An Experimental Study on the Mechanical Properties of M30 Grade Concrete Incorporating Silica Fume and Polypropylene Fibre

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Abstract: *A growth of interest in the modification of conventional concrete by adding supplementary cementitious materials and synthetic fibre has occurred due to the increasing demand of sustainable, durable and high-performance construction material. This is an experimental study that explores the behaviour of M30 grade concrete with the use of silica fume as a partial substitute of cement (5, 10, 15 and 20 percent by weight) and incorporation of polypropylene fibres (0.5, 1, 1.5, and 2 percent by weight). Some of the experimental program involved the preparation of standard cube, prism, and cylinder test specimen which were tested on compressive, flexural, and split tensile strength at curing ages of 7, 28, 56, and 90 days. Its findings have shown that silica fume replacement level of 10 percent is optimum as it increased compressive strength by 25.3 percent relative to conventional concrete. Moreover, the polypropylene fibre concentration was added (1 to 1.5 percent) to increase tensile and flexural strength, crack resistance, and ductility. The silica fume decreased workability, which was controlled by the effective use of the superplasticizers. This paper has found that silica fume and polypropylene fibre are synergetic in improving the mechanical properties and durability of concrete, thus suitable in the high-performance and sustainable construction.*

Keywords: Cement, Silica Fume, Polypropylene Fibres, Compressive Strength, Flexural Strength, Split Tensile Strength, M30 Concrete, and Sustainable Materials

1 INTRODUCTION

Concrete is among the most used building materials throughout the world, because it is versatile, durable, and economical. The global production of concrete is estimated to exceed 10 billion tonnes every year, and it is the most used substance after water (Mehta and Monteiro, 2017). Cement, fine aggregates, coarse aggregates and water are the major components of the traditional concrete. Cement is the cementing agent, and it induces hydration reactions, which help in development of the concrete strength. Nevertheless, Ordinary Portland Cement (OPC) is a highly energy-demanding process, which is related to the considerable carbon dioxide emissions, which constitute 7-8% of the worldwide CO2 emissions (Scrivener et al., 2018). As such, eco-friendly solutions or change in the conventional cement-based systems should be developed to take care of the environmental impact of construction industry.

Supplementary cementitious materials (SCM) like fly ash, silica fume, slag, and rice husk ash are increasingly being utilized as substitutes of cement in concrete mixtures to replace cement partially. The materials are usually industrial by-products, which enhance the concrete performance at the same time solving the waste disposal environmental issues. One of the best pozzolanic materials is silica fume (SF). It is a by-product of the ferrosilicon and silicon metal industry, and it is amorphous silicon dioxide particles of ultrafine size (Patel and Shah, 2020). Silica fume when present in concrete combines with calcium hydroxide liberated during the hydration of cement to form more calcium silicate hydrate (C-S-H) gel, the major strength and durability provider. This pozzolanic activity not only greatly decreases permeability, but also increases compressive strength and resistance to hostile environments including sulphate attack and chloride penetration (Siddique, 2011).

Although, Concrete is brittle in nature and has low tensile strength. The structural performance is usually damaged by cracking as a result of shrinkage, loading or environmental stress. In order to overcome these drawbacks, fibre-reinforced concrete (FRC) has been introduced. The fibres, whether of steel, glass, carbon or synthetic fibres, are scattered throughout the concrete matrix to enhance the ductile, post-cracking behaviour, and toughness (Banthia and Gupta, 2004). Polypropylene fibre (PPF) is one of the synthetic fibres that have attracted interest because it is economical, inert and corrosion resistant, as well as capable of managing plastic shrinkage cracking (Bharath et al., 2021). The tensile and flexural strength, microcracking, and impact resistance of concrete can be significantly improved with a small quantity of polypropylene fibres (0.5%-2% of cement weight) added on them (Yin et al., 2020).

Silica fume combined with polypropylene fibre gains a two-fold advantage, silica fume helps improve the density of the matrix and compressive strength, whereas polypropylene fibre assists in crack management and toughness. It has been shown that silica fume enhances early and long-term strength, whereas polypropylene fibres enhance post-cracking behaviour and ductility (Akshatha, 2018; Selvapriya, 2019). Nonetheless, all these materials have a specific proportioning since silica fume can reduce the workability when it is too large, and dispersion when it is too high (Hemavathi et al., 2020). Thus, it is necessary to determine the best mix of silica fume replacement and polypropylene fibre dosage to attain the best performance in concrete.

