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RESEARCH

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Self-compacting concrete incorporating incinerated biomedical waste ash: a performance assessment

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Abstract

Rapid technological advancement is underway in the sphere of material science research. Several studies have been undertaken around the globe over the last four decades to improve the strength and durability performance of concrete. As a result of ongoing research and experimentation, concrete no longer just consists of the traditional materials of cement, aggregates and water but has transformed into an engineered custom material with efficient new ingredients in order to meet the demands of the expanding construction industry. In this experimental study, biomedical waste incinerator ash (BMIA) was employed as a partial substitute for cement in self-compacting concrete (SCC), designed for M30 grade. BMIA was partially replaced with cement in proportions of 0%, 5%, 10%, 15% and 20% by cement weight. This experimental work aimed to study the fresh, mechanical and durability characteristics of the SCC mixes incorporating BMIA. A suitable super-plasticizer was used to retain the rheological qualities of fresh concrete. To investigate the mechanical and durability characteristics, experiments on hardened concrete were performed. The results demonstrate that 5% of BMIA substitution for cement in the SCC mix had higher strength compared to all other mixes because BMIA's fine particles filled the voids in the hardened concrete. Scanning electronic microscopy (SEM) and X-ray diffraction (XRD) analyses were performed to examine the microstructure of BMIA substituted SCC versus conventional SCC mix. The chemical composition test revealed that BMIA can be employed in the SCC mix up to 5% efficiently, which will result in waste utilisation and disposal.

Keywords: SCC, Fresh and hardened concrete, BMIA, RCPT, Sorptivity, SEM analysis

Introduction

The modern construction industry demands good quality and highly workable concrete to construct the concrete structures. The special cases of architectural and structural designs provided with complex reinforcements necessitate the production of concrete that fulfils the proper passing and filling ability in addition to good structural and durability performance. SCC has a comparatively higher workability without segregation and compacts itself under its own weight, requiring no vibration while placing [1].

SCC could be produced by adopting three different methods/procedures [2]. Firstly, powder-type self-compacting concrete could be produced by utilising a low water-to-cement ratio and an adequate super-plasticizer content. Second, viscosity-modifying agents and appropriate admixtures are used to produce the viscosity agent-type SCC. The third form is the combination type SCC, in which viscosity-modifying admixtures are included, but the water-to-powder ratio is kept as low as possible [2–4].

The characteristics of SCC can be improved by adding the adequate/optimum quantity of chemical or mineral admixtures. Researchers have improved the characteristics of SCC by incorporating pozzolanic materials like fly ash, GGBS, bagasse ash and rice husk ash [4–6]. Similar to the above, there are many waste products produced as a result of various industrial operations, and one such product is biomedical waste incinerator ash (BMIA). Medical waste is one of the major wastes produced globally nowadays as a result of advances in medical technology, medical research and hospital operations. Rejected needles, blood waste, discarded microbiological samples, added living-being fabrics, used dressing and discarded protection equipment are all examples of medical waste [7]. The tremendous amount of waste that hospitals produce puts the environment in danger. Sometimes, non-infected plastic debris is routinely treated and recycled, but contaminated plastic is disposed of in an open landfill or incinerated [8, 9]. While there are other treatment options, incineration/pyrolysis is the most effective techniques to reduce on waste quantity and elimination of pathogens [9]. It was found that waste segregated in yellow bags was being sent to the incineration process to biomedical treatment facilities [10].

Here, we briefly present an overview of related work that is available in the literature. Tzanakos et al. (2014) [11] used medical waste ash as the primary raw material to produce geopolymers. The leachability of heavy metals inherent in the medical waste ash used to make the geopolymers was reduced through geopolymerization. Similarly, Aissa et al. (2018) [12] examined the effects of using ash from the incineration of pharmaceutical waste on the characteristics of high-performance concrete. In the study by Kaur et al. (2019) [13], the incinerated biomedical waste ash was partially substituted as fine aggregate, and experiments were conducted to assess the permeation properties and strength of concrete. The control mix and concrete mix with 5% biomedical waste ash offered more resistance to chloride-ion penetration. Not only just ash and slag wastes utilised, but other wastes such as rubber, glass powder, almond shells and plastic waste material are also used in SCC production [14–16].

Many researchers have worked on utilising biomedical waste ash in concrete production [13]. The presence of heavy metal concentrations in the concrete was a major issue reported due to the use of such incinerated ash. However, several treatment procedures have been developed to treat incinerated biomedical waste ash to bring down the concentration of heavy metals and other chemical residues to permissible limits [17]. The concrete specimens made with incinerated biomedical waste ash were relatively denser because the finer particles filled the pores/voids in the concrete, which led to better mechanical strength of concrete [13]. An overview of advantageous uses of incinerated biomedical waste ash in building materials, as well as the characteristics of its leachate, is provided in the study by Rajor et al. (2012) [18].

