



**REPUBLIC OF TÜRKİYE
HARRAN UNIVERSITY
INSTITUTE OF GRADUATE EDUCATION**

MASTER THESIS

**Experimental Evaluation and Numerical Modeling Of Mechanical Properties of
Polymeric Fiber-Reinforced Cementitious Composites**

AREE IBRAHIM EZZAT EZZAT

CIVIL ENGINEERING DEPARTMENT

**Şanlıurfa
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Thesis Supervisor: Prof. Dr. KASIM MERMERDAŞ**

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ABSTRACT

MASTER THESIS

EXPERIMENTAL EVALUATION AND NUMERICAL MODELING OF MECHANICAL PROPERTIES OF POLYMERIC FIBER-REINFORCED CEMENTITIOUS COMPOSITES

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This study investigates the mechanical behavior of polymeric fiber reinforced cementitious composites (PFRCCs), focusing on how factors such as fiber type, fiber dosage, and water to binder (W/B) ratio affect flexural strength (FS). A total of 82 mixes were examined, including 42 experimental mortar mixes and 40 from the literature, incorporating polypropylene (PP) and polyvinyl alcohol (PVA) fibers in varying volume fractions (0–1.4%) with two W/B ratios (0.30 and 0.45). Mechanical properties, particularly compressive strength (CS) and flexural strength (FS), were tested using standardized methods. To address gaps in previous research, additional parameters including fiber aspect ratio, fiber tensile strength, sand to aggregate ratio, and binder content were considered to provide a more comprehensive understanding of their influence. For predictive modeling, Multiple Linear Regression (MLR) and Gene Expression Programming (GEP) were applied based on input parameters such as fiber type, fiber content, W/B ratio, and specimen geometry. The results showed that a lower W/B ratio (0.30) consistently yielded superior mechanical performance, with flexural strength reaching up to 9.59 MPa, and the optimal fiber content for FS enhancement was between 0.6% and 1.0%. Among the two fiber types, PVA provided better results than PP due to its stronger bond with the cement matrix. In terms of modeling, GEP outperformed MLR by effectively capturing nonlinear relationships, achieving an R^2 of 0.90 for training and 0.74 for validation, compared with MLR's lower R^2 of 0.68. Overall, the study offers valuable insights into the role of polymeric fibers in enhancing the mechanical properties of cementitious composites, while the predictive models particularly GEP serve as practical tools for engineers to optimize the design of fiber-reinforced concrete in diverse structural applications.

KEYWORDS: Mechanical properties, Polymeric fibers, Fiber-reinforced cementitious composites (FRCC), Flexural strength, Gene Expression Programming (GEP), Multiple Linear Regression (MLR).

ABSTRACT

YÜKSEK LİSANS TEZİ

POLIMERİK FİBERLE TAKVİYELİ ÇİMENTO KOMPOZİTLERİNİN MEKANİK ÖZELLİKLERİNİN DENEYSEL DEĞERLENDİRİLMESİ VE SAYISAL MODELLEME

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Bu çalışma, polimerik fiber takviyeli çimentolu kompozitlerin (PFRCC) mekanik davranışlarını incelemekte ve özellikle fiber tipi, fiber dozajı ve su/bağlayıcı (W/B) oranı gibi faktörlerin eğilme dayanımı (FS) üzerindeki etkilerine odaklanmaktadır. Toplam 82 karışım değerlendirilmiş olup, bunların 42'si deneysel harç karışımı ve 40'ı literatürden alınmıştır. Karışımlarda polipropilen (PP) ve polivinil alkol (PVA) lifleri %0–1.4 arasında değişen hacim oranlarında ve iki farklı W/B oranı (0.30 ve 0.45) ile kullanılmıştır. Mekanik özellikler, özellikle basınç dayanımı (CS) ve eğilme dayanımı (FS), standart yöntemlere göre test edilmiştir. Önceki araştırmalardaki boşlukları gidermek amacıyla, lifin boy/en oranı, lif çekme dayanımı, agrega-kum oranı ve bağlayıcı miktarı gibi ek parametreler de dikkate alınarak daha kapsamlı bir değerlendirme yapılmıştır. Öngörüşel modelleme için, fiber tipi, fiber miktarı, W/B oranı ve numune geometrisi gibi girdilere dayalı olarak Çoklu Doğrusal Regresyon (MLR) ve Gen İfade Programlama (GEP) yöntemleri uygulanmıştır. Sonuçlar, düşük W/B oranının (0.30) sürekli olarak daha yüksek mekanik performans sağladığını, eğilme dayanımının 9.59 MPa'ya ulaştığını ve FS için optimum fiber içeriğinin %0.6–1.0 arasında olduğunu göstermiştir. İki fiber tipi arasında, PVA lifleri, çimento matrisi ile daha güçlü bağlanması sayesinde PP'ye göre daha iyi sonuç vermiştir. Modelleme açısından, GEP, doğrusal olmayan ilişkileri etkili bir şekilde yakalayarak MLR'den üstün performans göstermiş, eğitim için 0.90 ve doğrulama için 0.74 R^2 değerine ulaşırken, MLR'nin R^2 değeri 0.68'de kalmıştır. Genel olarak, bu çalışma polimerik liflerin çimentolu kompozitlerin mekanik özelliklerini geliştirmedeki rolüne ilişkin değerli bulgular sunmakta, özellikle GEP ile geliştirilen öngörüşel modeller mühendisler için lif takviyeli betonun çeşitli yapısal uygulamalarda tasarımını optimize etmeye yönelik pratik araçlar sağlamaktadır.

ANAHTAR KELİMELER: Mekanik özellikler, Polimerik fiberler, Fiberle takviyeli çimento kompozitleri (FRCC), Eğilme dayanımı, Gen İfade Programlama (GEP), Çoklu Doğrusal Regresyon (MLR).

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1. INTRODUCTION

1.1. Background

Cementitious composites, containing mainly of Portland cement, water, and mineral aggregates are the most generally used materials for construction industry due to their cost affective, availability, and workability (Mehta & Monteiro, 2014). However, traditional concrete shows fundamental brittleness and has limited tensile capacity, which often leads to early age cracking, low indications for fracture energy, and sudden tensile failure or flexural loads (Naaman, 2018). These limitations become mostly critical in structural elements subjected to dynamic or impact loading, destructive environments, or repeated cycled stresses.

To improve the ductility and crack resistance of concrete, fibers have been incorporated into cementitious matrices, leading to the development of fiber-reinforced cementitious composites (FRCCs). Fibers enhance both strength and toughness by bridging microcracks and distributing stresses more evenly throughout the matrix, particularly after the first-crack formation (Li et al., 2004; Faghihmaleki & Rastkar, 2022). Among the different fiber types, synthetic polymeric fibers such as polypropylene (PP) and polyvinyl alcohol (PVA) have attracted increasing attention due to their corrosion resistance, durability, and lightweight properties (Şahmaran & Li, 2009; Rao et al., 2019). Polypropylene (PP) fibers are widely used in cementitious composites because of their chemical stability, hydrophobic nature, and relatively low cost, which make them effective in improving toughness and reducing cracking. In this study, two different PP fibers (PP1 and PP2) were considered, differing in mechanical strength and geometry, to evaluate how fiber properties influence the performance of the mixes. In contrast, polyvinyl alcohol (PVA) fibers exhibit distinct characteristics that contribute differently to the mechanical behavior of cementitious composites.

Polypropylene (PP) fibers are widely used in cementitious composites because they are chemically stable, hydrophobic, and relatively inexpensive. These features make them suitable for improving toughness and reducing cracking. In this study, two types of PP fibers which labeled (PP1 and PP2) were selected. The two grades varied in size and mechanical strength, which made it possible to examine how fiber geometry influences the overall performance of the mixes. On the other hand, polyvinyl alcohol (PVA) fibers have very different characteristics. They are hydrophilic, form strong bonds with the cement paste, and are able to generate many fine cracks rather than one dominant crack (Kang et al., 2016; Li, 2003). This

property gives PVA composites greater tensile strain capacity and, under certain conditions, leads to strain-hardening behavior.

In this study, to observe the combined effect of fiber type and content, 42 mortar mixes were designed and tested using two water to binder (W/B) ratios (0.30 and 0.45) and fiber volumes ranging from 0% to 1.4%. A high range water reducing admixture (HRWRA) was incorporated to maintain acceptable workability, particularly in the low W/B mixes where fresh concrete tends to stiffen. Mechanical tests were conducted on each mix, with flexural strength (FS) treated as the main response variable, while independent factors included fiber type, fiber volume, fiber aspect ratio, and the W/B ratio. Alongside laboratory testing, two modeling approaches were employed: Multiple Linear Regression (MLR) to identify linear relationships and estimate parameter contributions, and Gene Expression Programming (GEP), an evolutionary algorithm capable of capturing complex nonlinear behaviors without predefined mathematical forms (Ferreira, 2001; Cevik et al., 2010). The comparison of these methods provided a more reliable basis for interpreting and validating the experimental findings. By integrating direct material testing with computational modeling, this research establishes a balanced framework for understanding and improving polymeric fiber-reinforced composites, and the results are expected to support engineers and researchers in designing next- generation construction materials that are durable, crack-resistant, and sustainable.

1.2. Objective

The primary objective of this research is to investigate the influence of polymeric Fiber reinforcement (PFRC) on the mechanical performance (with particular focused on FS &CS), specifically the flexural strength of cementitious composites for both experimental testing and analytical modelling. The study aims to:

1- Experimentally evaluate flexural strength (FS) of mortar composites reinforced with various kinds and doses of polymeric fibers, including two types of polypropylene (PP1 and PP2) and one polyvinyl alcohol (PVA) fiber, under different water-to-binder (W/B) ratios.

2- Evaluate the effect of fiber volume fraction, fiber type, and W/B ratio on key mechanical properties, such as flexural strength (FS) and compressive strength (CS), aiming to bridge gaps observed in previous studies.

3- Develop model of prediction for flexural strength (FS) using:

- ♦ Multiple Linear Regression (MLR) to identify significant variables and their linear relationships.
- ♦ Gene Expression Programming (GEP) to capture the complex, nonlinear interactions among mix design parameters (X1-X12), which have not been fully explored in any previous researches.

4- Address gaps in previous predictive studies by incorporating additional parameters such as fiber aspect ratio, sand to aggregate ratio, fiber tensile strength, and binder content to enhance the robustness and accuracy of the developed models.

5- Compare the outcome results of (MLR and GEP) Models and validate their accuracy of prediction using statistical measures including the coefficient of determination (R^2), Root Mean Squared Error (RMSE), and Mean Absolute Percentage Error (MAPE).

6- Provide practical recommendations for the optimal fiber types and dosages for improving the performance, workability, and durability of cementitious composites in various structural applications, advancing the knowledge on polymeric fiber reinforcement in concrete.

1.3. Scope of the Study

This study focuses on both experimental and analytical investigation of the mechanical properties of polymeric fiber reinforced cementitious composites (PFRC), with particular insists on flexural strength (FS). Three types of polymer fibers were considered, two parameters of polypropylene (PP1 and PP2) and one type of polyvinyl alcohol (PVA) fiber. The mixes are mortar based (Portland cement and fine natural sand), with no adding coarse aggregates, forming a mortar-based composite.

The mix design variables are included fiber volume dosages ranging from 0% to 1.4%, and two water-to-binder (W/B) ratios, 0.30 and 0.45, were considered to evaluate the influence of water content on strength. A high-range water-reducing admixture (HRWRA) was used to improve workability and to secure uniform dispersion of the fibers, while no supplementary cementitious materials such as silica fume or fly ash were added. A total of 42 mortar mixes were casted and tested for their mechanical properties (compressive strength CS and flexural strength FS).

Flexural strength FS was tested using a three-point bending test as per according ASTM standards to ensure consistent results.

In addition to experimental program, analytical modeling techniques were employed to predict flexural strength FS outcomes. Both (MLR & GEP) methods were applied, by preparing and using a combined dataset of 82 mixes consisting 42 mixes from experimental works and 40 mixes taken from existing literature to compare with train and validate the predictive models. The performance of these models was evaluated using statistical indicators such as the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute percentage error (MAPE), allowing for a comparative assessment between linear and nonlinear predictive approaches.

The scope of the study has certain limitation, it does not focus on long-term durability characteristics, such as shrinkage, permeability, or resistance to freeze- thaw cycles. Moreover, only small-scale prismatic specimens were tested, and thus the findings may not fully capture the behavior of full-scale structural elements.

1.4. Significance of the Study

The growing demand for durable and sustainable construction materials has highlighted the importance of developing advanced cementitious composites capable and can overcome the brittleness of conventional concrete and will investigates the role of polymeric fibers for used two grades of polypropylene (PP1 and PP2) and one type of polyvinyl alcohol (PVA) to enhance the mechanical behavior for cement- based materials. Their inclusion of these fibers is shown to enhance flexural strength FS and crack resistance, which are key for structural elements subjected to bending and tensile stresses.

Moreover, the study contributes to the field through the application of data driven modeling techniques, by applying Multiple Linear Regression (MLR) and Gene Expression Programming (GEP), which offer practical and efficient tools for predicting FS based on key mix design parameters (X_1 to X_{12}). These predictive models provide valuable guidance for engineers and researchers in optimizing composite formulations without the need for exhaustive experimental procedures. In addition, the research aligns with broader goals of sustainable construction by advocating for the use of polymeric fibers, which are corrosion-resistant, lightweight, and more durable than conventional steel reinforcements in harsh environments. The findings thus support the adoption of fiber-reinforced composites in applications requiring long-term durability and minimal correction.

