Mechanical characteristics of self-compacting concrete with silica fume and stone dust

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Abstract. Stone dust is a byproduct of stone crushing and is used as a partial substitute for natural sand in the production of concrete. Therefore, this research aimed to analyze the effect of stone dust as sand substitute material on the mechanical properties of self-compacting concrete (SCC) using silica fume to enhance performance and limit industrial waste. The experiment was conducted by creating concrete mix using 9% silica fume as a cement substitution and varying percentages of stone dust as a sand replacement at 0%, 2.5%, 5%, 7.5%, 10%, and 12.5%. The parameters tested were compressive strength, modulus of elasticity (MOE), and modulus of rupture (MOR), after concrete reached 28 days of age. The results indicated that all mix with 9% silica fume and variations in stone dust met the requirements for SCC. The highest compressive strength, MOE, and MOR were achieved at 5% stone dust variation with a value of 54.69 MPa, 21420.23 MPa, and 8.5 MPa, respectively. This research shows that the use of stone dust as a substitute material can enhance concrete quality and provide an environmentally friendly solution for managing industrial waste.

1 Introduction

Self-compacting concrete (SCC) is an important innovation in modern construction. Some of the advantages of using SCC include the ability to accelerate casting process and reduce the need for labor for compaction as well as finishing [1], provision of better quality, specifically in elements with dense reinforcement, reduced permeability, and high concrete durability [2]. Additionally, it has the potential to eliminate the need for vibration during concrete compaction, reducing noise pollution [3]. This shows the suitability of SCC for structures

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with dense reinforcement and structural positions that are difficult to reach during casting [4].

A valuable material that is commonly added to concrete mix is silica fume, a byproduct of the ferrosilicon alloy industry with high-quality pozzolanic components [5]. It has a very fine particle size, approximately 100 times finer than cement, and contains a high concentration of pozzolanic material [6]. Silica fume reacts with $Ca(OH)_2$ during cement hydration to form a calcium silicate hydrate (C-S-H) gel that has excellent binding properties [6], [7].

Stone dust is another useful material in concrete mix, a byproduct of rock crushing industry. The quantity of stone dust increases with the demand for aggregates for construction. However, the uncontrolled disposal can lead to environmental problems. Due to similar composition, stone dust is used as substitute for fine aggregate to enhance the workability and compressive strength of concrete [7].

Previous investigations have independently examined the incorporation of silica fume and stone dust in self-compacting concrete formulations. The utilization of silica fume as partial cement replacement within the 5-15% range has demonstrated compressive strength enhancement ranging from 8.6% to 19.0% [8]. Conversely, stone dust application as fine aggregate substitute has been investigated across replacement levels spanning 10-40%. Research evidence indicates that stone dust replacement up to 30% can enhance both workability and compressive strength characteristics, whereas replacement exceeding 30-40% without compositional adjustments may compromise concrete performance [9]. A limited number of investigations have attempted to combine silica fume and stone dust in self-compacting concrete systems. Karthick and Nirmalkumar [10] documented that a combination comprising 20% silica fume and 20% stone dust yielded high-strength self-compacting concrete with optimal performance based on slump-flow, V-funnel, L-box testing, and scanning electron microscopy analysis. Additional research has explored mechanical aspects of these combined materials. However, these investigations have generally been confined to several discrete replacement percentage points and have not systematically explored the interaction mechanisms between both materials across broader ranges. Therefore, this research aimed to analyze the effect of stone dust as sand substitute material on the mechanical properties of SCC using silica fume to enhance performance and limit industrial waste. The method focused on optimizing the use of industrial waste as an alternative material to produce high-performance, environmentally friendly SCC.

2 Experimental Investigation

This research was conducted in a laboratory setting using an experimental design. The independent variable was stone dust content, while the dependent variables were concrete compressive strength, modulus of elasticity (MOE), and modulus of rupture (MOR). The experiment on SCC concrete used silica fume, 9% of the cement weight, to substitute for the amount of cement in concrete mix. Meanwhile, stone dust was used to replace the amount of fine aggregate at variations of 0%, 2.5%, 5%, 7.5%, 10%, and 12.5%. Concrete mix design used a water-cement ratio of 0.332 and a superplasticizer of approximately 1.50% of the binder weight. The amounts of each concrete constituent are listed in Table 1.

