Exploring the Mechanical and Durability Properties of Sustainable Bentonite Concrete

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Abstract

The rising global demand for cement has posed significant environmental challenges, including excessive energy consumption, depletion of natural resources, and contributions to climate change. Supplementary cementitious materials (SCMs) offer a sustainable solution by providing eco-friendly alternatives for cement production. They enable the development of durable and environmentally friendly concrete. This study investigates the individual and combined effects of bentonite and silica fume as partial replacements for cement in polypropylene fiber (PF)-reinforced concrete. The experimental program consisted of 18 unique mixes, including one control mix that used only OPC as the binder. Six primary mixes replaced 10% OPC with bentonite, incorporating micro-PF at varying levels from 0% to 1.25% (in 0.25% increments). Another six mixes replaced 10% OPC with silica fume, maintaining the same PF variations. Additionally, five tertiary mixes combined 15% bentonite and 5% silica fume as SCMs, with PF content ranging from 0.25% to 1.25%. Performance evaluation included tests for slump, compressive strength, splitting tensile strength, and water absorption. Results revealed that increasing PF content beyond 0.75% mostly adversely affected concrete properties.

Keywords: Bentonite, Silica Fume, Polypropylene fiber, Workability, Compressive Strength, Split Tensile Strength, Water Absorption.

1. Introduction

The Earth's climate is rapidly changing, primarily due to excessive CO_2 emissions, making their reduction a critical focus for sustainable development. The construction industry significantly contributes to these emissions, with ordinary Portland cement (OPC) production exceeding 4 billion tons annually, releasing nearly one ton of CO_2 per ton of cement [1][2]. This process also depletes natural resources, increasing pressure on the sector to develop sustainable alternatives that maintain OPC’s performance while aligning with green building practices [2].

Supplementary cementitious materials (SCMs), such as bentonite (BN), silica fume (SF), fly ash, and ground granulated blast furnace slag (GGBFS), offer a promising solution by minimizing the environmental impact of concrete production and enhancing durability [3][4]. For example, Pakistan has over 36 million tons of BN, a potential natural pozzolan [5]. SCMs improve concrete performance by reducing porosity, strengthening the interfacial transition zone (ITZ), and enhancing resistance to acid attacks and chloride ion migration [5][6][7]. Using SCMs, like calcined blast furnace slag, can also reduce costs and emissions while improving durability [8]. Blends of SF and BN create denser microstructures, leading to stronger and more durable concrete [4].

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However, incorporating SCMs may cause issues like plastic shrinkage and cracking, which can be mitigated by adding micro-polymer fibers like polypropylene fibers (PF). PF enhances mechanical properties, such as compressive, tensile, and flexural strength, while reducing shrinkage [8]. Although the effects of SF, calcined BN, and fibers on concrete are individually well-documented [9][10], limited research explores the combined impact of uncalcined BN, SF, and PPF. Moreover, the potential of using higher proportions of BN and SF as cement substitutes remains underexplored. This research investigates the combined effect of uncalcined BN, SF, and PF on concrete, with a focus on its mechanical properties and durability characteristics.

2. Experimental Program

The materials utilized in this research included silica fume (SF), bentonite (BN), and ordinary Portland Cement (OPC) Type-I (Fig. 01), with SF and BN serving as partial substitutes for OPC following ASTM C150 standards. BN was sourced locally from Kattha Saghir in Punjab, Pakistan, while SF was imported from Sika Industry. Fine aggregates were acquired from the Lawrencepur quarry and screened through a 4.75-mm sieve, and coarse aggregates from Margalla with a maximum particle size of 19 mm. Sieve analysis of the fine aggregates was performed as per ASTM C136/C136M-19 standards [11]. Polypropylene fibers (PFs), 19 mm in length and 20 µm in diameter, were also incorporated into the concrete mixtures. The physical properties of the aggregates and PFs are detailed in Tables 1 and 2 [12], with PF characteristics provided by the manufacturer. Tap water was used for mixing and curing, and a BASF 8514 superplasticizer was added to counteract the reduction in workability caused by the inclusion of BN, SF, and PF.

