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Analytical exploration of self-consolidating concrete (SCC) mix proportions via the Taguchi method

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Abstract

To address the challenge of limited space within structural elements containing densely packed reinforcement, Self-Compacting Concrete (SCC) was developed. This study focuses on optimizing the experimentation process using Design of Experiments (DoE). Taguchi's standard L(3) orthogonal array (OA) was utilized, consisting of four factors with three levels each, resulting in nine trial mixes. The factors examined include water-powder ratio, cementitious material content, superplasticizer dosage, and steel fiber content. The aim is to maximize both compressive and tensile strength of the SCC. The results indicate that specific proportions of the constituent materials lead to enhanced compressive and split tensile strength. Notably, steel fibers and fly ash content significantly contribute to strength improvement, while the dosage of superplasticizer plays a crucial role in influencing the fresh concrete characteristics of SCC.

Keywords: Self Compacting Concrete (SCC), Design Of Experiment (Doe), Super Plasticizer, Fly Ash, High Range Water Reducers, Compressive Strength, Split Tensile Strength And Steel Fibre.

Introduction

Journal of Geotechnical Engineering
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Self compacting concrete (SCC) is a specialized form of concrete, enhanced with Super Plasticizers and Viscosity Modifying Agents (VMA), that eliminates the need for manual compaction and naturally expels air voids during its placement. This unique composition enables SCC to achieve thorough compaction effortlessly, preserving its strength and durability without requiring significant external force. This characteristic not only makes SCC efficient but also contributes to its sustainability by conserving energy[1-6].

The advancement of self-compacting concrete (SCC) within the construction industry is pivotal for addressing the challenges associated with traditional cast-in-place concrete methods. SCC's ability to achieve optimal compaction without being affected by factors such as reinforcement configuration, labor skill, or structural layout is attributed to its exceptional fluidity and resistance to segregation, allowing it to be pumped over longer distances with ease.

The inception of self-compacting concrete can be traced back to 1986 when Professor Hajime Okamura first proposed the concept, subsequently leading to the development of a prototype at the University of Tokyo in Japan in 1988. The mechanism behind SCC's self-compactability involves not only the high deformability of its mortar but also its ability to flow effectively around and through the confined spaces of reinforcing bars[7-12].

Achieving self-compactability involves more than just the deformability of the paste; it also entails resistance to segregation between coarse aggregate and mortar as the concrete flows through the confined spaces of reinforcing bars. The key characteristic of self-compacting concrete (SCC) is its homogeneity, which enables it to remain unsegregated during transportation and placement[13-18].

Objectives

Following are the objectives of this work.

Journal of Geotechnical Engineering
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Publication date:10-4-2024

i. To develop a systematic methodology for determining the optimum proportions of different parameters which gives high flow ability, passing ability and highest value of compressive strength and tensile strength.
ii. To analyze the influence of different factors at different levels by using Taguchi method (DoE).

Material

Cementitious Material: For all test specimens, we utilized Ordinary Portland cement (53 Grade), with its characteristics assessed according to IS 12269-1987 standards. The specific gravity of the cement was measured at 3.13, while its standard consistency was found to be 34%[19].

B. Fly Ash: Fly ash is a residual product obtained from coal-based industries or thermal power plants. Typically, it is collected from the boiler or the bottom of the plant, also known as bottom ash. This fine particulate matter is gathered using electrical precipitators. Historically, fly ash was disposed of through chimneys into the atmosphere as industrial waste. However, it has gained significant importance in construction due to its mineral content, making it suitable for use as a mineral admixture or a by-product in cement production. Fly ash, previously considered waste, has become an essential material in construction, particularly evident in the production of Portland pozzolana cement and the widespread use of fly ash bricks[20-22].

Class C Fly Ash: This type of fly ash is derived from the burning of sub-bituminous coal or lignite coal. It possesses high lime content but relatively low amounts of silica, alumina, and iron[23].

Class F Fly Ash: Produced through the combustion of anthracite coal or bituminous coal, Class F fly ash contains low lime content but higher levels of silica, iron, and alumina[24].