Objectives of the Study

The current study will serve to fill these gaps, by experimentally testing the mechanical performance of the M30 grade concrete when part of the cement is substituted with silica fume and on the application of polypropylene fibres. The specific objectives are:

- To establish the compressive strength of concrete mixes with 5, 10, 15 and 20 percent silica fume at 7, 28, 56 and 90 days of curing.
- To compare flexural and split tensile strengths of concrete containing the silica fume in optimum contents with and without polypropylene fibre (0.5%, 1%, 1.5 and 2 percent).
- To determine the optimum dosage of silica fume and polypropylene fibre that gives the best outcome in terms of improvement of mechanical properties.
- To evaluate the technical viability of a silica fume and polypropylene fibre use as sustainable materials to make sustainable and durable concrete.

2 LITERATURE REVIEW

One of the key areas of research in the last few decades has been the development of sustainable, high-performance concrete. Additional cementitious materials (SCMs) including fly ash, silica fume and slag, fibre reinforcement and improvement have all been researched widely as a way of enhancing the service life and the mechanical properties of the traditional cementitious composites. This section is a review of the current research in silica fume and polypropylene fibre in concrete with a bias on the ones that are relevant to M30-M40 grade concretes.

2.1 Silica Fume in Concrete

Silica fume (SF) or micro-silica is the by-product of silicon and ferrosilicon alloy industry. Its very fine particle size (approximately 100 times less than the size of cement grains) and the presence of high amorphous silica (>85%) will be an effective pozzolanic material (Siddique, 2011). Upon incorporation with concrete, it reacts with calcium hydroxide to form more calcium silicate hydrate (C-S-H) that forms a more dense microstructure making the structure stronger and more durable.

According to Lokeshwari et al. (2023), the complete replacement of OPC by silica fume leads to significant improvement in compressive strength and durability up to 15% replacement, above which the strength begins to decrease. On the same note, Hemavathi et al. (2020) conducted research on the use of high-performance concrete with 20 per cent silica fume and learned that when silica fume was combined with glass fibres, there were significant increases in compressive and tensile strength.

Previous studies by Rafat Siddique (2011) also defined the main characteristics of silica fume and proved that its effect was positive in terms of reducing permeability and enhancing resistance to sulphate attack and chloride ions penetration. Mechanical properties are not only increased through the use of pozzolanic reaction but it also helped in sustainability because industrial by-products are used in the production, which would have been a cause of environmental pollution.

Selvapriya (2019) and Akshatha (2018) pointed out that the ideal percentage of fume contents is between 7.5 and 12.5% of cement substitution, at which compressive and flexural strengths are both beneficial. Nonetheless, the workability decreases as the fume of silica becomes higher, and superplasticizers have to be used.

2.2 Polypropylene Fibre in Concrete

The use of fibre reinforcement has been widely known as a way of dealing with the brittle nature of concrete. Polypropylene fibre (PPF) is a synthetic fibre that is among the widely used due to its cheapness, availability and resistance to chemicals (Banthia and Gupta, 2004). It is normally added in small quantities (0.1-2% by weight of cement) and is used to manage plastic shrinkage cracks, permeability and to enhance toughness.

According to Yin et al. (2020), the polypropylene fibres increased tensile and flexural strength of concrete, but not compressive strength. Bharath et al. (2021) noted that addition of 1-1.5% PPF gave optimum enhancement in split tensile strength which stimulated ductility and post-crack behaviour.

The microstructural effects of PPF have been examined in other studies. Song et al. (2005) establish that polypropylene fibres fill microcracks and slow down the crack propagation, which increases the fracture toughness of concrete. In addition, they cannot be degraded in adverse environments as their chemically inert and hydrophobic attributes, unlike steel fibres, which are highly likely to corrode (Chandra and Ohama, 1994).

2.3 Combined Use of Silica Fume and Polypropylene Fibre

Though the effects of silica fume and those of polypropylene fibre have been thoroughly documented separately, their joint application have been comparatively less represented in the literature. Akshatha (2018) experimented with M45 concrete that included silica fume and steel fibre, showing that the two helped to increase compressive and tensile characteristics. Applied to polypropylene fibres, Hemavathi et al. (2020) demonstrated that silica fume in combination with glass or synthetic fibres gave a better result in terms of bonding the matrix and fibre as the denser microstructure of silica fume enables fibres to contact the cementitious paste more efficiently.

According to Selvapriya (2019), silica fume enhances early strength and polypropylene fibre enhances post-cracking behaviour, which results in a more robust system to sudden brittle failure. These results match the overall opinion that an optimum level of silica fume of approximately 10% and fibre level of 1-1.5% give moderate gains in compressive, tensile and flexural characteristics.

