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Mechanical performance of M-30 Grade concrete incorporating Pyrogenic silica (silica fume) and Marble powder as partial Cement Replacements

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Abstract

The extensive use of ordinary Portland cement (OPC) in concrete construction has raised serious environmental and cost-related concerns. This research investigates the performance of high-strength concrete incorporating Pyrogenic silica (silica fume) SiO_2 and marble powder ($CaCO_3$) as combined partial replacements for cement. Six Batches of M30-grade concrete mixtures were designed with OPC substitution levels ranging from 0% to 25%. Mechanical properties such as compressive strength, split tensile strength, and flexural strength were evaluated at 7, 14, and 28 days, along with workability characteristics. The results demonstrate that Pyrogenic silica (silica fume) SiO_2 contributes to enhanced strength development through pozzolanic activity, whereas marble powder ($CaCO_3$) improves microstructural compactness by acting as a filler material. An optimal replacement level of 15% SF and 5% MP achieved the highest strength enhancement, highlighting the effectiveness of SF–MP blends in producing sustainable and high-performance concrete.

Keywords: High-strength concrete; Pyrogenic silica (silica fume); Marble powder; Partial cement replacement; Mechanical properties; Sustainable concrete.

Introduction

Concrete is an indispensable material in modern construction due to its strength, adaptability, and long-term durability. It is widely employed in buildings, roads, dams, and offshore structures. The performance of concrete is influenced by factors such as material composition, proportioning, and construction practices, including mixing, curing, and compaction. However, the extensive use of ordinary Portland cement (OPC) has raised environmental concerns owing to its high energy consumption and substantial CO_2 emissions. In response, researchers have explored Adjuvant cementitious materials to reduce cement usage while improving concrete performance. Industrial by-products such Pyrogenic silica (silica fume) SiO_2 and marble powder ($CaCO_3$) have shown significant potential in this regard. Pyrogenic silica SiO_2, an ultrafine pozzolanic material obtained from silicon alloy industries, enhances strength development, whereas marble powder ($CaCO_3$), generated as waste during marble processing, contributes to environmental pollution if not properly managed. This study focuses on the combined application of Pyrogenic silica and marble powder in high-strength concrete (HSC) to achieve improved mechanical performance, efficient waste utilization, and reduced environmental impact[1,2].

Objective: This research is intended to investigate the suitability of Pyrogenic silica (silica fume) SiO_2 and marble powder ($CaCO_3$) for use as supplementary adjuvant materials in M30 grade concrete through a comparative benchmarking approach. The study examines the influence of varying replacement levels of these materials on the workability characteristics of fresh concrete. It further evaluates the effect of partial cement substitution with Pyrogenic silica (silica fume) SiO_2 and marble powder ($CaCO_3$) on the compressive strength development of M30 grade concrete. The investigation also addresses changes in split tensile strength resulting from the incorporation of these materials. Additionally, the flexural strength response of concrete mixes containing different proportions of Pyrogenic silica (silica fume) SiO_2 and marble powder ($CaCO_3$) is assessed. Finally, the study aims to determine the optimal replacement proportion that yields improved strength performance and to provide a comprehensive comparison of the mechanical behaviour of concrete modified with Pyrogenic silica (silica fume) SiO_2 and marble powder ($CaCO_3$)[3].

Materials Use: The binding agent used in this investigation was Ordinary Portland Cement of 43 grade, manufactured in accordance with the specifications of IS 8112:1989. Fine aggregate consisted of naturally sourced river sand falling within Zone II classification. The coarse aggregate employed was crushed stone of natural origin with a nominal maximum particle size limited to 20 mm. Pyrogenic silica, characterized as an ultrafine industrial material generated through flame-based, high-temperature hydrolysis of silicon tetrachloride ($SiCl_4$) or related chlorosilane compounds, was incorporated as a supplementary component. Marble powder used in the study was collected as an industrial waste product from marble cutting and surface polishing processes. Clean tap water meeting the quality requirements prescribed in IS 456:2000 was utilized for the preparation and curing of all concrete mixes[4-6].

Methodology

Mix design was carried out for M30 grade concrete in which ordinary Portland cement was partially replaced with 0–25% Pyrogenic silica (silica fume), while the marble powder (MP) content was kept constant[7,8], as shown in Table-1. The water–cement ratio was maintained at 0.45.

Table-1: Formulation of Mix Design where Marble Powder constant.

