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RESEARCH ARTICLE

Effect of local metakaolin developed from natural material soorh and coal bottom ash on fresh, hardened properties and embodied carbon of self-compacting concrete

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Abstract

The carbon dioxide emissions from Portland cement production have increased significantly, and Portland cement is the main binder used in self-compacting concrete, so there is an urgent need to find environmentally friendly materials as alternative resources. In most developing countries, the availability of huge amounts of agricultural waste has paved the way for studying how these materials can be processed into self-compacting concrete as binders and aggregate compositions. Therefore, this experimental program was carried out to study the properties of self-compacting concrete (SCC) made with local metakaolin and coal bottom ash separately and combined. Total 25 mixes were prepared with four mixes as 5, 10, 15, and 20% replacement of cement with metakaolin; four mixes as 10, 20, 30, and 40% of coal bottom ash as partial replacement of fine aggregates separately; and 16 mixes prepared combined with metakaolin and coal bottom ash. The fresh properties were explored by slump flow, T_{50} flow, V-funnel, L-box, and J-ring sieve segregation test. Moreover, the hardened properties of concrete were performed for compressive, splitting tensile and flexural strength and permeability of SCC mixtures. Fresh concrete test results show that even if no viscosity modifier is required, satisfactory fresh concrete properties of SCC can be obtained by replacing the fine aggregate with coal bottom ash content. At 15% replacement of cement with local metakaolin is optimum and gave better results as compared to control SCC. At 30% replacement of fine aggregate is optimum and gave better results as compared to control SCC. In the combined mix, 10% replacement of cement with metakaolin combined with 30% replacement of fine aggregate with coal bottom ash is optimum and gave better results as compared to control SCC.

Keywords Metakaolin · Cement substitute material · Coal bottom ash · Sand substitute ingredient · SCC · Fresh and hardened properties of SSC · Embodied carbon · Sustainability

Introduction

Self-compacting concrete (SCC) is a highly workable concrete that can be spread over the packed reinforcement bars, seals overall corners of the formwork, and attains compacted situation under its self-weight. Hence, there is no any vibrator used for the compaction of concrete. To accomplish such conduct, the principle necessities of fresh properties of SCC are filling capacity, passing capacity, and more segregation obstruction. The initial two assets can be accomplished by utilizing a chemical admixture (such as a superplasticizer). To protect the cohesion of the SCC mixture, an enormous amount of supplementary cementing material (SCM) and viscosity-modifying admixture (VMA) is needed (EFNARC 2005).

The construction industry is increasingly using the concepts of sustainability and durability. Cement is the most frequently utilized building ingredient in the construction

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engineering. It is a vital comprehensive constituent and liable for high content of CO_2 discharge. Hendricks et al detailed that the measure of CO_2 discharges from cement production relies upon the manufacturing technology, procedure, clinker or cement proportion, and fuel utilized. It is presumed that the utilization of alternative fossil fuels and mixed cement may diminish CO_2 releases by 20 to 40% and 20% correspondingly (Hendriks et al. 1998). Moreover, Hwang et al estimated the consumption of limestone, electrical energy, and fossil fuels to create 1 t of OPC ranging from 1.19 to 1.47 t, from 96.30 to 119.60 kWh and 68.10 to 97.30 kg, respectively (Hwang et al. 2015). The use of augmented energy, alternate raw constituents, and decrease amounts of cement clinker will reduce CO_2 emanations from the cement manufacturing (Damtoft et al. 2008; Bheel et al. 2020). The use of pozzolanic ingredients increases the concrete durability and reduces CO_2 emissions, since robust construction's structure want less repair and preservation, so it can also extend the life of the structure (Guneyisi et al. 2008). The use of volcanic ash is a trend that is attracting more and more attention, as well as increasing awareness of people about ecological protection and sustainable construction (Papadakis and Tsimas 2002). Therefore, in the long term, there are good reasons to expand the use of any by-products or pozzolanic materials to partially replace cement in mortar and concrete. It is generally believed that volcanic ash significantly improves the resistance to chloride ions through a combination of chloride ions and pour filling (Rafik et al. 2010). The addition of pozzolanic materials to SCCs can improve strength and durability, lower costs, and avoid side effects caused by improper compaction (Eva et al. 2011).

The durability of the pozzolanic concrete is improved owing to the pozzolanic response of different mixes existing in the concrete throughout the hydration cycle (Poon et al. 2001). The most usually utilized pozzolanic constituents are fly ash, silica fume, MK, and rice husk ash. However, the calcium hydroxide (CH) and calcium silicate hydrate (C–S–H) are framed during the hydration of OPC in concrete. Besides, the calcium hydroxide is the greatest solvent hydration item, and it is a poor connection between concrete and cement in terms of durability perspective. Thus, the concrete is showing to water, the calcium hydroxide would disintegrate, expanding the permeability and in this manner, the production of concrete is more susceptible due to leaching and chemical attack (Keerio et al. 2021). However, the pozzolanic MK reaction will form other cemented C-H-H gels and crystalline products, including calcium aluminate hydrate and aluminosilicate hydrate (C2ASH8, C4AH13, and C3AH6). These products of volcanic ash contribute to the narrowing of common pores (Badogiannis and Tsivilis 2009). Wild et al. (1996) reported that the improved pore system makes the concrete denser, making it much more difficult to transport water and other corrosive chemicals, thereby reducing the diffusion frequency of injurious ions. Hwang et al. 2015) assessed carbon dioxide emissions from cement production. Ordinary Portland cement is producing carbon dioxide by calcining limestone and silica reaction at temperatures below 1500 °C.

In this regard, it is conveyed that the utilization of MK in concrete makes it possible to improve the compressive strength of the mixture, particularly in the early stages of hydration. Kim et al. (2007) stated that the strength of the concrete was measured using a Korean MK, and it was recommended that a 10% MK replacement would be a suitable replacement. In terms of durability, the literature has reported a positive effect of MK. Recently Shekarchi et al. (2010) state that when the amount of replacement MK was 15%, concrete transport performance, recorded in terms of water permeability, gas permeability, water absorption, resistivity, and ion diffusion rate, increased by 50%, 37%, 28%, 450%, and 47% correspondingly. Researchers have reported an optimistic influence of adding MK on the corrosion resistance of samples (Parande et al. 2008; Batis et al. 2005). For example, Batis et al. (2005) showed that the use of MK, regardless of whether it is used as a substitute for sand or cement, can improve the corrosion performance of mortar samples.

The increase in the use of concrete has led to an increase in cement volumes and a gradual increase in demand for fine aggregates, which negatively affected the environment. In terms of reducing environmental pollution, the use of industrial waste may be a suitable solution for achieving sustainable development and solving the growing problem of carbon dioxide (CO_2) invention (Mangi et al. 2018; Keerio et al. 2020). The CBA is measured as a green and ecologically friendly construction substantial that can reduce the cement content in concrete production. It is a waste ingredient that was introduced by the Construction Industry Development Board (CIDB) for the use of recycled materials in concrete production (Dwikojuliardi 2015). Moreover, the CBA is formed by burning coal in thermal power plants and is measured as the main waste of fly ash (FA). The CBA contains pozzolanic properties due to the existence of silicon oxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3). During cement hydration, calcium hydroxide reacts with CBA to form additional calcium aluminate hydrate (CAH) and calcium silicate hydrate (CSH) (Bheel et al. 2021a, b). Cheriaf et al. (1999) argued that proper grinding can develop the pozzolanic activity of CBA, and 6 h of grinding CBA can increase the strength activity index by 27% after 28 days. Hence, in concrete, it is partially replaced by fine aggregate and cement.

The use of CBA in the construction industry is one of the best possible options for reducing the environmental problems caused by lack of discharge sources and increased CBA productivity. Overall, India produces about 105 million tons of CBA per annum from various thermal power plants, which generate 68% of the country's electricity. Because CBA has the same particle size distribution and additional pozzolanic properties as NFA, CBA is promoting its use in the current and future construction industry (Lauritzen and Petersen 2004.; Yogesh and Rafat 2014). Thus, the SCC has been studied many times, and it is possible to replace NFA with CBA. In some studies (Abidin et al. 2014; Aswathy and Mathews 2015; Ibrahim et al. 2015; Jamaluddin et al. 2016; Ratchayut and Somnuk 2008), in the production of SCC, the bottom ash of coal was also mixed with cement additives such as FA and MK. But the NFA was replaced by 10–30% of CBA along with FA, and a water-reducing agent was added simultaneously (Rafat et al. 2012a, b). It was observed that SCCs with CBA and FA could be designed to meet the compulsory requirements of the fresh SCC. For green concrete requirements, the best CBA content to replace NFA is 10% (Ibrahim et al. 2015). Taking into account the mechanical properties of SCC mixture in the literature studies, it was found that the optimal percentage of CBA can replace NFA up to 20%. Furthermore, the advantageous effects of CBA have also been observed in some important studies, as most of the mechanical properties of SCCs obtained by adding only 10–15% CBA instead of NFA improved overall performance (Aswathy and Mathews 2015). Likewise, it was observed that SCC obtained by replacing 10% NFA with CBA has the same behavior. The compressive and indirect tensile strength is increased about 20% with the assimilation of 15% CBA (Abidin et al. 2014; Jamaluddin et al. 2016). Few authors have investigated the tensile strength of SCC, and it was perceived that NFA can be effectively replaced by CBA without compensating the overall performance at various curing periods (Dwikojuliardi 2015). Regarding durability, the water absorption rate is reduced up to 15% replacement levels of NFA with CBA (Abidin et al. 2014; Ratchayut and Somnuk 2008). The optimum level of CBA was found to be 10% for SCC and in NVC in most of the earlier investigations (Abidin et al. 2014; Jamaluddin et al. 2016). Similarly, an improvement in durability properties has been observed in terms of capillary water absorption, electrical resistivity, carbonation resistance, and chloride penetration of concrete blended with 10% of CBA instead of NFA (Cheriaf et al. 1999).

Cement production requires huge energy, whereas Pakistan faces acute crises of energy, and the cost of cement is rising to result in an overall rise in the construction cost. Though there are so many studies performed on MK as cementitious materials and CBA as fine aggregates individually, there is no experimental study conducted on MK as PC replacement and CBA as fine aggregates together in SCC mixture. Therefore, this study proposes a method that increases the properties of SCC and reduces the cement production and embodied carbon by replacing cement with local MK and sand replacement with CBA separate and combined in the SCC mixture. Moreover, the numerous tests in terms of slump flow, T50 flow, visual segregation index, V-funnel, L-box, J-ring, and sieve segregation were performed to measure the workability of SCC mixtures blended with separate and combined local MK as a replacement for cement and CBA as fine aggregates. In addition, the hardening performance was evaluated in terms of compressive, tensile, and flexural strength and water penetration depth of SCC mixtures blended with separate and combined local MK as a replacement for cement and CBA as fine aggregates.

