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Combined influence of Waste Marble Powder and Silica Fume on the Mechanical Properties of Structural Cellular Lightweight Concrete

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Abstract

Structural cellular concrete, also known as foam concrete, is a versatile building material that has gained popularity in the construction industry due to its distinct characteristics. Marble dust is an industrial byproduct that is generated in huge quantities across the whole world, causing major environmental problems. The objective of this research is to investigate the rheological and mechanical characteristics of cellular concrete containing waste marble powder (WMP) and silica fume (SF) combinations. Fresh and mechanical tests were conducted on concrete mixes that included 5, 10, 15 and 20% marble powder in addition to a constant 5% silica fume, as well as a control mix without WMP and SF. Slump flow and fresh unit weight were the rheological properties of the mixes investigated. Experiments were also carried out to determine the mechanical strengths of water-cured specimens after 7 and 28 days. The results of the slump flow test implied that slump flow diameter varies from 695 to 717 mm and the highest fresh density of mixes was recorded as 1784 kg/m^3. The combination of WMP and SF resulted in compressive and splitting tensile strength improvements of 31.48% and 21.02% at 28 days, respectively. The recommended replacement percentage of WMP and SF combinations for structural cellular concrete has been determined to satisfy both compressive strength and splitting tensile strength.

Keywords: *structural cellular concrete; waste marble powder (WMP); silica fume (SF); mechanical concrete properties; slump flow.*

1 Introduction

Cellular concrete is a combination of cement, water, fine aggregate, and air voids in which stable foam is incorporated into the concrete. Cellular concrete is renowned for its high fluidity, low cement content, low aggregate consumption, and exceptional thermal insulation (Chica & Alzate, 2019; Ramamurthy et al., 2009). Compared to conventional concrete, the use of cellular concrete in structural components not only reduces the framework's weight but also lowers the construction project's carbon footprint. The environmental impact analyses conducted by LEED (Leadership in Energy and Environmental Design, United States) found that cellular concrete technology is environmentally sustainable and could contribute to the manufacturing of sustainable building components (Shanmugam, 2010). Cellular concrete with a density of 300–1200 kg/m^3 is typically used for insulation, infill, and non-load-bearing structures, whereas cellular concrete having a density of 1200–1600 kg/m^3 is generally used for structures that support loads (Raj et al., 2019).

The inclusion of industrial waste into concrete contributes in the production of low-cost and sustainable construction materials (Ince et al., 2020). In recent years, industrial wastes have been used extensively as partial material replacements in the production of concrete and related construction materials. Marble stone is a well-known building construction material and marble waste generates when cutting marble blocks or slabs into the desired shapes and sizes. The marble sector in Bangladesh is relatively modest, although it is steadily expanding. Marble is primarily mined in the highlands of Bangladesh's Sylhet, Cox's Bazar, and Chattogram districts. During the mining operations of marble stone, almost 50% of dust is generated as a waste, while the remaining 15% is generated during processing (Kore et al., 2020). A reliable estimation of the amount of marble waste generated in Bangladesh is not possible since no record exists for its production and generation.

Several studies stated that, marble powder has the capacity to perform as a void filler in concrete and greatly increase the strength and durability of cellular concrete (Bayraktar et al., 2021). In terms of the mechanical properties of cellular concrete, it has been suggested that 5-20% marble dust is an acceptable cement replacement under standard water curing conditions (Zhang et al., 2020). Furthermore, other studies found that 10-15% of marble powder is satisfactory for use as replacement of cement in terms of compressive strength (Aditto et al., 2023). However, introducing silica fume and other alternative materials reduces the degree of porousness of cellular concrete (Hilal et al., 2014). A review of relevant literature exploring WMP and SF-incorporated cellular concrete's potential use in structural components is quite a few.

