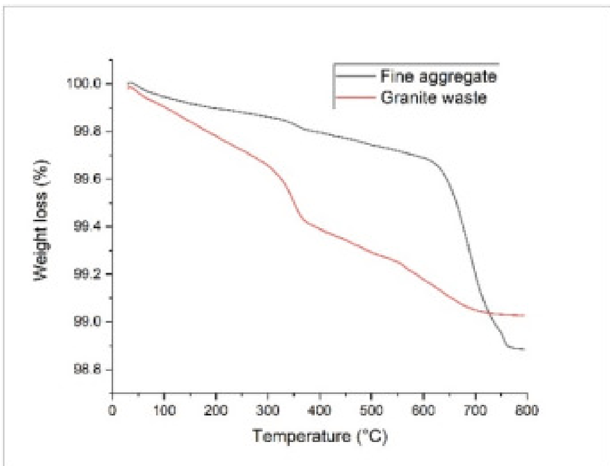

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Fig. 3. TGA pattern of GW and fine aggregate.

2.2. Mixture details

Nine SCC mixtures were formulated as per the guidelines given in the EFNARC standards [41]. Out of nine SCC mixtures, one mixture (FA0GW0) was prepared with only OPC binder named as OPC based control mixture, and one mixture (FA30GW0) was prepared by integrating cement and fly ash at a level of 70% and 30%, respectively, named as fly ash blended control mixture. While remaining mixtures, which are fly ash blended, were formulated by replacing fine aggregate with GW at varying amounts of 20%, 25%, 30%, 35%, 40%, 50%, and 60%. Details of developed SCC mixtures and their mixture IDs are presented in Table 3. A high-range water reducer superplasticizer (SP) of Glenium Sky 8777 (polycarboxylate ether based) was utilized. SP doses were varied to maintain the target slump flow of 750±30 mm. Water correction was applied to compensate for aggregates' water absorption. Percentage voids, determined according to ASTM C642 ↗ [42], are also depicted in Table 3.

Table 3. SCC mix proportions (Kg/m^3).

Mixture ID	Cement	FA	Fine aggregate	GW	Coarse aggregate	Water[d]	SP dose	Permeable voids (%)	Compressive strength (MPa)[e]
FA0GW0[a]	548.53	–	968.35	–	698.17	204.47	2.61	8.89	45.87
FA30GW0[b]	383.97	164.56	968.35	–	698.17	204.47	0.82	8.62	38.83
FA30GW20[c]	383.97	164.56	774.68	193.67	698.17	211.23	0.77	8.48	41.70
FA30GW25[c]	383.97	164.56	726.26	242.09	698.17	212.92	0.74	7.76	42.53
FA30GW30[c]	383.97	164.56	677.85	290.51	698.17	214.60	0.80	7.34	46.67
FA30GW35[c]	383.97	164.56	629.43	338.92	698.17	216.29	0.93	7.58	43.60
FA30GW40[c]	383.97	164.56	581.01	387.34	698.17	217.98	1.04	7.92	39.10
FA30GW50[c]	383.97	164.56	484.18	484.18	698.17	221.36	1.21	8.46	35.90
FA30GW60[c]	383.97	164.56	387.34	581.01	698.17	224.74	1.70	8.91	32.63

a

OPC-based control mixture (without FA and GW).

b

FA blended control mixture (without GW).

c

FA blended mixtures (with 20%–60% GW).

d

Effective water was 191.99 kg/m3 for each mix.

e

28 days water cured compressive strength (before exposure to fire).

2.3. Testing procedure

Fresh characteristics tests for all the developed SCC fulfilled the approval criteria for satisfactory SCC as suggested by EFNARC standards [41]. Outcomes for fresh characteristics tests in detail are reported in earlier study [35].

The real fire attack was determined using gas regulated furnace (fitted with K type thermocouple for recording the inner temperature) as presented in Fig. 4. The furnace was designed to maintain the inside temperature as per the ISO 834 guidelines [43]. A digital meter connected to the furnace was utilized to record the temperature reading during exposure. The furnace chamber had a dimension of 520×520×1050mm. Compressive strength, water absorption, and UPV tests were performed on 100mm cubes to determine the fire performance, according to BIS 516 [44], ASTM C642 ↗ [42], and BIS 13311 [45] standards, respectively.

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Fig. 4. Fire attack test apparatus.

Specimens were initially water cured for 28 days. The samples were kept in an oven at a temperature of 60±5°C until the constant weight was achieved. The samples were then put in the furnace for exposure to varying elevated temperatures of 200±10°C, 400±10°C, 600±10°C, and 800±10°C followed by cooling of specimens for one day at room temperature (27±2°C). The change in weight, compressive strength, water absorption, and UPV values were noted after being subjected to desired elevated temperature, and an average of three specimens was reported. These noted values were then compared with their initial values observed at room temperature. Besides, advanced FTIR analysis was performed on the powder samples (passed from 90μm sieve) to determine the modification in chemical behaviour of developed specimens after being subjected to fire attack. Powder sample was collected from the mid location of each sample.

