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Performance Modeling of Self-Compacting Concrete: Effects of Admixtures and Curing Conditions

Vishal Bhatt[1], Harsh Rathore[1], Sanjeev Kumar Verma[1,2]

[1]*Department of Civil Engineering, School of Engineering and Technology, Sanjeev Agrawal Global Educational (SAGE) University, Bhopal (Madhya Pradesh), India,*
[2]*Dean Academics, SAM Global University, Raisen, Bhopal Road (M.P.) India*

This research investigates the impact of varying proportions of Metakaolin, M-sand, and steel fibers on the performance of self-compacting concrete (SCC), with a focus on workability, mechanical properties, and durability. SCC's unique self-leveling and self-compacting properties eliminate the need for mechanical vibration, making it an essential material for complex architectural structures. However, incorporating sustainable admixtures like Metakaolin and M-sand poses challenges in balancing workability and strength. The study adopts a factorial experimental design, analyzing 65 mix proportions under three curing conditions: standard moist, steam, and autoclave curing. Key tests include slump flow, compressive strength, and Rapid Chloride Penetration Test (RCPT). The results reveal that higher proportions of admixtures reduce workability and strength but enhance acid resistance and sustainability. This study is useful for bridging critical gaps in the existing knowledge base. The findings provide actionable insights for engineers and researchers aiming to enhance SCC's applicability in modern construction while adhering to sustainability goals.
Keywords: Self-Compacting Concrete (SCC), Metakaolin, M-sand, Steel fibers, Curing conditions, Workability, Mechanical properties.

1. Introduction

1.1 Background

Self-compacting concrete (SCC) is a high-performance material that flows under its weight, eliminating the need for mechanical vibration. SCC's unique properties, such as superior flowability and filling ability, make it ideal for complex architectural and structural elements. However, its performance is influenced by various factors, including admixtures and curing conditions. Several researchers perform work related this - The use of innovative materials and techniques in self-compacting concrete (SCC) has been explored in various studies. Gautam et al. (2023) investigated the use of bone-china ceramic powder waste (BCPW) and granite cutting waste (GCW) as substitutes for cement and natural fine aggregates in SCC. The study found that waste materials could enhance the performance of SCC, although the optimal dosages for maximum benefit remain uncertain (Gautam et al., 2023). Similarly, Jagadesh et al. (2023) developed a machine learning model to analyze SCC with recycled aggregates using several techniques, including Extra Gradient Boosting and Random Forest. While the model offered insights into SCC behavior, its accuracy needs further validation with additional data (Jagadesh et al., 2023).

In another study, Yang et al. (2022) focused on the tensile and compressive creep performance of self-compacting rubberized concrete (SCRC) at early stages. They observed that SCRC showed potential in applications requiring good creep performance, although optimizing the rubber content is essential for improving its overall performance (Yang et al., 2022). Meanwhile, Gültekin et al. (2022) explored the effects of glass or basalt fibers on SCC. Their results indicated that while basalt fibers decreased workability, they improved flexural strength and fracture energy, suggesting that fiber addition needs careful consideration of its effects on various properties (Gültekin et al., 2022).

Sahoo et al. (2022) studied the influence of ground granulated blast furnace slag (GGBFS) on the mechanical and structural properties of SCC. They found that a 20% GGBFS replacement improved structural performance, reducing crack size (Sahoo et al., 2022). Similarly, Ramkumar et al. (2022) assessed the workability and strength of high-flowable SCC incorporating hybrid steel fibers, noting that the inclusion of steel fibers enhanced concrete's performance, though the optimal fiber content remained undetermined (Ramkumar et al., 2022).

Several other studies explored the use of alternative materials like copper slag (ArunChaitanya et al., 2022), tobacco waste ash (Thammaiah et al., 2022), and marble waste (Kumar et al., 2022) in SCC. These materials showed promising results, particularly in improving the compressive strength and durability of concrete, although the optimal dosages and long-term performance require further research (ArunChaitanya et al., 2022; Thammaiah et al., 2022; Kumar et al., 2022).