Table 1. Concrete Mix Design.

Stone dust (%)	Fine aggregate (kg/m3)	Stone dust (kg/m3)	Coarse aggregate (kg/m3)	Cement (kg/m3)	Silica fume (kg/m3)	Super plasticizer (lt/m3)	Water (lt/m3)
0	934.00	0	787	424.06	41.94	6.99	155
2.5	910.65	23.35	787	424.06	41.94	6.99	155
5	887.30	46.70	787	424.06	41.94	6.99	155
7.5	863.95	70.05	787	424.06	41.94	6.99	155
10	840.60	93.40	787	424.06	41.94	6.99	155
12.5	817.25	116.75	787	424.06	41.94	6.99	155

To determine when the test specimens qualify as SCC, testing was performed on fresh concrete. The parameters tested for SCC included filling, passing ability, and resistance to segregation. These tests showed the fresh concrete mix capacity to flow and stay uniform during casting. Each parameter was evaluated using slump flow, L-box, and V-funnel testing. To assess the mechanical properties of concrete, testing for compressive strength, MOE, and MOR was performed. These tests were carried out at 28 days of age utilizing a compression testing machine. The specimens for the compressive strength and MOE testing were cylindrical, measuring 15 cm in diameter and 30 cm in height. For the MOR, a beam measuring 10 x 10 x 40 cm was used and tested with a universal testing machine.The purpose of testing concrete's compressive strength was to measure how much load it can withstand until it fails. Testing was performed following ASTM C39/C39M-21 standards [11]. Concrete compressive strength value can be calculated using Equation 1.

$$fc' = \frac{P}{A} \quad (1)$$

where:
fc' : Concrete compressive strength (MPa or N/mm^2)
P : Axial compressive force (N)
A : Concrete cross-sectional area (mm^2)

MOE was tested according to ASTM C469-02 standards using a compression testing machine and a cylindrical compressometer [12]. The data applied on load and concrete deformation were used to create a stress-strain relationship graph, where MOE value was calculated using Equation 2.

$$MOE = \frac{\sigma}{\varepsilon} \quad (2)$$

where:
MOE : Concrete's Modulus of Elasticity (MPa)
σ : Stress (MPa) = $\frac{P}{A}$
ε : Strain = $\frac{\Delta L}{L}$
ΔL : Deformation of the testing specimen (mm)
L : Original length of the testing specimen (mm)

MOR measures the ability of concrete to resist bending loads before cracking, which provides essential information about the ability of concrete to handle tensile forces caused by bending moments in structures like beams or plates. Specifically, MOR is determined through flexural tensile testing following ASTM C293/C293M-16 standards [13]. In this testing, concrete specimen is placed on two supports and loaded at its center. When the load is applied, deflection occurs, creating tensile stress at the bottom of the specimen and compressive stress at the top, as shown in Figure 1. When the tensile stress reaches its maximum, concrete will crack.

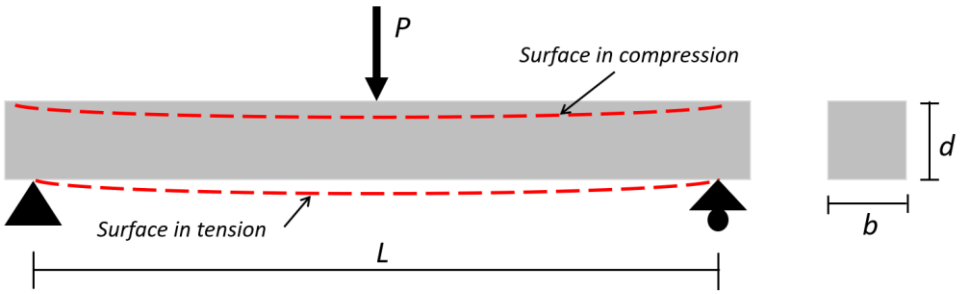

Fig. 1. MOR Testing

MOR can be calculated based on Equation 3:

$$MOR = \frac{3PL}{2bd^2} \quad (3)$$

where :
MOR : Modulus of rupture (MPa)
P : Maximum total load on the testing beam (N)
L : Beam span length (mm)
b : Width of the testing beam (mm)
d : Height of the testing beam (mm)

3 Experimental Results and Discussion

The results of the fresh concrete testing were compared with the EFNARC 2005 regulatory standards [14]. Table 2 shows that all variations in stone dust content meet the requirements for the SCC category.

