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INVESTIGATION OF SELF-COMPACTING CONCRETE UTILIZING DIFFERENT SUPPLEMENTARY POZZOLANIC MATERIALS FOR CEMENT REPLACEMENT

C. Rajamallu[1], Durga Chaitanya Kumar Jagarapu[2], M. Karthik Kumar[1], Arunchaitanya Sambangi[3], S. Sai Charan[4], Chiranjeevi Rahul Rollakanti[5] and Shalin Prince[5]
[1]Department of Civil Engineering, Lakireddy Bali Reddy College of Engineering, Mylavaram, India
[2]Department of CE, Koneru Lakshmaiah Education Foundation, Vaddeswaram, Andhra Pradesh, India
[3]Department of CE, Seshadri Rao Gudlavalleru Engineering College, Gudlavalleru, Andhra Pradesh, India
[4]Department of CE, Sir C R Reddy College of Engineering, Eluru, Andhra Pradesh, India
[5]Department of Civil and Mechanical Engineering, Middle East College, Muscat, Oman
E-Mail: jd2sai@yahoo.co.in

ABSTRACT

This study enhances self-compacting concrete (SCC) properties by adjusting the mix design, reducing the water-to-cement ratio, and adding permeability-reducing admixtures (GGBS, fly ash, silica fume, bentonite). Different admixture proportions were tested to improve mechanical characteristics. Four SCC mixtures were formulated, varying GGBS and fly ash (0-70%) and silica fume and bentonite (0-20%). Auromix 300 plus (0.6% by weight of cement) was used as a chemical admixture. Strength properties (compressive, flexural, split tensile, elastic modulus) were evaluated on specimens cured normally for 28 days, then in NaCl for 56-112 days. Optimal mixtures were found: GGBS 30% for compressive strength, bentonite 10% for flexural and split tensile strength. Results indicate increased strength and reduced porosity by incorporating these materials.

Keywords: GGBS, silica fume, fly ash, bentonite, Auromix 300 plus, self-compacting concretes.

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1. INTRODUCTION

The shelter is a fundamental human need, and concrete stands as the cornerstone of modern construction, comprising a mixture of cement, sand, crushed rock, and water. As the world's most ubiquitous construction material, concrete offers versatility, as it can be molded into various shapes and sizes on-site. When reinforced with steel, concrete gains unique strength and durability, making it indispensable in construction projects. Over time, reinforced concrete structures have faced exposure to diverse environmental conditions, leading to deterioration and subsequent maintenance challenges. Recognizing the need for concrete structures with minimal maintenance requirements over their service life, there arises a pressing necessity for the development of highly durable concrete formulations. Achieving this goal necessitates the creation of concrete compositions that prioritize longevity and resilience.

The use of supplementary pozzolanic materials such as fly ash, silica fume, and metakaolin enhances the properties of self-compacting concrete. It discusses the effects of these materials on the workability, strength, durability, and microstructure of SCC [1]. The study investigates the performance of self-compacting concrete incorporating rice husk ash (RHA) as a partial replacement for cement. It evaluates the fresh properties, mechanical properties, and durability aspects of SCC with varying proportions of RHA [2]. The influence of metakaolin on the fresh and hardened properties of self-compacting concrete [3]. It investigates the effects of metakaolin content on the workability, compressive strength, and microstructure of SCC through experimental studies. The effects of silica fume on the properties of self-compacting concrete. It examines the influence of silica fume content on the rheological behavior, mechanical properties, and durability performance of SCC through laboratory experiments and analysis [4]. The utilization of fly ash as a cement replacement in self-compacting concrete. It provides an overview of the properties of SCC incorporating fly ash, including workability, strength development, and durability characteristics based on existing literature [5].

The feasibility and effects of replacing a significant portion of cement with fly ash in SCC [6]. It investigates fresh and hardened properties, focusing on workability, strength, and durability [7]. The incorporation of various waste materials, such as silica fume and palm oil fuel ash, in SCC. They assess fresh properties, mechanical strength, durability, and microstructural characteristics. The performance of SCC with silica fume as a partial cement replacement [8]. It examines fresh and hardened properties, emphasizing strength development and durability enhancement. The influence of nano-silica on SCC properties, including fresh behavior, mechanical strength, and microstructure [9]. They assess the potential of nano-silica as a supplementary material. The impact of metakaolin on SCC properties, focusing on workability, mechanical strength, and durability. It explores the potential benefits of metakaolin as a cement replacement material [10].

2. MATERIALS AND METHODOLOGY

This section provides detailed information about the concrete mixes used, the materials employed, the preparation of test specimens, and the determination of parameters relevant to the study, such as strength and durability. Subsequent sections outline the experimental setup, the conducted tests, and the reference codes utilized throughout the testing process. Fresh concrete underwent laboratory testing to assess its compliance with the self-compacting concrete requirements outlined in the EFNARC guidelines from 2005.

2.1 Material Characterization

2.1.1 Cement

Grade 53 Ordinary Portland cement, adhering to IS: 12269-2013 standards, was utilized. To prevent moisture exposure, the cement was stored in an airtight container within a room with controlled humidity. Laboratory tests were conducted, and the results are presented in Tables 1 and 2.

Table-1. Physical properties of cement.

Properties	Obtained value	Limits as per IS:12269-2013
Specific gravity	3.15	--
Standard consistency	32%	--
Initial setting time	120min	≥ 30 min
Final setting time	280min	≤ 600 min
Strength for 7days	29.3N/mm^2	33
Strength for 28 days	50.63N/mm^2	53

Table-2. Chemical composition of cement.

