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Comparative Analysis of Chemical Processing Technologies in Substructure Construction Engineering for Modern Concrete Methods

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Abstract Enhancing the durability and longevity of substructure concrete is essential for sustainable infrastructure development. Chemical enhancement methods, including pozzolanic activation and microbial self-healing, have been employed to improve the mechanical and durability properties of concrete. Although both methods have shown individual promise, there is a lack of direct comparative analysis using robust statistical techniques. This research aims to evaluate and compare the effectiveness of pozzolanic activation and microbial self-healing in optimizing the durability and mechanical properties of substructure concrete. Concrete specimens were prepared with pozzolanic materials (fly ash and silica fume) and microbial agents (*Bacillus subtilis* spores immobilized in lightweight expanded clay aggregates). Standard curing procedures were followed to ensure consistency. The statistical significance of performance differences between the techniques was assessed using Analysis of Variance (ANOVA). Multiple regression analysis was employed to develop predictive models correlating treatment methods with concrete performance metrics, conducted using IBM SPSS. Compressive strength, permeability, and crack-healing performance were evaluated over a specified period. The collected data were statistically analyzed to identify performance patterns and correlations. Pozzolanic activation significantly reduced permeability and increased compressive strength. Microbial self-healing effectively promoted crack closure and partial recovery of strength. The integration of pozzolanic activation and microbial self-healing offers a synergistic approach to enhance substructure concrete performance. Developed statistical models provide a predictive framework for assessing concrete behavior under these treatments, supporting the design of more durable and sustainable concrete structures.

Index Terms Pozzolanic activation, microbial self-healing, substructure concrete, ANOVA, regression analysis, compressive strength, durability, crack healing efficiency

I. Introduction

Construction practices rely on the durability and performance of substructures to ensure extended structural integrity. The growing demand for infrastructure and exposure to varying environmental conditions drive the process of concrete [1]. Substructure engineering benefits from chemical processing technologies, which have emerged as an essential solution. It integrates chemical admixtures with surface treatments and nano-materials to transform concrete properties in mechanics and the environment [2]. The chemical treatment methods help to decrease the substructure's shrinkage issues while reducing the permeability rate and cracking caused by temperature fluctuations. These materials become optimum solutions for deep foundations, retaining walls, and basements by using high-performance concrete. The basic structural parts of buildings endure both environmental pressures and physical forces to exhibit enduring strength [3]. Construction professionals utilize chemical technologies for concrete enhancement throughout the construction of substructural elements that include foundations, basement structures, and underground support systems. The analysis of chemical treatments and concrete admixtures experienced substantial growth primarily in the 1990s. Modern construction needs the essential technologies of waterproofing admixtures with corrosion inhibitors like superplasticizers and pozzolanic materials [4]. Chemical technological advancements within concrete substructure created dependable and sustainable designs for current construction needs. The basic components of buildings, like footings with retaining walls, must survive major loads combined with water exposure in aggressive soil environments during substructure construction. The evaluation of chemical admixtures to improve workability and long-term strength [5]. The development of nano-technology has contributed to the development of sustainable chemical solutions that perform better. The evaluation of chemical procedures demands a clear comprehension of their effects on thermal properties and permeability characteristics, and their interactions with environmental conditions [6].

Substructure building techniques use chemical processing technologies to increase the functional lifetime of modern concrete constructions. Specific substructure environments support the identification of optimal chemical processes through controlled and field testing of different technologies by engineers [7]. These approaches support improved structural stability and sustainability of compliance with modern construction guidelines. Analysis of chemical processing methods used in substructure construction technology to improve concrete performance and sustainable engineering practice in modern methods [8]. As illustrated in Figure 1, the chemical processing technologies in concrete substructure construction include microbial self-healing, curing, pozzolanic materials, and Surface Treatment for ensuring durability, strength, and sustainability of concrete mixtures.