Biomedical waste incinerator ash (BMIA) was used as a partial replacement for cement in this experimental study, as it acts as a mineral admixture. Here, efforts are made to use BMIA in a constructive fashion, which adds to the enhanced performance of concrete at its optimal level and leads to eco-friendly concrete.

Novelty of the research

India produces over 3 million metric tonnes of medical waste annually, and the volume is anticipated to increase by 8% every year [19]. Usually, hospital incinerators or industry-standard biomedical waste incinerators are commonly used to incinerate biomedical waste. One of the main concerns is the eco-friendly disposal of incinerator bottom ash, which is typically created by the incineration of inorganic and organic constituents of biomedical waste. Since several years, researchers have been working on the sustainable utilisation of incinerated medical waste ash in concrete due to an increase in the quantity of wastes produced by medical facilities. Some have evidently showed that bottom ash from medical waste incineration could be successfully used in concrete production by partial replacement. Nowadays, concrete structures are built using SCC due to its ease of handling, high strength and performance. The incorporation of incinerated biomedical waste ash in the production of SCC is a sustainable idea to reduce the waste accumulation in the environment. Hence, the experimental investigation was conducted to enhance the quality of SCC by using the incinerated biomedical waste ash.

Experimental programme

Materials

In concrete, cement acts as binding material, and it is available in different grades based on strength and setting time. In this work, OPC 43 grade cement which satisfied the specifications of IS: 269–2015 [20] when tested as per IS: 4031–1998 (parts 4 & 5) [21, 22] standards was used. The test results are presented in Table 1.

Incinerated medical waste ash was collected from Medicare Environmental Management (P) Ltd. Dabaspet, near Bengaluru, India. The BMIA sample contained unwanted particles, which are segregated by using 90-μm sieve. The tests conducted on BMIA

Table 1 Properties of 43 grade cement

Tests conducted	Results obtained	IS: 269–2015 requirements
Normal consistency, (%)	32	No standard value
Specific gravity	3.15	No standard value
Initial setting time (min)	45	Not less than 30
Final setting time (min)	190	Not more than 600
Fineness		
Dry sieving, (%)	2.39	< 10
Blains air permeability value (m^2/kg)	287	225
Soundness		
Le Chatelier value (mm)	1	< 10
Autoclave, (%)	0.076	0.8
Compressive strength (MPa)		
At 3 days	27.84	> 23
At 7 days	37.33	> 33
At 28 days	48.28	> 43

Table 2 BMIA chemical composition

Chemical compounds	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Others
Percentage by weight	12.11	7.82	1.94	47.8	0.18	0.55	0.25	9.17	20.18

Table 3 Test results of heavy metals in BMIA as per RoHS compliance

Parameter	Results (ppm)	Max. limit (ppm)
Pb	50	1000
Hg	Nil	1000
Cd	< 10	100

Table 4 Test results of crushed stone sand (m-sand) characteristics

Tests conducted	Results obtained	IS: 383–2016 requirements
Specific gravity	2.62	No standard value
Grading zone	Zone II	Medium grade
Water absorption, (%)	0.80	-
Bulk density (kg/m^3)	1700	-
Fineness modulus	2.69	-

Table 5 Test results of coarse aggregate characteristics

Tests conducted	Results obtained	IS: 383–2016 requirements
Size	20 mm and downsize	-
Shape	Cubical	-
Specific gravity	2.74	No standard value
Water absorption, (%)	0.81	-
Bulk density (kg/m^3)	1550	-
Fineness modulus	7.58	-
Impact strength, (%)	23.88	< 30
Crushing strength, (%)	26.78	< 30

include the specific gravity test, analysis of chemical constituents and RoHS (Restriction of Hazardous Substances [23]) tests. The specific gravity of BMIA was 2.60. Table 2 presents the results of BMIA chemical composition.

As mentioned in Table 3, the major heavy metals such as lead, mercury and cadmium were much lesser than the permissible limits as per RoHS compliance [23].

The crushed stone sand (m-sand) was used as fine aggregate in this experimental study which was procured from the local crusher. These fine aggregates comply with IS: 383–2016 [24] standard conforming to zone II. Table 4 shows the basic test results of fine aggregates.

Coarse aggregates were collected from the local crushers. The basic tests on coarse aggregate were examined in accordance with IS: 2386–3 (1963) [25] standard. The test results are as shown in Table 5.

Chemical admixtures are necessary to achieve better workability and strength as low water-to-cement ratio is considered in SCC. In this experimental investigation, Plastol UltraFlow 4000 was used as chemical admixture (super-plasticizer) which was supplied by TREMCO (construction products group). The specific gravity of chemical admixture was 1.1.

Mix proportions

The current study aimed to investigate the use of BMIA in the production of self-compacting concrete of M30 grade (target compressive strength of 30 N/mm^2 at 28 days). The SCC mix proportions were determined based on the guidelines in IS: 10,262–2019 [26] and IS: 456–2000 [27]. Further referring to the literature [13], the percentage replacement of BMIA with cement was fixed at 5%, 10%, 15% and 20% by weight. Initially, a conventional self-compacting concrete mix was prepared without the addition of BMIA. After that, concrete mix calculations for partial replacement of 5% of BMIA were carried out, and similarly for higher percentage, replacements such as 10%, 15% and 20% addition were made. Table 6 presents the designed SCC mix proportions.

