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PERFORMANCE OF SELF-COMPACTING CONCRETE WITH INCORPORATION OF SILICA FUME AND COAL BOTTOM ASH

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Abstract- With increasing emphasis on sustainable construction practices, supplementary cementitious materials (SCM's) used in the production of concrete has gained a lot of attention. In current study, the effects of partial Portland cement (PC) replacement with Silica Fume (SF) and Coal Bottom Ash (CBA) on the mechanical and fresh characteristics of self-compacting concrete (SCC) are investigated. By replacing PC with SF and CBA, which are industrial by-products, the environmental impact of concrete production can be reduced while improving its performance. Ten SCC mixes were examined, with varying replacement percentages: SF at 5%, 10%, and 15%; and CBA at 15%, 20%, and 25% by weight of cement content. The investigation of mechanical characteristics through compressive strength and split tensile strength tests, as well as the examination of fresh properties using the slump flow and J-ring tests, gives insightful data.

The results shows that combined incorporation of SF & CBA at 5% & 15% shows a better slump as compared to high replacement level of both the SCM's. The slump of mixes with different ratio goes on decreasing with the increasing percentage of CBA and SF although it falls in acceptable limit. Due to fineness, enhanced surface area and porosity of CBA the water demand increases which cause the decrease of workability. The 28-days Compressive strength and Spilt tensile strength are 28.56 MPa & 2.75 MPa at optimum dosage M-1(5 % SF & 15 % CBA) respectively which are less than control but significantly near control sample strength. The strength decreases with the increase of CBA & SF ratios due to slow pozzolanic reaction of CBA at early ages which however improves at later stages. Moreover, the CBA has enough potential to be employed in SSC production along with SF.

Keywords- Fresh Properties, Self-Compacting Concrete, Compressive Strength, Coal Bottom Ash, Split Tensile strength.

1. Introduction

The production of Portland cement has witnessed significant growth during the industrial revolution, but its environmental impact in terms of carbon dioxide emissions and cost implications in developing nations like Pakistan cannot be ignored. The manufacture of cement significantly increases worldwide carbon dioxide emissions, accounting for over 7% of the total, thereby exacerbating global warming [1].

The Annual Greenhouse Gas Index (AGGI) reaching 1.49 in 2021 reflects a 49% increase in the warming influence of greenhouse gas emissions [1][2]. To address these challenges and promote sustainable construction practices, the utilization of supplementary cementitious materials has gained prominence. Natural pozzolans, known for their unique qualities have garnered significant attention in the construction industry [3]. Researchers are examining how admixtures affect the mechanical properties and durability in both fresh and hardened state to improve the properties of SCC [4]. The mechanical characteristics of the SCC were enhanced by the inclusion of mineral admixtures by up to 15% when compared to regular Portland cement. Up to a certain proportion of replacement, metakaolin in SCC significantly enhanced the mechanical characteristics and reduced concrete specimen absorption [5].

Concrete has been tested using Coal Bottom Ash (CBA), a by-product resulted from coal combustion in thermal power plants, in place of cement. The type of furnace and coal source employed affect the chemical composition and quality of CBA. Meeting certain standards, such as fineness requirements according to ASTM C618, is necessary to activate its pozzolanic properties [6][7]. Concrete's compressive and tensile strength along with durability, and micro structural properties are increased as a result of the reduction in CBA particle size since it has more surface area. Utilizing CBA in concrete production not only provides an economical method of disposal but also encourages sustainability by conserving natural resources [8].In order to use CBA as pozzolanic material for its replacement against cement , its chemical composition should be in accordance with ASTM C618 for FA Class F or Class C for which the total amounts of $SiO_2 + Al_2O_3 + Fe_2O_3$ higher than 70% or 50 % respectively, while $SO_3$and LOI must not exceed 5.0 and 6.0%.Moreover the combustion of Lignite or Sub-bituminous coal with a high calcium content falls in class C, while bituminous or anthracite coal with a low calcium contents falls in class F [9]. The utilizing of silica fume with FA & CBA blended cement mortars showed that blended cement with FA & CBA showed lower compressive strength than that of ordinary Portland cement while blended cement with SF showed increased strength [10]. A by-product of quartz reduction in an electric arc furnace known as Silica Fume (SF) has been widely used as a pozzolan in concrete. Its submicron particle size, ranging from 20 nm to 500 nm, contributes to enhanced compressive strength and improved durability when added in optimal quantity [11].