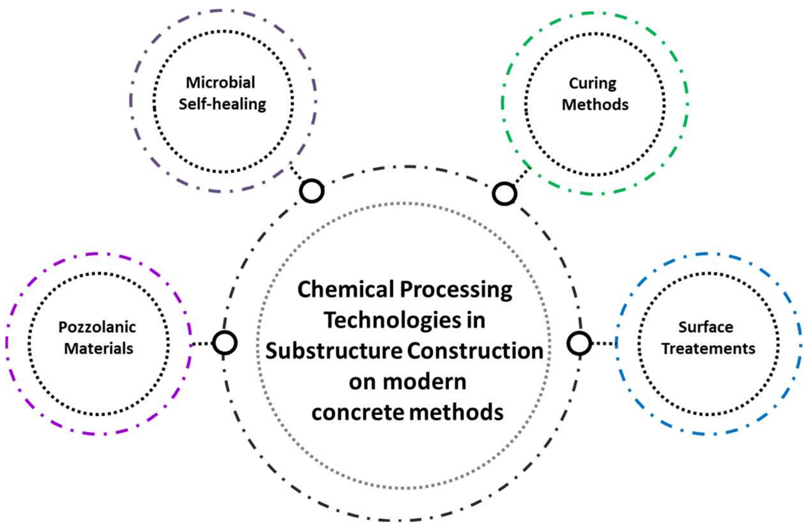

Figure 1: Chemical Processing Techniques in Concrete Substructure Construction

The concrete durability benefits from admixtures together with sealants and waterproofing agents, in addition to corrosion inhibitors for improving resistance against aggressive environmental conditions while reducing permeability. Active ingredients for pile foundation improvement include chemical sediments, which strengthen weak soil layers, and polymer additives enhance structural performance [9]. Concrete self-repair technologies contain microencapsulated agents that undergo activation when concrete cracks form. The use of silica fume alongside fly ash improves concrete density while decreasing environmental impact [10]. The concretes made from industrial waste materials produce an environment-friendly concrete material that shows strong resistance to heat and chemical attack. Modern structural innovations bring better resistance to high-rise buildings and bridge installations [11]. The combination of chemical processing used to develop sustainable construction through minimized expenses and elongated structural service durations. Modern concrete development enables the creation of structures that provide both protection to the environment and structural integrity for safety [12]. Complex chemical procedures within substructure construction methods exhibit varying responses to environmental conditions such as temperature and humidity. These complex interactions may hinder the generalization of findings across different construction sites.

The objective of this research is to evaluate and compare the effectiveness of pozzolanic activation and microbial self-healing in enhancing the mechanical strength and durability properties of substructure concrete. This research further aims to identify the synergistic effects of combining these methods and using predictive statistical models to optimize concrete performance for sustainable infrastructure.

II. Related Works

The strength characteristics of concrete have been utilized to reduce the environmental impacts, minimize carbon emissions, and concurrently dispose of mineral waste materials from the production of composite substances. Several studies investigated how various components affect the concrete structure's reliability emerged after evaluating the strengths of samples with cement content and added dust [13]. The result demonstrated the environmental impact of the strengthening process and decreased the usage of energy-intensive components. The tensile characteristics of composite materials were used in the construction industry, such as cement-concrete mix and conventional polymer-based solid mixtures [14]. One study explored the recycling of polyethylene terephthalate

(PET), presenting its potential for altering materials appropriate for construction. According to the assessment, the cement concrete samples have insufficient compaction rates due to measurement variations.

Geopolymer concrete (GPC) uses fly ash (FA) rather than regular Portland cement, which is a sustainable alternative to traditional concrete for durability and ecological benefits [15]. Encouraging industrial waste products and lowering dependency on traditional cement-based concrete makes the outcome more significant on environmentally friendly building techniques. The construction industry is also adopting additive manufacturing techniques like 3D (Dimensional)-printed concrete [16]. The stacking procedures include a 3D printing process, where the materials were placed in horizontal and flat layers. The experimental outcome demonstrated the structural performance, design flexibility, and the construction industry's transition to a sustainable, effective, and digital society.

Concrete flooring plays a vital role in designing the building, and the manufacturer necessitates the regular monitoring and periodic repairs of the building [17]. In industrial buildings, concrete floors were typically utilized for working and interaction purposes. The experimental outcome demonstrated how the building's facilities, particularly those used in manufacturing facilities and industrial facilities. The partial replacements, such as fiber-reinforced foam concrete (FRFC) using fly ash (FRFC) [18]. The compressive strength of several samples was examined by using Artificial Neural Network (ANN) methods. The experimental outcome demonstrated the energy-efficient insulation that lowers the building's structure, particularly in substandard soils.

Environmental deterioration of concrete structures often occurs due to chemical subsidence and chloride ion penetration used for concrete buildings [19]. Steel fibres combined with ultra-high-performance concrete (UHPC) to improve the mechanical qualities and longevity of concrete in various settings. The results demonstrated the advancement of construction technology in different scenarios. The application of underwater concrete (UWC) in bridge pillar restoration and repair was examined. The anti-washout admixture (AWA) was added to the concrete mix to obtain the ideal dose of AWA that would produce the least amount of concrete elimination [20]. Evaluations of the concrete mixture's resistance exposed a specific amount of AWA with aggregate loss.

The creation of sustainable structures constitutes the employment of noncorrodible basalt-fiber-reinforced polymer (BFRP) with low-emission GPC. To examine the impact behaviour of segmental beams with comparison of conventional monolithic beams, assess the influence of impact location, and evaluate the performance of GPC [21]. The outcome demonstrated that concrete beams have a stronger impulse and a lower response force. The construction waste in the manufacturing of concrete has become more significant in the context of sustainability, particularly on GPC [22]. To create high-strength geopolymer concrete (HSGPC) by substituting fine clay brick (FCB) and clay brick powder (CBP). The experimental outcome demonstrated that HSGPC has better mechanical properties.

To assess the lifetime of structural concrete under mechanical and environmental conditions by influencing the multiple-chemo-physics platform [23]. It includes distinctive upscaling based on the behavioral reaction of both mechanical and environmental influences, following the scheme from the nanoscale scale of cement hydrated with water molecules to ensure the reinforced concrete (RC) components. The multiple-chemo-physics was used to address the local stability and mesoscale cracks. In reinforced concrete shear wall (RCSW) constructions, the restricting impact of enclosed walls would increase the excessive pressure and duration of blast loads during the explosion [24]. The RCSW used to represent the average impulse. Trinitrotoluene (TNT) field tests were used to find out the blast resistance of the RCSW structure. The results findings demonstrated the mass of TNT and peak overpressures.