Chemical Property	Results	Limits as per IS:12269-2013
Lime Saturation Factor (%)	0.82	0.66 min to 1.02 max
Alumina Iron Ratio (%)	1.2	Min 0.665
Insoluble Residue (%)	0.95	Max 2%
Magnesia (%)	2.4	Max 6%
Sulphuric Anhydride (%)	1.1	2.5% to 35
Loss on Ignition (%)	2.2	Max 5%

2.1.2 Fine aggregate

In this study, self-compacting concrete was prepared using natural river sand sourced from zone II of the Krishna River basin in Vijayawada, Andhra Pradesh. The fine aggregate underwent various tests by the IS 383-1970 code to ensure compliance. To control the water content in the concrete, the material was dried at room temperature for 24 hours. The conducted tests, as per IS 383 - 1970 standards, and their outcomes are summarized in Table-3.

Table-3. Physical content of fine aggregate.

S. No.	Content	Value
1	Specific Gravity	2.603
2	Fineness Modulus	2.70
3	Bulk Density (kg/m^3) Loose Compacted	 1610 1682
4	Absorption of Water	1.0
5	Relative density of sand	2.61%

2.1.3 Ground granulated blast furnace slag (GGBS)

The ground-granulated blast-furnace slag (GGBS) used in this study is produced at the VTPS facility in Gannavaram, Andhra Pradesh, India. GGBS, a by-product of iron and steel manufacturing, is formed by rapidly quenching molten iron slag. It possesses high cementitious properties, aiding in the formation of calcium silicate hydrates (CSH) that improve concrete strength, durability, and appearance. When combined with Ordinary Portland cement and other pozzolanic materials, GGBS contributes to resilient concrete structures. Despite its initial latency, GGBS undergoes a secondary reaction with lime from cement, forming crucial compounds for cementation, and enhancing its overall performance.

$$\mathrm{OPC}\ \left({}^{C_3S}/_{C_2S}\right) + H_2O - - - - - - C - S - H + Ca(OH)_2$$

Product of hydration of GGBS:

$$\mathrm{GGBS}\ \left({}^{C_2AS}/_{C_2}\,MS\right) + H_2O - - - - - - - - - - - - - - C - S - H + SiO_2$$

Reaction of Pozzolanic material:

$$SiO_2 + Ca(OH)_2 + H_2O - - - - - - - - - - - - C - S - H$$

Ground-Granulated Blast-Furnace Slag (GGBS) is employed as a partial substitute for cement in concrete at varying proportions of 0%, 30%, 50%, and 70%. This substitution enhances concrete durability and extends the lifespan of structures. The chemical and physical properties of GGBS are detailed in Table-4.

Table-4. Chemical and physical properties of GGBS.

Chemical Properties		Physical Properties	
Lime (CaO)	34.5%	Specific gravity	2.90
Silica (SiO_2)	32%	Blaine's fineness	3350cm^2/gm
Alumina (Al_2O_3)	14.5%	Bulk density	1.0

Iron oxide (Fe_2O_3)	0.7%	Color	off-white

2.1.4 Silica fume

Silica fume is a by-product of the silicon metal extraction process, commonly produced in electric furnaces used for silicon metal and alloy manufacturing. Raw materials such as coal, charcoal, quartz, and wood chips are typically employed in this process. Due to its fine particle size, silica fume is often used as a mineral additive in high-strength concrete production. It boasts a remarkable strength-to-weight ratio and enhances durability by offering corrosion resistance against chemical salts and iron attacks. The physical and chemical characteristics of silica fume are outlined in Table-5.

Table-5. Physical and chemical properties of silica fume.

Chemical Properties		**Physical properties**	
SiO_2	96.90%	Specific Gravity	2.25
Al_2O_3	0.20%	Specific Surface Area	26, 810 kg/m^3
MgO	0.20%	Particle size	0.1µm
CaO	0.30%	Color	Light gray
Fe_2O_3	0.20%		
K_2O	0.30%		
Na_2O	0.20%	**---**	---

2.1.5 Bentonite and its classification

Bentonite, highly plastic clay comprising at least 85% of the clay mineral montmorillonite, owes its name to the American town of Fort Benton, where its discovery and initial applications occurred. Valued commercially for its natural bleaching properties akin to those of fuller's earth, it is sometimes referred to as bleaching clay. Bentonite exists in two primary forms: Swelling (or sodium) bentonite, and non-swelling (or calcium) bentonite. While calcium bentonite is commonly known as bentonite, sodium bentonite is often called fuller's earth. Key properties of bentonite include robust dry bonding strength, high shear and compressive strength, low permeability, and minimal compressibility. For our project, we are employing calcium bentonite. The chemical formula of calcium bentonite is CaO Al2O3 4(SiO2) H2O. Detailed physical and chemical properties of bentonite are provided in Tables 6 and 7, which showcase the characteristics of the bentonite used in this study.

Table-6. Physical properties of bentonite.

S. No.	Property	Test values
1	Color	Light yellow
2	Size	70 microns
3	Swell	60%
4	Nature	Pozzolanic

Table-7. Chemical properties of bentonite.

