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Mix Design for High Strength Concrete with Fly Ash, Silica, and Ether-Based Superplasticizers

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A B S T R A C T

In recent years, there has been a noticeable growth in the need for high-strength concrete in modern buildings. Superplasticizers like ether-based admixtures and extra cementitious elements like fly ash and silica fumes are frequently used in concrete to obtain high strength and durability. However, to assure the best performance, numerous factors must be carefully taken into account throughout the mix design process for high-strength concrete using these ingredients. In this work, concrete mixes containing fly ash, silica, and ether-based superplasticizers were designed and tested for M70-grade concrete using Indian Standard norms. According to the findings, these components can be used to increase the compressive strength and workability of high-strength concrete while still following Indian Standard mix design guidelines. For researchers and practitioners in the building sector, this study offers helpful insights into the process of mix design for high-strength concrete containing fly ash, silica, and ether-based superplasticizers.

Keywords: SCM, superplasticizers, HSC

Introduction

High-strength concrete construction relies heavily on mix design. In the creation of high-strength concrete, the use of supplementary cementitious materials (SCMs) including fly ash, silica fume, and superplasticizers like ether-based admixtures has grown in popularity. These components can considerably improve the concrete's strength, durability, and workability while lowering its environmental impact.

The qualities of the raw materials, the intended strength and workability of the concrete, and the necessary curing time must all be carefully taken into account when designing high-strength concrete using SCMs and superplasticizers. Creating an ideal mix design that contains the precise ratios of each component to obtain the desired qualities of the concrete entails the process.

In this study, fly ash, silica fume, and ether-based superplasticizers will be used to investigate the mix design for high-strength concrete. We'll look into how different ratios of these ingredients affect the concrete's strength, workability, and other characteristics. The goal of the project is to give a thorough understanding of the mix design procedure and how it is used in a high-strength concrete building.

The research will also investigate how employing SCMs in high-strength concrete affects the environment. Byproducts of silicon manufacture and coal combustion, respectively, fly ash and silica fume, when used in concrete, can lessen the quantity of the trash that is dumped in landfills. Furthermore, the usage of superplasticizers can result in less water being used to produce concrete, preserving water resources.

Ultimately, the goal of this study is to give a thorough grasp of the mix design for high-strength concrete employing fly ash, silica fume, and ether-based superplasticizers. This study will help create sustainable and effective construction methods by investigating the characteristics and environmental effects of this kind of concrete.

1.1 Ordinary Portland cement-53 grade cement conforming IS 269

Ordinary Portland Cement that conforms to the Indian Standard IS 269 is produced by grinding high-quality clinker with gypsum and a specific percentage of pozzolanic material or fly ash. According to the IS 269 standard, OPC 53 grade cement must have a minimum compressive strength of 53 MPa at 28 days of curing. This strength level is ideal for construction projects that require high strength, such as bridges, dams, high-rise buildings, and industrial structures. OPC 53 grade cement has a lower heat of hydration, making it suitable for mass concrete structures.

The benefits of OPC 53 grade cement also include faster setting time, better workability, and finer particle size, which improve mix quality and handling. This cement is available in both bag and bulk forms and is widely used in the construction industry for precast concrete products, high-performance concrete, and ready-mix concrete. Its high strength and low heat of hydration also make it suitable for use in hot weather conditions.

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1.2 Fly ash

Fly ash is a byproduct generated from the combustion of pulverized coal in thermal power plants, and it is widely used as a mineral admixture in high-strength concrete (HSC) production. Its pozzolanic properties react with calcium hydroxide in the presence of water, forming additional cementitious compounds that enhance the strength and durability of concrete.

The incorporation of fly ash in HSC mixtures has numerous benefits, including improved workability, reduced heat of hydration, and increased resistance to sulfate attack and alkali-silica reaction. Additionally, the use of fly ash can reduce the amount of cement required, which can lower the cost and environmental impact of concrete production.