The inclusion of bottom ash along with fly ash in cement blends has been explored, although it leads to lower early-age compressive strength due to the slow pozzolanic reaction. SF with its large surface area and high SiO_2content, results in increased strength development due to high rate of pozzolanic reaction. [10].When silica fume is added to concrete, the weak area of the aggregate-cement paste interface bonds better. It aids in the development of early strength because of the higher rate of pozzolanic reaction that result in C-S-H. [12]. The partial replacement of bottom ash along with significant quantity of silica fume can increase the benefits obtained from partial replacement of cement alone with bottom ash [13].In the past, researchers have performed experiments to study the impact of CBA replacement with cement in normal concrete, but fewer studies have been performed when it comes to SCC. This research aims to investigate the incorporation of SF and CBA in self-compacting concrete as partial replacements against cement. The study's main objective is to assess their impact on mechanical and fresh qualities, such as workability, compressive strength, and split tensile strength. The consumption of sustainable materials can be optimized; this research contributes to the development of environmentally friendly concrete with enhanced performance.

2. Experimental Procedure

2.1 Materials

This study utilizes Ordinary Portland Cement (OPC) type I, which conforms to ASTM C150 standards, as the primary binding component. OPC has specific characteristics such as an initial and final setting time of 45 minutes and 330 minutes respectively and a specific gravity of 3.1 g/cc [14]. Both CBA obtained from power plant and SF are incorporated as SCMs to enhance the concrete properties, Table 1 provides the chemical composition of OPC, CBA, and SF

Table1 Chemical composition of OPC, CBA and SF

Chemicals	SiO2 (%)	TiO2 (%)	Al2O3 (%)	Fe2O3 (%)	MnO (%)	MgO (%)	CaO (%)	Na2O (%)	K2O (%)	P2O3 (%)	LOI (%)
OPC	17.9	-	10.7	3.60	-	1.8	62.8	0.9	1.4	-	0.9
CBA	37.47	-	8.57	4.86	-	0.73	10.33	0.14	0.31	-	0.08
SF	94.5	-	0.09	0.10	-	0.43	0.23	-	0.93	-	2.7

For the preparation of SCC, fine aggregate (FA) sourced from Lawrencepur and coarse aggregate (CA) sourced from Kirana hills in Sargodha are utilized. The maximum size of the coarse aggregate used is 12 mm, meeting the specifications of ASTM C33/M, and satisfying the criteria set by ERNARC [15]. Table 2 provides an overview of the physical properties of both fine and coarse aggregates.

Table 2 Physical Properties of fine and Coarse Aggregate.

	FA	**CA**
Sp. Gravity	2.73	2.68
Water Absorption (%)	1.3	0.5
Bulk Density(Kg/m^3)	-	1612
Fineness Modulus	2.99	-

The coal-fired power station of Sitara Chemicals Industries Pvt. Ltd. in Faisalabad provided CBA that was employed in this investigation as a partial replacement for cement. The CBA sample underwent sieving through a No. 4 sieve and was subjected to both X-ray Diffraction (XRD) analyses to ensure, it met the necessary requirements as a pozzolanic material. The sample was dried and ground at Pakistan Council of Scientific & Industrial Research (PCSIR) Laboratories Peshawar until it reached the desired fineness of 45 μm or less [16]. The chemical composition of the CBA, as shown in Table 1, indicates that the sum of SiO_2, Al_2O_3 and Fe_2O_3 is 50.9%, complying with the ASTM C 618 requirements for Class C [17]. The XRD pattern, depicted in Figure 1, demonstrates the presence of both amorphous and crystalline phases with Quartz and Mullite being the predominant crystalline phases. SF, on the other hand, was obtained from a local supplier in Rawalpindi. As a result of the reduction of high quality quartz with coal in an electric arc furnace, it is an amorphous polymorph of silicon dioxide. It is typically in the form of ultrafine powder, with particle sizes ≤ 0.15 μm [18].