Materials and methods

Materials

Ordinary Portland cement (OPC) has been utilized in this experimental study, and its physical properties and chemical composition are summarized in Table 1. The fine aggregates are used which are composed of hill sand passing from 4.75mm, crushed stone passing from 12mm, and retained on 4.75-mm sieves. Local metakaolin (MK) was produced from local natural material soorh available in billions of tons in district Thatta, Sindh, Pakistan, by calcination at 800°C for 2 h (Table 2). The MK was used as cement replacement at various dosages, after sieving it from a sieve No 325. The SEM images of local MK are shown in Fig. 1. Moreover, the chemical composition and physical property comparison of OPC, soorh, and developed MK are presented in Table 1.

Mix proportion

The SCC mixtures were prepared with a water/binder ratio of 0.38 (EFNARC 2005). Total five mixtures were made in which one mixture was prepared of only cement, while other mixtures were made of 5%, 10%, 15%, and 20% of developed MK by the cement's weight. Furthermore, the detail of mixed proportions is exhibited in Table 3.

Table 1 Physiochemical properties of binder (OPC, soorh, and developed metakaolin)

Constituent	OPC (%)	Soorh (%)	Metakaolin (%)	CBA (%)
SiO_2	20.78	55.89	62.18	36.67
Al_2O_3	5.11	23.51	21.67	26.131
CaO	60.89	-------	3.01	5.107
MgO	3.0	3.53	3.41	1.757
Fe_2O_3	3.17	8.15	3.01	14.022
K_2O	-----	5.89	1.85	0.927
Na_2O_3	-----	1.89	1.03	2.535
TiO_2	-----	1.14	1.03	2.535
In_2O_3	-----	-----	0.80	
LOI (%)	1.71	7.40	0.50	1.064
Specific gravity	3.15	2.64	2.60	

Table 2 Constitute composition of natural material soorh and developed metakaolin (Saand et al. 2016)

Components	Soorh (%)	Developed metakaolin (%)
Quartz	47.1	36.3
Illite	27.4	42.9
Stevensite	12.1	16.5
Kalonite	11.9	--
Calcite magnesium	0.8	4.3
Hematite	0.7	--

Table 3 Chemical composition of CBA

Constituents	Percentage by weight of CBA Lakhra power plant
SiO_2	36.67
Al_2O_3	26.131
CaO	5.107
MgO	1.757
Fe_2O_3	14.022
K_2O	0.927
Na_2O_3	2.535
TiO_2	2.535

Methods

The fresh properties of SCC have been studied out by using the method specified in EFNARC (2005). The filling ability tests respected slump flow, V-funnel, and T50 flow time test, while passing capability tests, like J-ring and L-box, were also performed. Moreover, a sieve segregation test was carried out. Various trial mixes with and without superplasticizers were prepared to develop the SCC. However, the hardened concrete tests were conducted after the achievement of early fresh concrete tests, and it was dispensed into the molds. Moreover, the concrete samples were removed from mold on 1 day after casting, and then these samples were kept in the curing water tank until the testing day. Hence, the five concrete cube samples were utilized for exploring the compressive strength of SCC after 3, 28, and 180 days under EN 12390-3 (2009). Additionally, the five cylinders were cast for splitting tensile strength of SCC at 3, 28, and 180 days as per EN 12390-6 (2009).

The flexural strength test on the prism samples of the OPC control mix and metakaolin-modified mixes of self-compacted concrete at the age of 28 days was conducted as per BS EN 12390-5: 2009. Specimens of 500 mm × 100 mm × 100 mm were cast, and these specimens were used for the given testing age.

The cubical samples (100 mm × 100 mm × 100 mm) were cast and de-molded later 24 h. After de-molding all samples were kept in curing tank for curing at 3, 28, and 180 days and then the specimens were kept in a pressure cell and subjected to a water pressure of 0.5 MPa for 72-h duration for water penetration depth as per EN B (2000). After subjecting to

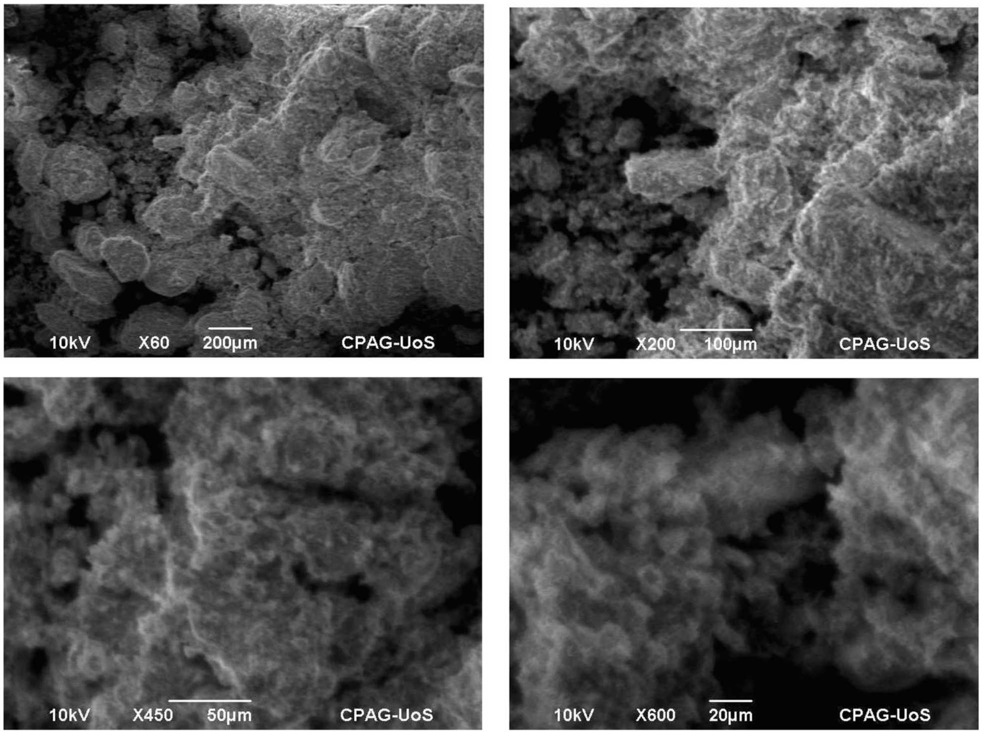


Fig. 1 SEM images of local developed metakaolin

the required water pressure, the samples were divided into two halves in Universal Testing Machine, and a water-penetrated moistened surface was measured as water penetration depth (Table 4).

Embodied carbon assessment

It was utilized to study the sustainability benefits by using MK and CBA for the carbon content of the concrete mix being assessed. The embodied carbon of materials was obtained from the literature study as shown in Table 5. The carbon embodied for concrete mixes was estimated by using Eq. (1). The *CO2e*, *Wi*, and CO2*i* in Eq. (1) display the embodied carbon of concrete, weight per unit volume of material, and embodied carbon of materials, respectively.

$$CO_{2e} = \sum_{i=1}^{n} \left(W_i \times CO_{2i}\right) \qquad (1)$$

Fresh concrete results

The results of fresh properties of SCC with the inclusion of local metakaolin are tabulated in Table 5.

Slump flow

The fresh properties of SCC with the inclusion of MK were investigated, and the outcomes were given in Table 6. The recommended values of slump flow are 650–850mm (EFNARC 2005). Without using superplasticizers and using 1% superplasticizers, the observed slump flow of control and MK SCC was less than the recommended values. By using 2% and 3% superplasticizers, the slump flow of control and MK SCC was within the recommended range. As the quantity of MK increased, the slump flow decreased due to MK's more specific surface area than that of cement; this outcome of the study is correlated to Guneyisi and Gesoglu (2008). However, in liquefying action, the use of SP enhances the flowability by dropping plastic viscosity and yielding stress. Moreover, a high slump flow can be accomplished owing to the dissolving action of SP by reducing the water demand which entrapment

Table 4 Details of mix proportions (kg/m^3)

Concrete mix	Cement	MK	CBA	W/B (%)	Water	FA	CA	SP (%)
CM	500	0	--	0.38	190	900	650	2
MK5	475	25	--	0.38	190	900	650	2
MK10	450	50	--	0.38	190	900	650	2
MK15	425	75	--	0.38	190	900	650	3
MK20	400	100	--	0.38	190	900	650	3
CBA10	500	--	90	0.38	190	810	650	5
CBA20	500	--	180	0.38	190	720	650	9
CBA30	500	--	270	0.38	190	630	650	13
CBA40	500	--	360	0.38	190	540	650	17
MK5CBA10	475	25	90	0.38	190	810	650	5
MK5CBA20	475	25	180	0.38	190	720	650	9
MK5CBA30	475	25	270	0.38	190	630	650	13
MK5CBA40	475	25	360	0.38	190	540	650	18
MK10CBA10	450	50	90	0.38	190	810	650	5
MK10CBA20	450	50	180	0.38	190	720	650	12
MK10CBA30	450	50	270	0.38	190	630	650	16
MK10CBA40	450	50	360	0.38	190	540	650	20
MK15CBA10	425	75	90	0.38	190	810	650	7
MK15CBA20	425	75	180	0.38	190	720	650	13
MK15CBA30	425	75	270	0.38	190	630	650	17
MK15CBA40	425	75	360	0.38	190	540	650	22
MK20CBA10	400	100	90	0.38	190	810	650	7
MK20CBA20	400	100	180	0.38	190	720	650	13
MK20CBA30	400	100	270	0.38	190	630	650	17
MK20CBA40	400	100	360	0.38	190	540	650	22

Table 5 Embodied carbon of materials

Materials	Embodied carbon ($kgCO_2/kg$)	"References"
Cement	0.82	Flower and Sanjayan (2007)
MK	0.33	Meddah et al. (2018)
CBA	0.015	Kalaw et al. (2016)
Superplasticizer	0.72	Long et al. (2015)
Water	0	Yang et al. (2013)
FA	0.0139	Turner and Collins (2013)
CA	0.0408	Turner and Collins (2013)

among flocculated particles. Using a 2% superplasticizer, the observed value of slump flow of control mix is within range, while CBA SCC has been less than the required slum flow, i.e., 650mm. By using 5%, 9%, 13% and 17% superplasticizer the slump flow of CBA10, CBA20, CBA30, and CBA40-SCC has been observed within the required range of (EFNARC 2005). As the magnitude of CBA enhanced, the slump flow has been reduced due to the porosity of CBA, which saturate more water with a higher content of CBA. The outcome achieved indicated the CBA structures, which have a rough form that decreases interparticle abrasion among aggregates contrasted with the control mix. This trend has been observed by other researchers (Aswathy and Mathews 2015). In the combined utilization of local metakaolin and