Determination of fresh concrete properties

Self-compacting concrete is mainly evaluated by its flow and fresh properties, which allow it to be easily placed and compacted without any bleeding or segregation. The tests (as shown in Fig. 1) were conducted for assessing flow properties as per EFNARC guidelines [28] to ensure the better workability of the design mixes.

Mechanical properties

Compressive strength test

SCC was poured into 150-mm cube moulds to cast specimens. As per the guidelines of IS: 516–1959 [29], the compressive strength of SCC cubes was tested at 7, 14 and 28 days of curing. Compression test was conducted in a universal testing machine (UTM) of 2000-kN capacity.

Split tensile strength test

The cylindrical SCC specimens were cast and tested as per the guidelines specified in Indian Standard Code IS: 516–1959 [29]. The cylindrical specimens, which were water cured for 7, 14 and 28 days, were used to perform the test in UTM.

Table 6 Mix proportions

BMIA content (%)	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Water (kg/m^3)	BMIA (kg/m^3)	Chemical admixture (kg/m^3)	w/c ratio (%)
0	450	880	875	180	0	6.3	0.40
5	427	889	862	180	23	6.3	0.40
10	405	873	875	180	45	6.3	0.40
15	383	881	862	180	68	6.3	0.40
20	360	865	875	180	90	6.3	0.40

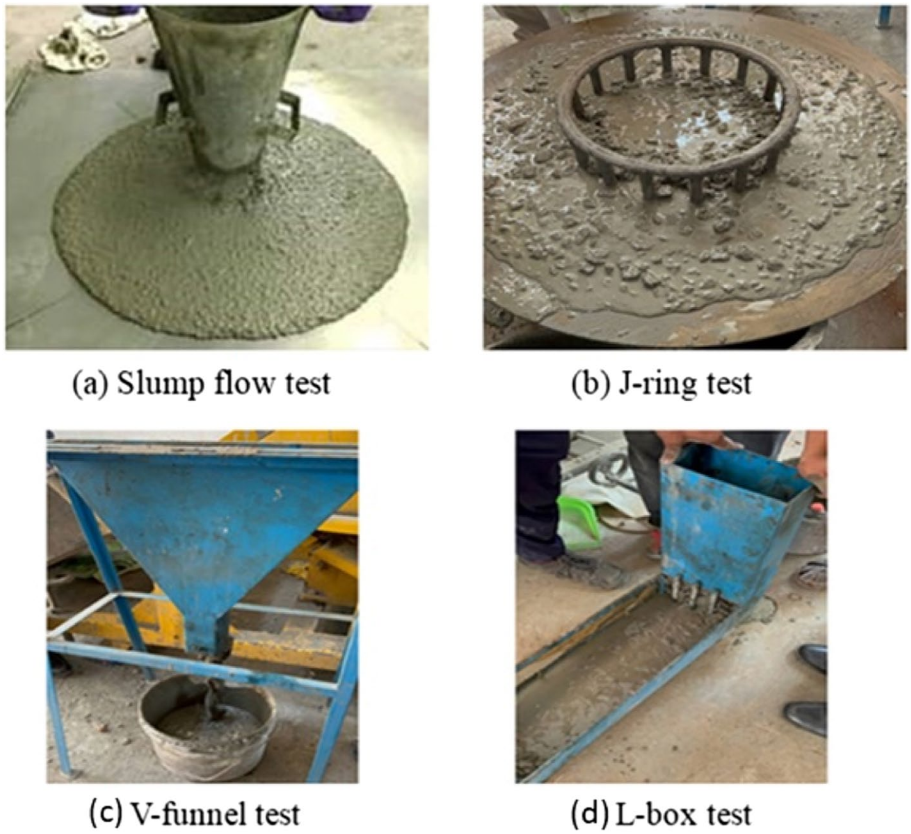

Fig. 1 Tests for fresh SCC properties. **a** Nature of flow showing no segregation. **b** Consistency and uniformity of SCC in J-ring test. **c** Consistent SCC flow in V-funnel test. **d** L-box testing showing uniform SCC quality

Flexural strength of concrete

Beam specimens of SCC mixes were prepared and cured to test the flexural strength. The prepared SCC beam specimens were subjected to 4-point bending test in the UTM. The maximum load at failure was recorded.

