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Synergistic effect of recycling waste coconut shell ash, metakaolin, and calcined clay as supplementary cementitious material on hardened properties and embodied carbon of high strength concrete

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ABSTRACT

Researchers are investigating eco-friendly binders like coconut shell ash (CSA), metakaolin (MK), and calcined clay (CC) as supplementary cementitious materials (SCM) in high-strength concrete (HSC). Abundantly available as industrial or agricultural waste, these materials, when combined with Portland cement (PC), offer synergistic benefits. This not only improves concrete performance but also addresses waste disposal issues, presenting a sustainable and environmentally friendly solution for long-term use in HSC production. However, this study performed on fresh and mechanical characteristics of HSC blended with CSA, MK, and CCA alone and together as SCM after 28 days of curing. A total of 504 samples of standard concrete were cast and the cubical samples were tested to achieve the targeted compressive strength about 80 MPa after 28 days. The experimental results indicated that the rise in tensile, flexural and compressive strengths of 9.62%, 8.27%, and 10.71% at 9% of CSA, MK, and CC as SCM after 28 days of curing. As SCM content increases, the density, porosity and water absorption of concrete decrease. Moreover, the workability of fresh concrete is getting reduced when the concentration of SCMs increases in HSC. In addition, the concrete's sustainability assessment revealed that employing 18% MK, CC, and CSA as SCM reduced carbon emissions by approximately 11.78%. It is suggested that using 9% CC, MK and CSA together in HSC yields the best results for practical applications in civil engineering.

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1. Introduction

Since the dawn of human invention, concrete has possessed significant impotence, 1 that is created by mixing aggregates, binder, and water [2]. Concrete is a crucial construction material utilized in projects related to infrastructures around the globe. It is considered as the global second most extensively utilised material. Therefore, the growing demand for the basic constituents of concrete will increase resources needs. Despite its usefulness as a binding element in the manufacturing of concrete, Portland cement (PC) has a substantial impact on natural resource depletion [3]. The extensive usage of concrete components necessitates the development of economical and commonly available materials that give similar or better strength when employed as a concrete component [4]. Cement is an expensive ingredient of concrete, and its manufacturing releases a substantial amount of CO_2 into the environment [5–8]. Each ton of PCs emits nearly 1 ton of CO_2 into the environment and consumes basic resources approximately 1.6 tons [9]. To lower cement costs and CO_2 emissions [9,16], various researchers have sought to substitute partially cement with commonly available agricultural and industrial waste, including silica fume (SF) and rice husk ash (RHA) [10], Egg shell powder [11–13], and fly ash (FA) [14,15], to decrease cement price and CO_2 emissions.

Concrete production, from an environmental standpoint, is responsible for a significant amount of toxic gas emissions. Each year, approximately 1.6 billion tons of concrete is manufactured worldwide, accounting for 7% of overall CO_2 release into the atmosphere [17]. Besides, the usage of agricultural and industrial waste materials in the building sector addressed global issues such as environmental problems, building material expenses, raw material shortfalls, and growing energy needs [18]. Several research investigated the application of manufactured and natural pozzolanic components as a partial substitute for PC, that would reduce use of cement, conserve energy, and minimize toxic pollutants in the surroundings. The usage of synthetic pozzolanic components also solves landfilling issues of industrial waste [19]. Researchers are spotlighting the usage of PC alternative materials, that have minimum environmental consequences of cement production [20]. The application of cement alternative material like waste ingredients including metakaolin [22], SF, coal bottom ash (CBA) [23], coconut shell ashes, waste glass [24,25], sugarcane bagasse ash, RHA and corn cob ashes, saves consumption of energy and lower the emissions of greenhouse gas 1, 21. These materials are most common examples of manufactured and natural pozzolanic components that can be used to enhance the strength and resilience of concrete [26]. In this pilot study, the combination of Metakaolin (MK), calcined clay (CC), and coconut shell ash (CSA) is a by-product of industrial/agricultural waste and is considered waste because it creates environmental pollution. These pozzolans perform almost at a similar substitution level, which can improve concrete's the permeability as well as compressive strength [27]. However, metakaolin application results in greater interfacial transition zone strength development than the other compounds [28]. Metakaolin pozzolanic is a natural material that is produced by burning kaolin clay at a controlled temperature of 650–800 °C. In recent years, MK has been introduced commercially to the concrete manufacturing industry [29]. Several researchers have undertaken investigations to enhance the concrete's strength with MK. These investigations discovered that using MK significantly improve development of strength.

Poon et al. [30] calculated the impact of Metakaolin concentration on hardened properties of concrete. Their study revealed that increasing MK quantity in concrete decrease porosity and improve strength. Regarding strength development, MK concrete with a w/b ratio of 0.5 performed much better than MK concrete with a w/b ratio of 0.3. At 28 days, the pores size and porosity of the concrete dropped dramatically. Whereas the similar trend was reported by Jin and Li, [31]. According to Ahmed et al. [32], the mixing 15% MK to concrete can increase the flexural and crushing strength. Furthermore, they discovered that MK concrete performed better in terms of concrete permeability-related measures. Dinakar et al.,[33] discovered that 10% MK in concrete is the best alternative for compressive strength. As 10% of the cement was substituted with MK, it reached 106 MPa. Additionally, the similar trend was followed by elastic modulus values and splitting tensile strength. The results also agree with previous investigations in this area [34,35].

In addition, calcined clay (CC) is a newly promising type of pozzolanic material that emits less CO_2. Although we have presented some well-known and thoroughly researched SCMs in the previous section, but their distribution is outside the scope of commercial cement production. Nevertheless, clays and limestone are the world's most spread natural resources. The widespread usage of calcined clays has the potential to address the expanding demand for cement substitute materials. Calcined clay manufacture uses identical equipment to PC and has a similar investment cost, approximately. Calcination of clay at lower temperatures (750–850 °C) consumes less energy than clinker, which is about 1450 °C [36]. Moreover, limestone calcined clay cement (LC3) manufacturing typically releases around 30% a smaller amount CO_2 than PC production [36]. Owing to the addition of LC3 produces an excessive number of AFm phases, (i.e., mono and hemi carboaluminate), leading to a complimentary reaction between CC and limestone. Being a very reactive pozzolan, CC can immediately enhance its pore structure in micro level [37]. Dhandapani et al. [38] investigated the durability and strength of concretes using calcined limestone and clay. The outcome revealed LC3 binder demonstrated equivalent mechanical strength growth, improved chloride resistance, capillary water absorption, lower gas permeability, and rapid improvement of durability metrics when compared to PC.

Furthermore, coconut shell ash (CSA) is employed as agricultural waste. This trash is freely available because there is no other purpose for it other than landfilling. Partial substitution of cement with a locally available wastes will not just reduce the need for cement in buildings projects but will also lessen the related throw out of the waste in land, which is important given the environmental problems associated with cement. It was discovered that CSA may be utilised to partially substitute cement in concrete. The resultant concrete's various mechanical and fresh properties were assessed. The strength development of concrete incorporating CSA has been the subject of numerous investigations by various researchers. Their research has shown that using CSA significantly improved the development of strength. Hasan et al. [39] investigated hardened concrete binary mixed with stone dust (SD) and coconut shell ash (CSA). In this research investigation, number of concrete samples were cast for mechanical characteristics of concrete. However, the shrinkage test, crushing strength, and flexural strength test of concrete were augmented by 53.0%, 7.5%, and 3.5% when 10% of CSA and SD as substituted for cement in concrete at 28 days correspondingly. Kumar et al. [40] reported using different ratios of CSA and eggshell powder (ESP) in concrete to investigate the hardened concrete. Flexural, tensile, and compressive strengths increased by 14.15%, 8.5%, and 8%, respectively, when substituting CSA and ESP for cement. Utsev et al. [41] evaluated the crushing strength of concrete inclusions containing 0–30% CSA. The results showed that a 10% substitution was optimal where compressive strength improved more than it decreased. A. Bhartiya and M. Dubey. [42] examined the impact of ESP and CSA contents on concrete crushing strength. It was found that the concrete's strength could be enhance by 10% by adding CSA and ESP.

