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Effects of Supplementary Cementitious Materials on the Fresh and Hardened Properties of High-Strength Self-Compacting Concrete

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Abstract

Due to the excessive use of natural resources for raw materials, sustainable practices have become a key concern in the construction industry. The monument and sculpture industries have overgrown because of increased marble demand from major aesthetic and construction projects. The massive disposal of marble powder (MP) poses significant environmental and safety threats. Despite its higher cement consumption and greenhouse gas emissions, high-strength self-compacting concrete (HSSCC) is employed. This study aims to develop cost-effective and environmentally friendly HSSCC using marble powder (MP), fly ash (FA), and silica fume (SF). The effects on fresh properties were evaluated using slump flow, and J-ring slump flow tests. The mechanical characteristic was examined using a compressive strength test. In addition, the non-destructive properties were assessed through an ultrasonic pulse velocity (UPV) test. The use of supplementary cementitious materials (SCMs) such as MP, FA, and SF has been shown to improve the properties of concrete. Furthermore, the mechanical properties of the concrete increased as the percentage of MP in it increased. Including SCMs improves concrete's fresh characteristics, making it more workable. The usage of SF, FA, and MP in HSSCC at 10%, 10%, and 20%, respectively, generated the optimum mechanical characteristics.

Keywords: *Self-compacting concrete; Silica fume; Fly ash; Marble powder; Environmental impact.*

1 Introduction

Self-compacting concrete (SCC) is a kind of concrete that doesn't need any additional energy to compact into position. To strengthen and standardize concrete, it was invented in Japan (Okamura & Ouchi, 2003). The mix constitution is customized to meet all fresh and hardened concrete performance parameters by incorporating chemical admixtures such as fly ash, silica fume, and superplasticisers. Increased emissions of CO_2 from cement manufacturers have contributed to the actualization of the expected global warming. It is anticipated that by 2020, cement manufacturing would increase its emissions of CO_2 by 50% from the current level of one ton per year. Each year, 13,500 million metric tons of greenhouse gases are released during the extensive use of energy needed to make Portland cement (Malhotra, 2002).

Waste products from several industries, including granulated ground blast furnace slag (GGBFS), fly ash (FA), mining waste (MW), marble powder (MP), rice husk ash (RHA), Metakaolin (MK) and so on have effectively replaced the proportion of cement for concrete. MK, FA, MP, SF, RHA, GGBFS, and chemical admixtures are only some of the mineral admixtures that have been studied in SCC (Bode Venkata Kavyateja et al., 2020; B. V. Kavyateja et al., 2020; Singh et al., 2017). After the process of carving, sculpting, and polishing marble, a powder called marble powder (MP) is the remaining inert waste. The ecology, the biosphere of the atmosphere, and world health are all in grave danger as a result of this. MP is increasingly being considered as a potential cement replacement in cementitious materials (Aditto et al., 2023). Numerical research suggested replacing SF with 10–20% cement to generate SCC with superior strength and minimal greenhouse gas emissions (Choi et al., 2017; Singh et al., 2017).

Overall, the use of supplementary cementitious materials (SCMs) in place of cement in high-strength self-compacting (HSSCC) has been met with gratifying outcomes (Vivek & Dhinakaran, 2017). The main motive of this research is aimed at promoting the reuse of waste for ecologically sound development by analyzing behavioural trends of procedures and the efficacy of HSSCC with MP integrated at ratios ranging from 0% to 20%, alongside the constants of 10% FA and 20% SF. The utilization of SCMs and disposal wastes such as SF, FA, and MP results in greater savings (Soomro et al., 2021). This research evaluates the fresh and mechanical properties of HSSCC to develop eco-friendly construction processes. Many nations are increasingly adopting the usage of SCC now. SCC might solve the industry-wide issue of improper concrete laying. There should be studies on the best ratios and combinations of these materials, as well as their long-term durability and effectiveness in a variety of conditions. More research is required to understand how these components will influence the fresh properties and economic viability of HSSCC. Filling up the knowledge gaps will boost awareness and utilization of alternative components in HSSCC construction, resulting in more high-performance and sustainable concrete solutions. However, additional study and improvement are required to quantify and standardize the methodologies for evaluating the self-compacting properties of SCC.