1.3 Silica Fumes

Silica fume is a supplementary cementitious material that has proven to be effective in enhancing the compressive strength, flexural strength, and abrasion resistance of high-strength concrete. It is a byproduct of the production of silicon metal and ferrosilicon alloys, and its fine particle size and high surface area allow it to react with calcium hydroxide to form additional C-S-H gel, which is the primary binding material in concrete. When used in small quantities (typically less than 10% by weight of the cementitious material), silica fume can be a valuable addition to concrete mixes. However, due to its fine particle size, it can be challenging to handle and requires proper mixing and placement techniques for optimal results

1.4 PCE-based superplasticizers

Polycarboxylate ether (PCE) based superplasticizers are a type of chemical admixture that is frequently used to improve the workability and flowability of high-strength concrete. These admixtures work by dispersing cement particles, reducing the water content required to achieve a workable mix, and delaying the setting time of the concrete.

In high-strength concrete, PCE-based superplasticizers play an important role in achieving the desired strength, durability, and other properties. Their high degree of dispersibility enables them to effectively separate cement particles and reduce the water content in the mix, which improves workability and facilitates placement, while also reducing the water-cement ratio to improve strength.

1.5 Importance and usefulness of High strength concrete

High-strength concrete is a crucial building material that provides superior compressive strength and durability. It is commonly utilized in construction projects where the structural integrity of a building or structure is essential. The incorporation of fly ash, silica fumes, and ether-based superplasticizers in high-strength concrete can significantly improve its properties, making it more suitable for demanding applications.

The High strength concretes are very essential for the following reasons:

- High-strength concrete has excellent compressive strength and durability, making it ideal for use in critical structures such as bridges, tunnels, and high-rise buildings.
- It has a higher strength-to-weight ratio compared to traditional concrete, making it suitable for applications where the weight of the structure is a concern.
- High-strength concrete is less prone to cracking or failure under pressure, and it can withstand higher loads and stresses.
- It provides significant cost savings in the long run by reducing the need for maintenance and repairs over time.
- High-strength concrete has a longer lifespan compared to traditional concrete, reducing the need for frequent replacement or repairs.
- It can be designed to meet specific requirements, such as resistance to earthquakes, fire, or other environmental factors.
- Sustainable materials such as fly ash can be used in the production of high-strength concrete, reducing its environmental impact.
- High-strength concrete improves the safety and security of structures, reducing the risk of accidents or failures.
- It offers greater design flexibility and allows for more creative and innovative structures.

2. Literature Review

High-strength concrete (HSC) is becoming more and more popular in India because it has several benefits, including smaller structural dimensions, greater durability, and less expensive maintenance. HSC manufacture, however, necessitates the use of pricey resources and frequently generates higher CO2 emissions. Researchers are now looking into different materials and mix designs to create HSC that is both affordable and sustainable as a result of this. Using fly ash, silica, and ether-based superplasticizers, the research done by Indian writers on mix design for HSC is summarised in this overview of the literature.

A by-product of burning coal, fly ash is readily accessible in India. Its use in concrete has been demonstrated to enhance workability, lower the need for water, and boost strength. The impact of fly ash on the compressive strength of HSC was examined in a study by Jadhav et al. (2017) [1]. According to the study, a 30% weight replacement level of fly ash in cement produced a 28-day compressive strength of 80 MPa.

A by-product of the manufacture of silicon and ferrosilicon alloys, silica fume is also easily accessible in India. Concrete's strength and durability have been found to increase as a result of its use in HSC. The impact of silica fume on the compressive strength and workability of HSC was examined in a study by Patil et al. (2018) [2]. The study discovered that a 10% weight replacement level of silica fume in cement produced a 28-day compressive strength of 90 MPa.

Superplasticizers made of ether are used in HSC to increase workability without using more water. Superplasticizers based on ether are frequently used in India since they are efficient and inexpensive. The impact of several ether-based superplasticizer kinds and dosages on the workability and compressive strength of HSC was examined in a study by Karade et al. (2019) [3]. The study discovered that 2% by weight of cement was the ideal superplasticizer dosage and that the type of superplasticizer had no discernible impact on the compressive strength of HSC.

Scholars have researched the mix design of HSC employing fly ash, silica, and ether-based superplasticizers in great detail. A mix design for HSC was suggested in a study by Basha et al. (2017) [4] with a goal compressive strength of 90 MPa. 180 kg/m3 of fly ash, 70 kg/m3 of silica fume, and 0.75% by weight of cement-based superplasticizer made up the mix design. According to the investigation, the mix design produced 92 MPa of compressive strength after 28 days.