(a) (b) (c)

Figure 1. Material (a) Polypropylene fibers (b) Bentonite (c) Silica fume

Table 1. Physical characteristics of the aggregates.

Properties	Fine Aggregates (FA)	Coarse Aggregates (CA)
Size range (mm)	-	12-19
Specific gravity	2.70	2.68
Water Absorption (%)	1.29	0.51
Loose density (Kg/m3)	-	1415
Rodded density (Kg/m3)	-	1565
Fineness modulus	2.75	-

Table 2. Polypropylene fibers' properties [12]

Properties	Value
Tensile Strength at breakage (MPa)	30-40
Flexural strength (MPa)	40-55
Elongation at breakage (%)	100-600

Tensile modulus (MPa)	1135-1550
Specific gravity	0.9-0.91

Table 3 presents the experimental schedule, which includes 18 distinct concrete mixtures. The control mix, labeled B0-S0-PF0, consisted solely of OPC as the binder. Six primary mixtures (B10-S0-PF0 to B10-S0-PF1.25) were developed by incorporating micro-PF at varying rates, starting at 0% and increasing incrementally by 0.25% to a maximum of 1.25% of the concrete weight. Another set of six mixtures (B0-S10-PF0 to B0-S10-PF1.25) incorporated supplementary cementitious materials (SCMs), specifically 10% silica fume (SF) and 0% bentonite (BN), combined with micro-PF in the same range of 0% to 1.25%. Five tertiary mixtures (B15-S5-PF0.25 to B15-S5-PF1.25) included 15% BN, 5% SF, and micro-PF ranging from 0.25% to 1.25%. The mix design followed a 1:2:4 proportion determined through trials and maintained a fixed water-to-cement ratio of 0.6. A 60–90 mm target slump was set to achieve the desired workability.

Table 3. The composition of concrete mixes.

Mix ID	OPC (kg/m3)	BN (kg/m3)	SF (kg/m3)	PPF (% of Concrete's mass)	Water (Litter/m3)	Superplasticizer (% binder's mass)	FA (Kg/m3)	CA (Kg/m3)
B0-S0-PF-0 (Control)	320	0	0	0.00	160	0.9	740	1150
B10-S0-PF-0	288	32	0	0.00	160	0.9	740	1150
B10-S0-PF-0.25	288	32	0	0.25	160	1.0	740	1150
B10-S0-PF-0.50	288	32	0	0.50	160	1.2	740	1150
B10-S0-PF-0.75	288	32	0	0.75	160	1.4	740	1150
B10-S0-PF-1.00	288	32	0	1.00	160	1.6	740	1150
B10-S0-PF-1.25	288	32	0	1.25	160	1.75	740	1150
B0-S10-PF-0	288	0	32	0.00	160	0.9	740	1150
B0-S10-PF-0.25	288	0	32	0.25	160	1.0	740	1150
B0-S10-PF-0.50	288	0	32	0.50	160	1.2	740	1150
B0-S10-PF-0.75	288	0	32	0.75	160	1.4	740	1150
B0-S10-PF-1.00	288	0	32	1.00	160	1.6	740	1150
B0-S10-PF-1.25	288	0	32	1.25	160	1.75	740	1150
B15-S5-PF-0.25	256	48	16	0.25	160	1.0	740	1150
B15-S5-PF-0.50	256	48	16	0.50	160	1.2	740	1150
B15-S5-PF-0.75	256	48	16	0.75	160	1.4	740	1150
B15-S5-PF-1.00	256	48	16	0.75	160	1.6	740	1150

B15-S5-PF-1.25	256	48	16	1.25	160	1.75	740	1150

Eighteen concrete mix batches with varying compositions were prepared using a three-stage mixing method. Initially, binders and aggregates were dry-mixed. In the next stage, water was added in two steps: the first portion ensured uniform blending, while the remaining water, combined with a superplasticizer, was introduced later. Micro PF fibers were then incorporated to avoid clumping due to excessive mixer revolutions. For each mix, three samples were cast to determine average values. The concrete slump was measured before casting according to ASTM C143 [13].

