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The Exploration of the Characteristics of Concrete Incorporating Ultrafine Coal Bottom Ash and Spent Garnet

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ABSTRACT

The building sector is a significant contributor to global carbon emissions, primarily due to the production of cement, a crucial construction material. The need for sustainable building practices has spurred research into alternative materials to traditional cement and sand. Two such materials, ultrafine coal bottom ash (uCBA) and spent garnet (SG), have shown potential as substitutes for cement and fine aggregate, respectively. This research examines the effectiveness of uCBA as a partial replacement for cement and SG as a partial replacement for fine aggregate in concrete, at varying levels of 3%, 6%, and 9% for uCBA and 10%, 20%, and 30% for SG. Initially, the chemical composition analysis was conducted using an X-ray fluorescence spectrometer (XRF), and the particle morphology of uCBA, OPC, and SG was examined through field emission scanning electron microscopy (FE-SEM). Then, the study evaluates the performance of these materials based on slump value, compressive strength, and splitting tensile strength, with specimens undergoing 28, 56, and 90-day curing periods. Results indicate that integrating uCBA and SG in concrete at levels of 3% and 10%, respectively, enhances compressive and splitting tensile strength while decreasing environmental impact. Moreover, workability improves with higher substitution levels. Overall, this research indicates that uCBA and SG hold great potential as replacements for cement and fine aggregate in concrete, providing a means to mitigate the environmental impact of construction.

1. Introduction

Concrete is a widely used construction material that has been used for centuries due to its durability, strength, and versatility. It is composed of cement, aggregates, water, and sometimes

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additives that are mixed together to form a paste that hardens and binds the aggregates into a solid mass. In recent years, there has been a growing interest in developing sustainable and eco-friendly concrete that can reduce the environmental impact of construction. This is due to the use of cement in concrete continues to pose environmental and performance-related challenges. Cement production is energy-intensive and contributes to significant carbon dioxide emissions, leading to climate change [1]. While, the use of fine aggregate in concrete production can have a significant impact on the environment, particularly through its contribution to the depletion of natural resources and the emission of greenhouse gases. Fine aggregate is extracted from rivers, beaches, and other natural sources, causing disruption to ecosystems and loss of biodiversity [2]. Moreover, the high demand for fine aggregate in construction has led to illegal sand mining and unsustainable practices in some areas, exacerbating environmental issues. As a result of that, the growing demand for sustainable building materials has prompted the exploration of alternative materials to traditional cement and fine aggregate in construction. Ultrafine coal bottom ash (uCBA) and spent garnet (SG) are two such materials that have shown promise as replacements for cement and fine aggregate, respectively [3,4].

Coal bottom ash (CBA) is produced from the unburnt matter of coal during combustion [5] and tends to have a coarser and rougher surface texture compared to FA [6,7]. Thus, it constitutes 10%-20% of the coal ash generated during the coal combustion process [8]. However, while fly ash (FA) is commonly utilized in the production of pozzolanic Portland cement, CBA is not widely used [5,9]. Singh *et al.,* [10] stated, the use of ground CBA has been found to enhance compressive strength, while flexural strength is improved only when lower levels of ground CBA are employed. Nevertheless, the use of CBA as a cement replacement in concrete can enhance its compressive strength after 28 days [11], though it may decrease workability [6]. Additionally, CBA can decrease the hydration process and reduce salt penetrability in concrete, making it a potentially suitable alternative construction material [12]. Furthermore, the fineness of CBA plays a vital role in achieving better strength [4]. It is due to the ability of ultrafine material to fill the pores which affected the density and improved mechanical strength of the specimen [13]. Research has demonstrated that ultrafine CBA (uCBA) can enhance the compressive strength and durability of concrete while also decreasing its environmental impact [4]. Nevertheless, there has been limited investigation into the use of uCBA in concrete mixtures. This study aims to examine the efficiency of uCBA as a partial cement replacement in concrete mix.

SG, on the other hand, is a waste material generated during the cutting of hard materials and abrasive blasting [14]. It has been found to possess good mechanical properties and can be used as a partial replacement for fine aggregate in concrete [15]. Besides that, the rough, angular shape of the finer SG particles strengthens the link between paste and aggregate thus improves the pore structure which results in better mechanical properties [16]. In addition, incorporating SG into concrete displayed adequate workability. However, replacing fine aggregate with higher levels of SG led to a decrease in strength [17]. To address this issue, uCBA was included in the concrete mix alongside SG.