S. No.	Chemicals Properties	Percentage by Weight (%)
1	$Al2O_3$	21.118
2	$Si0_2$	49.634
3	Fe_2O_3	3.235
4	TiO_2	0.498
5	Na_2O	0.449
6	CaO	0.65

2.1.6 Fly Ash and its classification

Fly ash, a by-product of coal combustion in thermal power plants is annually generated at about 184 million tons. Recognized as a pozzolanic material, it enhances concrete strength and durability as a partial substitute for cement. In this study, fly ash sourced from the NTPS thermal power plant in Vijayawada, Andhra Pradesh, India adheres to IS 3812 (Part 1) 2003 standards. Various concrete mixes with fly ash substitutions ranging from 0% to 70% were evaluated for their properties. Recent research suggests that fly ash can reduce early-age cracking by lowering curing temperatures. Table-8 and 9 detail the physical and chemical properties, and Figure-4 illustrates the specific fly ash utilized.

Table-8. Chemical properties of fly ash.

S. No.	1	2	3	4	5	6	7	8	9
Property	pH	Calcium Oxide (Cao)	Silica (SiO_2)	Alumina (Al_2O_3)	Iron Oxide (Fe_2O3)	Magnesium Oxide (MgO)	Sulphur (SO_3)	Na_2O	Loss of Ignition
Test Values	10.27	7.80	57.60	21.90	2.70	1.68	0.41	10.27	7.8

Table-9. Physical properties of fly ash.

S. No.	Property	Test values
1	Specific Gravity	2.15
2	Fineness(m^2/kg)	450
3	Bulk Density (kg/m^3)	700-800
4	Color	Light Grey

5	Specific area (kg/m^3)	355 kg/m^3

2.1.7 Coarse aggregate

In this experimental study, coarse aggregate with a particle size of 10 mm was sourced from hard broken granite obtained from the batching plant of Koneru Lakshmaiah Education Foundation. The coarse aggregate underwent characterization tests by the IS 383-1970 code to assess its properties. To regulate the water content in the concrete mix, the coarse aggregate was dried at room temperature for 24 hours.

2.1.8 Water

Typically, cement requires hydration with approximately 30% of its weight in water. Water plays a vital role in concrete as it actively engages in chemical reactions with cement and enhances workability. However, it is essential to add water judiciously, as excess water can compromise the strength of concrete and lead to issues like bleeding and segregation.

2.1.9 Admixture

The current study utilizes AUROMIX 300 PLUS as a plasticizer and Glenium Stream 27 as a VMA (Viscosity Modifying Admixture). This information was obtained from M/s Degussa Construction Chemical (India) Pvt. Ltd., Mumbai, the manufacturer of these admixtures. Table-10 displays the properties of these admixtures as provided by the manufacturer. Dosage: The recommended dosage of AUROMIX 300 PLUS typically ranges from 0.5 to 1.5 liters per 100 kg of cementitious material. However, dosages outside this range are permissible, pending trial mixes.

Table-10. Properties of admixture.

S. No.	Description	Value
1	Relative Density	1.085 kg/liter
2	pH	≥ 6
3	Principle constituent	Polycarboxylate Ether
4	Conforming standards	ASTM C-494, EN 934-2, IS 9013
5	Expected water reduction	< 20%
6	Chloride ion content	< 0.2%

3. EXPERIMENTAL TEST RESULTS AND ANALYSIS

3.1 Mix Design

The concrete used was of M40 grade. Various mix proportions were formulated, with cement being substituted by different quantities of GGBS, Fly Ash, Silica Fume, and Bentonite. The percentage change in GGBS and Fly Ash was set at 30%, 50%, and up to 70%, while the percentage change in Silica Fume and Bentonite was set at 5%, 10%, and up to 20%.

3.2 Output Constituent Materials for SCC

Table-11 provides the necessary material quantities for the mixes, including SCC with varying percentages of GGBS, fly ash, Silica fume, and Bentonite, for Mix (M40 Grade) as per IS: 10262-2017 and EFNARC guidelines.

Table-11. Output of constituent materials quantities.

S. No	Mix↓	Slump (mm)	T_{50} (sec)	V-Funnel (sec)	L-Box (h_2/h_1)	U-Box (h_1-h_2) mm	J-Ring (mm)
	Limits→	**640-800**	**2-6**	**7-27**	**0.75 -1.0**	**0 -30**	**0-10**
1	CM	760	5.2	12	0.95	29	6
2	30GGBS	730	5.8	18	0.88	21	7
3	50 GGBS	750	6.3	19	0.90	28	8
4	70 GGBS	770	6.8	22	0.92	30	9
5	30Fly Ash	765	4.8	16	0.84	18	6.5
6	50Fly Ash	730	4.6	18	0.86	20	6.6
7	70Fly Ash	738	4.5	19	0.87	15	6.85
8	5 SF	680	2.9	8	0.76	14	7
9	10 SF	672	4.2	10.4	0.78	22	8
10	15 SF	655	5.3	11.2	0.8	25	8
11	20 SF	650	5.5	11.8	0.82	28	9
12	5 BN	700	3 c	7.8	0.91	15	8
13	10 BN	740	4.5	8.5	0.87	21	8
14	15 BN	750	4	11.4	0.84	25	9
15	20 BN	730	3.5	12.8	0.83	27	9

3.3 Methodology

This section outlines the test methods employed to evaluate the fresh and hardened properties of SCC.