Table 6 Fresh properties of SCC

Concrete mix	Filling ability properties			Passing ability properties		Segregation resistance property	SP (%)
	Slump flow (mm)	V-funnel (sec)	T_{50} flow (sec)	L-box (ratio)	J-ring (mm)	Sieve segregation (%)	
CM	740	7.4	2.8	0.83	2.5	8.43	2
MK5	710	9.8	3.6	0.95	6	5.11	2
MK10	695	11.2	4.8	0.97	7.5	4.88	2
MK15	635	9.1	3.4	0.88	3.8	10.1	3
MK20	580	11.4	4.6	0.98	8.3	6.78	3
CBA10	735	11.2	4.98	0.85	4.5	5.26	5
CBA20	760	11.89	4.89	0.92	7.4	4.56	9
CBA30	755	10.22	4.8	0.87	8.7	7.23	13
CBA40	750	12	4.3	0.89	6.8	7.35	17
MK05CBA10	745	8.39	3.4	0.89	3.8	8.45	5
MK05CBA20	750	10.22	3.8	0.92	7.8	6.67	9
MK05CBA30	750	9.84	4.3	0.9	8.1	5.72	13
MK05CBA40	752	11.42	4.8	0.88	8.6	6.82	18
MK10CBA10	760	8.4	3.7	0.88	3.8	6.24	5
MK10CBA20	745	9.5	4.4	0.89	4.2	7.18	12
MK10CBA30	755	10.3	4.9	0.95	5.6	6.38	16
MK10CBA40	730	10.2	4.1	0.91	8.4	6.1	20
MK15CBA10	745	9.7	3.9	0.91	4	5.27	7
MK15CBA20	750	10.3	4.3	0.94	4.2	6.91	13
MK15CBA30	755	10.5	4.8	0.9	7.3	5.79	17
MK15CBA40	750	8.7	4.2	0.94	6.9	7.35	22
MK20CBA10	750	9.6	4.4	0.85	5	6.39	7
MK20CBA20	720	10.2	4.8	0.87	6.3	5.71	13
MK20CBA30	725	11.1	3.9	0.91	6.8	6.4	17
MK20CBA40	745	11.66	4.3	0.95	6.2	6.24	22

CBA, as the quantity of MK and CBA increased, more quantity of SP is needed to satisfy the required range of slump flow. Maximum 22% SP is used to satisfy the requirements of slump flow of MK20CBA40 mix.

V-funnel

The recommended values of the V-funnel are 6–12s (EFNARC 2005). Without using superplasticizers and using 1% superplasticizers, the observed V-funnel flow of the control and the MK SCCs exceeded the recommended range. By using 2% and 3% superplasticizers, the V-funnel of the control and the MK SCC were within the recommended range. As the quantity of MK increased, the V-funnel time decreased. The V-funnel time displays a distinct tendency to rise with growth in the content of MK. This outcome deemed that the accumulation of MK in concrete made the mixtures extra viscous. This finding is related to the other research investigations (Guneyisi and Gesoglu 2008; Hassan et al. 2010). Finally, it was revealed that there is no need for any viscosity-modifying agent in concrete mixtures while using MK in concrete. By using a 2% superplasticizer, the observed value of the V-funnel test of control mix is within range, while CBA SCC has been more than the required V-funnel, i.e., 12s. By using 5%, 9%, 13%, and 17% superplasticizer the value of the V-funnel test of CBA10, CBA20, CBA30, and CBA40-SCC has been observed within the required range of (EFNARC 2005). As the quantity of CBA increased, the V-funnel has been increased owing to the porosity of CBA contrasted with the control mix. CBA saturate more water with a higher content of CBA. The outcome achieved suggested the CBA structure, which has a rough form that decreases interparticle abrasion among aggregates and showed that the excessive inclusion of coal bottom ash has declined the viscosity of SCC mixtures. This trend has been observed by other researchers (Aswathy and Mathews 2015). In the combined utilization of local metakaolin and CBA, as the quantity of MK and CBA increased, more quantity of SP is needed to satisfy the required range of V-funnel. Maximum 22% SP is used to satisfy the requirements of the V-funnel of MK20CBA40 mix.

T50 flow

The recommended values of T50 flow time are 2–5s (EFNARC 2005). Table 6 indicates that the T50 flow time was estimated in the range of 2.80 to 4.6 s. As the quantity of MK is increased, the T50 flow increased. The outcome was cleared that the T50 flow time of SCC was augmented with the addition of 20% MK. This observation was related to Guneyisi et al. (2009). From Table 4, it was indicated that the T50 flow possessed higher plastic viscosity for a given MK content. Using a 2% superplasticizer, the observed T_{50} flow time of control mix is within range, while CBA SCC has been less than the required value of T_{50} flow time test, i.e., more than 5 s. By using 5%, 9%, 13%, and 17% superplasticizer the T_{50} flow time of CBA10, CBA20, CBA30, and CBA40-SCC have been observed within the required range of (EFNARC 2005). As the quantity of CBA is enhanced, the T_{50} flow time has been improved owing to the porosity of CBA contrasted with the cement because CBA saturated more water with a greater content of CBA. The outcome achieved denoted of the CBA structures, which have the rough form that decreasing interparticle abrasion among aggregates and directed the excessive inclusion of coal bottom ash declined the viscosity of SCC mixtures. This trend has been observed by other researchers (Aswathy and Mathews 2015). In the combined utilization of local metakaolin and CBA, as the quantity of MK and CBA increased, more quantity of SP is needed to satisfy the required range of T50 flow. Maximum 22% SP is used to satisfy the requirements of T50 flow of MK20CBA40 mix.

Blocking ratio (L-box test)

It is utilized to evaluate the flow of SCC concrete and the level by which it is subject to blocking by reinforcement. The results of the L-box tests are shown in Table 6. The recommended values for the L-box test are 0.8–1.0. Without using superplasticizers and using 1% superplasticizer, the observed values of control and the MK SCC exceed the recommended range. By using 2% and 3% superplasticizers, the L-box value of control and the MK SCC were observed within the recommended range. As the quantity of MK increased, the L-box is decreased, due to MK's more specific surface area than that of cement. This observation is correlated to Guneyisi and Gesoglu (2008). By using a 2% superplasticizer, the observed value of L-box test of control mix is within range, while CBA SCC has been more than the required value of L-box (blocking ratio), i.e., less than 1.0. By using 5%, 9%, 13%, and 17% superplasticizer the value of L-Box ratio of CBA10, CBA20, CBA30, and CBA40-SCC has been observed within the required range of (EFNARC 2005). As the quantity of CBA increased, the L-box ratio has also been increased due to a decrease in cohesiveness and a lack of paste volume of CBA contrasted with the control mix. This trend has been detected by other researchers (Aswathy and Mathews 2015). In the combined utilization of local metakaolin and CBA, as the quantity of MK and CBA increased, more quantity of SP is needed to satisfy the required range of L-box. Maximum 22% SP is used to satisfy the requirements of the L-box of the MK20CBA40 mix.

J-ring

The recommended values of the J-ring test (EFNARC 2005) are 0–10mm. Without using superplasticizers and using a 1% superplasticizer, the observed values of the control and the MK SCC exceeded the recommended values. By using 2% and 3% superplasticizers, the observed J-ring values of the control and the MK SCC were within the recommended range as shown in Table 6. As the quantity of MK increased, J-ring decreased due to MK's more specific surface area than that of cement. This similar study is related to Guneyisi and Gesoglu (2008). By using a 2% superplasticizer, the observed value of the J-ring test of control mix is within range, while CBA SCC has been less than the required value of the J-ring test, i.e., less than 10 mm. By using 5%, 9%, 13% and 17% superplasticizer the J-ring of CBA10, CBA20, CBA30, and CBA40-SCC has been observed within the required range of (EFNARC 2005; Lauritzen and Petersen 2004). As the magnitude of CBA increased, the J-ring has been reduced due to the porosity of CBA contrasted with the cement. As the measure of CBA augmented the J-ring reduced due to a decrease in cohesiveness and lack in paste volume of CBA contrasted with the control mix. This trend has been witnessed by other researchers (Aswathy and Mathews 2015). In the combined utilization of local metakaolin and CBA, as the quantity of MK and CBA increased, more quantity of SP is needed to satisfy the required range of J-ring. Maximum 22% SP is used to satisfy the requirements of J-ring of MK20CBA40 mix.

Sieve segregation

The recommended range of sieve segregation is 0–12% (EFNARC 2005). Without using superplasticizers and using 1% superplasticizers, the observed values of the control and the MK SCC exceeded the recommended range. By using 2% superplasticizers, the J-ring values of control and MK SCC were within the recommended range as displayed in Table 6. As the quantity of MK increased, the sieve segregation increased due to MK's more specific surface area as compared to cement. This similar trend of the experimental study is related to Guneyisi and Gesoglu (2008). By using a 2% superplasticizer, the observed value of sieve segregation of control mix is within range, while CBA SCC has been less than the required sieve segregation, i.e., less than 12%. By using 5%, 9%, 13%, and 17% superplasticizer the value of sieve segregation of CBA10, CBA20, CBA30, and CBA40-SCC has been observed within the required range of (EFNARC 2005). As the magnitude of CBA increased, the sieve segregation has been reduced owing to the porosity of CBA contrasted with the cement. CBA has saturated more water with a greater content of CBA. The outcome achieved suggested the CBA structure, which has a rough form that decreasing interparticle abrasion among aggregates and showed the excessive inclusion of coal bottom ash declined the viscosity of SCC mixes. This trend has been observed by other researchers (Aswathy and Mathews 2015). In the combined utilization of local metakaolin and CBA, as the quantity of MK and CBA increased, more quantity of SP is needed to satisfy the required range of sieve segregation. Maximum 22% SP is used to satisfy the requirements of sieve segregation of the MK20CBA40 mix.

The conclusion on the fresh properties of SCC with an accumulation of MK exhibited that the use of MK up to 20% satisfies the performance of fresh-state requirements associated with greater segregation resistance, deformability, passing, and filling capabilities using 2 and 3% SP without using VMA. In the utilization of CBA as a fine aggregate replacement to develop SCC, as the quantity of CBA is increased, more SP is needed to satisfy the requirement of all fresh properties of SCC. Maximum 17% SP is used for 40% replacement of fine aggregate with CBA to satisfy the fresh properties of SCC. In the combined utilization of MK as cement replacement and CBA as fine aggregate replacement, maximum of 22% SP is used to develop the SCC.