In conclusion, writers have thoroughly researched the usage of fly ash, silica, and ether-based superplasticizers in mix design for HSC. According to studies, silica fume and fly ash should be used to substitute cement at levels of 30% and 10%, respectively. The research also revealed that 2% by weight of cement is the ideal dosage of ether-based superplasticizer.

Table 1 summarizes the key findings of the studies reviewed in this literature review, including the replacement level of cement with fly ash and silica fume, the dosage of ether-based superplasticizer, and the resulting compressive strength of HSC.

Table 1: Summary of Key Findings

Study	*Fly Ash Replacement Level*	*Silica Fume Replacement Level*	*Superplasticizer Dosage*	*Compressive Strength (MPa)*
Jadhav et al. (2017)	0.3	N/A	N/A	80
Patil et al. (2018)	N/A	0.1	N/A	90
Karade et al. (2019)	N/A	N/A	0.02	N/A
Basha et al. (2017)	0.3	0.1	0.0075	92

Overall, the studies reviewed in this literature review demonstrate that the use of fly ash, silica, and ether-based superplasticizers can improve the strength and workability of HSC while also promoting sustainability by reducing the use of cement. The proposed mix design in Basha et al. (2017) [4] can serve as a guideline for producing HSC with a target compressive strength of 90 MPa using these alternative materials. However, further research is needed to explore the effects of other factors such as curing conditions, aggregate type, and water-to-cement ratio on the performance of HSC using these materials.

3. Methodology

The mix design proportions for high-strength concrete were determined using an Excel sheet [5], providing a convenient and efficient approach to achieving the desired strength and workability. Material properties, exposure conditions, and workability requirements were inputted into the sheet, which calculated the required amounts of cement, aggregates, water, and chemical admixtures. This method ensured accuracy and consistency in the mix design process while saving time and effort compared to traditional methods. Furthermore, the Excel sheet allowed for easy modification of mix designs based on changing requirements or available materials. Overall, the use of an Excel sheet for mix design proved to be an effective and practical tool for achieving high-strength concrete proportions.

3.1 stipulations for proportioning

Table 2: Stipulations for proportioning

Grade designation	M 70
Type of cement	OPC 53 grade conforming to IS 269
Silica fume	Conforming to IS 15388
Maximum nominal size of aggregate	20 mm
Exposure conditions	Severe (for reinforced concrete)

Workability	50 mm (slump)
Method of concrete placing	Manual
Degree of supervision	Good
Type of aggregate	Crushed angular aggregate
Maximum cement (OPC) content	450 kg/m^3
Chemical admixture type	Superplasticizer (Polycarboxylate ether based)

3.2 Test Data for Materials

Table 3: Test Data for Materials

Cement used	OPC 53 Grade conforming to IS 269
Specific gravity of cement	2.99
Specific gravity of	
Coarse aggregate	2.97 (at SSD condition)
Fine aggregate	2.55 (at SSD condition)
Fly ash	2.2
Silica fume	2.2
Chemical admixture	0.98
Water absorption of	
Coarse aggregate	Nil
Fine aggregate	0.5 percent
Moisture content of	
Coarse aggregate	Nil
Fine aggregate	Nil

In the laboratory, several tests were conducted to determine the properties of the materials used in the concrete mix design. The specific gravity tests were performed on the coarse aggregate, fine aggregate, and cement to determine their densities. Water absorption tests were conducted on the coarse and fine aggregates to determine their porosity. Additionally, a sieve analysis was conducted on the fine aggregate to determine its gradation and classification based on the zones defined in relevant standards. These tests are essential in establishing the material properties required for accurate and reliable mix design. The data obtained from these tests enable the selection of the appropriate materials, including aggregates and cement, which meet the desired characteristics for the mix design, such as strength, workability, and durability. By conducting these tests, we can ensure the production of a high-quality and robust concrete mix that meets the requirements of the project.