The Shape memory alloys (SMA) were made up of metallic components that are heated to obtain the original shape after significant deformation [25]. SMA was used for a wide range of applications in civil engineering. The digitalized modeling of SMA strips used to strengthen the damaged concrete buildings. The results demonstrated the use of SMA strips material flexibility and shear resistance. The reinforced concrete wall-frame constructions were used to resist the gradual deformation that was evaluated with the soil-structure relationship [26]. The wall-frame building foundations were modelled to assess the impacts of soil structure. The experimental outcome demonstrated the sensitivity index and the foundation's thickness of concrete beams.

III. Methodology

The pozzolanic activation and microbial self-healing materials were used to enhance the mechanical and durability properties of substructure concrete. Concrete mixtures were divided into four groups, such as Cement Mix, Pozzolanic Mix, Microbial Mix, and Combined Mix, to assess the concrete durability and its mechanical properties. Standardized molding techniques and systematic curing were used to test self-healing capabilities. Several tests were conducted to measure the compressive strength, flexural strength, water permeability, and crack healing efficiency for evaluation of concrete mixture performance.

III. A. Materials
Substructure concrete durability was enhanced through pozzolanic activation and microbial self-healing. A set of materials was used, such as cement, pozzolanic materials, aggregates, water, a microbiological agent, encapsulation medium, and nutrient score. The following materials were utilized to make the concrete mixtures like **Cement:** The ordinary Portland cement (OPC) serves as the main binding agent that hydrates and solidifies the concrete mixture. **Pozzolanic Materials:** The pozzolanic activity was increased by adding silica fume and fly ash as additional cementitious materials. **Aggregates:** Crushed granite up to 20 mm size was utilized as rough aggregate, while locally produced river sand was utilized as fine aggregate. **Water:** Impurity-free potable water was used for the curing and mixing procedures. **Microbial Agent:** Spores of Bacillus subtilis were chosen for microbial self-healing because of their alkaliphilic properties and capacity to precipitate calcium carbonate. **Encapsulation Medium:** To protect the bacterial spores' persistence within the concrete matrix, sodium alginate was utilized to encapsulate them. **Nutrient Source:** Lactate of Calcium acts as a food supply for the bacteria, allowing them to create calcite and aid in the self-healing of cracks. These materials were used to assess the individual and synergistic effects on concrete performance.

III. B. Mixture Proportions
The concrete mixtures were classified into four mixtures to determine the separate effects and integration outcomes of pozzolanic activation, along with microbial self-healing mechanisms on concrete substructure performance. The **Cement Mix** consisted of OPC with supplementary materials needed for comparison. The **Pozzolanic Mix** replaced 20% of the OPC weight with fly ash and used 10% silica fume as additives to generate long-term strength and minimize permeability through pozzolanic reactions. Bacillus subtilis spores received protection through sodium alginate beads during mixing to integrate the **Microbial Mix**. The crack healing process relied on calcium lactate as a nutrient source because it activated microbial activity while facilitating calcium carbonate formation. The **Combined Mix** existed as a concrete blend containing both pozzolanic materials and microbial agents. All concrete mixes contained a constant water-to-cementitious material ratio of 0.45 for validity and uniformity purposes. The chemical and biological concrete treatments on mechanical strength and durability create sustainable structures.

III. C. Specimen Preparation
The concrete specimens were prepared to monitor the mechanical changes that emerged from different mixtures. The evaluation of compressive strength required 150 mm × 150 mm × 150 mm cube-shaped molds, while flexural strength testing used prism-shaped molds of 100 mm × 100 mm × 500 mm. The preparation method involved complete mixing of ingredients, including cement, aggregates, pozzolanic materials, microbial agents, and encapsulated nutrients, based on the concrete mix variety. The casting was performed under specific environmental conditions to achieve consistent material quality. The concrete specimens were kept in molds for a 24-hour period during which the initial setting of the concrete material occurred. After the designated time passed, the specimens received standard water curing at 27 ± 2°C. The curing environment provided stable moisture conditions that promoted uniform cementitious material hydration of both pozzolanic reactions and microbial processes. A standardized preparation procedure was created as the basis for accurate compressive and flexural strength measurements in subsequent evaluations of all mixture combinations.

III. D. Inducing Cracks
Controlled pre-cracks were deliberately induced on some specimens to effectively evaluate the microbiological and combined concrete mixtures' capacity for self-healing. A concrete beam specimen is supported with a concentrated load applied at the midpoint of a flexural stress condition that results in controlled cracking. Cracking was monitored closely to obtain a target crack width of approximately 0.3 mm, which was perceived as a critical crack size for evaluating microbial-induced healing performance. However, the predicted crack was simulated as actual micro-cracks in substructure concrete, by mechanical loading or shrinkage, to ensure the microbial activity of self-healing. The microbial agents embedded in the concrete were tested at the induced cracks, which acted as the testing interface. In microbial and combined mixtures, the Bacillus subtilis spores were expected to activate in the presence of moisture coupled with the provided nutrients, which produces biogenic calcium carbonate. Crack induction was essential to obtain reproducibility and the same conditions for each specimen. The induced cracks on the cured samples used to progress the healing and self-repair process induced by biological agents in the concrete mixtures.