The goal of this research is to explore alternate solutions to the environmental impact of concrete production, which is a growing concern worldwide. The utilization of uCBA as partial cement replacement and SG as partial fine aggregate replacement presents an opportunity to tackle several environmental and construction-related challenges simultaneously. Enhancing the physical and mechanical strength of concrete is a critical aspect of construction, and this research has the potential to result in more robust and enduring structures. This study aims to demonstrate this by investigating the chemical composition and physical properties of uCBA and SG, as well as examining the mechanical properties and morphology of concrete mixtures containing uCBA and SG.

2. Materials and Methods

2.1 Materials

This study utilized Type-1 42.5N Ordinary Portland cement (OPC) that complied with MS 197-1:2014 [18]. Fine aggregate, which had passed through a 5 mm sieve, and a coarse aggregate with a maximum size of 20 mm were also used. The raw CBA was acquired from TNB Jana Manjung Sdn Bhd in Perak, while SG was obtained from Boustead Naval Shipyard Sdn Bhd, also located in Perak. To reduce their water content, all of the raw materials were oven-dried at 110±5°C for 24 hours upon delivery. This drying process ensured that the raw materials were sufficiently dry for the experiments to be conducted.

The dried CBA was ground into ultrafine particles in the subsequent step, as depicted in Figure 1, involving multiple grinding processes. On the other hand, SG only required to be sieved through a 1.18 mm sieve to eliminate undesirable components.

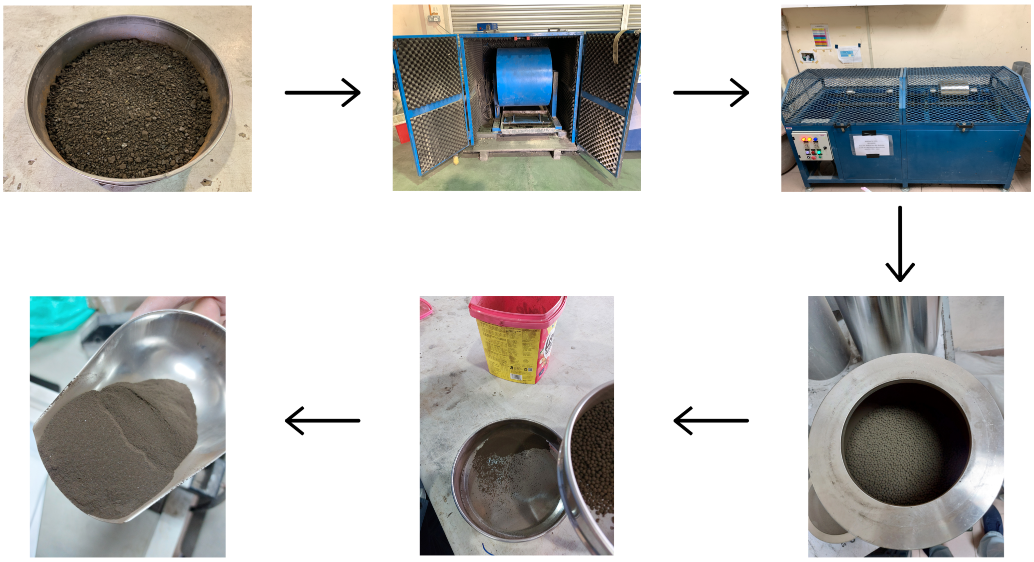


Fig. 1. The process of producing uCBA

The resulting uCBA and SG were placed in an airtight plastic bag and stored in a drum, the sample of uCBA an SG as shown in Figures 2a and 2b.

(a) (b)

Fig. 2. The sample of (a) uCBA and (b) SG

Table 1 and Table 2 display the physical properties and chemical composition of uCBA, OPC, SG, and fine aggregate used in this study. The chemical composition was determined using an X-ray fluorescence spectrometer (XRF). According to ASTM C618-23e1 [19], the chemical composition of uCBA satisfies the requirements for Class C ash, which has both pozzolanic and cementitious properties.