MIX	OPC (%)	SF (%)	MP (%)
Batch Mix-1	100%	0%	0%
Batch Mix-2	90%	5%	5%
Batch Mix-3	85%	10%	5%
Batch Mix-4	80%	15%	5%
Batch Mix-5	75%	20%	5%
Batch Mix-6	70%	25%	5%

Mix design was carried out for M30 grade concrete in which ordinary Portland cement was partially replaced with 0–25%marble powder (MP), while the Pyrogenic silica (silica fume) content was kept constant[7,8], as shown in Table-2. The water–cement ratio was maintained at 0.45.

Table-2: Formulation of Mix Design where Pyrogenic Silica (Silica Fume) constant.

MIX	OPC (%)	MP (%)	SF (%)
Batch Mix-1	100%	0%	0%
Batch Mix-2	90%	5%	5%
Batch Mix-3	85%	10%	5%
Batch Mix-4	80%	15%	5%
Batch Mix-5	75%	20%	5%
Batch Mix-6	70%	25%	5%

Workability: Workability is a handling characteristic of fresh concrete that governs its ease toblended, transported, cast, & compaction without any loss of cohesion. A concrete mix with good workability can be fully compacted with minimal effort while remaining free from Grout separation(segregation) and Laitance formation (bleeding). The handling characteristic of all Batch mixes of concrete in the current analysisappraise using the slump test method. The results indicated that all mixes achieved slump values within the acceptable range of 20–80 mm, signifying adequate workability for practical applications.

Splitting Tensile Test: The tensile demeanor of concrete was indirectly appraised through the splitting tensile strength method. Cylindrical embodiment were placed horizontally between the upper plate and bottom plate of a compression testing machine, and a load was implement uniformly via the vertical axisprior to splitting failure occurred. The test achieve on cylinder embodiment of 300 mm height and 100 mm diameter.Upon completion of 28 days of water curing, the embodiment were withdrawn from the water and the embodiment were left undisturbed for a short duration to eliminate superficial moisture ahead of testing. Mechanical loading was applied through a 2000 kN compression testing system, with all test steps conducted in conformity with IS 1199 and associated IS: 516[9,10]. The splitting tensile strength was determined using the equation:

$$f_t = \frac{2P}{\pi DL}$$

Where: P represents theload applied at failure, D is the embodiment diameter, and L is the embodiment length.

Flexural Strength Test: Concrete beam embodiment underwent flexural evaluation using equipment housed in the Structural Engineering laboratory using a high-capacity loading equipment rated at 2000 kN. All embodiment were tested following a uniform and standardized procedure. After 28 days of curing, the beam surfaces were prepared by sanding to achieve a smooth finish, followed by whitewashing and labeling for identification. The application of white wash facilitated clear observation of crack initiation and propagation at various stages of loading. The beam specimens were subjected to two-point transverse loading. Which allowed simultaneous and uniform application of load at two points, ensuring reliable evaluation of flexural behavior[9,10].

For Two-Point Loading (as per IS: 516)

$$f_r = \frac{P \times L}{b \times d^2}$$

Where: f_r= Flexural strength (MPa), P= Peak load sustained at the point of failure (N), L= Clear span of the beam (mm), b= Width of the beam embodiment (mm), d= Depth of the beam embodiment (mm).

Observations and Evaluation: General: In experimental program Pyrogenic silica (silica fume) SiO_2 and marble powder ($CaCO_3$) were employed as Adjuvant materials in M30 grade concrete with take over some amount ranging from 0% to 25%. Concrete embodiment consisting of nine cubes, six beams, and six cylinders were cast using standard concrete made with cement, sand, and crushed stone aggregate. To reviewing the cumulative effect of Pyrogenic silica (silica fume) SiO_2 and marble powder ($CaCO_3$), the cement content was reduced to 75%, and the remaining 25% of the cement binder was substituted with different ratios of Pyrogenic silica (silica fume) SiO_2 and marble powder ($CaCO_3$).

Investigation of Initial and Final Setting Behavior of M30 Grade Concrete: Initial & Final Setting time for concrete where Ordinary Portland cement was partially replaced with 0–25% Pyrogenic silica (silica fume), while the marble powder (MP) content was kept constant shown in Table-3.

Table-3: Investigation of Initial and Final setting Behavior of concrete where Marble Powder is kept constant.

Trial Mix	Setting Time (minutes)		Depth of Penetration (mm)
	Initial	Final	
Batch Mix-1	33	587	7
Batch Mix-2	35	575	7
Batch Mix-3	41	591	7
Batch Mix-4	45	588	7
Batch Mix-5	51	538	7
Batch Mix-6	45	543	7

Initial & Final Setting time for concrete where Ordinary Portland cement was partially replaced with 0–25% Marble Powder (MP), while the Pyrogenic silica (silica fume) content was kept constant shown in Table-4.