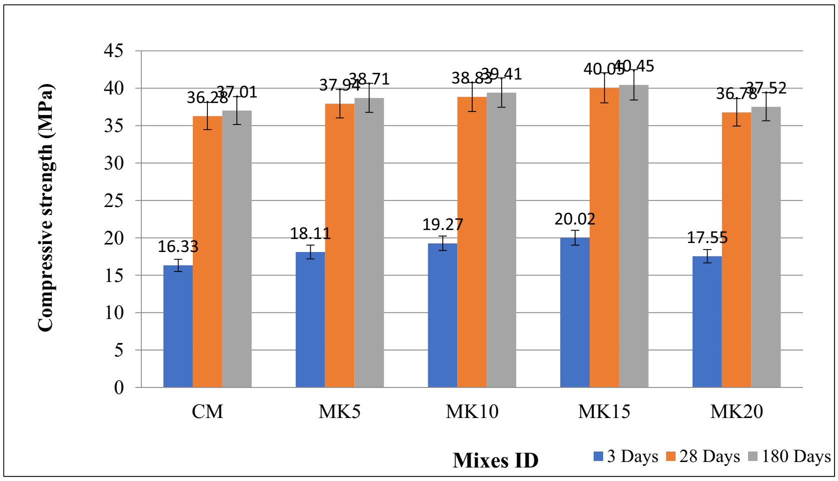
Hardened concrete results

The compressive, tensile, flexural strength and water penetration depth were performed on hardened concrete for all SSC mixes.

Compressive strength

Figure 2 shows that maximum compressive strength is increased as 22.6%, 10.39%, and 9.29% more than that of control mix at 15% of MK as a cementitious component at 3, 28, and 180 days, respectively. However, it was deemed that the compressive strength of SCC with the inclusion of 5 to 15% MK is more than that of the SCC without the addition of MK as cementitious substantial. This increment may be due to the influence by the active pozzolanic reaction of MK, and the silica content in MK particles enhances the development of C-S-H, a gel responsible for strength development (Wild et al. 1996; Guru et al. 2013). The major factors that contribute to the strength of MK SCC are (i) the filling consequence, (ii) the dilution consequence, and (iii) the pozzolanic response of MK with CH (Wild et al. 1996; Khatib and Hibbert 2005; Said-Mansour et al. 2011). Besides, the compressive strength of SCC was estimated reduced while utilizing the MK more than 15% (Rahmat and Yasin 2012). This study is similar to Parande et al. (2008) where it was described that the accumulation of 15% MK as a cementitious constituent gives an excellent result than the other substitution levels. The almost same trend of results of compressive strength of concrete using metakaolin has been observed by different researchers (Poon et al. 2006; Mermerdaş et al. 2012). Wild et al. 1996) and Ding

Fig. 2 Compressive strength of MK SCC at 3, 28, and 180 days



and Li 2002) analyzed that the compressive strength of concrete with the inclusion of 20%, and 25% MK was lower than that of concrete with an accumulation of 15% MK due to the dilution effect of clinker. The dilution effect of clinker is a result of replacement level for cement with an equal extent of MK. In MK concrete, the filler consequence, the pozzolanic reaction of MK with CH, and compounding influence respond as opposed to the dilution effects (Wild et al. 1996; Parande et al. 2008; Ding and Li 2002). Hassan et al. (2010) stated that the compressive strength was enhanced by 22% while using 25% of MK by the weight of cement after 28 days. Vejmelková et al. (2011) conveyed that the MK used in SCC provides compressive strength that rises quickly at the initial stage of hardening. Similarly, Melo and Carneiro (2010) presented that the content of MK increases in SCC that results in reducing the compressive strength of SCC (Okan et al. 2012).

Figure 2 indicates that the compressive strength of SCC with an accumulation of MK is improved at an early age (3–28 days) as well as later age of 180 days, though, the frequency of strength growth was more important at the early age. The latter study was related to the outcomes obtained in earlier studies (Wild et al. 1996; Abidin et al. 2014). Additionally, it was informed that the highest input to the strength progress of concrete on initial periods due to the pozzolanic reaction of MK (Poon et al. 2001).

It is obvious from Fig. 3 that the compressive strength of the CBA SCC mix is enhanced as compared to the control mix with the replacement of F.A by CBA, with the substitution range of 10 to 30 %. It is oblivious that the optimum compressive strength, 41.56 MPa (i.e., 14.55% increase contrasted with the control mix) at 28 days, has been attained at 30% replacement of F.A with CBA. This has happened due to the permeable refinement and pozzolanic response of bottom ash in the concrete matrix (Zainal Abidin et al. 2015). On further substitution of F.A by CBA, the compressive strength of SCC mix blended with CBA is reduced than that of concrete without CBA. This indicated that the strength of the concrete mixture was declined with enhance in the magnitude of CBA, owing to the substitution of the resilient substantial with the fragile ingredient and enhanced porosity. The reduction in the free water content of concrete with the addition of CBA has happened owing to the saturation of part of water by the permeable particles of the coal bottom ash internally also contributed to some extent in excluding adverse the influence of the aspects accountable for decreased compressive strength (Aswathy and Mathews 2015). In the combined utilization of MK as cement replacement and CBA as fine aggregate replacement, maximum compressive strength 44.81 MPa is observed at 10% MK as cement replacement with 30% replacement of fine aggregate with CBA which is 23.51% more than that of control mix at 28 days.

Figure 4 revealed that by the combined use of local metakaolin and CBA, maximum compressive strength is 44.81 MPa achieved at 28 days at 10% replacement of cement with metakaolin combined with 30% replacement of fine aggregate with coal bottom ash which is 23.51% more than that of control SCC.

Splitting tensile strength

Figure 5 shows that the split tensile strength of SCC with the inclusion of 5% to 20% MK is more than that of the SCC without the addition of MK as cementitious substantial. As shown in Fig. 2, the maximum split tensile strength is increased as 10.43%, 10.19%, and 10.0% respectively than that of control mix at 3. 28 and 180 days respectively at 15% substitution of cement with metakaolin. This may be due to the effect of the active pozzolanic reaction of MK and silica content in MK particles that enhances the formation of C-S-H, a gel responsible for strength development (Wild et al. 1996; Guru et al. 2013). On extra substitution of cement by MK, the split tensile strength of MK SCC is declined than that of control concrete (Rahmat and Yasin 2012). This similar trend of this study is related to that where it was observed about the

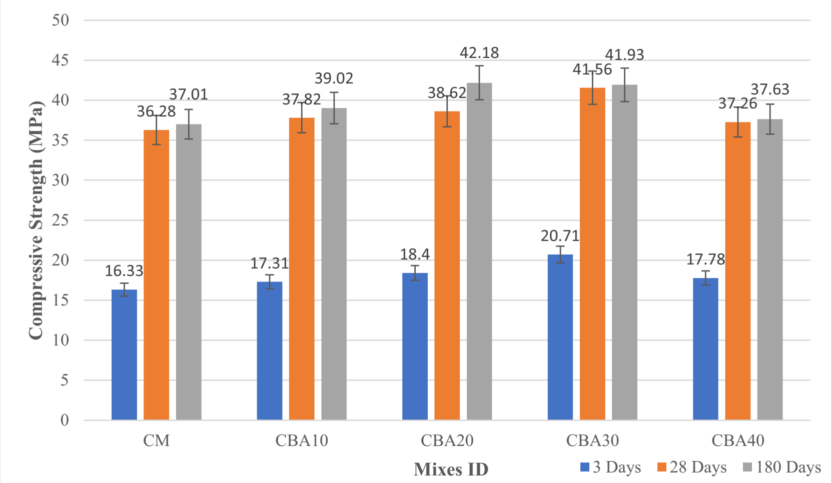


Fig. 3 Compressive strength of CBA SCC at 3, 28, and 180 days

tensile strength of SCC with an accumulation of 5% to 15% MK is achieved maximum than that of control mixes (Billong et al. 2011).

Figure 6 illustrates that the split tensile strength of the CBA SCC mixture is enhanced as compared to the control mix with the replacement of F.A by CBA, with the substitution limit from 10 to 30 %. It is oblivious that the optimum split tensile strength, 4.16 MPa (i.e., 14.6% enhanced contrasted with the control mix) at 28 days, has been attained at 30% replacement of F.A with CBA. On further replacement of F.A by CBA, the split tensile strength of CBA SCC concrete is declined than that of control mix concrete. The outcomes proposed that the attachment between cement paste and aggregate has been the most significant aspect in influencing the stability of concrete especially the tensile strength. The enhancement in the substitution status of coal bottom ash had formed more permeable concrete with high permeability spread around the CBA aggregate surface, hence decreasing its stability. This trend has been observed by other researchers (Aswathy and Mathews 2015). Kadam and Patil 2014) have explored that the tensile strength has been enhanced while using 10–30% substitution, and after that, it has been reduced for the rest substitution after 7th, 28th, 56th, and 112th days, respectively. According to Soman et al. (2014), the tensile strength has been enhanced by 0.70%, 5.70%, and 12.16% which is recorded for 10%, 20%, and 30 % substitution after 7 days correspondingly. In the combined utilization of MK as cement replacement and CBA as fine aggregate replacement, maximum tensile strength of 4.48 MPa is observed at 10% MK as cement replacement with 30% replacement of fine aggregate with CBA which is 23.42% more than that of control mix at 28 days.

It is observed from Fig. 7 that by the combined use of local metakaolin and CBA, maximum tensile strength is 4.48 MPa achieved at 28 days at 10% replacement of cement with metakaolin combined with 30% replacement of fine aggregate with coal bottom ash which is 23.42% more than that of control SCC. Furthermore, Fig. 8 presents the correlation between compressive strength and split tensile strength on 28 days blended with MK as a replacement for PC and CBA as fine aggregates in the SCC mixture. It is evident from Fig. 8 that

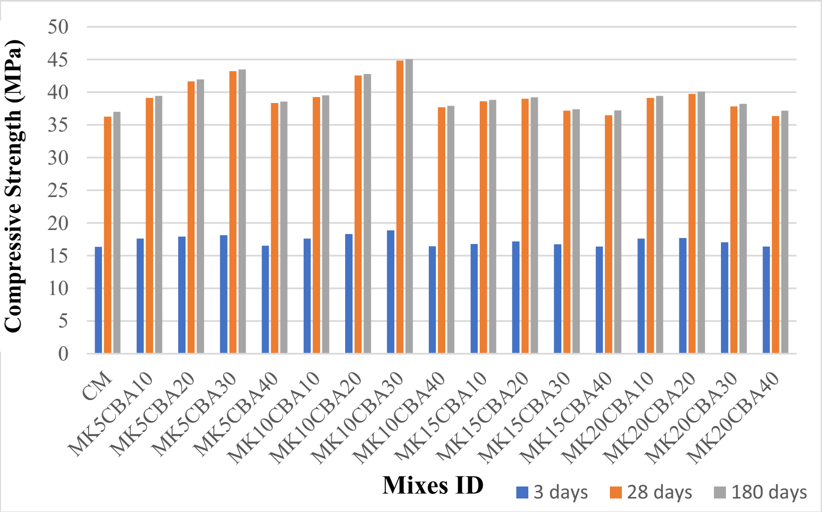


Fig. 4 Compressive strength of MK CBA SCC at 3, 28, and 180 days

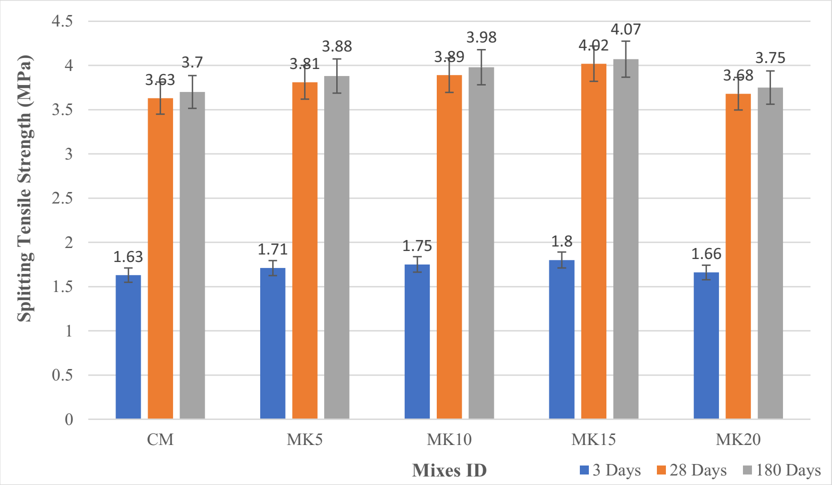


Fig. 5 Tensile strength of MK SCC at 3, 28, and 180 days

there is a good correlation between these two properties. Therefore, the equation presented in Fig. 8 will be useful in estimating or predicting either the compressive strength or the split tensile strength if one of the values of the unknown is available.