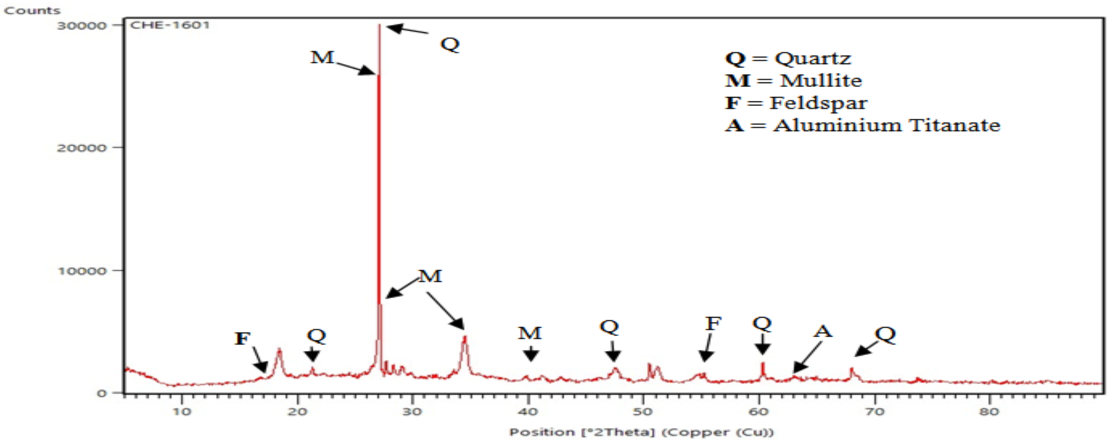


Fig.1 XRD of Coal Bottom Ash used in present study

2.2 *Mix Proportions and Sample Preparation*

To assess the mechanical and fresh characteristics of (SCC) ten different mixes were prepared. These mixes consisted of a control mix (CC) and nine variations with varying percentages of both SF & CBA. The compositions of the mixes were as follows: M1 (5% SF and 15% CBA), M2 (5% SF and 20% CBA), M3 (5% SF and 25% CBA), M4 (10% SF and 15% CBA), M5 (10% SF and 20% CBA), M6 (10% SF and 25% CBA), M7 (15% SF and 15% CBA), M8 (15% SF and 20% CBA), and M9 (15% SF and 25% CBA). All ingredients were precisely weighed during the batching process. To ensure uniformity and homogeneity, the mixing procedure recommended by previous studies was followed [19]. Viscocrete-3110 super plasticizer (SP) was used within the supplier's specified range to achieve the desired workability of the SCC as shown in Figure 2 (a), (b), (c). The development of the optimal SCC mixes was achieved through iterative adjustments based on the mix design. Cylindrical specimens with dimensions of 150mm x 300mm were casted to investigate the mechanical properties as depicted in Figure 2(d).

(a) *(b)*

(c) *(d)*

Fig.2: Preparation of samples, (a) Dry mixing of ingredients, (b) CBA, FA & OPC, (c) Super plasticizer (SP) Viscocrete-3110, (d) freshly casted cylinders

2.3 Testing of Specimen

Self-compacting concrete (SCC) was prepared, and the fresh properties were evaluated in light of EFNARC-recommended guideline with slump cone and J-ring as shown in Figure 3 (a) (b) [20]. For the evaluation of mechanical properties, three samples were prepared for each mix to obtain average value. Compressive strength testing was conducted on 150 mm x 300 mm cylinders, following the ASTM C39 standard test method, while split tensile strength was determined according to ASTM C496. Tap water was utilized during sample preparation and curing.

(a) *(b)*

Fig 3: Evaluation of Fresh and hardened properties (a) Slump flow test (b) J-Ring test

All mixtures were kept at a constant water-to-binder ratio of 0.38, and the necessary slump was obtained by changing the super plasticizer viscocrete 3110 dosage to satisfy the requirements established by EFNARC. The cured samples were stored at 23 ± 2°C for 28 days, immersed in clean water, and subsequently subjected to compressive and split tensile strength testing with Universal Testing Machine (UTM).

3 Results and Discussion

3.1Slump Flow

The slump test, in accordance with ASTM C1611, was used to evaluate each mixture's workability performance [21]. The results indicated that the workability decreased with increasing amounts of both CBA and SF, with a more pronounced decrease noted at higher substitution levels, as shown in Figure 4.

However, the slump flow measurements for all the mixes fell within the range of 550-650 mm. A slump flow within the range of 500-700 mm is considered satisfactory for self-compacting concrete, as it allows for adequate flowability while avoiding segregation issues [22].