2.4 International and Indian Research Trends

The world is increasingly focusing on using waste by-products in the construction materials to ensure that they are sustainable. The silica fume is already used in the North American market and European markets to manufacture bridges, marine buildings, and high-rise buildings that require concrete with high strength (ACI Committee 234, 2006). In India, studies are also looking at the blending of SCMs, including fly ash, silica fume and GGBS with OPC so as to come up with greener concretes in the infrastructure building (Patel and Shah, 2020).

Indian researchers, including Abhinav et al. (2017), have overviewed the prospect of silica fume in enhancing durability, and there is need to have more experimental researches on medium-strength concretes like M30. Also the Bureau of Indian Standards (IS 10262: 2009; IS 456: 2000) has given the design of mix incorporating SCMs though, in practice, it is often subject to availability and cost factors.

3 MATERIALS AND MIX DESIGN

3.1 Materials

The experimental program was conducted using the following materials:

- Cement: Ordinary Portland Cement (OPC) 43 grade in line with the requirements of IS:8112-1989 having specific gravity of 3.11 and fineness of 4%.
- Fine Aggregate: River sand which is locally available and meets Zone-II of the IS:383-1970 with a specific gravity of 2.48 and fineness modulus of 3.21.
- Coarse Aggregate: Granite, Crushed and greater than 20 mm in size with specific gravity of 2.69, water inertia of 0.45 and modulus of fineness of 7.08.
- Water: Clear potable water, which is not contaminated and can be mixed with concrete and cured according to the requirements of IS:456-2000.
- Silica Fume (SF): It is a by-product of silicon metal manufacturing and it has specific gravity of 2.3, a surface area of 150-300 cm2/gl, and silica content more than 85%.
- Polypropylene Fibre (PPF): Short monofilament fibres with lengths of 6-12 mm and high tensile strength and chemical resistant, which are percentages (0.5, 1, 1.5 and 2) of the cement weight.

Table 1 Properties of Cement

Property	Value
Specific Gravity	3.11
Fineness	4%
Initial Setting Time	30 min
Final Setting Time	600 min

Table 2 Properties of Fine Aggregate

Property	Value
Specific Gravity	2.48
Fineness Modulus	3.21
Grading	Zone-II

Table 3 Properties of Coarse aggregate

Property	Value
Specific Gravity	2.69
Water Absorption	0.45%
Bulk Density	1420 kg/m^3

3.2 Mix Design

The mix proportions were calculated using IS 10262:2009 for M30 grade concrete. Target mean strength was taken as 38.25 N/mm^2. The water-cement ratio was fixed at 0.45, suitable for severe exposure conditions.

Table 4 Mix Proportion for M30 Grade Concrete

	Cement	Fine Aggregate	Coarse Aggregate	Water
Quantity (kg/m^3)	360	669.3	1186.4	162
Proportion	1	1.94	3.29	0.45

The control mix was designated as **M0**. Silica fume was used to replace cement at levels of 5%, 10%, 15%, and 20%. Polypropylene fibres were incorporated at 0.5%, 1%, 1.5%, and 2% by cement weight.

4 DISCUSSION OF TEST OUTCOMES

Mechanical characteristics of the concrete were evaluated by means of compressive strength, flexural strength, and split tensile strength at the ages of curing, 7, 28, 56 and 90 days.

Compressive Strength: The findings revealed that the strength grew as silica fume replacement grew to 10 percent and then it started decreasing. At 28 days, the optimum mix (10% SF) gave 49.49 MPa in contrast to 42.07 MPa of the control mix. To increase compressive strength, polypropylene fibres were added at 1 percent and this increased to 52.73 MPa and had much better performance since the additives, SF and PPF, worked together in synergy.