Table 2. Fresh Concrete Testing Results

Stone dust content (%)	Slump Flow Testing				L-box Testing		V-funnel Testing	
	T_{500} (second)	Standard EFNARC 2005	Diameter (mm)	Standard EFNARC 2005	H_2/H_1	Standard EFNARC 2005	Time (second)	Standard EFNARC 2005
0	3.53	2-5 second	740	600-800 mm	0.96	0.8-1	7.11	6-12 second
2.5	3.69		726		0.93		7.35	
5	3.78		705		0.92		7.47	

7.5	3.83		697		0.89		7.70	
10	4.14		681		0.85		7.98	
12.5	4.22		675		0.81		8.69	

The results of concrete compressive strength, MOE, and MOR testing for each level of stone dust content are indicated in Table 3.

Table 3. Concrete Compressive Strength, MOE, and MOR Testing Results

Stone dust content (%)	Concrete Compressive Strength (MPa)	MOE (MPa)	MOR (MPa)
0	49.83	20280.37	5.85
2.5	53.52	20464.28	7.26
5	54.69	21420.23	8.50
7.5	50.90	19916.78	7.47
10	45.35	17265.22	6.55
12.5	42.83	15118.58	5.45

As shown in Figures 2 through 4, the compressive strength, MOE, and MOR of concrete increase with higher levels of stone dust, which partially replaces the fine aggregate. Maximum results are observed at stone dust content of 5%. After reaching this peak, the compressive strength, MOE, and MOR of concrete decline.

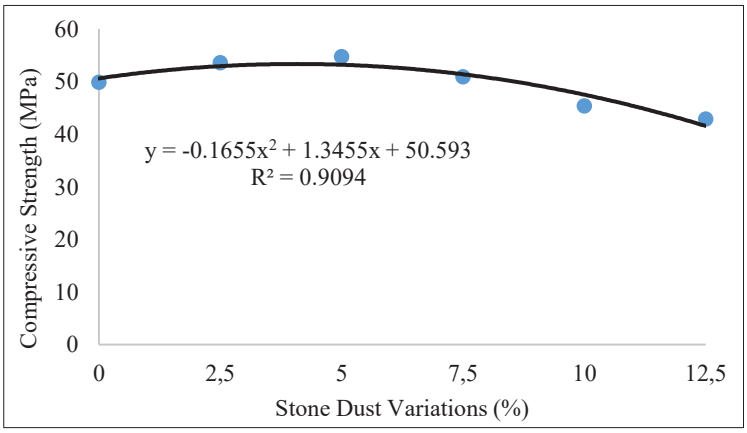

Fig. 2. Graph of the relationship between concrete compressive strength and variations in stone dust content

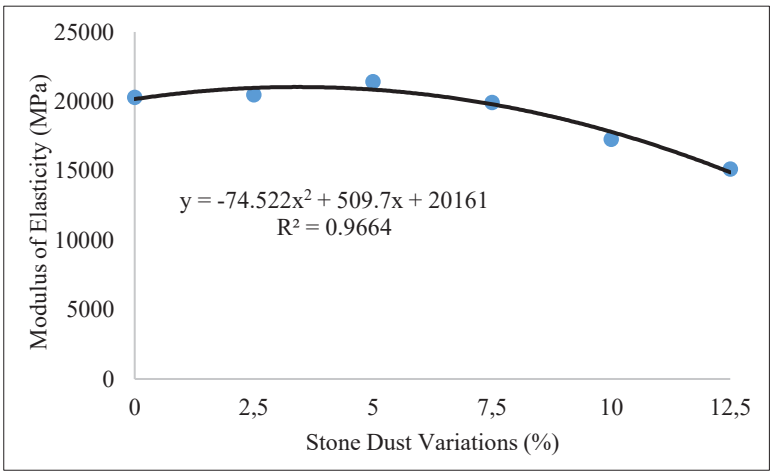

Fig. 3. Graph of the relationship between concrete's MOE and variations in stone dust content.