Flexural strength

Figure 9 reveals that the maximum flexural strength is increased as 7.07% more than that of the control mix at 15% of MK as a cementitious component at 28 days. However, it was deemed that the flexural strength of SCC with the inclusion of 5 to 15% MK is more than that of the SCC without the addition of MK as cementitious substantial. This increment may be due to the influence of the active pozzolanic reaction of MK, and the silica content in MK particles enhances the development of C-S-H, a gel responsible for strength development (Guru et al. 2013; Wild et al. 1996). Moreover, further addition of MK in SCC obtained a reduction in flexural strength of SCC as compared to SCC without the inclusion of MK.

Figure 10 shows that flexural strength of CBA SCC concrete is enhanced as compared to control mix with the substitution of F.A by CBA, with the substitution limit from 10 to 40%. It is oblivious that the optimum flexural strength, 6.65 MPa (i.e., 14.65% enhancement contrasted with the control mix) at 28 days, has been attained at 30% replacement of F.A with CBA. On further replacement of F.A by CBA, the flexural strength of CBA SCC concrete is declined as compared to control mix concrete. The coal bottom ash supplanting (CBA30) provided optimum flexural strength. The reduced flexural strength of the sample as the substitution status of coal bottom ash enhanced has been alleged due to the weak interparticle abrasion among the aggregate, as bottom ash particles have been sphere shaped. This study is concerned with Bhuvaneshwari et al has stated that concrete with a 30% substitution of bottom ash (BA) with sand indicated more flexural strength for normal samples (Bhuvaneshwari and Murali 2013). M.P. Kadam and Patil 2014) investigated that

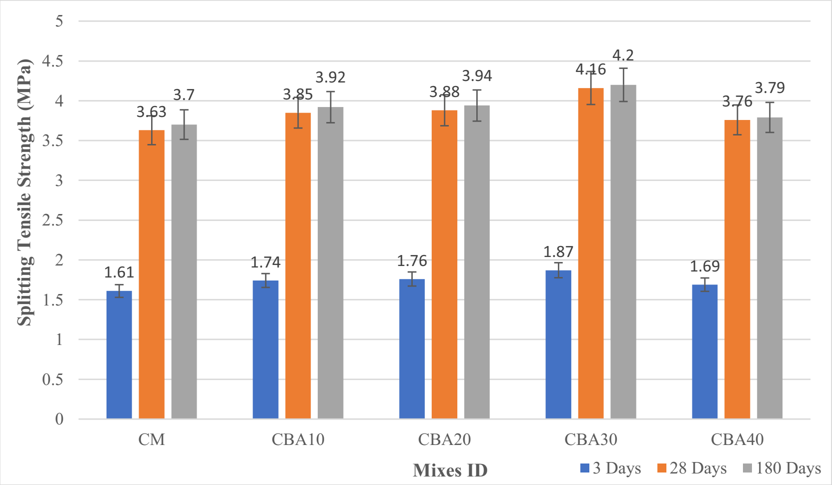


Fig. 6 Tensile strength of CBA SCC at 3, 28, and 180 days

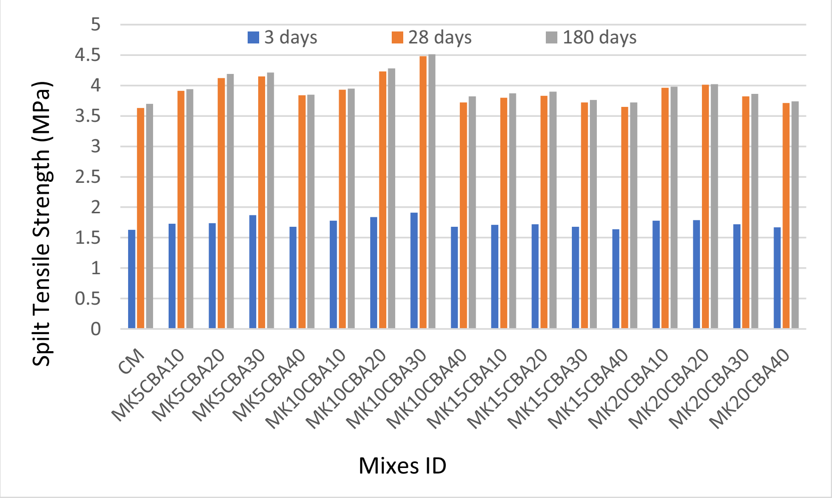


Fig. 7 Tensile strength of MK CBA SCC at 3, 28, and 180 days

the flexural strength has been enhanced up to 30% replacement of BA and beyond it gets reduced. Soman et al. (2014) has also detected that 30% substitution of fine aggregate by bottom ash contributed comparable flexural strength at the curing period of 28 days. In the combined utilization of MK as cement replacement and CBA as fine aggregate replacement, maximum flexural strength of 7.17 MPa is observed at 10% MK as cement replacement with 30% replacement of fine aggregate with CBA which is 23.62% more than that of control mix at 28 days.

It is observed from Fig. 11 that by the combined use of local metakaolin and CBA, maximum flexural strength is 7.17 MPa achieved at 28 days 10% replacement of cement with metakaolin combined with 30% replacement of fine aggregate with coal bottom ash which is 23.62% more than that of control SCC. In addition, Fig. 12 shows the correlation between flexural strength and compressive strength of SCC at 28 days blended with MK as a replacement for PC and CBA as fine aggregates in the SCC mixture. It can be seen from Fig. 12 that there is a good linear correlation between these properties. However, there is a more linear correlation between flexural strength and compressive strength. Nonetheless, the two formulas in Fig. 12 will be useful in predicting the properties of SCC mixtures.

Water penetration depth

Permeability is one of the most important parameters of concrete durability. The less permeability of concrete shows enhanced resistance against chemical attacks. Once water enters into the concrete, various soluble salts together with chloride ions infiltrate into concrete and cause corrosion. In general, it gives the impression that lesser permeability shows improved durability in concretes (Wesche et al. 1989; Ramezanianpour et al. 2011). The permeability of concrete can be evaluated by the water penetration test, and the validity of the water penetration test has been approved by BS EN 12390-8 (2000).

The water penetration depth test presented in Fig. 13 revealed that the water penetration depth of SCC mixtures with an accumulation of 5 to 15% MK is decreased than that of

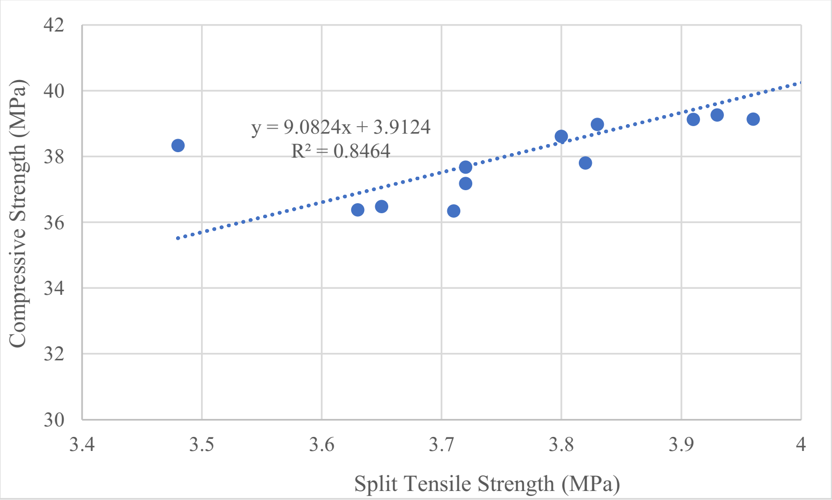
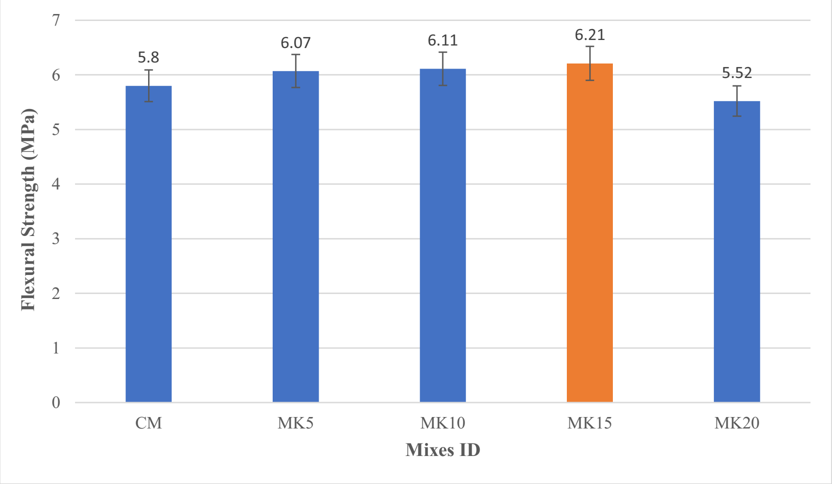


Fig. 8 Correlation between compressive strength and split tensile strength of SCC at 28 days

Fig. 9 Flexural strength of MK SCC at 28 days



SCC without MK at 28 and 180 days. However, the maximum reduction in water penetration depth of SCC mixtures was found as 34.0% and 33% at 15% of MK as cementitious ingredients at 28 and 180 days, respectively. This may due to the filling consequence and effect by the active pozzolanic reaction of metakaolin and the silica content in metakaolin (Parande et al. 2008; Wild et al. 1996). Almost the same behavior in terms of water penetration is reported by Güneyisi et al. 2012) that the permeability was reduced by 29% at 15% of MK as cementitious constituent as compared to plain concrete.