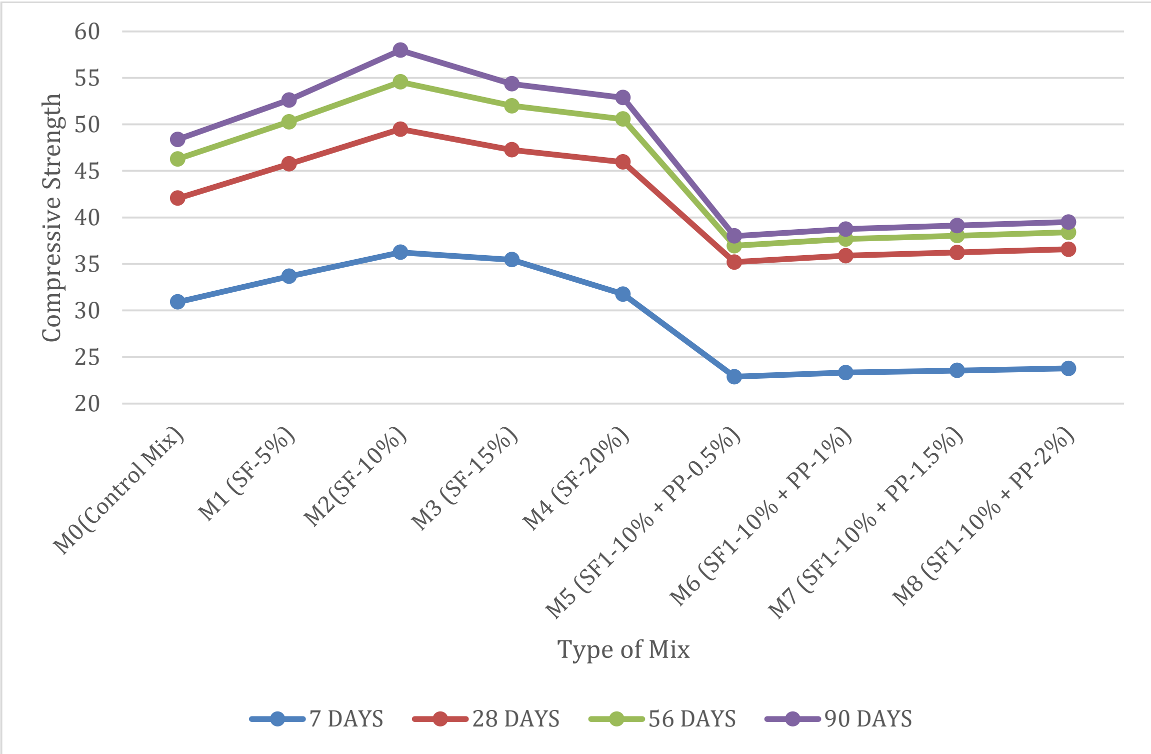

Figure 1 Compressive Strength of Concrete Mixes

Flexural Strength: There was 4.92 MPa flexural strength of control mix at 28 days. At 10% probability of silica fume, this value rose to 5.57 MPa whereas addition of 1.5% PPF resulted in 5.15 MPa. Maximum flexural strength (5.43 MPa) occurred with SF 10% +PPF 2%, which means that fibre has had a contribution to the bending resistance.

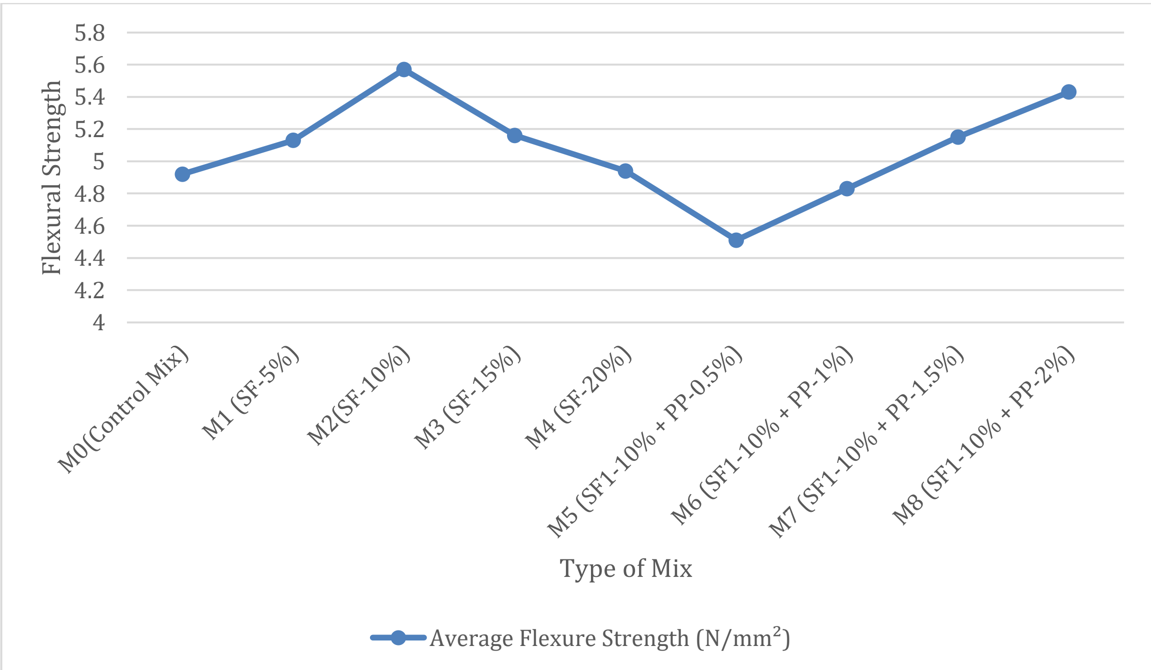

Figure 2 Flexural Strength of Concrete Mixes

Split Tensile Strength: Strength was recorded to be 3.56 MPa at 28 days. At 10 percent SF, tensile strength became 3.94 MPa. Fibres of polypropylene at 1.5 and 2 percent enhanced tensile strength more to 4.73 and 4.91 MPa, respectively.