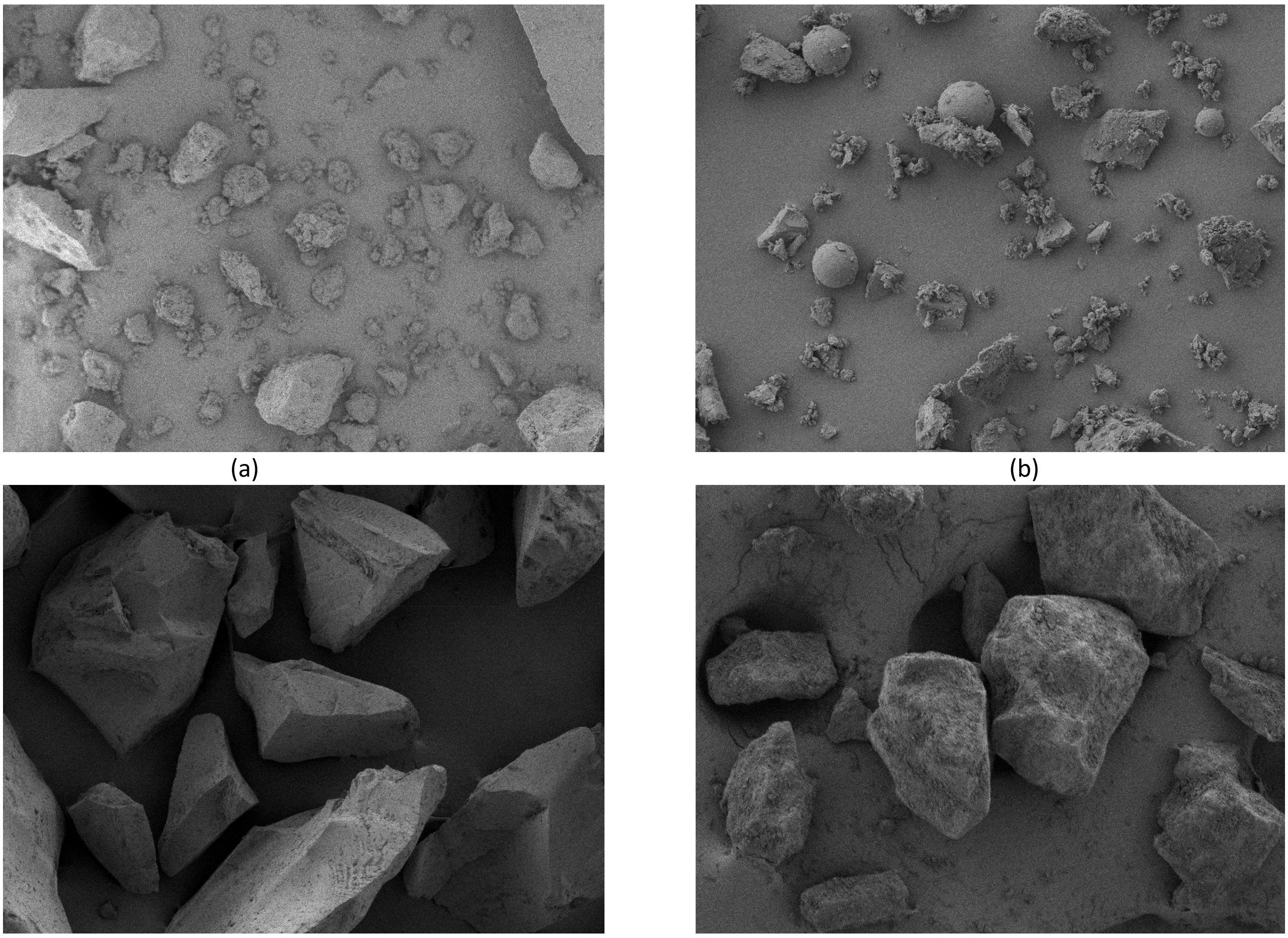
Table 1
Physical properties of uCBA, OPC, SG, and fine aggregate

Characteristic	uCBA	OPC	SG	Fine Aggregate
Specific gravity	1.57	3.14	4.1	2.59
Fineness Modulus	-	-	1.75	2.98
Water Absorption (%)	-	-	1.4	2.5

Table 2
Chemical composition of uCBA, OPC, SG, and fine aggregate

Oxide (%)	uCBA	OPC	SG	Fine Aggregate
CaO	11	64.5	2.47	-
SiO_2	26.2	18.5	29.2	88.3
Al_2O_3	10.2	5.19	17.5	6.14
Fe_2O_3	17.3	4.36	39.7	0.19
MnO	0.18	-	1.12	-
K_2O	0.69	0.39	-	0.17
Ti_2O_5	-	-	-	-
MgO	2.76	2.28	3.22	-
Na_2O	0.23	0.25	-	-
K_2O_2	-	-	-	-
TiO_2	0.71	0.2	1.23	0.29
P_2O_5	0.15	-	-	-
SO_3	0.43	3.81	-	-
BaO	0.12	-	-	-
SrO	-	-	-	-
ZnO	-	0.13	0.26	-
ZrO_2	-	-	0.55	0.38
B_2O_3	-	-	1.87	-

Figures 3a, 3b, 3c, and 3d reveal the particle morphology of uCBA, OPC, SG, and fine aggregate by using field emission scanning electron microscopy (FE-SEM), indicating that SG has a less porous and more angular shape than fine aggregate, which translates to lower water absorption due to its surface texture. Conversely, uCBA exhibits an irregular and angular shape with a rough surface texture. Despite the rough surface texture of uCBA resulting from its ultrafine particle size and primarily composed of carbon, uCBA is hydrophobic and oleophobic in nature. According to a study [20], the hydrophobicity of ultrafine fly ash (UFA) gradually increased with its presence.



