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Evaluating resistance of ceramic waste tile self-compacting concrete to sulphuric acid attack

Ram Vilas Meena [a], Ankit Singh Beniwal [a], Abhishek Jain [b], Rakesh Choudhary [b], Ramswaroop Mandolia [c]

[a] Department of Civil Engineering, JECRC University, Jaipur 303905, India
[b] Department of Civil Engineering, Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur 302017, India
[c] Department of Civil Engineering, Malaviya National Institute of Technology, Jaipur 302017, India

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Highlights

- Acid attack resistance of SCC containing ceramic waste tile (CWT) was evaluated as a replacement of fine aggregate.
- Improved resistance of CWT based mixtures was observed after exposure to acid attack.
- FTIR and XRD analysis showed a lower decay of CSH gel and lower formation of ettringite in CWT based mixtures.

- Incorporating CWT in SCC reduced the cost, embodied energy and embodied carbon dioxide emission.

Abstract

Ceramic waste tile aggregates produced from mixed coloured tile were utilized in self-compacting concrete (SCC). This research was aimed at assessing the performance of SCC in sulphuric acid environment by introducing ceramic waste tile (CWT) as natural fine aggregate replacement in different ratios (0%, 20%, 40%, 60%, 80% and 100%). SCC samples were exposed to a 3% sulphuric acid solution for 7, 28, 90 and 180 days. The transformation of mass, compressive strength, and micro-structure were used to assess the performance of concrete. It was discovered that CWT was sacrificial in nature when the SCC samples were subjected to an acidic environment, which helped to prevent damage to the cement hydration components that provided the strength. X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR) showed that the presence of CWT led to substantially less damage to the hydration products. Furthermore, the increment in replacement level after 60% has shown an increment of void ratio, leading to reduction in preliminary mechanical characteristics. It was concluded that 60% replacement level may provide the highest optimum performance in terms of compressive strength and sulphuric acid resistance. According to economic and ecological studies, SCC mixtures that comprise CWT are economical and have lower embodied energy and lesser CO_2 emissions.

Previous Next

Keywords

Ceramic waste tile; Self-compacting concrete; Acid attack; X-ray diffraction; Fourier transform infrared spectroscopy

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1. Introduction

Every growing country's economic progress is largely dependent on modernization and expanding its infrastructure. Population growth and economic reasons have combined to increase further demand, which has resulted in an unparalleled increase in industrial output worldwide. Generally, natural resources were used to extract and deplete this need. Large amounts of industrial waste are also generated as a byproduct of the procedure. Global warming, pollution, soil degradation, etc., are just a few of the negative environmental impacts that have been brought about as a result. The problem of finding sustainable construction materials and infrastructure is therefore put to the scientific community. Thus, researchers are continuously searching for new and green alternative materials for natural resources to attain sustainable infrastructure development, which is also beneficial. Various industrial by-products and stone wastes like granite, marble, limestone, sandstone, kota-stone, quartz stone as partial or full substitutions of the fine and coarse aggregate have the potential to be used beneficially [1].

Self-compacting concrete (SCC) is the most popular variety due to its higher fresh characteristics and better durability. Japanese first time developed SCC in 1980 [2]. SCC reduced the cost of labour and times of construction due to rapid rate of placement. SCC decreases construction noise and provides better external finishing, strength and durability. The main intent of SCC is to have a homogenous mix without leading to segregation, and it must be flowable. However, higher fine aggregate content was needed to attain fresh SCC properties (passing ability, flowability and segregation resistance). Overusing river sand as a fine aggregate in the construction industry has caused the river beds to diminish. Additional issues include decreased stream water storage, reduced water tables, degraded river beds, etc. As a result of the aforementioned issues, several states have been forbidden by the Indian government from mining or extracting river sand [3]. Design life of at least 50 years is expected for self-compacting concrete structures [4]. Due to sulfuric acid attack, they are occasionally impaired in only a few years. The impairment shows development of chemical by-products which often get chipped off the surface of concrete elements, causing alteration in mass, strength, and the shape of structural elements made of this concrete [5]. With the increasing rate of deterioration, it becomes essential to repair and occasionally replace the whole damaged concrete structure, which is expensive and creates numerous social difficulties [6].

Moreover, a significant amount of studies have been conducted previously on the use of various wastes in SCC [7], [8], [9], [10], [11]. Topcu et al. [10] examined the behavior of SCC mixes when waste marble dust was used as filler material. They reported that these mixes had not affected fresh properties at up to 200 kg/m^3 waste marble replacement. However, marble dust has reduced the mechanical characteristics of hardened SCC, particularly at content levels slightly over 200 kg/m^3. Gupta and siddique [11] tested the durability of SCC mixtures having fly ash and copper slag as binder material and natural river sand substitution. The substitution of river sand up to 30% copper slag displayed enhanced strength and durability characteristics. Choudhary et al. [12] observed the increased mechanical strength on the utilization of fly ash (along with silica fume and marble waste) as cement substitution in SCC. Jain et al. [13] noted an improvement in the fresh characteristics and mechanical strength with the substitution of waste granite as fine aggregate in SCC. Ceramic tile is one of the types of glazed, unglazed and porcelain tile available in the states of Gujarat, Rajasthan, Uttar Pradesh, and Haryana. India has an annual production of ceramic tile around a 1266 million square meter [14]. Ceramic tile is a mixture of sand and clay. Physically this is durable, strong, hard, highly resistant and non-slippery homogenous ceramic tile. As of this, it serves as decoration in both housing and commercial structures. It is available in various colors white, red, blue, brown, green or their groupings [14]. Due to the massive amount of solid waste that ceramic industry dumps, the manufacture of ceramic tile has presented a major danger to the local ecosystem. Processing, transporting, fixing, and demolition processes produce waste ceramic solid. It is seen in India that about 30% of ceramic production is discarded as waste by the ceramics industry [9]. The non-standard tile can exceed up to 7% of the total manufacture of the ceramic tile sector [15]. This ceramic waste can be utilized as aggregate (both fine and coarse) and binder in concrete, mortar, SCC and geopolymer concrete. It can also be used in soil stabilization, pavement and production of bricks. Thus**,** utilizing the ceramic waste tile (CWT) as fine aggregate in SCC provides better economic and environmental aspects. The use of ceramic waste by various researchers is detailed below.