Furthermore, whereas numerous research has been undertaken utilizing MK, CSA, and CC as individual cementitious constituents, but there are no any research investigations performed using MK, CSA, and CC combined as cementitious constituents in high strength concrete (HSC). Therefore, the focus of this study is done on fresh, hardened and embodied carbon of HSC blended with several ratios of MK, CSA, and CC separate and combined as a cementitious substance. The primary reason for repurposing these wastes is to reduce environmental issues, reduce CO_2 emissions, and classify MK, CSA, and CC for long-term concrete construction.

2. Materials and methods

2.1. Materials

For this study, Portland cement (PC), calcined clay (CC), metakaolin (MK), and coconut shell ash (CSA) were employed as binding materials, and the chemical compositions of the binding agents are given in Table 1. The powder form samples of all binding materials were taken for X-ray fluorescence (XRF) analysis and the oxides composition were acquired from XRF. However, the CSA employed in present research was made by coconut shells processing. After being dried, the shells of coconuts were smashed into small pieces. Those smashed coconut shells are burned for roughly 6 hours at a high temperature between 500°C to 550°C to create the ash (like, CSA). To make the CSA particles finer, they were chilled and mashed. The CSA was then sieved. To replace the PC, only CSA that passed through a sieve with a number of 75 microns was employed. Besides, Metakaolin is an ordinary pozzolanic substance and a substantial by-product derived from the controlled combustion of kaolin clay at temperatures between 650 and 800 ^{0}C. It was sieved through 75 μm after burning to eliminate undesirable particles and is utilised as a partial substitution for cement in concrete. Moreover, the CC ingredients were attained by burning clay at 700 ^{0}C-850 ^{0}C for two hours to make its pozzolanic characteristics active. Therefore, the calcined clay (CC) is sieved through a mesh of 75 μm to remove the large particles before being used as a cement substitute material in concrete. The X-ray diffraction (XRD) method is used for the examination of the crystallographic arrangement of substances by assessing the diffraction pattern generated by the interaction of X-rays with the specimen. X-ray diffraction (XRD) analysis may provide significant insights into the mineral composition and crystalline phases of materials such as coconut shell ash, calcined clay, and metakaolin. The comprehension of the structural features of these materials is of utmost importance for academics and companies, as it enables the optimisation of their utilisation in diverse applications within this construction sector. The X-ray Diffraction (XRD) of CSA, MK and CC are mention in Figs. 1, 2 and 3 respectively. Sand that was available locally, close to the river side, and debris free was utilized as fine mixture, and it was filtered through 4.75 mm sieves while the crushed stone was used as coarse aggregate having 20 mm in size for this research work. The physical properties were carried out on aggregates, as shown in Table 2. Figs. 4 and 5 depict the analysis of sieve curves for fine aggregates and coarse aggregates in line with ASTM C136 [43]. For this experiment, fresh and potable water was used.

2.2. Mix proportions of high strength concrete

Using the ASTM C192/C192M-19 [44] code, seven concrete mixtures, shown in Table 3, were made for this experiment. As a cementitious ingredient, same quantities of CSA, calcined clay (CC), and metakaolin (MK) were used to substitute Portland cement (PC) at percentages of 0%, 1%, 2%, 3%, 4%, 5%, and 6% separate, 2%, 4%, 6%, 8%, 10% and 12% combined two materials as well as 3%, 6%, 9%, 13%, 15%, and 18% combine three materials in the production of concrete. One batch of concrete contained no PC replacement material, whereas the six contained 1%, 2%, 3%, 4%, 5% and 6% of MK, six mixtures possess 1%, 2%, 3%, 4%, 5% and 6% of CC, six mixtures were prepared with 1%, 2%, 3%, 4%, 5% and 6% of CSA, six mixtures were conducted using 2%, 4%, 6%, 8%, 10% and 12% of MK and CC together, and remaining mixtures were made of 3%, 6%, 9%, 12%, 15%, and 18% of PC substituted with MK, CC, and CSA combined, respectively. In this investigation, all concrete mixtures were made to have a compressive strength of around 80 MPa at a water-binder ratio of 0.35. A total of 465 samples of high-strength concrete (cylinders, prisms and cubes) were casted, demoulded, and cured for 28 days in water.

Table 1
Chemical Composition of PC, MK, CC, and CSA.

Materials	Oxides (%)							Physical Property
	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	SO_3	LOI	Specific Gravity
CSA	44.50	16.23	15.18	3.40	0.38	0.71	9.78	1.42
CC	57.58	21.40	15.22	2.86	0.98	–	1.20	2.26
MK	62.18	21.67	3.01	3.22	1.04	0.78	–	2.60
PC	20.78	5.11	3.17	60.22	0.18	2.86	2.45	3.13

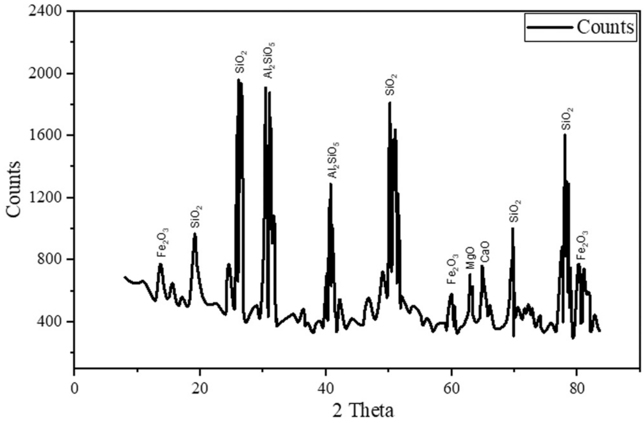

Fig. 1. XRD of CSA.

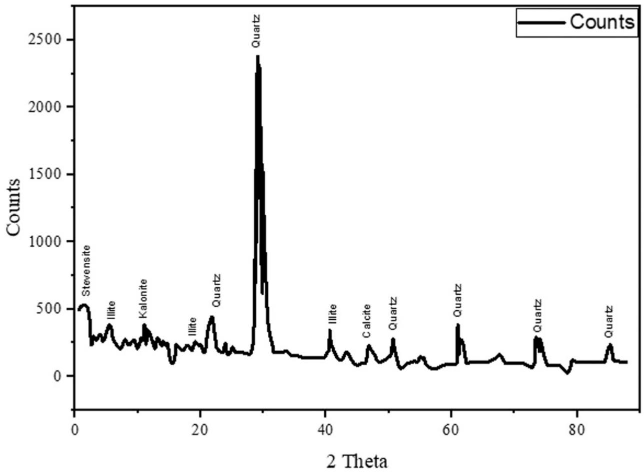

Fig. 2. XRD of MK.