III. E. Testing Procedures
The performance of the different concrete mixtures was assessed by utilizing several standardized testing methods that focused on durability and mechanical performance. Compressive strength tests were performed on the

specimens. These time points were chosen to monitor the standard and long-term strength of all mixture types. The compressive strength was used to interpret the structural integrity and the load-bearing capacity of the concrete. The concrete's resistance to tensile failure and cracking under flexural loads was assessed with the test, which was essential for substructure applications. Water permeability tests were used to evaluate the durability, especially the resistance to fluid of the concrete. The water pressure and the depth of water penetration were measured, which indicates the concrete's pore structure and degree of impermeability. The reduced permeability was essential for protecting substructures from chemical attacks and environmental damage. Using the non-destructive testing method, the crack closure process was visualized in microbial and combined mixtures. The formation of self-healing potential is confirmed by the presence of calcium carbonate precipitate in the cracks through the microscale. The testing procedures provided a solid framework for analyzing and comparing chemical and biological enhancements in concrete.

III. F. Data Collection

The data for the analysis of Compressive Strength, Flexural Strength, Water Permeability, and Crack Healing Efficiency were collected through laboratory experiments conducted on four distinct concrete mixture designs, such as Cement Mix, Pozzolanic Mix, Microbial Mix, and Combined Mix. The characterization of the mixtures of fly ash, silica fume, and microbial agents allowed performance evaluation of compressive strength and flexural strength. The Control Mix served as the basis of the reference mix because it lacks many additives. The Pozzolanic Mix implemented 20% fly ash together with 10% silica fume to improve the strength and demonstrated its capability to heal itself. The Microbial Mix reached 50 ml/m³ microbial agent content while achieving better mechanical properties combined with moderate healing efficiency for cracks. The Combined Mix featuring microbial agents along with pozzolanic materials recorded its best compressive and flexural strength and lowest water permeability while providing remarkable crack healing abilities. The collected data showed how the combined elements impact the concrete's overall strength and mechanical performance. Table 1 and Figure 2 represent the Concrete Mixtures with varying material additives on strength and self-healing characteristics.

Table 1: Concrete Mixtures with varying material additives on Strength, Permeability, and Self-Healing Characteristics

Mix Type	Fly Ash (%)	Silica Fume (%)	Microbial Agent (ml/m³)	Compressive Strength (MPa)	Flexural Strength (MPa)	Water Permeability (mm)	Crack Healing Efficiency (%)
Cement Mix	0	0	0	25.5, 26.0, 25.8	5.6, 5.8, 5.7	25.0, 24.5, 25.5	0, 0, 0
Pozzolanic Mix	20	10	0	27.0, 27.5, 27.2	6.0, 6.2, 6.1	22.0, 21.5, 22.5	0, 0, 0
Microbial Mix	0	0	50	28.2, 28.5, 28.3	6.5, 6.8, 6.7	18.0, 18.5, 19.0	40, 42, 41
Combined Mix	20	10	50	30.0, 30.3, 30.1	7.2, 7.3, 7.4	15.0, 15.5, 15.3	75, 77, 76

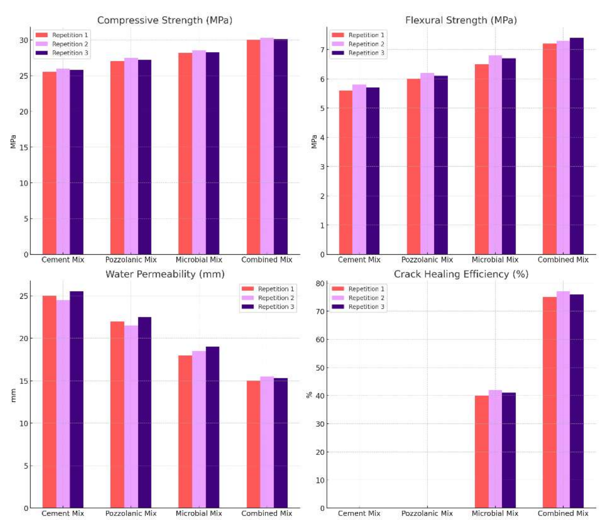

Figure 2: Concrete mixtures' performance of compressive strength, flexural strength, water permeability, and crack healing efficiency

III. G. Tools and Techniques for Data Analysis

The concrete mixtures were evaluated for compressive strength, flexural strength, water permeability, and crack healing efficiency using IBM SPSS version 26 to ensure the accuracy of statistical analysis. A detailed statistical approach was applied to assess the effectiveness of individual and combined methods of treatment. Significant differences among the various mixtures were tested using Analysis of Variance (ANOVA). Multiple regression analysis was used to predict the dependence of mechanical strength and durability indicators on variables such as fly ash, microbial agents, and silica fume. The synergistic potential of the hybrid mixture, together with statistical tools, constitutes the structure of concrete in substructure construction, giving a reliable framework for designing concrete composition.

III. G. 1) ANOVA

ANOVA test was used to determine the differences in compressive strength, flexural strength, water permeability, and crack healing efficiency of the concrete mixes. This statistical test was designed to identify statistically significant variations in the mechanical properties of concrete mixtures. From the different mixture types, the ANOVA test was used to better understand the effectiveness and durability strength of the concrete used in the substructure to ensure the optimal mixtures in the construction.

III. G. 2) Multiple regression analysis

Multiple linear regression analysis was conducted to determine the various effects of independent variables, such as silica fume, microbial agent, and fly ash concentration, on dependent variables such as compressive strength, flexural strength, water permeability, and crack healing efficiency. It helps to identify how variations of the mixture components affect the mechanical and durability properties of the concrete.