Mechanical properties were assessed through compressive and splitting tensile. Compressive strength tests on 150 mm × 150 mm × 150 mm cubes were conducted after 90 days of curing following BS standards [14]. Splitting tensile strength was evaluated on 150 mm × 300 mm cylinders after 90 days, in line with ASTM C496 [15]. Durability tests, including water absorption, were performed on three 100 mm × 50 mm cylindrical specimens cored from concrete cubes as per ASTM C642 [16]. All mechanical tests were carried out using a 3000 KN compression testing machine at a loading rate of 0.15 MPa/s. Figure 2 provides detailed testing setups.

(a) (b) (c) (d)

Figure 2. (a) Workability, (b) Compressive Strength Test, (c) Split Tensile Strength Test, (d) Water Absorption Test

3. Results and Discussion

A detailed statistical analysis of the experimental data is provided in Table 4, which presents key statistical insights. This includes the mechanical and durability properties of sustainable bentonite concrete examined in this study. The table summarizes the minimum, maximum, range, average, and standard deviation (St. Dev) values of the experimental results.

Table 4a. The average of the experimental results

Mix ID	Slump (mm)	Compressive strength (MPa)	Split tensile strength (MPa)	Water Absorption (%)
B0-S0-PF-0 (Control)	75	17.2	2.40	8.07
B10-S0-PF-0	69	17.5	2.44	7.93
B10-S0-PF-0.25	62	18.2	2.45	7.79
B10-S0-PF-0.50	59	18.1	2.47	7.75
B10-S0-PF-0.75	57	18.2	2.48	7.65
B10-S0-PF-1.00	54	17.4	2.42	7.98
B10-S0-PF-1.25	49	16.6	2.39	8.29

B0-S10-PF-0	68	17.4	2.42	7.88
B0-S10-PF-0.25	67	17.4	2.43	7.91
B0-S10-PF-0.50	65	17.5	2.44	7.85
B0-S10-PF-0.75	61	17.6	2.46	7.73
B0-S10-PF-1.00	56	17.3	2.47	7.90
B0-S10-PF-1.25	52	17.2	2.45	8.11
B15-S5-PF-0.25	61	18.5	2.47	7.53
B15-S5-PF-0.50	59	18.7	2.48	7.49
B15-S5-PF-0.75	56	18.7	2.49	7.45
B15-S5-PF-1.00	53	18.4	2.48	7.42
B15-S5-PF-1.25	51	18.3	2.47	8.13

Table 4b. The key statistical insights

Mix ID	Minimum	Maximum	Difference	Average	St. Dev
Workability (mm)	49	75	26	59.66	7.051
Compressive strength (MPa)	16.6	18.7	2.2	17.8	0.612
Split Tensile Strength (MPa)	2.39	2.29	0.10	2.45	0.030
Water Absorption (%)	7.42	8.29	0.87	7.83	0.248

3.1. Workability

The inclusion of BE (B10-S0-PF0) and SF (B0-S10-PF0) resulted in a slight reduction in slump values compared to the control mix (B0-S0-PF0). A more pronounced decrease in slump was observed in mixtures containing 15% BE and 5% SF (B15-S5-PF0.25 to B15-S5-PF1.25). This reduction in workability can be linked to the flaky particle shape of BE and the finer particle size of SF, as highlighted in previous studies [3][17][4]. Figure 3 illustrates that the mix with B15-S5-PF1.25 experienced the highest workability loss, with a 36.75% slump reduction relative to the control mix. Furthermore, the incorporation of PF caused a noticeable decline in workability due to increased internal friction within the blends, despite maintaining a consistent water-to-binder ratio. Therefore, adding PF can adversely impact the workability of concrete mixtures containing SCMs.