Further investigations have included the use of waste products such as glass powder, sugar cane bagasse ash, and palm oil fuel ash in SCC, with studies showing improved mechanical properties but highlighting the need for long-term durability assessments (Bharathi et al., 2022; Gupta et al., 2022; Thanh et al., 2021). Other materials like micro-encapsulated phase change materials (MPCM), nano-silica, and graphene oxide have also been explored for enhancing thermal and mechanical properties, though their application requires additional studies on long-term performance and cost-effectiveness (Khalaf et al., 2021; Lee et al., 2022; Gao et al., 2022).

In conclusion, while these studies offer valuable insights into the potential of various materials for enhancing SCC, further research is essential to optimize the dosages, evaluate long-term durability, and address potential environmental and economic challenges associated with their use.

1.2 Problem Statement

Despite advancements in SCC, research lacks a comprehensive understanding of the combined effects of admixtures and curing methods. Existing studies primarily focus on isolated factors, leaving a gap in optimizing SCC for various applications.

1.3 Objectives

a) To analyze the effects of Metakaolin, M-sand, and steel fibers on SCC properties.

b) To evaluate the impact of curing conditions, including standard, steam, and autoclave curing.

c) To identify optimal combinations of admixtures and curing methods.

d) To develop a performance model to guide SCC optimization.

2. Methodology

2.1 Materials

a) Cement: Ordinary Portland Cement (Grade 43).

b) Fine Aggregate: M-sand as a sustainable alternative to river sand.

c) Coarse Aggregate: Crushed stone (10-12.5 mm).

d) Admixtures: Metakaolin, steel fibers, polycarboxylate ether superplasticizer, and viscosity-modifying agents.

e) Water: Potable water, maintaining a water-cement ratio of 0.35.

2.2 Mix Design

a) SCC mixes were prepared with varying proportions of Metakaolin (5%-20%), M-sand (5%-20%), and steel fibers (0.5%-2.0%).

b) A control mix without replacements was used for baseline comparisons.

2.3 Testing Procedures

a) Workability: Slump flow, T50 flow time, and V-funnel tests.

b) Mechanical Properties: Compressive and flexural strength tests.

c) Durability: Water absorption, Rapid Chloride Penetration Test (RCPT), and acid resistance.

2.4 Curing Methods

a) Standard Moist Curing: 25±2°C water immersion.

b) Steam Curing: 60±2°C for 8 hours.

c) Autoclave Curing: High-pressure steam at 120±2°C.

3. Experimental Results

The table 1 presents the results of the experiments performed over the prepared 65 specimens. This table highlights the impact of varying proportions of Metakaolin, M-sand, and steel fibers on the workability, compressive strength, and flexural strength of self-compacting concrete. As the admixture levels increase, there is a notable decrease in workability metrics such as slump, flow time, and V-funnel time. For instance, mix 1 with 5% Metakaolin, 5% M-sand, and 0.5% steel fibers shows a slump of 160 mm and a compressive strength of 38 MPa, while mix 65 with the highest proportions exhibits a slump of just 40 mm and compressive strength of 4 MPa.

The table-1 also illustrates the interplay between admixture proportions and mechanical properties. While initial increases in steel fibers improve compressive and flexural strength (e.g., mix 4 reaches a peak compressive strength of 44 MPa), excessive proportions lead to significant performance declines. This is particularly evident in mixes with higher M-sand and Metakaolin levels, where strength and workability deteriorate rapidly.

Table 1- Experimental Results

Mix No	Metakaolin (%)	M sand (%)	Steel Fibers (%)	Slump (mm)	Flow Time (s)	V-Funnel Time (s)	Compressive Strength (MPa)	Flexural Strength (MPa)
1	5	5	0.5	160	11	19	38	7
2			1	170	10	18	40	8
3			1.5	180	9	17	42	9
4			2	190	8	16	44	10
5	5	10	0.5	150	12	20	35	6
6			1	160	11	19	38	7
7			1.5	170	10	18	40	8
8			2	180	9	17	42	9
9	5	15	0.5	140	13	21	30	5
10			1	150	12	20	32	6
11			1.5	160	11	19	35	7
12			2	170	10	18	38	8
13	5	20	0.5	130	14	22	28	4
14			1	140	13	21	30	5
15			1.5	150	12	20	32	6
16			2	160	11	19	35	7
17	10	5	0.5	120	15	23	25	3.5
18			1	130	14	22	28	4
19			1.5	140	13	21	30	5
20			2	150	12	20	32	6
21	10	10	0.5	110	16	24	20	2.5
22			1	120	15	23	25	3.5
23			1.5	130	14	22	28	4
24			2	140	13	21	30	5
25	10	15	0.5	100	18	26	18	2
26			1	110	16	24	20	2.5
27			1.5	120	15	23	25	3.5
28			2	130	14	22	28	4
29	15	20	0.5	90	20	28	15	1.5
30			1	100	18	26	18	2
31			1.5	110	16	24	20	2.5
32			2	120	15	23	25	3.5
34	15	5	0.5	80	22	30	12	1
35			1	90	20	28	15	1.5
36			1.5	100	18	26	18	2