3.2.1 Test Data for Fine Aggregate (Sieve Analysis)

Table 4: Test Data for Fine Aggregate

TRIAL 1

IS Sieve No.	*Wt. retained on the sieve*	*Percentage retained on the sieve*	*Cumulative % retained on the sieve*	*Cumulative % passing*
4.75 mm	22	2.2	2.2	97.8
2.36 mm	29	2.9	5.1	94.9
1.18 mm	39	3.9	9	91
600 micron	535	53.5	62.5	37.5
300 micron	324	32.4	94.9	5.1
150 micron	46	4.6	99.5	0.5
Below 150 micron	3	0.3	99.8	0.2
	1000 g			
			FINENESS MODULUS	2.73

TRIAL 2

IS Sieve No.	*Wt. retained on the sieve*	*Percentage retained on the sieve*	*Cumulative % retained on the sieve*	*Cumulative % passing*
4.75 mm	25	2.5	2.5	97.5
2.36 mm	28	2.8	5.3	94.7
1.18 mm	47	4.7	10	90
600 micron	505	50.5	60.5	39.5
300 micron	331	33.1	93.6	6.4

150 micron	59	5.9	99.5	0.5
Below 150 micron	3	0.3	100	0
	1000 g			
			FINENESS MODULUS	2.71

TRIAL 3

IS Sieve No.	*Wt. retained on the sieve*	*Percentage retained on the sieve*	*Cumulative % retained on the sieve*	*Cumulative % passing*
4.75 mm	23	2.3	2.3	97.7
2.36 mm	31	3.1	5.4	94.6
1.18 mm	43	4.3	9.7	90.3
600 micron	517	51.7	61.4	38.6
300 micron	332	33.2	94.6	5.4
150 micron	51	5.1	99.7	0.3
Below 150 micron	2	0.2	100	0
	1000 g			
			FINENESS MODULUS	2.73

- **The Fine aggregate belongs to Zone II.**

3.2.2 Test Data for Cement (Le Chatelier's Flask)

Table 5: Test Data for Test Data for cement

Weight of Cement	*Final Volume*	*Initial Volume*	*Specific Gravity(G)*
64	21.5	0.1	2.99
64	22.5	0.9	2.96
64	21.7	0.4	3.00
	AVERAGE SPECIFIC GRAVITY OF CEMENT		**2.99**

3.2.3 Test Data for Coarse Aggregate (Pycnometer Test)

Table 6: Test Data for Coarse Aggregate

Weight of Sample	*Weight of Pycnometer + sample + water*	*Weight of Pycnometer + water*	*Weight of Oven Dry sample*	*Specific Gravity of Coarse Aggregate*	*Water Absorption*
W1 (g)	W2	W3	W4	G	
200	1620	1487	200	2.99	0.00
200	1620	1487	200	2.99	0.00
200	1619	1487	200	2.94	0.00
		AVERAGE SPECIFIC GRAVITY OF COARSE AGGREGATE		**2.97**	

3.2.4 Test Data for Fine Aggregate (Pycnometer Test)

Table 7: Test Data for Fine Aggregate

Weight of Sample	*Weight of Pycnometer + sample + water*	*Weight of Pycnometer + water*	*Weight of Oven Dry sample*	*Specific Gravity of Fine Aggregate*	*Water Absorption*
W1 (g)	W2	W3	W4	G	
250	1706	1554	249	2.54	0.40
250	1708	1554	248	2.58	0.81
250	1706	1554	249	2.54	0.40
		AVERAGE SPECIFIC GRAVITY OF FINE AGGREGATE		**2.55**	

3.3 Mix Design

The mix design of high-strength concrete according to IS 10262-2019 involves several steps to achieve the desired strength and durability properties. Firstly, the characteristic strength of the concrete is determined based on the specified compressive strength at 28 days. Then, the water-cement ratio is selected based on the exposure conditions and the maximum size of the aggregate.

Next, the proportions of fine and coarse aggregates are determined based on the selected water-cement ratio. The quantity of cement, water, and aggregates is then calculated based on the mix proportions. The mix design also takes into consideration the use of chemical admixtures, which are added to improve the workability, strength, and durability of the concrete.

Finally, the mix design is verified through trial mixes, which are tested to ensure that the desired strength and other properties are achieved. The mix design of high-strength concrete according to IS 10262-2019 is a systematic and rigorous process that ensures the quality and performance of the final product.

3.3.1 Target Strength

$f'ck = fck + 1.65\,S$ or $f'ck = fck + X$ whichever is higher.

Where,

- $f'ck$ = target average compressive strength at 28 days,
- fck = characteristic compressive strength at 28 days,
- S = standard deviation
- X = factor based on the grade of concrete.

3.3.2 Air Content

According to the nominal maximum size of the aggregate, Table 6 (IS 10262:2019) shows the approximation of the amount of air entrapped in normal (non-air-entrained) concrete.