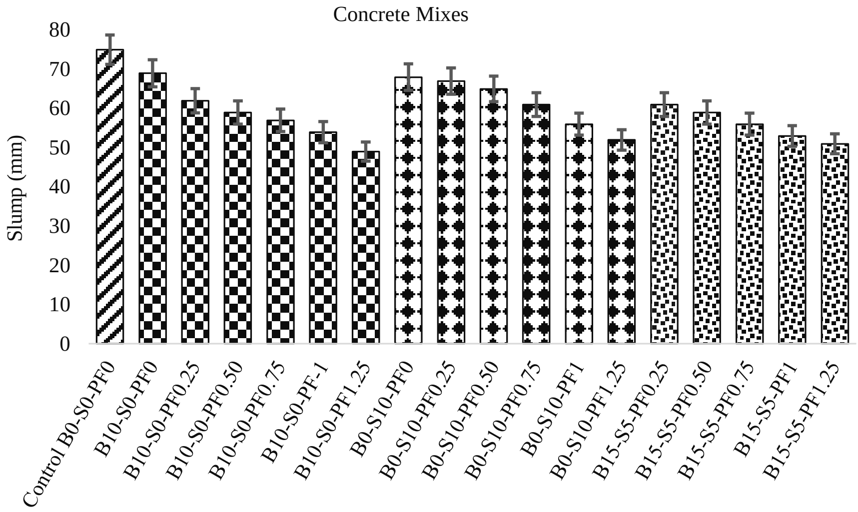

Figure 3. Slump test results

3.2. Compressive strength

The compressive strength results for all mixtures are illustrated in Fig. 4. Incorporating 10% bentonite (BE) in mix B10-S0-PF0 and 10% silica fume (SF) in mix B0-S10-PF0 slightly improved compressive strength after 90 days of curing, with increases of 2% and 1.5%, respectively, compared to the control mix (B0-S0-PF0). A minor additional increase was observed in mixes (B15-S5-PF0.25 to B15-S5-PF1.25) containing 15% bentonite and 5% silica fume compared to those with BE and SF individually. Mixes with 15% bentonite and 5% silica fume (B15-S5-PF0.25 to B15-S5-PF1.25) exhibited superior compressive strength compared to those containing 10% bentonite (B10-S0-PF0.25 to B10-S0-PF1.25) or 10% silica fume (B0-S10-PF0.25 to B0-S10-PF1.25).

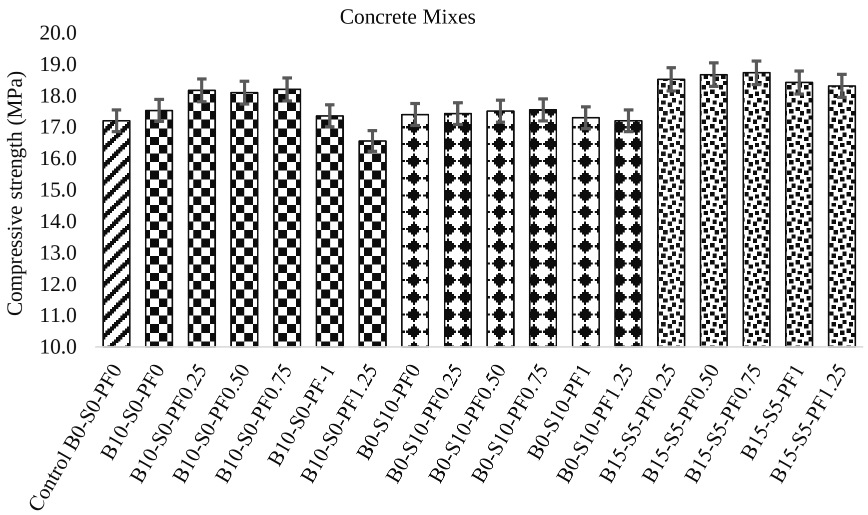

Figure 4. Compressive strength

This enhancement is attributed to the pozzolanic reaction and filler effect of supplementary cementitious materials (SCMs), which generate additional cementitious compounds and produce a denser, more refined concrete microstructure [18][19]. The addition of polypropylene fibers (PF) to SCM concrete mixtures showed no substantial improvement in compressive strength. PF content up to 0.75% (e.g., B10-S0-PF0.25 to B10-S0-PF1.25, B15-S5-PF0.25 to B15-S5-PF1.25, and B0-S10-PF0.25 to B0-S10-PF1.25) resulted in slight strength enhancements, attributed to the bridging effect of fibers, which delayed crack propagation, minimized stress concentrations, and led to narrower, more closely spaced cracks [20][21][22]. However, increasing PF content beyond 0.75%