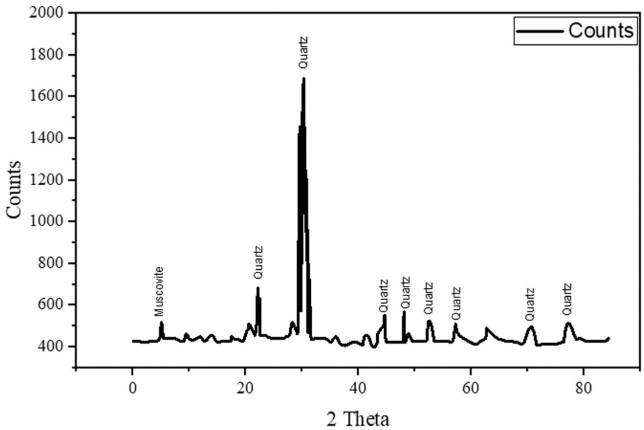

Fig. 3. XRD of CC.

Table 2
Physical Properties of the aggregate.

Property	FA	CA
Fineness Modulus	2.35	-
Specific Gravity	2.60	2.68
Absorption (%)	1.54	0.77
Bulk density (kg/m^3)	1780	1640

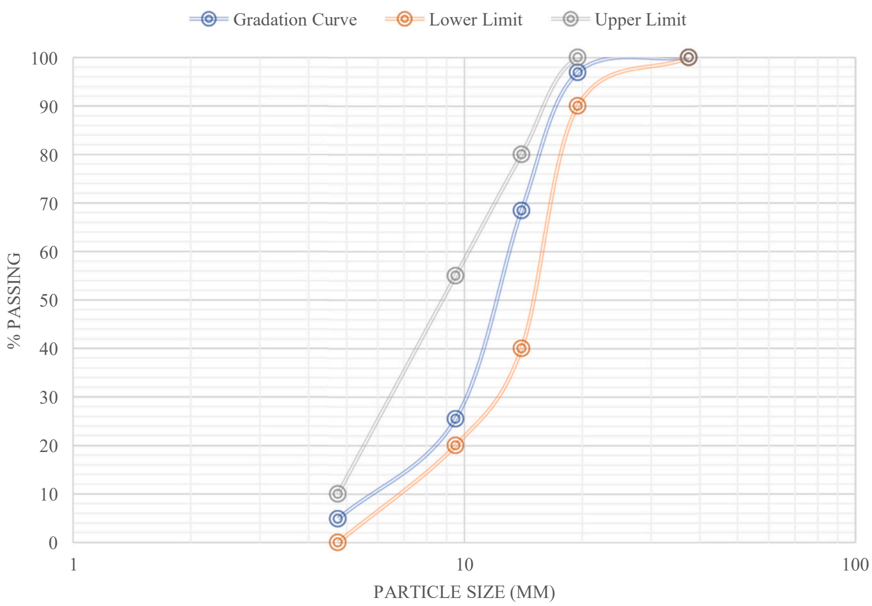

Fig. 4. Grading Curve of Coarse Aggregates (CA).

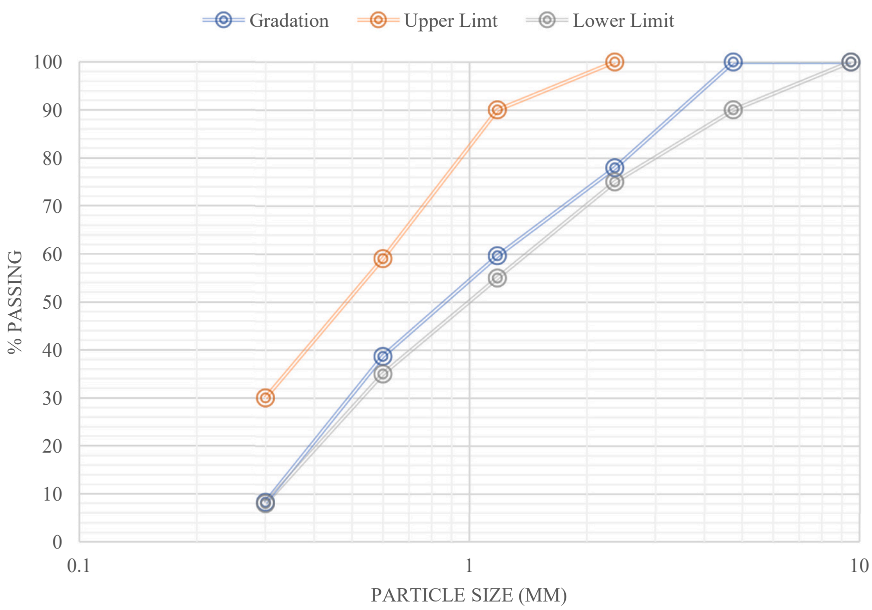

Fig. 5. Grading Curve of Fine Aggregates (FA).

Table 3
Mix Proportions of HSC.

Mix ID	Binders (%)				Components required for making 1 m^3 of HSC (kg)						
	PC	MK	CC	CSA	PC	MK	CC	CSA	CA	FA	Water
CM	100	0	0	0	595	0	0	0	1480	695	208
MK1	99	1	0	0	589.05	5.95	0	0	1480	695	208
MK2	98	2	0	0	583.10	11.90	0	0	1480	695	208
MK3	97	3	0	0	577.15	17.85	0	0	1480	695	208
MK4	96	4	0	0	571.20	23.80	0	0	1480	695	208
MK5	95	5	0	0	565.25	29.75	0	0	1480	695	208
MK6	94	6	0	0	559.30	35.70	0	0	1480	695	208
CC1	99	0	1	0	589.05	0	5.95	0	1480	695	208
CC2	98	0	2	0	583.10	0	11.90	0	1480	695	208
CC3	97	0	3	0	577.15	0	17.85	0	1480	695	208
CC4	96	0	4	0	571.20	0	23.80	0	1480	695	208
CC5	95	0	5	0	565.25	0	29.75	0	1480	695	208
CC6	94	0	6	0	559.30	0	35.70	0	1480	695	208
CSA1	99	0	0	1	589.05	0	0	5.95	1480	695	208
CSA2	98	0	0	2	583.10	0	0	11.90	1480	695	208
CSA3	97	0	0	3	577.15	0	0	17.85	1480	695	208
CSA4	96	0	0	4	571.20	0	0	23.80	1480	695	208
CSA5	95	0	0	5	565.25	0	0	29.75	1480	695	208
CSA6	94	0	0	6	559.30	0	0	35.70	1480	695	208
MK1CC1	98	1	1	0	583.10	5.95	5.95	0	1480	695	208
MK2CC2	96	2	2	0	571.20	11.90	11.90	0	1480	695	208
MK3CC3	94	3	3	0	559.30	17.85	17.85	0	1480	695	208
MK4CC4	92	4	4	0	547.40	23.80	23.80	0	1480	695	208
MK5CC5	90	5	5	0	541.50	29.75	29.75	0	1480	695	208
MK6CC6	88	6	6	0	523.60	35.70	35.70	0	1480	695	208
MK1CC1CSA1	97	1	1	1	577.15	5.95	5.95	5.95	1480	695	208
MK2CC2CSA2	94	2	2	2	559.30	11.90	11.90	11.90	1480	695	208
MK3CC3CSA3	91	3	3	3	541.45	17.85	17.85	17.85	1480	695	208
MK4CC4CSA4	88	4	4	4	523.60	23.80	23.80	23.80	1480	695	208
MK5CC5CSA5	85	5	5	5	505.75	29.75	29.75	29.75	1480	695	208
MK6CC6CSA6	82	6	6	6	487.90	35.70	35.70	35.70	1480	695	208

2.3. *Testing methods*

2.3.1. *Slump testing*

The slump testing was performed to determine "the workability of fresh concrete." The slump was measured instantly following mixing as per BS EN 12350–2 methods [45].