3. Results and discussion

3.1. Weight loss

The percentage gain and loss in weight for each mixture exposure to fire as compared to that of their original weight (taken at room temperature) are presented in Fig. 5. All the mixture showed a loss in weight with the increase in temperature might be due the loss of water on exposure to fire. At up to

400°C temperature, the weight loss was due to the evaporation of capillary water followed by adsorbed and interlayer water. Whereas beyond 400°C temperature, weight loss was due to the evaporation of chemically combined water and disintegration of cement hydrate products [9].

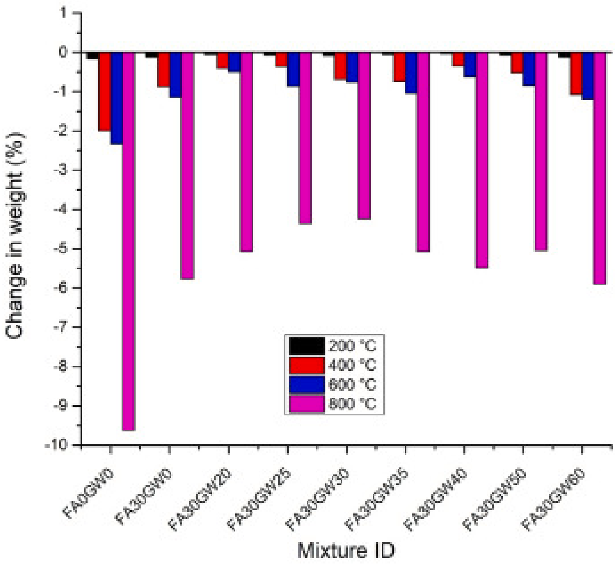

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Fig. 5. Change in weight for SCC mixture exposed to varying temperatures.

When compared to that of FA blended SCC with no GW (FA30GW0 mixture), the loss in weight was found slightly lower in fly ash blended SCC containing GW except FA30GW60 mixture. This might be due the lower expulsion of water associated to the superior GW aggregate-cement paste bonding [30,35]. Sudarshan and Vyas [18] found about 6% weight loss, on exposure to fire attack at up to 800°C temperature, for the substitution of about 70% coarse aggregate by marble waste in NCC. Whereas in this study, weight reduced by 6% for substitution of about 60% fine aggregate by GW in SCC on exposure to fire at up to 800°C temperature. Besides, the lowest weight loss was observed around 4% for FA30GW30 mixture. This might be due to the lower trapping of water during mixing within the SCC mixture containing up to 35% GW [31].

Compared to OPC based control SCC made without FA and GW (FA0GW0 mixture), all the FA blended SCC made with and without GW exhibited lesser weight loss. This might be due to the lower disintegration of cement hydrate products since FA blended SCC exhibited a lower amount of portlandite and CSH gel. It has been reported by Peng and Huang [6] that disintegration of portlandite and CSH gel as similar to a loss of water on exposure to fire is equally responsible for the mass loss of cement composite matrix. AzariJafari et al. [5] also observed the lesser weight loss for FA blended SCC than control concrete with no FA.

3.2. Compressive strength

The percentage gain and loss in compressive strength for each mixture exposure to fire than their original compressive strength (taken at room temperature) is depicted in Fig. 6. All SCC mixtures revealed a gain in strength at 200°C temperature but a loss in compressive strength was seen with rise in temperature beyond 200°C. The increase in compressive strength at 200°C temperature may be due to the reduction of un-hydrated phases, causing the improvement of concrete microstructure

[9,46]. The release of water on exposure to fire partially improves the strength by moving cement gel films near each other owing to increasing Van-der Waal forces [23,24]. However, on increasing the temperature beyond 200°C, the loss of compressive strength could occur due to the physical and chemical alterations, thermal incompatibility between aggregate and cement paste, pore pressure effect, and disintegration of cement hydrates [7,19].

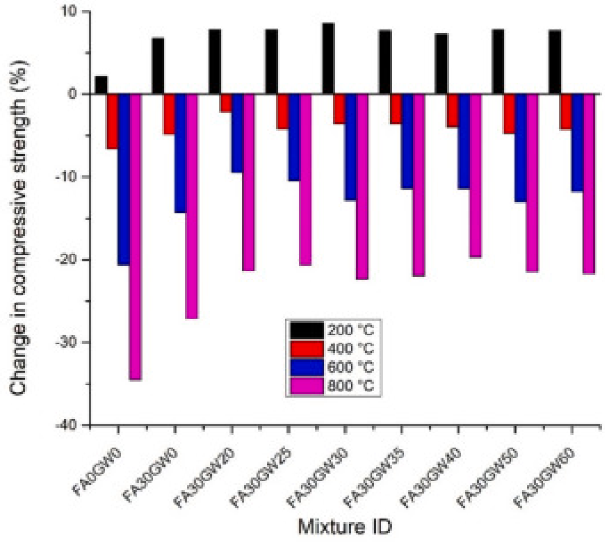

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Fig. 6. Change in compressive strength for SCC mixture exposed to varying temperatures.