Siddique et al. [16] studied the outcome of ceramic bone china fine aggregate on chloride penetration, corrosion resistance, resistance to abrasion and voids percentage of the concrete mix. They observed that chloride penetration and abrasion depth were reduced on increasing the ceramic bone china substitution in concrete as fine aggregate. Mohit and Sharifi [17] found beneficial effects in compressive strength at up to 10% waste ceramic inclusion with cement in mortar mixtures. However, the compressive strength was reduced with higher waste ceramic substitution. Senthamarai et al. [18] noted the durability of concrete mixtures having waste ceramic electrical insulators as coarse aggregate substitution from six different w/c ratios (0.35 to 0.60 with an increment of 0.5). The durability characteristics like sorptivity, volume of voids, water absorption and rapid chloride penetration were decreased with a reduction in w/c ratio. Rojas et al. [19] noticed an improvement in the durability characteristics of waste ceramic modified cement paste. The pozzolanic activity of waste ceramic, which contributes more CSH gel and improves pore structure, was responsible for increased durability performance. Sivaprakash et al. [20] observed that substituting fine aggregate by 10–50% waste ceramic resulted in decrement in mechanical strength of concrete. Medina et al. [21] noted the water resistance behavior of recycled sanitary-ware incorporated concrete mixes. They concluded that 25% coarse aggregate replacement with recycled sanitary ware accelerated the water resistance of the concrete mixture. Agrawal et al. [22] inspected that the concrete having 40% waste ceramic fine and coarse aggregate attained similar workability and mechanical strength than control concrete. Torgal and Jalali [15] studied the compressive strength and durability of the concrete prepared with crushed fine and coarse ceramic tiles. It was concluded that concrete compressive strength and durability might be somewhat enhanced by incorporating crushed ceramic tiles. Ogrodnik et al. [23] reported the impact of the fire on the compressive strength of concrete made with or without waste ceramic. They observed the better fire resistance of concrete prepared using waste ceramic compared to without waste ceramic mixture. Dhanasekar et al. [24] observed a higher split tensile and compressive strength for concrete containing up to 20% CWT than reference concrete. Subas et al. [25] concluded that the substitution of cement with up to 15% ceramic waste powder is beneficial in making of self-consolidating concretes. Brekailo et al. [26] studied the potential of producing eco-mortar with red ceramic and observed better resistance against sulfate attack on inclusion of ceramic waste. Younis et al. [27] examined the effect of brick wastes and crushed ceramic as coarse aggregate replacement in the manufacture of self-curing concrete and exhibited accepted outcomes regarding the mechanical, durability and microstructure analysis for the production self-curing concrete. Sivakumar et al. [28] noted that concrete integrating waste ceramic had minimum mass loss reduction related to concrete prepared without waste ceramic. Jerônimo et al. [29] revealed that replace of 20–30% cement by waste ground clay bricks in SCC provided better compressive strength because of the decrease in the porosity.

From the past literature studies, it was observed that there are many studies on waste ceramic incorporation in mortar and concrete, which focus mostly on fresh, mechanical and durability properties. Still, existing literature lacks a study of the durability properties of SCC in acidic environments. In this research, the durability performance of SCC containing CWT was evaluated in acidic environmental conditions**.**

This study intended to judge the SCC made with ceramic waste tile (CWT) when exposed to an acidic environment. Formerly, the fresh characteristics and mechanical strength of similar SCC blends have been assessed [30]. All the mixtures satisfied the European Guidelines standards for SCC fresh characteristics [31]. The durability of SCC was assessed in this study for sulphuric acid resistance, which would help in determining the performance of CWT based SCC in harsh acidic environments. Such sulphuric acid-resistant concrete can withstand aggressive atmospheric conditions and thus increasing the life of the structure. To investigate the microstructural behavior of SCC, FTIR and XRD studies were done. Moreover, ecological and economic analyses were also carried.

2. Experimental investigation

2.1. Raw materials used

Ordinary Portland cement (OPC) of 43 grade was utilized, as confirmed by BIS 8112 [32]. The fine aggregate used as per BIS 383 [33] was locally available materials Zone-II river sand with a maximum size of 4.75 mm. In this research work, the utilized crushed CWT is displayed in Fig. 1. According to BIS 383 [33], crushed basalt-based stone with a 10 mm maximum size was utilized as coarse aggregate. Fig. 2 depicts grain size analyses of CWT and river sand. It is distinctly visible from Fig. 3 that the river sand particles are smooth and granular, whereas CWT particle surfaces are rough and angular. To maintain the flowability, a superplasticizer based on poly carboxylic ether (PCE) was used. The essential properties of river sand, CWT, coarse aggregates, and cement are reported in Table 1. The chemical component of natural river sand and CWT was determined by the technique of X-ray fluorescence (XRF) and is depicted in Table 2.

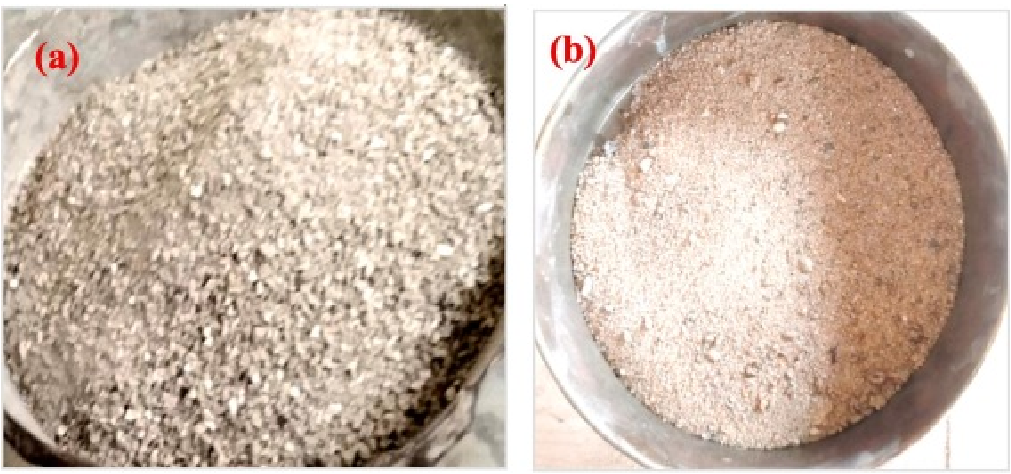


Fig. 1. Raw materials (a) CWT; (b) fine aggregate.

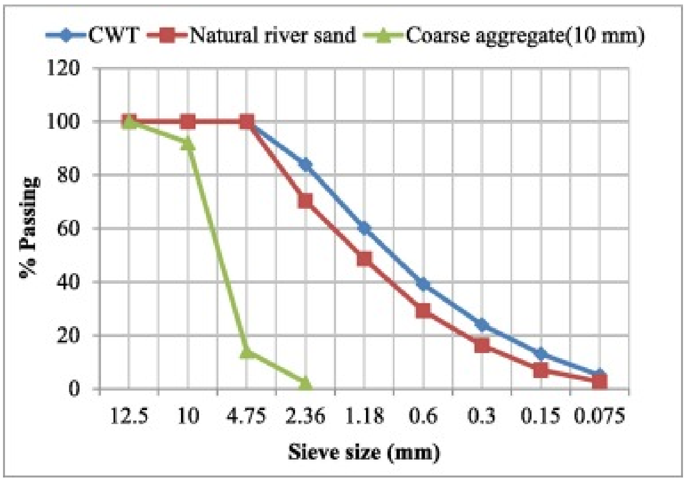


Fig. 2. Sieve analyses of CWT, river sand and coarse aggregate (10 mm).