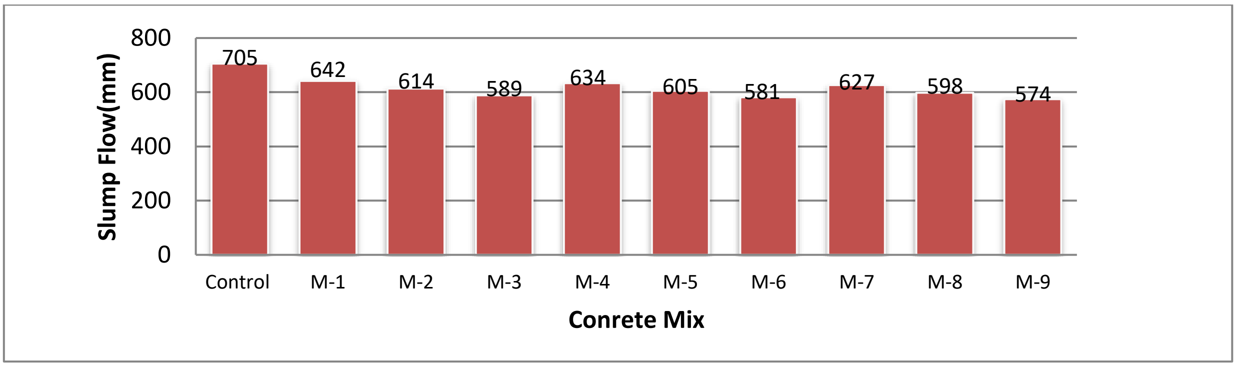
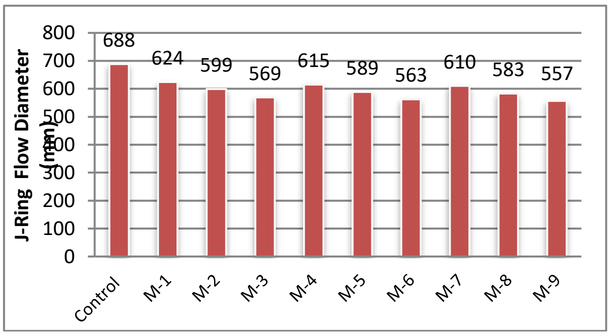


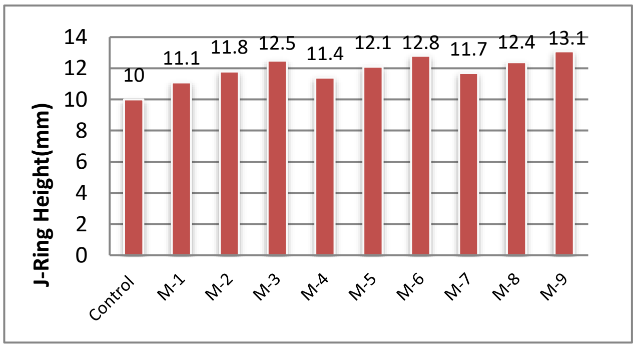
Figure 4: Slump Test Results

3.2 J-Ring

The passing ability of SCC containing CBA and SF was evaluated using the J-Ring test, which assesses the concrete's ability to flow through a confined and constricted area without vibration [20]. The inside and outside height differences between the bars of the J-Ring were measured for each mix, and the spread diameter was recorded, as shown in Figure 5 (a) and (b). The results varied for each blend. As the substitution level of both SCM's increases, height difference between the bars of the J-Ring increased and spread diameter of the concrete decreased. This can be attributed to the higher viscosity and shear stress resulting from the increased fineness and porosity of the concrete due to CBA and SF.