(a) (b) (c) (d)

Fig. 3. The morphology by FE-SEM of (a) uCBA with 1000x magnify, (b) OPC with 1000x magnify, (c) SG with 500x magnify, and (d) fine aggregate with 500x magnify

Table 3 displays the initial and final setting time of the uCBA mix with OPC. The presence of uCBA in cement paste contributed to a decrease in the reactivity of the OPC, resulting in a slower setting due to the relatively low CaO content of the uCBA compared to the OPC.

Table 3
Setting time of uCBA mix with OPC

	Control	3% uCBA	6% uCBA	9% uCBA
Initial (min)	135	140	165	175
Final (min)	190	200	210	255

The results of particle size analysis, as presented in Figure 4, demonstrate that the uCBA used in this study had an average size of approximately 1.014 µm, with 90% of the particles measuring less than 1.257 µm. In comparison, OPC had an average size of around 15.236 µm, with 90% of the particles measuring less than 29.088 µm. This means that uCBA was finer than OPC.

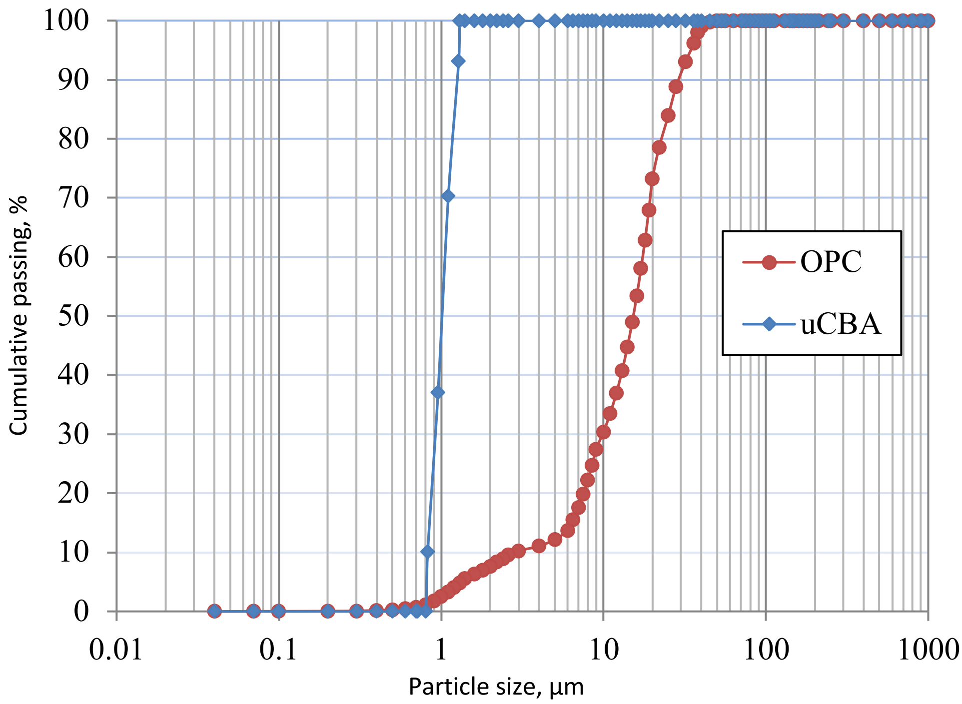


Fig. 4. Particle size distribution by cumulative passing of uCBA and OPC

While Figure 5 displays the data obtained from sieve analysis of SG and fine aggregate, which indicates that the particle size of SG was finer than fine aggregate. The fineness modulus of SG was 1.75, with 99.8% passing 600 µm, whereas the fine aggregate had a fineness modulus value of 2.98, with only 28% passing 600 µm as shown in Table 1. The sieve analysis was carried out by following BS 882:1992 [21] and BS EN 1260:2002+A1:2008 [22]