Table-4: Investigation of Initial and Final setting Behavior of concrete where Pyrogenic Silica is kept constant

Trial Mix	Setting Time (minutes)		Depth of Penetration (mm)
	Initial	Final	
Batch Mix-1	31	583	7
Batch Mix-2	35	509	7
Batch Mix-3	39	565	7
Batch Mix-4	46	540	7
Batch Mix-5	48	544	7
Batch Mix-6	44	547	7

Workability: Each batch mix was evaluated for feasibility using the slump test to assess the workability of fresh concrete. To maintain uniformity across all mixes, the water–cement ratio was kept constant at 0.45. The measured slump values for the different batch mix compositions with constant marble powder content are presented in Figure-1. Similarly, Figure-4 also illustrates the slump values of mixes prepared with constant pyrogenic silica (silica fume) content. These results highlight the variation in workability arising from changes in mix composition under fixed marble powder and silica fume proportions. These results help in understanding the effect of individual replacement materials on workability.

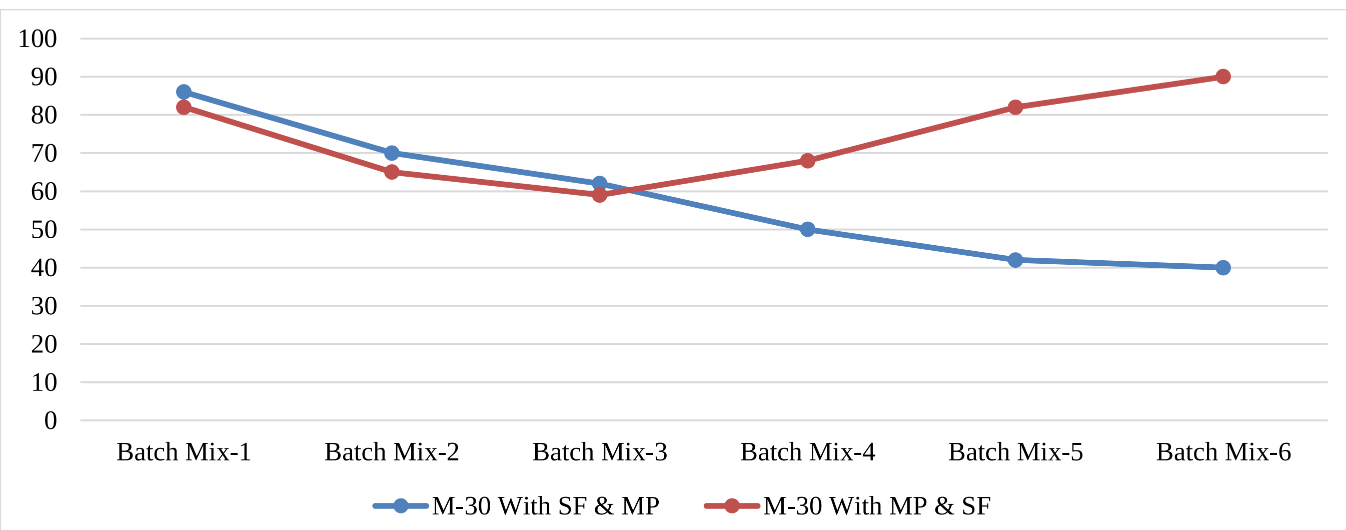

Figure-1: Combined Workability of M30 grades concrete.

Evaluation of Compressive Force Performance: The compressive Force performance of M30 grade concrete incorporating different batch mix proportions was evaluated at curing maturation period of 7, 14, and 28 days. This section presents and discusses the test outcome obtained at each curing maturation period. The compressive force values for all batch mixes where partially replacement of cement with Pyrogenic Silica (Silica Fume) 0-25% and Marble Powder kept constant are presented in Figure-2.

The compressive force values for all batch mixes where partially replacement of cement with Marble Powder 0-25% and Pyrogenic Silica (Silica Fume) kept constant are presented in Figure-3 the variation in strength with curing age. The Figure also compare the compressive force of the modified batch mixes with the control mix (100% OPC + 0% SF + 0% MP) and highlight the differences in strength development among all mixes[11].

Evaluation of Split Force Performance: The results of the splitting tensile strength tests conducted on concrete specimens prepared with different mix proportions and cured for varying durations are presented and discussed in this section. Two series of mixes were considered: one in which pyrogenic silica (silica fume) partially replaced cement in the range of 0–25% while marble powder content was kept constant, and another in which marble powder replaced cement in the same range while the pyrogenic silica content remained constant. The splitting tensile strength tests were carried out after curing periods of 7, 14, and 28 days to evaluate the development of strength with age shown in Figure-4 and Figure-5.