The water penetration test presented in Fig. 14 is covered that the water penetration depth of modified mixes has been reduced contrasted with the CM with the replacement of F.A by the CBA with 10% to 30%. The optimum reduction in water penetration depth was found as 13.5 mm (i.e., 33.49 % decrease compared to control mix) at 30% substitution of F.A with CBA. On additional substitution of F.A by CBA, the water penetration depth of CBA SSC concrete has been enhanced contrasted with the control mix concrete after 28 days. Almost the same behavior in terms of water penetration has been reported by different researchers (Khatri and Sirivatnanon 1997; Ratchayut and Somnuk 2008). However, the water penetration test presented in Fig. 14 has shown that the water penetration depth of modified mixes has been declined contrasted with the CM by the replacement of F.A by the CBA with 10 to 30%. The optimum reduction in water penetration depth has been found as 10.2 mm (i.e., 41.04 % decrease compared to control mix) at 30% substitution of F.A with CBA. On additional substitution of F.A by CBA, the water penetration depth of CBA SSC concrete has been increased contrasted with the control mix concrete after 180 days. The same behavior in terms of water penetration has been reported by Al-Fasih Mohammed et al. (2019), where in the substitution of 20% fine aggregate with CBA, the water penetration depth has been enhanced with growth in the extent of CBA as a sand substitution. It was identified that the CBA used as sand substitution has declined concrete resistance for water absorption. This similar study has been detected by Marto et al. (2011). Hashemi et al. (2018) described that the

Fig. 10 Flexural strength of CBA SCC at 28 days

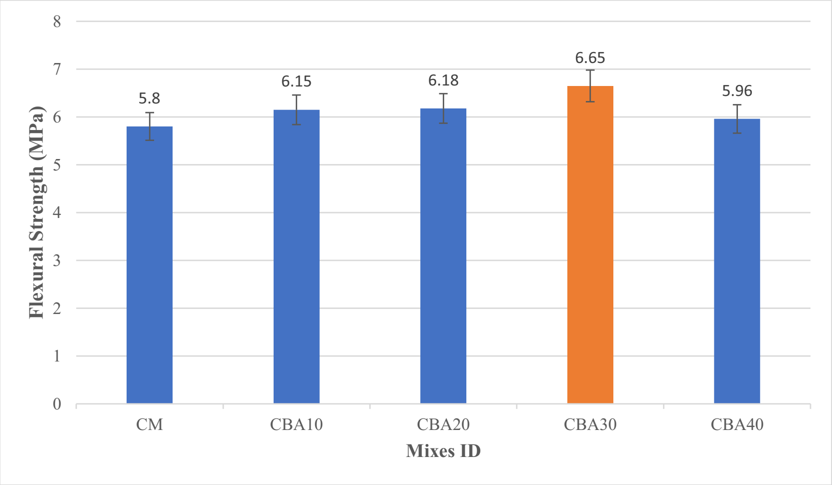
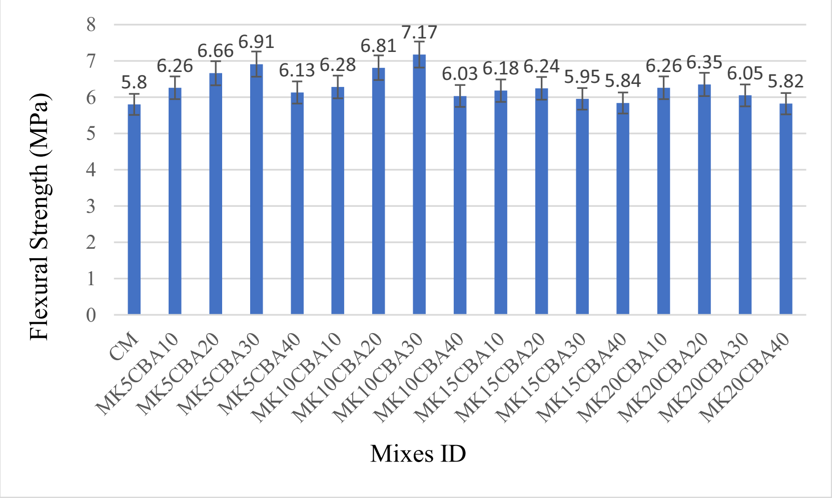


Fig. 11 Flexural strength of CBA MK SCC at 28 days



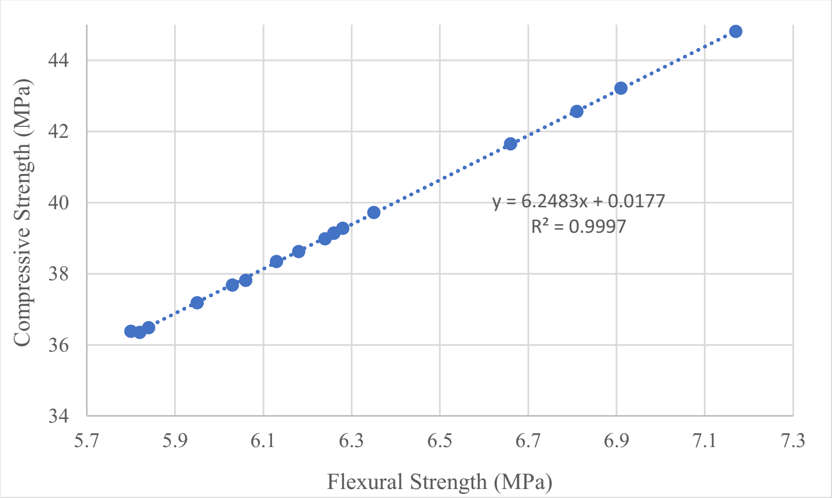
growing need for water has happened owing to the permeable texture of CBA causing the enhancement of the permeability of concrete. Hence, the CBA saturated high amount of water in concrete contrasted with that of the control mix. Therefore, this occurrence illustrates the CBA to have more porous behavior contrasted with the control mix concrete (Hassan et al. 2010). Almost the same behavior in terms of water penetration has been reported by different researchers (Ratchayut and Somnuk 2008; Khatri and Sirivivatnanon 1997).

It is observed from Fig. 15 that by the combined use of local metakaolin and CBA, a minimum water penetration depth of 9.76 mm is achieved at 28 days at 10% replacement of cement with metakaolin combined with 30% replacement of fine aggregate with coal bottom ash which is 36.45 % less than that of control SCC.

Sustainability assessment

Table 4 shows the data of embodied carbon for materials which are used in this investigational study, and Eq. (1) was used to calculate the quantity of embodied carbon content for twenty-five SCC mixtures including various percentages of MK as a PC replacement and CBA as a sand ingredient. Figure 16 indicates the embodied carbon of SCC mixture inclusion with 0–20% of MK as a cementitious material. The embodied carbon is recorded by 2.72%, 5.44%, 8.10% and 10.72% at 5%, 10%, 15% and 20% of PC replaced with MK are lower than that of the control mix of SCC. It was perceived that the embodied carbon is decreased as the dosages of PC replaced with MK increase in the SCC mixture. This similar type of trend was performed by Bheel et al. 2021a, b) where the embodied carbon is reduced as the content of coconut shell ash rises in concrete. Related studies were observed by Bheel and Adesina (2020). However, Fig. 17 represents the embodied carbon of SCC mixture including 10–40% of CBA as a replacement for fine aggregates in mixture. The embodied carbon of the SCC mixture is noted by 0.50%, 1.16%, 1.82% and 2.50% at 10%, 20%, 30% and 40% of fine aggregates replaced with CBA is higher than that of the control mix of the SCC. It can be observed that the embodied

Fig. 12 Correlation between compressive strength and flexural strength of SCC at 28 days



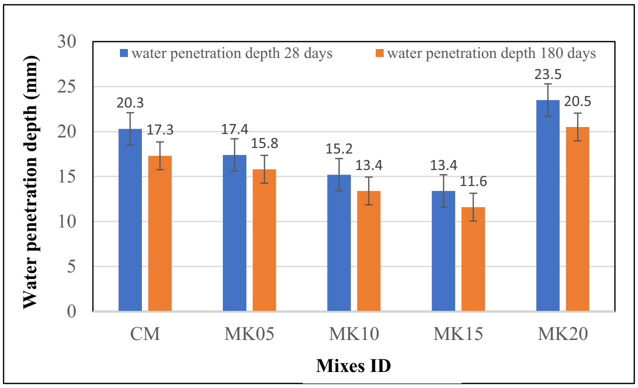


Fig. 13 Water penetration depth of MK SCC at 28 and 180 days

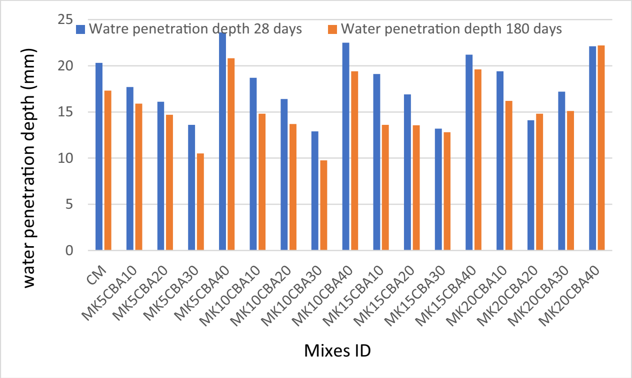


Fig. 15 Water penetration depth of MKCBA SCC at 28 and 180 days

carbon of SCC is increased with growth in the extent of CBA as sand replacement in the SCC mixture. Figure 18 displays the calculated quantity of embodied carbon of SCC including 0–20% of MK as PC replacement and CBA as sand replacement in SCC mixture. The highest embodied carbon is calculated by 450.45 kgCO_2/m^3 at control mix of SCC, and minimum embodied carbon is noted by 405.15 kgCO_2/m^3 at 20% of PC replaced with MK and 10% of fine aggregates replaced with CBA in SCC mixture. From Fig. 18, it has been observed that the embodied carbon is reduced as the dosages of PC replaced with MK and fine aggregates replaced with CBA increase in the SCC mixture. Therefore, when using environmentally friendly materials (such as recycled waste), the embodied carbon in the concrete mix can be more reduced.

Conclusions

It was concluded from the conducted research that:

- It was detected that using of local metakaolin and CBA resulted in increased amount of super-plasticizer to develop the SCC. To develop SCC by using local metakaolin as cement replacement for 5, 10, 15 and 20% metakaolin, 2% and 3% SP are used, respectively, while to develop SCC with CBA as 10, 20, 30, and 40% fine aggregate replacement, 5%, 9%, 13%, and 17% superplasticizer is used. In the combined utilization of MK as cement replacement and CBA as fine aggregate replacement, maximum 22% SP is used to develop the SCC.