caused a decline in compressive strength, likely due to poor fiber distribution, clumping, low workability, and increased pore formation.

3.3. Split tensile strength

Figure 5 shows the splitting tensile strength results for all mixtures. The addition of bentonite (BE) in mixes (B10-S0-PF) and silica fume (SF) in mixes (B0-S10-PF0-B0) improved the tensile strength after 90 days, with B0-S10-PF0 and B10-S0-PF0 increasing by 2% and 1.5%, respectively, compared to the control mix (B0-S0-PF0). Mixtures with polypropylene fibers (PF), including (B10-S0-PF0.25 to B10-S0-PF1.25), (B0-S10-PF0.25 to B0-S10-PF1.25), and (B15-S0-PF0.25 to B15-S5-PF1.25), showed peak tensile strength at 0.75% PPF content, with a decline beyond this point. Among these, the B15-S0-PF0.25 to B15-S5-PF1.25 mixes performed better than B10-S0-PF0.25 to B10-S0-PF1.25 and B0-S10-PF0.25 to B0-S10-PF1.25 mixes.

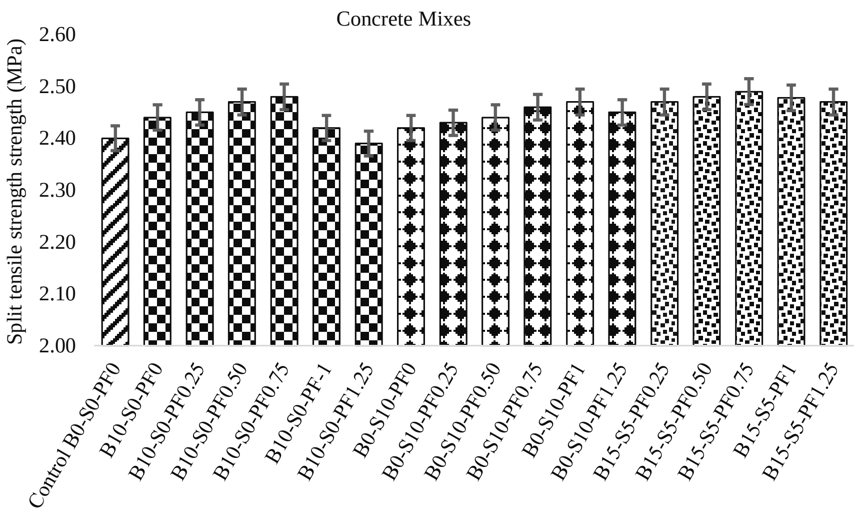

Figure 5. Split tensile strength

The improvement in tensile strength is attributed to the rough surface texture of PPF, which strengthens the bond within the concrete matrix [23]. Additionally, during cracking, the fibers act as bridges, restraining crack formation and propagation, reducing brittleness, and enhancing post-cracking behavior [24]. However, increasing the PPF content beyond 0.75% led to a reduction in strength due to the introduction of critical stress points in the matrix. This reduction is further influenced by factors such as decreased workability, fiber clumping, pore formation [25][26], and increased microstructural inhomogeneity [27], all of which negatively affect tensile strength.