38			2	110	16	24	20	2.5
39	15	10	0.5	70	24	32	10	1
40			1	80	22	30	12	1.5
41			1.5	90	20	28	15	2
42			2	100	18	26	18	2.5
42	15	15	0.5	60	26	34	8	1
43			1	70	24	32	10	1.5
44			1.5	80	22	30	12	2
45			2	90	20	28	15	2.5
46	20	20	0.5	50	28	36	6	0.8
47			1	60	26	34	8	1
48			1.5	70	24	32	10	1.5
49			2	80	22	30	12	2
50	20	5	0.5	40	30	38	4	0.6
51			1	50	28	36	6	0.8
52			1.5	60	26	34	8	1
53			2	70	24	32	10	1.5
54	20	10	0.5	30	32	40	2.5	0.4
55			1	40	30	38	4	0.6
56			1.5	50	28	36	6	0.8
57			2	60	26	34	8	1
58	20	15	0.5	20	34	42	1	0.3
59			1	30	32	40	2	0.4
60			1.5	40	30	38	4	0.6
61			2	50	28	36	6	0.8
62	20	20	0.5	10	36	44	0.5	0.2
63			1	20	34	42	1	0.3
64			1.5	30	32	40	2	0.4
65			2	40	30	38	4	0.6

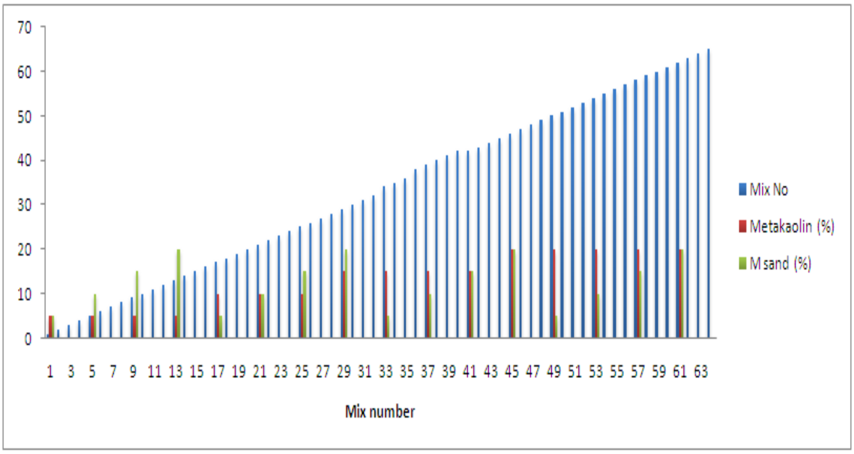

Figure 1 – Mix proportions considered

3.1 Major observations

Workability decreased with higher proportions of Metakaolin, M-sand, and steel fibers.

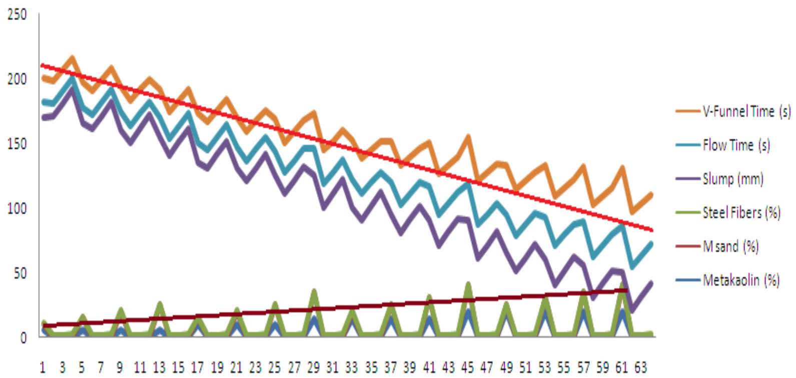

Figure 2- Relationship between workability and admixture propotions

Strength decreased with increasing admixture proportions. Optimal compressive strength (38 MPa) was observed for 5% Metakaolin and 5% M-sand.