Rapid chloride penetration test

RCPT examines the resistance offered by the SCC specimen against chloride penetrability. The specimens of dimensions 100 mm in diameter and 50 mm in thickness were prepared as per ASTM C 1202 [30]. The RCPT machine has cells that are connected to the input–output cabinet. The cylindrical specimens were fitted tightly in the cells and taken care for no leakage of solutions. These cells have a positive and negative ends in which 0.3M NaOH and 3% NaCl are filled in the apparatus. A voltage of 60V DC was supplied and maintained throughout the test; when the electrical current passes through the specimen, the readings are noted down at every 30-min interval, and this process continues for 6 h. The charges (in Coulombs) passed through the SCC specimen are compared to the standard results as given in table mentioned in ASTM C 1202 [30], demonstrating the penetrability of chloride ions into the SCC specimen. If more charges pass through the specimen, this means that the chloride

Fig. 2 Rapid chloride penetration test arrangements

Fig. 3 Sorptivity test arrangements

ions are more penetrable. Figure 2 shows the rapid chloride penetration test apparatus and its accessories.

Sorptivity test

Most of the time, concrete is exposed to aggressive environments. Hence, the rate of penetration of water or liquids into the concrete is mainly controlled by absorption due to capillary rise. This test procedure was conducted as per ASTM C 1585–04 [31]. After the curing period, test samples were placed in the oven for 3 days at 50 °C temperature, and then, the dried samples were placed in the container to allow air to circulate around the concrete samples. The samples are taken out of the container, and the initial mass of the test specimen in grams is noted down. The sides of each specimen and its face which is not exposed to water are sealed. The specimens are placed in the pan with the help of a support device, and water was filled up to 1 to 3 mm above the supports; the water level must be maintained throughout the test duration. The weight of the specimen is noted down initially (before placing the specimen on the support device) and then start the timer and record the mass at 60 s, 5 min, 10 min, 20 min and 30 min. Continue the same procedure for every 1 hour up to 6 hours and record the corresponding reading. Figure 3 shows the sorptivity test arrangement.

Scanning electronic microscope (SEM) analysis

The microstructural analysis was carried out using scanning electron microscope (SEM) images for the SCC specimens with BMIA replacement and without BMIA replacement.

The required samples for the SEM test were collected from the core of the prepared SCC specimens.

Results and discussion

Fresh properties

Slump flow test

The reference SCC mix was first tested for slump flow and followed by SCC mixes with BMIA content. After the test, the measured diameter in the flow table of the SCC mix without BMIA was about 718 mm. The slump flow diameter of BMIA substituted SCC mixes was observed as 710 mm, 700 mm, 685 mm and 660 mm for 5%, 10%, 15% and 20% replacement levels, respectively. The slump flow range to satisfy the EFNARC specification is 650 to 800 mm. From the slump flow results, it was observed that EFNARC specifications were satisfied by the reference and all BMIA substituted SCC mixes. The slump flow value decreases with an increase in the BMIA content, which is mainly due to more water absorption by the fine BMIA particles present in the SCC mixes. Test results are shown in Table 7. The slump flow test conducted is shown in Fig. 1a.

T-500-mm flow test

A T-500-mm flow test was performed to determine the flowability of SCC mix, i.e. the time (in seconds) required for SCC to flow about 500 mm diametrically. The test results are presented in Table 7. The reference SCC mix achieved the target flow diameter at 2.49 s, and the SCC mixes with 5%, 10%, 15% and 20% BMIA content achieved the target flow at 3.2, 4.1, 4.6 and 5 s, respectively. The time taken for 500 mm of flow increased because the flowability of SCC mixes decreased with an increasing BMIA percentage. All the tested SCC mixes were well within the permissible range of the EFANARC specification for the T-500-mm test; the acceptable range is 2 to 5 s. As a result, the addition of up to 20% BMIA has no effect on the SCC fresh properties because the particle sizes of BMIA are compatible with cement in its fresh state.

J-ring test

J-ring test was conducted to assess the passing ability of all SCC mixes. The SCC mix with 5% BMIA achieved a lower value compared to other SCC mixes. The test results are as shown in Table 7. The values of J-ring test were 8.1 mm, 7 mm, 8 mm, 8.9 mm and 10 mm for SCC with 0%, 5%, 10%, 15% and 20% BMIA contents, respectively. The SCC mix with 5% achieved a lower value owing to its optimal blending of finer particles of

Table 7 Results of fresh properties of SCC mixes

SCC properties	BMIA percentages in SCC mixes				
	0%	5%	10%	15%	20%
Slump flow (mm)	718	710	700	685	660
T_{500mm} (s)	2.5	3.2	4.1	4.6	5.0
J-ring value (mm)	8.1	7.0	8.0	8.9	10.0
V-funnel value (s)	6.89	7.52	9.30	10.60	11.40
L-box ratio	0.907	0.853	0.836	0.804	0.800

BMIA within the mix. The J-ring values must be between 0 and 10 mm as per EFNARC guidelines; the lower value indicates the uniformity in the flow of concrete compared to others. The J-ring test conducted is shown in Fig. 1b.