The objective of this research is to look into the potential influence of WMP and SF on the rheological and mechanical properties of structural cellular concrete. The study gives an in-depth analysis of the combined influence of WMP and SF on the rheological and hardened properties of SCLC. This study adds to the growing body of literature on eco-friendly building materials by demonstrating that discarded marble dust improves structural cellular concrete's workability and thermal insulation capability while lessening the structural weight by efficient waste utilization. The article offers insightful information on cellular concrete's performance, which creates more resilient and environment-friendly lightweight structures.

2 Materials

In this study, OPC of type I (CEM I/52.5N) was utilized as a convenient locally available binder in this research. Additionally, the silica fume used in this research was purchased from the local market. The unprocessed WMP was obtained from a local granite company known as "Green Granite and Marble Ltd." The collected WMP was then oven-dried before being sieved through a 300µm sieve to eliminate larger particles. Following that, the WMP was crushed to achieve the desired fineness. In this study, a locally available PCE-based superplasticizer was utilized. Local washed sand from the river, frequently referred as Sylhet-sand, was obtained from a local provider and used as fine aggregate in this experiment. Table 1 and 2 summarizes the chemical and physical properties of all materials used in this experiment respectively.

Table 1. Chemical properties of cement, marble powder and silica fume.

Material	Percentages of chemical components								
	SiO_2	Na_2O	CaO	Al_2O_3	MgO	Fe_2O_3	K_2O	SO_3	LOI
OPC	19.01	1.20	66.89	4.58	1.26	3.2	2.76	0.45	1.24
Marble Powder	5.5	0.0	45.65	0.43	5.96	0.21	0.01	0.05	42.19
Silica fume	89.94	0.21	0.75	0.51	1.52	0.65	0.47	0.09	5.26

Table 2. Physical characteristics of OPC, fine aggregate, marble powder, silica fume and foaming agent.

Properties	**OPC**	**FA**	**WMP**	**SF**	**Foaming agent**
Specific gravity	3.15	2.72	2.75	2.23	1.02
Loose unit weight (kg/m^3)	1440	1687	1380	600	1020
Moisture content (%)	-	3.62	1.54	0.23	-
pH	-	-	-	-	6.7 in solution
Chemical identity	-	-	-	-	Polyoxyethylene Alkyehter Sulfate

3 Experimental programs

3.1 Mix design of all WMP-SF incorporated SCLC mixes

In this work, the structural cellular concrete mix proportions were calculated in accordance with ACI 523.3R-93 and ACI 318-19(22) standards. The mixes were defined as SFxMy, where x and y were the replacement percentages. Table 3 presents the mix ratios of all cellular concrete batches.

Table 3. Mix proportion of all MP-SF incorporated SCLC mixes.

Mix ID	**Cement (kg/m^3)**	**SF (kg/m^3)**	**MP (kg/m^3)**	**Fine Aggregate (kg/m^3)**	**Water (kg/m^3)**	**SP (%)**	**Foam (ltr/m^3)**
Control	540.21	0	0	1080.42	270.10	0.2	280
SF5M5	486.19	27.01	27.01	1080.42	270.10	0.2	280
SF5M10	459.18	27.01	54.02	1080.42	270.10	0.2	280
SF5M15	432.17	27.01	81.03	1080.42	270.10	0.2	280
SF5M20	405.16	27.01	108.04	1080.42	270.10	0.2	280

3.2 Preparation of stable foam and mortar composite

In this study, foam was generated manually by using a paint mixer attached to a high-speed drilling machine. Composite mortar slurry was prepared separately. Before mixing the slurry with foam, the flowability of the slurry was evaluated using a flow table test. At last, foam was progressively mixed with the mortar slurry and the density of the fresh mix was continuously measured to achieve the target density. Figure 1 illustrates the manual generation of stable foam and mixing the foam with mortar composites using a mixer machine. The density of produced foam was 60 kg/m^3 which fulfilled the guideline of ASTM C796/C796M.