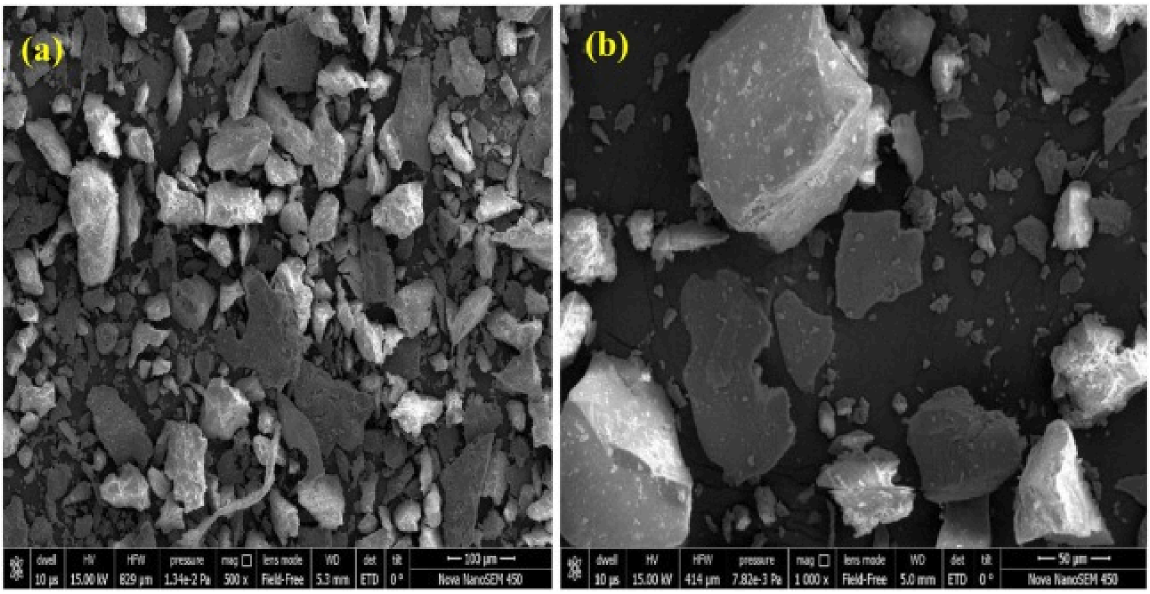


Fig. 3. SEM image (a) CWT (b) Fine aggregate.

Table 1. Cement, river sand, CWT and coarse aggregate properties.

Materials	Water absorption (%)	Specific gravity	Fineness modulus	28-day compressive strength (MPa)	Consistency (%)
Cement	–	3.15	–	42.3	28
River sand	1.3	2.65	2.61		–
CWT	1.87	2.37	2.29		–
Coarse aggregate	0.24	2.75	–		–

Table 2. Chemical component of CWT and fine aggregate.

Chemical composition (%)	CWT	Fine aggregate
Al_2O_3	14.42	11.76
CaO	2.13	2.35
SiO_2	75.09	78.97
Fe_2O_3	0.44	2.67
MgO	1.05	0.73
K_2O	1.07	2.75

Chemical composition (%)	**CWT**	**Fine aggregate**
Na_2O	4.50	–
TiO_2	0.04	–
LOI	0.52	0.45

2.2. Mix proportioning methodology

Mix proportions of SCC used in this research are shown in Table 3. Natural river sand (fine aggregate) was substituted by CWT based on weight at different percentages as 0%, 20%, 40%, 60%, 80%, and 100%. A total of six SCC mixtures were created, comprising 560 kg/m^3 overall binder content, 1659 Kg/m^3 total aggregate content, and uniform water-cement ratio (0.33). The SCC mixture has nomenclature as Px that includes x% substitution of fine aggregate with CWT.

Table 3. Mixture proportions of SCC (Kg/m^3) [30].

Mixture ID	**P_{0}**	**P_{20}**	**P_{40}**	**P_{60}**	**P_{80}**	**P_{100}**
Cement	560	560	560	560	560	560
Fine aggregate	928	742.4	556.8	371.2	185.6	0
CWT	0	185.6	371.2	556.8	742.4	928
Coarse aggregate	731	731	731	731	731	731
Water	186	186	186	186	186	186
Admixture (%)	0.9	0.9	0.93	1.25	1.56	2.12
w/c ratio	0.33	0.33	0.33	0.33	0.33	0.33

2.3. Testing procedure

2.3.1. Fresh characteristics

In order to be classified as SCC, a concrete must meet all fresh characteristics standards for flowability, viscosity and passing ability as per recommendations made by EFNARC guidelines [34]. For this, slump flow, U-box, T_{500} time, L-box, V-funnel time, J-ring flow were conducted.

2.3.2. Compressive strength

Compressive strength test was performed on 100 mm sized cubes after curing for duration of 7, 28 and 365 days. Compressive strength was performed as per BIS 516 [35]. To assess the compressive strength of SCC samples, the digital compression testing machine (CTM) utilized had a capacity of 2000 kN. Cube specimens were tested until failure at a uniform rate of compression loading (0.233 N/mm^2/sec). For evaluating final compressive strength, for each mixture, average of three cube samples was taken.

2.3.3. Acid attack

Acid resistance experiment on SCC mixes was conducted according to ASTM C267-12 [36]. Acid attack experiment on concrete specimens was performed by using 3% H_2SO_4 solution for different exposure periods for 7, 28, 90 and 180 days. This test was performed at a room temperature, as shown in Fig. 4. The H_2SO_4 solution was regularly refreshed for maintaining a constant concentration during the experiment. The influence of H_2SO_4 on concrete mixes was tested by calculating the difference in weight and compressive strength. Compressive strength outcomes for acid exposed specimens were compared with the respective 28 days water curing samples. Variations in compressive strength and weight were obtained with accordance to equation 4 and 5, respectively:

$$\text{Variation in weight } (\%) = \frac{W_a - W_{sb}}{W_a} \times 100 \tag{4}$$

$$\text{Variation in compressive strength } (\%) = \frac{F_c - F_{sb}}{F_c} \times 100 \tag{5}$$

where

Fig. 4. SCC samples exposed to acid solution (a) 7 days (b) 180 days.

W_a is oven dry weight of 28 day water cured SCC specimen; W_{sb} is the weight of acid exposed SCC specimen for different exposure periods at a saturated surface dry state; F_c is the compressive strength of 28 day cured SCC specimen; F_{sb} is the compressive strength of acid exposed SCC specimen for different exposure periods at a saturated surface dry state.

2.3.4. Microstructural properties

FTIR study was conducted using K-Br method (Perkin Elmer Spectrum) setup. FTIR study was performed on concrete specimen immersed in acid solution for 180 days. In this analysis wavelengths ranged in between 400 and 4000 cm^{-1}. X-ray Diffraction (XRD) was conducted in order to check the mineral phases in concrete samples immersed in acid solution for 180 days. The XRD patterns of SCC were carried out with following parameters, scanning range of 10⁰ to 90⁰ along with a step size of 0.02⁰.

