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Experimental Investigation on Polypropylene Fiber-Reinforced Concrete with Partial Replacement of Cement by Quartz Powder

Banavath Balaji Naik[1], Dr. D. V. Prasada Rao[2]

[1]*PG Student, Department of Civil Engineering, SV University College of Engineering, Tirupati, Andhra Pradesh, India*

[2]*Professor, Department of Civil Engineering, SV University College of Engineering, Tirupati, Andhra Pradesh, India*

ABSTRACT - *Ordinary Portland cement (OPC) is the primary binding agent in conventional concrete, but its industrial synthesis accounts for significant energy consumption and carbon dioxide emissions. This investigation evaluates the performance of M30 grade concrete produced by incorporating Quartz Powder (QP) as a partial replacement for OPC alongside Polypropylene Fiber (PPF) as secondary reinforcement. The research was carried out in two distinct experimental phases: Phase 1 identified the optimal replacement fraction of QP (evaluated at 5%, 10%, 15%, and 20% by weight of cement), while Phase 2 investigated the synergistic addition of PPF (at 0.5%, 1.0%, and 1.5% by volume) to the optimized QP matrix. Mechanical strength parameters including compressive strength across 3, 7, 28, and 56 days, 28-day split tensile strength, flexural strength, drop-weight impact resistance, and static modulus of elasticity were systematically assessed. Additionally, chemical durability was quantified through 28-day immersion tests in 5% HCl and 5% $MgSO_4$ solutions. Experimental results demonstrate that a 10% QP replacement level yields optimal particle packing and hydration performance, achieving a 28-day compressive strength of 44.1 N/mm^2 (a 9.80% increase over the control concrete), split tensile strength of 3.2 N/mm^2 (+12.98%), flexural strength of 4.7 N/mm^2 (+10.83%), and failure impact energy of 753.1 J (37 blows). Incorporating 1.0% PPF into this 10% QP matrix further enhanced overall mechanical performance, achieving peak compressive strengths of 26.6, 33.0, 46.9, and 50.1 N/mm^2 at 3, 7, 28, and 56 days, respectively. At 28 days, this hybrid mix achieved a split tensile strength of 4.6 N/mm^2 (+59.51% over control) and a flexural strength of 6.0 N/mm^2 (+40.61% over control), alongside a failure impact resistance of 1200.9 J (59 blows, a 78.8% increase). The static modulus of elasticity reached 30.9 × 10^3 N/mm^2, representing a 16.63% increase compared to the control mix. In aggressive chemical environments, the optimum hybrid concrete exhibited superior resistance, restricting compressive strength loss to 15.64% in HCl and 9.25% in $MgSO_4$, compared to 21.22% and 11.24% for conventional concrete. Overall, combining 10% Quartz Powder with 1.0% Polypropylene Fiber optimizes structural performance while reducing OPC consumption by 34 kg/m^3, offering a sustainable, high-performance concrete solution.*

Keywords: Cement Concrete, Quartz Powder, Polypropylene Fiber, Fiber-Reinforced Concrete, Compressive Strength, Impact Resistance, Modulus of Elasticity, Durability.

1. INTRODUCTION

Concrete is the most widely consumed engineered material worldwide, serving as the backbone of modern civil infrastructure including high-rise buildings, bridges, pavements, dams, and marine structures. Its ubiquity stems from its impressive compressive strength, adaptability, widespread raw material availability, and cost-effectiveness. However, conventional concrete exhibits inherent mechanical deficiencies, notably low tensile capacity, low strain at fracture, brittle failure modes, and susceptibility to microcracking under thermal and hygral stresses. Furthermore, the global production of Ordinary Portland Cement (OPC) is highly energy-intensive and acts as a major contributor to global greenhouse gas emissions, accounting for approximately 7–8% of anthropogenic carbon dioxide emissions worldwide.

To mitigate these environmental and structural challenges, modern concrete technology emphasizes two complementary strategies: substituting a portion of OPC with supplementary mineral fillers or Pozzolans, and incorporating discrete short fibers as secondary reinforcement. Quartz Powder (QP) is a crystalline, silica-rich mineral material pulverized to sub-100 μm fineness. When integrated into cementitious mixes, fine QP particles act as physical micro-fillers that occupy microscopic voids between larger cement grains and aggregates. This particle-packing effect densifies the interfacial transition zone (ITZ), refines the pore network, and promotes secondary nucleation, thereby improving both mechanical strength and transport properties.