2.3.2. *Hardened properties*

The failure stress of materials assessed under uniaxial compressive load and was determined using compression strength testing according to the BS EN 12390–3 procedure. [46]. Following BS EN 12390–6 [47], cube samples (100×100×100 mm) were made as well as the split tensile test on cylindrical samples (100×200 millimetres) were performed. Additionally, the flexural test was conducted on prims of concrete (100×100×500 mm) subjected to a single concentrated load BS EN 12390–5 code [48]. For each proportion, three concrete samples were cast at Seven, Twenty-eight, and ninety days, respectively. Nonetheless, the water absorption was measured using 100×100×100 mm cubes in accordance with BS 1881–122 [49] and concrete's density was measured after twenty-eight days using BS EN 12390–7 [50], respectively. Furthermore, the porosity analysis was conducted via the vacuum saturation method. On the 28th day, the specimens of HSC were put in a vacuum desiccator for this experiment. This investigation aims to ascertain the proportion of air spaces present in HSC specimens, since this factor might directly impact their longevity efficiency. Three HSC specimens (100 mm×50 mm) of HSC were subjected to desiccation in an oven for a duration of 72 hours, or until a stable weight was achieved. Subsequently, every specimen was cooled, and its mass on drying was noted. The specimens were fully immersed in a vacuum chamber for 72 hours, until every bubble was no longer observable. The experimental setup for testing is indicated in Fig. 6.

3. Results and discussions

3.1. *Workability of high strength concrete*

To assess the workability of freshly produced mixed concrete, the slump test was conducted. The slump values for various mixed samples of HSC, including several concentrations of CC, MK, and CSA, alone and together as SCM, are presented in Fig. 7. However, concrete can be mounted into any desired shape in its fresh structure due to its workability. Besides, MK, CSA, and CC have an adverse effect on workability. The results show that when the MK, CC, and CSA contents increase, the concrete workability decreases. The fresh concrete workability was recorded as very low by 25 mm at 18% of MK, CC, and CSA together as a substitute for cement, while the

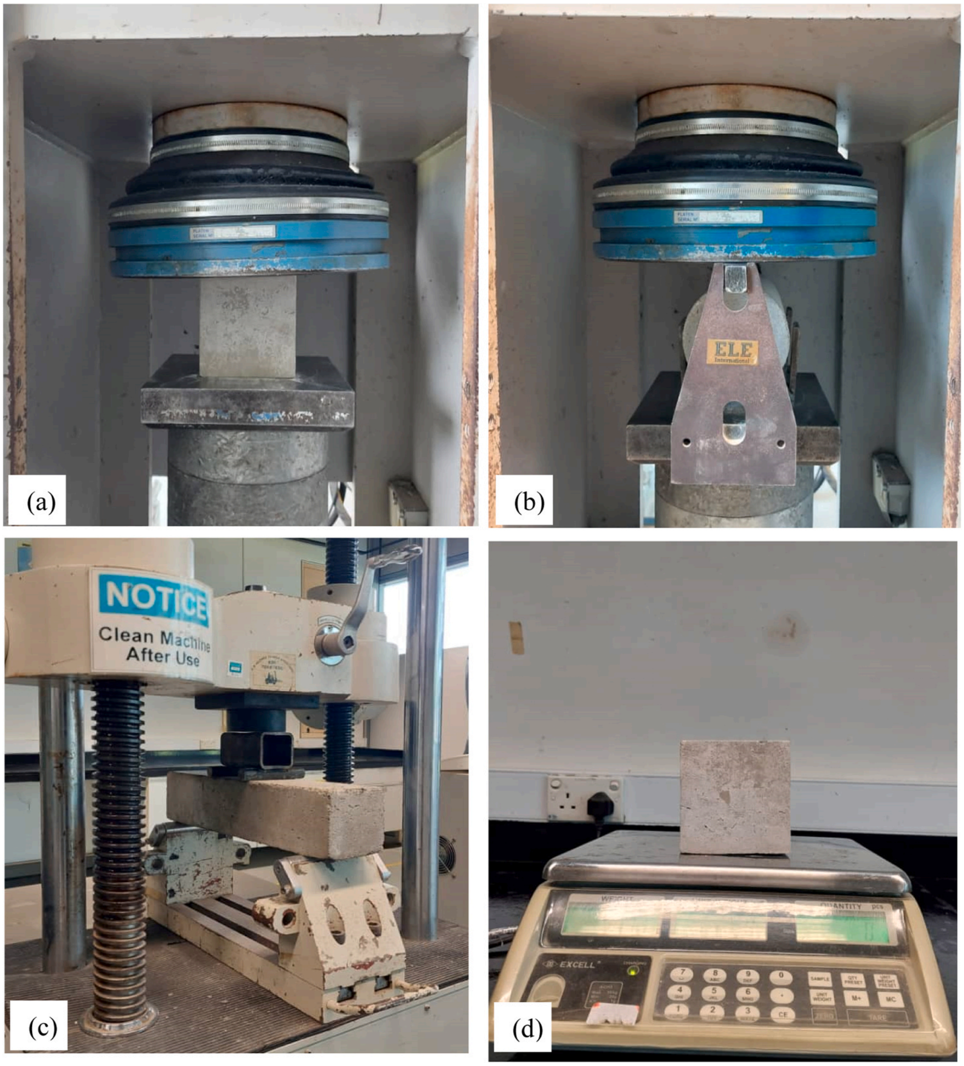

Fig. 6. Experimental Setup for (a) Compressive Strength Test, (b) Splitting Tensile Strength Test, (c) Flexural Strength Test, and (d) Dry Density Test.

fresh concrete's flow was reported as very high by 72 mm at 0% of MK, CC, and CSA as SCM. With the addition of MK, CC, and CSA as SCM in concrete, the flow of fresh concrete decreased. This may be because MK, CC, and CSA have a finer texture than PC, which means that it absorbs more water as the amount of MK, CC, and CSA in high-strength concrete rises. Porosity of MK, CC, and CSA particles relative to natural fine aggregates and cement is one of the potential causes of reduced workability of HSC because porous substance allows concrete to absorb water rapidly, leaving less contents of free water in the mixtures for its workability properties [51,52]. According to Rid et al. [15] the use of MK, CC, and CSA rises in high-strength concrete, which lowers the workability of HSC. Singhal et al. [53] and Ashish [54] both noted a similar outcome.