3. Results and discussions

3.1. Fresh characteristics

The authors of this research previously noted that all the produced SCC blends fulfilled the requirements set out by EFNARC guidelines for successful SCC mixes [31]. The outcomes of slump flow, T_{500}, U-box, V-funnel, L-box and J-ring are displayed in Table 4. The filling ability, passing ability and viscosity were reduced on using CWT in the production of SCC. The slump flow values varied from 721 to 663.5 mm for SCC mixture containing 0–100% CWT. T_{500} time and V-funnel time for SCC mixture increased with the addition of CWT. This might be ascribed to the increased viscosity of SCC mixture prepared with CWT. The rough and irregular shape of CWT particles may increase the friction between aggregate and binder, resulting in reduced filling ability and passing ability of SCC mixes. The SCC mixtures were categorized as (SF2) based on the diameters of slump, and viscosity was classified as VF1 based on time from V-funnel [34]. A detailed discussion of the influence of CWT on fresh characteristics has previously been reported by authors [30].

Table 4. Testing outcomes of fresh characteristics with standard deviation.

Mix Code	**P_0**	**P_{20}**	**P_{40}**	**P_{60}**	**P_{80}**	**P_{100}**
Slump-flow (mm)	721±5.45	713±3.25	702±4.92	687.3±6.95	674.3±7.65	663.5±8.15
T_{500} time (sec)	3.12±0.06	3.14±0.04	3.17±0.05	4.02±0.09	5.36±0.04	6.75±0.09
J-ring (mm)	2.20±0.33	2.50±0.30	3.30±0.32	5.90±0.38	8.70±0.37	10.60±0.32
L-box ratio	0.91±0.004	0.90±0.006	0.87±0.007	0.84±0.005	0.81±0.009	0.77±0.008
V-funnel time (sec)	7.31±0.05	7.46±0.04	7.89±0.08	9.86±0.04	13.6±0.09	18.49±0.10
U-Box(mm)	3.00±0.31	5.00±0.35	9.00±0.37	14.0±0.30	21.0±0.39	29.00±0.34

3.2. Compressive test results

The results of compressive strength experiment outcomes at the age of 7, 28, and 365 curing are depicted in Fig. 5. The highest compressive strength for CWT replacement was observed for P_{60} mixture compared to the control SCC mixture at all curing periods. This is possible due to the pozzolanic nature, rough surface and angular shape of CWT, and CWT produced denser mortar matrix. Also, CWT particles having a rough surface and angular shape would result in good interlocking with cement paste and enhanced compressive strength. Gautam et al. [37] used ceramic waste bone china powder and waste granite cutting as a binder and fine aggregate replacement in SCC, respectively, and observed higher strength on substitution levels of up to 10% ceramic waste bone china powder and 30% waste granite cutting. Siddique et al. [38] specified that incorporating bone china ceramic in concrete implies compressive strength improvement compared to reference concrete.

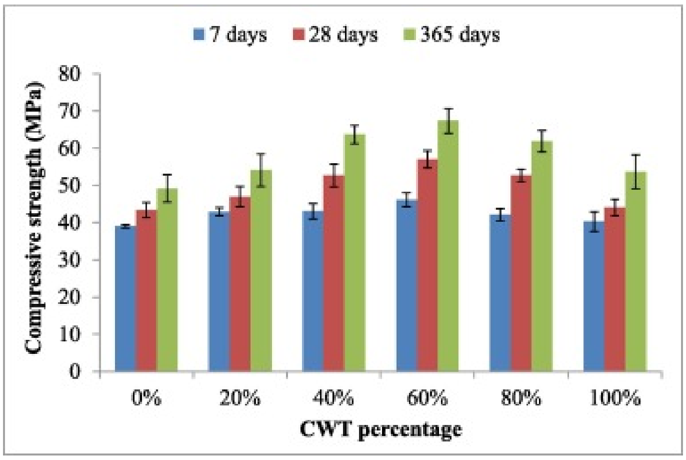


Fig. 5. Compressive strength of tested SCC.

3.3. Sulphuric acid attack test results

3.3.1. Change in weight

The variations in weight of SCC mixes are presented in Fig. 6. Increasing **s**ulphuric acid exposure continuously from 7 to 180days leads to weight loss for all SCC mixes. All the damage in the concrete cubes was observed to be completely superficial. The highest damage was detected for the control mix as compared to CWT substitution. This reduction in weight might be due to CWT being more durable relative to natural aggregates [28]. Therefore on continuous acid exposure, minimum mortar paste was lost. Additionally, it can also be shown from Fig. 7 that scaling happened more often on control samples which caused the degradation of higher surface layers compared to CWT self-compacting concrete samples.

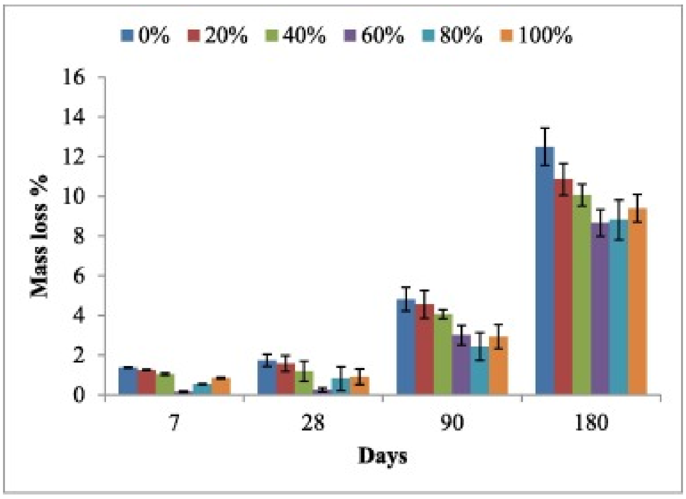


Fig. 6. Mass loss percentages in SCC samples.

