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The Impact of Pozzolan Incorporation on the Strength of Concrete Reinforced with Hybrid Fibers and Confined by FRP Wrapping Systems

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Abstract

Time, cost and quality are three important factors in implementation that have an important impact on the manufacturing industry. Any progress or development that improves these three factors will always be of interest to civil engineers. Whenever these developments affect the construction industry, sufficient research should be done on their benefits and harms and the necessary measures should be taken to implement them in the construction industry. The use of pozzolans and Fiber-Reinforced Polymers (FRP) systems is an important factor in increasing the strength properties of concrete. The FRP system is defined as fibers and resins used to make composite layers, so that the resins used are used to bond several composite layers to the concrete surface and coatings are used to protect the materials. Reinforcement of building columns with the help of twists is one of the common methods to increase the strength and strength of these columns. Another factor that increases the strength of concrete is the use of pozzolans. The aim of this study was to investigate the different percentages of pozzolans and the number of FRP turns in increasing the strength properties of concrete. For this purpose, having three mixing schemes A, B and C, the required samples of these three schemes are removed. Mixing scheme A does not have pozzolans and mixing designs B and C have 10 and 20% of pozzolans, respectively. Samples No. 1 have no turns and Samples 2 and 3 have one or two turns. Compressive strength tests have shown that we see the highest percentage increase in resistance in specimens B, which has 10% pozzolan. The results showed that the simultaneous use of 10% pozzolan and 2 rounds of FRP had a significant effect on increasing the compressive strength of the samples at the age of 90 days. The results for the tensile strength test show that the use of pozzolan and FRP screw has a small effect on its increase and this effect is about 6% in most cases.

Keywords: FRP helix, Pozzolan, Compressive strength, Tensile strength, Permeability.

1 | Introduction

Over recent decades, the advantages of strengthening reinforced concrete structures using Fiber-Reinforced Polymers (FRP) have been demonstrated by numerous researchers [1]. FRP is a composite material consisting of two main components: Fibers and a matrix, wherein the reinforcing fibers are enveloped by a polymeric

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matrix. The fibers provide the composite's strength and stiffness, while the matrix, by binding the fiber assembly together, serves to transfer stress and strain between the fibers and protect them against environmental factors. Fibers may be oriented in a single direction or in two directions at any desired angle relative to each other [2].

The confinement effectiveness of FRP wrapping is significantly influenced by the cross-sectional geometry of the structural member. Ozbakkaloglu [3] investigated the compressive behavior of concrete-filled FRP tube columns and assessed critical column parameters affecting confinement performance. Furthermore, Cole and Belarbi [4] examined the confinement characteristics of rectangular FRP-jacketed RC columns and demonstrated that square and rectangular sections do not experience confinement to the same extent as circular sections, because, unlike circular sections, the confinement pressure in these sections is non-uniform. Almusallam [5] conducted comprehensive research on the behavior of normal and high-strength concrete cylinders confined with E-glass/epoxy composite laminates, confirming the significant enhancement in compressive strength and ductility achieved through external FRP confinement.

FRP systems have emerged for the strengthening of concrete structures and serve as an alternative to traditional methods such as bonding steel plates, enlarging the cross-section through re-concreting, and external prestressing. Given the drawbacks of these methods—such as low efficiency or the requirement for specialized equipment and technology—strengthening techniques utilizing these composites are increasingly being developed [6]. However, the use of FRPs also entails certain limitations. Among the constraints associated with the use and application of these composites in structural engineering are their high cost and brittle failure, or their linear stress-strain behavior. The use of hybrid FRP is one of the proposed strategies to address these limitations [1]. Compressive and tensile strength of concrete are among the most critical properties of concrete for designers and quality control engineers [7]. The use of hybrid FRP fibers, despite its advantages, also presents certain drawbacks, notably the lack of adequate compressive and tensile strength. To address this issue, the present study investigates the use of pozzolan to enhance its strength.

Today, a major transformation in concrete technology is taking place in most parts of the world to achieve high-strength concretes [8]. The application of pozzolan to obtain high-strength and durable concrete has become prevalent in the concrete industry over the past several years [9]. The extremely fine particle size, significant pozzolanic activity, and its reaction with calcium hydroxide present in cement reduce porosity and permeability while enhancing durability and strength in concretes [10]. The first use of this material in concrete dates back to 1962, at the Jupia Dam in Brazil. Although the use of pozzolan in the concrete industry has a relatively short history, it has rapidly gained acceptance as an effective material for increasing concrete strength [1]. Recent studies have demonstrated that the combination of pozzolanic materials with FRP confinement can yield synergistic effects on the mechanical properties of concrete [11]. Yu et al. [11] investigated the compressive behavior of FRP-confined concrete-encased steel columns and highlighted the importance of confinement in enhancing structural performance under compressive loads.