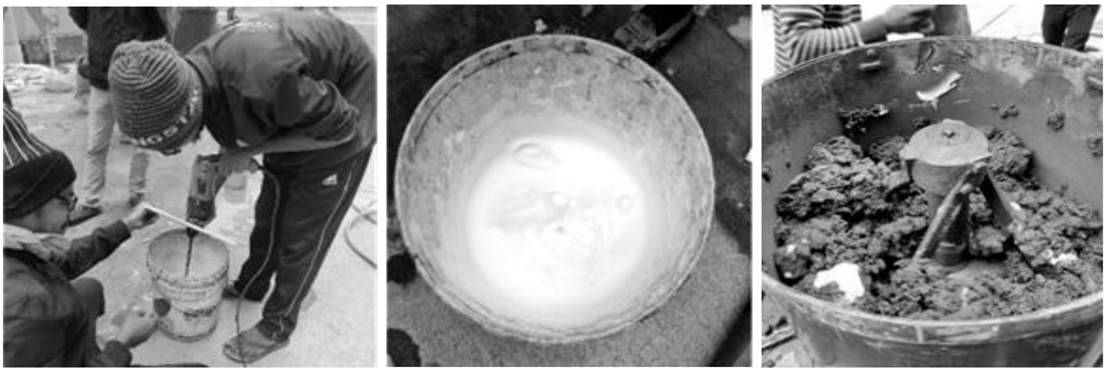

Figure 1. Manual generation of foam and mixing with composite mortar.

3.3 Specimen preparation and testing methods

Standard cylindrical molds of 100 x 200 mm were used to perform the compressive and splitting tensile strength tests. Fresh concrete's rheological qualities were tested within a few minutes after each mixing. The specimens were then placed in an environment with a temperature of about 30^{0}C and demolded after 24 hours of hardening period.

For ensuring the flowability of fresh mix, slump flow test was conducted in accordance with the code of ASTM C1611/C1611M. The fresh density test was carried out in line with ASTM C138/C138M to ensure that the fresh mixes satisfied the criteria of cellular concrete. Similarly, ASTM C39/C39M and ASTM C496/C496M standards were used to carry out the compression and splitting tensile strength tests, respectively. Three samples were tested and the average was taken as mean value of the strength.

Figure 2. Slump flow, compressive and splitting tensile strength test arrangements.

4 Results and discussion

4.1 Flowability: slump flow and T_{50} test results

The combined influence of WMP and SF on the slump flow diameter and T_{50} time of various mixes are shown in Figure 3. According to the data, increasing the percentages of marble powder reduced the slump spread diameter. In general, waste marble powder has a tendency to absorb some of the water which is required to keep concrete at the correct consistency and workability. As a result, there is less water available to lubricate and facilitate the flow of the concrete particles, which lowers the slump flow as well as increase the flow time of the concrete. In addition, marble powder frequently has high specific surface area, which might enhance friction in the concrete mixture (Corinaldesi et al., 2010). From Figure 4, It is noticeable that all the SCLC mixes were in acceptable flow limit as per EFNARC (2005). However, it was discovered that the addition of marble powder and silica fume increased the flow time, T_{50} proportionally. In terms of slump flow spread, a flow time reduction rate of 1.25 to 6.38% was observed for WMP-SF-incorporated SCLC relative to the reference mix.

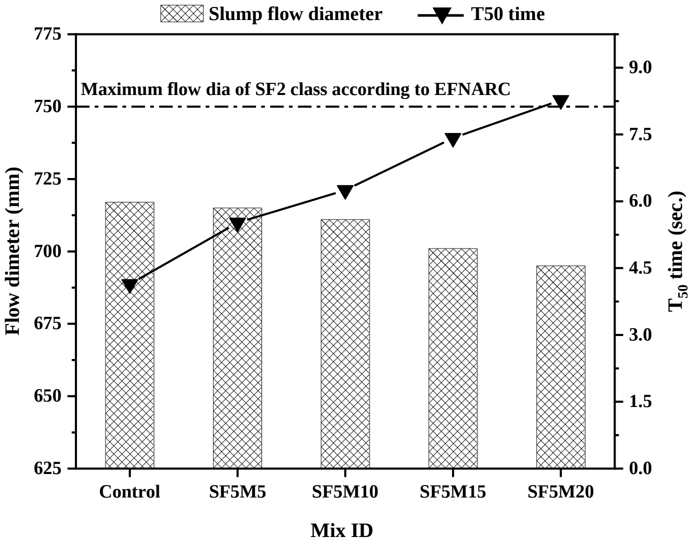

Figure 3. Slump flow diameter and T_{50} time of all fresh mixes.