Table 8: Table 6 of IS10262:2019

Nominal Maximum Size of Aggregate(mm)	*Entrapped Air, as % of the Volume of Concrete*
10	1
12.5	0.8
20	0.5

3.3.3 Selection of Water-cementitious ratio

The ratio of water to cementitious materials needed to achieve the specified target strength and nominal maximum aggregate size is chosen from Table 8 of IS 10262:2019. The maximum permitted W/C ratio is chosen based on the exposure circumstances.

Table 9: Table 8 of IS10262:2019

Target Compressive Strength at 28 days (N/mm^2)	*Water-cementitious material ratio*		
	Nominal Maximum Size of Aggregate (mm)		
	10	**12.5**	**20**
70	0.36	0.35	0.33
75	0.34	0.33	0.31
80	0.32	0.31	0.29
85	0.3	0.29	0.27
90	0.28	0.27	0.26
100	0.26	0.25	0.24

3.3.4 Selection of Water content

From Table 7 of IS 10262:2019, water content for the Maximum Nominal size of Aggregate is chosen which is for a Slump Value of 50 mm without any Chemical Admixture using Angular Coarse Aggregate

Table 10: Table 7 of IS 10262:2019

Nominal Size of Aggregate(mm)	*Maximum Water content (kg/m3)*
10	200
12.5	195
20	186

For any Slump Value X, Water content is calculated as

$$WC_X = WC_{50} + \frac{X - 50}{25} \times \frac{3}{100} \times WC_{50}$$

- As superplasticizer (Polycarboxylate ether based) is used, the water content can be reduced by 30 percent. Hence, the reduced water content $Reduced\ WC = 0.70 \times WC_X$

3.3.5 Calculation of cementitious content

$$Cementitious\ Content = \frac{Water\ Content}{\frac{W}{C}\ ratio} \geq \text{Minimum cementitious content as per Table 5 of IS 456: 2000}$$

Table 11: Table 5 of IS 456: 2000

Exposure Conditions	*Maximum free water cement ratio*	*Minimum Cement Content(kg/m3)*
Mild	0.55	300
Moderate	0.5	300
Severe	0.45	320
Very Severe	0.45	340
Extreme	0.4	360

- If there is the presence of cementitious materials like Fly Ash, Silica Fumes, GGBS, etc., the cementitious Content is increased by 10%.
- Since the Cementitious content has been increased, Water to cement ratio needs to be revised.

$$Revised\ \frac{w}{c} = \frac{water\ content}{cementitious\ content\ after\ increase}$$

- $Cement\ Content\ =\ cementitious\ content\ after\ increase - Mineral\ Admixture\ (like\ Fly\ Ash, Silica\ fumes, etc)$
- Cement content is checked against the Maximum allowable cement content as per IS 456:2000 i.e., 450kg/m^3.

3.3.6 Proportion of Volume of Coarse and Fine Aggregate

As per IS 10262:2019, conforming to different types of Zones of Fine Aggregate and Nominal maximum size of aggregate, Volume proportioning of Coarse aggregate per unit volume of Total Aggregate is found for w/c ratio equal to 0.3

Table 12: Table 10 of IS 10262:2019

(Only When W/C Ratio is 0.3)

Nominal Maximum size of aggregate	*Volume of Coarse Aggregate per unit volume of Total Aggregate for different zones of Fine Aggregate*		
	Zone III	*Zone II*	*Zone I*
10	*0.56*	*0.54*	*0.52*
12.5	*0.58*	*0.56*	*0.54*
20	*0.68*	*0.66*	*0.64*

Now, Volume of coarse aggregate per unit volume of Total aggregate for any water-cement ratio is given by,

$$Volume\ of\ coarse\ aggregate\ per\ unit\ volume\ of\ Total\ aggregate\ for\ any\ \frac{w}{c}\ ratio = VC_{@\frac{w}{c}=0.3} + \frac{0.3-\frac{w}{c}}{0.05} \times 0.01$$

Note - This proportion is for manual method of placing

- For Pumping,Volume of coarse aggregate per unit volume of Total aggregate is reduced by 5 percent.