V-funnel test

This test was conducted to observe the filling ability of SCC mixes. The EFNARC specification gives the range for flow time in a V-funnel test as 6 to 12 s for an SCC mix. The test results are as shown in Table 7. A flow time of 6.89 s, 7.52 s, 9.3 s, 10.6 s and 11.4 s was achieved by SCC mixes with 0%, 5%, 10%, 15% and 20% BMIA content, respectively. A high paste viscosity due to the substitution of BMIA and intense interparticle friction might be linked to excessive flow time, which resulted in lower deformability of the SCC mix with 20% BMIA. The V-funnel test conducted is shown in Fig. 1c.

L-box test

This test was conducted to observe the passing ability of SCC mixes through vertically placed bars in the L-box. The L-box ratios were observed as 0.907, 0.853, 0.836, 0.804 and 0.8 for 0%, 5%, 10%, 15% and 20% BMIA substituted SCC mixes, respectively. The results of the same are presented in Table 7. The range of L-box ratios are 0.8 to 1 as per EFNARC specification, which was achieved by all the tested SCC mixes. The test conducted is shown in Fig. 1d.

Tests on hardened concrete

Compressive strength results

The compressive strength of all the SCC specimens was determined at 7, 14 and 28 days of curing. The results are as shown in Fig. 4. The compressive strength of SCC mix with 5% BMIA content showed an increased strength of 9.2%, 10.09% and 5.12% at 7, 14 and 28 days, respectively, as compared to that of reference SCC mix. The replacement of 10, 15 and 20% BMIA in SCC offered decreased compressive strength at all curing ages as

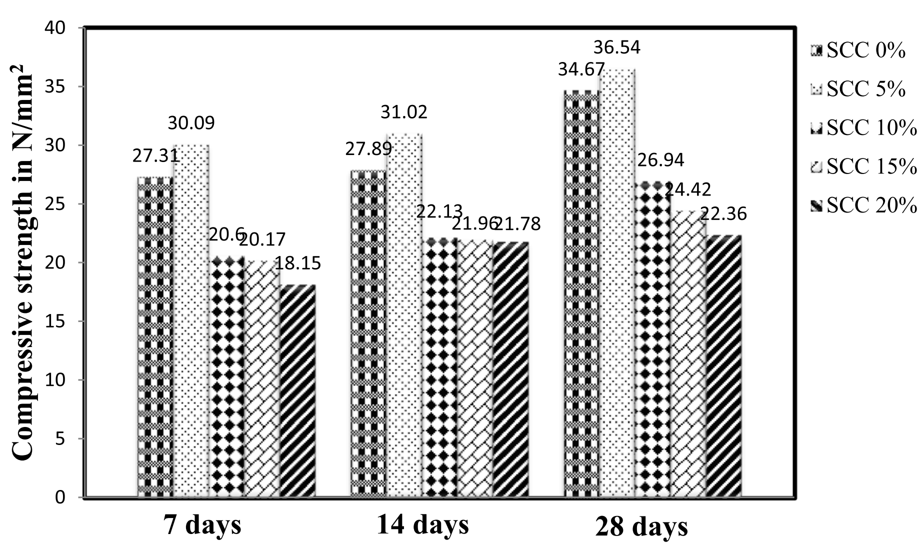

Fig. 4 Variation of compressive strength due to the substitution of BMIA at different doses

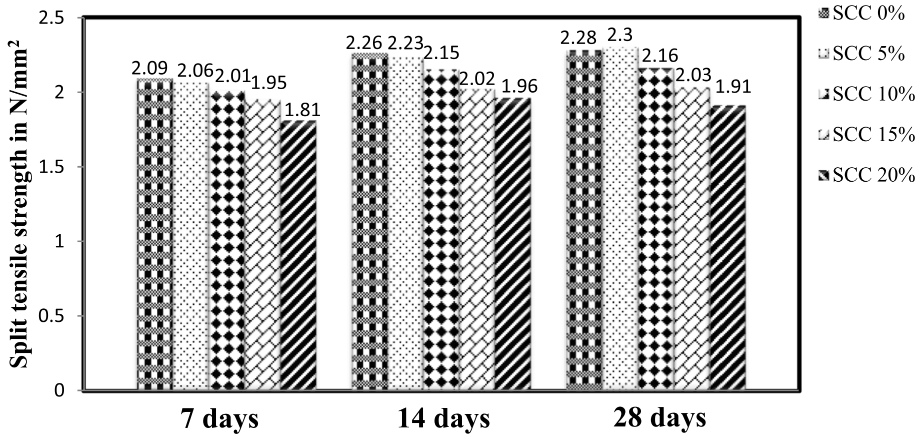

Fig. 5 Variation of split tensile strength due to addition of BMIA at different ages