Finally, by integrating experimental results with computational modeling, the study bridges a critical gap in the literature and encourages the wider use of predictive tools in the design and development of innovative cementitious materials.

2. PREVIOUS STUDIES

2.1. Cementitious Composites

Polymer fiber-reinforced cementitious composites (PFRC) have gained substantial interest due to their improved mechanical properties and enhanced durability. Among synthetic fibers, polypropylene (PP) and polyvinyl alcohol (PVA) are the most widely studied and both have been shown to influence the behavior of cement-based materials when subjected to different loads and environmental conditions.

Dawood and Ghanim (2020) examined and tested mortar mixes containing polypropylene fibers (PP) in dosages ranging from 0% to 0.8% by volume. Their results indicated that fiber addition decreased flowability and density due to the increased internal friction and lower specific gravity of the fibers. Nevertheless, a modest fiber dosage (0.2%) led to marked improvements in mechanical properties. Compressive strength (CS) increased by 4–10%, while flexural strength (FS) and splitting tensile strength increased by 12% and 13%, respectively, at lower fiber contents. At higher dosages (>0.4%), the need for superplasticizers became evident to retain workability, and splitting tensile strength declined beyond 0.8%, highlighting the importance of optimal fiber dosage.

Noushini et al. (2018) studied synthetic fiber-reinforced geopolymer concrete and reported that while polypropylene fibers slightly reduced compressive strength (by 1%–7%) due to their low modulus of elasticity, they significantly enhanced flexural behavior. The use of fibrillated PP fibers increased flexural toughness by up to 2.5 times, and polyolefin fibers notably improved fracture energy by more than 14 times, affirming the value of fiber morphology in controlling crack propagation and ductility.

Mori et al. (2017) focused on the influence of polypropylene short fibers on the flexural and shear response of concrete. Their findings demonstrated that PP fibers enhanced flexural ductility and minimized size-dependent reductions in shear strength. Furthermore, these fibers reduced fire-induced explosive spalling, making them suitable for structures exposed to extreme thermal conditions.

Similarly, Abid et al. (2018) investigated engineered cementitious composites (ECCs) with PP fiber contents up to 2% by volume. While compressive strength showed marginal improvement, both splitting tensile strength and flexural strength

exhibited substantial gains. A 157% increase in tensile strength was recorded at 2% fiber content, illustrating the effectiveness of PP fibers in enhancing post-cracking performance and energy absorption.

The Role of PVA fibers on concrete properties has also been widely researched. Noushini, Samali, and Vessalas (2013) studied the effect of fiber length (6 mm and 12 mm) and Volume content (0.25% and 0.5%) on dynamic properties. Their results showed that a small amount of PVA fibers (0.25%) improved both compressive (CS) and tensile strength, with shorter fibers giving slightly better performance. possibly due to poor dispersion and increased porosity. The dynamic modulus of elasticity remained largely unchanged, though an increase in fiber volume led to a slight decrease in resonant frequency.

Atahan et al. (2013) Evaluated short-cut PVA fiber-reinforced composites under static and impact loading. They tested the fiber contents ranging from (0.5 to 2.0) % and water-to-cement W/C ratios of (0.25 and 0.35) %, Their results showed that increasing the fiber volume improved both compressive strength (CS) and impact resistance. When the combination of higher fiber contents with higher water- to-cement W/C ratios further enhanced energy absorption, highlighting the importance of optimizing mix design for performance under demanding conditions.

These studies collectively show the importance of fiber type, dosage, and interaction with the cement matrix in shaping the mechanical performance of cementitious composites. Polymeric fibers such as PP and PVA provide advantages in (toughness, crack control, and durability) which these making them attractive alternatives to conventional reinforcement, particularly in applications where light weight and corrosion resistance are important.

2.2. Polymeric Fibers in Concrete

The integration of polymeric fibers into cementitious composites has become effective technique way to enhance and improve the properties of concrete in terms of tensile behavior, toughness, and long-term durability. Unlike traditional reinforcement, polymeric fibers are randomly distributed throughout the matrix, enabling multi-directional crack control and more uniform stress distribution. Among the most studied and applied synthetic fibers in this category are polypropylene (PP), polyvinyl alcohol (PVA), polyethylene (PE), aramid, and nylon, each offering distinct mechanical and durability benefits.as Table f2.1 is Comparative Summary of Polymeric Fibers in Concrete.

Table 2.1. Comparative summary of polymeric fibers in previous studies

Property	PP	PVA	PE	Aramid	Nylon
Density (g/cm ³)	~ 0.91 [Ahmed et al., 2020; Pakravan et al., 2017]	~ 1.3 [Noushini et al., 2013; Shahmaran & Li, 2009]	~ 0.97 [Pakravan & Ozbakkaloglu, 2019]	~ 1.44 [Pakravan & Ozbakkaloglu, 2019]	~ 1.15 [Yap et al., 2013; Pakravan et al., 2017]
Tensile Strength (MPa)	300–600 [Abid et al., 2018; Wei et al., 2022]	>1000 [Atahan et al., 2013; Shahmaran & Li, 2009]	up to 3000 [Pakravan et al., 2017]	>3000 [Pakravan & Ozbakkaloglu, 2019]	300–800 [Yap et al., 2013; Pakravan et al., 2017]
Modulus of Elasticity (GPa)	3–5 [Ahmed et al., 2020; Fallah & Nematzadeh, 2017]	40–60 [Noushini et al., 2013; Atahan et al., 2013]	50–120 [Pakravan et al., 2017]	60–130 [Pakravan & Ozbakkaloglu, 2019]	2–4 [Yap et al., 2013; Pakravan et al., 2017]
Matrix Bond	Low (mechanical) [Ahmed et al., 2020; Li, 2003]	Strong (chemical) [Li & Lepech, 2006; Noushini et al., 2013]	Moderate (if treated) [Pakravan et al., 2017]	Moderate [Pakravan et al., 2017]	Moderate [Yap et al., 2013]
Crack Control	Moderate [Ahmed et al., 2020; Dawood & Ghanim, 2020]	High [Shahmaran & Li, 2009; Bheel et al., 2023]	High [Pakravan & Ozbakkaloglu, 2019]	High [Pakravan & Ozbakkaloglu, 2019]	Moderate [Yap et al., 2013]
Impact Resistance	High [Abid et al., 2018; Atahan et al., 2013]	Very High [Atahan et al., 2013; Noushini et al., 2013]	High [Pakravan et al., 2017; Feng et al., 2019]	Very High [Pakravan & Ozbakkaloglu, 2019]	High [Yap et al., 2013; Atahan et al., 2013]
Notable Uses	Pavements, fire protection [Ahmed et al., 2020; Akça et al., 2015]	ECCs, seismic retrofitting [Li, 2003; Li & Lepech, 2006]	ECCs, lightweight armor [Pakravan et al., 2017]	Blast & impact resistant [Pakravan & Ozbakkaloglu, 2019]	Tunnel lining, shotcrete [Yap et al., 2013]

Polymeric fibers provide many advantages that increase the mechanical and durability properties of fiber-reinforced concrete:

- ♦ **Enhanced Crack Resistance:** Polymeric fibers help bridge and stop microcracks, thereby delaying their propagation and reducing the likelihood

of macrocrack formation. This means that the concrete will be stronger in both tensile and flexural strength (Li et al., 2004).

- ♦ Improved Toughness and Ductility: Adding synthetic fibers like PVA and PE makes concrete much better at absorbing energy. This enhancement is especially beneficial in constructions subjected to seismic loads and dynamic stresses (Atahan et al., 2013; Li and Lepech, 2006).
- ♦ Increased Impact and Fatigue Resistance: Polymeric fibers like aramid and nylon are very strong against to repeated loading and sudden impacts. These fibers are commonly used in structures subjected to high-cycle fatigue or high-impact applications (Naaman, 2018; Soutsos et al., 2012).
- ♦ Reduced Plastic Shrinkage Cracking: Early-age cracking due to plastic shrinkage is a major issue in cementitious materials. Fibers such as PP are very effective in controlling shrinkage cracks by providing internal restraint during the hydration process (Dawood and Ghanim, 2020).
- ♦ Durability and Chemical Resistance: Polymeric fibers generally possess excellent resistance to corrosion and alkali environments. Adding them will enhances the durability of concrete, particularly when it is exposed to harsh environmental such as marine or industrial settings (Rao et al., 2019).
- ♦ Lightweight and Easy Handling: compared with steel fibers, synthetic polymeric fibers are lightweight and easier to mix and distribute within the matrix. This makes it easier to handle and use, and it also makes structural elements lighter (Noushini et al., 2018).
- ♦ Sustainability and Recyclability: The use of recycled polymer fibers, such as nylon from waste sources, not only improves mechanical performance but it also helps the environment by keeping trash out of landfills and lowering the carbon footprint of concrete (Kim et al., 2020).

2.2.1. Polypropylene Fibers

Polypropylene (PP) fibers are widely used in cementitious composites because they are non-corrosive, hydrophobic, lightweight, and relatively inexpensive, making them a common choice for improving ductility and post-cracking behavior. Their tensile strength is usually between (300 and 600) MPa, and their modulus of elasticity is modest (3 to 5 GPa). which this limits their ability to increase elastic stiffness but contributes greatly to energy absorption and crack control (Rao et al., 2019).

Dawood and Ghanim (2020) studied and reported that mortars with up to 0.4% PP had better compressive (CS) and flexural strengths (FS). However, when the amount of fiber dosages exceeded 0.8%, but performance declined mainly due to the fibers didn't spread out well and clumped together. In another study Noushini et al. (2018) studied that fibrillated and Polypropylene PP fibers significantly increased the flexural toughness and fracture energy in geopolymer concrete. Similarly, Mori et al. (2017) highlighted the role of PP fibers in enhancing ductility and reducing explosive spalling when they are exposed to fire.

2.2.2. Polyvinyl Alcohol (PVA) Fibers

Polyvinyl alcohol (PVA) fibers have tensile strength (above 1000 MPa) and strong bonding with cement due to their hydrophilic nature. Their modulus of elasticity ranges from (40 and 60) GPa, which makes them suitable for high performance uses that need and requiring ductility and strain-hardening behavior.

Noushini et al. (2013) showed that even 0.25% uncoated PVA fibers significantly improved both compressive (CS) and flexural strength (FS), with shorter fibers yielding better results. Atahan et al. (2013) and Abid et al. (2018) reported improvements in impact resistance and splitting tensile strength, highlighting their effectiveness under dynamic and seismic loading. Li et al. (2004) emphasized the tight microcrack width control to less than 100 μm provided by surface oil-free PVA fibers, which also contributes to self-healing properties in engineered cementitious composites (ECCs).

2.2.3. Polyethylene (PE) Fibers

PE fibers, especially ultra-high molecular weight polyethylene (UHMWPE), are good for lightweight high strength composites because they have high tensile strength (up to 3GPa) and low density. Their hydrophobic nature makes it hard and limits bonding for them; however, surface treatments improve matrix compatibility. Research by Li and Lepech (2006) shows that PE fibers can enable strain-hardening and the production of many cracks similar to PVA, especially in ECCs.

2.2.4. Aramid Fibers

Aramid fibers are usually known through commercial names like Kevlar, are known for their extremely high tensile strength (greater than 3 GPa), thermal stability, and resistance to chemical attack. They are used in specialized applications and areas such as blast resistant structures and military infrastructure. While the cost of aramid fibers is considerably higher than that of more common synthetic fibers,

their superior energy absorption makes them effective in hybrid fiber systems (Naaman, 2018).

2.2.5. Nylon Fibers

Nylon fibers offer good toughness, elasticity, and good chemical resistance, making them a useful option in certain cementitious composites. While they absorb water and may swell slightly, their impact resistance and crack-bridging performance make them suitable for applications like shotcrete, tunnel linings, and precast components.

The modulus of nylon fibers is relatively low, generally between (2 and 4) GPa, which favors post-crack performance rather than stiffness enhancement (Soutsos et al., 2012).

2.3. Challenges and Considerations

The addition of polymeric fibers into cementitious composites provides various advantages, several challenges and practical considerations must be addressed to ensure their effective use in structural applications:

- ♦ **Workability Reduction:** The addition of polymeric fibers, particularly in higher volume fractions which makes to reduce the workability of fresh concrete. This is due to the increased internal friction and the tendency of fibers to form agglomerations or "balls" especially in mixes with low water-to-cement W/C ratios. Studies by Dawood and Ghanim (2020) observed significant reductions in flowability beyond 0.6%PP fiber content, requiring the use of high range water reducing admixtures to restore workability.
- ♦ **Dispersion and Uniformity:** Achieving a uniform distribution of fibers throughout the matrix is very important and critical to satisfy and for consistent mechanical performance. Improper dispersion, it might cause weak spots and inconsistent cracking behavior. Noushini et al. (2018) emphasized the need for careful mixing procedures and, in some cases, surface treated or fibrillated fibers to improve dispersion.
- ♦ **Bonding Limitations:** Some polymeric fibers, particularly (PE and PP), exhibit hydrophobic surfaces that hinder chemical bonding with the cement matrix. This limitation might reduce the effectiveness of stress transfer across cracks. Surface modifications such as plasma treatment or chemical coatings have been explored to improve fiber-matrix interaction (Li and Lepech, 2006).