4.2 Density

Figure 4 illustrates the fresh and hardened densities of all WMP-SF-incorporated SCLC mixes. According to the experimental data, it was found that fresh density ranges between 1744.5 kg/m^3 and 1784.6 kg/m^3. Both fresh and hardened density increased up to 10% replacement of marble powder compared to the control specimen and was then gradually reduced. A maximum hardened density of 1776.2 kg/m^3 was obtained for 10% replacement of WMP. The increasing trend of density resulting from the decrease in porosity might be attributable to the absorbency and infill characteristics of marble powder. However, after 10% marble powder substitution, the density begins to decrease. Since marble powder has a specific gravity that is lower than cement, incorporating a greater proportion of MP resulted in a decrease in fresh and hardened density.

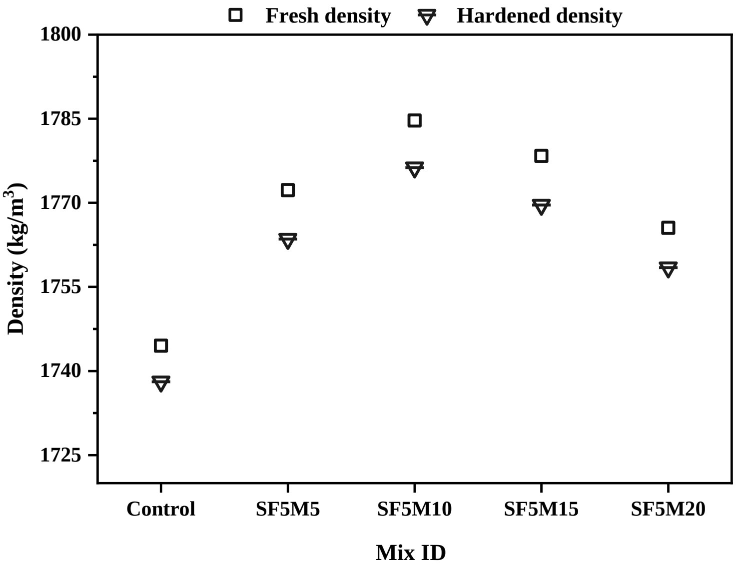

Figure 4. Fresh and hardened density of all mixes.

4.3 Compressive strength test results

Figure 5 represents the cylindrical compressive strengths with changing profile at 7 and 28 days. According to test results, the mix containing 10% marble powder and 5% silica fume combination had the highest compressive strength at both 7 and 28 days. All mixes including SF5M10 showed the higher values of compressive strength compared to control mix. Higher amounts of marble powder (greater than 10% by volume) result in a reduction in strength due to the dilution effect, which generates an alkali-silica reaction as a result of the increased quantity of inert silica available in the mix (Ahmad et al., 2021). At 28 days, however, the compressive strength of the control, SF5M5 and SF5M10 mixes was 19.80 MPa, 24.61 MPa and 26.08 MPa respectively. After that, the compressive strength of SF5M15 and SF5M20 had decreased to 22.13 MPa and 20.69 MPa respectively. According to experimental data, SF5M10 showed a maximum 31.7% improvement of compressive strength in comparison with the reference specimen at 28 days. According to numerous studies, approximately 10% marble dust may be substituted for cement without compromising the mechanical characteristics of the resultant mix (Vardhan et al., 2015).