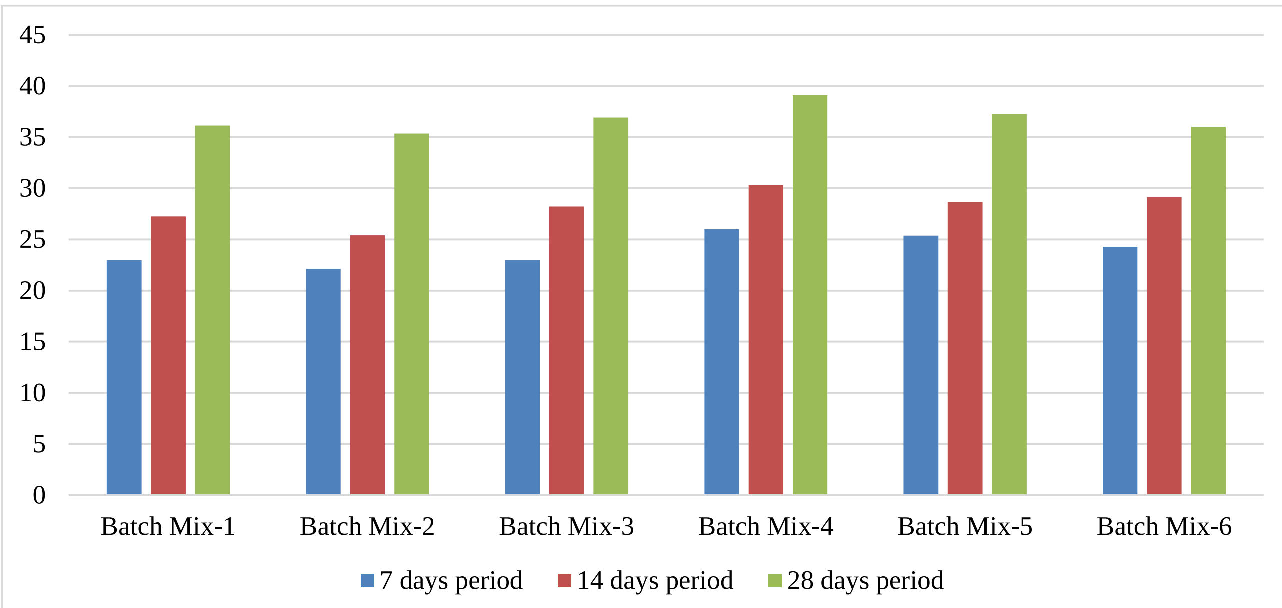

Figure-2: Compressive Force for all curing maturation days for M30 where Marble Powder Constant.

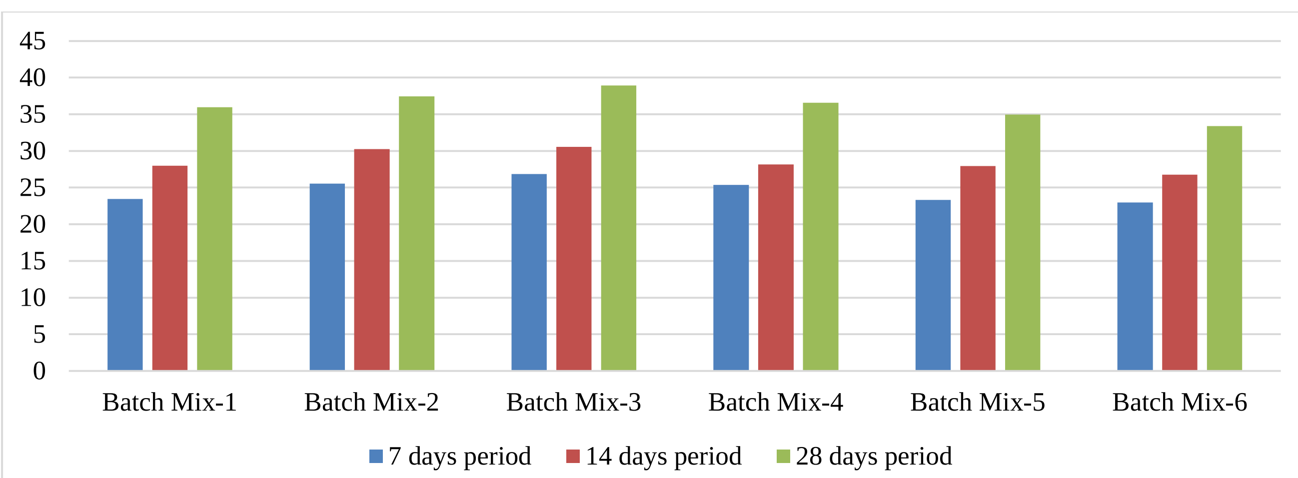

Figure-3: Compressive Force for all curing days for M30 where Pyrogenic silica Constant.