3.3.7 Adjustments in Mix Design for water

For Fine Aggregate

$$Fine\ Aggregate\ (Dry) = \frac{Mass\ of\ FA\ in\ SSD\ Condition}{1 + \frac{\%\ water\ absorption}{100} - \frac{\%\ moisture\ content}{100}}$$

$$Extra\ water\ required\ for\ FA\ to\ simulate\ a\ SSD\ condition(A) = mass\ of\ FA\ in\ SSD\ condition - mass\ of\ FA\ in\ dry\ condition$$

For Coarse Aggregate

$$Coarse\ Aggregate\ (Dry) = \frac{Mass\ of\ CA\ in\ SSD\ Condition}{1 + \frac{\%\ water\ absorption}{100} - \frac{\%\ moisture\ content}{100}}$$

$$Extra\ water\ required\ for\ CA\ to\ simulate\ a\ SSD\ condition(B) = mass\ of\ CA\ in\ SSD\ condition - mass\ of\ CA\ in\ dry\ condition$$

$$Total\ water\ required = water\ requirement + A + B$$

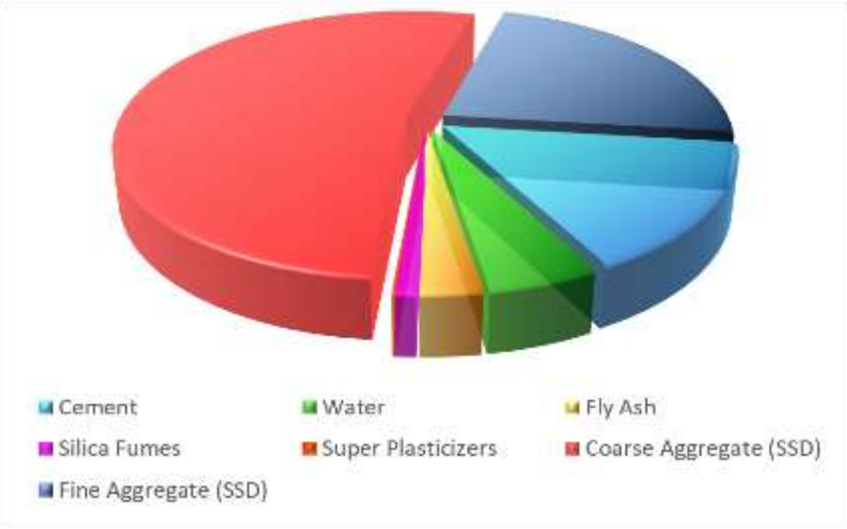
3.3.8 Mix Proportion for M70

The mix design proportioning for M70 concrete was performed using an Excel sheet. The Excel sheet was used to calculate the amount of cement, water, fine aggregate, coarse aggregate, fly ash, superplasticizers and silica fumes needed to produce a concrete mix with a compressive strength of 70 MPa.

Table 13: Mix Proportion for M70 from Excel sheet [5]

Materials	***Quantities (kg/m^3)***
Cement	394.55
Water	133.09
W/C Ratio	0.26
Fly Ash	73.98
Silica Fumes	24.66
Super Plasticizers	2.47
Coarse Aggregate (SSD)	1358.36
Fine Aggregate (SSD)	581.74

Fig. 1: Mix Proportion for M70 from Excel sheet [5]



Result and Discussion

The data presented below shows the compressive strength of concrete samples at 7 days and 28 days. The compressive strength is an essential property of concrete that determines its ability to withstand loads and stress. In this study, three samples were tested at each age, and the average compressive strength was calculated.

The compressive strength of the concrete samples at 7 days was found to be 45.03 N/mm2, while at 28 days, it was found to be 70.07 N/mm2. These results indicate that the compressive strength of concrete increases with time, and the concrete gains more strength as it ages. This is due to the hydration process of cement, where it reacts with water to form a strong bond.

The compressive strength of the concrete samples at 28 days is significantly higher than at 7 days, which is expected as concrete gains strength with time. The results are also within the acceptable range for concrete compressive strength, as per industry standards.

Overall, the results obtained in this study suggest that the concrete samples used in this study have sufficient strength to withstand loads and stresses. However, more tests may be required to determine the durability of the concrete over the long term.

In conclusion, the compressive strength of the concrete samples at 7 days and 28 days was found to be within acceptable limits. These results are essential for the construction industry as they provide crucial information for the design and use of concrete in various applications.