At 200°C temperature, the FA blended SCC containing GW showed a higher gain in strength than FA30GW0. While, on increasing the temperature beyond 200°C, FA blended SCC containing GW showed a lower loss in strength than the FA30GW0 mixture. Superior aggregate-paste bonding might have moderated the volumetric expansion caused by thermal variation between concrete ingredients [47]. The presence of slightly higher or comparable hydration products in FA blended SCC made with GW might have provided better resistance against fire for those mixtures than that of the FA30GW0 mixture. The literature has reported that GW burning improves its pozzolanic activity [48,49], which may be causing enhanced compressive strength for FA blended SCC made with GW. The comparatively better firmness of GW against fire than the fine aggregate (Fig. 3) also imparted higher resistance against fire for FA blended SCC made with GW.

Several researchers saw similar changes on exposure to fire for the inclusion of various stone wastes in cement composites. Thomas and Harilal [22] found about 32% compressive strength loss for employing cold bonded quarry dust aggregate in NCC as a coarse aggregate at 400°C temperature. Tiwari et al. [19] found about 52% compressive strength loss for employing marble waste and foundry waste in NCC as cement and sand at 1000°C temperature, respectively. Sudarshan and Vyas [18] reported that the compressive strength of marble-based NCC was reduced by up to 45% on subjecting to fire at up to 800°C temperature. In this study, the compressive strength of SCC containing 30% GW (FA30GW30 mixture) reduced by 22% on exposed to fire at up to 800°C temperature.

When compared to FA0GW0, all the FA blended SCC showed higher compressive strength against elevated temperature. This might be due to the lower availability of portlandite ($Ca(OH)_2$) in FA blended SCC. It has been reported that the disintegration of $Ca(OH)_2$ is one of the factors that cause the loss of strength on exposure to fire [46,50,51]. The development of auxiliary CSH gel in the presence of pozzolanic materials might also provide better residual compressive strength on exposure to fire [5,23,52]. AzariJafari et al. [5] also found a lower strength loss for FA blended SCC than control mix without FA.

3.3. Ultra-sonic pulse velocity (UPV)

This test evaluates the concrete quality and helps assess the durability of concrete according to BIS 13311 [45]. The concrete quality will be excellent, good, medium, and doubtful if the UPV values are in the range of >4.5 km/s, 3.5–4.5 km/s, 3.0–3.5 km/s, and <3.0 km/s, respectively. The higher the UPV values, the better will be the concrete quality.

The UPV values for each mixture exposed to varying temperatures are depicted in Fig. 7. All SCC mixtures showed an increment in UPV at 200 °C temperature; however, a decrement in UPV was seen with the rise in temperature beyond 200 °C. Up to 600 °C temperature, concrete quality for all the concrete mixtures (except FA0GW0 mixture) was found to be better than medium concrete quality grading as per BIS 13311 [45].

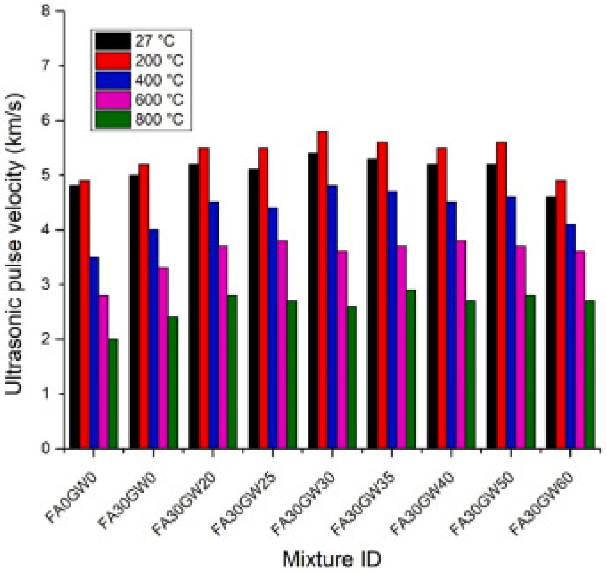

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Fig. 7. UPV values for SCC mixture exposed to varying temperatures.

Compared to the FA30GW0 mixture, all the FA blended SCC containing GW showed higher UPV at each particular temperature. The higher UPV values for FA blended SCC containing GW might be due to the lesser micro-cracks formations associated with superior GW aggregate-paste bonding and slightly superior hydration products [35]. The higher UPV values indicated a better quality against elevated temperature for FA blended SCC containing GW than FA30GW0, thereby enhancing compressive strength for FA blended SCC containing GW. The results of UPV for the FA blended SCC containing GW mixture corroborate the outcome of compressive strength test results on exposure to fire. The better UPV on exposure to fire was also observed by Sudarshan and Vyas [18] for marble-based NCC, for the inclusion of the marble waste aggregate in NCC as a coarse aggregate.