3.2. Compressive strength of high-strength concrete

The influence of MK, CC, and CSA as SCM on concrete's compressive strength of HSC after 28 days is displayed in Fig. 8. However, the compressive strength was improving when the replacement concentration of MK, CC and CSA rises individually up to 6% as SCM in HSC at 28 days consistently. Besides, the combined influence of MK and CC up to 10% as SCM was providing optimum strength of HSC for 28 days. Moreover, the optimum strength observed was 93 MPa at 9% of MK, CC, and CSA as SCM, and the minimum value was recorded by 78 MPa using 18% of MK, CC, and CSA as SCM after 28th days. The compressive strength was enhanced by incorporating up to 9 percent when MK, CC, and CSA together were used as SCM. This enhancement in strength is related to the fineness particles of CC, CSA and MK which plugs the micropores, in comparison to the other HSC constituents and make the concrete dense [55,56]. The cement hydration decreases over 9% of MK, CC, and CSA as SCM because these materials have a lower cementing feature than PC

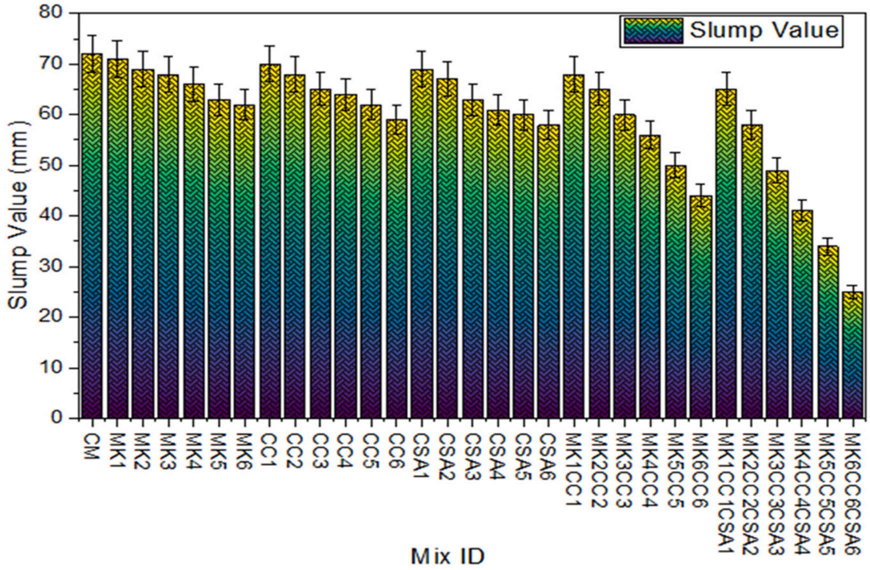

Fig. 7. Workability of green Concrete.

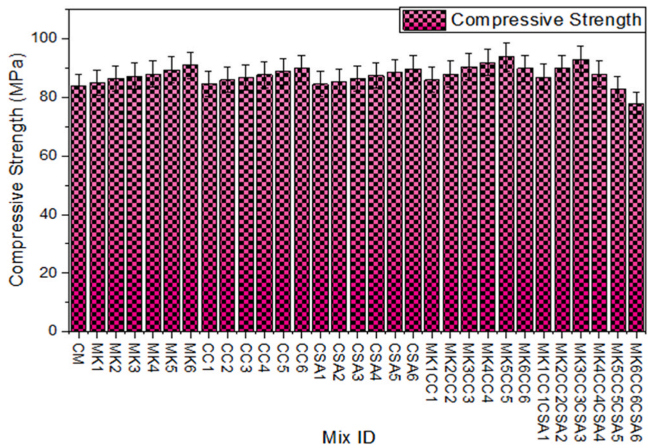

Fig. 8. Compressive Strength of HSC.

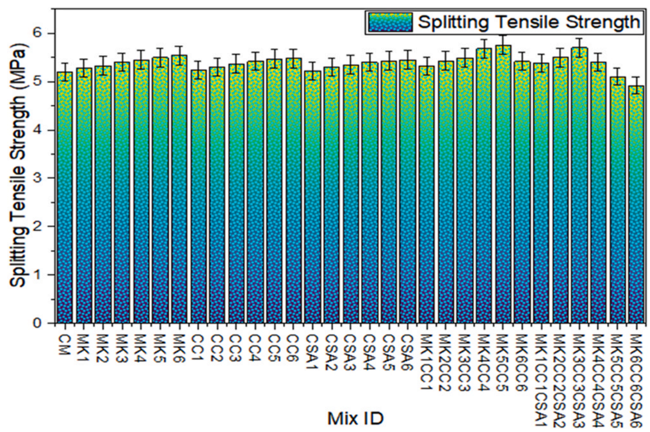

Fig. 9. Splitting Tensile Strength of HSC.

therefore, the compressive strength is going to reduced. To produce an appropriate concrete structure, 10% of GSA was substituted with cement, as most prior works [57–59], reported 20% substitution of ternary (SCBA&RHA) concrete increased 20% of compressive strength. That research also observed an increase in strength when ternary cementitious elements were used in concrete. However, the optimal volume percentage is essential to composite's compressive strength, which is dependent on filler effect of pozzolanic, reactivity, and the pace at which cement starts hydrating. [60]. Similar observations were conducted by Rid et al. [15].

3.3. Splitting tensile strength

The cylindrical specimens of HSC combinations were utilized to test the splitting tensile strength including CC, MK, and CSA alone and together as SCM, as shown in Fig. 9. Although the splitting tensile strength increased as MK, CC, and CSA substitution concentrations increased steadily over the course of 28 days, each reached 6% as SCM in HSC. Furthermore, the combined impact of MK and CC was up to 10% as SCM supplied HSC with its maximum strength for 28 days. Moreover, the experimental results showed that after twenty-eight days of constant use, the splitting tensile strength increased by 5.70 MPa at 9% of MK, CC, and CSA as SCM, while the minimum values reported were 4.92 MPa at 18% of MK, CC, and CSA as SCM. It is noticed that the split tensile strength is marginally increased with the accumulation of MK, CC, and CSA as SCM up to 9% at a 28-day curing period. This rise in strength is caused by the higher specific surface areas of MK, CC, and CSA than those of PC, which extend the concrete's interfacial transition zone to a particular point, further inclusion of MK, CC, and CSA in HSC, the strength begins to decline as a result of the lesser pozzolanic reaction of MK, CC, and CSA in the HSC combination with respect to the hydration reaction of PC [22,52,57]. On the same way, the increase in splitting tensile strength may have been caused by the cement's ongoing hydration reaction as well as the pozzolanic reaction of the MK, CC, and CSA as SCM over time. More hydration products were formed as a result, and the microstructure also became denser. As MK, CC, and CSA are added to the HSC mix, the calcium hydroxide needed to make the final product begins to decrease strength due to the diluting impact these additives have on PC. Similar findings were reported in the 10% CSA blend in concrete, which increased tensile strength [57]. A likewise work was also done by Bheel et al., [61]. The optimal cement replacement for the split tensile strength is therefore 10% TCM. A relation $ft = 1.1037e^{0.0213fcu}$ should be considered for developing a link between the tensile and compressive strengths of concrete when PC is replaced with MK, CC, and CSA. In after mentioned relation the ft represents concrete's tensile strength and concrete's compressive strength is denoted by f_{cu}. The relationship demonstrates how increasing compressive strength increases indirect tensile strength. The concrete's tensile strength enhancement was also noticed by Prakash et al., [62]. A basic reference to design standards show that split tensile strength should be correlated to the square root of compressive strength, e.g., $ft = k1\sqrt{fc}$. Besides, the k1 factor of HSC ranges from 0.55 to 0.59. Furthermore, there is a proportionality between splitting tensile strength and compressive strength, as seen in Fig. 10. When one of these properties is identified, the formulas in Fig. 10 can be utilized to evaluate compressive strength or splitting tensile strength.