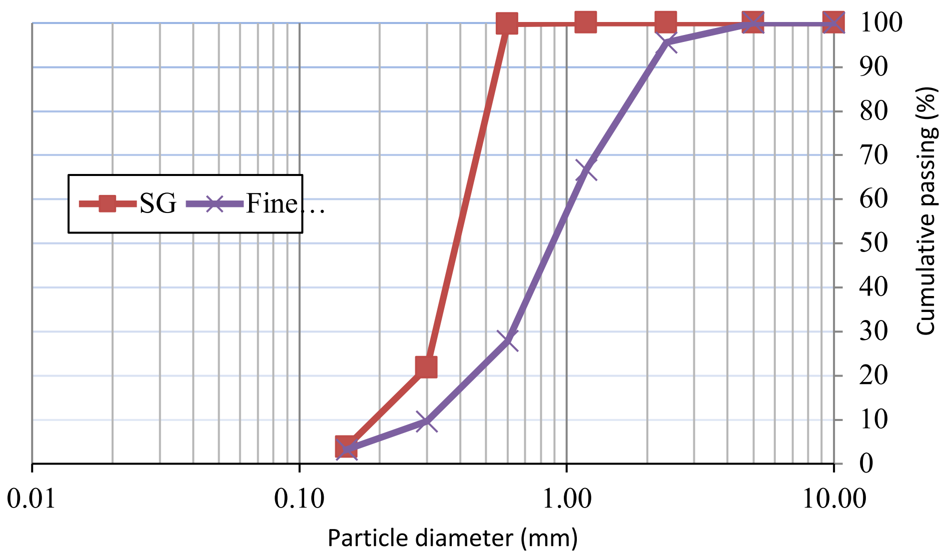


Fig. 5. Sieve analysis of SG and fine aggregate

2.2 Mixture Proportion

In this study, the mix ratios design was summarized in Table 4, adhering to the design of normal concrete mixes [23]. The aim was to achieve the desired concrete strength, with a concrete grade of 30 and a water-cement ratio of 0.54 being used in the design. In addition, uCBA was used as a cement replacement at rates of 3%, 6%, and 9%, while SG was used as a fine aggregate replacement at rates of 10%, 20%, and 30%.

Table 4
Mix proportion design (kg/m^3)

Mixes	Cement	uCBA	Coarse Aggregate	Fine Aggregate	SG	Water
M1	380	-	875	910	-	205
M2	368.6	11.4	875	819	91	205
M3	368.6	11.4	875	819	91	205
M4	368.6	11.4	875	819	91	205
M5	357.2	22.8	875	728	182	205
M6	357.2	22.8	875	728	182	205
M7	357.2	22.8	875	728	182	205
M8	345.8	34.2	875	637	273	205
M9	345.8	34.2	875	637	273	205
M10	345.8	34.2	875	637	273	205

2.3 Specimen Casting and Curing

In order to determine the compressive strength, ninety (90) concrete specimens of size 100 mm cubes were used following BS EN 12390-3: 2019 [24], while ninety (90) concrete specimens of size 100 mm diameter cylinders were used to determine the splitting tensile strength following BS EN 12390-6: 2009 [25]. After being demoulded 24 hours after casting, all specimens underwent a curing period of 28, 56, and 90 days in a water tank.

3. Results and Discussions
3.1 Slump Test

In Figure 6, the slump value of concrete was measured for various levels of uCBA and SG by following BS EN 12350-2: 2019 [26]. The study tested nine different levels of uCBA at 3%, 6%, and 9% and SG at 10%, 20%, and 30%. A control sample (M1) was used as a reference with a slump value of 139 mm. For the 3% of uCBA mixture, the slump values for SG 10%, SG 20%, and SG 30% were 158 mm (M2), 189 mm (M3), and 198 mm (M4), respectively. While, for the 6% of uCBA mixture, the slump values for SG 10%, SG 20%, and SG 30% were 188 mm (M5), 203 mm (M6), and 213 mm (M7), respectively. Finally, for the 9% of uCBA mixture, the slump values for SG 10%, SG 20%, and SG 30% were 198 mm (M8), 226 mm (M9), and 231 mm (M10), respectively. The results showed that as the percentage of uCBA and SG increased, the slump value generally increased as well. The highest slump value of 231 mm was observed in mixture M10 with 9% uCBA and 30% SG, which was 166% higher than the control sample. The lowest value of 158 mm was observed in M2, which was 114% higher than the control. Further analysis shows that within each CBA mixture, increasing the percentage of SG also leads to an increase in slump value. These findings indicate that both uCBA and SG significantly affect the workability of the concrete. The less porous surface of SG and the high specific gravity result in the water used for mixing not being disturbed. Additionally, the oleophobic nature of uCBA also contributes to the increased slump value.