- ♦ Long-Term Durability: as Synthetic fibers are generally resistant to corrosion, their long-term performance under harsh environmental conditions , e.g. UV exposure, freeze thaw cycles, or chemical attack which largely depends on the fiber type. For example Nylon fiber are prone to moisture absorption, which can affect on dimensional stability (Soutsos et al., 2012).
- ♦ Cost and Availability: While (PP and nylon fibers) are not too expensive, high-performance fibers such as PVA, aramid, and UHMWPE tend to be more expensive, which can limit their use to specialized applications. This means that as economic analysis, it should be performed to balance cost with performance benefits (Naaman, 2018).
- ♦ Standardization and Design Guidelines: Despite growing interest in fiber-reinforced concrete (FRC), there are still no specific standards for mix design, performance evaluation, and long-term durability of polymeric fiber composites. More experimental validation and standard for practices are needed to support their general implementation in mainstream construction (Kim et al., 2020).

2.4. Mechanical Properties of Polymeric Fiber-Reinforced Cementitious Composites

The mechanical properties of polymeric fiber-reinforced cementitious composites (PFRC) are influenced by several factors including fiber type, volume fraction, aspect ratio, and bond characteristics with the matrix. These properties govern the overall behavior of the composite under tensile, compressive, and flexural loads.

- ♦ Compressive Strength CS: While polymeric fibers do not directly improve CS, low dosages can help keep the structure stable under compressive loads by bridging microcracks. Dawood and Ghanim (2020) found that up to 0.4% PP fibers contributed to slight improvements in CS.

Noushini et al. (2018) noted a 1–7% decrease in CS due to low fiber modulus and air entrapment. Abid et al. (2018) and Noushini et al. (2013) indicated that fibers aid crack arrest, contributing indirectly to compressive behavior.

- ♦ Flexural Strength FS: Fiber incorporation enhances the load-bearing capacity under bending, with synthetic fibers like (PP and PE) showing improved post-cracking performance. Noushini et al. (2018) demonstrated that fibrillated PP fibers increase the flexural toughness of geopolymer concrete by more than 2.5 times. Dawood and Ghanim (2020) reported a 12% increase at 0.2% PP content, while Abid et al. (2018) observed 30–40% improvement with PP in ECCs. PVA fibers performed better than PP in flexural applications due to their higher bond with the matrix (Atahan et al., 2013).

- ♦ Tensile Strength and Strain-Hardening: Fibers such as (PVA and PE) can greatly improve tensile performance by promoting multiple microcracking and strain-hardening behavior. This is especially evident in (ECCs), which exhibit enhanced ductility and crack width control (Li et al., 2004). Dawood and Ghanim (2020) observed 40% improvement in splitting tensile strength with PP fibers. Mori et al. (2017) and Noushini et al. (2013) affirmed the efficiency of short PP and PVA fibers in tensile and post-crack enhancement.
- ♦ Splitting Tensile Strength: The addition of polymeric fibers significantly enhances splitting tensile strength by providing crack-bridging mechanisms. Abid et al. (2018) reported a 157% increase in splitting tensile strength with 2% PVA fiber in ECCs. These improvements are crucial in seismic-resistant applications and high-stress zones.
- ♦ Impact Resistance and Toughness: Aramid and nylon fibers are especially effective in enhancing toughness and energy absorption when subjected to dynamic loads. Atahan et al. (2013) confirmed that increased fiber content improves impact resistance and reduces failure severity in high- strain-rate applications.
- ♦ Modulus of Elasticity: The elastic modulus of the composite varies with fiber type. High-modulus fibers like PVA and aramid contribute to stiffness enhancement, while low-modulus fibers like PP mainly improve toughness without considerably enhancing stiffness (Soutsos et al., 2012).

2.5. Modeling Techniques

Numerical modeling plays a pivotal role in understanding and predicting the behavior of cementitious composites under varying loading and environmental conditions. These techniques make easier to study and analysis of fiber-matrix interactions, crack development, and performance optimization with minimal reliance on costly and time-consuming experiments.

- ♦ Finite Element Method (FEM): FEM is one of the most widely used tools for simulating the mechanical behavior of fiber-reinforced composites (FRC). It enables accurate visualization of stress distribution, crack propagation, and structural deformation. FEM has been employed to analyze nonlinear behaviors such as post-cracking, yielding, and strain localization in fiber-reinforced cementitious composites (Zhao et al., 2014).
- ♦ Discrete Element Method (DEM): Unlike FEM, DEM models the interaction between discrete particles or elements, making it particularly effective for studying fracture mechanisms and fiber pull-out behavior at the mesoscale. Li and Wang (2015) utilized DEM to capture interfacial bonding effects and crack initiation patterns in fiber-reinforced concrete.
- ♦ Mesh-Free Methods: Techniques such as Smoothed Particle Hydrodynamics (SPH) are mesh-independent and highly effective in modeling dynamic and high-strain-rate events like impact or blast loading. Pamin et al. (2016) demonstrated that SPH provides accurate simulation of large deformations and multiple crack formations in fiber-reinforced materials.
- ♦ Generalized Inverse Problem (GIP) Method: The GIP method serves as a powerful mathematical framework to extract material properties from experimental data by minimizing the deviation between observed and predicted responses. In the context of cementitious composites, Güler and Kuru (2017) successfully applied GIP to calibrate constitutive models, predict post-peak softening, and optimize mix parameters such as fiber volume and matrix toughness. Its strength lies in adapting to complex, nonlinear systems where direct measurement of material constants is challenging.

3. MATERIALS AND METHODS

This study works on combines experimental testing with predictive modeling to evaluate the influence of polymeric fibers on the mechanical properties of mortar composites. We used two types of polymeric fibers, polypropylene (PP) and polyvinyl alcohol (PVA), were used in varying dosages and water-to-binder (W/B) ratios (0.30 and 0.45). The experimental program casted 42 samples of mortar mixes, which were later combined with 40 mixes extracted from published literature to build a comprehensive dataset as we worked in 4.3.

Predictive models for flexural strength (FS) were then developed for the combined data's by using Multiple Linear Regression (MLR) and Gene Expression Programming (GEP).

3.1. Data Collection and Analysis

To develop a reliable predictive model for flexural strength (FS), a comprehensive dataset consisting of 82 fiber-reinforced mortar and concrete mixes was compiled. This dataset integrates two sources: 40 mixes taken and collected from published studies and 42 additional mixes which tested and developed experimentally as part of this study. All mixes were formatted according to a standardized structure using 12 twelve defined input variables (X_1 to X_{12}), as shown in Table 3.1. These variables cover critical parameters such as mix composition, fiber characteristics, and specimen geometry, ensuring consistent input for modeling.

Table 3.1. Input Variables for Flexural Strength (FS) Modeling

Variables	Descriptions
X_1	Water to binder ratio
X_2	Binder content (kg/m^3)
X_3	Sand to aggregate ratio
X_4	Fiber tensile strength (MPa)
X_5	Fiber content (%)
X_6	Fiber modulus of rupture (MPa)
X_7	Fiber aspect ratio (length/diameter)
X_8	Compressive strength (fc) (MPa)
X_9	Mold area used in compressive strength testing
X_{10}	Moment of inertia (I) of the flexural specimen
X_{11}	Specimen length (cm)
X_{12}	Flexural test mold factor (geometry/material correction)

The dataset spans a wide range of fiber types, volume fractions, binder contents, and testing setups, and is suitable for both regression-based and symbolic modeling techniques. Each mix entry includes the measured flexural strength (FT), which serves as the target output for model training and evaluation. Table 3.2 shows the input variables and corresponding (FT) values for the 40 mix designs collected from published literature. These were carefully selected based on the availability of complete data and relevance to the scope of this research.

Table 3.2. Literature-Based Dataset Input Variables (X_1 – X_{12}) and Flexural Strength (FS)

#	Ref.	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	FT
1	Bheel et al. (2023)	0.25	1305	1.00	4.75	1600	1	41000	462.00	25.0	62.6	13.02	50.0	11
2		0.25	1305	1.00	4.75	1600	1.5	41000	462.00	25.0	54	13.02	50.0	11
3		0.25	1305	1.00	4.75	1600	2	41000	462.00	25.0	48	13.02	50.0	10
4	Abd Elmoaty et al. (2022)	0.26	1734	1.00	0.25	700	2	4300	833.33	100.0	53	104.17	50.0	5.1
5		0.26	1683	1.00	0.25	700	4	5300	833.33	100.0	48	104.17	50.0	7
6		0.26	1632	1.00	0.25	700	6	6300	833.33	100.0	46	104.17	50.0	8.5
7	Atahan et al. (2013)	0.25	1000	1.00	0.25	1400	2	35000	200.00	49.0	81.4	9.84	60.0	9.9
8		0.25	1000	1.00	0.25	1400	1.5	35000	200.00	49.0	77.8	9.84	60.0	11
9		0.25	1000	1.00	0.25	1400	1	35000	200.00	49.0	78.9	9.84	60.0	9.6
10		0.25	1000	1.00	0.25	1400	0.5	35000	200.00	49.0	87.4	9.84	60.0	9.9
11		0.35	1000	1.00	0.25	1400	2	35000	200.00	49.0	75	9.84	60.0	9.7
12		0.35	1000	1.00	0.25	1400	1.5	35000	200.00	49.0	70.8	9.84	60.0	8.1
13		0.35	1000	1.00	0.25	1400	1	35000	200.00	49.0	62.2	9.84	60.0	8.1
14	Abid et al. (2018)	0.26	1254	1.00	0.20	300	0.5	4000	666.67	100.0	43	200.08	23.5	3.2
15		0.26	1254	1.00	0.20	300	1	4000	666.67	100.0	45	200.08	23.5	4.3
16		0.26	1254	1.00	0.20	300	1.5	4000	666.67	100.0	44	200.08	23.5	6.5
17		0.26	1254	1.00	0.20	300	2	4000	666.67	100.0	42	200.08	23.5	7.2
18	Noushini et al. (2018)	0.35	430	0.37	20.00	1500	0.25	41700	428.57	78.5	67	833.33	40.0	6.8
19		0.35	430	0.37	20.00	1500	0.5	41700	428.57	78.5	61.5	833.33	40.0	6.3
20		0.35	430	0.37	20.00	1500	0.25	41700	857.14	78.5	64.5	833.33	40.0	6.7
21		0.35	430	0.37	20.00	1500	0.5	41700	857.14	78.5	58.5	833.33	40.0	6.2
22	Başşürücü et al. (2022)	0.57	350	0.60	16.00	350	0.4	3500	240.00	225.0	30.1	833.33	40.0	9
23		0.57	350	0.60	16.00	350	0.8	3500	240.00	225.0	28.1	833.33	40.0	6.5
24	Noushini et al. (2013)	0.30	800	0.45	20.00	450	0.5	3500	818.00	78.5	60.4	833.33	55.0	6.7
25		0.30	800	0.45	20.00	450	0.5	3500	345.00	78.5	59.1	833.33	55.0	6.1
26		0.30	800	0.45	20.00	450	0.5	3500	927.00	78.5	59	833.33	55.0	5.8
27	Wei et al. (2022)	0.37	365	0.43	25.00	565	0.6	5900	608.97	100.0	35.8	833.33	40.0	5.7
28		0.37	365	0.43	25.00	565	0.9	5900	608.97	100.0	39.2	833.33	40.0	5.9
29		0.37	365	0.43	25.00	565	1.2	5900	608.97	100.0	36.8	833.33	40.0	5.7
30		0.37	365	0.43	25.00	565	1.5	5900	608.97	100.0	35	833.33	40.0	5.3
31	Dawood & Ghanim (2020)	0.40	585	1.00	1.18	689	0.2	4800	666.67	25.0	52.5	21.33	16.0	10
32		0.40	585	1.00	1.18	689	0.4	4800	666.67	25.0	54.8	21.33	16.0	9.8
33		0.40	585	1.00	1.18	689	0.6	4800	666.67	25.0	55.8	21.33	16.0	9.6
34		0.40	585	1.00	1.18	689	0.8	4800	666.67	25.0	51	21.33	16.0	9.4
35	Jassam et al. (2022)	0.30	450	0.38	10.00	700	0.1	3500	333.33	78.5	55.4	200.08	28.0	4.6
36		0.30	450	0.38	10.00	700	0.2	3500	333.33	78.5	55.9	200.08	28.0	4.6
37		0.30	450	0.38	10.00	700	0.3	3500	333.33	78.5	54.3	200.08	28.0	4.5
38		0.30	450	0.38	10.00	700	0.4	3500	333.33	78.5	49.8	200.08	28.0	4.1
39		0.30	450	0.38	10.00	700	0.5	3500	333.33	78.5	48.6	200.08	28.0	4

3.2. Experimental Program

3.2.1. Materials

3.2.1.1. Cement

The cement used in this experimental program is ÜNYE - CEM II /A - M (P-LL) 42.5 R, which classified under strength class 42.5 R, It consists primarily of clinker, which making up about (65 to 79) % of its content, and specific gravity of approximately 3.15 g/cm³, and its fineness measured by the Blaine method ranges between (350 to 450) m²/kg. The initial setting time is not less than 45 minutes, while the final setting time does not exceed 600 minutes, ensuring a practical balance between workability and early strength gain, The chemical composition of the Portland cement used in this study is presented in Table 3.3

Table 3.3. Chemical Composition of Portland Cement (by weight percentage)

Compositions, %	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	K ₂ O	Na ₂ O
Portland cement	62.23	20.38	2.427	4.57	1.107	2.51	1.405	0.079

3.2.1.2. Aggregate

The fine aggregate used in this study was natural river sand with a maximum particle size of 4.75 mm, had a specific gravity of 2.63 g/cm³ and a moisture content of approximately 5%. The water absorption of the sand was tested at 1.4%, indicating its ability to retain moisture relative to its dry mass. The fineness modulus was measured at 2.8, A sieve Gradations of sand was tested and a well-graded distribution suitable for mortar applications. Figure 3.1 presents the sieve analysis of the fine aggregate, tested and compared as per the standards specified in AASHTO M 6 / M 80 and BS 882-M.