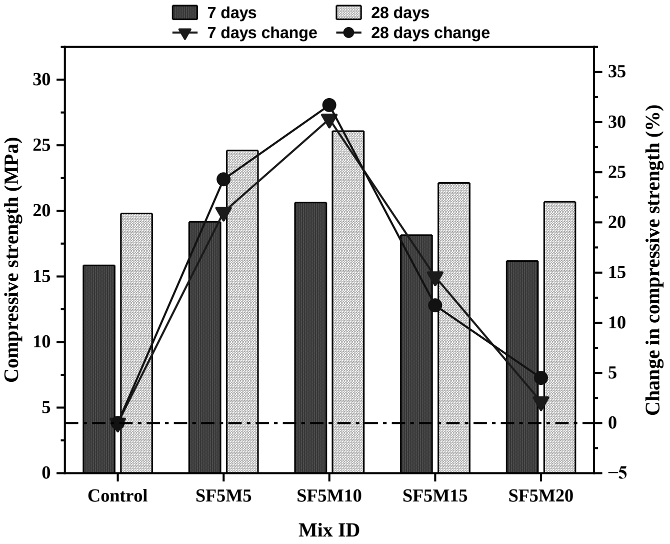

Figure 5. Compressive strength and it’s changing profile of all specimen at 7 and 28 days.

4.4 Splitting tensile strength test results

Figure 6 illustrates the mean split tensile strength of all the WMP-SF incorporated SCLC mixes at 7 and 28 days. For control mix the splitting tensile strengths of 1.82 MPa and 2.53 MPa were obtained at 7 and 28 days, respectively. At 7 and 28 curing ages, maximum splitting tensile strength of 2.31 MPa and 3.05 MPa were achieved for the mix SF5M10. Whereas the lowest strength was obtained 2.39 MPa for SF5M20 mix at 28 days.

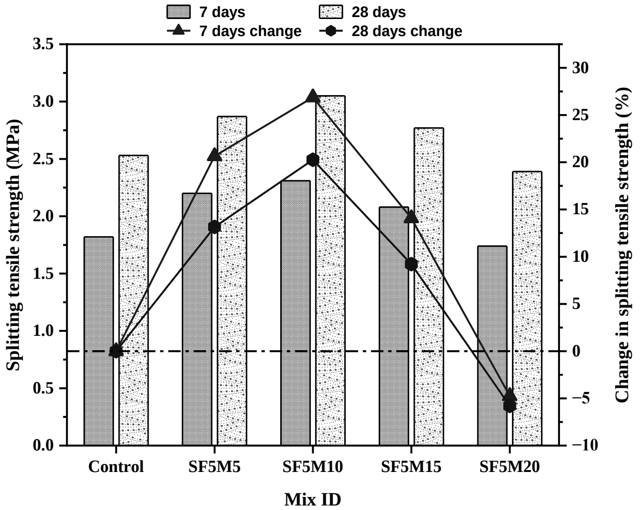

Figure 6. Splitting tensile strength and it’s changing profile of all specimen at 7 and 28 days.

5 Conclusions

Based on the findings of the experiment, we may conclude the following:

1. The fresh concrete's workability reduced marginally. A higher proportion of replacement gradually lowered the slump flow diameter. The fresh density was increased up to 10% incorporation of WMP and then decreased. However, it was ensured that all specimens containing the WMP and SF combination fulfilled the EFNARC guideline's acceptable requirement.
2. Mixtures with varied concentrations of WMP substitution had a significant impact on compressive strength. However, combining silica fume with WMP greatly enhanced the strength of SCLC. At 28 days, the combination of 10% WMP and 5% SF demonstrated a maximum compressive strength of 26.08 MPa.
3. A greater percentage of replacement also enhanced the splitting tensile strength, up to 10% WMP incorporation. At 28 days, a maximum splitting tensile strength of 3.05 MPa was obtained for 10% WMP and 5% SF. The subsequent substitution of cement resulted in a significant decrease in tensile strength.
4. On the basis of these findings, structural cellular concrete can be recommended for use in structures subject to load bearing elements.

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