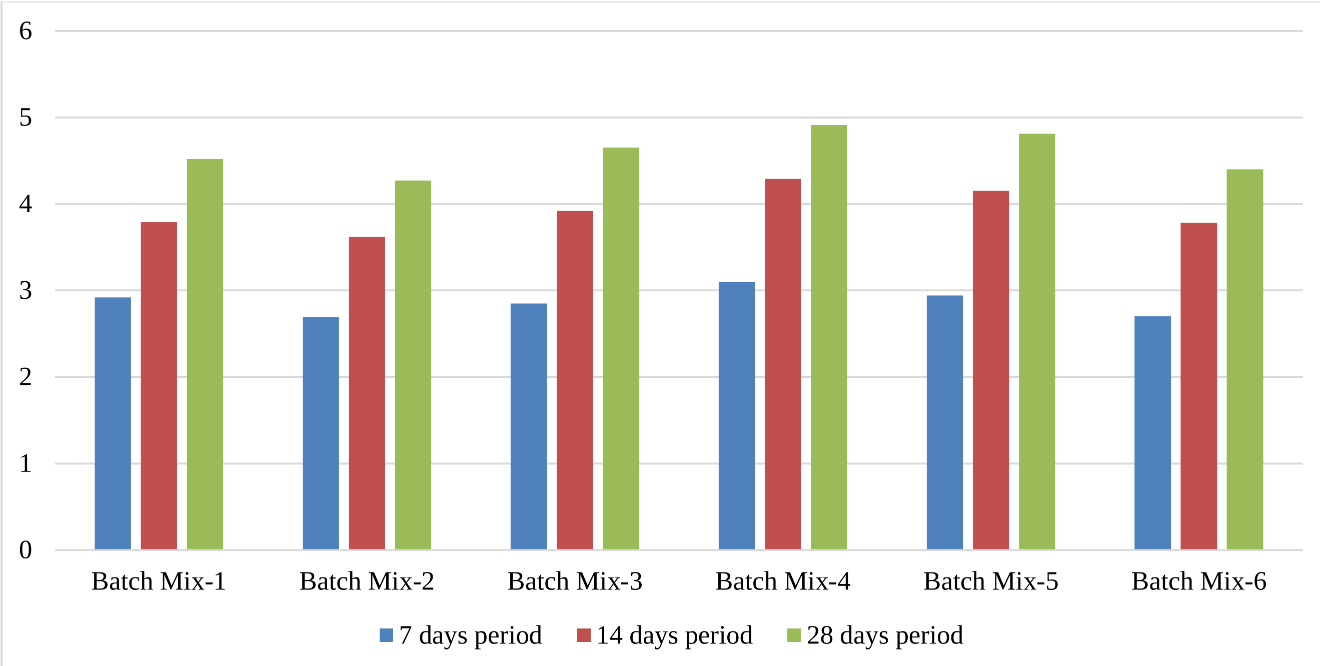

Figure-4: Split Tensile Force for all curing maturities period for M-30 where Marble Powder Constant.