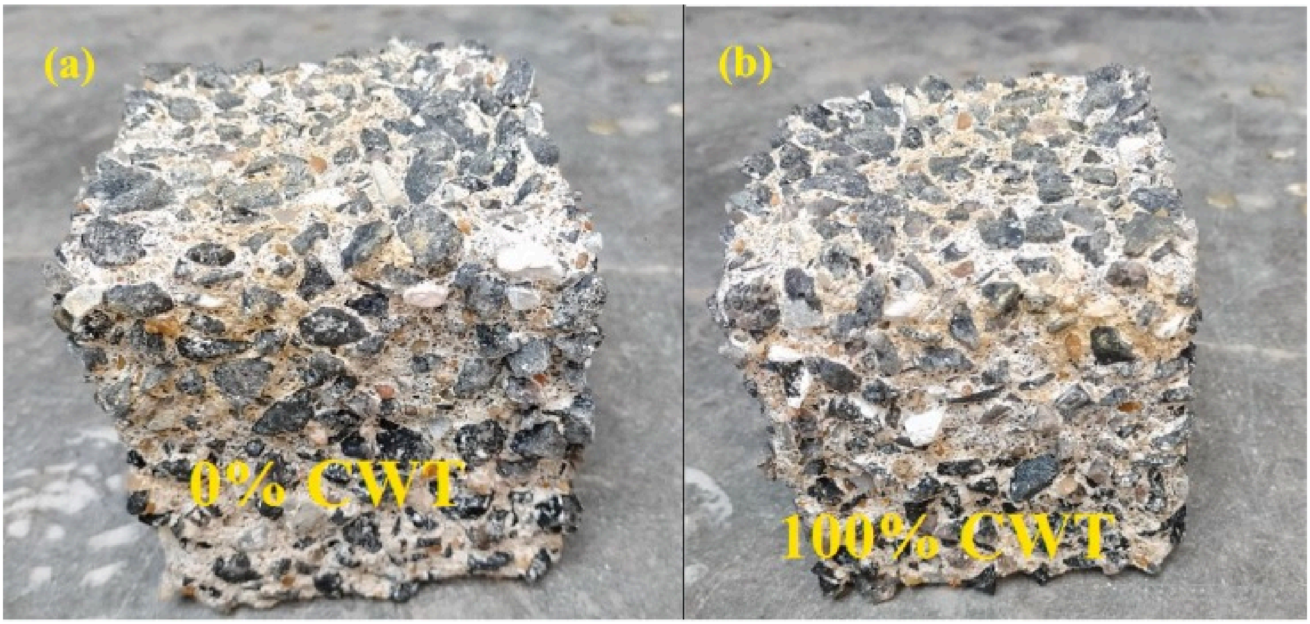


Fig. 7. Acid-attacked SCC samples: (a) reference mix (0% CWT), (b) 100% CWT.

3.3.2. Variation in compressive strength

The 7, 28, 90 and 180 days acid attacked compressive strength variation is presented in Fig. 8. It was detected that the fall in compressive strength raises crescively with the increment in exposure period for all SCC mixtures. This relies on the newly formed chemical products on acid exposure. With acid exposure period of 7 to 180 days, the observed loss in compressive strength of SCC containing CWT was less than the reference mix. The least compressive strength loss was observed in mix P_{40}, P_{60} and P_{80} which were 23.39%, 22.31% and 24.98%, respectively, for 180 days acidic environment. The highest compressive strength loss was detected in mix P_0 (control), P_{20} and P_{100}, which was 34.94, 28.73 and 27.22%, respectively. Outcomes have revealed that concrete mixes containing 60% CWT have the lowest compressive strength loss. Huseien et al. [39] reported loss in weight and strength too gradually reduced with increasing content of ceramic waste tile powder substituting ground blast furnace slag in alkali-activated SCC. Ash et al. [40] tested the influence of SCC containing waste ceramic powder and 25% fly ash on exposure to HCl acid solution for 91 days. After exposure, the reduction in compressive strength of SCC for 25% fly ash and 5% waste ceramic powder was detected less compared to control mix.

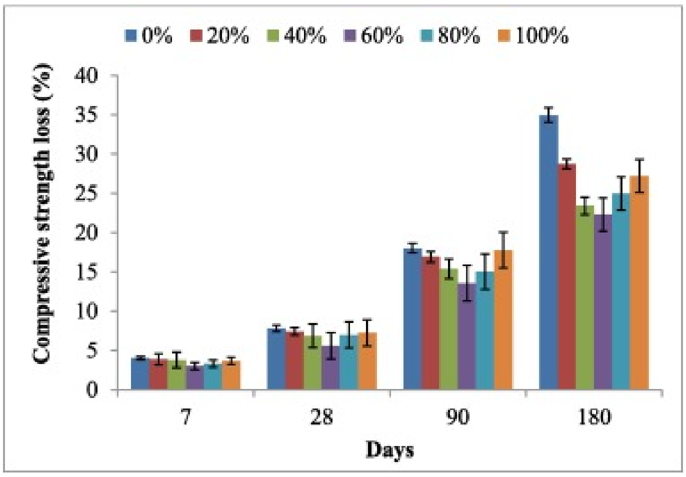
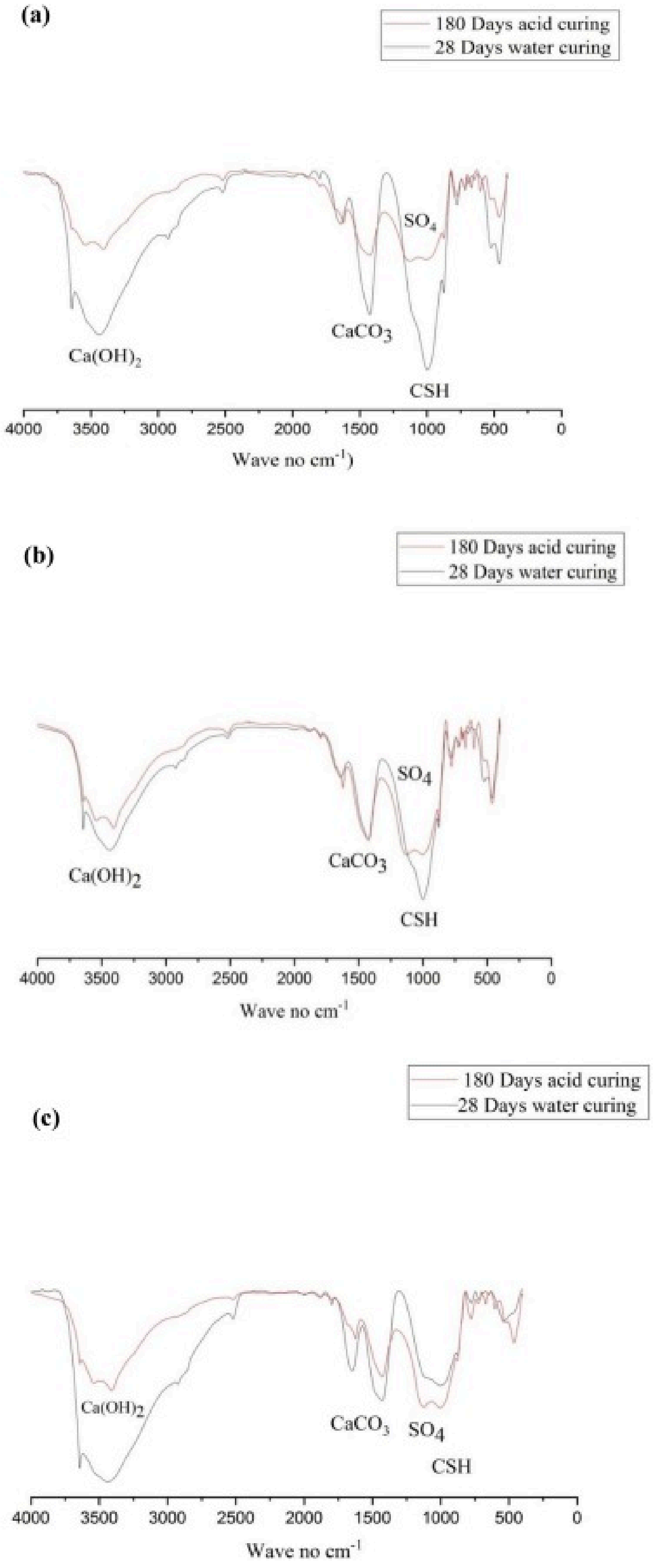


Fig. 8. The loss of compressive strength percentage in SCC samples.