Compared to FA0GW0, all the FA blended SCC showed higher UPV values at each particular temperature. It has been earlier reported by Bui et al. [16] and AzariJafari et al. [5] that incorporation of pozzolanic substance (for instance, FA in this study) reduce the formation of micro-cracks and capillary pores, thereby providing better UPV values for all the FA blended SCC mixtures.

3.4. Water absorption

This test indirectly evaluates the internal pore network and permeability of the concrete matrix. The percentage gain and loss in water absorption for each mixture exposure to fire as compared to that of their initial water absorption (taken at room temperature) are depicted in Fig. 8. All the samples showed a loss in water absorption at 200°C temperature. In contrast, the gain in water absorption was observed on increasing the temperature beyond 200°C. The higher loss in water absorption (at 200°C temperature) and lower gain in water absorption (beyond 200°C) for a concrete matrix compared to other mixtures generally indicates a lesser pore network and lesser permeability. Thus, in this study, the increase in voids can be confirmed by the gain in water absorption with the increment of temperature, which caused the dwindling of aggregate-cement paste bonding, thereby causing the loss of compressive strength. Further, the gain in water absorption increased by about three times at the temperature beyond 400°C (Fig. 8), indicating the rapid decline in the quality of all mixtures. Tiwari et al. [19] also observed a rapid decrease in the quality of NCC containing marble waste and foundry waste at a temperature beyond 400°C.

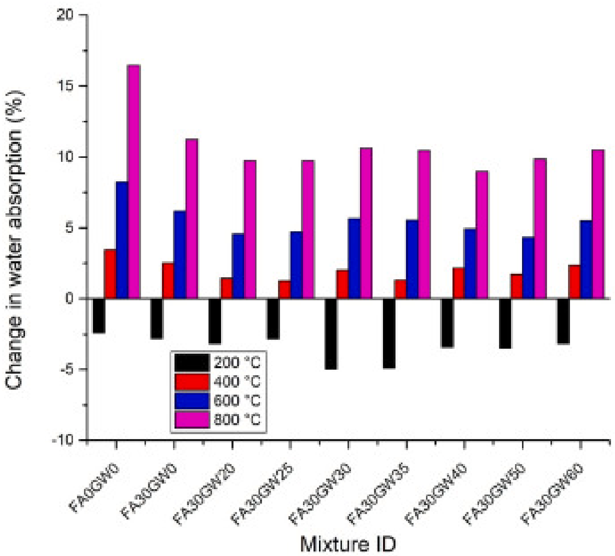

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Fig. 8. Change in water absorption for SCC mixture exposed to varying temperatures.

When compared to the FA30GW0 mixture, all the FA blended SCC containing GW showed a higher loss in water absorption (at 200°C) and lower gain in water absorption (at 400°C, 600°C and 800°C). The better resistance against water absorption for FA blended SCC containing GW might be due to the lesser micro-cracks formations associated with superior GW aggregate-paste bonding [35]. These results indicated better stability and lesser permeability for FA blended SCC containing GW than FA30GW0 mixture, confirming the better compressive strength for those mixtures subjected to fire. Sudarshan and Vyas [18] found better resistance against water absorption for marble-based NCC when exposed to fire and Tiwari et al. [19] also observed lower water absorption for NCC containing marble waste and foundry waste when exposed to fire.

Compared to that of FA0GW0 mixture, all FA blended SCC (made with and without GW) showed better resistance against water absorption (i.e. higher loss of water absorption at 200°C temperature and lower gain in water absorption beyond 200°C temperature) at each particular temperature. These results indicated the lower porosity of all FA blended SCC (made with and without GW) than FA0GW0 mixture, which confirms the better compressive strength for those mixtures.

3.5. FTIR

FTIR analysis shows the absorbance bands of molecular groups at varied wavelengths (presented in Table 4). FA0GW0, FA30GW0, FA30GW30, and FA30GW60 mixtures were selected for FTIR analysis, and results for these mixes are displayed in Fig. 9(a–d), respectively. The variations in hydrated phases of SCC mixes, after exposure to 800°C of temperature, were compared with mixtures of normal temperature (27°C).

Table 4. Wave number for distinct molecular group in FTIR analysis [61].

Molecular group	**Wave number (cm^{-1})**	**Reference**
Portlandite (O-H)	3646	[53,62]
Calcium silicate hydrate (Si-O)	996, 1005	[63,64]
Quartz (Si-O-Si)	450-650, 778	[64,65]
Calcium carbonate (C-O)	882, 1422	[66,67]
Methyl and methylene (CH_2/CH_3)	2850–2925	[68]
Water (O-H)	1646, 3444	[67]