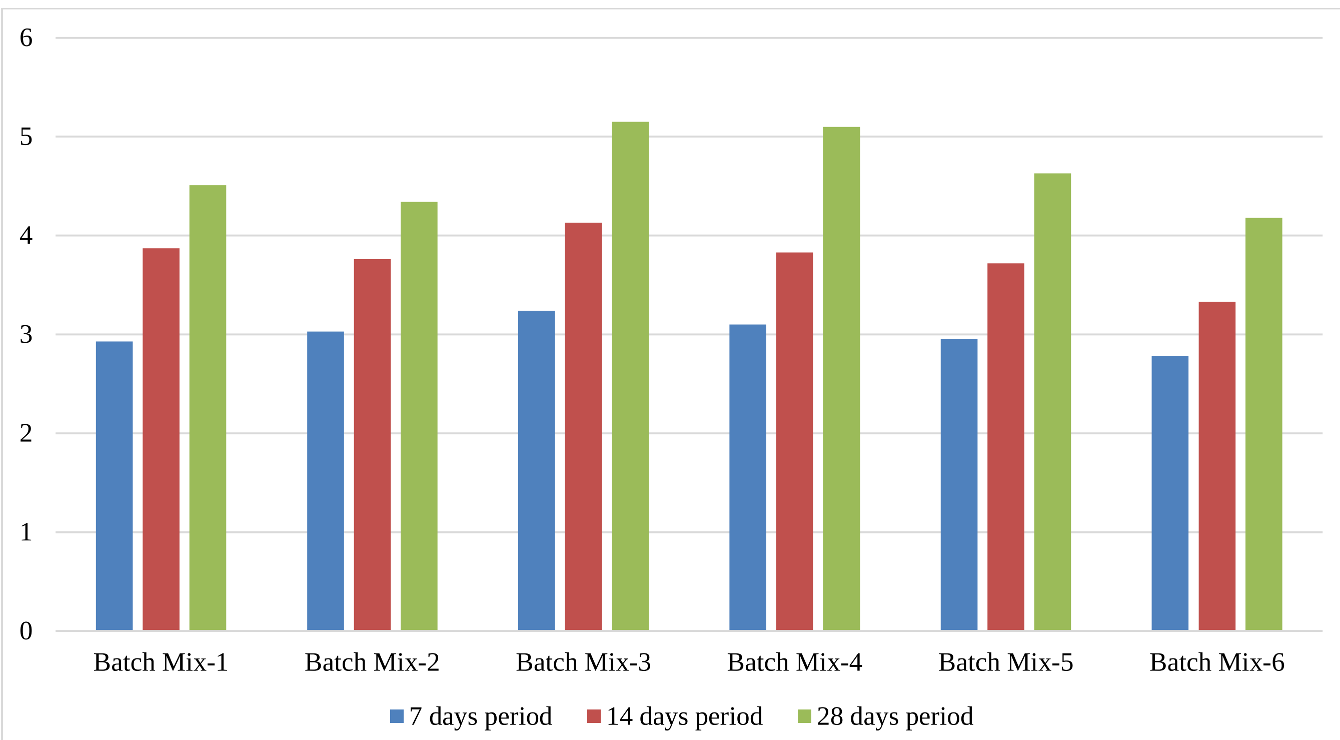

Figure-5: Split Tensile Force for all curing maturities period for M-30 where Pyrogenic silica Constant.

Flexural Force Performance Observation: This section presents and analyzes the flexural load behavior of M30 grade concrete specimens prepared with different batch mixes and cured for varying durations. Two series of mixes were considered: one in which pyrogenic silica (silica fume) partially replaced cement in the range of 0–25% while marble powder content was kept constant, and another in which marble powder replaced cement within the same range while the pyrogenic silica content remained unchanged. The flexural performance of all specimens was evaluated at three curing stages: 7, 14, and 28 days shown in Figure-6 and Figure-7.