(a)

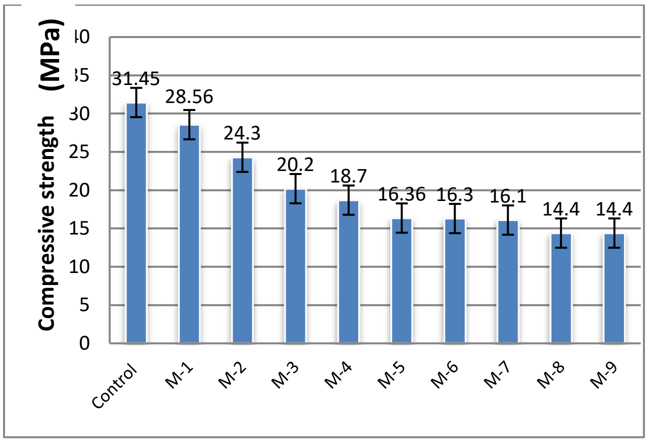


(b)

Fig.5: J-Ring Test Results, (a) J-Ring Flow Diameter Results (b) J-Ring Heights Results

3.3 Compressive Strength

Compressive strength testing was conducted following the guidelines of ASTM C-39 [24]. The results, depicted in Figure 6, illustrate the strength variations for different percentages of CBA and SF. After 28 days of curing, the mixture with 5% SF and 15% CBA had the highest strength among other however it was less than the control mix. The compressive strength began to decrease as the percentages of both replacements raise. After 28 days of curing, the lower compressive strength indicates that the pozzolanic reactivity during the early stages did not initiate properly which ultimately produce the desired C-S-H gel within concrete matrix [23]. The addition of SF at lower replacement levels demonstrated a significant increase in strength, comparable to that of the control mix. But the addition of CBA led to a reduction in compressive strength [22]. The improved strength with addition of SF is associated with micro-fillet effect and enhanced pozzolanic reactivity between SF and calcium hydroxide, leading to the development of C-S-H gel. On the other hand, the pozzolanic activity of CBA with lime is relatively low during the early stages and starts to increase significantly after 28 days [25].The pozzolanic capacity of a material refers to its ability to react with $Ca(OH)_2$, and the rate of this reaction depends on factors such as temperature, water-to-solid ratio, alkaline content, and, most importantly, the surface area of the pozzolan. After 14 days of curing, CBA's beneficial pozzolanic effect becomes more prominent, while consumption of $Ca(OH)_2$ only begins to occur after 90 days of curing period [9].



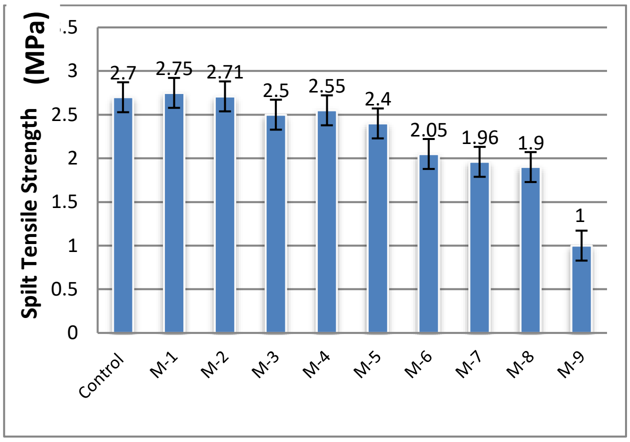


Fig 6. Compressive strength test results at 28 days Fig 7. Split Tensile strength test results at 28 days

3.4 Split tensile Strength

The split tensile strength of the SCC cylinders was evaluated following ASTM C-496. As depicted in Figure 7, the results show decline of split tensile strength with increasing percentages of both CBA and SF. The findings suggest that the inclusion of CBA and SF negatively impacts the split tensile strength. Mix M-1(5% SF and 15% CBA) had the highest split tensile strength among the evaluated mixtures after 28 days of curing period. It is important to note that the strength of the concrete begins to decrease when the amount of SF exceeds 5% and with an increasing percentage of CBA. However, a slight improvement in strength was observed at later stages of curing.

4 Conclusions

In conclusion, this study demonstrated the potential of both the SCM's (CBA &SF) as viable replacements for cement in (SCC). The findings revealed that.

- With the increase of CBA and SF percentages, the workability of the SCC mixes decreased while still meeting the required slump criteria.
- Optimum replacement levels of 5% SF and 15% CBA were identified, offering satisfactory workability and acceptable mechanical strength. Although the compressive strength and split tensile strength of these mixes were lower compared to the control mix, they were suitable for normal to medium strength concrete applications.

Future research should focus on investigating the long-term effects of CBA and exploring additional sources of this sustainable material. Overall, the incorporation of CBA and SF in SCC presents a promising approach for enhancing sustainability in concrete production and addressing waste management challenges.

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