Concurrently, synthetic fibers specifically Polypropylene Fibers (PPF) have gained widespread acceptance in cementitious composites. Polypropylene fibers are lightweight, non-corrosive, chemically inert, and exhibit high tensile strength. When distributed uniformly within concrete, PPF units provide multi-directional secondary reinforcement. Their primary role is restricting plastic shrinkage cracking, controlling microcrack initiation, bridging macrocracks under mechanical loading, and enhancing post-cracking ductility and impact energy absorption.

Although individual contributions of mineral admixtures and synthetic fibers are established in civil engineering literature, there remains a critical need to systematically evaluate their combined synergistic response in structural concrete grades. This investigation investigates the physical, mechanical, dynamic impact, and durability behavior of M30 grade concrete modified with partial QP cement replacement (5–20% by weight) and PPF inclusion (0.5–1.5% by volume). The main objective is to determine optimal mix proportions that maximize structural performance while supporting carbon footprint reduction in concrete construction.

2. REVIEW OF LITERATURE

Extensive research has investigated the role of fine mineral fillers in enhancing matrix densification and mechanical response in cement-based composites. Neville (2011) and Mehta and Monteiro (2014) established that the strength and durability of concrete depend fundamentally on particle grading, hydration kinematics, and ITZ microstructural integrity. Lin et al. (2018) demonstrated that micro-sized Quartz Powder significantly refines the pore structure of cement pastes by acting as an effective filler, thereby increasing early-age hydration kinetics and reducing capillary porosity. Tavares et al. (2020) evaluated hybrid mineral systems containing Quartz Powder and silica fume, noting that ultra-fine quartz particles enhance particle packing efficiency and improve compressive strength development up to optimal replacement thresholds. Matos et al. (2023) highlighted the valorization of Quartz Powder in self-compacting concrete formulations, reporting improved rheological stability and matrix density without compromising long-term hydration strength. Similarly, Yang et al. (2024) developed hydration models for cement-quartz hybrid systems, confirming that quartz powder acts as a physical nucleation site for calcium silicate hydrate (C-S-H) deposition. Safitri et al. (2023) further verified the efficacy of quartz-based mineral additives in high-performance reactive powder concretes.

Regarding fiber reinforcement, Shetty (2007) noted that incorporating discrete fibers converts brittle concrete failure into a ductile mode by providing post-cracking crack-bridging mechanics. Polypropylene fibers, in particular, improve impact resistance, dynamic energy absorption, and durability against aggressive environmental agents by restricting crack connectivity. Combining micro-fillers with synthetic fibers has been reported to create synergistic effects: micro-fillers strengthen the matrix-fiber bond by densifying the ITZ surrounding individual fiber filaments. The present investigation builds upon these foundational principles by systematically evaluating M30 concrete under combined Quartz Powder and Polypropylene Fiber modifications.

3. MATERIALS AND EXPERIMENTAL PROGRAM

3.1 Raw Material Characterization

The constituent materials utilized in this experimental study were subjected to standard laboratory characterization in accordance with relevant Indian Standard (IS) codes:

- Cement: Ordinary Portland Cement (OPC) 53 grade conforming to IS 269 was used as the primary binding agent. The measured specific gravity of the cement was 3.11.
- Fine Aggregate: Locally sourced natural river sand conforming to Zone II grading of IS 383:2016 was utilized as fine aggregate. The specific gravity of the fine aggregate was 2.58.
- Coarse Aggregate: Crushed angular granite stones of 20 mm and 10 mm nominal maximum sizes were blended in a 60:40 ratio. The specific gravities were 2.63 for 20 mm coarse aggregate and 2.65 for 10 mm aggregate.
- Quartz Powder: Quartz Powder (QP) was obtained as a processed, silica-rich mineral powder characterized by an average particle size of 90 µm (100% passing 100 µm sieve), a specific gravity/density of 2.65 g/cm^3, and a chemical silica (SiO_2) purity of 99.76%.
- Polypropylene Fibers: Monofilament Polypropylene Fibers were employed as secondary reinforcement. The fibers featured a length of 12 mm, diameter of 0.02 mm (aspect ratio = 600), specific gravity of 0.91, and a minimum tensile strength of 600 MPa.