3.4 Fresh Properties Tests of SCC

Commonly used test methods to assess the workability of freshly mixed concrete include the slump, T50, V-Funnel, U-Box, and J-Ring tests. These methods adhere to IS-1199-1959 and EFNARC guidelines and are conducted in the laboratory across various mixtures. The outcomes of these tests are presented in Table-12.

Table-12. Fresh properties of SCC with cement replaced by various % of GGBS, fly ash, silica fume and bentonite for M_{40} mix grade.

S. No	Mix	Cement	GGBS	Fly Ash	SF	BN	F. A	C.A	W/B ratio	Admixture	Water
1	CM	500	0	0	0	0	866.66	839.86	0.4	3	200
2	30GGBS	350	150	0	0	0		827.03	0.4	3	200
3	50 GGBS	250	250	0	0	0		818.07	0.4	3	200
4	70 GGBS	150	350	0	0	0		810.35	0.4	3	200
5	30Fly Ash	350	0	150	0	0		827.03	0.4	3	200
6	50Fly Ash	250	0	250	0	0		818.07	0.4	3	200
7	70Fly Ash	150	0	350	0	0		810.35	0.4	3	200
8	5 SF	350	0	0	25	0		827.03	0.4	3	200
9	10 SF	250	0	0	50	0		818.07	0.4	3	200
10	15 SF	150	0	0	75	0		810.35	0.4	3	200
11	20 SF	350	0	0	100	0		827.03	0.4	3	200
12	5 BN	350	0	0	0	25		827.03	0.4	3	200
13	10 BN	250	0	0	0	50		818.07	0.4	3	200
14	15 BN	150	0	0	0	75		810.35	0.4	3	200
15	20 BN	350	0	0	0	100		827.03	0.4	3	200

3.5 Experimental Outcomes and Discussions

In this study, fresh properties of Self-Compacting Concrete (SCC) were assessed through tests like slump flow, V-Funnel, T50, and L-box to measure flowability, viscosity, passing ability, and filling ability, respectively, following EFNARC guidelines (2002). Mixtures with constant fine aggregate but varied GGBS, fly ash, Silica fume, and Bentonite were tested. GGBS and Fly ash substituted cement up to 70%, while Silica fume and Bentonite were up to 20%. Results showed slump flow values (650-770 mm) within SCC norms (640-800 mm), indicating good segregation and flow. T50 times (2.9-6.8 sec) suggested the potential for reduced segregation. V-Funnel flow times (7.8-22 sec) met SCC requirements, indicating good filling ability. L-box test ratios (H2/H1 > 0.75) showed no blockage tendency. Silica fume and bentonite replacements improved viscosity and cohesion. U-box test differences (H1-H2 > 14mm) suggested increased Fly ash and GGBS content reduced viscosity and promoted segregation.

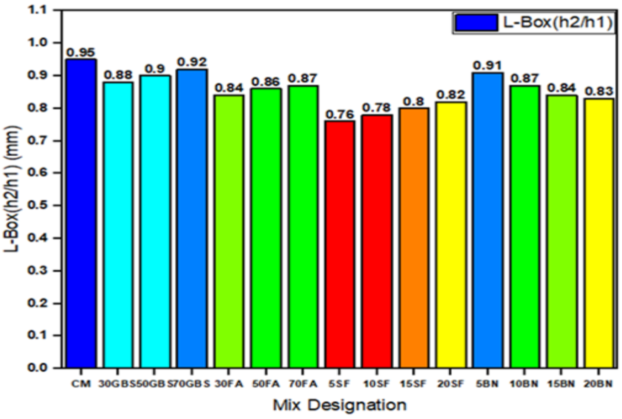

Figure-1. L Box flow time.

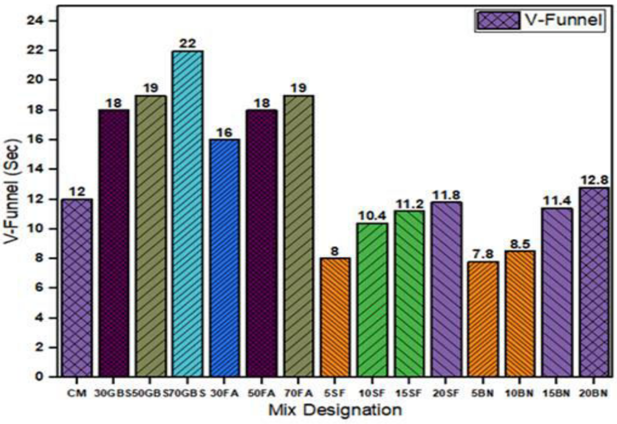

Figure-2. V funnel flow time.

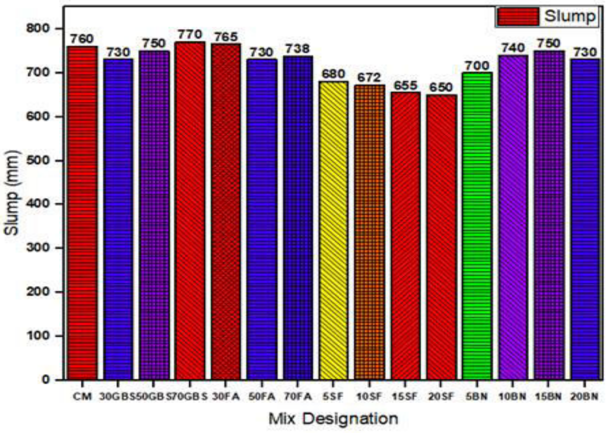

Figure-3. V-Funnel slump.