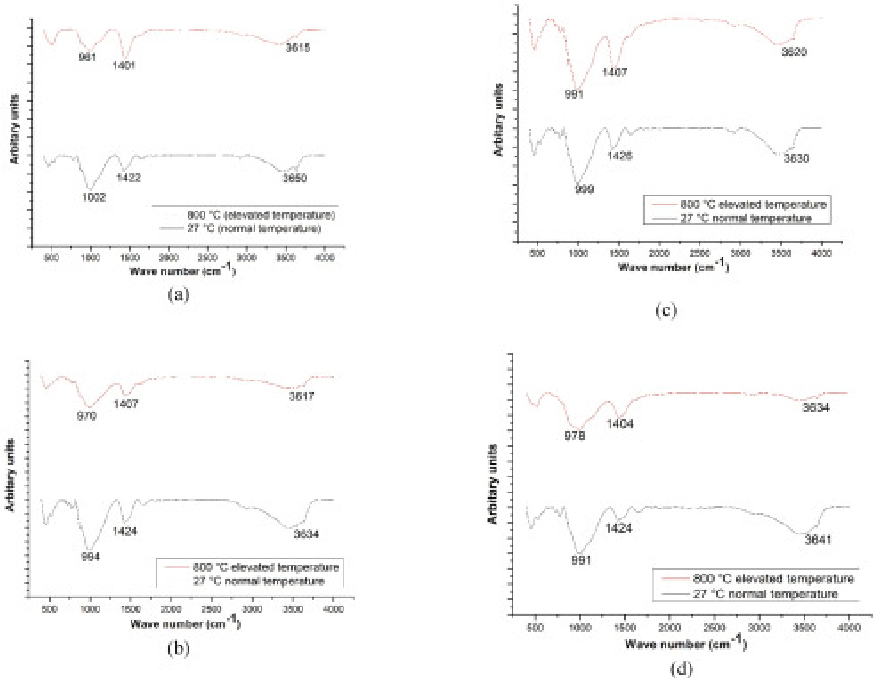

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Fig. 9. FTIR analysis results for SCC mixes (a) FA0GW0, (b) FA30GW0, (c) FA30GW30, (d) FA30GW60.

Significant variations were found in portlandite ($Ca(OH)_2$), calcium carbonate ($CaCO_3$), and CSH bands after being subjected to fire. The observed wave number for these bands are listed in Table 5. A Change in the wave number to a lower position implies the weakening of molecular groups [53,54]. Fig. 9(a–d) and Table 5 indicate that portlandite, $CaCO_3$, and CSH bands shifted to the lower side after being subjected to fire, which was the reason for weight loss and compressive strength loss of fire-exposed mixtures.

Table 5. FTIR Wave number (cm^{-1}) of portlandite, $CaCO_3$ and CSH for selected mixtures.

Mixture no. (exposure condition)	Molecular group		
	Portlandite (O-H)	CSH (Si-O)	Calcium carbonate (C-O)
FA0GW0 (27°C normal temperature)	3650	1002	1422
FA0GW0 (800°C elevated temperature)	3615	961	1401
FA30GW0 (27°C normal temperature)	3634	994	1424
FA30GW0 (800°C elevated temperature)	3617	970	1407
FA30GW30 (27°C normal temperature)	3630	999	1426
FA30GW30 (800°C elevated temperature)	3620	991	1407
FA30GW60 (27°C normal temperature)	3569	991	1424
FA30GW60 (800°C elevated temperature)	3634	978	1404

The fire-exposed FA30GW0, FA30GW30, and FA30GW60 mixtures showed 17, 10, and 7 cm^{-1} shifting of $Ca(OH)_2$ bands than corresponding unexposed mixes, respectively. Likewise, fire-exposed FA30GW0, FA30GW30, and FA30GW60 mixtures showed 24, 8, and 13 cm^{-1} shifting of the CSH bands than the corresponding unexposed mixes, respectively. The relatively lower shifting of the portlandite and CSH bands for FA30GW30 and FA30GW60 mixtures than FA30GW0 mixture confirms the lower weight loss and compressive strength loss for those mixtures.

Moreover, the fire-exposed FA0GW0 mixture showed 35 cm^{-1} and 41 cm^{-1} shifting of portlandite and CSH bands than the corresponding unexposed mixtures. The relatively higher shifting of portlandite and CSH bands caused the lowest compressive strength for the FA0GW0 mix than all the FA blended mixtures.

3.6. Sustainability analysis

Experimental results show that using GW as fine aggregates can improve the fire performance of FA blended SCC. To promote the field utilization of GW, a detailed sustainability analysis has been carried out by including economic and environmental parameters. The sustainability assessment of GW has been carried out in three parts, i.e., normalization, sustainability assessment of developed materials, and recommendations for field translations.