2 Materials and methodologies for experimentation

2.1 Materials

Type I ordinary Portland cement (OPC) was utilized in this study. A maximum size of 19 mm was employed for the coarse aggregates in this investigation. After being sieved through a 4.75 mm opening, river sand was utilized as a fine aggregate (ASTM, 2018). From a local dealer in Dhaka, Bangladesh, a silica fume was received. Fly ash was collected from a well-respected cement factory in Bangladesh. Additionally, marble powder was obtained from an industrial company in Narayanganj, Bangladesh. To make the material more flexible, a superplasticizer made from polycarboxylic ether was added. Figure 1 illustrates the grading curve for both fine and coarse aggregates.

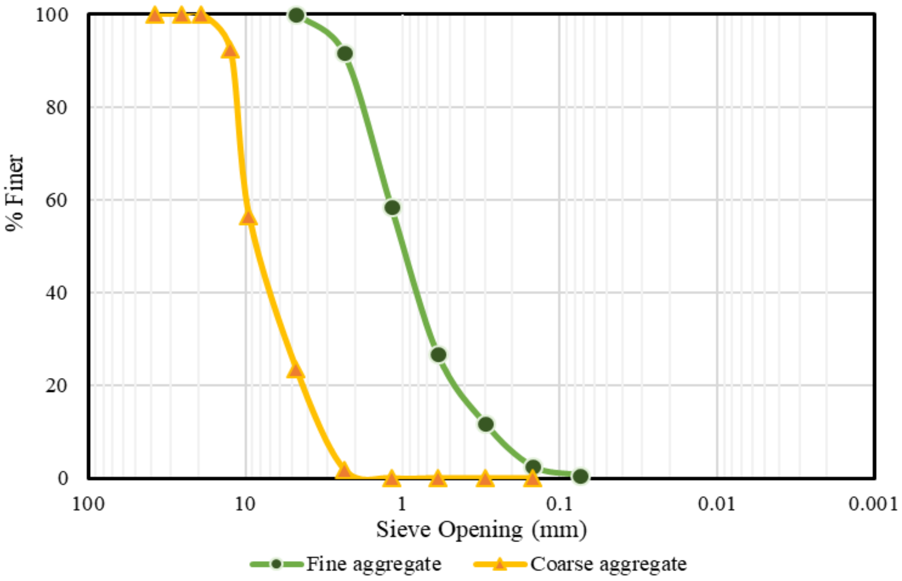

Figure 1. Gradation curve for fine and coarse aggregate

2.2 Mix proportion

All batches were mixed by EFNARC as indicated in Table 1 (EFNARC, 2005). The substitution percentages for marble powder were established at 0%, 5%, 10%, 15%, 20%, and 20% and 10% constant silica fume and fly ash, respectively. The water-to-binder proportion was maintained constant at 0.36 in each batch mixture, and a superplasticizer (SP) was used to regulate the amount of water added. Each of the SCC samples was then given the designations S20FA0M0, S20FA10M0, S20FA10M5, S20FA10M10, S20FA10M15, and S20FA10M20 in that order, with mix ID S20FA0M0 serving as the reference mixture. The whole blending procedure was conducted by EFNARC (2005) standards.

Table 1: The proportions of ingredients in each batch of HSSCC

Materials	**S20FA0M0**	**S20FA10M0**	**S20FA10M5**	**S20FA10M10**	**S20FA10M15**	**S20FA10M20**
OPC (kg/m^3)	440	385	357.5	330	302.5	275

Marble powder (kg/m^3)	-	-	27.5	55	82.5	110
Fine aggregate (kg/m^3)	962.5	962.5	962.5	962.5	962.5	962.5
Coarse aggregate (kg/m^3)	797.5	797.5	797.5	797.5	797.5	797.5
Silica fume (kg/m^3)	110	110	110	110	110	110
Fly ash (kg/m^3)	-	55	55	55	55	55
Water (kg/m^3)	198	198	198	198	198	198
Superplasticizer (%)	1.5	1.5	1.5	1.5	1.5	1.5