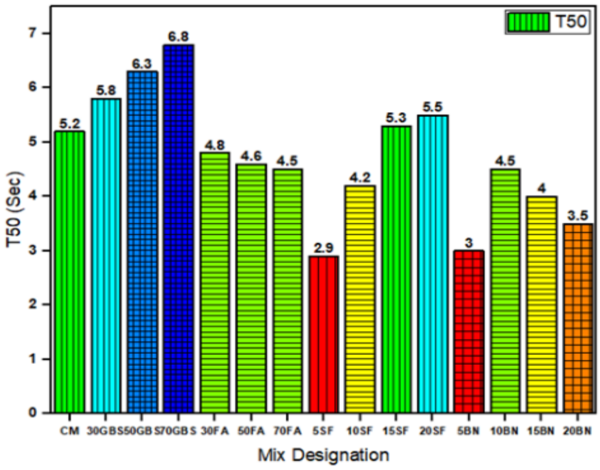

Figure-4. L - Box slump flow time.

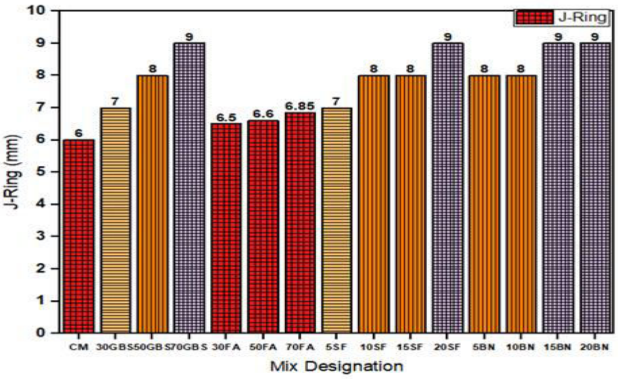

Figure-5. J-ring slump.

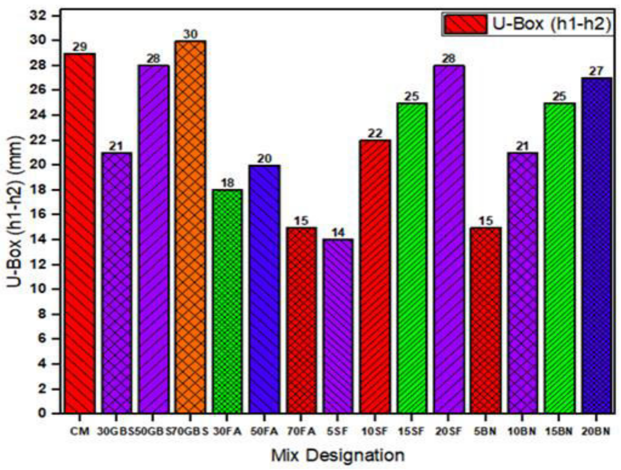

Figure-6. U-box slump.

3.6 Harden Properties of SCC

To assess the strength of both conventional and self-compacting concrete, various tests were conducted on standard specimens including cubes (150 × 150 × 150 mm), beams (150 × 150 × 1000 mm), and cylinders (150 mm diameter and 300 mm long). These tests were carried out on the 7th and 28th days under normal water curing conditions and on the 56th, 84th, and 112th days under NaCl curing. The hardened properties were evaluated following the procedures outlined by the Bureau of Indian Standards (BIS). Flexural strength, compressive strength, and modulus of elasticity were determined by IS: 516(BIS 2004), while the split tensile test was conducted according to IS: 5186(BIS 1999).

3.7 Compressive Strength

The compressive strength test aimed to assess the strength development of both conventional concrete (CC) and self-compacting concrete (SCC) specimens. Specimens sized at 150 mm × 150 mm × 150 mm, as specified in IS: 516-1959, were utilized. Table-13 presents the results for 7 days and 28 days under normal curing, and 56, 84, and 112 days under NaCl curing. The accompanying figure depicts a bar chart and graphical representation of the strength of various proportions of SCC cube specimens.

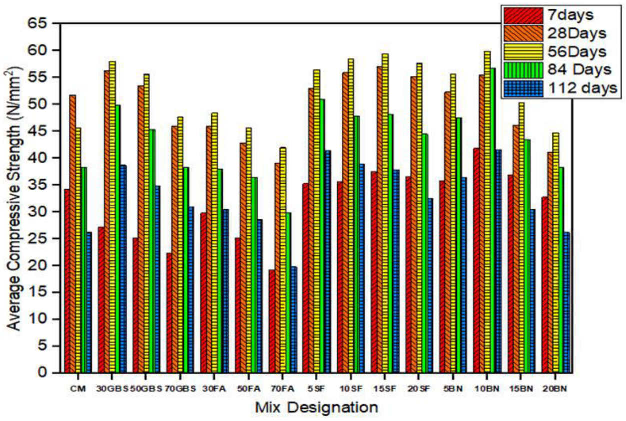

Figure-7. Compressive strength for normal curing and NaCl curing.

3.8 Experimental Outcomes and Discussions

cube compressive strength test results, while Table-13 offers detailed data. Analysis shows that SCC with 30% GGBS, 30% Fly ash, 15% Silica fume, and 10% Bentonite exhibited 28-day compressive strength increases of 8.7%, 12.5%, 10.16%, and 7.17%, respectively, compared to the control mix. Strength gains were significant after 28 days due to delayed pozzolanic reactions and slow hydration rates, contributing to later-stage strength development. Notably, 30% Fly ash replacement led to a 30% strength gain from 28 to 56 days, but 70% Fly ash mix showed lower strength due to delayed hydration. Silica fume gradually increased strength, attributed to filler effect and denser microstructure. However, 20% Bentonite replacement reduced strength due to decreased C3S and C2S phases and reduced water availability for hydration, leading to increased porosity and decreased compactness.