Material Properties: Table No. 1 summarizes the physical and chemical properties of the constituent materials.

Table No. 1 Properties of Raw Constituent Materials

Material	Property Parameter	Measured Value
Cement (OPC 53 Grade)	Specific Gravity	3.11
Fine Aggregate	Specific Gravity	2.58
Fine Aggregate	Grading Zone (IS 383)	Zone II
Coarse Aggregate (20 mm)	Specific Gravity	2.63
Coarse Aggregate (10 mm)	Specific Gravity	2.65
Quartz Powder	Density	2.65 g/cm^3
Quartz Powder	Average Particle Size	90 µm (<100 µm)
Quartz Powder	Silica Content (SiO_2)	99.76%
Polypropylene Fiber	Fiber Length	12 mm
Polypropylene Fiber	Fiber Diameter	0.02 mm
Polypropylene Fiber	Specific Gravity	0.91

3.2 Mix Proportioning

The baseline M30 grade concrete mixture was proportioned in strict compliance with IS 10262:2019 guidelines. The designed mix proportion was 1: 2.07: 3.55 by weight, with a water-to-cementitious material (w/cm) ratio of 0.45. The baseline material quantities per cubic meter of concrete were: 340 kg OPC, 703 kg fine aggregate, 1206 kg coarse aggregate (723.6 kg of 20 mm and 482.4 kg of 10 mm), and 153 kg water.

3.3 Experimental Plan and Specimen Preparation

The experimental program was executed in two systematic steps:

Phase 1 (Quartz Powder Optimization): QP was substituted for cement at levels of 0% (Control Mix), 5%, 10%, 15%, and 20% by weight. Compressive strength tests were conducted at 3, 7, 28, and 56 days. Split tensile strength, flexural strength, drop-weight impact resistance, and static modulus of elasticity were tested at 28 days to determine the optimum QP replacement ratio.

Phase 2 (Fiber Synergy Investigation): Using the optimal 10% QP matrix identified in Phase 1, Polypropylene Fibers were incorporated at volume fractions of 0.5%, 1.0%, and 1.5%. Compressive strength (3, 7, 28, 56 days), 28-day split tensile, 28-day flexural, drop-weight impact resistance, 28-day static modulus of elasticity, and chemical durability (acid and sulphate immersion for 28 days) were comprehensively evaluated.

Specimens were cast using standard steel molds: 150 mm cubes for compressive strength and chemical durability, 150 mm × 300 mm cylinders for split tensile strength and modulus of elasticity, 100 mm × 100 mm × 500 mm prisms for flexural strength, and 150 mm diameter × 63.5 mm thick cylindrical discs for drop-weight impact tests. All specimens were compacted on a vibrating table, demolded after 24 hours, and cured in water tanks at 27 ± 2 °C until their designated testing ages.

4. RESULTS AND DISCUSSION

4.1 Effect of Quartz Powder Replacement on Compressive Strength

Compressive strength results for concrete mixes incorporating 0% to 20% Quartz Powder across 3, 7, 28, and 56 days of curing are detailed in Table No. 2.

Table No. 2 Compressive Strength Development of Concrete at Various Curing Ages under Varying Quartz Powder Replacement Levels

Mix Designation	3 Days (N/mm²)	7 Days (N/mm²)	28 Days (N/mm²)	56 Days (N/mm²)
Control (0% QP)	23.3	25.9	40.1	42.7
5% QP	21.8	27.2	42.0	44.9
10% QP (Optimum)	**24.6**	**30.1**	**44.1**	**48.3**
15% QP	15.8	26.2	39.2	41.9
20% QP	14.8	21.1	35.8	39.2

As presented in Table No. 2, compressive strength increases progressively up to a 10% QP replacement level across all curing ages. At 28 days, the 10% QP mixture achieved 44.1 N/mm², representing a 9.80% enhancement over the control concrete (40.1 N/mm²). At 56 days, the 10% QP concrete reached 48.3 N/mm² (+13.11% over control). This enhancement is attributed to the micro-filler effect of quartz particles (~90 µm), which pack efficiently into inter-granular voids, reducing micro-porosity and densifying the matrix.