3.4. Microstructural properties

3.4.1. Acid attack FTIR analysis

Internal phase transformation during H_2SO_4 exposure was examined for SCC mixtures (P_0, P_{20}, P_{40}, P_{60}, P_{80} and P_{100}). The FTIR spectra of SCC mixtures immersed at 28 days water curing and 180 days H_2SO_4 solution are displayed in Fig. 9. Considerable changes were observed in the molecular groups of O-H ($Ca(OH)_2$ or portlandite), SO_4 (ettringite) and Si-O (CSH gel) as shown in Table 5. Bands of $Ca(OH)_2$, CSH gel, and ettringite are observed around 3556–3645 cm^{-1} [41], [42], 961–1006 cm^{-1} [43], [44], and 1121–1164 cm^{-1} [45], respectively. It has been reported that the shifting of wave number to lower side indicates the dwindling of bond length of different molecular groups [41], [42]. From Table 5, it has been detected that maximum consumption of portlandite was observed for the P_0 mixture, followed by the P_{100} mixture after 180 days of sulphuric acidic exposure. The figure exhibits that the breakdown of portlandite intensifies with the rise in exposure periods for H_2SO_4 curing of specimens, leading to the formation of calcium sulphate and ettringite. The formation of auxiliary ettringite bands in acid exposed mixtures indicates the impression of acid attack. The absorbance bands of ettringite were found to be lower for CWT based SCC mixtures than the P_0 mixture, which indicated the lower formation of ettringite in CWT based SCC mixtures. The lower formation of ettringite in CWT based SCC mixtures caused the lower loss of strength for those mixtures than the P_0 mixture. Further, the SCC sample containing CWT showed the lower shifting of CSH gel compared to control mix, indicating better resistance against acid attack for CWT based SCC mixes. The relatively lower shifting of CSH bands and lower formation of ettringite in CWT based mixtures than the control mixes might be the reason for lower loss of compressive strength for those mixtures.


(a)
180 Days acid curing
28 Days water curing
SO4
CaCO3
Ca(OH)2
CSH
4000
3500
3000
2500
2000
1500
1000
500
0
Wave no cm-1)
(b)
180 Days acid curing
28 Days water curing
SO4
Ca(OH)2
CaCO3
CSH
4000
3500
3000
2500
2000
1500
1000
500
0
Wave no cm-1
(c)
180 Days acid curing
28 Days water curing
Ca(OH)2
CaCO3
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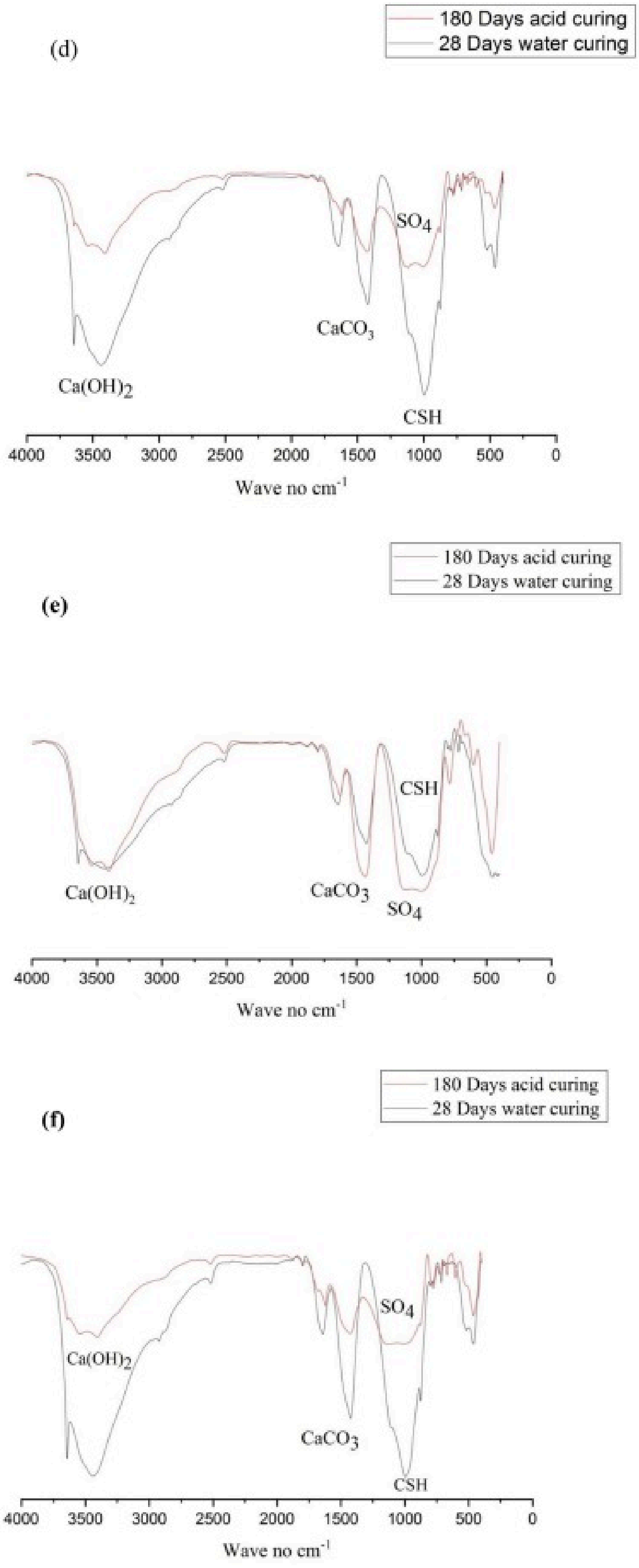