Table-13. Average compressive strength of SCC under normal and NaCl curing.

S. No	Mix Designation	Average Compressive Strength (N/mm^2)				
		7 Days	28 Days	56 Days	84 Days	112 Days
1	CM	34.31	51.82	45.70	38.29	26.23
2	30 GGBS	27.25	56.36	58.07	49.86	38.74
3	50 GGBS	25.11	53.46	55.59	45.36	34.92
4	70 GGBS	22.38	45.99	47.70	38.29	30.93
5	30 Fly Ash	29.80	46.04	48.45	37.99	30.48
6	50 Fly Ash	25.20	42.90	45.65	36.48	28.56
7	70 Fly Ash	19.26	39.02	41.99	29.88	19.83
8	5 Silica fume	35.27	53.03	56.45	50.99	41.48
9	10 Silica fume	35.69	55.92	58.44	47.88	38.93
10	15 Silica fume	37.53	57.09	59.44	48.20	37.90
11	20 Silica fume	36.58	55.21	57.65	44.48	32.56
12	5 Bentonite	35.78	52.34	55.66	47.56	36.42
13	10 Bentonite	41.87	55.54	59.88	56.82	41.56
14	15 Bentonite	36.91	46.20	50.35	43.45	30.48
15	20 Bentonite	32.77	41.08	44.73	38.23	26.25

4. FLEXURAL STRENGTH

The flexural strength test aimed to evaluate the flexural strength development of conventional concrete (CC) and blended self-compacting concrete (SC) specimens. Results, measured as modulus of rupture (MR) in MPa, were obtained. Beam specimens (1000 × 150 × 150 mm) were prepared and tested under a two-point beam bending setup using a 200-ton capacity loading frame. Each mix was tested at ages 7, 28, 56, 84, and 112 days, following IS 516:1959 procedures.

Flexural strength can be determined by using formulas.

1. Fracture occurs within the middle third span

$$f_{cr} = \frac{\mathrm{PL}}{\mathrm{b\ x\ d}^2}$$

2. Facture occurs outside the middle third span, but within 5%of span length

$$f_{cr} = \frac{3\mathrm{PL}}{\mathrm{b\ x\ d}^2}$$

Here, P = Load at ultimate point in kN l = length of specimen (beam) in mm

b = breadth of specimen in mm d = depth of beam in mm

4.1 Detailing of Beam Specimen

The beam detailing depicted in Fig. 8 was created using AUTOCAD software. The figure illustrates a beam specimen measuring one meter in length, featuring four 8mm diameter main bars and 6mm diameter stirrups spaced at 86mm center-to-center. Additionally, the cross-section detailing of the beam specimen is provided alongside the main illustration. Please refer to Table-14 for further details.

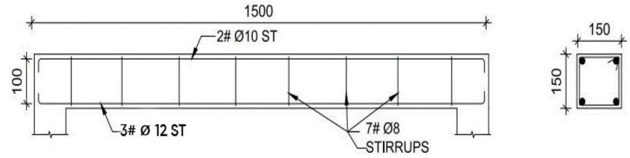

Figure-8. Schematic diagram of L/S and C/S of beam specimen.

4.2 Flexural Strength Test Results of Various Proportions of SCC Beam Specimens which is Under Normal Curing and NaCl Curing

The beam specimens, prepared with different proportions, underwent both normal curing and NaCl curing. Subsequently, they were subjected to testing at the ages of 7 days, 28 days, 54 days, 84 days, and 112 days, respectively.

Table-14. Flexural strength of SCC under normal curing and NaCl curing.

S. No	Mix Designation	Average Flexural Strength (N/mm^2)				
		Before exposure to NaCl solution		After exposure to NaCl solution		
		7Days	28Days	56Days	84Days	112Days
1	CM	5.98	11.91	10.21	8.05	6.48
2	30GGBS	7.54	14.28	15.74	10.16	8.237
3	50 GGBS	8.33	15.33	16.67	11.80	10.05
4	70 GGBS	6.59	10.99	11.75	9.28	7.592
5	30 Fly Ash	9.02	12.47	13.82	10.32	8.82
6	50 Fly Ash	7.52	14.95	15.88	11.05	9.42
7	70 Fly Ash	6.49	10.52	11.05	8.99	7.13
8	5 SF	7.66	14.48	15.95	10.42	8.46
9	10 SF	9.55	17.83	18.55	12.92	10.47
10	15 SF	8.44	15.33	16.05	11.16	9.56
11	20 SF	8.02	13.37	14.69	10.79	8.79
12	5 BN	15.15	18.56	19.27	13.25	11.19
13	10 BN	18.98	21.31	22.82	15.39	12.89
14	15 BN	17.4	20.51	21.05	14.26	11.86
15	20 BN	15.82	18.98	19.69	13.79	11.68

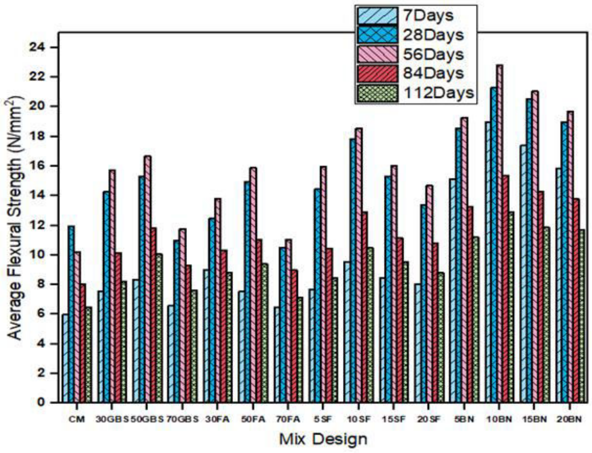

Figure-9. Flexural strength for normal and NaCl curing.