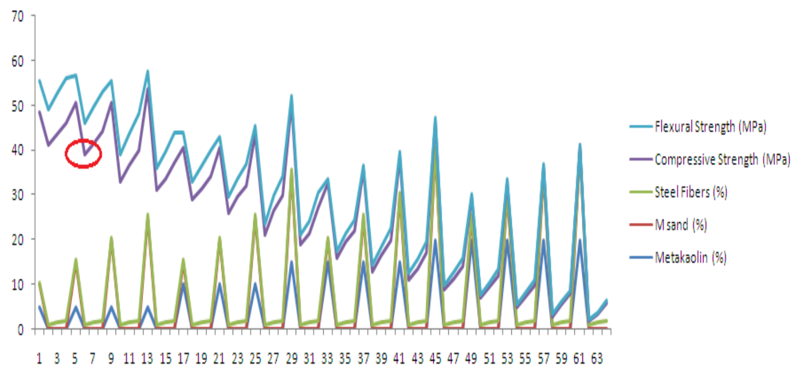

Figure 3: Strength vs. Admixture Proportion.

3.3 Durability

- Higher admixture levels increased water absorption and RCPT values, indicating reduced durability.
- Acid resistance improved marginally with moderate levels of Metakaolin and M-sand.

4. Data Analysis and Discussion

4.1 Statistical Analysis

- Analysis revealed significant effects of admixture proportions on SCC properties.
- Regression models demonstrated high predictive accuracy for compressive strength and workability.

4.2 Curing Conditions

Steam and autoclave curing enhanced early strength, with autoclave curing yielding the highest compressive strengths. However, long-term performance under these curing regimes requires further evaluation. Three curing methods (standard moist curing, steam curing, and autoclave curing) were evaluated for their impact on SCC properties. Table 2 highlights the compressive strength results under different curing regimes for selected mixes.

Table 2: Compressive Strength under Different Curing Conditions

Mix No	Curing Method	Compressive Strength (MPa)
8	Standard Moist	42
8	Steam	45
8	Autoclave	48
29	Standard Moist	12
29	Steam	14
29	Autoclave	16

4.3 Optimization

The trade-off between sustainability and performance necessitates balanced mix designs. The findings suggest optimal proportions of 5%-10% Metakaolin, 5%-10% M-sand, and 0.5%-1.0% steel fibers.

5. Conclusions and Recommendations

5.1 Key Findings

a) Increasing the proportions of Metakaolin, M-sand, and steel fibers was found to significantly reduce workability, as evidenced by lower slump flow and longer V-funnel times.

b) Mechanical properties, such as compressive and flexural strengths, decreased with higher admixture levels due to challenges in achieving adequate particle packing and bonding.

c) Steam and autoclave curing methods were highly effective in mitigating the strength losses typically associated with high admixture proportions, promoting rapid strength gain and improved durability indices.

d) Optimal SCC mix designs that included moderate levels of Metakaolin (5%-10%) and M-sand (5%-10%) combined with steel fibers (0.5%-1.0%) demonstrated a balance between sustainability and structural integrity.

e) The use of sustainable materials such as Metakaolin and M-sand contributed to reduced environmental impact without compromising essential performance characteristics.

f) Durability tests indicated that mixes with controlled proportions of admixtures exhibited better acid resistance and satisfactory chloride ion penetration resistance, making them suitable for harsh environmental conditions.

5.2 Future Work

a) Conduct long-term studies on the durability and environmental impact of SCC mixes optimized with sustainable materials.

b) Extend the research to include a broader range of admixtures and innovative curing techniques to expand practical applications.

5.3 Practical Implications

This study establishes a robust foundation for designing sustainable, high-performance SCC, offering insights for practical applications in modern construction. By addressing both environmental concerns and engineering requirements, it facilitates the adoption of SCC in projects demanding cost-effectiveness and superior performance.

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