Journal of Geotechnical Engineering
Research paper
Vol 11,issue 1,2024
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Fine Aggregates The fine aggregate employed in this study is ordinary sand, free from contaminants, and has passed through a 4.75 mm IS sieve. Its specific gravity was determined to be 2.65[25].

Coarse Aggregates: Locally sourced coarse aggregate, passing through a 20 mm IS sieve and retained on a 10 mm IS sieve, was utilized. The specific gravity of the coarse aggregate was measured at 2.8.

Super Plasticizer: CERA HYPERPLAST XR-W40, a high-range water-reducing admixture, was used in this research. This admixture, belonging to the polycarboxylate ether group, exhibits a pale yellow color and has a specific gravity of 1.08.

F. Fibers: This study incorporates three types of commercially available steel fibers, each with an aspect ratio (length to diameter ratio) of 50.

Methodology

Experimental Design: The Design of Experiment (DoE) serves as a systematic approach aimed at enhancing the quality of specific material parameters. In this research, we conducted an experimental investigation to assess the impact of steel fibers at various dosages of cementing material and superplasticizer. To optimize the experimentation process, we employed the Design of Experiments (DoE) pioneered by Taguchi. This method, also known as the "Taguchi method," utilizes improved techniques to simultaneously reduce the number of experiments required. We evaluated nine mixes of self-compacting concrete (SCC), with detailed compositions provided in Table 1.

Table 1- Mix Parameters and their levels

Variable	Water Cement Ratio	Fly Ash	Steel Fibres	Super plasticizer

Journal of Geotechnical Engineering
Research paper
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Acceptance date:9-4-2024
Publication date:10-4-2024

	Code	Absolute	Code	Absolute	Code	Absolute	Code	Absolute
1	P1	0.4	Q1	0	R1	50	S1	0.8
2	P2	0.38	Q2	20	R2	30	S2	1.2
3	P3	0.36	Q3	40	R3	15	S3	1.6

Result and Discussion

In this investigation, we employed a standard L9 (34) orthogonal array (OA) consisting of four parameters, each with three levels of material factors, allowing for the variation of a total of nine trial mixes. The L9 orthogonal array, as detailed in Table 2, was utilized for this purpose. Optimization was conducted using Taguchi's method. Table 2 presents the design matrix of the L9 (3^4) orthogonal array, indicating the parameters along with their respective coding Fig 1-10.

Table 2 Design matrix of L_9 (3^4) orthogonal array with parameters and their coding

Variable	Variable 1		Variable 2		Variable 3		Variable 4	
	Water Cement Ratio (%)		Fly Ash (%)		Steel Fibres (mm)		Superplasticizer (%)	
	Code	Absolute	Code	Absolute	Code	Absolute	Code	Absolute
1	P1	0.4	Q1	0	R1	50	S1	0.8
2	P1	0.4	Q2	20	R2	30	S2	1.2
3	P1	0.4	Q3	40	R3	15	S3	1.6
4	P2	0.38	Q1	0	R2	30	S3	1.6
5	P2	0.38	Q2	20	R3	15	S1	0.8
6	P2	0.38	Q3	40	R1	50	S2	1.2

Journal of Geotechnical Engineering
Research paper
Vol 11,issue 1,2024
Receiving date:03-4-2024
Acceptance date:9-4-2024
Publication date:10-4-2024

7	P3	0.36	Q1	0	R3	15	S2	1.2
8	P3	0.36	Q2	20	R1	50	S3	1.6
9	P3	0.36	Q3	40	R2	30	S1	0.8

The evaluation of self-compacting concrete (SCC) mixes was carried out using typical proportion materials, and the details of these mixes are provided in Table 3.