3.4. Flexural strength

The effect of MK, CC, and CSA individually and together as SCM on the concrete's flexural strength is shown in Fig. 11. However, the flexural strength was improving when the replacement concentration of MK, CC and CSA rises individually up to 6% as SCM in HSC at 28 days consistently. Besides, the combined influence of MK and CC up to 10% as SCM was providing optimum strength of HSC for 28 days. According to the findings, using 9% MK, CC, and CSA as SCM in the concrete mixture increased flexural strength by 6.15 MPa, while using 18% MK, CC, and CSA as SCM resulted in a minimum value of 5.46 MPa after 28 days. The experimental results show that the flexural strength of HSC mix increased when the accumulation of CSA, MK and CC to 9% together as SCM and further addition of it, the strength gets decline. This enhancement in flexural strength is related to the fineness particles of mineral admixtures which seals the voids left by the HSC components which improved the interfacial transition zone of HSC and make denser. After addition of 9% MK,

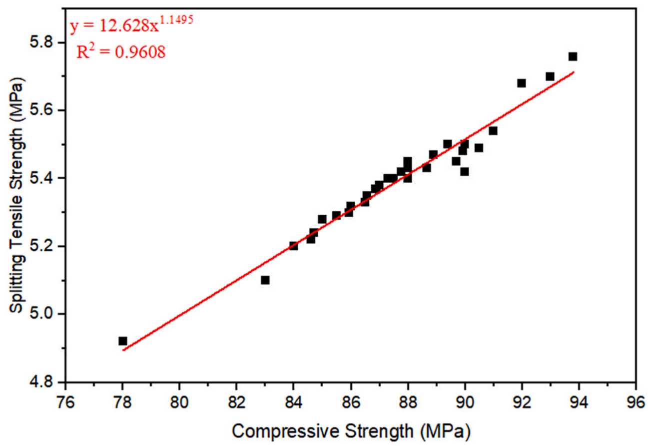

Fig. 10. Correlation between compressive strength and splitting tensile strength of HSC.

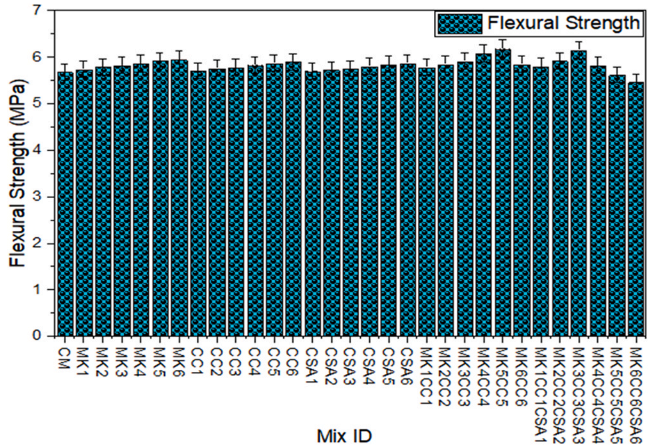

Fig. 11. Flexural Strength of High-Strength Concrete.

CC and CSA, the diluting impact of MK, CC, and CSA is causing the strength to decrease, which may be accompanied by an insignificant quantity of calcium hydroxide in HSC [52,57]. It also reveals that the addition of MK, CC, and CSA as SCM in the concrete mixture does not negatively affect the responses related to hydration unless a blend containing 18% MK, CC, and CSA as replacement for PC is applied. The flexural strength of HSC did not considerably increase with the addition of 18% TCM, as shown in Fig. 11. This observation might be attributed to MK, CC, and CSA as SCM dilution on the PC, resulting in the fact that the interface's transition zone was not enhanced, affecting the long-term flexural strength [60]. Jhatial et al. [63], reported that, the pozzolanic reaction cost 22% of overall Calcium hydroxide formed by hydration process of cement. Pozzolanic materials, like FA, have a relatively low pozzolanic activity in the early stages. [64]. More pozzolanic content, however, might reduce compressive strength, as noted by Bheel et al. [65, 66] and Memon et al. [67], This is due to the restricted Calcium hydroxide from the calcium silicate reactions [13]. Calcium hydroxide for the pozzolanic reaction is boosted when MK, CC, and CSA are added into the concrete mix. This allows for a higher replacement content. Using MK, CC, and CSA together is advantageous because they utilize unreacted free Calcium hydroxide and create secondary C-S–H gels, which reinforce concrete and allow for a larger PC content [15]. A basic reference to design standards shows that flexural strength should be correlated to the square root of compressive strength, e.g., $f_{lex} = k1\sqrt{fc}$. Besides, the k1 factor of HSC ranges from 0.61 to 0.64. Furthermore, Fig. 12 illustrates the relationship between compressive and flexural strength. The graphs show that there is a strong linear relationship between these features. Nevertheless, the relationship between compressive strength and flexural strength is more linear. However, the two equations in Fig. 12 can be utilized to estimate the parameters of concrete mixtures.

3.5. Water absorption

Following the method outlined in BS 1881–122, concrete mixture's water absorption was measured and displayed in Fig. 13. At twenty-eight days, the water absorption of HSC blended with MK, CSA, and CSA separate and combined was replaced by PC, as shown in Fig. 13. However, the concrete's water absorption decreases as MK, CSA, and CSA replacement percentages separate or combined in concrete increase. Although the water absorption observed at 3%, 6%, 9%, 12%, 15%, and 18% of CSA, CC, and MK as SCM was 3.42%, 3.08%, 2.89%, 2.56%, 2.25%, and 1.79%, which is substantially lesser than the control mixture at 28 days respectively. It has been shown that a decrease in water absorption will result with the addition of more CC, CSA, and MK cementitious materials to concrete. Due to the higher specific surface area of CC, CSA, and MK, which is connected with the reduction in water absorption, these materials absorb more water than the other constituents of concrete. This phenomenon was noticed by Bheel et al., [68], who found that when concrete's percentages of RHA replaced with PC and sand replaced with CBA combined increased, water absorption decreased. Keerio et al., [69] conducted similar experiments and found that replacing some of the SF in concrete with PC and some of the sand with glass powder growths reduced the amount of water the concrete absorbed.

3.6. Dry density

Fig. 14 illustrates the concrete's bulk density when blended with MK, CC, and CSA separate and combined as SCM after 28 days. With the control mix and concrete combined with MK, CC, and CSA as substitution for PC, it was noticed that curing age has direct proportionality with bulk density. When concrete hardens, it is anticipated that water will be consumed in hydration, and the resulting product will occupy less space than the source water and cement [70]. The dry density of HSC is dropping when the concentration of MK, CC and CSA rises separate in HSC for 28 days correspondingly. After 28 days, the ideal density of 2368 kg/m3 was attained with 0% MK, CC, and CSA as SCM, while the minimum density was determined with 18% MK, CC, and CSA as SCM. It has been observed that the bulk density decreases as the proportion of mineral admixtures increases. This drop in dry density is due to the mineral admixtures' specific gravity that is lower than cement as shown in Table 1. This outcome is consonant with Bheel et al. [71] where, after 28 days,

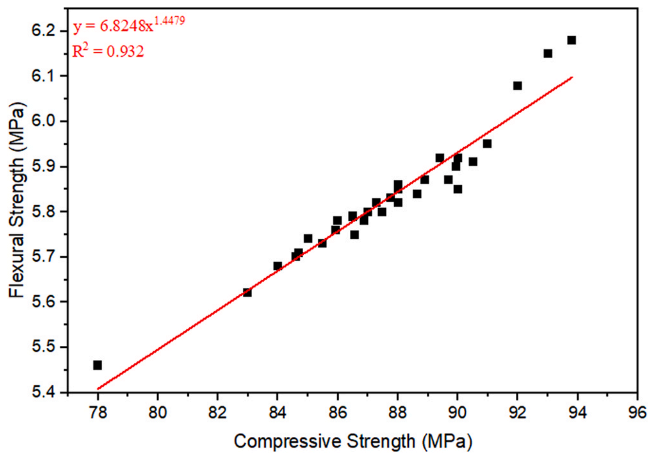

Fig. 12. Correlation between compressive strength and flexural strength of high-strength concrete.