Normalization is done by adopting a suitable correction factor based on the compressive strength of all concrete mixes. It is assumed that additional concrete will be used during construction to compensate for the reduced compressive strength and vice versa. Furthermore, the usage of the additional construction material will increase the dead load, which will increase the requirement of concrete. Mahzuz et al. [55] showed that for up to 20-story concrete structures, the increase in dead load is less than 10% for less than 50% reduction in strength. It can be said that if the strength of concrete reduces then additional concrete will be required to meet the structural requirements [55]. It was reported by Mahzuz et al. [55] that there is a 5% and 10% increase in concrete requirement for a maximum 20% and 50% reduction in strength, respectively. Therefore, conservative dead load corrections of 1.00, 1.05, and 1.10 have been adopted in case of strength increase, decrease up to 20%, and decrease between 20% and 50%, respectively. The correction factor is determined using the ratio of compressive strength of the given concrete mix and dead load correction, as shown in Eq. (1). Highest correction factor for a given mix is used to ensure that all concrete mixes meet the performance of control concrete (FA0GW0) at each and every exposure temperature. The correction factor for normalization is then used for subsequent sustainability analysis.

$$correction\ \text{factor} = max\left(\left\{\frac{cs'at\ T^{\circ}C}{CS\ at\ T^{\circ}C} \times f_{DL} : T = 27, 200, 400, 600, 800\right\}\right) \quad \text{eq 1}$$

Here, CS $\rightarrow$ compressive strength of given mix.

CS’ $\rightarrow$ compressive strength.
of control mix

$$f_{DL} \rightarrow \text{dead load correction factor} \begin{cases} = 1.00 \forall \frac{CS\ at\ T^{\circ}C}{CS'\ at\ T^{\circ}C} \geq 1.00 \\ = 1.05 \forall \frac{CS\ at\ T^{\circ}C}{CS'\ at\ T^{\circ}C} \geq 0.80 \\ = 1.10 \forall \frac{CS\ at\ T^{\circ}C}{CS'\ at\ T^{\circ}C} \geq 0.50 \end{cases}.$$

The sustainability assessment of given mixes has been carried out regarding economic and environmental costs. For the third dimension of sustainability, it is assumed that waste utilization improves the social aspect of GW incorporated SCC mixes; hence, a separate analysis has not been carried out. The individual costs of raw materials used for economic and environmental assessment is shown in Table 6. The economic costs have been adopted per the prevailing market rates in Rajasthan (India) and may vary with time and location. The equivalent carbon cost and embodied energy have been adopted from the literature [[56], [57], [58]]. In the initial analysis, transportation costs (for 5 km) have been included for GW, as the material is currently a waste [59,60]. The economic and environmental costs of GW incorporated SCC mixes after normalization for fire performance have been shown in Table 7.

Table 6. Cost factor of different raw materials.

Cost factor	Cement	FA	Fine aggregate	GW	Coarse aggregate	Water	SP dose
Economic (INR/kg)	6.50	1.50	1.50	0.14	1.00	0.05	150.00
Environmental							
Embodied energy (MJ/kg)	4.80	0.10	0.081	0.38	0.083	0.20	11.50
Eq. CO_2 emission ($kgCO_2e/kg$)	0.93	0.004	0.0051	0.01	0.0048	0.0008	0.60

Table 7. Normalized economic and environmental cost for GW and FA incorporated SCC.

Mixture ID	Actual material costs			Correction factor	Normalized material cost		
	Economic (INR/m^3)	Embodied energy (MJ/m^3)	Eq. CO_2 emission ($kgCO_2e/m^3$)		Economic (INR/m^3)	Embodied energy (MJ/m^3)	Eq. CO_2 emission ($kgCO_2e/m^3$)
FA0GW0	6117.86	2840.24	520.15	1.00	6117.86	2840.24	520.15
FA30GW0	5026.56	2046.22	366.70	1.24	6232.94	2537.31	454.70
FA30GW20	4756.01	2104.90	367.62	1.15	5469.41	2420.64	422.76
FA30GW25	4685.74	2119.38	367.84	1.13	5294.89	2394.89	415.66
FA30GW30	4628.99	2134.88	368.12	0.98	4536.41	2092.18	360.75
FA30GW35	4582.72	2151.19	368.43	1.10	5041.00	2366.31	405.28
FA30GW40	4533.46	2167.27	368.74	1.23	5576.15	2665.74	453.55
FA30GW50	4427.44	2198.85	369.32	1.41	6242.69	3100.38	520.74
FA30GW60	4369.40	2234.12	370.09	1.55	6772.58	3462.88	573.63

Table 7 shows that with up to 40% incorporation of GW, both environmental and economic costs of SCC are reduced as compared to control concrete. On further incorporation of GW, the strength of SCC decreased, which increased the economic and environmental costs at 50% and 60% incorporation of GW, respectively. The results suggest that the use of GW up to 40% presents a sustainable solution under the given economic and environmental cost factors. The optimum composition of GW utilization is at 30% (FA30GW30), which reduces the economic cost, embodied energy, and equivalent CO_2 emission by 25.85%, 26.34%, and 30.64%, respectively.