However, increasing QP replacement to 15% and 20% led to strength reductions, with 28-day values dropping to 39.2 N/mm² (-2.24% vs control) and 35.8 N/mm² (-10.72% vs control), respectively. Excessive cement replacement dilutes the primary OPC fraction, reducing total C-S-H gel formation. Furthermore, high finer fraction contents increase water demand, leading to reduced workability and less effective compaction. Thus, 10% QP is established as the optimum cement replacement threshold.

4.2 Effect of Quartz Powder on Split Tensile and Flexural Strengths

The variations in 28-day split tensile and flexural strengths for Quartz Powder modified concrete are summarized in Table No.3.

Table No.3 Split Tensile Strength and Flexural Strength of Concrete at Varying Quartz Powder Replacement Levels

Mix Designation	Split Tensile Strength (N/mm²)	% Change vs Control	Flexural Strength (N/mm²)	% Change vs Control
Control (0% QP)	2.90	-	4.20	-
5% QP	3.10	+6.90%	4.30	+2.38%
10% QP (Optimum)	**3.20**	**+10.34%**	**4.70**	**+11.90%**
15% QP	2.80	-3.45%	3.30	-21.43%
20% QP	2.60	-10.34%	3.20	-23.81%

Both split tensile strength and flexural strength exhibited peak performance at 10% QP replacement. Split tensile strength reached 3.20 N/mm² (a 10.34% increase over control), while flexural strength reached 4.70 N/mm² (a 11.90% increase). Beyond 10% replacement, tensile and flexural strengths degraded markedly, dropping to 2.60 N/mm² and 3.20 N/mm² at 20% QP, respectively. These observations confirm that matrix densification from QP enhances tensile resistance up to 10% replacement, but binder dilution dominates at higher replacement fractions.

4.3 Combined Effect of 10% QP and Polypropylene Fibers on Mechanical Strengths

To address the brittle failure nature of unreinforced matrix, Polypropylene Fibers (0.5%, 1.0%, and 1.5% by volume) were incorporated into the optimized 10% QP concrete mix. Table No. 4 summarizes the compressive strength development of the hybrid mixes.

Table No. 4. Influence of Polypropylene Fiber Dosage on Compressive Strength of 10% Quartz Powder Concrete at Various Curing Ages

Mix Designation	3 Days (N/mm²)	7 Days (N/mm²)	28 Days (N/mm²)	56 Days (N/mm²)
Control Concrete (0% QP, 0% PPF)	23.3	25.9	40.1	42.7
10% QP + 0.5% PPF	24.9	30.8	45.9	49.3
10% QP + 1.0% PPF (Optimum)	**26.6**	**33.0**	**46.9**	**50.1**
10% QP + 1.5% PPF	15.9	20.2	43.6	47.5

The addition of 1.0% PPF to the 10% QP concrete achieved peak compressive strength values of 26.6, 33.0, 46.9, and 50.1 N/mm² at 3, 7, 28, and 56 days, respectively. At 28 days, this represents a 16.96% increase over the control concrete (40.1 N/mm²) and a 6.35% increase over the 10% QP concrete without fibers (44.1 N/mm²). Increasing fiber content to 1.5% resulted in lower compressive strengths across early ages (15.9 N/mm² at 3 days) due to fiber balling, increased air entrapment, and compaction difficulties.

Table No.5 presents the 28-day split tensile and flexural strength gains achieved by the hybrid mixes.

Table No.5. Influence of Polypropylene Fiber Dosage on Split Tensile Strength and Flexural Strength of 10% Quartz Powder Concrete

Mix Designation	Split Tensile Strength (N/mm²)	Gain vs Control	Flexural Strength (N/mm²)	Gain vs Control
Control Concrete (0% QP, 0% PPF)	2.90	-	4.24	-
10% QP Concrete (0% PPF)	3.20	+10.34%	4.70	+11.90%
10% QP + 0.5% PPF	3.80	+31.03%	5.10	+21.43%
10% QP + 1.0% PPF (Optimum)	**4.60**	**+59.51%**	**6.00**	**+40.61%**
10% QP + 1.5% PPF	3.90	+34.48%	5.60	+33.33%

The synergy between 10% QP and 1.0% PPF produces dramatic improvements in tensile and flexural capacities. The 28-day split tensile strength reached 4.60 N/mm², representing a 59.51% increase over the baseline control (2.865 N/mm²). Similarly, flexural strength reached 6.00 N/mm², a 40.61% increase over control (4.24 N/mm²). Polypropylene fibers act as physical crack-bridging elements across developing microcracks, transmitting tensile forces across matrix fissures and preventing catastrophic brittle fracture.