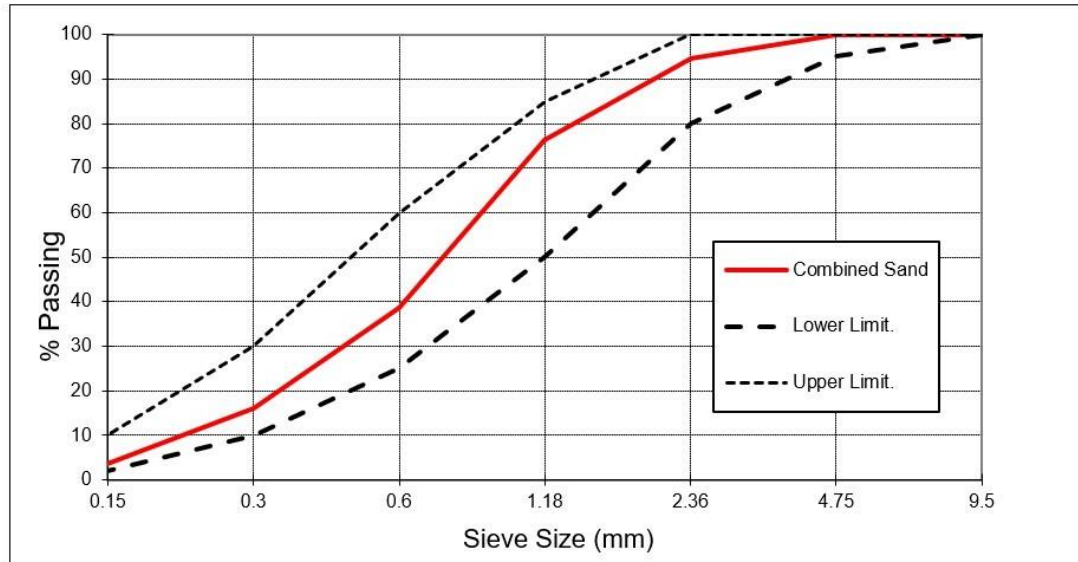


Figure 3.1. Grading curve of fine aggregate

3.2.1.3. Polymeric Fibers

In this study, polypropylene (PP) and polyvinyl alcohol (PVA) fibers are used to reinforce the cementitious composites and evaluate their mechanical properties. These fibers were selected based on their mechanical properties, durability, and compatibility with cementitious matrices.

Polypropylene (PP) fibers were used in two lengths, 6 mm and 19 mm, both composed of 100% polypropylene material. PVA fiber (lengths 12 mm) as in Table 3.4 The characteristic properties of the fibers used are summarized in the table below:

Table 3.4. Characteristic properties of the fibers

Fiber Type	Density (g/mL)	Fiber Length (mm)	Elastic Modulus (MPa)	Tensile Strength (MPa)	Diameter (μ m)	Aspect Ratio (l/d)
Polypropylene (PP2) - 6 mm	0.9	6 mm	3500	550	10	600
Polypropylene (PP1) - 19 mm	0.9	19 mm	3500	550	10	1900
Polyvinyl Alcohol (PVA)	1.3	12.0 mm ± 2.0	1235	1235	90	133.33

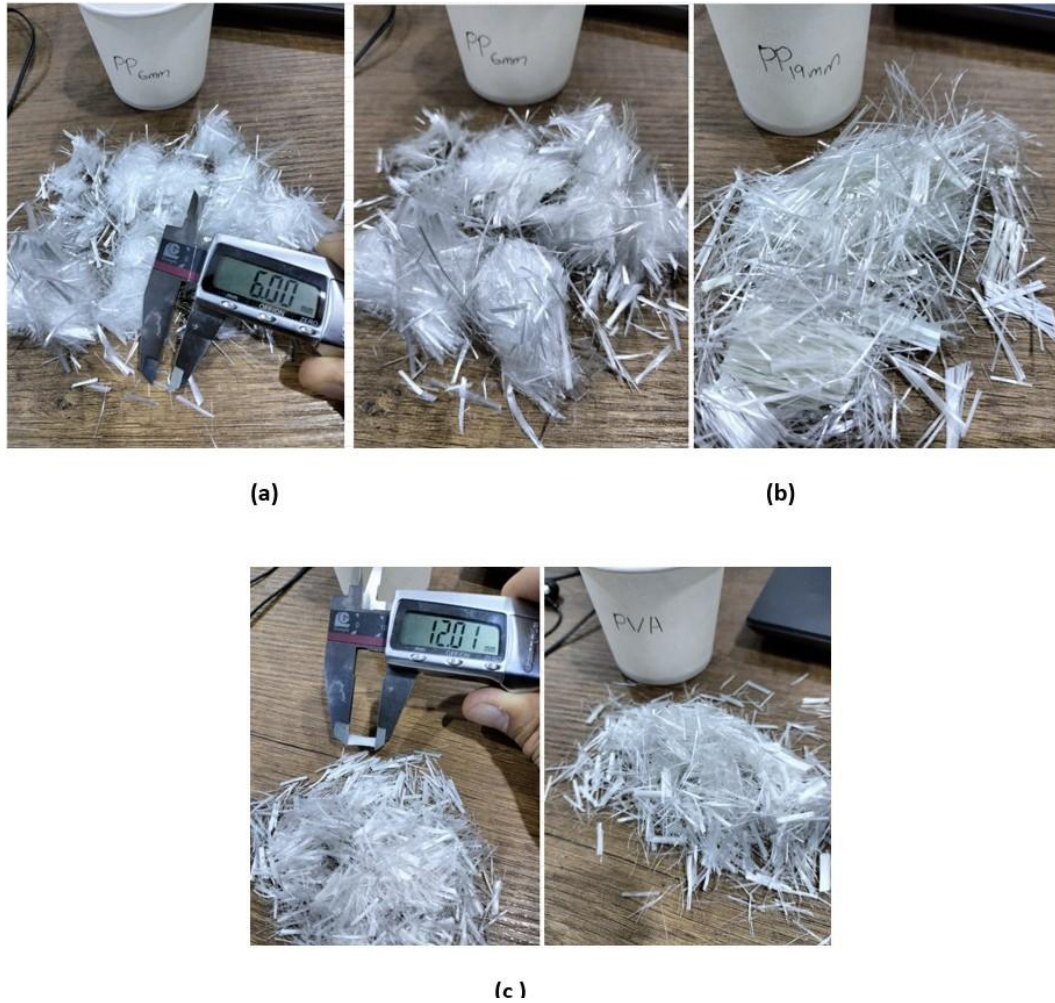


Figure 3.2. Photographic view of: (a) Polypropylene fibers (6mm) (b) Polypropylene fibers (19mm); (c) Polyvinyl alcohol (PVA) fibers (12mm).

3.2.1.4. Water

Potable tap water was used for all mixing and curing procedures in this study. The water complied with the requirements of ASTM C1602 for mixing and curing, it was free from impurities that could negatively affect cement hydration or concrete durability. The use of clean, drinkable water helped maintain consistency in the mix and ensured the reliability of test results related to mechanical performance.

3.2.1.5. Superplasticizer

The admixture used as superplasticizer in this study was Polisan Politon 777 W, a polycarboxylate-based high-range water-reducing admixture. This chemical admixture played a crucial role in improving the workability of the fiber-reinforced mixes without increasing the water to binder W/B ratio. Its efficient water reduction capability allowed for better dispersion of fibers and uniform consistency in fresh

concrete. The admixture appeared as a light brown liquid with a specific gravity of approximately (1.08 ± 0.02) and a pH value ranging between 7.0 and 9.0. With very low sodium and alkali contents, The dosage rate varied between 0.5% and 2.0% by weight of the total binder, tailored according to the specific mix design parameters and performance requirements.

3.2.2. Equipment

3.2.2.1. Mixing Equipment

A laboratory-scale concrete mixer was used to prepare the cementitious composite mortar mixtures. This mixer enabled consistent and thorough blending of all components (cement, sand, water, high-range water-reducing admixture (POLITON 777 W), and polymeric fibers (PP or PVA)). The mixing procedures as per ASTM C305 (Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency).

The process began with a one-minute dry mix of cement, sand, and fibers to promote uniform distribution. Afterwards, half of the mixing water was added, and the remaining portion was combined with the admixture before being gradually introduced into the mixture. The mixer was continue operated for an additional two minutes to achieve full incorporation of the liquid phase. Adding water and admixture in stages was essential for maintaining uniformity in the mixture in order to reducing and preventing fiber agglomeration.

The quantities of all materials were weighted with a digital scale which compliant as per ASTM C138. This ensured accuracy in maintaining target water-to-cement W/C ratios and fiber contents for every mixes.



(a) mixer for uniform blending of components.



(b) a digital weighing scale.

Figure 3.3. Laboratory mixing Device

3.2.2.2. Molding Equipment

Two types of molds were used: $50 \times 50 \times 50$ mm cube molds for compressive strength (CS) tests and $40 \times 40 \times 160$ mm prism molds for flexural strength (FS) tests as shown in Figure 3.4. the samples were prepared and tested in accordance with ASTM C109 (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars and ASTM C348 Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars), respectively.

**Figure 3.4.** Molds used for production of test specimens

Prior to casting, the inner surfaces of the molds were coated with a release agent to facilitate easy demolding. The fresh ECC mortar was placed into the molds in three successive layers. Each layer was compacted using a vibration table in accordance with ACI 309R – Guide for Consolidation of Concrete, ensuring the removal of entrapped air and achieving uniform fiber dispersion throughout the specimen.

3.2.2.3. Curing Equipment

Proper curing of the ECC mortar specimens was critical to ensure the development of intended mechanical properties. After 24 hours of initial setting, the specimens were demolded and subjected to two distinct curing regimes: water curing and humidity chamber curing.

Water curing was performed in a controlled curing tank maintained at $20 \pm 2^\circ\text{C}$, in accordance with ASTM C511 – Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes. This method provided continuous moisture exposure to support complete hydration.

Alternatively, specimens designated for humidity curing were placed in a curing chamber with a controlled environment of 90–95% relative humidity and a temperature of $23 \pm 2^\circ\text{C}$. This setup met the requirements of ASTM C192 – Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.



Figure 3.5. Curing tank.

3.2.2.4. Testing Equipment

Compressive strength (CS) tests were tested by using a digital compression testing machine, in accordance with ASTM C109 (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars). As per standard the Cube specimens ($50 \times 50 \times 50$ mm) were centrally placed on the loading platform, and a compressive load was applied at a constant rate of 0.25 MPa/s until failure. The maximum load was recorded and used to compute the CS.

Flexural strength (FS) tests were performed on prismatic specimens ($40 \times 40 \times 160$ mm) using a flexural testing apparatus under a three-point bending Setup according to ASTM C348 (Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars). After adding the specimen, the load was applied at the mid-span with a constant loading rate of 1.0 MPa/s, and the peak force at failure was used to calculate the modulus of rupture or FS.



Figure 3.6. Flexural and compressive testing devices

3.2.3. Mix Proportions and Preparation

3.2.3.1. Experimental Mix Proportions

The Cementitious Composite mixes were prepared and tested in a controlled laboratory environment to find and examine the influence of key mix parameters (particularly water to binder ratio (W/B), fiber type, and fiber volume fraction) on the mechanical performance of the material, with a focus on flexural strength (FS).

Two W/B ratios were selected (0.30 for high-performance as low water content mixes, and 0.45 for more workable compositions).

Accordingly, the mixes were designated using the marks “L” for low W/B (0.30) and “H” for high W/B (0.45), as summarized in Table 3.5.

Table 3.5. Mix proportions for cementitious composites

#	Mix. ID	Fiber Vol. %	Cement (kg)	Sand (kg)	W/C %	Admix. (kg)	#	Mix. ID	Fiber Vol. %	Cement (kg)	Sand (kg)	W/C %	Admix. (kg)
1	L0	0	1:2.75		0.3	2%	23	H0	0	1:2.75		0.45	1%
2	L 0.2 PP1	0.2					24	H 0.2 PP1	0.2				
3	L 0.4 PP1	0.4					25	H 0.4 PP1	0.4				
4	L 0.6 PP1	0.6					26	H 0.6 PP1	0.6				
5	L 0.8 PP1	0.8					27	H 0.8 PP1	0.8				
6	L 1.0 PP1	1					28	H 1.0 PP1	1				
7	L 1.2 PP1	1.2					29	H 1.2 PP1	1.2				
8	L 1.4 PP1	1.4					30	H 1.4 PP1	1.4				
9	L0	0					31	H 0.2 PP2	0.2				
10	L 0.2 PP2	0.2					32	H 0.4 PP2	0.4				
11	L 0.4 PP2	0.4					33	H 0.6 PP2	0.6				
12	L 0.6 PP2	0.6					34	H 0.8 PP2	0.8				
13	L 1.0 PP2	1					35	H 1.0 PP2	1				
14	L 1.2 PP2	1.2					36	H 1.2 PP2	1.2				
15	L 1.4 PP2	1.4					37	H 1.4 PP2	1.4				
16	L0	0					38	H 0.2 PVA	0.2				
17	L 0.2 PVA	0.2					39	H 0.4 PVA	0.4				
18	L 0.4 PVA	0.4					40	H 0.6 PVA	0.6				
19	L 0.6 PVA	0.6					41	H 0.8 PVA	0.8				
20	L 1.0 PVA	1					42	H 1.0 PVA	1				
21	L 1.2 PVA	1.2					43	H 1.2 PVA	1.2				
22	L 1.4 PVA	1.4					44	H 1.4 PVA	1.4				

For all mixes, a fixed sand to cement volume ratio of 2.75:1 was maintained to ensure consistent particle packing, workability, and density.