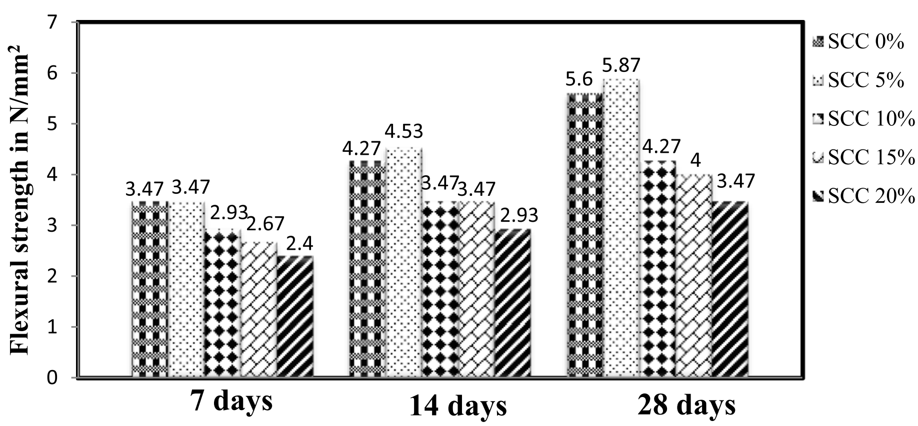

Fig. 6 Variation of flexural strength due to addition of BMWA at different ages

compared to that of the reference SCC mix. The optimum replacement was observed to be 5%. This shows the finer particles of BMIA powder act as filler material. However, the addition of more than 5% BMIA to the SCC mix does not lead to a strength increase because of the reduction in cement/binder content.

Split tensile strength results

The tensile strength of all the SCC specimens was determined at 7, 14 and 28 days of curing. The results are as shown in Fig. 5. The split tensile strengths obtained were 2.09 MPa, 2.26 MPa and 2.28 MPa for reference SCC mix at 7, 14 and 28 days, respectively. Similarly, the strengths were 2.06 MPa, 2.23 MPa and 2.3 MPa for SCC with 5% BMIA at 7, 14 and 28 days, respectively. The SCC with 5% BMIA had a tensile strength that was slightly higher by 1% than the reference SCC mix with reference to specimens of 28 days curing period. The tensile strength of SCC with 10, 15 and 20% BMIA was deceased by 5.5%, 12.3% and 19.3%, respectively, when compared to that of the reference mix at 28 days curing period. BMIA replacement above 5% was shown to induce a slight loss in split tensile strength.

Table 8 Rapid chloride penetration test results

Specimen	Total charge passed (Coulombs)	Chloride-ion penetrability	% reduction in permeability compared to SCC 0%
SCC 0%	1984	Low	-
SCC 5%	1854	Low	6.55
SCC 10%	1667	Low	15.97
SCC 15%	1577	Low	20.51
SCC 20%	1410	Low	28.93

Table 9 Chloride penetrability according to ASTM C-1202

Total charge passed in Coulombs	Chloride-ion penetrability
> 4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very low
< 100	Negligible

Flexural strength results

The flexural strength of all the SCC specimens was determined at 7, 14 and 28 days of curing; the obtained test results are presented in Fig. 6. The flexural strengths obtained were 3.47 MPa, 4.27 MPa and 5.6 MPa for reference SCC mix at 7, 14 and 28 days, respectively. Similarly, the strengths were 3.47 MPa, 4.53 MPa and 5.87 MPa for SCC with 5% BMIA at 7, 14 and 28 days, respectively. The SCC with 5% BMIA flexural strength was slightly higher (4.6%) than the reference SCC mix at 28 days. The flexural strength of SCC with 10, 15 and 20% BMIA contents had decreased strength of 30%, 40% and 60%, respectively, when compared to that of the reference mix. It was noticed that more than 5% replacement of BMIA in SCC led to a reduction in flexural strength; this may be because BMIA particles in the concrete had a lower pozzolanic or reactivity.

Rapid chloride penetration test (RCPT) results

RCPT test was conducted on disc specimens at 28 days to know the permeability of the various SCC mixes, and the results are presented in Tables 8 and 9. From Table 8, it could be observed that the control SCC mix without any BMIA had higher permeability compared to SCC mixes with BMIA. The microstructure refinement and increased density due to the presence of BMIA seem to be the reason for decreased permeability.

The chloride ion penetrability was decreasing with increase in BMIA percentage. The total charge passed was 1984 C, 1854 C, 1667 C, 1577 C and 1410 C through the SCC mixes with 0%, 5%, 10%, 15% and 20% of BMIA, respectively. Though there was reduction in total charge passed with increase in BMIA percentage, the decrease in permeability was marginal to significant, through all specimens, and are classified under "low" permeability category as indicated in Table 8 of ASTM C-1202 specifications [30].