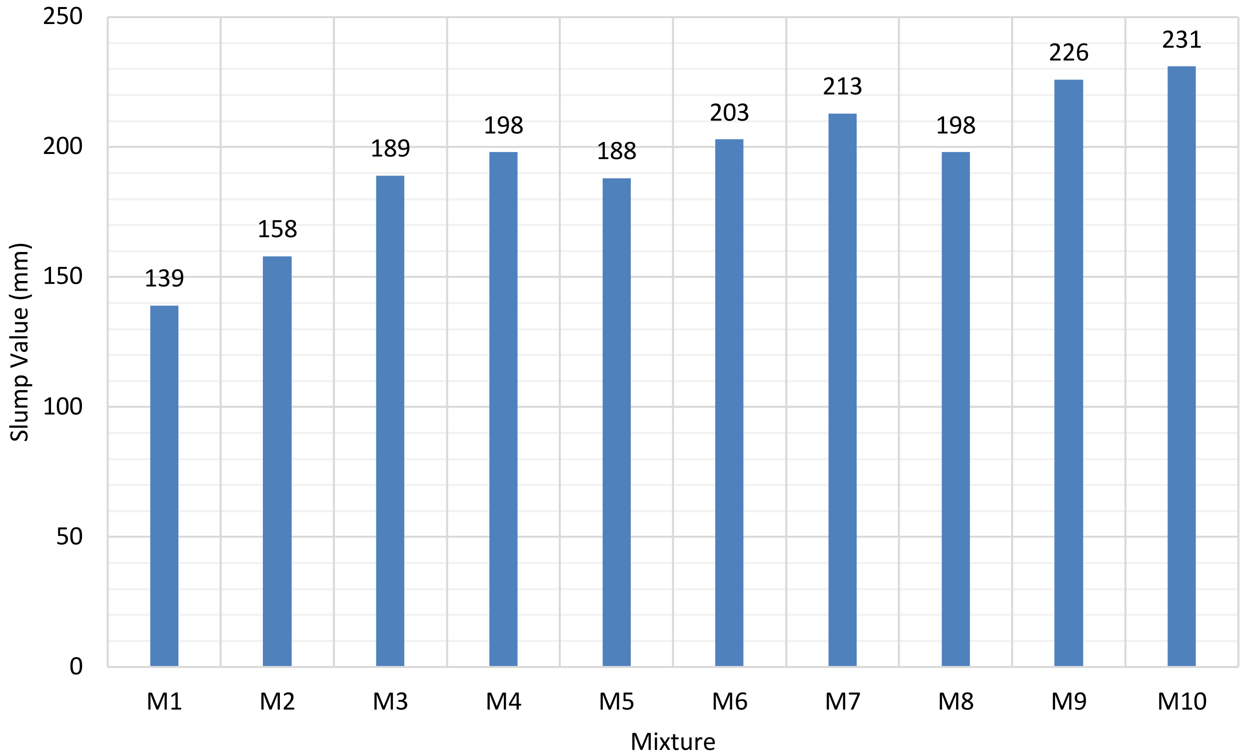


Fig. 6. Slump test

3.2 Compressive Strength Test

In Figure 7, the compressive strength values of concrete containing uCBA and SG are presented. The control sample (M1) had a compressive strength of 44.1, 46.9, and 49.7 MPa at 28, 56, and 90 days of curing, respectively. The results indicated that the compressive strength gradually decreased with the addition of uCBA and SG to the mix. At the age of 28 days, only the mixture with 3% of uCBA (M2, M3, and M4) exceed the control sample (M1). While at 56 days, M7, M9, and M10 had lower compressive strength than M1, and the same pattern was observed at 90 days. Therefore, increasing the level of uCBA and SG reduced the compressive strength of the concrete. The data showed that M2 had the highest compressive strength at all ages, followed by M3, while M10 had the lowest compressive strength. Furthermore, the high level of fineness and replacement of uCBA and SG in concrete could lead to the occurrence of alkali-silica reactions. This reaction could form a gel-like substance within the concrete that could expand over time and cause cracking and deformation, reducing the structural integrity of the concrete.