4.3 Experimental Outcomes and Discussions

The flexural strength of all concrete mixes is shown in the figure. The 10% Bentonite replacement level demonstrated the highest strength across all tested ages, attributed to improved microstructures from slower hydration rates and pozzolanic reactions. Mixes with 50% GGBS, 50% Fly ash, and 15% Silica fume showed comparable strength to the control mix at 28 and 56 days, possibly due to enhanced interfacial bonding and mechanical interlocking. Flexural strength increased with GGBS and Fly ash up to 50%, but decreased thereafter, attributed to lower viscosity, and weakened alkali-silica reaction. GGBS at 70% replacement exhibited lower strengths at low concentrations but comparable strengths at higher concentrations.

4.4 Split Tensile Strength

Tensile strength tests were conducted according to IS: 5816-1999 guidelines using cylindrical specimens measuring 150 mm in diameter and 300 mm in length. Specimens were positioned in a centering jig with precise alignment along the top and bottom of the loading plane. The jig was placed in the testing machine to centrally locate the specimen, ensuring parallelism of upper and lower platens for cylindrical specimens. The load was applied gradually at a rate of approximately 2 N/sq.mm/min (2.3 kN/sec) without sudden shocks. Three specimens for each mix were tested at ages 28, 56, 84, and 112 days, with results presented in Table-15 for both conventional and self-compacting concrete.

Table-15. Split tensile strength results of SCC under normal and NaCl curing.

S. No.	Mix Designation	Average Split Tensile Strength (in MPa)			
		Before Exposure to NaCl	After Exposure to NaCl		
		28 Days	56 Days	84 Days	112 Days
1	CM	4.25	4.12	3.5	2.01
2	30GGBS	5.28	5.4	3.87	2.76
3	50 GGBS	5.05	5.17	3.69	2.57
4	70 GGBS	4.42	4.54	3.57	2.65
5	30 Fly Ash	4.37	4.42	3.48	2.94
6	50 Fly Ash	4.19	4.26	3.52	2.19
7	70 Fly Ash	3.75	3.82	2.88	1.91
8	5 SF	4.49	4.8	3.6	2.58
9	10 SF	4.37	4.42	3.88	3.44
10	15SF	3.99	4.15	3.12	2.69
11	20SF	3.59	3.82	3.58	2.73
12	5BN	4.42	4.6	3.7	2.58
13	10BN	5.3	5.58	4.12	3.69
14	15 BN	4.82	5.14	3.92	2.74
15	20 BN	4.52	4.72	3.85	2.44

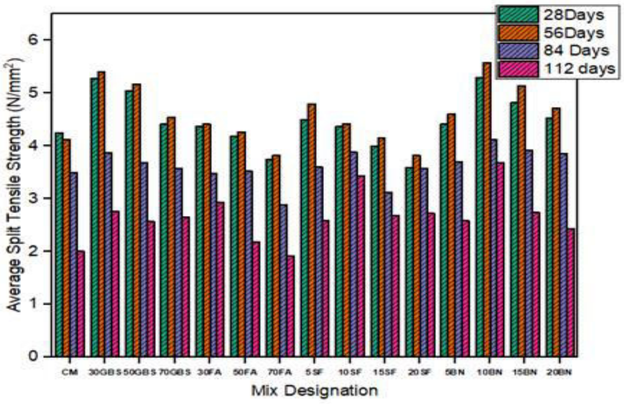

Figure-10. Split tensile strength results for normal and NaCl curing.

4.5 Experimental Outcomes and Discussions

Split tensile strength tests were conducted on self-compacting concrete specimens with varied replacements: 0%, 30%, 50%, and 70% for GGBS and Fly ash, and 5%, 10%, 15%, and 20% for Silica fume and Bentonite. Tests were conducted at ages 28, 56, 84, and 112 days, as shown in Table-15. The highest split tensile strength observed was with 10% Bentonite replacement: 5.3 N/mm² at 28 days, 5.58 N/mm² at 56 days, 4.12 N/mm² at 84 days, and 3.69 N/mm² at 112 days. While most mixes met structural concrete criteria, the 70% Fly ash mix did not, possibly due to unhydrated cement particles or prolonged pozzolanic reaction. Increased silica fume replacement improved strength due to fineness and superior packing. Optimal strength was achieved with 10% Bentonite replacement, densifying microstructure, and increasing strength. Conversely, the lowest strength was with 70% Fly ash replacement due to a high filler effect, low bonding, and weak alkali-silica reaction.