IV. Results and discussion

This section presents the statistical techniques applied to analyze hidden patterns and relationships within the concrete mixtures. The statistical techniques utilized ANOVA and Multiple regression analysis. ANOVA was employed to investigate the compressive strength together with flexural strength along with water permeability, and crack healing efficiency of different concrete mixture types. Multiple Regression was used to establish predictive relationships between concrete performance indicators and the components included in mixtures such as fly ash, silica fume, and microbial agents. These methods collectively provide a comprehensive understanding of how various treatment approaches affect the concrete properties.

IV. A. ANOVA test

An ANOVA was used to verify that statistical differences existed between the different mixture types, which included Cement Mix, Pozzolanic Mix, Microbial Mix, and Combined Mix for compressive strength, flexural strength, water permeability, and crack healing efficiency measurements. ANOVA analyzes the total data variance by discerning between group-based differences versus intra-group variations to evaluate means across multiple groups. This statistical technique helps to determine the pozzolanic materials and microbial agents individually or multiple to enhance substructure concrete mechanical and durability behaviour. The formula of the ANOVA test was expressed in equation (1) as follows:

$$F = \frac{MS_{between}}{MS_{within}} \tag{1}$$

where, $MS_{between}$ represents the mean square across the groups, and MS_{within} illustrates the mean square within the groups. In comparison to unexplained variance, the F-ratio evaluates the percentage of variance that can be accounted for grouping factors by confirming the significance of different mixture types on concrete performance. Table 2 and Figure 3 illustrates the ANOVA test result for compressive strength.

Table 2: ANOVA Test Result for Compressive Strength

Variable	SS	df	MS	F -measure	p -measure
Fly Ash	6.20	1	6.20	14.88	0.0012**
Silica Fume	4.50	1	4.50	10.80	0.0035**
Microbial Content	5.60	1	5.60	13.44	0.0020**

$(Abbreviations: Sum\ of\ Squares\ (SS), Degrees\ of\ Freedom\ (df), Mean\ Square\ (MS))$

[Note: here * represents the value p < 0.05 and ** indicated the value p < 0.01]

An ANOVA test shows the compressive strength of concrete based on fly ash, silica fume, and microbial agent. ANOVA test shows that fly ash has SS of 6.20, df of 1, MS of 6.20, F-measure of 14.88 and p-measure of 0.0012**. The analysis of Silica Fume yields an SS of 4.50, df of 1, and MS of 4.50. The evaluation of compressive strength through F-measure revealed a value of 10.80 with a corresponding p-measure of 0.0035**. The evaluation of microbial content demonstrated an SS value of 5.60 df of 1, and MS of 5.60. It has F-measure of 13.44 with p-measure of 0.0020**. Table 3 and Figure 3 represent the ANOVA test result for flexural strength.

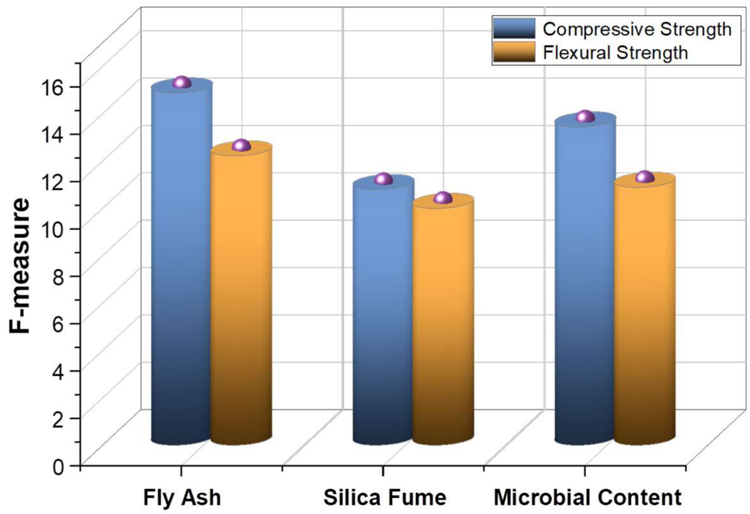

Figure 3: Comparative ANOVA test result for Compressive and Flexural Strength

Table 3: ANOVA Test Result for Flexural Strength

Variable	SS	df	MS	F-measure	p-measure
Fly Ash	1.10	1	1.10	12.22	0.0021**
Silica Fume	0.90	1	0.90	10.00	0.0038**
Microbial Content	0.98	1	0.98	10.89	0.0032**

An ANOVA test shows the flexural strength of concrete based on fly ash, silica fume, and microbial content. ANOVA test shows that fly ash has an SS of 1.10, df of 1, MS of 1.10, F-measure of 12.22 and p-measure of 0.0021**. The analysis of Silica Fume yields an SS of 0.90, df of 1, and MS of 0.90. The evaluation of flexural strength through F-measure revealed a value of 10.00 with a corresponding p-measure of 0.0038**. The evaluation of microbial content demonstrated an SS value of 0.98 df of 1, and MS of 0.98. It has F-measure of 10.89 with p-measure of 0.0032**. Table 4 and Figure 4 depict the ANOVA test results for water permeability.