2.3 Experimental methodologies

Utilizing the slump flow and the J-ring flow test, the workability and viscosity characteristics of fresh materials were determined according to the BS EN 12350-8 (2010) and BS EN 12350-12 (2010) guidelines (EN, 2010). The cylinder specimen was evaluated through a compressive strength assessment according to ASTM C39 criteria (ASTM, 2005). Water cure durations of 7 and 28 days were selected for the cylindrical molds with dimensions of 100 x 200 mm utilized for measuring the influence of SF, MP, and FA on the compressive strength of HSSCC. At 28 days, the pulse velocities were analyzed using ultrasonic pulse velocity (UPV) tests in line with ASTM C597 (ASTM, 2009).

3 Results and discussion

3.1 Influence of SCM on fresh properties

The slump flow and J-ring flow for the control mix and several SCC variations are displayed in Figure 2. Slump rates with regard to 675 and 740 mm were achieved, which is within the range accepted by EFNARC for SCC slump flow. According to the slump flow analysis, the optimal value for the mixture of S20FA10M10 was 740 mm, whereas the value for the control mixture was 675 mm. Compared to the control mixture S20FA0M0, the slump flow values for the mixes containing 0% to 20% MP, as well as the constant 10% FA and 20% SF, were 1.88%, 7.43%, 9.62%, 5.94%, and 5.08%, correspondingly. When comparing the SCC mix with and without MP, the J-ring flow rate was much higher with the SCC mix including MP. Slump flow was measured at 740 mm, which is near the 715 mm that would have been optimal for the control mixture in a J-ring. A combination of replacing 0% to 20% of the MP with 10% and 20% FA and SF, accordingly, resulted in increases in J-ring flow rates of 4.21%, 11.71%, 19.22%, 16.63%, and 15.04% contrasted with the control mix. The performance benefits of MP come from the finer particles' reduced internal friction and quicker circulation. Ayyadurai et al. found that compared to a reference concrete mix, concrete produced with 5 to 20% MP and 15% SF had enhanced workability and passing ability in both the slump and J-ring flow tests.