The fiber volume fraction was varied from (0 to 1.4) %, by using three types of polymeric fibers: PP1 (19mm), PP2 (6mm), and PVA (12mm). The mixes also included a high-range water-reducing admixture (Polisan Politon 777 W), dosed by volume at 2% of cement volume for low W/B mixes and 1% for high W/B mixes, to enhance workability and support fiber dispersion.

3.2.3.2. Mixing Procedure

A standardized sequence of mixing was followed to ensure homogeneity and to avoid fiber clumping. The dry materials of cement, fibers, and sand were first blended in a clean pan mixer for approximately two to three minutes. Thereafter, half of the mixing water was gradually introduced, followed by the remaining portion premixed with the required amount of admixture. Mixing continued for an additional two minutes until a uniform and consistent paste was obtained. In total, forty-four mixes were prepared by varying fiber types, dosages, and W/B ratios, as illustrated in Figure 3.7.



(a)



(b)

(c)

Figure 3.7. Mixing Procedure for FRCC Specimens (a) Materials weighing, (b) Dry blending of materials and (c) mix resting to release air voids.

3.2.3.3. Flowability Test

The flowability of the fresh fiber mortar was measured using the flow table test in accordance with ASTM C1437. The mortar was placed into a standard flow mold on a flow table, tamped, and the mold removed. The table was dropped 25 times in 15 seconds. The average diameter of the mortar spread was measured in two perpendicular directions and recorded as the flow value in millimeters. An example of the flow test procedure is shown in Figure 3.8.



Figure 3.8. Flow Table Test for Fiber Mortar :(a) test apparatus, (b) filling & tramping stage, (c) finishing stage, and (d) measuring stage

3.2.3.4. Casting and Curing

After mixing, the fresh mortar was poured into molds prepared for subsequent mechanical testing. Prismatic specimens with dimensions of $40 \times 40 \times 160$ mm were cast for flexural strength (FS) tests, while cubic specimens of $50 \times 50 \times 50$ mm were cast for compressive strength (CS) tests. Before casting, all molds were lightly coated with a release agent to facilitate easy demolding. The mortar was then placed into the molds in three successive layers, with each layer carefully compacted on a vibrating table to eliminate entrapped air and ensure uniform density. Following casting, the specimens were kept under ambient laboratory conditions for 24 hours, after which they were demolded, labeled, and transferred to a curing tank maintained at $20 \pm 2^\circ\text{C}$.

All samples remained in a controlled environment for 28 days before testing, as in Figures 3.9 and 3.10, which illustrate the specimen preparation process, including mold lubrication, weight recording, compaction, finishing, labeling, and hardened weight measurement.



Figure 3.9. Photographic view of specimen preparation: (a) oiled molds, (b) empty mold weight, (c) finishing and Vibration machine and (d) Finishing and labeling



Figure 3.10. Demolding and Unit Weight Measurement

3.2.3.5. Mechanical Testing Procedure

To evaluate the mechanical performance of the fiber-reinforced cementitious composites (FRCC), compressive and flexural strength tests were performed on specimens after 28 days of curing, in accordance with the relevant ASTM standards. All specimens were tested under controlled laboratory conditions using calibrated digital testing machines. The testing setups are shown in Figure 3.11.

Compressive strength was determined using $50 \times 50 \times 50$ mm cube specimens, following ASTM C109 (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars). A uniformly increasing load was applied at a controlled rate of 0.25 MPa/s until failure. The maximum load at failure was recorded, and compressive strength was calculated using the formula:

$$CS = P / A \quad (1)$$

where:

CS = compressive strength (MPa)

P = maximum load at failure (N)

A = cross-sectional area of the cube (mm²)

Flexural performance was assessed using $40 \times 40 \times 160$ mm prism specimens in a three-point bending configuration, as specified in ASTM C348 – Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars. The span length was set at 100 mm, and the load was applied at mid-span at a constant loading rate of 1.0 MPa/s until fracture. The modulus of rupture was calculated based on the failure load using the following formula:

$$FS = 3 P L / (2 b d^2) \quad (2)$$

where:

FS = flexural strength (MPa)

P = load at fracture (N)

L = span length (mm)

b = specimen width (mm)

d = specimen depth (mm)

For each mix design, a minimum of three specimens were tested for both compressive and flexural strength. The average value of the three replicates was reported as the representative strength for that mix.



(a)

Figure 3.11. Photographic views from Harran University Laboratory: (a) Compressive strength



(b)

Figure 3.12. Photographic views from Harran University Laboratory: (b) Flexural strength test



(c)

Figure 3.13. Photographic views from Harran University Laboratory: (c) Specimen shape after flexural failure indicating fiber pull-out and crack patterns and compressive samples show brittle fracture and crushed edges.

3.3. Model Development

This chapter presents the development process of predictive models aimed at estimating the flexural strength (FS) of polymeric fiber-reinforced cementitious composites (PFRCC). Two modeling techniques were adopted in this study: Multiple Linear Regression (MLR), a conventional statistical method, and Gene Expression

Programming (GEP), an evolutionary algorithm known for capturing complex, nonlinear relationships. Both approaches were applied to Combined data's that from experimental and literature-based results, with the objective of identifying the most influential parameters (X_1 to X_{12}) governing mechanical performance.

The modeling process began with the collection and combining of 82 mix designs, comprising 42 samples casted and tested in the laboratory and 40 additional mixes that were taken from published sources. Each mix was described using 12 twelve independent input variables (X_1 to X_{12}), which included mix proportions, fiber mechanical properties, and specimen geometry related factors. The flexural strength (FS) was designated as the dependent variable to be predicted by both models.

For the GEP model, the dataset was randomly divided into a training set (80%) and a validation set (20%) to evaluate the model's generalizability. Symbolic regression techniques were tested through GeneXproTools (version 5), utilizing diverse combinations of mathematical functions and gene structures to evolve optimal model expressions as we made in 4.3.2. This approach enabled the derivation of interpretable equations while accommodating nonlinear interactions among variables.

Same Entire combined data sets were developed for MLR model without any partitioning. The linear model was calibrated using the least squares method, which fits a linear equation to the observed data by minimizing the sum of squared residuals. MLR provided a straightforward and interpretable baseline model, enabling clear identification of the significance and weight of each input parameter as we worked in article 4.3.1.

To assess and compare the performance of the two models, several statistical indicators were employed. These included the Coefficient of Determination (R^2), which quantifies the proportion of variance explained by the model; the Mean Absolute Percentage Error (MAPE), which measures the average percentage error between predicted and actual values; and the Root Mean Squared Error (RMSE), which captures the dispersion of prediction errors. Together, these metrics provided a comprehensive evaluation of model accuracy, robustness, and reliability.

4. FINDINGS

4.1. Flexural and Compressive Strength of Mixes.

The experimental program produced the flexural strength (FS) and compressive strength (Fc) values of 44 mortar mixes with different fiber types, dosages, and W/B ratios. These results, summarized in Table 4.1, form the basis for evaluating the influence of polymeric fibers on the mechanical performance of the composites.

Table 4.1. Flexural and Compressive Strength Results for Fiber-Reinforced Composites mixes:

#	Mix ID	W/C =0.3 %		#	Mix ID	W/C =0.45 %	
		Compressive Strength CS (Mpa)	Flexural Strength FS (Mpa)			Compressive Strength CS (Mpa)	Flexural Strength FS (Mpa)
1	L0	74.86	7.23	23	H0	49.06	6.05
2	L 0.2 PP1	75.03	7.69	24	H 0.2 PP1	53.67	6.87
3	L 0.4 PP1	76.70	8.34	25	H 0.4 PP1	59.83	7.12
4	L 0.6 PP1	78.25	9.55	26	H 0.6 PP1	65.60	7.52
5	L 0.8 PP1	81.43	9.59	27	H 0.8 PP1	68.67	7.96
6	L 1.0 PP1	81.33	9.40	28	H 1.0 PP1	62.80	7.77
7	L 1.2 PP1	77.80	8.76	29	H 1.2 PP1	59.23	7.74
8	L 1.4 PP1	75.23	7.70	30	H 1.4 PP1	53.80	7.04
1	L0	74.86	7.23	23	H0	49.06	6.05
9	L 0.2 PP2	75.30	7.34	31	H 0.2 PP2	54.67	6.14
10	L 0.4 PP2	77.17	7.47	32	H 0.4 PP2	55.87	7.35
11	L 0.6 PP2	78.20	7.93	33	H 0.6 PP2	60.13	7.73
12	L 0.8 PP2	75.63	7.01	34	H 0.8 PP2	55.30	6.93
13	L 1.0 PP2	71.87	6.89	35	H 1.0 PP2	49.30	6.51
14	L 1.2 PP2	64.10	6.59	36	H 1.2 PP2	41.47	6.30
15	L 1.4 PP2	54.97	6.13	37	H 1.4 PP2	39.10	5.82
1	L0	74.86	7.23	23	H0	49.06	6.05
16	L 0.2 PVA	75.17	7.41	38	H 0.2 PVA	49.73	6.98
17	L 0.4 PVA	80.20	7.47	39	H 0.4 PVA	55.43	7.85
18	L 0.6 PVA	81.80	8.53	40	H 0.6 PVA	57.53	7.96
19	L 0.8 PVA	86.90	9.09	41	H 0.8 PVA	67.73	8.03
20	L 1.0 PVA	77.63	7.60	42	H 1.0 PVA	66.10	7.64
21	L 1.2 PVA	71.47	7.13	43	H 1.2 PVA	65.87	6.82
22	L 1.4 PVA	71.20	7.00	44	H 1.4 PVA	63.83	6.11

4.2. Flow and Unit Weight of Mixes.

The fresh properties of the cementitious composites were assessed by measuring flowability and unit weight. Table 4.2 summarizes the results for all 44 mixes, showing how variations in fiber type, dosage, and W/B ratio influenced both workability and density of the mixes.

Table 4.2. Flowability and Unit Weight of Cementitious Mixes

#	Mix ID	W/C =0.3 %		#	Mix ID	W/C =0.45 %	
		Flow (cm)	Unit weight (kg)			Flow (cm)	Unit weight (kg)
1	L0	20.00	2365.23	23	H0	22.00	2266.01
2	L 0.2 PP1	19.00	2364.90	24	H 0.2 PP1	21.00	2262.60
3	L 0.4 PP1	18.00	2364.64	25	H 0.4 PP1	20.40	2257.19
4	L 0.6 PP1	17.00	2361.18	26	H 0.6 PP1	19.50	2255.73
5	L 0.8 PP1	16.00	2357.70	27	H 0.8 PP1	18.00	2253.10
6	L 1.0 PP1	15.00	2351.24	28	H 1.0 PP1	17.60	2251.20
7	L 1.2 PP1	15.50	2348.78	29	H 1.2 PP1	16.00	2249.34
8	L 1.4 PP1	14.50	2346.31	30	H 1.4 PP1	15.00	2243.30
1	L0	20.00	2365.23	23	H0	22.00	2266.01
9	L 0.2 PP2	19.50	2360.41	31	H 0.2 PP2	22.00	2263.29
10	L 0.4 PP2	18.40	2360.97	32	H 0.4 PP2	21.00	2261.12
11	L 0.6 PP2	19.00	2358.28	33	H 0.6 PP2	20.00	2260.71
12	L 0.8 PP2	18.00	2355.99	34	H 0.8 PP2	18.00	2260.43
13	L 1.0 PP2	17.00	2352.50	35	H 1.0 PP2	17.00	2255.93
14	L 1.2 PP2	16.30	2349.11	36	H 1.2 PP2	16.00	2253.10
15	L 1.4 PP2	15.40	2346.88	37	H 1.4 PP2	15.50	2244.70
1	L0	20.00	2365.23	23	H0	22.00	2266.01
16	L 0.2 PVA	20.00	2363.34	38	H 0.2 PVA	21.00	2265.77
17	L 0.4 PVA	19.50	2359.84	39	H 0.4 PVA	20.00	2264.20
18	L 0.6 PVA	18.40	2356.41	40	H 0.6 PVA	18.00	2263.84
19	L 0.8 PVA	18.00	2354.94	41	H 0.8 PVA	17.00	2255.31
20	L 1.0 PVA	17.30	2351.48	42	H 1.0 PVA	15.00	2254.09
21	L 1.2 PVA	16.70	2346.02	43	H 1.2 PVA	16.50	2248.20
22	L 1.4 PVA	15.00	2344.55	44	H 1.4 PVA	16.00	2247.10

4.3. Analytical Modeling

For predictive modeling, the experimental results were combined with 40 additional mixes compiled from the literature, producing a total dataset of 82 mixes. Tables 4.3 and 4.4 present the input parameters and test results for the literature and experimental datasets, respectively. This comprehensive database formed the basis for developing and validating the Multiple Linear Regression (MLR) and Gene Expression Programming (GEP) models for flexural strength (FS).