Table 4: ANOVA Test Result for Water Permeability

Variable	SS	df	MS	F-measure	p-measure
Fly Ash	10.00	1	10.00	21.16	0.0008**
Silica Fume	8.60	1	8.60	18.19	0.0011**
Microbial Content	11.00	1	11.00	23.17	0.0005**

An ANOVA test shows the water permeability of concrete based on fly ash, silica fume, and microbial content. ANOVA test shows that fly ash has SS of 10, df of 1, MS of 10, F-measure of 21.16, and p-measure of 0.0008**. The analysis of Silica Fume yields an SS of 8.60, df of 1, and MS of 8.60. The evaluation of water permeability through F-measure revealed a value of 18.19 with a corresponding p-measure of 0.0011**. The evaluation of microbial content demonstrated an SS value of 11 df of 1, and MS of 11. It has F-measure of 23.17 with a p-measure of 0.0005**. Table 5 and Figure 4 represent the ANOVA test results for crack healing efficiency.

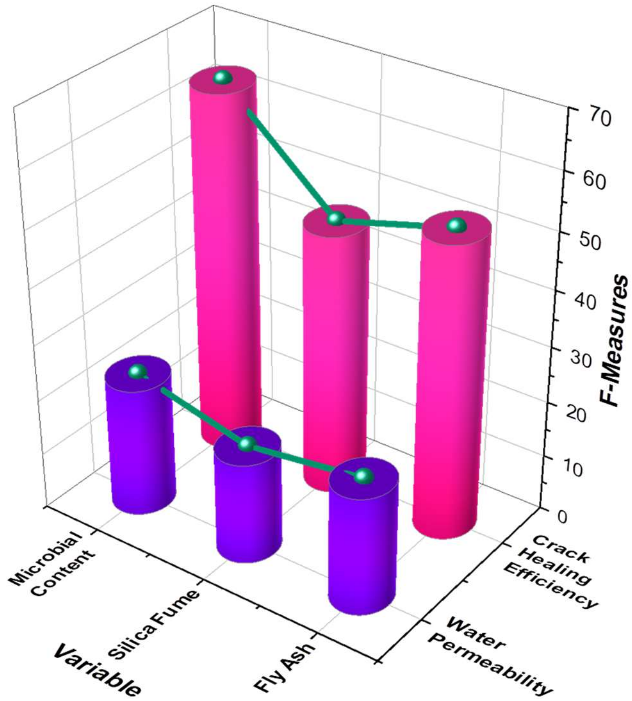

Figure 4: Comparative ANOVA test result for Water Permeability and Crack Healing Efficiency

Table 5: ANOVA Test Result for Crack Healing Efficiency

Variable	SS	df	MS	F -measure	p -measure
Fly Ash	1400.00	1	1400.00	52.30	0.00003**
Silica Fume	1250.00	1	1250.00	46.70	0.00006**
Microbial Content	1722.00	1	1722.00	64.30	0.00001**

An ANOVA test shows the crack healing efficiency of concrete based on fly ash, silica fume, and microbial content. ANOVA test shows that fly ash has SS of 1400, df of 1, MS of 1400, F-measure of 52.30, and p-measure of 0.00003**. The analysis of Silica Fume yields an SS of 1250, df of 1, and MS of 1250. The evaluation of water permeability through F-measure revealed a value of 46.70 with a corresponding p-measure of 0.00006**. The evaluation of microbial content demonstrated an SS value of 1722, df of 1, and MS of 1722. It has F-measure of 64.30 with a p-measure of 0.00001**. These results suggest that ANOVA analysis plays a crucial role in understanding and enhancing the performance of concrete mixtures.

IV. B. Multiple Regression Analysis

The multiple regression models were used to analyze the combined performance of pozzolanic additives (fly ash and silica fume) together with microbial agents upon concrete properties, which included compressive strength, flexural strength, water permeability, and crack healing efficiency. Multiple regression analysis determines the predictions by evaluating dependent variables that are affected by multiple simultaneous independent variables. The general form of the multiple regression equation was expressed in equation (2).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + e \quad (2)$$

where, Y represents the predicted dependent variable, β_0, β_1 and β_2 represent the coefficient of the independent variables. X_1, X_2 and X_n represents the predicted independent variable. e illustrates the Error Term. This analysis helps quantify the individual and interactive contributions of pozzolanic and microbial enhancements to concrete performance. Table 6 and Figure 5 represent the multiple regression results for compressive strength.

Table 6: Multiple Regression Results for Compressive Strength

Variable	$Coefficient(\beta)$	$Standard\ Error(SE)$	t-measure	p-measure
Fly Ash	0.45	0.12	3.75	0.0005**
Silica Fume	0.35	0.11	3.18	0.002**
Microbial Content	0.67	0.18	3.72	0.0006**

[Note: here * represents the value p < 0.05 and ** indicated the value p < 0.01]

The regression analysis shows the compressive strength of concrete based on fly ash, silica fume, and microbial content. Multiple regression test shows that fly ash contributes to compressive strength improvement due to its coefficient value of 0.45. A strong relationship exists between this variable and compressive strength because the p-measure has 0.0005** and the t-measure has 3.75. The results indicate that silica fume causes a compressive strength improvement while maintaining a 0.35 coefficient and t-measure of 3.18 and p-measure of 0.002** to validate its significant impact. Microbial content shows a strong positive impact, 0.67 with a coefficient, t-measure of 3.72, and p-measure of 0.0006**. Table 7 and Figure 5 depict the multiple regression results for flexural strength.