2 | Material Specifications

2.1 | Aggregates, Cement, and Pozzolan Used

The maximum coarse aggregate size is 19 mm. Pea gravel and washed sand were used in this study. The fineness modulus of the modified sand (passing through No. 8 sieve) is 2.7. Portland cement with a density of 3.15 g/cm^3 was used. The specifications of the cement, aggregates, and pozzolan used in this study are presented in *Table 1*.

Table 1. Physical characteristics of the aggregates employed.

Aggregate Type	Maximum Aggregate Size (mm)	Specific Gravity	Water Absorption (%)	Fineness Modulus
Gravel	19	2.61	1.69	—
Sand	—	2.51	2.67	2.7

2.2 | Hybrid Fiber-Reinforced Polymer Fibers

In this experiment, woven composite sheets with bidirectional fibers are used for wrapping the specimens under consideration. The specifications of the FRP used for confining the fabricated specimens are presented in accordance with *Table 2*.

Table 2. Mechanical and geometrical specifications of the FRP material employed.

Fiber Type	Thickness (mm)	Width (mm)	Ultimate Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Ultimate Strain (%)
FRP	1.2	50	3000	165	1.8

2.3 | Epoxy Adhesive

The FRP fibers are bonded to the surface of the specimens using Sikadur adhesive, which is specifically designed for application to concrete surfaces. This adhesive exhibits suitable viscosity for bonding and consists of two components: a resin and a hardener.

According to the available guidelines for bonding FRP sheets, the mixing ratio of resin to hardener is 2:1 by weight. The pot life of this adhesive under open conditions at room temperature is 70 minutes. The specifications of this adhesive are provided in *Table 3*.

Table 3. Physical and mechanical characteristics of the epoxy adhesive.

Property	Resin	Hardener
Density (g/cm^3)	1.15	0.98
Specific Gravity	1.8	2.0
Tensile Strength (kg/cm^2)	450–550	300–400

Fig. 1 illustrates the constituent components of the epoxy adhesive, including the resin and the hardener, along with the manner in which they are combined for application in bonding FRP fibers to the concrete surface.

a.

b.

c.

Fig. 1. Constituent components of the epoxy adhesive system; a. Resin, b. Hardener, and c. Filler.

3 | Mix Design Employed

3.1 | Mix Design of Concrete Incorporating Pozzolan

Given that the present research aims to examine the performance of FRP-wrapped concrete incorporating pozzolanic material, the mix design adopted for this study consists of a control (base) mix design, to which pozzolan is added at a replacement level of 20% by weight of the total cementitious materials in the base mixture.

Table 4. Mix proportions of concrete mixtures.

Mix Designation	Water-to-Cement Ratio	Cement (kg/m³)	Pozzolan Content (%)	Sand (kg/m³)	Gravel (kg/m³)	Superplasticizer (kg/m³)
A	0.61	316.4	0	1058.7	818.6	0
B	0.61	284.76	10	1058.7	818.6	0.7
C	0.61	253.12	20	1058.7	818.6	0

3.2 | Application of Fiber-Reinforced Polymers Fibers

The FRP sheets are first cut to the required dimensions. The epoxy adhesive is then uniformly spread over the prepared concrete surface using appropriate application tools. The cut FRP sheets are subsequently placed over the adhesive layer, and roller brushes are employed in a reciprocating motion along the fiber orientation to press the sheets firmly into the adhesive. This process ensures complete impregnation of the fibers with the resin and effectively removes any trapped air voids, which would otherwise compromise the bond integrity and overall strengthening performance. Following this, an additional layer of resin is applied as a top coat over the surface of the FRP sheets to ensure full saturation and surface protection (see *Fig. 2*). The curing period necessary for the resin to attain its final mechanical properties at ambient temperatures exceeding 27°C is 72 hours.

Fig. 2. Installation of FRP fibers over the Resin.

4 | Overview of the Experimental Program

The concrete mixes incorporated pozzolanic material, natural sand, pea gravel, and crushed stone aggregates, and were proportioned with a water-to-cement ratio of 0.61 in order to fulfill the objectives of the present study. A specified number of cubic and small cylindrical column specimens were cast for testing. All cast specimens were submerged in a curing tank and moist-cured for 28 days. After the curing period and upon surface drying, the outermost layer of each specimen was ground off using a mini angle grinder to expose a clean and uniform surface. Any surface defects, voids, or irregularities were then filled with a specialized epoxy adhesive to eliminate potential stress concentration points, and the entire surface of each specimen was carefully leveled and smoothed. Within each group of twelve specimens, one specimen was kept unstrengthened to serve as the reference control specimen, while the remaining specimens were retrofitted with either single, double, or triple layers of FRP, or with a hybrid configuration combining two different types of fibers.