Table 4.3. Literature Dataset (40 Mixes)

#	Ref.	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	FT
1	Bheel et al. (2023)	0.25	1305	1.00	4.75	1600	1	41000	462.00	25.0	62.6	13.02	50.0	11
2		0.25	1305	1.00	4.75	1600	1.5	41000	462.00	25.0	54	13.02	50.0	11
3		0.25	1305	1.00	4.75	1600	2	41000	462.00	25.0	48	13.02	50.0	10
4	Abd Elmoaty et al. (2022)	0.26	1734	1.00	0.25	700	2	4300	833.33	100.0	53	104.17	50.0	5.1
5		0.26	1683	1.00	0.25	700	4	5300	833.33	100.0	48	104.17	50.0	7
6		0.26	1632	1.00	0.25	700	6	6300	833.33	100.0	46	104.17	50.0	8.5
7	Atahan et al. (2013)	0.25	1000	1.00	0.25	1400	2	35000	200.00	49.0	81.4	9.84	60.0	9.9
8		0.25	1000	1.00	0.25	1400	1.5	35000	200.00	49.0	77.8	9.84	60.0	11
9		0.25	1000	1.00	0.25	1400	1	35000	200.00	49.0	78.9	9.84	60.0	9.6
10		0.25	1000	1.00	0.25	1400	0.5	35000	200.00	49.0	87.4	9.84	60.0	9.9
11		0.35	1000	1.00	0.25	1400	2	35000	200.00	49.0	75	9.84	60.0	9.7
12		0.35	1000	1.00	0.25	1400	1.5	35000	200.00	49.0	70.8	9.84	60.0	8.1
13		0.35	1000	1.00	0.25	1400	1	35000	200.00	49.0	62.2	9.84	60.0	8.1
14		0.35	1000	1.00	0.25	1400	0.5	35000	200.00	49.0	61.9	9.84	60.0	7.7
15	Abid et al. (2018)	0.26	1254	1.00	0.20	300	0.5	4000	666.67	100.0	43	200.08	23.5	3.2
16		0.26	1254	1.00	0.20	300	1	4000	666.67	100.0	45	200.08	23.5	4.3
17		0.26	1254	1.00	0.20	300	1.5	4000	666.67	100.0	44	200.08	23.5	6.5
18		0.26	1254	1.00	0.20	300	2	4000	666.67	100.0	42	200.08	23.5	7.2
19	Noushini et al. (2018)	0.35	430	0.37	20.00	1500	0.25	41700	428.57	78.5	67	833.33	40.0	6.8
20		0.35	430	0.37	20.00	1500	0.5	41700	428.57	78.5	61.5	833.33	40.0	6.3
21		0.35	430	0.37	20.00	1500	0.25	41700	857.14	78.5	64.5	833.33	40.0	6.7
22		0.35	430	0.37	20.00	1500	0.5	41700	857.14	78.5	58.5	833.33	40.0	6.2
23	Başsürücü et al. (2022)	0.57	350	0.60	16.00	350	0.4	3500	240.00	225.0	30.1	833.33	40.0	9
24		0.57	350	0.60	16.00	350	0.8	3500	240.00	225.0	28.1	833.33	40.0	6.5
25	Noushini et al. (2013)	0.30	800	0.45	20.00	450	0.5	3500	818.00	78.5	60.4	833.33	55.0	6.7
26		0.30	800	0.45	20.00	450	0.5	3500	345.00	78.5	59.1	833.33	55.0	6.1
27		0.30	800	0.45	20.00	450	0.5	3500	927.00	78.5	59	833.33	55.0	5.8
28	Wei et al. (2022)	0.37	365	0.43	25.00	565	0.6	5900	608.97	100.0	35.8	833.33	40.0	5.7
29		0.37	365	0.43	25.00	565	0.9	5900	608.97	100.0	39.2	833.33	40.0	5.9
30		0.37	365	0.43	25.00	565	1.2	5900	608.97	100.0	36.8	833.33	40.0	5.7
31		0.37	365	0.43	25.00	565	1.5	5900	608.97	100.0	35	833.33	40.0	5.3
32	Dawood & Ghanim (2020)	0.40	585	1.00	1.18	689	0.2	4800	666.67	25.0	52.5	21.33	16.0	10
33		0.40	585	1.00	1.18	689	0.4	4800	666.67	25.0	54.8	21.33	16.0	9.8
34		0.40	585	1.00	1.18	689	0.6	4800	666.67	25.0	55.8	21.33	16.0	9.6
35		0.40	585	1.00	1.18	689	0.8	4800	666.67	25.0	51	21.33	16.0	9.4
36	Jassam et al. (2022)	0.30	450	0.38	10.00	700	0.1	3500	333.33	78.5	55.4	200.08	28.0	4.6
37		0.30	450	0.38	10.00	700	0.2	3500	333.33	78.5	55.9	200.08	28.0	4.6
38		0.30	450	0.38	10.00	700	0.3	3500	333.33	78.5	54.3	200.08	28.0	4.5
39		0.30	450	0.38	10.00	700	0.4	3500	333.33	78.5	49.8	200.08	28.0	4.1
40		0.30	450	0.38	10.00	700	0.5	3500	333.33	78.5	48.6	200.08	28.0	4

Table 4.4. 42 datasets from experimental mixes

#	Ref.	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	FT
1	42 Mix Data set (Experimental)	0.30	595	1.00	4.75	550	0.2	4800	608.97	25.0	71.03	21.33	16.0	8.34
2		0.30	595	1.00	4.75	550	0.4	4800	608.97	25.0	74.70	21.33	16.0	8.76
3		0.30	595	1.00	4.75	550	0.6	4800	608.97	25.0	78.25	21.33	16.0	9.40
4		0.30	595	1.00	4.75	550	0.8	4800	608.97	25.0	81.43	21.33	16.0	9.59
5		0.30	595	1.00	4.75	550	1	4800	608.97	25.0	81.33	21.33	16.0	9.55
6		0.30	595	1.00	4.75	550	1.2	4800	608.97	25.0	77.80	21.33	16.0	7.71
7		0.30	595	1.00	4.75	550	1.4	4800	608.97	25.0	75.23	21.33	16.0	7.69
8		0.30	595	1.00	4.75	1400	0.2	41000	120.00	25.0	75.17	21.33	16.0	7.13
9		0.30	595	1.00	4.75	1400	0.4	41000	120.00	25.0	80.20	21.33	16.0	7.47
10		0.30	595	1.00	4.75	1400	0.6	41000	120.00	25.0	81.80	21.33	16.0	9.09
11		0.30	595	1.00	4.75	1400	0.8	41000	120.00	25.0	86.90	21.33	16.0	8.53
12		0.30	595	1.00	4.75	1400	1	41000	120.00	25.0	77.63	21.33	16.0	7.60
13		0.30	595	1.00	4.75	1400	1.2	41000	120.00	25.0	71.47	21.33	16.0	7.41
14		0.30	595	1.00	4.75	1400	1.4	41000	120.00	25.0	71.20	21.33	16.0	7.00
15		0.30	595	1.00	4.75	550	0.2	3500	200.00	25.0	76.30	21.33	16.0	6.13
16		0.30	595	1.00	4.75	550	0.4	3500	200.00	25.0	77.80	21.33	16.0	6.59
17		0.30	595	1.00	4.75	550	0.6	3500	200.00	25.0	78.20	21.33	16.0	6.89
18		0.30	595	1.00	4.75	550	0.8	3500	200.00	25.0	75.63	21.33	16.0	7.01
19		0.30	595	1.00	4.75	550	1	3500	200.00	25.0	71.87	21.33	16.0	7.93
20		0.30	595	1.00	4.75	550	1.2	3500	200.00	25.0	64.10	21.33	16.0	7.47
21		0.30	595	1.00	4.75	550	1.4	3500	200.00	25.0	54.97	21.33	16.0	7.34
22		0.45	545	1.00	4.75	1400	0.2	41000	120.00	25.0	49.73	21.33	16.0	6.11
23		0.45	545	1.00	4.75	1400	0.4	41000	120.00	25.0	55.43	21.33	16.0	6.82
24		0.45	545	1.00	4.75	1400	0.6	41000	120.00	25.0	57.53	21.33	16.0	7.64
25		0.45	545	1.00	4.75	1400	0.8	41000	120.00	25.0	67.73	21.33	16.0	8.03
26		0.45	545	1.00	4.75	1400	1	41000	120.00	25.0	66.10	21.33	16.0	7.96
27		0.45	545	1.00	4.75	1400	1.2	41000	120.00	25.0	65.87	21.33	16.0	7.85
28		0.45	545	1.00	4.75	1400	1.4	41000	120.00	25.0	63.83	21.33	16.0	6.98
29		0.45	545	1.00	4.75	550	0.2	3500	200.00	25.0	54.67	21.33	16.0	5.82
30		0.45	545	1.00	4.75	550	0.4	3500	200.00	25.0	55.87	21.33	16.0	6.30
31		0.45	545	1.00	4.75	550	0.6	3500	200.00	25.0	60.13	21.33	16.0	6.51
32		0.45	545	1.00	4.75	550	0.8	3500	200.00	25.0	55.30	21.33	16.0	6.93
33		0.45	545	1.00	4.75	550	1	3500	200.00	25.0	49.30	21.33	16.0	7.73
34		0.45	545	1.00	4.75	550	1.2	3500	200.00	25.0	41.47	21.33	16.0	7.35
35		0.45	545	1.00	4.75	550	1.4	3500	200.00	25.0	39.10	21.33	16.0	6.14
36		0.45	545	1.00	4.75	550	0.2	4800	608.97	25.0	53.67	21.33	16.0	7.04
37		0.45	545	1.00	4.75	550	0.4	4800	608.97	25.0	59.83	21.33	16.0	7.74
38		0.45	545	1.00	4.75	550	0.6	4800	608.97	25.0	65.60	21.33	16.0	7.77
39		0.45	545	1.00	4.75	550	0.8	4800	608.97	25.0	68.67	21.33	16.0	7.96
40		0.45	545	1.00	4.75	550	1	4800	608.97	25.0	62.80	21.33	16.0	7.52
41		0.45	545	1.00	4.75	550	1.2	4800	608.97	25.0	59.23	21.33	16.0	7.12
42		0.45	545	1.00	4.75	550	1.4	4800	608.97	25.0	53.80	21.33	16.0	6.87

4.3.1. Multiple Linear Regression (MLR) Model

Multiple Linear Regression (MLR) analysis was applied to the combined dataset of 82 mixes to establish relationships between input parameters (X1–X12) and flexural strength (FS). Table 4.5 summarizes the regression statistics, ANOVA results, and coefficients of the model, providing insights into the significance and contribution of each variable to FS prediction.

Table 4.5. Multiple Regression (MLR) Summary for Flexural Strength Prediction (FS)

Regression Statistics	
Multiple R	0.82567506
R Square	0.681739304
Adjusted R Square	0.626389618
Standard Error	1.026482991
Observations	82

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	-5.6099586	2.948	-1.903	0.061	-11.492	0.272	-11.492	0.272
X1	-4.549942	2.844	-1.600	0.114	-10.223	1.123	-10.223	1.123
X2	-0.0044103	0.001	-3.520	0.001	-0.007	-0.002	-0.007	-0.002
X3	10.9469945	1.631	6.710	0.000	7.692	14.202	7.692	14.202
X4	0.009095	0.083	0.110	0.913	-0.156	0.174	-0.156	0.174
X5	0.00764689	0.002	3.335	0.001	0.003	0.012	0.003	0.012
X6	0.06683265	0.198	0.338	0.737	-0.328	0.462	-0.328	0.462
X7	-0.0001572	0.000	-2.786	0.007	0.000	0.000	0.000	0.000
X8	0.00248128	0.001	3.245	0.002	0.001	0.004	0.001	0.004
X9	0.01305091	0.007	1.774	0.080	-0.002	0.028	-0.002	0.028
X10	0.01058967	0.016	0.675	0.502	-0.021	0.042	-0.021	0.042
X11	0.00216542	0.002	0.947	0.347	-0.002	0.007	-0.002	0.007
X12	0.04642998	0.018	2.591	0.012	0.011	0.082	0.011	0.082

The final regression equation for predicting FS is:

$$FS = - 5.610 - 4.550X_1 - 0.00441X_2 + 10.947X_3 + 0.0091X_4 + 0.00765X_5 + 0.0668X_6 - 0.00016X_7 + 0.00248X_8 + 0.0131X_9 + 0.0106X_{10} + 0.00217X_{11} + 0.0464X_{12}$$

4.3.2. Gene Expression Programming (GEP) Model

Gene Expression Programming (GEP) was applied to develop predictive models for flexural strength (FS) using different functions, gene sizes, and variable combinations. Among the tested models, Model 3 achieved the best performance with an R^2 of 0.90 for training and 0.74 for validation, confirming the strong predictive capability of GEP compared to MLR. The details of the tested models are presented in Table 4.6, and the constants of the selected Model 3 are given in Table 4.7.