4.4 Drop-Weight Impact Resistance

Impact resistance was evaluated using the ACI 544.2R drop-weight test method (4.54 kg hammer, 0.457 m drop height; energy per blow = 20.35 J). Table 6 details the blows and energy required to initiate the first visible crack (N1) and cause ultimate failure (N2).

As shown in Table No. 6, conventional concrete displayed brittle failure under drop-weight impact, failing after 33 blows (671.7 J) with a narrow post-crack margin (8 blows between first crack and failure). Incorporating 10% QP increased failure energy to 753.1 J (37 blows, +12.12%). The optimum hybrid mix (10% QP + 1.0% PPF) exhibited remarkable impact energy absorption: first crack occurred at 45 blows (915.9 J, an 80.0% increase over control), while complete failure required 59 blows (1200.9 J, a 78.8% increase over control). Furthermore, the post-cracking blow count expanded from 8 to 14 blows, confirming substantial post-cracking ductility and impact toughness.

Table No. 6. Drop-Weight Impact Resistance and Energy Absorption Capacity at First Crack and Failure for Control and Modified Concrete Mixes

Concrete	First Crack Blows (N1)	First Crack Energy (J)	Failure Blows (N2)	Failure Energy (J)
Control Concrete (M30)	25	508.8	33	671.7
10% Quartz Powder Concrete	28	569.9	37	753.1
10% QP + 1.0% PPF (Optimum)	45	915.9	59	1200.9

4.5 Modulus of Elasticity and Stress-Strain Behavior

Static modulus of elasticity (E_c) was evaluated at 28 days on 150 mm × 300 mm cylinders. Experimental stress-strain observations were recorded up to ultimate stress and compared against theoretical values predicted by the IS 456:2000 code formula ($E_c = 5000 \sqrt{f_{ck}}$). Table No. 7 presents the elastic parameters.

Table No. 7. Comparison of Experimental Modulus of Elasticity (E_c) with IS 456:2000 Theoretical Predictions at 28 Days

Mix Designation	Ultimate Stress (N/mm²)	1/3 Ultimate Stress (N/mm²)	Strain at 1/3 Stress (×10⁻⁶)	Experimental E_c (N/mm²)	IS 456 Code E_c (N/mm²)
Control Mix (100% OPC)	29.71	9.90	374	26.5×10^3	31.7×10^3
90% OPC + 10% QP	36.61	12.20	421	29.0×10^3	33.2×10^3
90% OPC + 10% QP + 1% PPF	38.82	12.94	419	30.9×10^3	34.3×10^3

The experimental static modulus of elasticity increased from 26.5×10^3 N/mm² for the control mix to 29.0×10^3 N/mm² (+9.43%) for the 10% QP mix, and reached 30.9×10^3 N/mm² (+16.63%) for the 10% QP + 1.0% PPF hybrid mix. The stress-strain curves demonstrated that the hybrid mix achieved a higher peak stress (38.82 N/mm²) and sustained larger ultimate strains (2220×10^{-6} vs 1517×10^{-6} for control), indicating enhanced ductility.

Experimental E_c values ranged between 83.6% and 90.1% of the code-predicted theoretical values (31.7×10^3, 33.2×10^3, and 34.3×10^3 N/mm² for control, 10% QP, and 10% QP + 1.0% PPF, respectively). This variance is consistent with standard IS 456:2000 provisions, which recognize a ±20% deviation allowance for experimental modulus evaluations.

4.6 Durability Performance: Acid and Sulphate Resistance

Chemical durability was evaluated by completely immersing 150 mm cube specimens for 28 days in 5% Hydrochloric Acid (HCl) solution and 5% Magnesium Sulphate ($MgSO_4$) solution. Table No. 8 summarizes the mass loss and compressive strength loss.