4.1 | Compressive Strength Test Results for FRP-Wrapped Cubic Specimens

In this section, the experimental results of compressive strength tests carried out under concentrated axial loading on cubic specimens—both those wrapped with FRP and those left unwrapped—are presented and discussed. To minimize variability and ensure comparability, all specimens were subjected to loading on a single designated test day. The obtained load-bearing capacities and corresponding compressive strength values for the confined (FRP-wrapped) and unconfined (unwrapped) specimens are compiled and reported.

4.2 | General Assessment of Compressive Strength Test Outcomes for Mix Designs A, B, and C

A comprehensive evaluation of the compressive strength test results is conducted across the three mix design categories designated as A, B, and C, in order to assess the influence of FRP wrapping on the compressive performance of specimens with varying pozzolan content and fiber configurations.

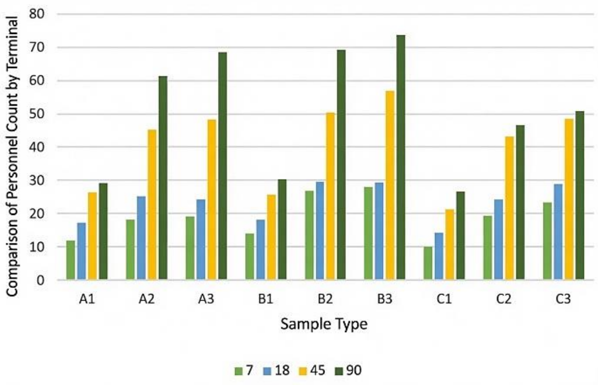

Fig. 3. Analysis of compressive strength test results for specimens obtained from mix designs A, B, and C.

A comparative evaluation of the specimens derived from the three mix designs—designated as A, B, and C—reveals that incorporating higher proportions of pozzolanic material may yield counterproductive outcomes. Specifically, when comparing the performance curves of mix design A (which contains no pozzolan) with those of mix design C (which incorporates 20% pozzolan), it becomes apparent that while FRP wrapping consistently enhances the compressive strength across all specimens, the inclusion of 20% pozzolan has led to a reduction in compressive strength for mix design C relative to the control (unwrapped) specimens.

In contrast, the compressive strength results of specimens from mix design B (with 10% pozzolan) demonstrate that the combined application of FRP wrapping and 10% pozzolan effectively increases compressive strength compared to the control specimens. When assessing the relative contribution of each factor—pozzolan addition versus FRP wrapping—to the improvement in compressive strength, the experimental findings clearly indicate that FRP wrapping exerts a more pronounced influence on enhancing compressive strength than does the incorporation of pozzolan.

4.3 | Tensile Strength Results of FRP-Wrapped Cylindrical Specimens

The tensile strength test results were obtained from testing the specimens at curing ages of 7, 18, 45, and 90 days. This test was carried out on cylindrical specimens. *Table 5* presents the splitting tensile strength values (i.e., the resistance of concrete specimens against splitting failure), which correspond to the hardened concrete tensile strength as determined by the widely recognized Brazilian tensile test method.

Table 5. Tensile strength test results (MPa).

Mix Design	Specimen ID	7 Days	14 Days	45 Days	90 Days
A	A1	2.5	2.5	2.8	2.9
	A2	2.5	2.65	3.0	3.26
	A3	2.6	2.81	3.3	3.45
B	B1	5.1	6.9	7.0	7.2
	B2	5.8	7.01	7.5	7.65
	B3	5.8	7.2	7.8	7.98
C	C1	4.2	6.1	6.1	7.8
	C2	4.5	6.2	6.2	6.9
	C3	4.7	6.4	6.4	6.95

The findings obtained from this test demonstrate that the incorporation of 20% pozzolan enhances the tensile strength of concrete relative to the control mix design A, which contains no pozzolan. Nevertheless, a comparative assessment of the tensile strength values between specimens incorporating 10% pozzolan (mix design B) and those incorporating 20% pozzolan (mix design C) reveals that an excessive dosage of pozzolan adversely affects the overall performance of the concrete. In particular, while both mixtures exhibit improved tensile strength, the increment observed in the 20% pozzolan mixture is notably less pronounced than that achieved with the 10% pozzolan content. This suggests that beyond a certain optimal level, the beneficial effects of pozzolanic addition begin to diminish, leading to a reduced rate of tensile strength enhancement.