Table 3 Details of Mix Proportion

Experiment No.	Water (kg/m3)	Cement (kg/m3)	Fly ash (kg/m3)	F.A (kg/m3)	C.A (kg/m3)	HRWR (kg/m3)	Steel fibres (kg/m3)
1	215	510	0	1008	781	4.08	4.4
2	215	408	102	1008	781	6.12	4.4
3	215	306	204	1008	781	8.16	4.4
4	194	510	0	1008	781	8.16	4.4
5	194	408	102	1008	781	4.08	4.4
6	194	306	204	1008	781	6.12	4.4
7	174	510	0	1008	781	6.12	4.4

Journal of Geotechnical Engineering
Research paper
Vol 11,issue 1,2024
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Publication date:10-4-2024

8	174	408	102	1008	781	8.16	4.4
9	174	306	204	1008	781	4.08	4.4

The purpose is to pick the best mixture of control parameters so that the product or process is most robust. The obtained results are given in table 4:

Table 4- Experimental Results

Experiment No.	**Fresh concrete test**		**Hardened concrete test**			
	Slump flow(mm)	**L-box (h2/h1)**	**Compressive strength (MPa)**		**Split tensile strength (MPa)**	
			7th day	**28th day**	**7th day**	**28th day**
Mix no.1	692	0.89	28	38	2.05	2.57
Mix no.2	710	0.94	26	42	2.02	2.92
Mix no.3	730	0.96	25	40	2	2.85
Mix no.4	700	0.94	34	46	2.22	2.88
Mix no.5	692	0.89	28	44	2.16	3.02
Mix no.6	690	0.86	23	39	1.96	2.48
Mix no.7	668	0.84	32	42	2.32	2.98

Journal of Geotechnical Engineering
Research paper
Vol 11,issue 1,2024
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Acceptance date:9-4-2024
Publication date:10-4-2024

Mix no.8	685	0.86	26	40	2.14	2.8
Mix no.9	680	0.86	26	39	2.12	2.82

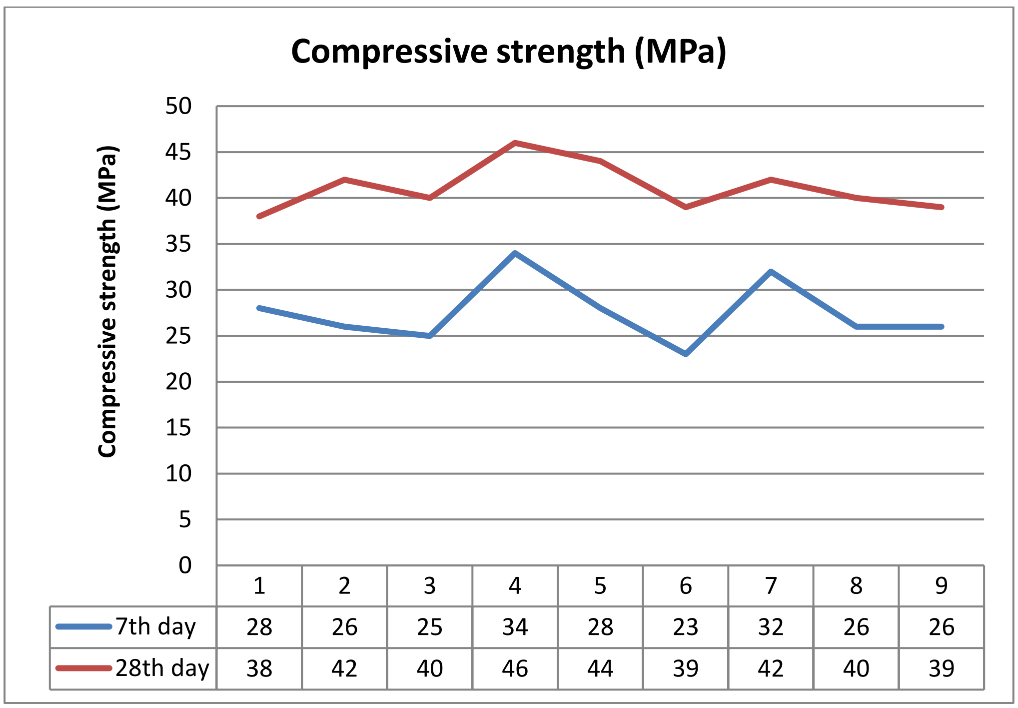

Fig-1. 7 days and 28 days Compressive Strength

Journal of Geotechnical Engineering
Research paper
Vol 11,issue 1,2024
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Publication date:10-4-2024