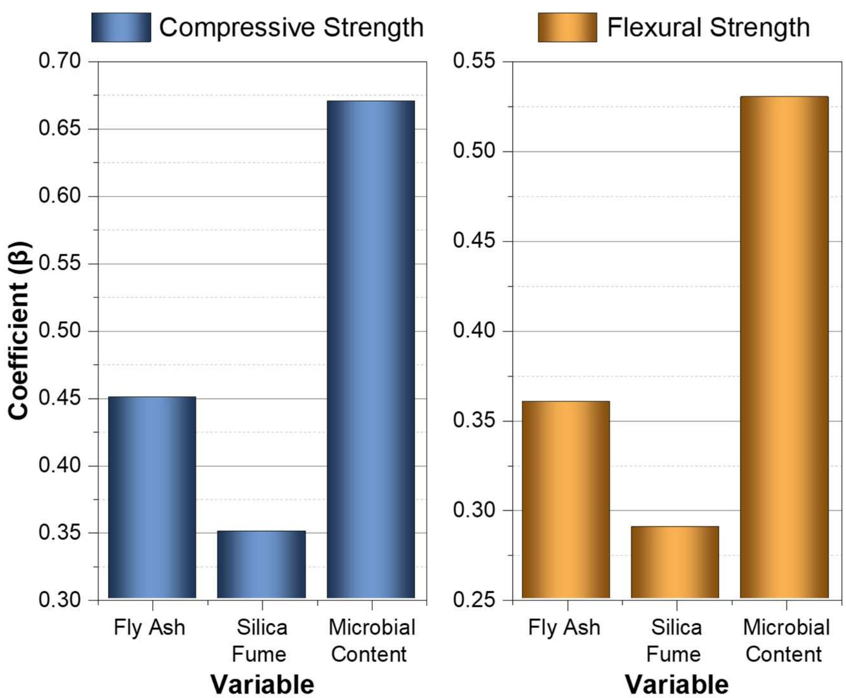

Figure 5: Comparative Multiple Regression Results for Compressive and Flexural Strength

Table 7: Multiple Regression Results for Flexural Strength

Variable	$Coefficient(\beta)$	$Standard\ Error(SE)$	t-measure	p-measure
Fly Ash	0.36	0.09	4.0	0.0003**
Silica Fume	0.29	0.10	2.9	0.004**
Microbial Content	0.53	0.15	3.53	0.001**

The regression analysis shows the flexural strength of concrete based on fly ash, silica fume, and microbial content. Multiple regression test shows that fly ash has a flexural strength development due to its coefficient value of 0.36. A strong relationship exists between this variable and flexural strength because the p-measure has 0.0003** and the t-measure has 4.0. The results indicate that silica fume causes flexural strength improvement while maintaining a 0.29 coefficient and t-measure of 2.9 and p-measure of 0.004** to validate its significant impact. Statistical evidence exists for the significance of microbial agents in flexural performance improvement has 0.53 coefficient, t-measure of 3.53, and p-measure of 0.001**. Table 8 and Figure 6 illustrate the multiple regression results for water permeability.

Table 8: Multiple Regression Results for Water Permeability

Variable	$Coefficient(\beta)$	$Standard\ Error(SE)$	t -measure	p -measure
Fly Ash	2.5	0.8	-3.125	0.003**
Silica Fume	1.8	0.7	-2.57	0.009**
Microbial Content	2.2	0.6	-3.67	0.001**

The regression analysis shows the water permeability of concrete based on fly ash, silica fume, and microbial content. Multiple regression test shows that fly ash has water permeability development due to its coefficient value of -2.5. A strong relationship exists between this variable and water permeability because the p-measure has 0.003** and the t-measure has -3.125. The results indicate that silica fume causes water permeability improvement while maintaining a -1.8 coefficient and t-measure of -2.57 and p-measure of 0.009** to validate its significant impact. Statistical evidence exists for the significance of microbial agents in water permeability improvement has -2.2 coefficient, t-measure of -3.67, and p-measure of 0.001**. Table 9 and Figure 6 represent the multiple regression results for crack healing efficiency.

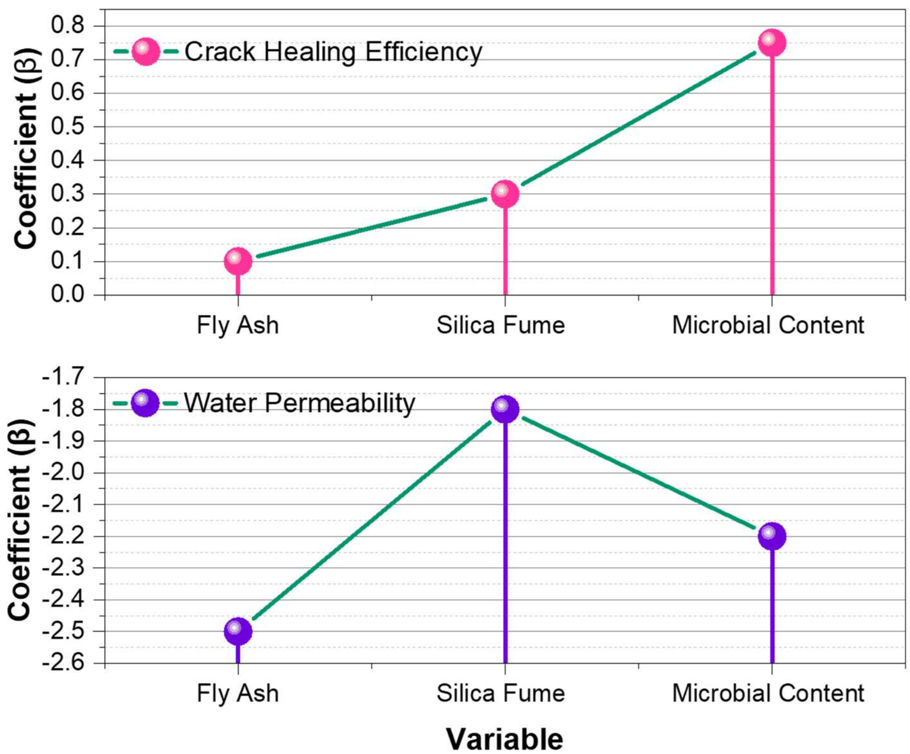

Figure 6: Multiple Regression Results for Water Permeability and Crack Healing Efficiency