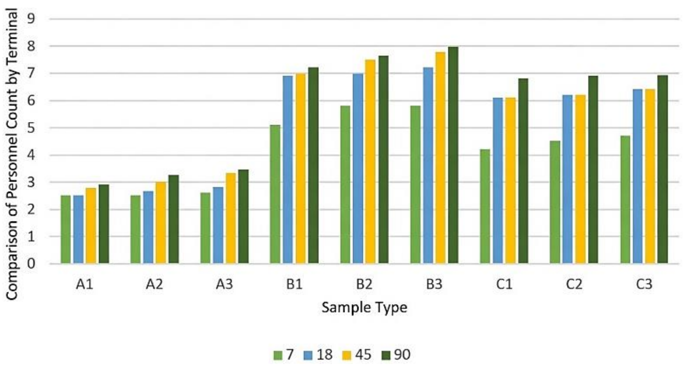

Fig. 4. Comparison of tensile strengths of fabricated specimens.

A concurrent comparison of the tensile strength results across all fabricated specimens reveals that the maximum enhancement in tensile strength is achieved when the concrete mixture incorporates 10% pozzolan and is confined with two layers of FRP wrapping. Furthermore, a comprehensive comparative analysis of the specimens derived from mix design A (control, without pozzolan) against those from mix designs B (10% pozzolan) and C (20% pozzolan) yields a significant finding: the combined application of 10% pozzolan and two layers of FRP wrapping proves to be the most effective strategy for increasing the compressive strength of concrete, surpassing the individual or alternative combinations of these parameters.

4.4 | Water Permeability Test

The results obtained from the water permeability tests conducted on specimens at curing ages of 45 and 90 days are summarized in *Table 6*.

Table 6. Water permeability coefficient (cm/s × 10^{10}).

Mix Design	Specimen ID	45 Days	90 Days
A	A1	22.9	18.16
	A2	20.9	16.16
	A3	18.5	14.6
B	B1	8.6	6.6
	B2	7.2	5.3
	B3	7.0	4.9
C	C1	5.6	3.3
	C2	4.4	2.1
	C3	3.2	1.9

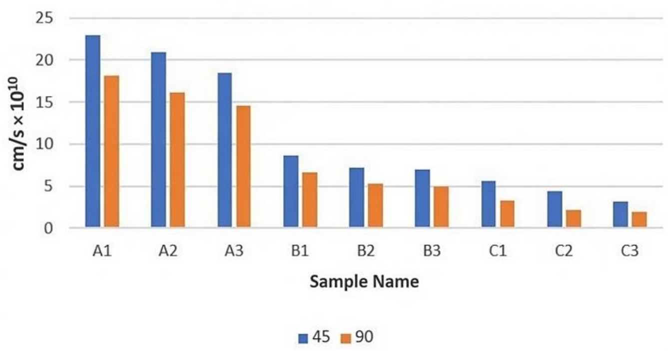

Fig. 5. Comparison of permeability of test specimens.

4.5 | Modulus of Elasticity

In the present study, in order to determine the modulus of elasticity of the concrete specimens, high-precision strain gauges were mounted on the cylindrical specimens as illustrated in the accompanying figure. This arrangement facilitated the precise measurement of axial strains induced in the specimens under varying levels of compressive loading. The modulus of elasticity was calculated in accordance with the standard testing protocol, which utilizes the strain value corresponding to 40% of the ultimate compressive strength, as expressed in the following relationship (*Eq. 1*).

$$E = \frac{\sigma_{40\sigma v}}{\varepsilon}. \tag{1}$$

To carry out the modulus of elasticity tests, each cylindrical specimen was positioned vertically within the compressive strength testing apparatus. A specialized deformation gauge (extensometer) was attached to the specimen's surface to monitor axial deformations. The load was then progressively applied until it reached 40% of the specimen's ultimate compressive capacity. During the test, the following parameters were systematically recorded: the gauge reading (in divisions), the corresponding axial deformation (length change), and the applied load (in tons). It is noteworthy that each division on the gauge scale corresponded to a deformation of 0.02 mm.

Table 7. Modulus of elasticity values (MPa).