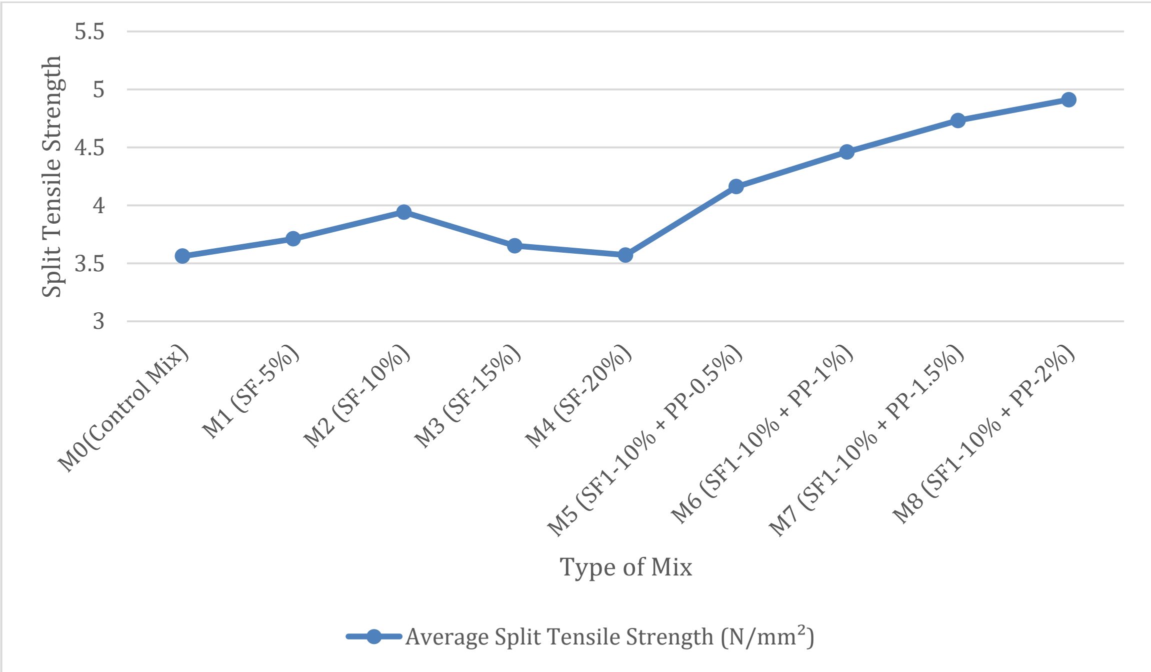

Figure 3 Split Tensile Strength of Concrete Mixes

Workability: Workability decreased with a rise in silica fume because it had a high surface area. But this was controllable with sufficient amount of water content and superplasticizers. Addition of fibre also minimized slump however enhanced toughness and crack control.

All in all, 10 percent silica fume and 1-1.5 percent polypropylene fibre offered the most balanced compressive, flexural and tensile strengths.

5 CONCLUSION

On the basis of the experiment study, the following findings can be made:

- Silica fume was found to greatly enhance the compressive, flexural, and tensile strength to an optimal point of 10 percent at the expense of cement.
- The strengths along with silica fume above 10% showed a downward trend which depicted dilution effects and poor workability.
- The addition of polypropylene fibre enhanced crack resistance, ductility, tensile behaviour, especially at the dosage of 1-1.5 percent.
- The mixed system (10% SF + 1% PPF) was found to gain a 25.3 percent more compressive strength than the control mix at 28 days.
- The maximum flexural strength was at 10% SF and 2% PPF with increase in bending resistance.
- Split tensile strength increased gradually with the volume of fibre to about 38 percent higher at 2 percent PPF.
- The addition of silica fume and fibre had an adverse effect on workability, and performance was controllable by the use of superplasticizers.
- Silica fume and polypropylene fibre synergy have been used to produce sustainable and high-performance grade of concrete M30.

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