4.6 Elasticity of Modules

In this study, we determined the modulus of elasticity for both conventional concrete and self-compacting concrete using 150 × 150 × 150 mm cubes tested on a compression testing machine. The modulus of elasticity of concrete represents the ratio of applied stress to the corresponding strain within the elastic limit. It reflects a material's resistance to deformation under stress and indicates its stiffness, with higher values indicating greater stiffness. The elastic modulus values for different concrete mixes are presented in Table-16.

Table-16. Young's modulus by experimental data and as per IS Code of various mixes.

S. No	Mix Designation	Youngs modulus as per experimental data (N/mm^2)	Youngs modulus as per IS:456-2000 (N/mm^2)
1	CM	22456.73	25343.63
2	30GGBS	25734.9	25343.63
3	50 GGBS	23221.22	25343.63
4	70 GGBS	24043.22	25343.63
5	30 Fly Ash	22403.59	25343.63
6	50 Fly Ash	23969.1	25343.63
7	70 Fly Ash	23225.44	25343.63
8	5 SF	24481.4	25343.63
9	10 SF	25350.39	25343.63
10	15SF	25314.31	25343.63
11	20SF	26192.7	25343.63
12	5BN	25406.77	25343.63
13	10BN	24420.36	25343.63
14	15BN	25343.63	25343.63
15	20BN	24859.63	25343.63

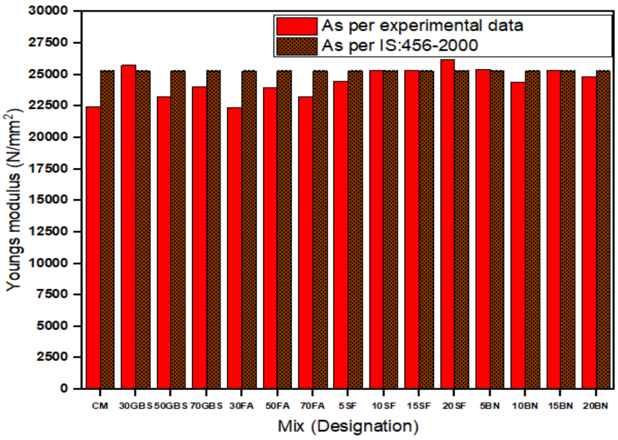

Figure-11. Youngs modulus of concrete.

4.7 Experimental Outcome and Discussions

The elastic modulus of self-compacting concrete, with varied GGBS, fly ash, Silica fume, and Bentonite replacements, was tested at ages 28, 56, 84, and 112 days, as shown in Figure-10. For example, at 28 days, M40 grade concrete with 20% Silica fume replacement achieved a maximum modulus of elasticity of 26192.7 MPa. Test results are summarized in Table-16 and graphically represented in Figure-11, highlighting superior results with 30% GGBS and 20% Silica fume replacements compared to the control mix. Generally, except for 30% Fly ash replacement, all mixes showed higher elastic modulus values than the control, possibly due to initial stresses, microcracks, and adhered mortar in the mix. Fly ash replacements exhibited lower elastic modulus, likely due to insufficient C-S-H gel development from lower OPC percentage, resulting in weak particle bonding.

5. CONCLUSIONS

In this section, key conclusions drawn from the experimental observations of various laboratory tests conducted on conventional concrete and self-compacting concrete (SCC) of grade M40, with partial replacement of GGBS, fly ash, Silica fume, and Bentonite against cement quantity, are highlighted.

Fresh Properties of SCC

- Fresh properties of SCC were examined through slump flow, V-Funnel, T50, L-box, U-box, and J-ring tests, following EFNARC (2002) guidelines.
- All SCC mixes in the investigation exhibited slump flow values within the specified range of 640 mm to 800 mm, ensuring good segregation and sufficient flow properties.
- The T50 time for SCC mixes varied from 2.9 sec to 6.8 sec, indicating higher flow times that help minimize segregation and bleeding.
- V-Funnel test results showed flow times ranging from 7.8 sec to 22 sec, meeting the requirements of allowable flow time with good filling ability and segregation resistance.
- L-box and U-box tests indicated passing ability and filling ability, respectively, with values above the

specified thresholds, suggesting minimal blockage and encouraging segregation.

Hardened Properties of SCC

- SCC with 30% GGBS, 30% Fly ash, 15% Silica fume, and 10% Bentonite replacements exhibited increased 28-day compressive strength compared to the control mix, attributed to reduced heat of hydration, refinement of pore structures, and increased resistance to chemical attack.

- A decrease in compressive strength was observed in 70% of Fly ash mixes due to the late formation of hydration products, leading to a lower presence of calcium hydroxide and inadequate pozzolanic reaction.

- Flexural strength analysis indicated that 10% Bentonite replacement levels consistently exhibited maximum strength across different curing periods, suggesting improved microstructure and resistance to chemical attack.

- Optimum results were obtained with 30% GGBS replacement, attributed to enhanced pozzolanic reaction and supplementary cementitious compound formation.

- SCC mixes incorporating up to 30% GGBS and Fly ash and up to 10% Silica fume and Bentonite replacements are feasible.

- Elastic modulus tests revealed that combinations of 30% GGBS and 20% Silica fume replacements exhibited superior results, indicating stiffness and resistance to deformation.

- Generally, elastic modulus values were higher in SCC mixes compared to control concrete, except for 30% Fly ash replacements due to incomplete pozzolanic reaction.

These conclusions underscore the potential for optimizing SCC mixes with appropriate replacement levels of supplementary materials to achieve desired mechanical and durability properties.

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