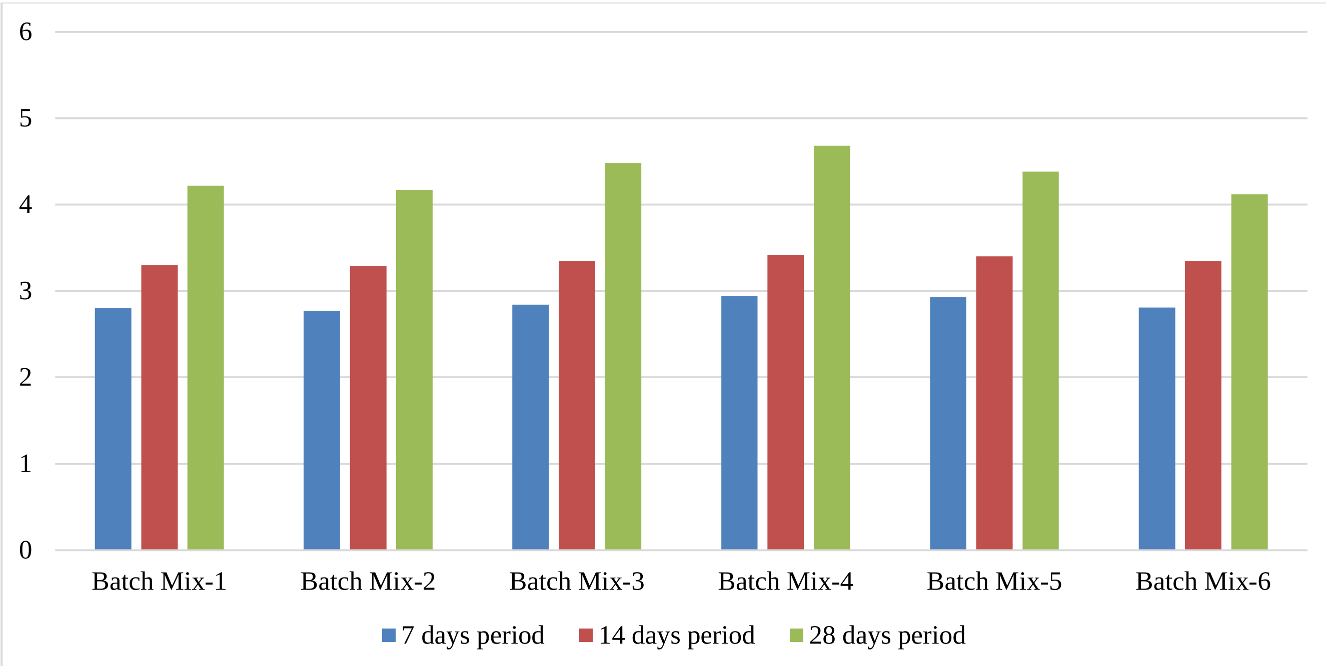

Figure-6: Flexural Strength for all curing days for M30 where Marble Powder Constant.

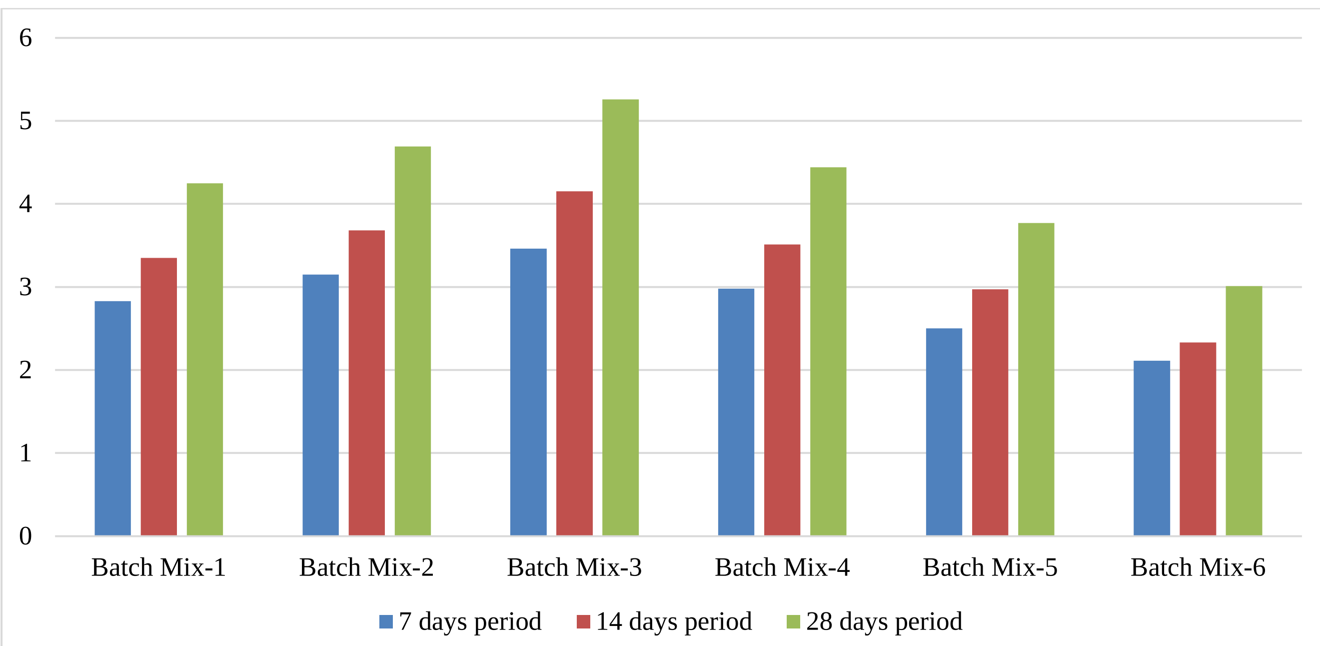

Figure-7: Flexural Strength for all curing days for M30 where Pyrogenic silica Constant.

Results and Discussion

The experimental investigation evaluated the influence of pyrogenic silica (silica fume, SiO_2) and marble powder ($CaCO_3$) as partial replacements of ordinary Portland cement on the fresh and hardened properties of M30 grade concrete. Two series of mixes were examined: (i) varying pyrogenic silica content (0–25%) with constant marble powder, and (ii) varying marble powder content (0–25%) with constant pyrogenic silica.

The performance of all mixes was assessed in terms of workability, compressive force, splitting tensile force, and flexural force at curing ages of 7, 14, and 28 days, and compared with the control mix (100% OPC).