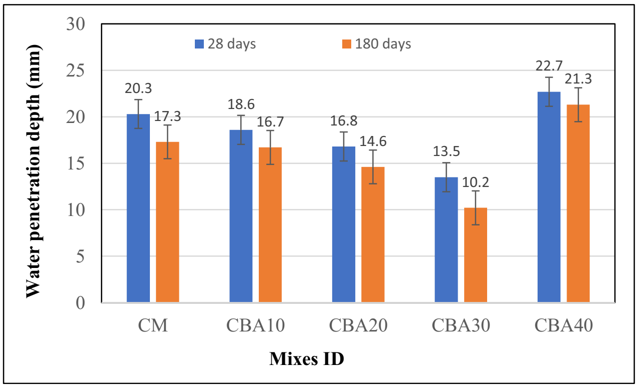


Fig. 14 Water penetration depth of CBA SCC at 28 and 180 days

- The maximum compressive strength is improved as 22.6%, 10.39%, and 9.29%, and maximum tensile strength is augmented as 10.43%, 10.19%, and 10.0% more than that of the control mix at 15% of MK as a cementitious component at 3, 28, and 180 days, respectively. It is oblivious that the optimum compressive strength, 41.56 MPa (i.e., 14.55% increase contrasted with the control mix) at 28 days, has been attained at 30% replacement of F.A with CBA. By the combined use of local metakaolin and CBA, maximum compressive strength is 44.81 MPa achieved at 28 days at 10% replacement of cement with metakaolin combined with 30% replacement of fine aggregate with coal bottom ash which is 23.51% more than that of control SCC. By the combined use of local metakaolin and CBA, maximum tensile strength is 4.48 MPa achieved at 28 days at 10% replacement of cement with metakaolin combined with 30% replacement of fine aggregate with coal bottom ash which is 23.42% more than that of control SCC.
- By the combined use of local metakaolin and CBA, maximum flexural strength is 7.17 MPa achieved at 28 days 10% replacement of cement with metakaolin combined with 30% replacement of fine aggregate with coal bottom ash which is 23.62% more than that of control SCC.
- The water penetration depth of SCC mixtures with an accumulation of 5 to 15% MK is decreased than that of SCC without MK and with 20% MK after 28 and 180 days. However, the maximum reduction in water penetration depth of SCC mixtures was found as 34.0% and 33% at 15% of MK as a cementitious ingredient after 28 and 180 days, respectively. The optimum reduction in water penetration depth was found as 13.5 mm (i.e., 33.49 % decrease compared to control mix mix) at 30% substitution of F.A with CBA. By the combined use of local metakaolin and CBA, a minimum water penetration depth

Fig. 16 Embodied carbon of concrete including MK

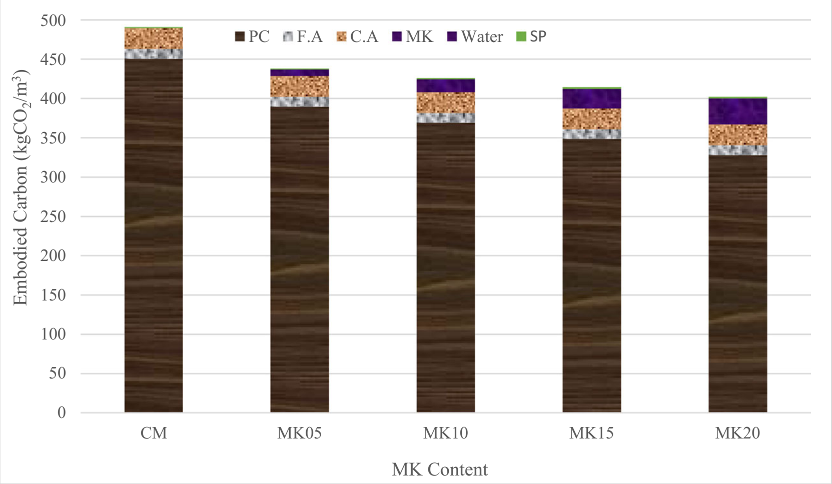


Fig. 17 Embodied carbon of concrete containing CBA

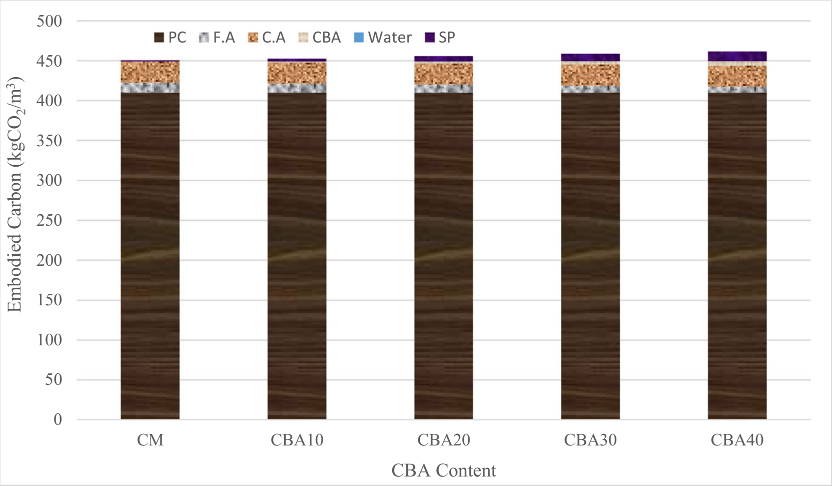
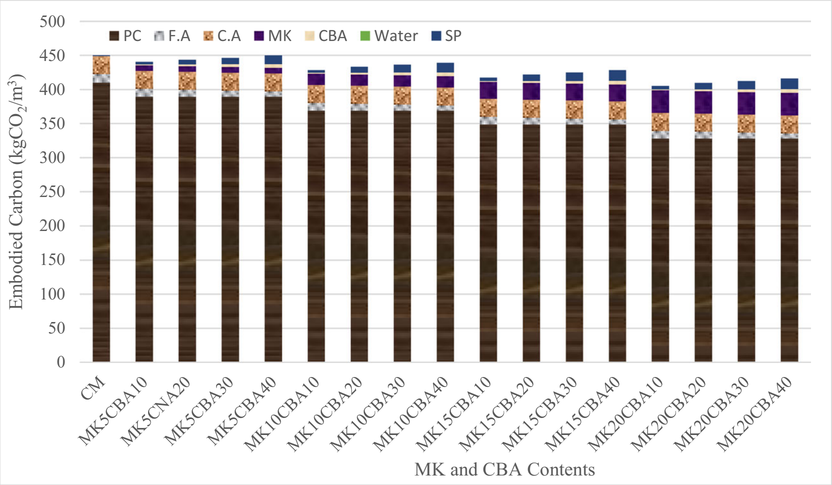


Fig. 18 Embodied carbon of concrete including MK and CBA



of 9.76 mm is achieved at 28 days at 10% replacement of cement with metakaolin combined with 30% replacement of fine aggregate with coal bottom ash which is 36.45 % less than that of control SCC.

- The embodied carbon is reduced with growth in the dosages of MK as PC replacement in the SCC mixture. However, the embodied carbon of the SCC mixture is increased as the extent of CBA as sand ingredient replacement rises in mixture. Moreover, the embodied carbon of SCC mixture is reduced while the increasing of MK as cementitious ingredients and CBA as fine aggregates replacement in the mixture.
- Based on investigated parameters, it can be concluded that at 15% replacement of cement with local metakaolin is optimum and gave better results as compared to control SCC. At 30% replacement of fine aggregate is optimum and gave better results as compared to control SCC. In the combined mix, 10% replacement of cement with metakaolin combined with 30% replacement of fine aggregate with coal bottom ash is optimum and gave better results as compared to control SCC.

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Author contribution Manthar Ali Keerio: data analysis, validation, and writing—original draft.

Abdullah Saand: supervision, methodology, writing (original draft), and funding acquisition.

Aneel Kumar: formal analysis and validation.

Naraindas Bheel: conceptualization, investigation, data analysis, validation, writing (original draft), and writing (review and editing).

Karm Ali: data analysis, validation, and writing (original draft).

Availability of data and material The data used in this study will be made available upon the request.

Declarations

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Abidin NEZ, Ibrahim MHW, Jamaluddin N, Kartini K, Hamzah AF (2014) The effect of bottom ash on fresh characteristic, compressive strength and water absorption of self-compacting concrete. Applied Mechanics and Materials Vol 660:145–151

Al-Fasih Mohammed Yahya Mohammed, Mohd Haziman Wan Ibrahim, Nurul Fasihah Basirun, Ramadhansyah Putra Jaya, Mohd Syahrul Hisyam Mohd Sani (2019) " Influence of partial replacement of cement and sand with coal bottom ash on concrete properties" International Journal of Recent Technology and Engineering (IJRTE) ISSN: 2277–3878, Volume-8 Issue-3S3.

Aswathy PU, Mathews MP (2015) Behaviour of self compacting concrete by partial replacement of fine aggregate with coal bottom ash. International Journal of Innovative Research in Advanced Engineering (IJIRAE) ISSN: 2349- 2163 2(10):2280–2289

Badogiannis E, Tsivilis S (2009) Exploitation of poor Greek kaolins, durability of metakaolin concrete. Cem Concr Compos 31:128–133

Batis G, Pantazopoulou P, Tsivilis S, Badogiannis E (2005) The effect of metakaolin on the corrosion behavior of cement mortars. Cem Concr Compos 27:125–130

Bheel N, Adesina A (2020) Influence of binary blend of corn cob ash and glass powder as partial replacement of cement in concrete. Silicon: 1–8

Bheel N, Memon AS, Khaskheli IA, Talpur NM, Talpur SM, Khanzada MA (2020) Effect of sugarcane bagasse ash and lime stone fines on the mechanical properties of concrete. Eng Technol Appl Sci Res 10(2):5534–5537

Bheel N, Kumar A, Shahzaib J, Ali Z, Ali M (2021a) An investigation on fresh and hardened properties of concrete blended with rice husk ash as cementitious ingredient and coal bottom ash as sand replacement material. Silicon:1–12

Bheel N, Mahro SK, Adesina A (2021b) Influence of coconut shell ash on workability, mechanical properties, and embodied carbon of concrete. Environ Sci Pollut Res 28(5):5682–5692

Bhuvaneshwari P, Murali R (2013) Strength characteristics of glass fibre on bottom ash based concrete. International Journal of Science, Environment and Technology, ISSN (p): 2277-663X, ISSN (e): 2278-3687 2(1):90–102

Billong N, Melo UC, Kamseu E, Kinuthia JM, Njopwouo D (2011) Improving hydraulic properties of lime–rice husk ash (RHA) binders with metakaolin (Mk). Constr Build Mater 25(4):2157–2161

Cheriaf M, Rocha JC, Pera J (1999) Pozzolanic properties of pulverized coal combustion bottom ash. Cem Concr Res 29:1387–1391

Damtoft JS, Lukasik J, Herfort D, Sorrentino D, Gartner EM (2008) Sustainable development and climate change initiatives. Cem Concr Res 38(2):115–127

Ding J-T, Li Z (2002) Effects of metakaolin and silica fume on properties of concrete. ACI Mater J 99(4):393–398

Dwikojuliardi R (2015) Malaysia and construction industry. Malaysia construction research journal 2(1):22–45

EFNARC (2005) The European guidelines for self-compacting concrete; specification production and use.