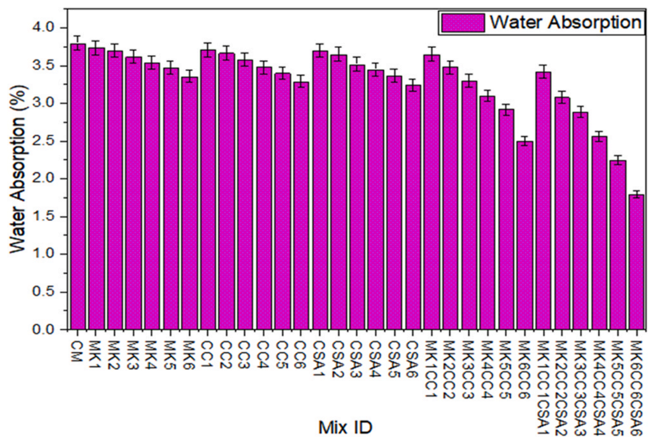

Fig. 13. Water Absorption of HSC.

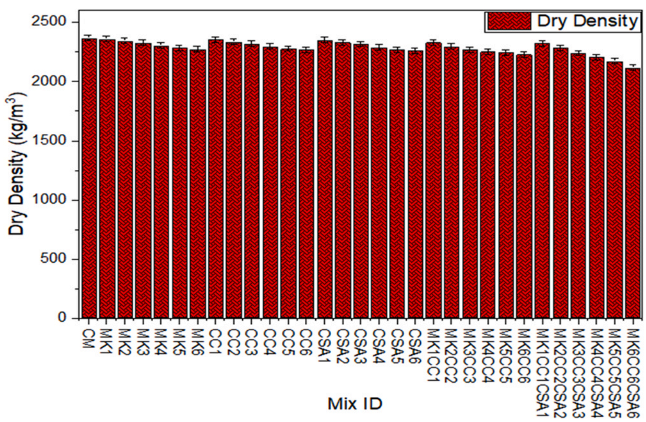

Fig. 14. Dry Density of HSC.

the density of concrete decreases with increasing tile powder and marble powder content. According to Raza et al. [72], the density of concrete decreased after 28 days as the quantity of wood - based ash increased.

3.7. Porosity of HSC

The Porosity of HSC blended with MK, CSA, and CSA separate and combined was replaced by PC at 28 days, as shown in Fig. 15. However, the concrete's porosity decreases as MK, CSA, and CSA replacement percentages separate or combined in concrete increase. Although the porosity of HSC observed at 3%, 6%, 9%, 12%, 15%, and 18% of CSA, CC, and MK as SCM was 14.89%, 27.66%, 40.43%, 45.74%, 51%, and 55.32%, which is substantially lesser than the control mixture at 28 days respectively. Research has shown that using MK, CSA, and CC as SCM increases in the mixture, resulting in a reduction in the porosity of HSC. Moreover, the CC, CSA, and MK have a greater fineness compared to the other constituents of HSC, causing a decrease in the porosity of HSC. This allows them to occupy the tiny pores of the combination. Fig. 15 demonstrates that the inclusion of CC, CSA, and MK as SCM in HSC leads to a substantial reduction in pore size in the HSC composition. Khan [73] suggests that replacing 8–12% of PC with SF in concrete can optimise CS and decrease concrete pores. Chindaprasirt and Rukzon [74] found that including approximately 20% of RHA as SCM in concrete leads to a decrease in porosity. Panesar and Zhang [75] asserted that using cement substitutes in concrete reduces its porosity. Researchers have found that adding SCMs to concrete at a level lower than 20% makes it less porous than the standard mix, which may be attributed to the chemical and physical effects of SCMs. An analogous pattern may be seen for every kind of PC alternative [76–82].

4. Sustainability analysis of high-strength concrete

4.1. Embodied carbon and eco-strength efficiency

To identify the concrete's embodied carbon dioxide, an impact assessment for environment is performed for all related concrete mixtures combining various substitutes of PC with MK, CC, and CSA as SCM integrated in the mixture. The values for embodied carbon over all concrete elements are shown in Table 4, which were taken from literature. For all concrete mixes, Eq. (1) [83] is employed to calculate the embodied carbon. The symbols E_e, CO_{2e}, W_i and i in Eq. (1) denotes unit volume weight (kg/m3) and overall embodied carbon for each concrete mixture. Furthermore, symbols like E_i and CO_{2i} represent the embodied carbon of the physical ingredients given in Table 4.

$$CO_{2e} = \sum_{i=1}^{n}(W_i \times CO_{2i}), \quad (1)$$

The embodied carbon of each mix, in addition to the design mix, was evaluated to assess concrete's environmental impact mixed with MK, CC, and CSA. The results are shown in Fig. 16 along with a comparison to the reference mix. Fig. 16 depicts Portland cement's significant carbon footprint in comparison to MK, CSA, CC, CA, FA, and water. Fig. 16 shows the embodied carbon of concrete compositions with several PC substitutes for MK, CC, and CSA separate and combined in HSC. Fig. 16 also represents that PC release the more carbon, followed by coarse and fine material. However, the impact of MK, CC, and CSA as a substitute for PC in the concrete mixture cannot be observed on the graph, indicating that their proportion to carbon intensity is negligible. Eq. (1) was applied to find out the amount of carbon of all concrete mixtures based on the data shown in Fig. 16. Table 4 reveals that the partial substitution of MK, CC, and CSA with PC till 18% significantly reduces the amount of carbon dioxide emitted by concrete mixtures. The "emitted carbon" for mixtures of concrete having 3%, 6%, 9%, 12%, 15%, and 18% of MK, CC, and CSA as substitutes for PC is 1.96%, 3.93%,

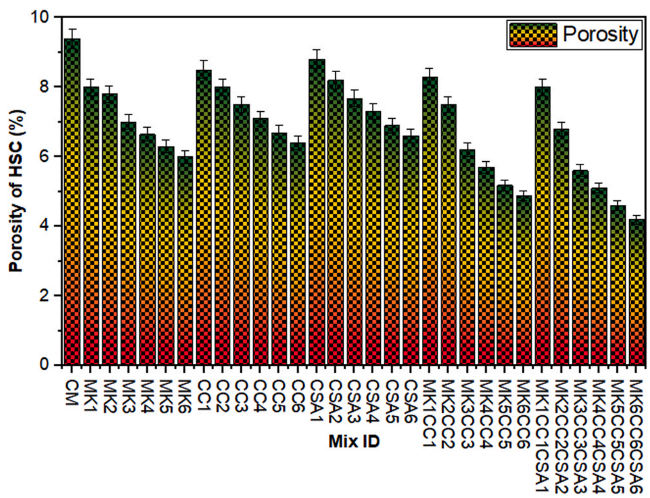

Fig. 15. Porosity of HSC.

Table 4
Embodied Carbon value of High-Strength Concrete Components.