3.4. Water Absorption

The durability of concrete is largely determined by its porosity and ability to absorb water. After 90 days of curing, water absorption tests were conducted, and the results in Fig. 6 show a slight decrease in water absorption with the addition of bentonite (BE) in the B10-S0-PF0 mix and silica fume (SF) in the B0-S10-PF0 mix, with reductions of 1.73% and 2.35%, respectively, compared to the control mix. Concrete mixes with 15% bentonite and 5% silica fume (B15-S5-PF0.25 to B15-S0-PF1.25) exhibited significantly lower water absorption than those with 10% bentonite and 0% silica fume (B10-S0-PF0.25 to B10-S0-PF1.25) or 0% bentonite and 10% silica fume (B0-S10-PF0.25 to B0-S10-PF1.25). This improvement is attributed to the enhanced microstructure from BE and SF, in line with previous studies [7][17][28].

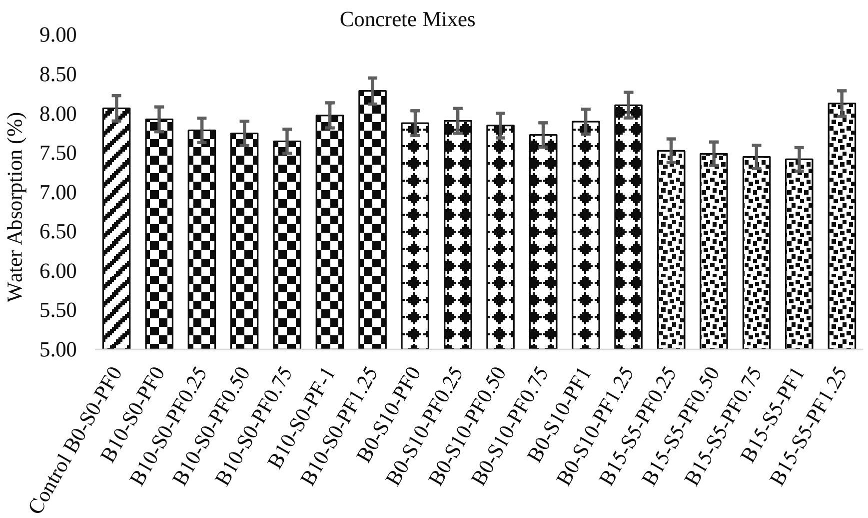

Figure 6. Water Absorption

4. Practical implementation

The suggested modifications in concrete composition, incorporating bentonite, silica fume, and polypropylene fibers, offer practical applications in real-world construction by improving both strength and durability. This sustainable mix is especially advantageous for infrastructure projects that require high cement content, as partially replacing cement with eco-friendly pozzolanic materials like silica fume and bentonite helps reduce environmental impact. Such an approach is particularly beneficial for structures exposed to harsh conditions, including bridges, marine structures, and pavements

5. Conclusions

This study examined the use of cement replacement with BN and SF in PPF concrete and their effects on the properties of the concrete. The key findings are as follows

1. The addition of supplementary cementitious materials (SCMs) such as silica fume (SF) and bentonite reduced the workability of concrete mixtures, primarily due to the fine particle size of SF and the flaky structure of bentonite particles. Moreover, incorporating polypropylene fibers (PF) further decreased workability.
2. The combination of bentonite (BE) and silica fume enhanced the compressive and tensile strengths of concrete, with PF content up to 0.75% providing additional improvements. However, increasing PF beyond this level negatively affected the mechanical properties.
3. Concrete mixtures containing 15% bentonite and 5% silica fume demonstrated superior strength compared to mixtures with 10% bentonite and 0% silica fume, or 0% bentonite and 10% silica fume, even when combined with PF.
4. The inclusion of SCMs lowered water absorption in concrete due to the filler effect and a denser microstructure resulting from pozzolanic reactions.
5. Increasing PPF content beyond 0.75% led to a decline in most mechanical concrete properties.

This section is not mandatory but can be added to the manuscript if the discussion is unusually long or complex.

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Abbreviations

The following abbreviations are used in this manuscript:

SCMs	Supplementary cementitious materials
BE	Bentonite
SF	Silica fume
FA	Fine Aggregate
CA	Coarse Aggregate

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