Table 4.6. Performance Metrics of GEP Model for Flexural Strength Prediction

No	Function	No. of Genes	Generation	Used Variables	Training		Validation	
					R ²	MAPE	R ²	MAPE
1	$+,-,*,/$	5	182160	X1(1), X2(1), X3(3), X4(4), X6(3), X8(4), X9(1), X10(4), X11(4)	0.79	8.76	0.70	16.87
2	$+,-,*,/$	6	161898	X1(3), X2(5), X3(8), X4(1), X5(2), X6(3), X7(6), X8(3), X9(2), X10(1), X11(1)	0.84	7.23	0.81	14.60
3	$+,-,*,/$	7	205476	X1(3), X2(2), X3(3), X4(9), X5(1), X6(5), X7(1), X8(2), X9(2), X10(2), X11(3), X12(3)	0.90	5.57	0.74	13.19
4	$+,-,*,/$	8	122429	X1(1), X2(3), X3(3), X4(5), X5(5), X6(8), X7(1), X8(2), X10(2), X11(5), X12(4)	0.87	6.18	0.72	12.60
5	$+,-,*,/, \exp, \text{Sqrt}$	5	364716	X1(1), X2(2), X3(3), X4(2), X5(2), X6(3), X7(1), X8(5), X9(5), X10(2), X12(3)	0.85	6.57	0.72	14.61
6	$+,-,*,/, \exp, \text{Sqrt}$	7	242218	X1(6), X2(1), X3(2), X4(3), X5(2), X6(6), X7(3), X8(2), X9(1), X10(2), X11(5), X12(1)	0.83	7.06	0.69	16.13
7	$+,-,*,/, \exp, \text{Sqrt}$	8	278710	X1(4), X2(2), X3(4), X4(3), X5(2), X6(5), X7(1), X8(1), X9(2), X10(2), X11(10), X12(2)	0.81	7.31	0.73	16.43
8	$+,-,*,/, \exp, \text{Sqrt}, x_2, \text{Sin}, \text{Cos}, \text{Tan}$	5	43448	X2(3), X3(1), X5(2), X7(2), X8(1), X9(1), X10(3), X11(1), X12(2)	0.81	7.25	0.72	16.11
9	$+,-,*,/, \exp, \text{Sqrt}, x_2, x_3, \text{Sin}, \text{Cos}, \text{Tan}, \text{Log}, \text{Cot}, \text{Sinh}, \text{Cosh}$	7	321068	X1(5), X2(4), X3(5), X4(4), X5(1), X6(2), X7(4), X8(1), X10(2), X11(1), X12(1)	0.89	8.23	0.75	13.29
10	$+,-,*,/, \exp, \text{Sqrt}, x_2, x_3, \text{Sin}, \text{Cos}, \text{Tan}, \text{Log}, \text{Cot}, \text{Sinh}, \text{Cosh}$	8	305082	X1(2), X3(3), X4(4), X6(1), X8(2), X10(1), X11(4), X12(1)	0.82	7.89	0.74	16.69

Table 4.7. Constants (c_0 – c_9) of GEP Genes Used in Model 3 for Flexural Strength Prediction

Gene	c0	c1	c2	c3	c4	c5	c6	c7	c8	c9
Gene 1	-2.0550	9.9707	-3.6198	5.4581	-4.1465	-5.5162	-5.0708	-8.3853	5.9028	-8.9349
Gene 2	-5.0570	-5.9221	1.4109	-5.6959	8.2217	-3.9282	-2.5474	3.2392	-6.9628	6.7547
Gene 3	-5.8097	-59.9322	-5.1505	-7.3028	-0.9881	-2.8855	9.9207	5.0993	-7.7651	-5.0247
Gene 4	-3.9092	7.0130	2.5248	-3.1188	-3.0034	9.4354	-2.6105	-3.5728	-1.4923	-7.0933
Gene 5	0.0009	-8.3018	-0.6308	-2.5242	-0.3702	5.4649	7.8668	0.1067	-6.8720	-6.0887
Gene 6	-9.0393	-2.9310	-2.4200	659.8894	9.3270	-5.7097	3.9463	-1.1201	7.4697	5.3279
Gene 7	6.2682	-2.4284	5.3843	-7.8173	-0.4575	-11.0313	-9.1504	-8.1272	7.1774	5.6169

The constants assigned to each gene of Model 3 are listed in Table 4.7. The final predictive function is obtained by summing seven expression trees (ET1–ET7):

$$FS = ET1 + ET2 + ET3 + ET4 + ET5 + ET6 + ET7$$

Sub-ET 1

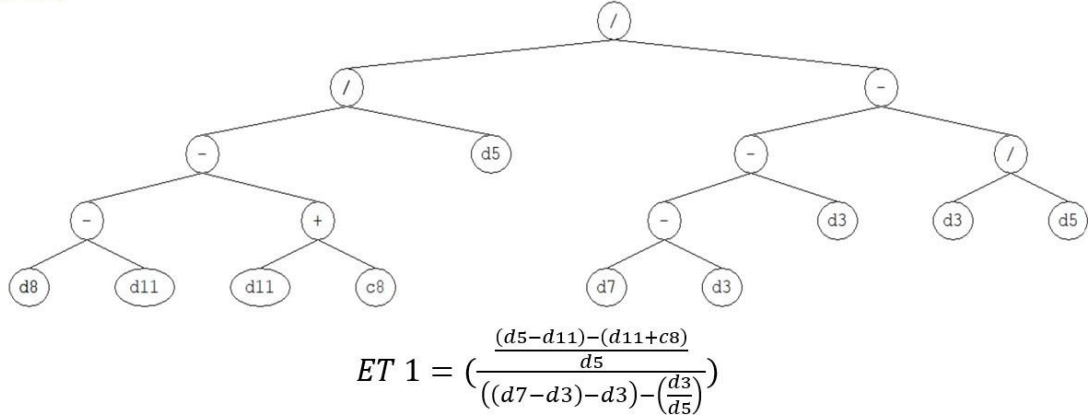


Figure 4.1. Sub ET1

Sub-ET 2

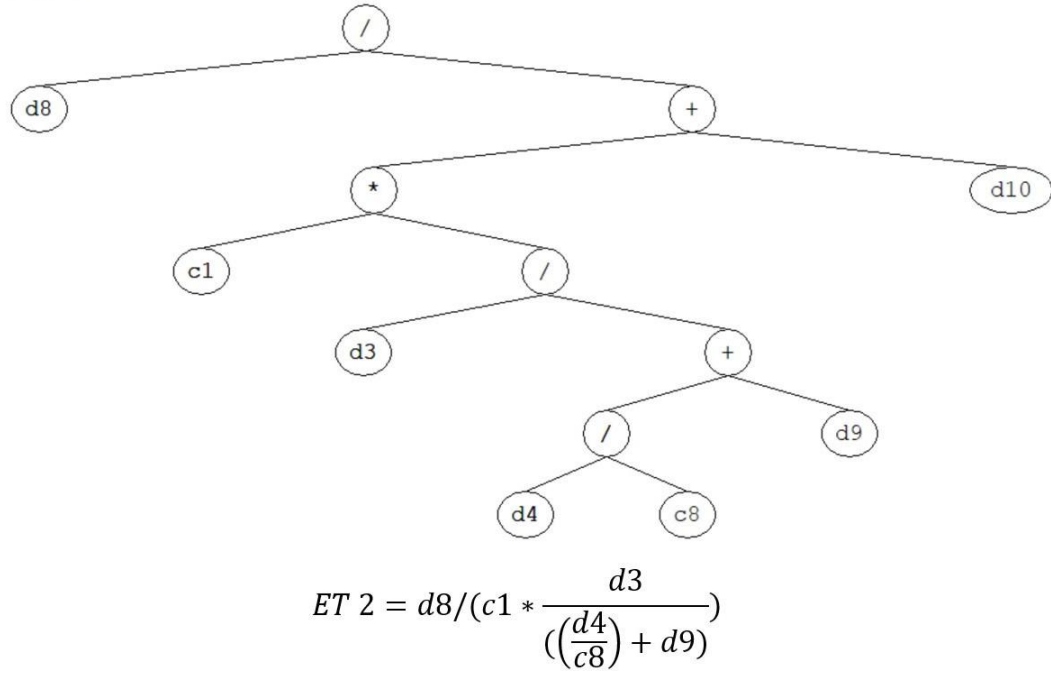
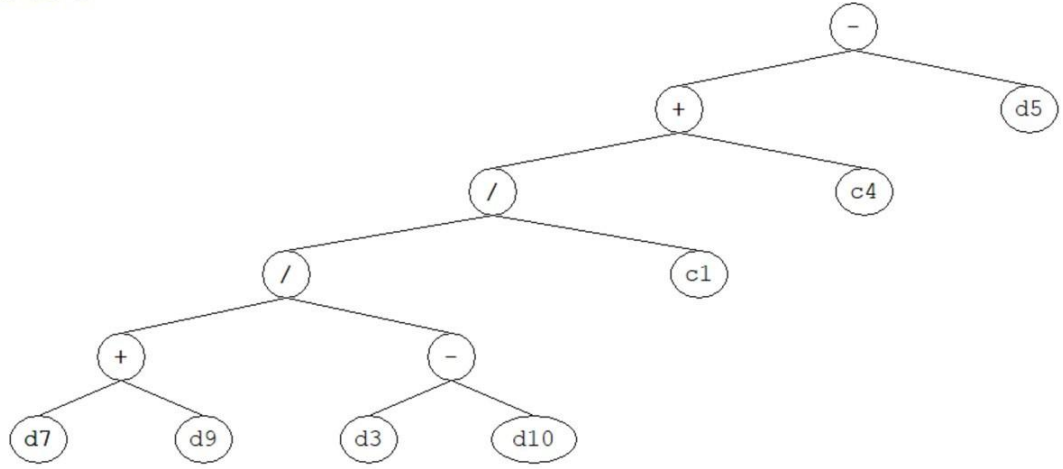


Figure 4.2. Sub ET2

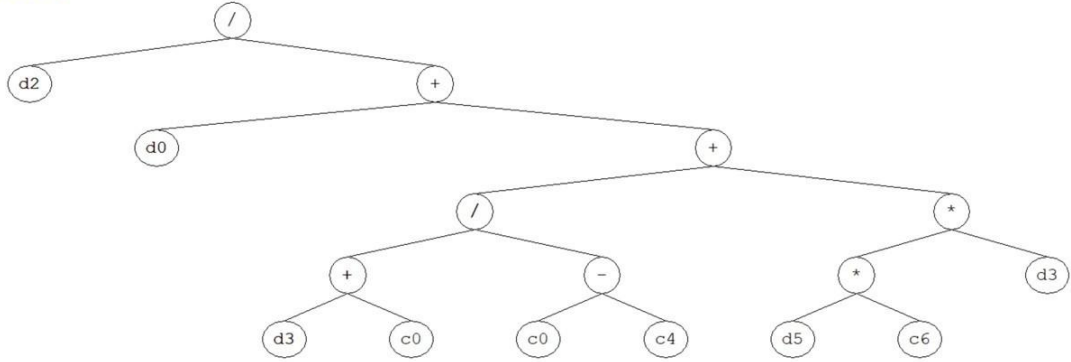
Sub-ET 3



$$ET\ 3 = \left(\left(\left(\frac{d7 + d9}{\frac{d3 - d10}{c1}} \right) + c4 \right) - d5 \right)$$

Figure 4.3. Sub ET3

Sub-ET 4



$$ET\ 4 = d2 / (d0 + \left(\left(\frac{d3 + c0}{c0 - c4} \right) + (d5 * c6) * c3 \right))$$

Figure 4.4. Sub ET4

Sub-ET 5

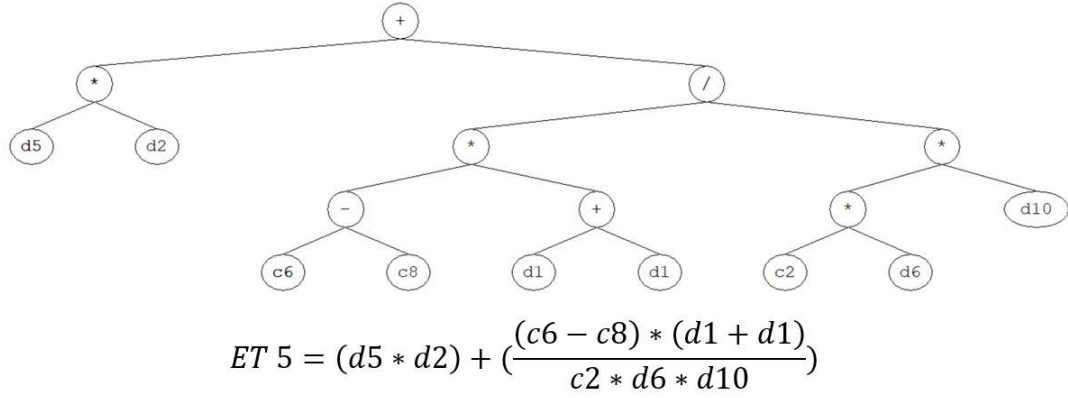
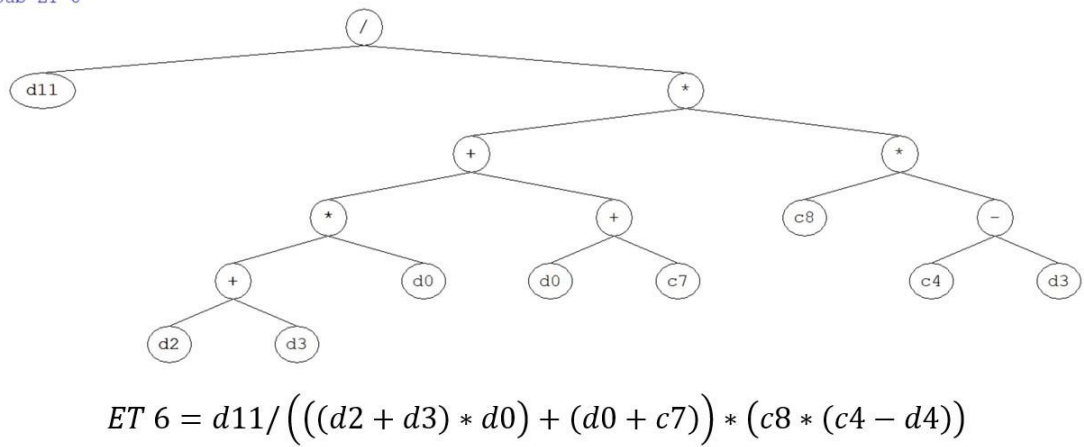