Now consider the scenario of field translation; GW will also hold certain costs to account for seigniorage, preparation charges, operational costs, and profit margins. The cost estimation for the preparation of GW has been shown in Table 8. The present cost estimate is based on the adopted technique for drying GW slurry, which is used to prepare GW as fine aggregates. The costs for GW are demonstrated with and without transportation costs, as the same can change with the distance of the construction site. It can be observed from the Table that in the adopted treatment methodology (excluding transportation), economic cost, embodied energy, and equivalent CO_2 emission of GW are 2.64 INR/kg, 1.28 MJ/kg, and 0.29 $kgCO_2e/kg$, respectively. It should be noted that the adopted drying technique significantly increased the energy demand for GW preparation, reducing the sustainability benefits. Alternative drying technologies, like solar dryers, can be explored to lower non-renewable energy usage and maximize the sustainability benefits of GW incorporation in fire-exposed concrete structures. In the present method, alternative drying technologies can potentially reduce the costs of GW (excluding transportation) to 0.50 INR/kg and eliminate carbon emissions and embodied energy.

Table 8. Raw material cost for present method of GW preparation.

Factor	Analysis	Costs
Seigniorage (A)	• As per the recent seigniorage of INR 100 per ton of granite waste adopted by another region of India (Tamil Nadu)	0.10 INR/kg 0.00 MJ/kg 0.00 $kgCO_2e/kg$
Transportation (B)	• 5 km transportation, loading and unloading for 2000 kg of GW (aggregate) costs INR 277.96. This translates to 0.14 INR/kg up to 5 km. • Fuel energy required for transportation is estimated as 0.075 MJ/kg/km, which translates to 0.378 MJ/kg for 5 km. • Carbon emission from transportation is estimated as 0.002 $kgCO_2e/kg/km$, which translates to 0.010 $kgCO_2e/kg$ for 5 km.	0.14 INR/kg 0.38 MJ/kg 0.01 $kgCO_2e/kg$
Preparation (C)	• Air drying of slurry for 24 h • Moisture level of slurry typically falls below 10%, or 0.1 kg/per kg of dry aggregate in open air drying • Oven temperature at 105° C, room temperature at 27 $^\circ$ C • Energy required (kJ/kg of moisture) = water heating+vaporization+steam heating	2.14 INR/kg 1.28 MJ/kg 0.29 $kgCO_2e/kg$

Factor	Analysis	Costs
	$= (100 - 27) \times 4.187 + 2250 + (105 - 100) \times .1.996 \cong 2565.6$ • Moisture heating efficiency for hot air drying at 105 ˚ C, is adopted as 0.20 based on the study by Urbano et al. [69] • Energy required for removing water (MJ/kg of water) $= 2565.6/0.20/1000 = 12.82$. • Energy required for aggregate preparation at 10% moisture level (MJ/kg of dry aggregate)=0.1×12.82=1.28 MJ/kg • Electricity required=0.36 kWh. • Cost of unit electricity adopted as INR 6.00/kWh and 0.82 $kgCO_2e/kWh$ • Cost for energy in form of electricity is INR 2.14/kg and 0.29 $kgCO_2e/kg$	
Operational (D)	• Operational costs (labour, maintenance, etc.) are assumed at 0.20 INR/kg • Earnings or profit is kept at 0.20 INR/kg margin of remaining costs	0.40 INR/kg 0.00 MJ/kg 0.00 $kgCO_2e/kg$
Costs other than transportation (E=A+C+D)		2.64 INR/kg 1.28 MJ/kg 0.29 $kgCO_2e/kg$
Total (B+E)		2.78 INR/kg 1.66 MJ/kg 0.30 $kgCO_2e/kg$

The GW preparation costs (with 5 km transportation) are used for determining the normalized material cost of 30% GW incorporation of SCC concrete, as shown in Table 9. Results show that the developed concrete mix FA30GW30 still presents a sustainable solution over control concrete. FA30GW30 shows 13.56%, 13.51%, and 14.77% reductions in economic cost, embodied energy, and equivalent CO_2 emission, respect ively. Fig. 10 compares the relative costs and fire performance of FA0GW0 and FA30GW30. It can be observed that the fire performance of FA30GW30 improves at higher exposure temperature and increase the gains from GW incorporation. The minimum sustainability gain is at ambient temperature, which can still justify the application of GW waste.

Table 9. Normalized material cost for the adopted drying technique at 30% GW incorporation of SCC.

Mixture ID	Normalized material costs in field			Comparison with control concrete (% of control)		
	Economic (INR/m^3)	Embodied energy (MJ/m^3)	Eq. CO_2 emission (kgCO_2e/m^3)	Economic	Embodied energy	Eq. CO_2 emission
FA0GW0	6117.86	2840.24	520.15	–	–	–
FA30GW30	5288.02	2456.60	443.32	86.44	86.49	85.23
[a]FA30GW30 (with alternative drying)	4678.76	2092.18	360.75	76.48	73.66	69.36
[a]FA30GW30 (for 22.73 km of transportation)	5429.36	2840.23	453.41	88.75	100.00	87.17

a

Special scenarios.