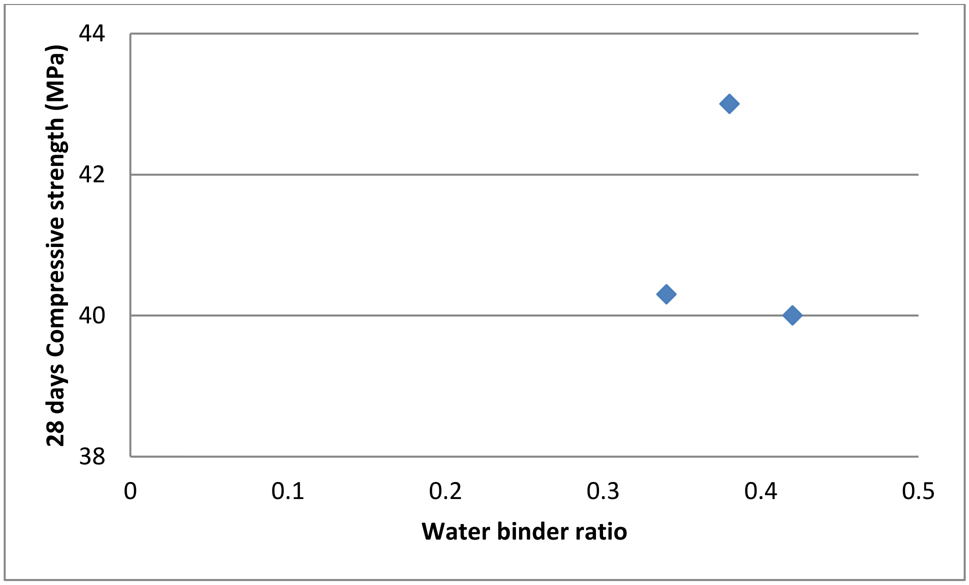

Fig-2. 28 Days Compressive Strength vs Water Binder Ratio

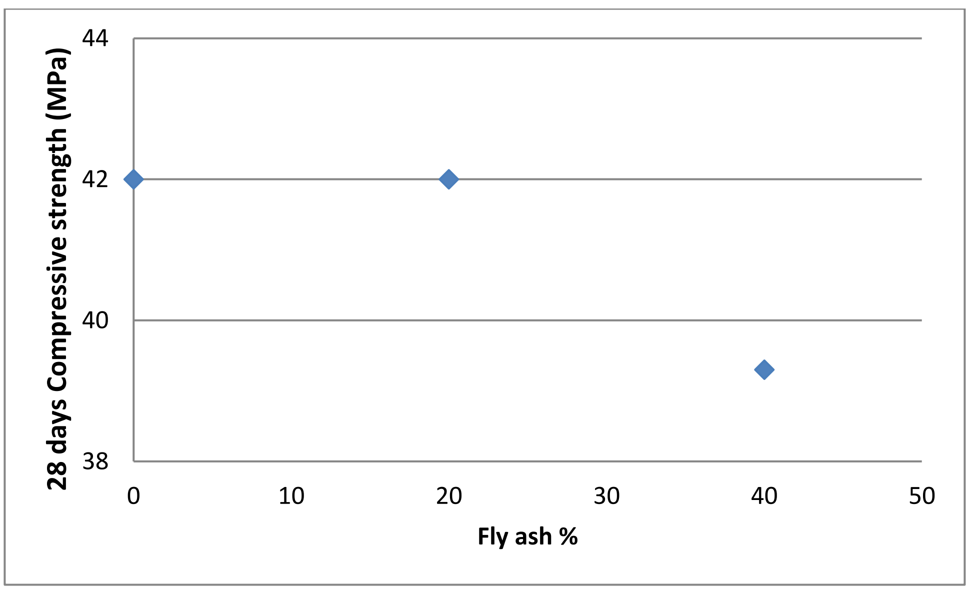

Fig-3. 28 Days Compressive Strength vs Fly Ash Content

Journal of Geotechnical Engineering
Research paper
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Publication date:10-4-2024