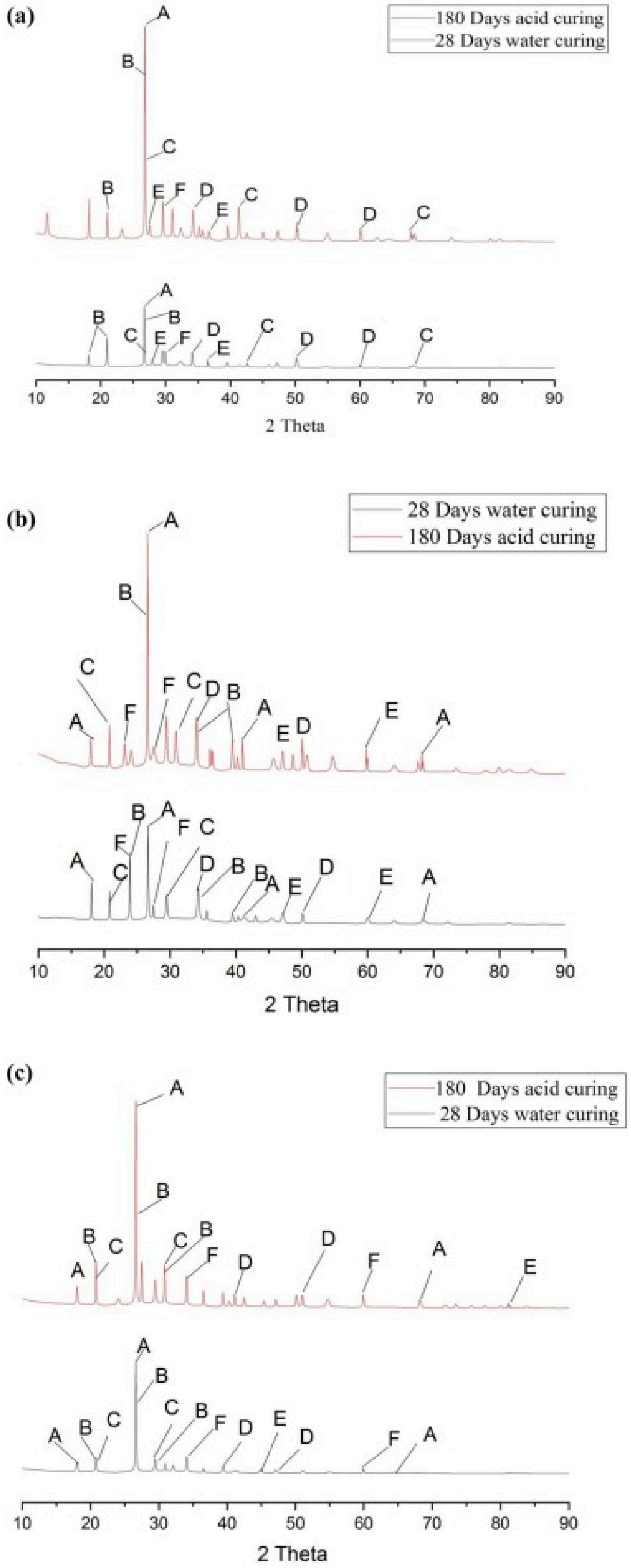
Fig. 9. FTIR spectra for acid exposed SCC mixes containing CWT: (a) P_0, (b) P_{20}, (c) P_{40}, (d) P_{60}, (e) P_{80}, (f) P_{100}.

Table 5. FTIR wave number (cm^{-1}) of CSH, portlandite and Ettringite for all mixtures.

Mix ID (exposure condition)	**Molecular group**		
	CSH	**Portlandite**	**Ettringite (SO_4)**
P_0(28 days water cured)	991	3645	–
P_0(180 days sulphuric acid exposed)	960	3556	1164
P_{20}(28 days water cured)	997	3639	–
P_{20}(180 days sulphuric acid exposed)	969	3587	1151
P_{40} (28 days water cured)	1001	3631	–
P_{40} (180 days sulphuric acid exposed)	978	3601	1135
P_{60} (28 days water cured)	1006	3627	–
P_{60} (180 days sulphuric acid cured)	994	3605	1121
P_{80} (28 days water cured)	995	3637	–
P_{80}(180 days sulphuric acid exposed)	973	3596	1147
P_{100}(28 days water cured)	994	3641	–
P_{100}(180 days sulphuric acid exposed)	968	3581	1155

3.4.2. Acid attack XRD analysis

XRD analysis was conducted on SCC specimens for 28 days water curing and 180 days acidic curing. The mineralogical composition of SCC samples was evaluated after 28 days of water curing and 180 days of exposure to sulphuric acid. The XRD analysis of various mixes containing CWT is shown in Fig. 10. The following mineral phases were detected: quartz (SiO_2), calcium silicate hydrate or CSH gel ($Ca_6H_2O_{13}Si_3$), calcium hydroxide or portlandite ($Ca(OH)_2$), calcite ($CaCO_3$), ettringite ($Ca_6Al_2(SO_4)_3(OH)_2{\cdot}26H_2O$), and microcline ($KAlSi_3O_8$). These phases are represented by alphabet numbers (A-F) in the figures, respectively.


(a)
180 Days acid curing
28 Days water curing
A
B
C
B
E
F
D
E
C
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B
B
C
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F
D
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2 Theta
(c)
180 Days acid curing
28 Days water curing
A
B
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C
B
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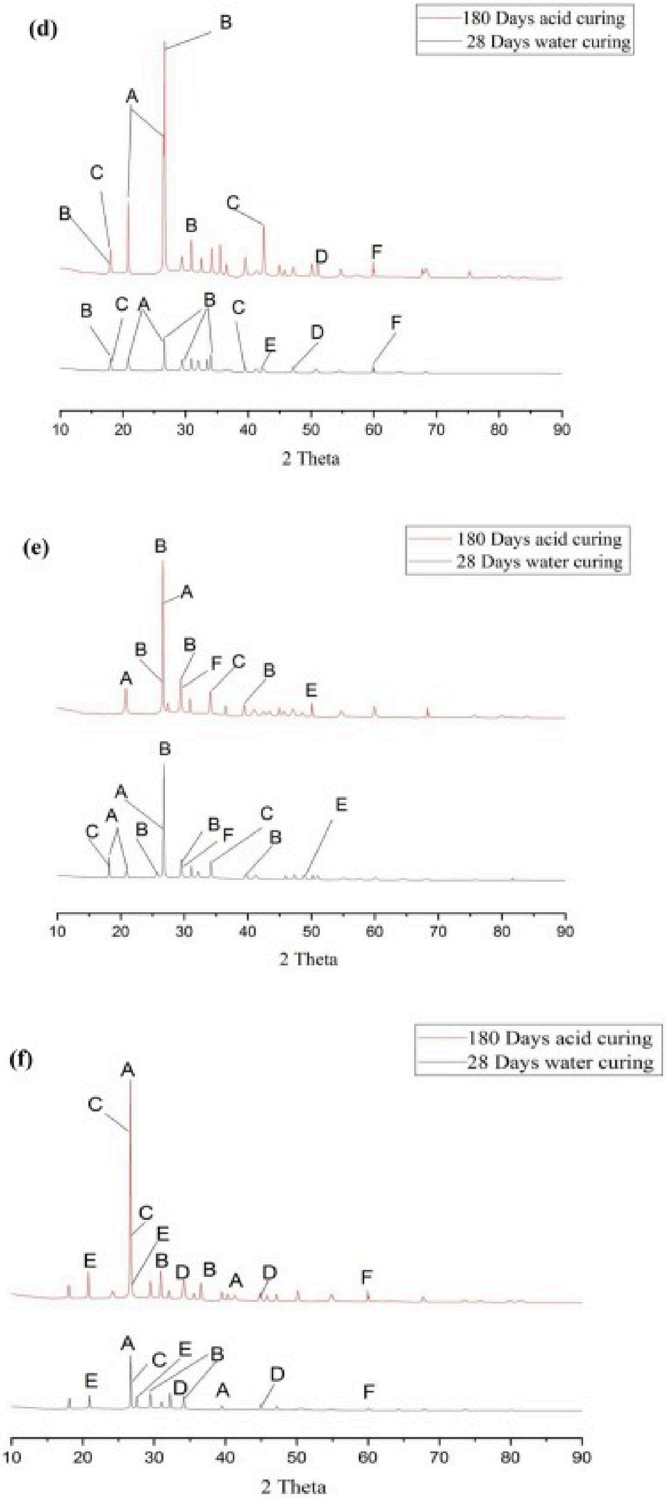

Fig. 10. XRD analysis of acid exposed SCC samples containing CWT: (a) P_0, (b) P_{20}, (c) P_{40}, (d) P_{60}, (e) P_{80}, (f) P_{100}.