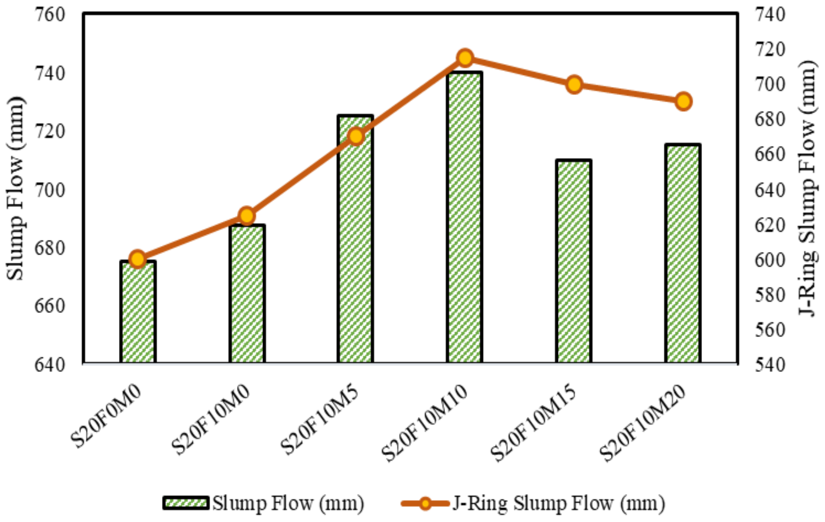

Figure 2. Slump and J-ring flow values of HSSCC mixes

3.2 Influence of SCM on compressive strength

During the 7, and 28-day curing periods, the compressive strength of HSSCC mixtures was assessed. Figure 3 demonstrates the compressive strength of HSSCC samples generated with increasing percentages of MP, together with unchanged quantities of SF and FA as a cement replacement. The typical mix S20FA10M10 had an outstanding compressive strength at both 7 and 28 days of curing, whereas the specimen S20FA10M20 exhibited the lowest. Compared to the control sample, the samples with 0%, 5%, 10%, and 15% showed a strength boost of 2.90%, 7.14%, 10.41%, and 2.77% after 7 days. The gains in strength were 3.11%, 7.38%, 10.96%, and 1.88% after 28 days. The pore filler effectiveness of MP and the pozzolanic action of FA contributed to the increased compressive strength. The 20% MP substitution weakened the material by 0.73% over 7 days and 0.56% over 28 days of curing ages. The strength of concrete might be lessened if MP was added in greater quantities due to the potential for an adverse effect on the material's interparticle contact. According to Ayyadurai et al. mixing concrete with 5 to 20% MP and 15% SF resulted in a modest improvement in compressive strength compared to the reference concrete mix.

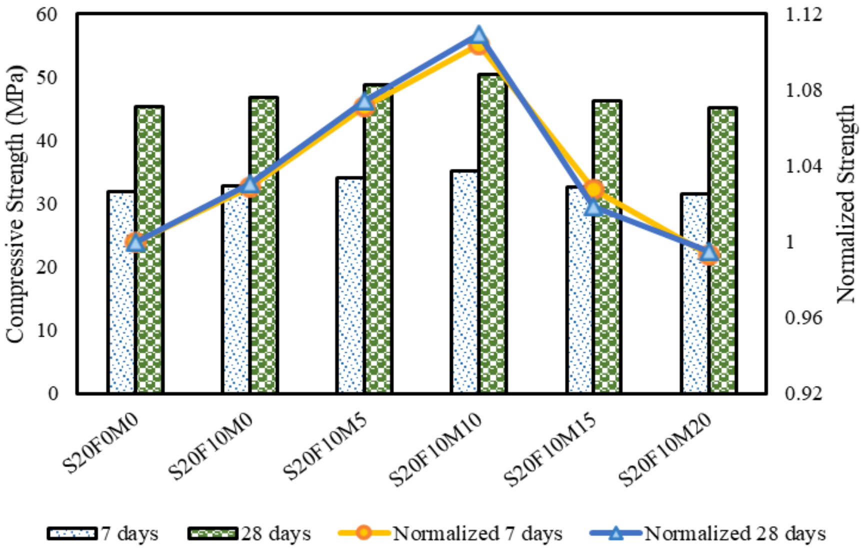

Figure 3. Compressive strength test of all HSSCC mixes

3.3 Influence of SCM on NDT properties

After 28 days, the ultrasonic pulse velocity (UPV) test was performed, the findings of which are displayed in Figure 4. According to the results, the proportion of MP fluctuated, while the proportions of FA and SF remained consistent. After 28 days, the UPV for the control mixture, S20FA0M0, was an impressive 4070 m/sec. Furthermore, UPV values may be raised by including MP at different concentrations, with the fixed amounts of

FA and SF remaining unchanged. For the S20FA10M10 mixture, the optimal UPV value was measured at 4291 m/sec during the 28-day curing periods. Compared to the control mix, the pulse velocity values improved by 3.51%, 4.23%, 5.39%, 2.80%, and 1.75% during the 28-day curing periods. This was in addition to the constant 10% SF and 20% FA and the 0%, 5%, 10%, 15%, and 20% MP replacements. This kind of study revealed that an increase in the percentage of replacement produced an increasingly dense structure and an improvement in the concrete density, both of which contributed to a greater pulse velocity. Nearly equivalent findings were seen with MP by Uysal and Yilmaz (2011) but this only included up to 10% of MP.