EN B (2000) Depth of penetration of water under pressure" British Standards Institution 12390-8.

Eva V, Martin K, Stefania G, Bartlomiej S, Robert C (2011) Properties of self-compacting concrete mixtures containing metakaolin and blast furnace slag. Constr Build Mater 25:1325–1331

Flower DJM, Sanjayan JG (2007) Green house gas emissions due to concrete manufacture. Int J Life Cycle Assess [Internet] 12(5): 282–288. Available from:. https://doi.org/10.1065/lca2007.05.327

Guneyisi E, Gesoglu M (2008) Properties of self-compacting mortars with binary and ternary cementitious blends of fly ash and metakaolin. Mater Struct 41:1519–1531

Guneyisi E, Gesoglu M, Mermerdas K (2008) Improving strength, drying shrinkage, and pore structure of concrete using metakaolin. Mater Struct 41:937–949

Guneyisi E, Gesoglu M, Ozbay E (2009) Evaluating and forecasting the initial and final setting times of self-compacting concretes containing mineral admixtures by neural network. Mater Struct 42:469–484

Güneyisi E, Gesoğlu M, Karaoğlu S, Mermerdaş K (2012) Strength, permeability and shrinkage cracking of silica fume and metakaolin concretes. Constr Build Mater 34:120–130

Guru JJ, Sashidhar C, Ramana RIV, Annie PJ (2013) Micro and macrolevel properties of fly ash blended self-compacting concrete. Mater Des 46:696–705

Hashemi SSG, Bin Mahmud H, Djobo JNY, Tan CG, Ang BC, Ranjbar N (2018) Microstructural characterization and mechanical properties of bottom ash mortar. J Clean Prod 170:797–804

Hassan AAA, Lachemi M, Hossain KMA (2010) Effect of metakaolin on the rheology of self-consolidating concrete. In: Khayat K, Feys D (eds) Proceedings of SCC 2010 design, production, and placement of SCC, vol 1. Springer, RILEM Publications, pp 103–112

Hendriks, C.A., Worrell, E., De Jager, D., Blok, K. and Riemer, P., 1998. Emission reduction of greenhouse gases from the cement industry. In *Proceedings of the fourth international conference on greenhouse gas control technologies* (pp. 939-944). Interlaken, Austria, IEA GHG R&D Programme.

Hwang JP, Jung MS, Lee CK, Jin SH, Ann KY (2015) Risk of environmental contamination arising from concrete structures, part I: CO2 emission. KSCE J Civ Eng 19:1224–1229

Ibrahim MHW, Hamzah AF, Jamaluddin N, Ramadhansyah PJ, Fadzil AM (2015) Split tensile strength on self-compacting concrete containing coal bottom ash. Procedia Soc Behav Sci 195:2280–2289

Jamaluddin, N., Hamzah, A.F., Ibrahim, M.H.W., Jaya, R.P., Arshad, M.F., Abidin, N.E.Z. and Dahalan, N.H., 2016. Fresh properties and flexural strength of self-compacting concrete integrating coal bottom ash. In *MATEC Web of Conferences* (Vol. 47, p. 01010). EDP Sciences.

Kadam MP, Patil YD (2014) The effect of sieved coal bottom ash as a sand substitute on the properties of concrete with percentage variation in cement. American Journal of Civil Engineering and Architecture 2(5):160–166

Kalaw ME, Culaba A, Hinode H, Kurniawan W, Gallardo S, Promentilla MA (2016) Optimizing and characterizing geopolymers from ternary blend of Philippine coal fly ash, coal bottom ash and rice hull ash. Materials 9(7):580

Keerio MA, Abbasi SA, Kumar A, Bheel N, ur Rehaman K, Tashfeen M (2020) Effect of silica fume as cementitious material and waste glass as fine aggregate replacement constituent on selected properties of concrete. Silicon:1–12

Keerio MA, Saand A, Chaudhry R, Bheel N, Soohu S (2021) The effect of local metakaolin developed from natural material soorh on selected properties of concrete/mortar. Silicon:1–10

Khatib J, Hibbert J (2005) Selected engineering properties of concrete incorporating slag and metakaolin. Constr Build Mater 19(6):460–472

Khatri RP, Sirivivatnanon V (1997) Role of permeability in sulphate attack. Cem Concr Res 27(8):1179–1189

Kim HS, Lee SH, Moon HY (2007) Strength properties and durability aspects of high strength concrete using Korean metakaolin. Constr Build Mater 21:1229–1237

Lauritzen EK, Petersen MB (2004) DEMEX consulting engineers A/S, Denmark. Disaster Planning, Structural Assessment, Demolition and Recycling 9:74

Long G, Gao Y, Xie Y (2015) Designing more sustainable and greener self-compacting concrete. Constr Build Mater [Internet] 84:301–306 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061815002263

Mangi SA, Ibrahim MHW, Jamaluddin N, Shahidan S, Arshad MF, Memon SA, Jaya RP, Mudjanarko SW, Setiawan MI (2018) Influence of ground coal bottom ash on the properties of concrete. International Journal of Sustainable Construction Engineering and Technology 9:26–34

Marto A, Awang AR, Makhtar AM (2011), "Compaction characteristics and permeability of Tanjung bin coal ash mixtures", in: IPCBEE in Proc. of the International Conference on Environment Science and Engineering: Selected Papers. Ed. By IACSIT Press, Singapore: pp. 134–137.

Meddah MS, Ismail MA, El-Gamal S (2018) Fitriani H. Performances evaluation of binary concrete designed with silica fume and metakaolin. Constr Build Mater [Internet] 166:400–412 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061818301624

Melo KA, Carneiro AMP (2010) Effect of metakaolin's finesses and content in self-consolidating concrete. Constr Build Mater 24:1529–1535

Mermerdaş K, Gesoğlu M, Güneyisi E, Özturan T (2012) Strength development of concretes incorporated with metakaolin and different types of calcined kaolins. Constr Build Mater 37:766–774

Okan K, Khandaker H, Ozbay E, Lachemi M, Sancak E (2012) Effect of metakaolin content on the properties self-consolidating lightweight concrete. Constr Build Mater 31:320–325

Papadakis VG, Tsimas S (2002) Supplementary cementing materials in concrete part I: efficiency and design. Cem Concr Res 32:1525–1532

Parande AK, Babu BR, Karthik MA, Kumaar KKD, Palaniswamy N (2008) Study on strength and corrosion performance for steel embedded in metakaolin blended concrete/mortar. Constr Build Mater 22:127–134

Poon CS, Lam L, Kou SC, Wong YL, Ron W (2001) Rate of pozzolanic reaction of metakaolin in high-performance cement pastes. Cem Concr Res 31:1301–1306

Poon C-S, Kou S, Lam L (2006) Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete. Constr Build Mater 20(10):858–865

Rafat S, Paratibha A, Yogesh A (2012a) Mechanical and durability properties of self-compacting concrete containing fly ash and bottom ash. Journal of Sustainable Cement-Based Materials 1(3):67–82

Rafat S, Paratibha A, Yogesh A (2012b) Influence of water/powder ratio on strength properties of self-compacting concrete containing coal fly ash and bottom ash. Constr Build Mater 29:73–81

Rafik A, Salah AA, El-Sayed E (2010) Properties and durability of metakaolin blended cements: mortar and concrete. Mater Constr 60:33–49

Rahmat M, Yasin MS (2012) Fresh and hardened properties of self-compacting concrete containing metakaolin. Constr Build Mater 35:752–760

Ramezanianpour AA, Pilvar A, Mahdikhani M, Moodi F (2011) Practical evaluation of relationship between concrete resistivity, water penetration, rapid chloride penetration and compressive strength. Constr Build Mater 25(5):2472–2479

Ratchayut K, Somnuk T (2008) Properties of self-compacting concrete in corporating bottom ash as a partial replacement of fine aggregate. Sci Asia 34:087–095

Saand A, Keerio MA, Bangwar DK, Samo MK (2016) Development of metakaolin as a pozzolanic material from local natural material Soorh. Arab J Sci Eng 41(12):4937–4944

Said-Mansour M, Kadri E, Kenai S, Ghrici M, Bennaceur R (2011) Influence of calcined kaolin on mortar properties. Constr Build Mater 25:2275–2282

Shekarchi M, Bonakdar A, Bakhshi M, Mirdamadi A, Mobasher B (2010) Transport properties in metakaolin blended concrete. Constr Build Mater 24:2217–2223

Soman K, Sasi D, Abubaker KA (2014) Strength properties of concrete with partial replacement of sand by bottom ash. International Journal of Innovative Research in Advanced Engineering (IJIRAE), ISSN: 2349-2163 1(7):223–227

Turner LK, Collins FG (2013) Carbon dioxide equivalent (CO2-e) emissions: a comparison between geopolymer and OPC cement concrete. Constr Build Mater [Internet] 43:125–130 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061813000871

Vejmelková E, Keppert M, Grzeszczyk S, Skaliński B, Černý R (2011) Properties of self-compacting concrete mixtures containing metakaolin and blast furnace slag. Construction and Building Materials, 25(3):1325–1331

Wesche K, Alonso IL, Bijen I, Schubert P, Berg WV, Rankers R (1989) Test methods for determining the properties of fly ash and of fly ash for use in building materials. Mater Struct 22(4):299–308

Wild S, Khatib JM, Jones A (1996) Relative strength, pozzolanic activity and cement hydration in superplasticised metakaolin concrete. Cem Concr Res 26:1537–1544

Yang K-H, Song J-K, Song K-I (2013) Assessment of CO2 reduction of alkali-activated concrete. J Clean Prod [Internet] 39:265–272 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652612004076

Yogesh A, Rafat S (2014) Microstructure and properties of concrete using bottom ash and waste foundry sand as partial replacement of fine aggregates. Constr Build Mater 54:210–223

Zainal Abidin NE, Wan Ibrahim MH, Jamaluddin N, Kamaruddin K, Hamzah AF (2015) The strength behavior of self-compacting concrete incorporating bottom ash as partial replacement to fine aggregate. In Applied Mechanics and Materials (Vol. 773, pp. 916–922). Trans Tech Publications Ltd