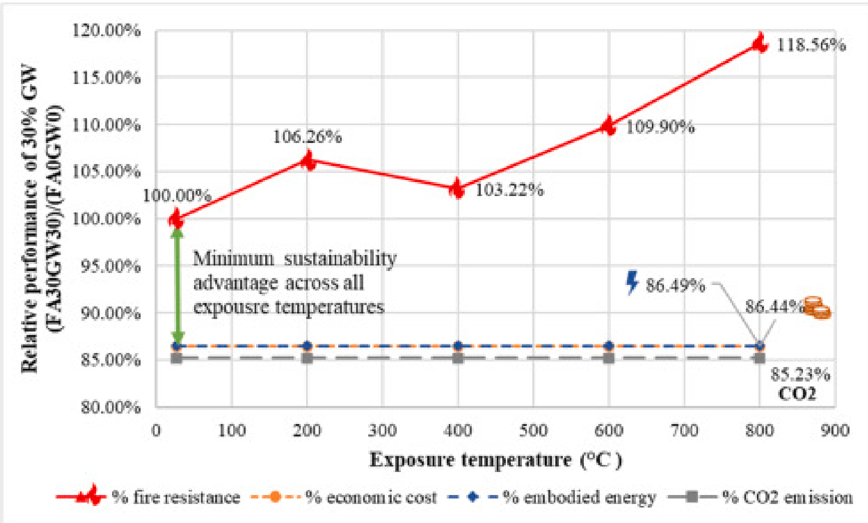

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Fig. 10. Improvement in fire performance of FA30GW30.

Table 9 presents two unique scenarios of analysis. The first scenario shows alternative drying technologies to eliminate the need for energy-based drying. This may also be achieved by accounting for the excess moisture of GW in the mix design of SCC. In this scenario, the economic cost, embodied energy, and equivalent CO_2 emission can be reduced by 23.52%, 26.34%, and 30.64%, respectively. The adopted drying method is considered in the second scenario, with a change in transportation distance. For a transportation distance of 22.73 km, the GW incorporated SCC shows the same carbon emission as control concrete, while economic costs and embodied energy are lower. The second scenario suggests that carbon emission becomes the limiting factor for long-distance applications of

GW. Study shows that up to 22.73 km from the GW source, the developed concrete mix FA30GW30 will remain a sustainable solution.

4. Conclusions

This study determines the real fire attack performance of FA blended SCC, including GW as a fine aggregate substitute. Based on the experimental analysis, the following inferences can be drawn:

- Loss in weight and compressive strength were found to be less for FA blended SCC containing GW than FA blended SCC with no GW (FA30GW0 mixture) after exposure to fire. Whereas all the FA blended SCC made with and without GW also exhibited less weight loss and compressive strength loss than the OPC based control SCC with no FA and GW (FA0GW0 mixture).

- All the FA blended SCC containing GW exhibited higher ultrasonic pulse velocity (UPV) on exposure to fire when compared to that of the FA30GW0 mixture. FA blended SCC made with and without GW also exhibited higher UPV than the FA0GW0 mixture.

- All the FA blended SCC containing GW exhibited better water absorption resistance on fire exposure than the FA30GW0 mixture. FA blended SCC made with and without GW also showed better endurance to water absorption than the FA0GW0 mixture.

- UPV and water absorption results revealed superior quality and lesser permeability against elevated temperature for FA blended SCC containing GW.

- Superior GW aggregate and cement paste bonding, higher firmness of GW against fire than natural fine aggregate, and lower dissolution of hydration products caused a better resistance to fire for FA blended SCC containing GW.

- Sustainability analysis results suggest that the use of GW up to 40% presents a sustainable solution under the given economic and environmental cost factors. The optimum composition of GW utilization is at 30% (FA30GW30), which reduces the economic cost, embodied energy, and equivalent CO_2 emission by 829.84 INR (13.56%), 383.64 MJ (13.51%) and 76.84 kgCO_{2e} (14.77%) per cubic meter of concrete, respectively.

- Overall, test results revealed that FA blended SCC containing GW (up to 60%) exhibits better post-fire properties, with optimum mechanical and durability properties at 30%. This study concluded that up to 40% GW, as a replacement to fine aggregate, could be positively incorporated in the production of FA blended SCC, where failure due to fire is a problem.

CRediT authorship contribution statement

Abhishek Jain: Conceptualization, Methodology, Writing – original draft, Investigation, Data curation, Visualization. **Rajesh Gupta:** Supervision, Writing – review & editing, Project administration. **Sanchit Gupta:** Writing – original draft, Data curation. **Sandeep Chaudhary:** Supervision, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Recommended articles

Data availability

Data will be made available on request.

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> …Meanwhile, the early compressive strength improved when 50% of the natural sand was replaced with granite waste. In terms of sustainability, Jain et al. [39] found that, taking into account the specified economic and environmental cost factors, using up to 40% of GW in place of fine aggregates could be beneficial for the production of SCC. The current study is part of the process of recycling and reusing waste in the construction industry, notably aggregates and cement, in an effort to decrease the extraction of aggregates and CO2 emissions while extending the life of landfills currently in saturation, which is very advantageous from an ecological and financial standpoint.…

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