A combined graphical representation comparing both types of mixes is provided in Figure-1. This graph clearly illustrates the variation in slump values with changing material proportions. The observations assist in evaluating the overall feasibility of the concrete mixes. Workability, evaluated through the slump test at a constant water–cement ratio of 0.45, was found to be strongly influenced by the type and level of cement replacement. Increasing pyrogenic silica content resulted in a noticeable reduction in slump due to its extremely fine particle size and high specific surface area, which increased water demand. In contrast, marble powder exhibited a relatively milder effect on workability, and at lower replacement levels, it slightly improved flow characteristics owing to its filler effect and enhanced particle packing. Despite the reduction in slump at higher silica fume contents, all mixes maintained workable consistency within acceptable limits, indicating practical feasibility.

While combined graphical representations illustrate in Figure-2 and 3 the variation in strength with curing age. The graphs also compare the compressive force of the modified batch mixes with the control mix (100% OPC + 0% SF + 0% MP) and highlight the differences in strength development among all mixes[11]. The compressive force of all concrete mixes increased with curing age, reflecting normal hydration and strength development. Mixes containing pyrogenic silica exhibited a significant improvement in compressive force up to an optimum replacement level of approximately 15%, beyond which a decline was observed. This enhancement is attributed to the pozzolanic reaction of silica fume, which converts calcium hydroxide into additional calcium silicate hydrate (C–S–H), leading to a denser and stronger microstructure.

In contrast, mixes incorporating marble powder showed marginal strength improvement at lower replacement levels due to improved packing density; however, higher marble powder contents resulted in reduced compressive force because of cement dilution and the absence of pozzolanic activity. The combined use of pyrogenic silica and marble powder demonstrated that silica fume governs strength development, while marble powder plays a secondary, supportive role.

The test results for the first series of mixes are shown in Figure-4. Similarly, the results for the second series of mixes are shown in Figure-5. These figures collectively illustrate the changes in splitting force (MPa) of all concrete mixes at different curing ages. Splitting tensile force followed trends similar to compressive force, with strength increasing with curing age for all mixes. Concrete containing pyrogenic silica showed a pronounced improvement in tensile performance up to the optimum replacement level, reflecting improved bonding within the cement matrix and a refined interfacial transition zone. The enhanced tensile resistance indicates better crack control and structural integrity.

Marble powder contributed only marginally to tensile strength enhancement at lower replacement levels, while higher contents led to a reduction in performance. Overall, pyrogenic silica proved to be significantly more effective than marble powder in improving tensile behavior.

The flexural strength results for the first series of mixes are shown in Figure-6, whereas the results for the second series are presented in Figure-7. Both tables and figures highlight the progressive development of flexural strength over time, benchmarked against the control mix (100% OPC, 0% SF, 0% MP). Additionally, the differences in flexural behavior among the various batch mixes at each curing stage are clearly demonstrated, providing insights into the influence of partial cement replacement with pyrogenic silica or marble powder on the flexural performance of concrete. Flexural force results further confirmed the beneficial role of pyrogenic silica in enhancing concrete performance. An increase in flexural strength was observed with curing age, with the highest values achieved at approximately 15% silica fume replacement. The improvement in flexural behavior is associated with a denser microstructure, improved aggregate–paste bonding, and increased resistance to micro-crack propagation.

Marble powder exhibited limited influence on flexural performance, with higher replacement levels causing a reduction in load-carrying capacity. The comparative evaluation indicates that flexural performance is more sensitive to the presence of reactive supplementary cementitious materials such as silica fume than to inert fillers like marble powder.

The combined analysis of fresh and hardened properties reveals a synergistic effect when pyrogenic silica and marble powder are used together at controlled levels. Pyrogenic silica primarily enhances mechanical strength through pozzolanic and micro-filling mechanisms, while marble powder contributes to improved particle packing and workability at lower dosages. The optimum performance was achieved for the mix containing 15% pyrogenic silica and 5% marble powder, which delivered superior compressive, splitting tensile, and flexural force values with acceptable workability.

Conclusion

From the experimental evaluation of M-30 grade concrete mixes containing varying proportions of Pyrogenic silica (silica fume) SiO_2 and marble powder ($CaCO_3$), it is concluded that Pyrogenic silica (silica fume) SiO_2 is a more effective cement replacement material than marble powder ($CaCO_3$) with respect to strength development. The peak compressive strength was observed at 15% Pyrogenic silica (silica fume) SiO_2 replacement with a constant marble powder content of 5% (Batch Mix-4), and the same combination resulted in maximum split tensile and flexural force values. The impressive performance of Pyrogenic silica (silica fume) SiO_2 can be attributed to its high pozzolanic reactivity and micro-filling ability. However, an increase in Pyrogenic silica (silica fume) SiO_2 dosage negatively affects the workability of concrete mixes. Marble powder ($CaCO_3$) can be used to replace part of the cement, but higher replacement levels reduce mechanical performance and disrupt workability if the Pyrogenic silica (silica fume) SiO_2 content remains unchanged[12].

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