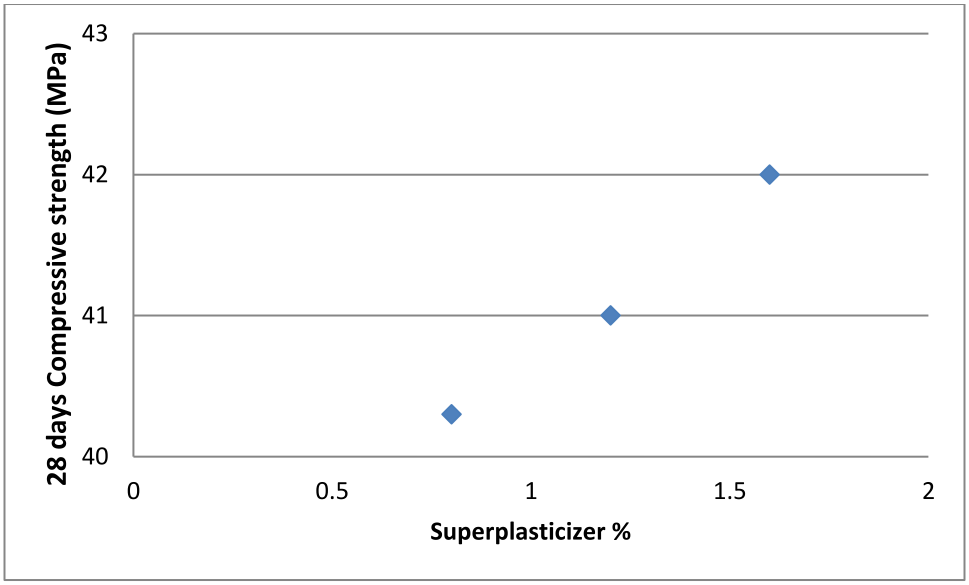


Fig-4. 28 Days Compressive Strength vs Superplasticizer %

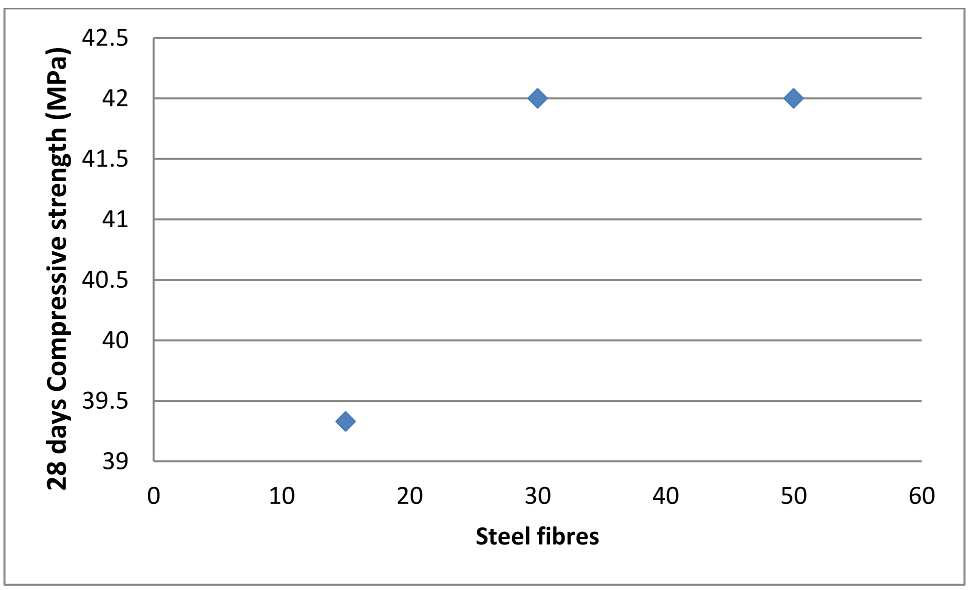
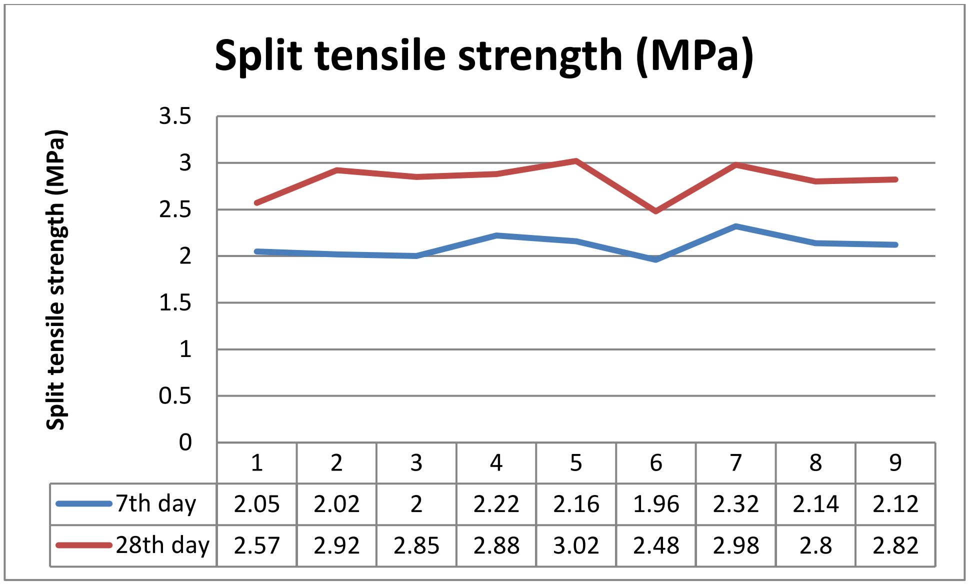