The intensity peaks of $Ca(OH)_2$ for all the mixtures were found to be lowered in acid exposed mixtures, as shown in Fig. 10. The progressive reduction in portlandite intensity was observed on increasing acid exposure time. This might be due to the reaction of $Ca(OH)_2$ with sulphuric acid to form additional hydration products. The lowering of portlandite intensity peaks on exposure to H_2SO_4, led to the formation of calcium sulphate and ettringite. The intensity peaks of portlandite were significantly reduced for P_0 mixture followed by P_{100} mixture after 180days of sulphuric acidic exposure. The intensity peaks of ettringite were found to be lower for CWT based SCC mixtures than the P_0 mixture, which indicated the lower formation of ettringite in CWT based SCC mixtures. The lower formation of ettringite in CWT based SCC mixtures caused a lower loss of strength for those mixtures than the P0 mixture.

Further, the formation CSH gel generally dominates the mechanical performance of concrete matrix. The intensity peaks of CSH gel were also found to be lowered in acid exposed mixtures, as shown in Fig. 10. The progressive reduction in CSH intensity was also observed on increasing acid exposure time might be due to the decalcification of CSH gel in the presence of sulfuric acid. SCC sample containing CWT showed the higher intensity peaks of CSH gel compared to the control mix, indicating better resistance against acid attack for CWT based SCC mixes. The relatively higher intensity peaks of CSH gel and lower intensity peaks of ettringite in CWT based mixtures than the control mixes might be the reason for the lower loss of compressive strength for those mixtures.

4. Economic and environmental aspect

The two main parameters for assessing the sustainability of concrete are embodied carbon dioxide emission (ECO_2e) and embodied energy (EE). ECO_2e was used to calculate CO_2 released in the environment while raw material processing, transporting, recycling, other construction practices, installation and operation of machinery, and the energy consumption was calculated using EE. In this research, the statistics of ECO_2e and EE for the raw materials used were adopted from previous literature [16], [37], [46], as displayed in Table 6. The main purpose of cost and ecological analysis in the current research is to show the impact of CWT in lowering the ECO_2e and EE for the production of SCC blends.

Table 6. Cost of raw materials, ECO_2e and EE of ingredients.

Materials	**Fine aggregate**	**Cement**	**CWT**	**Coarse aggregate**	**Admixture**	**Water**
Cost (Rs/kg)	3.2	8.2	0.5	1.1	160	0.06
ECO_2e ($kgCO_2e/kg$)	0.0051	0.93	0	0.0048	0.6	0.0008
EE (MJ/kg)	0.081	4.8	0	0.083	11.5	0.2

The amount of ECO_2e released and EE consumed by numerous SCC mixtures are estimated by multiplying the unit weight of the ingredient used for separate mixtures with the per unit value of ECO_2e and EE for the corresponding mixture. Table 7 shows the corresponding ECO_2e and EE statistics for different SCC blends. The lowest EE (2890.77 MJ/m^3) is shown by P_{40} mix. The substitution of CWT for fine aggregate may cause this decrease in EE value. Using CWT as concrete material significantly impacted the lowering of EE. However, the higher values of EE (2919 MJ/m^3 and 2922.38 MJ/m^3) were detected for the P_0 and P_{100} mixtures, respectively. Higher fine natural aggregate and the larger quantity of superplasticizer dosage needed for P_0 and P_{100} mixtures could be the reason for the increment in EE consumption. A similar pattern is observed for ECO_2e release data for different SCC blends. Cement has the highest contribution to ECO_2e release among all raw materials, followed by fine aggregate, coarse aggregate, and superplasticizer, with no ECO_2e contribution from CWT. As an outcome, CWT may produce a green and sustainable SCC mixture.

Table 7. EE, ECO_2e and cost analysis of self-compacting concrete blends.

Mixture ID	**Cost (INR/m^3)**	**EE (MJ/m^3)**	**ECO_2e (kgCO$_2$e/ m^3)**	**Cost (INR/ MPa/m^3)**
P_0	9181.70	2919.00	532.21	211.52
P_{20}	8680.58	2903.97	531.27	184.80
P_{40}	8205.06	2890.77	530.42	155.71
P_{60}	7991.94	2896.44	530.55	140.09
P_{80}	7767.62	2901.30	530.64	147.24
P_{100}	7768.90	2922.38	531.17	176.33

Cost analysis for developed SCC mixes is displayed in Table 7. It also covers the cost of compressive strength per MPa. When compared to P_0 mix, the P_{80} mix was shown to be the most economical blend. The P_{80} blend was shown to have an overall cost reduction of around 15% over the P_0 mix. Furthermore, P_{60} mix exhibited the lowest cost/28-day compressive strength/m^3 than the P_0 mixture despite having the high cost of fine aggregate. Hence, the primary cause of the decrease in the value of ECO_2e and EE for produced SCC mixtures was using CWT as substitute for fine aggregate.

5. Conclusions

The objective of this study was to analyze the performance of ceramic waste tile (CWT) as a fine aggregate in SCC in an aggressive acidic environment. For this, comprehensive studies comprising mechanical and microstructure investigation were performed on SCC mixes prepared with different proportions of CWT aggregate. The results of the research are outlined below:

- A decrement in the fresh characteristics of SCC was witnessed with the rise in CWT content. The rough and angular nature of CWT may be the reason for the decrement in the filling ability, passing, and viscosity ability.
- An increment in the compressive strength of SCC mixtures was observed with up to 60% CWT incorporation compared to reference SCC.
- A minor change has been detected in compressive strength and weight for CWT based concrete specimens when exposed to acidic environments. This is primarily related to the stable and durable behavior of CWT, which reduces the probability of disintegration of SCC constituents against acidic attack.
- FTIR and XRD analysis after prolonged exposure to sulphuric acid showed a lower decay of CSH gel and lower formation of ettringite in CWT based mixtures than the control mixes. CWT based mixtures were observed to be relatively stable against the acid attack compared to the control mixture.
- Ecological analysis outcomes showed that incorporating of CWT in SCC reduced the cost, embodied energy (EE) and embodied carbon dioxide emission (ECO_{2e}). The minimum ECO_2e emission and EE were found for P_{40} mix. Also, P_{60} mix exhibited the

lowest cost/28-day compressive strength/m^3 than the P_0 mixture despite having the high cost of fine aggregate.

- As an outcome, the incorporation of up to 80% CWT as a replacement to fine aggregate in SCC can be a feasible alternative for SCC structures subjected to acidic environments.

CRediT authorship contribution statement

Ram Vilas Meena: Conceptualization, Methodology, Data curation, Investigation, Writing – original draft, Visualization. **Ankit Singh Beniwal:** Visualization, Investigation, Writing – review & editing. **Abhishek Jain:** Visualization, Writing - original draft, Writing - review & editing. **Rakesh Choudhary:** Writing – review & editing. **Ramswaroop Mandolia:** Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Recommended articles

Data availability

No data was used for the research described in the article.

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