Specimen ID	Modulus of Elasticity (MPa)
A1	3768.8
A2	3990.9
A3	4110.1
B1	3640.2
B2	3750.1
B3	3910.2
C1	3680.2
C2	3760.1
C3	3850.2

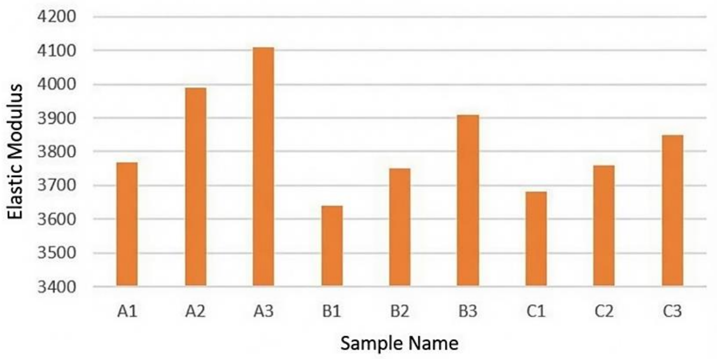

Fig. 6. Comparison of elastic modulus of test specimens.

With reference to *Table 7*, it is observed that as the pozzolan percentage increases, the modulus of elasticity decreases. This trend is considered natural and is attributed to the high porosity and lower specific gravity of pozzolan compared to natural aggregates, which consequently leads to a reduction in the modulus of elasticity. The application of FRP wrapping, however, results in an increase in the modulus of elasticity by up to 20%, as can be observed in specimen A2. The reduction in the modulus of elasticity of concrete upon the addition of pozzolan is primarily due to the weaker nature of pozzolan particles in comparison to natural aggregate particles.

5 | Discussion

Time, cost, and quality are three critical factors in construction execution that exert a significant influence on the construction industry. Any advancement or development that contributes to the improvement of these three factors is consistently of great interest to civil engineers. Whenever such developments prove impactful in the construction sector, sufficient research must be conducted on their benefits and drawbacks, and the necessary measures should be undertaken for their practical implementation in the construction industry. The use of pozzolan and FRP systems are among the key factors in enhancing the strength properties of concrete.

5.1 | Results Pertaining to Specimens from Mix Design A

The specimens of this mix design contained no pozzolan. Specimen A1 served as the control with no FRP wrapping, while specimens A2 and A3 were wrapped with one and two layers of FRP, respectively. The results indicate that the application of FRP wrapping enhanced the compressive strength of these specimens, with specimen A3 (two layers of FRP) exhibiting a more pronounced increase in strength.

In the tensile strength test of specimens from mix design A, it was observed that FRP wrapping was able to increase the tensile strength by 12% and 15% at 90 days for specimens with one and two layers of wrapping, respectively.

5.2 | Results Pertaining to Specimens from Mix Design B

The specimens of this mix design contained 10% pozzolan. Specimen B1 had no FRP wrapping, while specimens B2 and B3 were wrapped with one and two layers of FRP, respectively. The results demonstrate that the combined use of 10% pozzolan and FRP wrapping resulted in a substantial increase in the compressive strength of concrete, with this enhancement being clearly evident at 90 days.

In the tensile strength test of specimens from mix design B, it was observed that the simultaneous application of one and two layers of FRP wrapping along with 10% pozzolan was able to increase the tensile strength by 2% and 8%, respectively, in specimens containing 10% pozzolan.

5.3 | Results Pertaining to Specimens from Mix Design C

The specimens of this mix design contained 20% pozzolan. Specimen C1 had no FRP wrapping, while specimens C2 and C3 were wrapped with one and two layers of FRP, respectively. The results indicate that the combined use of 20% pozzolan and FRP wrapping resulted in a moderate increase in compressive strength; however, this increase was considerably less pronounced compared to the specimens from mix design B.

In the tensile strength test of specimens from mix design C, it was observed that the simultaneous application of one and two layers of FRP wrapping along with 20% pozzolan was able to increase the tensile strength by 1% and 2%, respectively, in specimens containing 20% pozzolan.

6 | Conclusion

In general, it can be concluded that the application of FRP wrapping enhances both the compressive and tensile strength of concrete, with this increase in strength being more prominently observed in specimens wrapped with two layers of FRP. Furthermore, according to the findings of this study, the use of specific percentages of pozzolan improves the strength properties of concrete, with specimens containing 10% pozzolan exhibiting the most favorable enhancement.

In the permeability test, the fabricated specimens were examined at curing ages of 45 and 90 days. Analysis of the results obtained from this test indicates that the combination of 20% pozzolan and FRP wrapping had a more beneficial effect on reducing the permeability of concrete. Due to its inherent properties, pozzolan is capable of filling the voids and pores within the concrete matrix, consequently leading to a reduction in concrete permeability.

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