Fig-5. 28 Days Compressive Strength vs Steel Fibres

Journal of Geotechnical Engineering
Research paper
Vol 11,issue 1,2024
Receiving date:03-4-2024
Acceptance date:9-4-2024
Publication date:10-4-2024



	1	2	3	4	5	6	7	8	9
7th day	2.05	2.02	2	2.22	2.16	1.96	2.32	2.14	2.12
28th day	2.57	2.92	2.85	2.88	3.02	2.48	2.98	2.8	2.82

Fig-6. 7 days and 28 days Split Tensile Strength

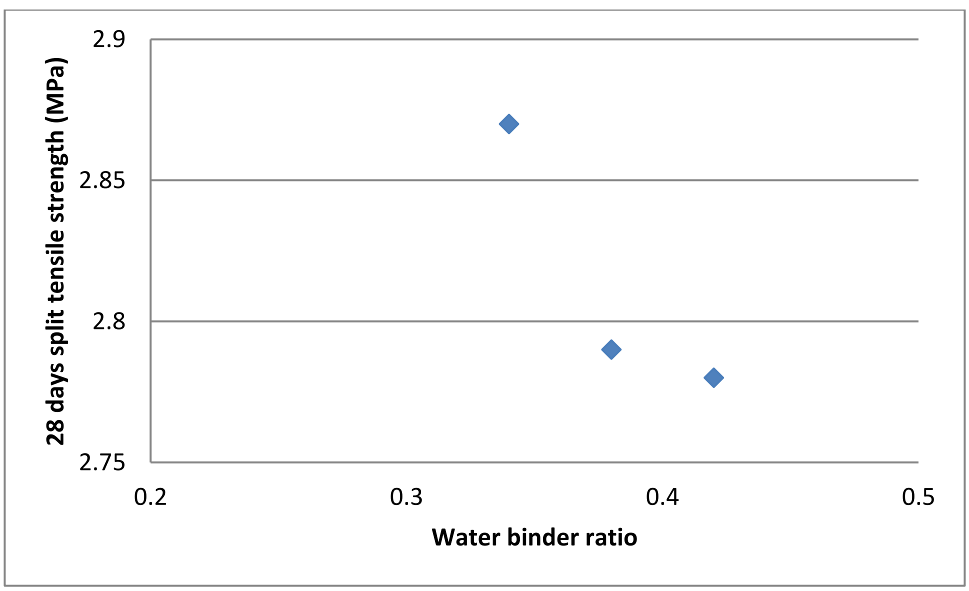


Fig-7. 28 Days Split Tensile Strength vs Water Binder Ratio

Journal of Geotechnical Engineering
Research paper
Vol 11,issue 1,2024
Receiving date:03-4-2024
Acceptance date:9-4-2024
Publication date:10-4-2024