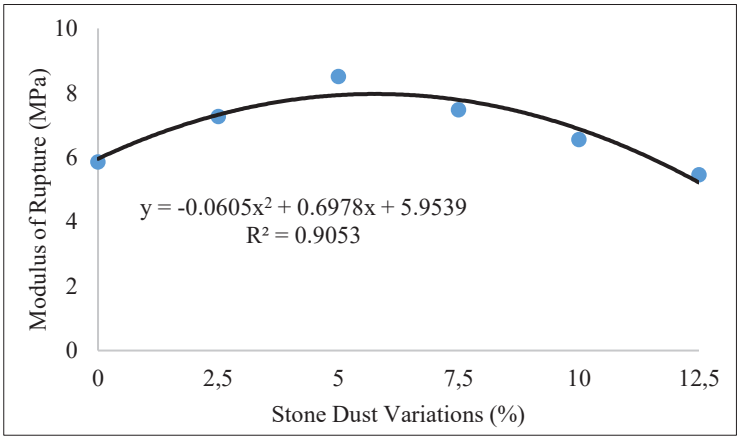

Fig. 4. Graph of the relation between concrete MOR and variations in stone dust content

The results showed that the replacement of stone dust yielded maximum values for compressive strength, MOE, and MOR of concrete, at 54.69 MPa, 214.20.23 MPa, and 8.5 MPa, respectively. The percentage increases compared to concrete with only natural sand were 9.76%, 5.62%, and 45.36%, respectively. After reaching the peak at 5% stone dust content, the compressive strength declined, MOE, and MOR values of concrete. This decline was caused by:

- Silt Content: Stone dust has a higher silt content than sand, which can cause impaired adhesion between stone dust particles and the cement particles. This could decrease the bond strength among particles in the concrete mix.

- Grain size: Stone dust has a smaller grain size than sand, which can reduce the mechanical strength of concrete. A smaller grain size can reduce the interlocking between aggregate particles in concrete mix.
- Load resistance: Stone dust has lower load resistance than sand. This can result in a lower compressive force of the resulting concrete because stone dust is unable to support the applied load effectively.
- Water absorption: Stone dust absorbs water more quickly than sand. This can increase the risk of cracking in concrete structures due to changes in the water volume in concrete mix.

The findings of this investigation align with several previous studies while also revealing notable distinctions. Karthick and Nirmalkumar [10] reported optimal performance at 20% stone dust replacement combined with 20% silica fume in high-strength self-compacting concrete, whereas the present study identifies 5% as the optimal stone dust content when combined with 9% silica fume. This discrepancy suggests that the optimal stone dust proportion is influenced by the silica fume dosage and the specific characteristics of the stone dust source. Similarly, research by Felixkala and Partheeban [15] demonstrated that quarry dust replacement up to 30% enhanced compressive strength in conventional concrete, which differs from the 5% optimum observed in this study for self-compacting concrete, indicating that the rheological requirements of SCC impose more stringent constraints on stone dust replacement levels.

4 Conclusion

The experimental investigation assessed stone dust utilization as fine aggregate replacement in silica fume-modified self-compacting concrete, demonstrating that all tested mixtures with 9% silica fume and stone dust proportions of 0%, 2.5%, 5%, 7.5%, 10%, and 12.5% fulfilled self-compacting requirements while exhibiting compressive strengths of 49.83, 53.52, 54.69, 50.90, 45.35, and 42.83 MPa, MOE of 20280.37, 20464.28, 21420.23, 19916.78, 17265.22, and 15118.58 MPa, and MOR of 5.85, 7.26, 8.5, 7.47, 6.55, and 5.45 MPa, respectively. The data clearly indicate that 5% stone dust replacement yielded optimal mechanical performance across all evaluated parameters, with subsequent increases in replacement level resulting in progressive deterioration of strength and stiffness characteristics.

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