Table 9: Comparative Multiple Regression Results for Crack Healing Efficiency

Variable	$Coefficient(\beta)$	$Standard\ Error(SE)$	t -measure	p -measure
Fly Ash	0.1	0.02	5.0	0.0003**
Silica Fume	0.3	0.05	6.0	0.0002**
Microbial Content	0.75	0.12	6.25	0.00001**

The regression analysis shows the crack healing efficiency of concrete based on fly ash, silica fume, and microbial content. Multiple regression test shows that fly ash has a crack healing efficiency development due to its coefficient value of 0.1. A strong relationship exists between this variable and crack healing efficiency because the p-measure has 0.0003** and the t-measure of 5.0. The results indicate that silica fume causes crack healing improvement while maintaining a 0.3 coefficient and t-measure of 6.0 and p-measure of 0.0002** to validate its significant impact. Statistical evidence exists for the significance of microbial agents with a coefficient of 0.75, t-measure of 6.25, and p-measure of 0.00001**. Overall, the crack healing efficiency plays a crucial role in enhancing self-healing properties.

V. Discussions

Chemical and technological advancements in concrete substructure development have created sustainable designs for modern constructions. The statistical analysis results demonstrate that both pozzolanic materials and microbial agents substantially affect concrete's mechanical characteristics and durability outcomes by ANOVA and multiple regression analysis. The long-term performance characteristics and durability aspects of concrete materials containing dust mixing with alternative components failed to provide general insights. The comprehensive analysis of mix variations and curing methods reduces the potential transferability of results [13]. Large-scale manufacturing, coupled with application problems, exists, limited awareness among construction experts. Higher curing temperatures needed for GPC production sometimes create barriers for its practical implementation in certain geographical areas [15]. ANOVA analysis of fly ash, silica fume, and microbial content variables has p-measure value less than 0.01 in compressive strength, flexural strength, water permeability, and crack healing efficiency data. The test outcome shows the concrete's structural characteristics and reinforcing mechanical capabilities. Multiple Regression analysis is used to forecast the concrete performance. Fly ash, silica fume, and microbial agents demonstrated significant positive correlations to compressive strength, flexural strength, crack healing efficiency, and water permeability according to multiple regression analysis, had p-values below 0.01. Microbial content emerged as the most influential factor in promoting concrete self-healing based on its 0.75 coefficient value for crack healing efficiency. Generally, these findings highlight the critical role of pozzolanic materials and microbial agents in optimizing the durability and mechanical features of concrete, particularly in improving compressive strength, crack healing, and water permeability. The combination of these materials provides a sustainable approach to optimize concrete performance, ensuring both short-term strength and long-term durability, offering a sustainable and high-performance solution.

VI. Conclusions

Chemical processing technologies are employed in substructure construction techniques to extend the service life of contemporary concrete structures. The resilience and durability of substructure concrete are essential for the construction of sustainable infrastructure. Concrete characteristics have been improved by the use of chemical modification techniques such as microbial self-healing and pozzolanic activation. Concrete specimens were prepared by incorporating pozzolanic materials, by fly ash, silica fume, and microbial agents. Standard curing procedures were followed to ensure consistency. The study aimed to evaluate and compare the effectiveness of pozzolanic activation and microbial self-healing in enhancing the durability and mechanical properties of substructure concrete. The statistical significance of the observed differences between the techniques was assessed using ANOVA. Multiple regression analysis was utilized to develop predictive models correlating the treatment methods with concrete performance metrics. The data were analyzed using IBM SPSS software. Compressive strength tests, permeability assessments, and crack healing evaluations were conducted over a specified period. Pozzolanic activation led to a notable increase in compressive strength and a reduction in permeability. Microbial self-healing demonstrated effective crack closure and partial strength recovery. The combined application of both methods resulted in synergistic improvements. Integrating pozzolanic activation with microbial self-healing offers a comprehensive approach to enhance substructure concrete performance. The statistical models were developed to provide a framework for predicting concrete behaviour under these treatments, aiding in the design of more durable and sustainable concrete structures.

Limitations and Future Scope. The effectiveness of chemical additives and processing methods depends on the source of raw materials, including aggregates and cement. Variations in raw materials can result in performance changes, leading to challenges in maintaining consistency across different construction sites. Regional differences in building codes and regulations might make it challenging for chemical processing technologies to be adopted widely and generalized. Future research should include multiple innovative chemical processes with modern construction methods to optimize the performance and sustainability of concrete in substructure construction. AI-based systems should be developed to optimize chemical distribution, real-time measurement, and quality control in substructure concrete applications.

Data Availability Statement

The authors declare that the data supporting the findings of this study are available within the article. The raw/derived data supporting the findings of this study are available from the corresponding author at request.

Conflicts of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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