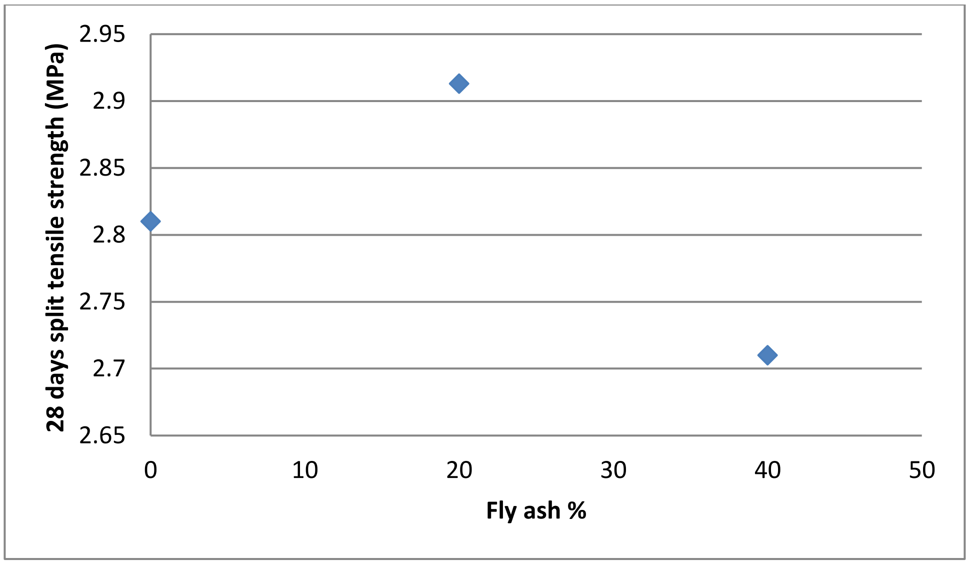


Fig-8. 28 Days Split Tensile Strength vs Fly ash %

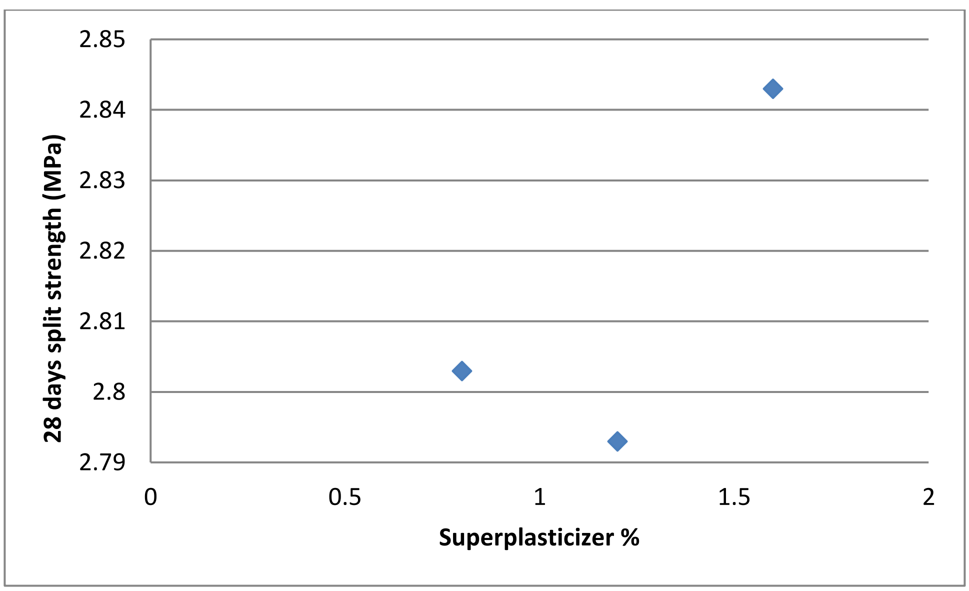


Fig-9. 28 Days Split Tensile Strength vs Superplasticizer %

Journal of Geotechnical Engineering
Research paper
Vol 11,issue 1,2024
Receiving date:03-4-2024
Acceptance date:9-4-2024
Publication date:10-4-2024