Table 14: Compressive strength at 7 days

Compressive strength at 7 days		
Sample No.	*Load (kN)*	*Compressive Strength (N/mm^2)*
Sample 1	1010	44.89
Sample 2	1040	46.2
Sample 3	990	44
Average Compressive Strength		45.03

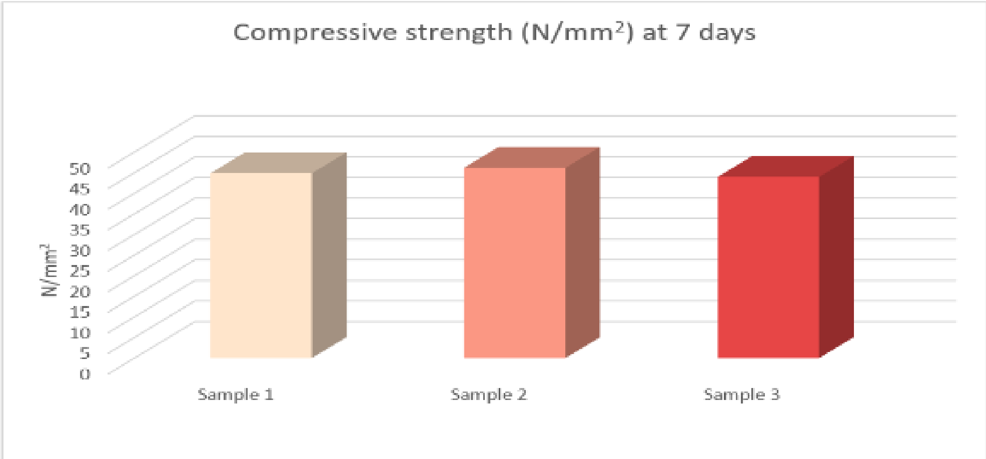


Fig. 2: Compressive strength at 7 days

Table 15: Compressive strength at 28 days

Compressive strength at 28 days		
Sample No.	***Load (kN)***	***Compressive Strength (N/mm^2)***
Sample 1	1580	70.2
Sample 2	1610	71.56
Sample 3	1540	68.45
Average Compressive Strength		70.07

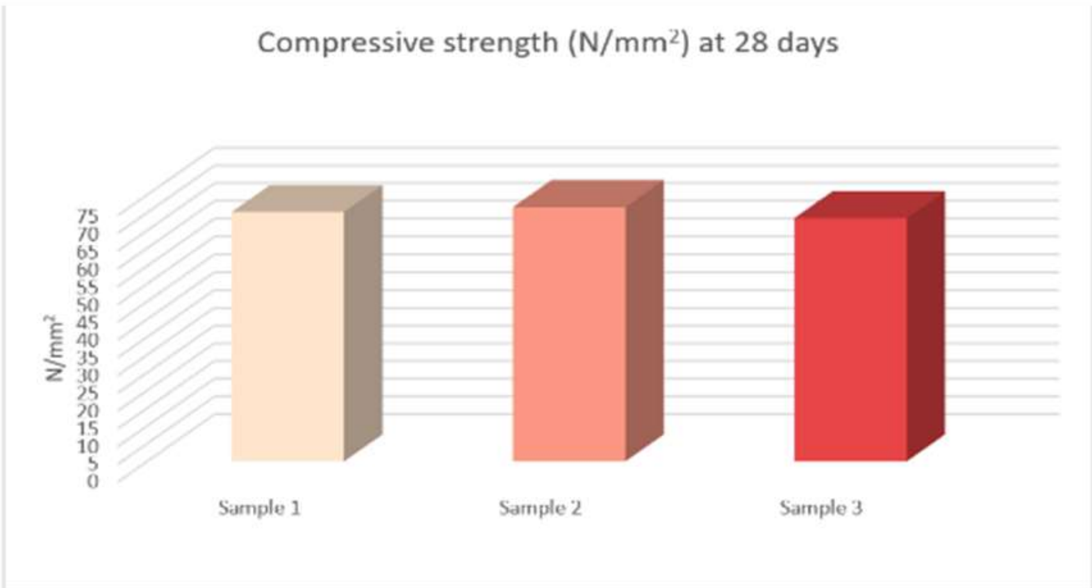


Fig. 3: Compressive strength at 28 days

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