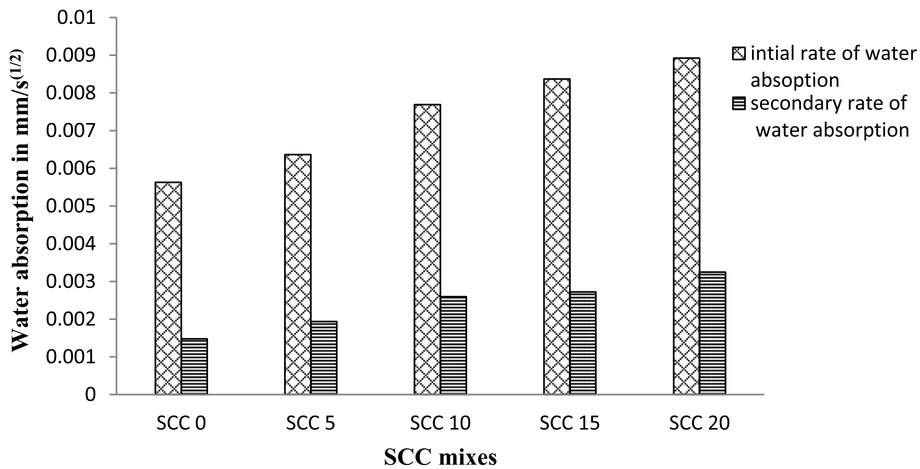

Fig. 7 Sorptivity test results

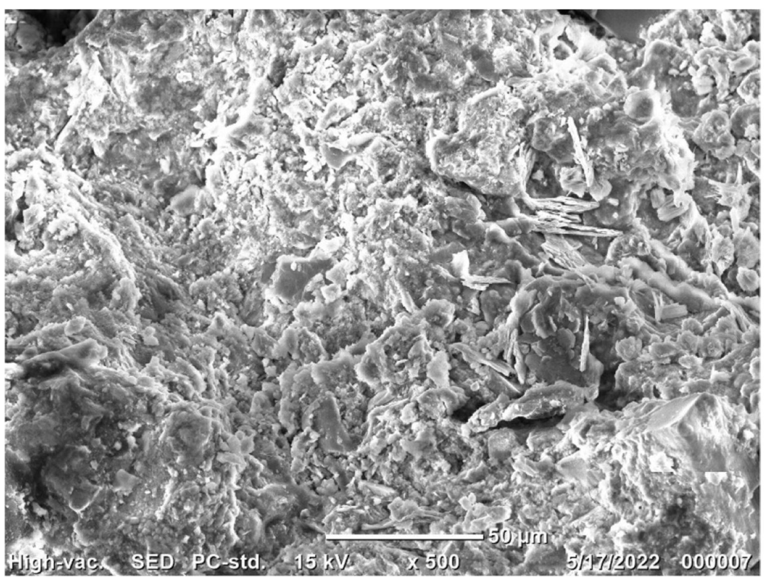

Fig. 8 SEM image of SCC mix with 0% BMIA

Sorptivity test

Sorptivity test was carried out on all the prepared SCC specimens. The test procedure was conducted according to ASTM C 1585–04 [31]. The initial phase of water absorption was higher than secondary phase in all the SCC specimens. From the results, rate of water absorption in both phases increased with an increase in BMIA replacement owing to more water absorption by the BMIA particles. The surface area increases with the reduction of voids in SCC with BMIA content, giving way for more absorption and adhesion of water molecules in the SCC specimens. The results are as shown in Fig. 7.

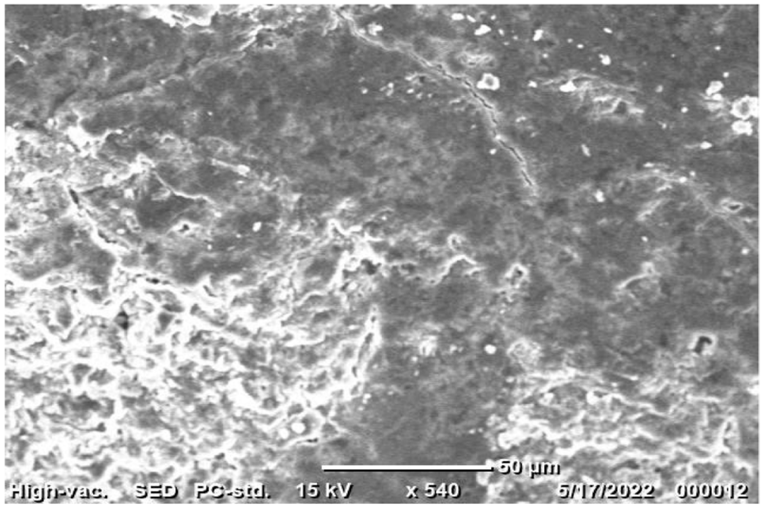

Fig. 9 SEM image of 20% BMIA substituted SCC

Scanning electronic microscope (SEM) analysis

Figure 8 illustrates the SEM image of reference self-compacting concrete (without BMIA), and Fig. 9 illustrates the SEM image of 20% BMIA-substituted SCC.

In Fig. 8, on keen observation of the hydration products, voids are clearly observed. Upon close observation, several interfacial transition zones (ITZ) could be seen, which are often the weakest part of the concrete. In the matrix, tiny C–S–H fibres, air voids and clusters of calcium hydroxide may be seen covering anhydrous calcium silicate grains. The interfaces between the aggregate paste and the voids provide enough area for highly crystalline phases to grow to a much larger size. Internal microcracks commonly develop in conjunction with the inhomogeneities in the microstructure of concrete.