Components	Embodied carbon ($kgCO_2/kg$)	References
Portland cement	0.93	[84]
Fine aggregates	0.0139	[85]
Coarse aggregates	0.0408	[85]
CC	0.23	[86]
MK	0.33	[87]
CSA	0.172	[57]
Water	0	[88]

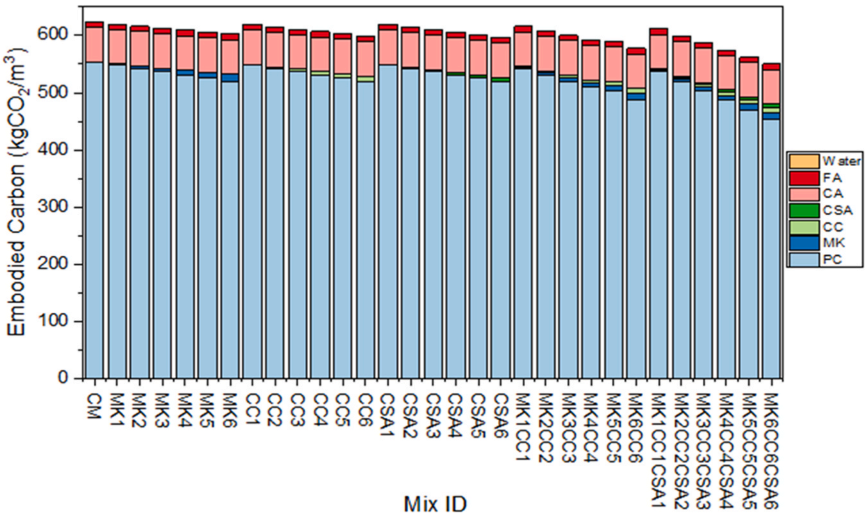

Fig. 16. Embodied Carbon of HSC.

5.89%, 7.85%, 9.82%, and 11.78% which is subsequently below than reference concrete. These results indicate that substituting MK, CC, and CSA separate and combined for cement reduces the carbon emissions of concrete mixtures.

Moreover, the eco-strength efficiency of concrete is evaluated using Eq. (2) [52], considering the compressive strength:

$$Eco-strength \quad Efficiency = \frac{Average28-Days \quad Compressive \quad Strength \quad of \quad Concrete}{Total \quad Embodied \quad Carbon \quad of \quad Concrete} \tag{2}$$

To better comprehend the impact on the environment of concrete, including MK, CC, and CSA, the eco-efficiency strength is calculated and presented in Fig. 17. However, the eco-strength efficiency was improving when the replacement concentration of MK, CC and CSA rises individually up to 6% as SCM in HSC at 28 days consistently. Besides, the combined influence of MK and CC up to 10% as SCM was providing optimum eco-strength efficiency of HSC for 28 days. Almost every concrete mix including 9% MK, CC, and CSA

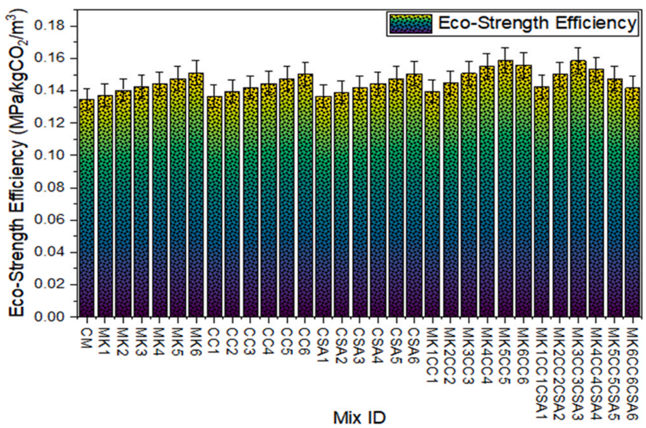

Fig. 17. Eco-strength Efficiency of High Strength Concrete.

as SCM exhibit greater eco-efficient strengths than that of the reference mix. Furthermore, 15% of MK, CC, and CSA as replaced with PC in HSC have slightly less eco-efficient strength, but 3%, 6%, 9%, and 12% of MK, CC, and CSA as replacements have higher eco-efficient strength than the reference mix. In addition, just at 18% level of replacement of MK, CC, and CSA as replaced with PC in HSC, the eco-efficiency strength is less than the strength of the reference mix. However, the concert's maximum eco-efficient strength is 0.158 MPa/$kgCO_2/m^3$ at 9% of MK, CC, and CSA as SCM, which is greater than the reference concrete's 0.134 MPa/$kgCO_2/m^3$ by 0.024 MPa/kgCO2/m3 and is nearly 17.74% of the eco-efficient strength of the reference concrete.

5. Conclusion

High-strength concrete's fresh, hardened, and embodied carbon as influenced by CC, MK, and CSA as SCM. Based on the findings of the experiments, one can come to the following conclusions:

- The application of CC, MK, and CSA separate or combined as cementitious materials in concrete reduces the workability of all mixtures because CC, MK, and CSA as SCM absorb more water. Nonetheless, because all concrete mixes containing 18% CC, MK, and CSA have a slump greater than 20 mm, they are appropriate for structural applications.
- After 28 days of curing, the concrete's compressive strength, split tensile strength, and flexural strength improved by 10.71%, 9.62%, and 8.27%, respectively, with 9% CC, MK, and CSA as SCM inclusion. The increase in strength could be attributed to the pore-filling impact of CC, MK, and CSA, as well as the SCM's pozzolanic response. Yet, at higher SCM dosages (i.e., greater than 9%), the mechanical characteristics fell dramatically because to the SCM's diluting effect on the PC.
- As the percentages of CC, MK, and CSA used as SCM in the hardened concrete increased after 28 days, the concrete became less porous and absorbed less water. Because their surface areas are the highest, CC, CSA, and MK absorb more water than the other constituents of concrete.
- Increases in the proportions of CC, MK, and CSA used as SCM in high-strength concrete led to a decrease in the material's dry density after 28 days. Ashes have a lower specific gravity than cement, which contributes to this reduction.
- The porosity of HSC is getting reduced while the concentration of CC, MK, and CSA as SCM separate and together increases in the mixture. This reduction in porosity is associated to the fineness particles of SCM which seals the micro pores of HSC that results in reducing porosity of HSC.
- The sustainability evaluation of the concrete samples reveals that SCM can reduce concrete's emitted carbon for CC, MK, and CSA as compared to the control samples. Using 18% CC, MK, and CSA as SCM, concrete mixes have a carbon emission reduction of roughly 11.78% compared to a control mix created with PC alone.
- The usage of 9% MK, CC, and CSA as SCM in concrete has been suggested since it yields good results for structural purposes.

CRediT authorship contribution statement

Tag-eldin Elsayed Mohamed: Conceptualization, Formal analysis, Supervision, Writing – review & editing. **Almujibah Hamad R.:** Conceptualization, Data curation, Formal analysis, Writing – review & editing. **Ghoto Asghar Ali:** Data curation, Writing – original draft, Formal analysis, Methodology. **Abbasi Suhail Ahmed:** Conceptualization, Data curation, Formal analysis, Writing – review & editing. **Bheel Naraindas:** Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. **Chohan Imran Mir:** Data curation, Investigation, Writing – original draft, Validation. **Benjeddou Omrane:** Data curation, Formal analysis, Software, Visualization. **Gonzalez-Lezcano Roberto Alonso:** Funding acquisition, Supervision, Writing – review & editing. **Ahmad Mahmood:** Conceptualization, Data curation, Formal analysis, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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