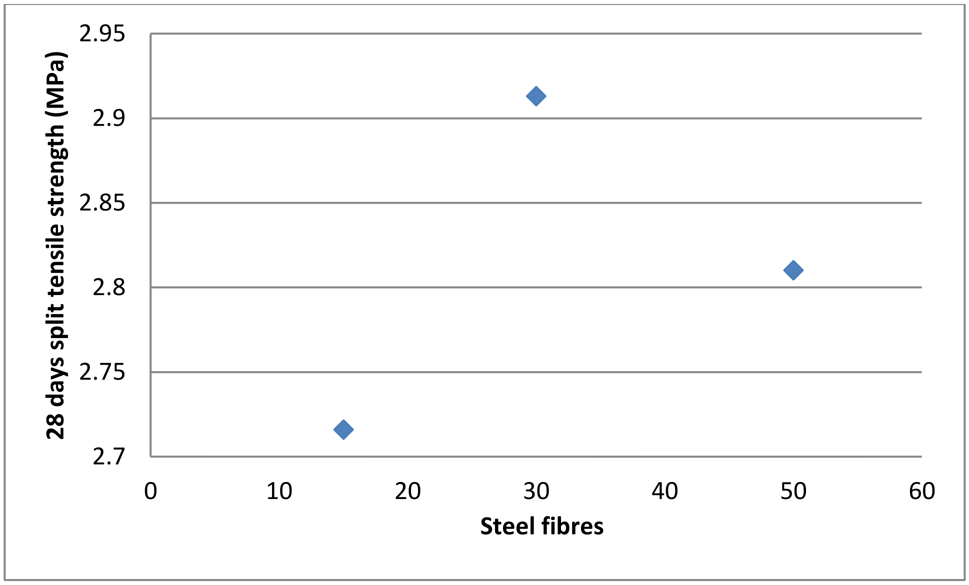


Fig-10. 28 Days Split Tensile Strength vs Steel fibres

The research findings revealed optimal proportions for various properties of the self-compacting concrete (SCC) mixes. For slump flow and L-box results, the most effective combination included a water powder ratio of 0.42% (P1), 40% fly ash content (Q3), 15mm steel fiber type (R3), and a superplasticizer content of 1.6% (S3). Satisfactory passing ability ratios were observed across all trials. Regarding compressive strength, the recommended ratios for both 7th and 28th days involved a water powder ratio of 0.38% (P2), 0% fly ash content (Q1), 30mm steel fiber type (R2), and a superplasticizer content of 1.6% (S3). Similarly, optimal ratios for split tensile strength varied, with key factors including a water powder ratio of 0.34% (P3) for 7th-day strength and 0.38% (P2) for 28th-day strength, along with variations in fly ash content, steel fiber type, and superplasticizer content. Notably, increasing fly ash percentage improved

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Acceptance date:9-4-2024
Publication date:10-4-2024

flowability and passing ability, with the most effective dosage observed at 40% replacement of cement material. Conversely, the optimal superplasticizer dosage of 1.6% by weight of cement significantly influenced SCC's fresh behavior, enhancing its self-compacting features.

Conclusions

i. Based on the experimental findings, all nine mixes demonstrate the ability to achieve high-strength concrete without the need for vibration, meeting the workability requirements outlined by EFNARC for SCC.
ii. A consistent decrease in workability characteristics (including passing ability, filling ability, and segregation resistance) is observed in the SCC mixes as the water-cement ratio decreases.
iii. It is evident that an increase in the water-cement ratio correlates with a decrease in strength characteristics.
iv. The research concludes that integrating steel fibers of various lengths (50mm, 30mm, and 10mm) into self-compacting concrete is feasible. Among these lengths, the 30mm fibers demonstrate optimal conditions for compressive strength, while the 15mm fibers excel in tensile strength.
v. The utilization of steel fibers and fly ash, both of which are waste materials, in concrete production contributes to environmental sustainability.
vi. Incorporating these materials enables cost-effective construction practices.

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Journal of Geotechnical Engineering
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Receiving date:03-4-2024
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Journal of Geotechnical Engineering
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