A non-uniform compact pore structure system with multiphase products, notably calcium silicate hydrate (C–S–H) and calcium alumino-sulphate hydrates, is being created when cement is partially substituted with biomedical waste incinerator ash in SCC mixes. In Fig. 9, lesser voids are noticed in the microstructure. The additional calcium silicate hydrate gel is formed due to the reaction of $Ca(OH)_2$ with reactive silica present in the BMIA. The voids are eliminated due to the filling of the pores by BMIA particles. The grey texture seen represents the denser outer and inner C–S–H matrix, and the whitish texture represents the formation of ettringite and tricalcium aluminate hydrate during the early stages of reaction.

X-ray diffraction (XRD) test results

The XRD test was conducted on cement and biomedical incinerator ash (BMIA) separately using a Jeol JCM-6000Plus instrument. The XRD plots obtained for both materials for the diffraction angle (2θ) from 10 to 90° are shown in the Fig. 10. From Fig. 10, it can be deduced that there are peaks at 29°, 33°, 34°, 41°, 52°, 60° and 63° for cement, and that similar peaks are seen even in BMIA. Based on the similarity of the

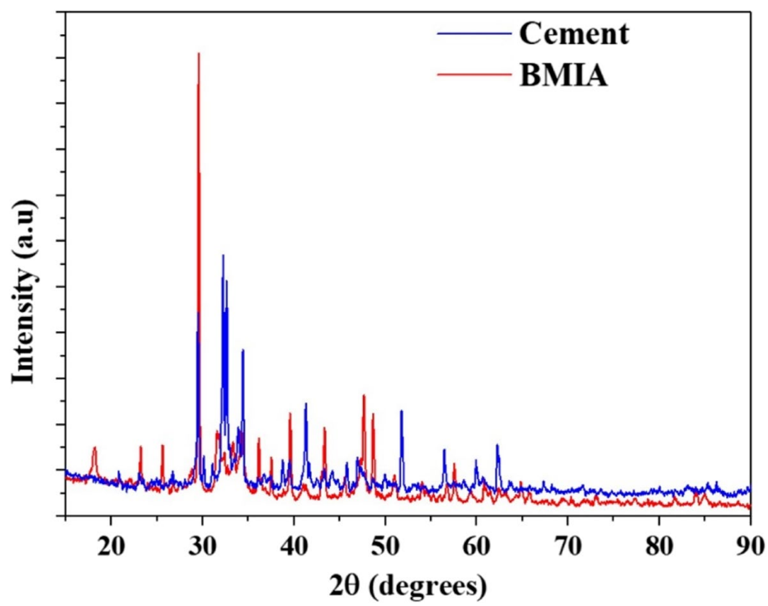

Fig. 10 XRD test for cement & BMIA

peaks, it can be concluded that similar compounds are present in both the materials, which help produce hydration products during curing period. The fact that the peaks are sharp and distinct suggests that both materials have an abundance of crystalline components. Hence, cement and BMIA form a composite powder material, which can be effectively used in SCC production.

Conclusions

Biomedical waste incinerator ash (BMIA) is a waste material which is freely available in the dumping yards of incineration plants. The utilisation of BMIA in SCC will enhance its properties as presented in the earlier sections. Based on the experiments conducted, the following conclusions are drawn:

- The workability properties of SCC decrease with the increase in BMIA content due to higher water absorption by the BMIA particles, but it can be compensated by using suitable dosage of super-plasticizer.
- Based on the mechanical strength results, it was found that the optimum level of substitution of BMIA in SCC was 5%. About 5% increase in compressive strength was observed when compared to that of control SCC mix. Similar trend of variation in split and flexural tensile strengths was observed.
- Reduced chloride permeability was observed in SCC specimens with BMIA. The permeability category of all SCC mixes was classified as "low". The reduction in chloride permeability was due to the presence of BMIA which aids pore refinement that leads to densification of microstructure.
- The initial and secondary rates of water absorption of SCCs with BMIA were marginally higher compared to those of the control SCC mix.
- In general, densification of microstructure was observed from the SEM images. However, at a few locations, micro-voids were observed in the case of SCC with 20%

BMIA. The XRD test results show the crystalline morphology of cement and BMIA particles.

- Finally, from the overall observation of the results, it can be concluded that about 5% of BMIA can be easily substituted for cement to produce SCC mixes, which enhance many of the performance characteristics of concrete, leading to an eco-friendly and sustainable solution.

Abbreviations

BMIA	Biomedical waste incinerator ash
SCC	Self-compacting concrete
SEM	Scanning electronic microscope
XRD	X-ray diffraction
RCPT	Rapid chloride penetration test
OPC	Ordinary Portland cement
RoHS	Restriction of certain hazardous substances
IS	Indian standard
UTM	Universal testing machine
ASTM	American Society for Testing and Materials
C–S–H	Calcium silicate hydrate

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Authors' contributions
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Declarations

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