Table No. 8. Mass Loss and Residual Compressive Strength of Concrete Specimens Exposed to 5% HCl and 5% $MgSO_4$ Solutions for 28 Days

Mix Designation	Mass Loss (HCl) (%)	Strength Loss (HCl) (%)	Residual Strength (HCl) (N/mm²)	Mass Loss $MgSO_4$ (%)	Strength Loss $MgSO_4$ (%)
Control Concrete	5.00%	21.22%	31.60	2.50%	11.24%
10% QP Concrete	3.60%	19.40%	35.54	1.80%	10.30%
10% QP + 1.0% PPF (Optimum)	1.10%	15.64%	39.60	1.80%	9.25%

Acid exposure (5% HCl) caused severe chemical degradation in conventional concrete, resulting in a 5.00% mass loss and a 21.22% reduction in compressive strength (dropping from 40.11 N/mm^2 to 31.60 N/mm^2). In contrast, the 10% QP + 1.0% PPF hybrid mix restricted mass loss to 1.10% and compressive strength loss to 15.64%, maintaining a residual strength of 39.60 N/mm^2 (25.32% higher than control in acid). Quartz powder filler refines the capillary pore network, restricting acid ingress, while polypropylene fibers prevent micro-cracking during acid-induced matrix degradation.

Sulphate exposure (5% $MgSO_4$) produced lower overall deterioration than acid attack. Compressive strength loss decreased from 11.24% in control concrete to 9.25% in the 10% QP + 1.0% PPF mix (retaining a residual strength of 42.60 N/mm^2). The results confirm that acid attack is significantly more aggressive than sulphate attack, and that the hybrid QP-PPF concrete exhibits superior chemical durability in aggressive environments.

5. CONCLUSIONS

Based on the comprehensive experimental investigation evaluating Quartz Powder (QP) and Polypropylene Fiber (PPF) in M30 grade concrete, the following conclusions are drawn:

1. Optimum Quartz Powder Replacement: Substituting 10% OPC with fine Quartz Powder (90 μm) yields peak mechanical gains, achieving a 28-day compressive strength of 44.1 N/mm^2 (+9.80%), split tensile strength of 3.2 N/mm^2 (+10.34%), and flexural strength of 4.7 N/mm^2 (+11.90%) compared to control concrete. Higher replacement levels (15–20%) cause strength degradation due to binder dilution.
2. Optimum Polypropylene Fiber Content: Incorporating 1.0% PPF by volume into the 10% QP concrete provides optimal secondary reinforcement, producing 28-day and 56-day compressive strengths of 46.9 N/mm^2 (+16.96% vs control) and 50.1 N/mm^2 (+17.33% vs control), respectively.
3. Tensile and Flexural Synergy: The combined 10% QP + 1.0% PPF mix delivers exceptional tensile capacity, achieving a 28-day split tensile strength of 4.6 N/mm^2 (+59.51% over control) and a flexural strength of 6.0 N/mm^2 (+40.61% over control) through effective crack-bridging mechanics.
4. Enhanced Impact Resistance: The 10% QP + 1.0% PPF concrete hybrid mix exhibits superior dynamic toughness, requiring 45 blows (915.9 J, +80.0%) to initiate first crack and 59 blows (1200.9 J, +78.8%) to cause failure in drop-weight impact testing, with post-crack resistance expanding from 8 to 14 blows.
5. Stiffness and Ductility: Static modulus of elasticity of concrete increased to 30.9 × 10^3 N/mm^2 (+16.63% over control), while ultimate strain at failure increased from 1517 × 10^{-6} to 2220 × 10^{-6}, confirming enhanced matrix stiffness and post-peak ductility.
6. Superior Chemical Durability: In 5% HCl solution, the optimum hybrid mix reduced 28-day strength loss from 21.22% (control) to 15.64% and mass loss from 5.00% to 1.10%. In 5% $MgSO_4$ solution, strength loss was restricted to 9.25% (vs 11.24% for control).
7. Sustainability and Economic Impact: Replacing 10% cement with Quartz Powder reduces OPC consumption by 34 kg/m^3 of concrete. This lowers material costs, reduces embodied carbon dioxide emissions, and provides an eco-friendly high-performance material for structural engineering applications.

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