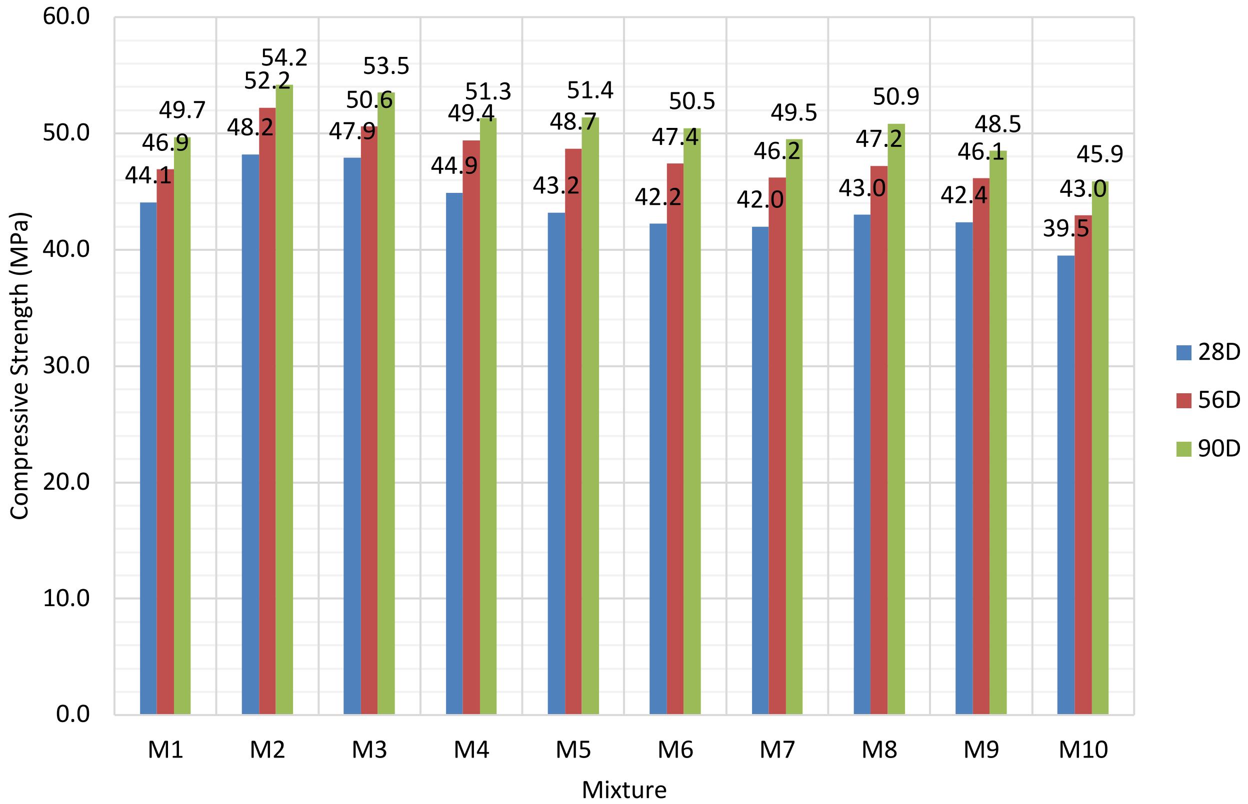


Fig. 7. Compressive strength test

3.3 Splitting Tensile Strength Test

Figure 8 displays the splitting tensile strength performances of concrete, revealing that increasing the levels of uCBA and SG in the mixture leads to a decrease in the splitting tensile strength. However, certain mixtures, specifically M2, M3, and M4, exhibit greater strength than M1 at all ages, whereas M8 and M9 display lower strengths compared to M1 at all ages. M2 boasts the highest strength, whereas M10 possesses the lowest strength when compared with M1. These findings indicate that combining uCBA with SG as a partial replacement in concrete results in better strength at lower replacement levels because the expansion of C-S-H gel is minimal when compared with higher replacements. Additionally, the internal stresses that develop in concrete may cause cracking or deformation, reducing its strength and durability. The utilization of uCBA and SG as a filler in concrete results in a less porous mixture than regular concrete, reducing the space available for the expansion of C-S-H gel.