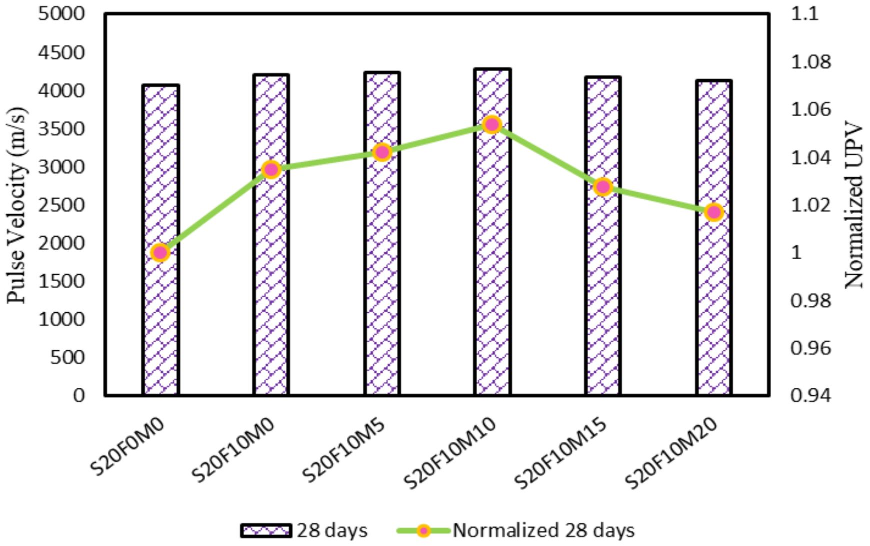

Figure 4. UPV test of all HSSCC mixes

3.4 Relationship between DT and NDT properties

Since the patterns shown in UPV data were so close to those observed in compressive strength, the connection between each of them was further investigated. Figure 5 exhibits the interactions between compressive strength and UPV for each possible combination. The coefficient of regression (R^2) value is about 80.58%, thus reflective of generally satisfactory outcomes. Therefore, it is obvious that there is a very significant beneficial correlation between compressive strength and pulse velocity (Datta et al., 2022). Compressive strength and pulse velocity are related, as revealed by Equation (1).

$$y = 0.0237x - 51.912 \tag{1}$$

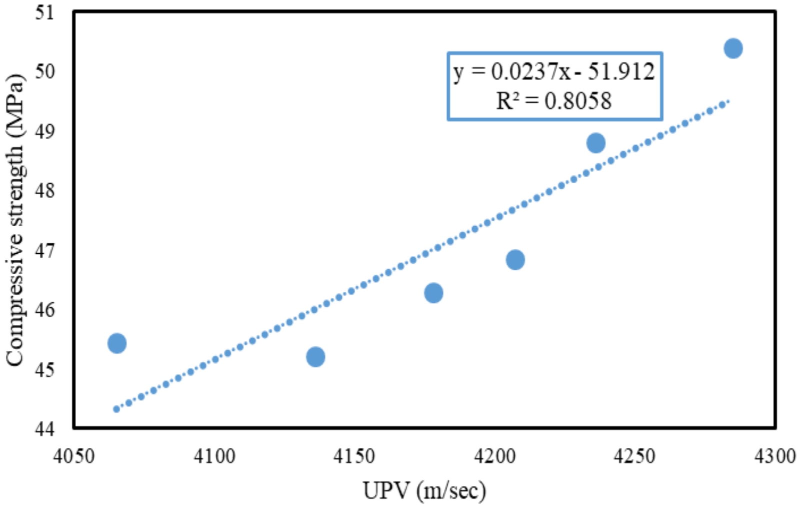

Figure 5. Correlation between DT and NDT properties

4 Conclusion

This research examines the implications of fly ash, marble powder, and silica fume on a concrete specimen. The acquired findings of fresh and mechanical characteristics of concrete revealed distinctive characteristics in varying concrete mix percentages. This investigation supports the notion that MP inclusion enhances concrete workability. For compressive strength, a cement substitution comprised of 10% FA, 20% SF, and 10% MP has been exhibited to improve mechanical performance with no adverse impacts. In contrast to the baseline combination, the HSSCC mixture S20F10M10 had a higher UPV value. However, the inclusion of MP, FA, and SF together at greater replacement levels results in a lessening in compressive strength and UPV values. Thus, 10% MP, 10% FA, and 20% SF constitute the optimal HSSCC combination. The effectiveness of the S20F10M10 mix was assessed as opposed to other mixes.

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