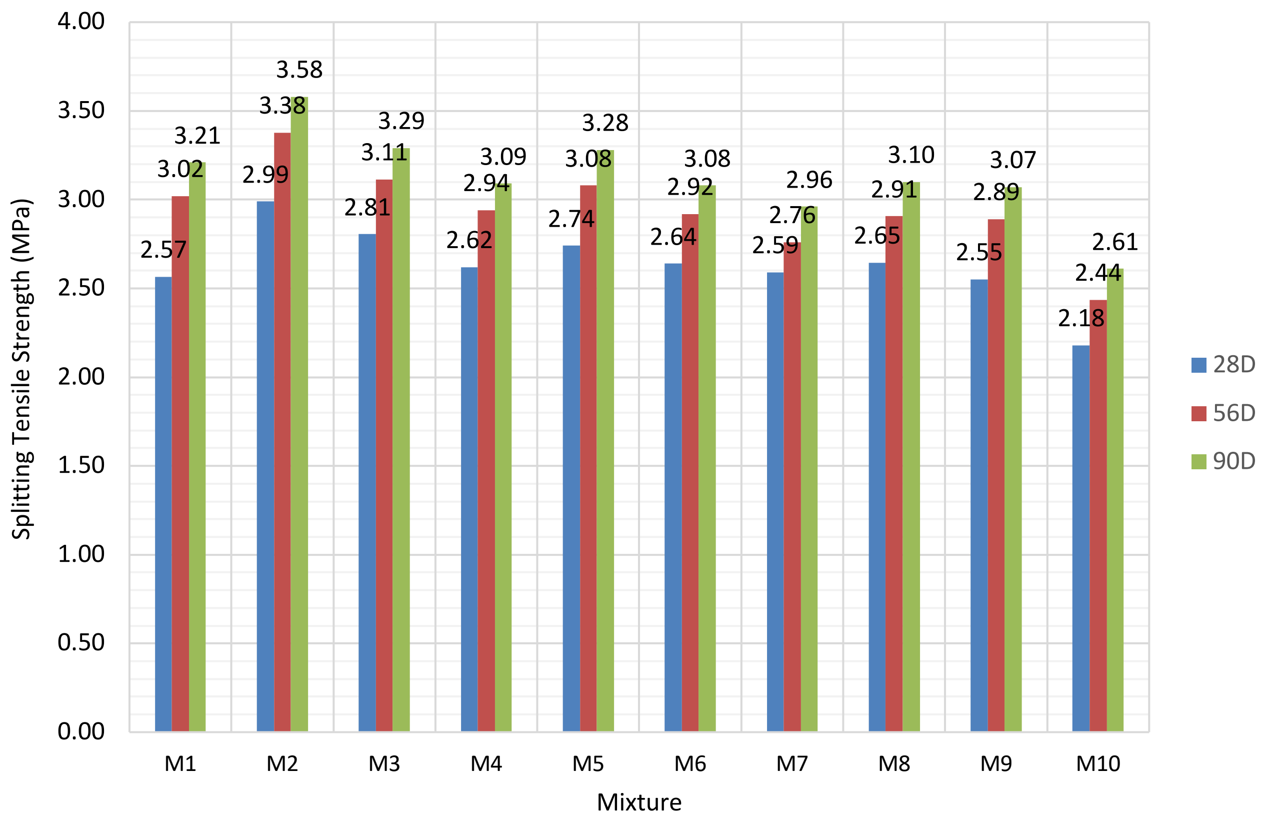


Fig. 8. Splitting tensile strength test

4. Conclusions

On the basis of the experiments presented in this study, the following conclusions were made;

i. The workability of concrete containing uCBA and SG was found to be higher compared to the control mix. This is due to the fact that the surface of SG is more solid than the fine aggregate and the specific gravity of SG is higher than fine aggregate. Additionally, the chemical composition of uCBA, which contains lower levels of CaO than OPC, also contributes to better workability.
ii. The compressive strength of the concrete decreased at a certain level of replacement due to the presence of uCBA and SG. However, the mixture with 3% uCBA (M2, M3, and M4) was satisfactory and exceeded the strength of the control mix (M1). Concrete containing 6% uCBA (M5 and M6) showed lower strength than the control at 28 days of curing, but surpassed the control at 56 and 90 days of curing.
iii. The splitting tensile strength of concrete containing uCBA and SG was higher than the control (M1) at 28 days of curing, except for M9 and M10 where the strength was lower than M1. At 56 and 90 days of curing, only concrete mixtures M2 and M3 surpassed M1. An increase in tensile strength indicates the development of C-S-H gel in the concrete due to the presence of uCBA and SG.
iv. Excessive filler in concrete disrupts C-S-H gel expansion it may cause cracking or deformation of concrete, leading to a reduction in its strength and durability. Wherein, the C-S-H gel serves the purpose of filling gaps between cement particles itself.

Based on the current findings, it is indicated that incorporating 3% uCBA and 10% SG as an alternative to cement and fine aggregate in concrete delivers satisfactory strength performances and declared as optimum replacement level. Therefore, it is recommended for future works to carry out further research on the strength and durability performances under aggressive environment.

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