Figure 4.5. Sub ET5

Sub-ET 6



Sub-ET 7



$$ET\ 7 = c8$$

Figure 4.6. Sub ET6&7

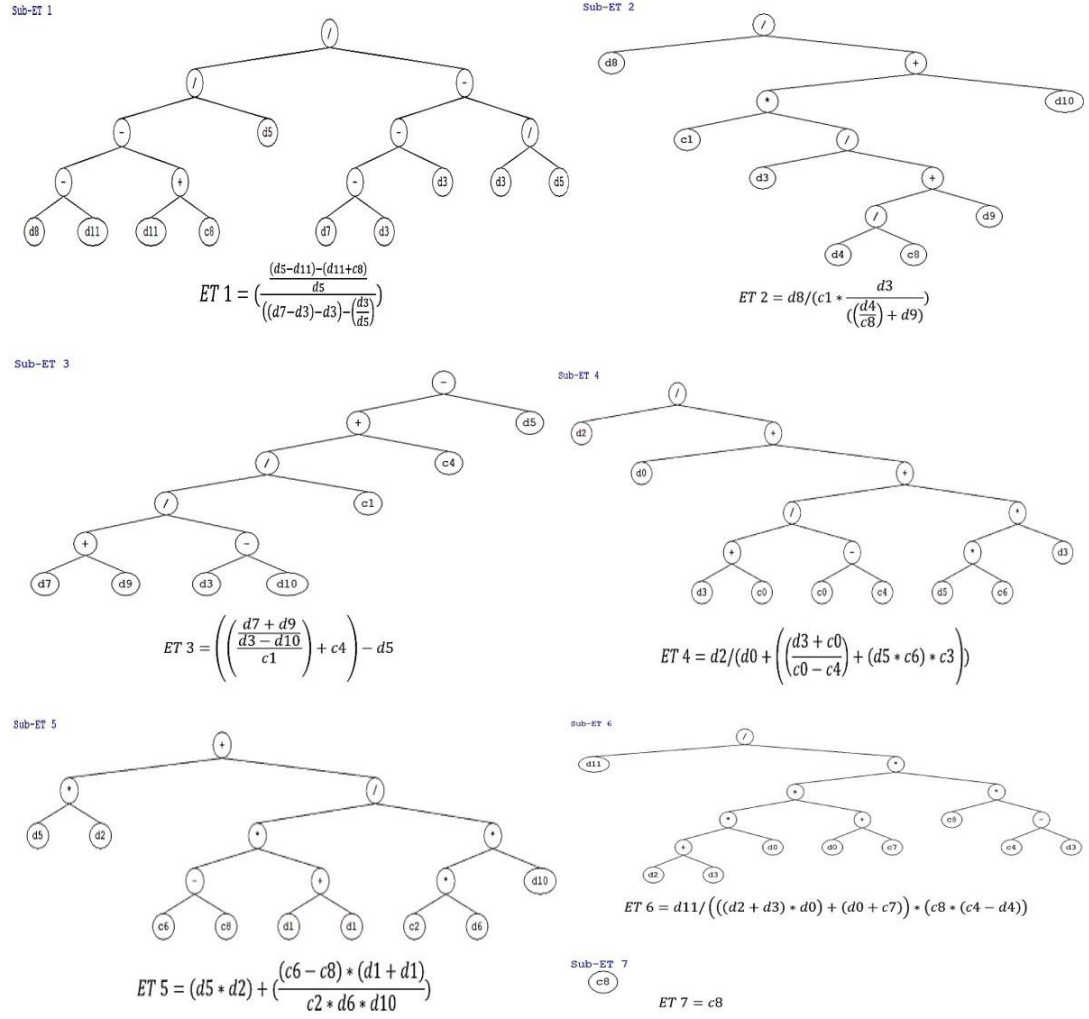


Figure 4.7. Expression Tree of GEP Model No. 3

5. DISCUSSION

5.1. Mechanical Properties

The water cement (W/C) ratio plays a critical role in determining the mechanical and physical properties of fiber-reinforced cementitious composites. From Experimental results (Figures 4.1 & 4.2) that the two ratios tested (0.3 and 0.45)%, it was clear that the lower W/C ratio of 0.3% consistently led to better mechanical results than W/C ratio of 0.45.

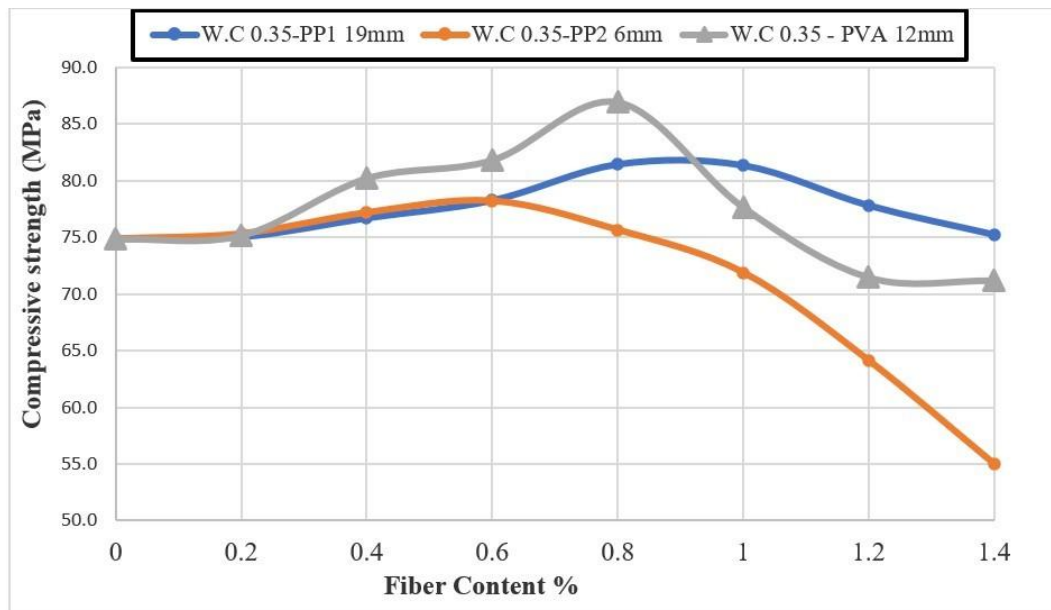


Figure 5.1. Compressive strength at W/C = 0.35

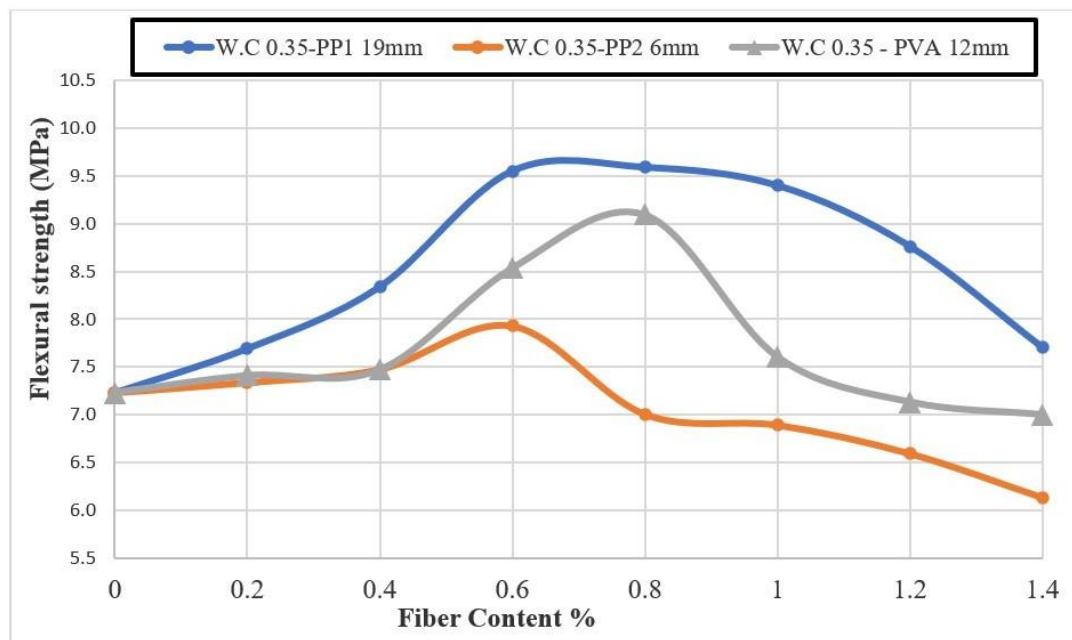


Figure 5.2. Flexural strength at W/C = 0.35

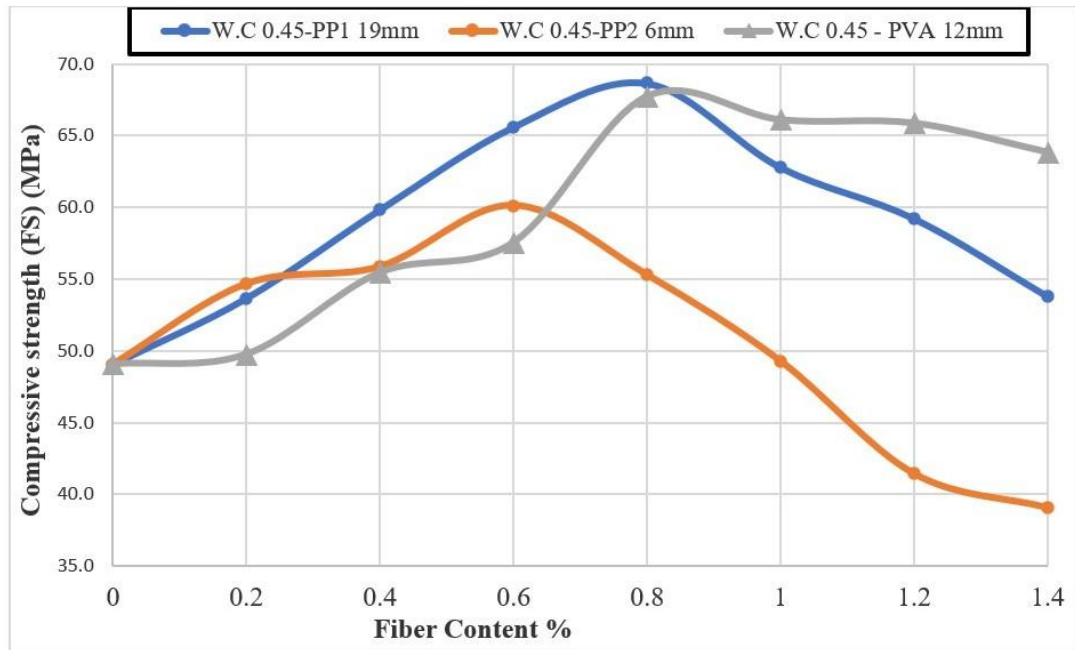


Figure 5.3. Compressive strength at W/C = 0.45

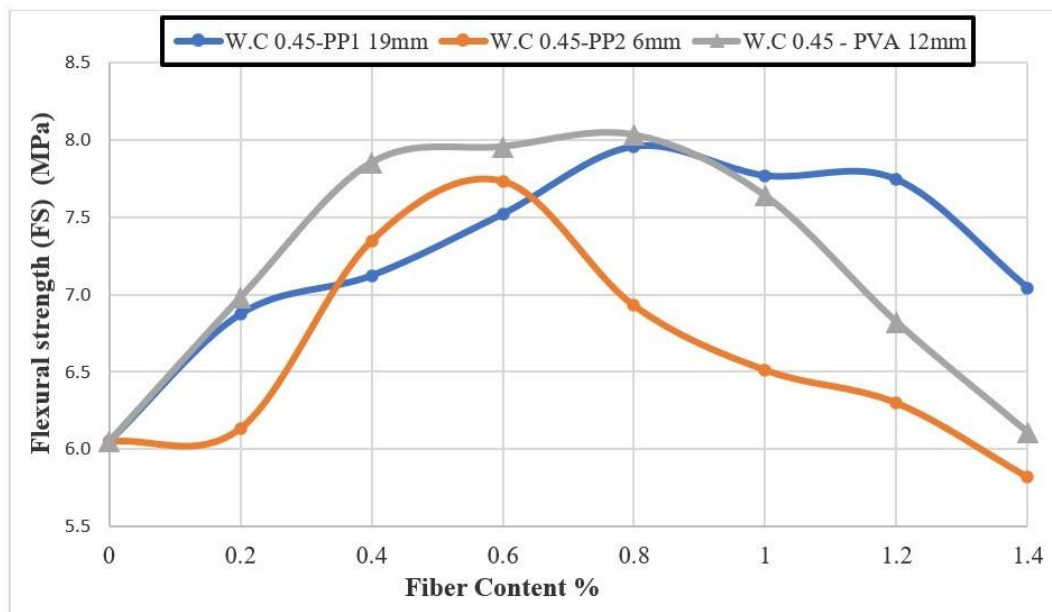
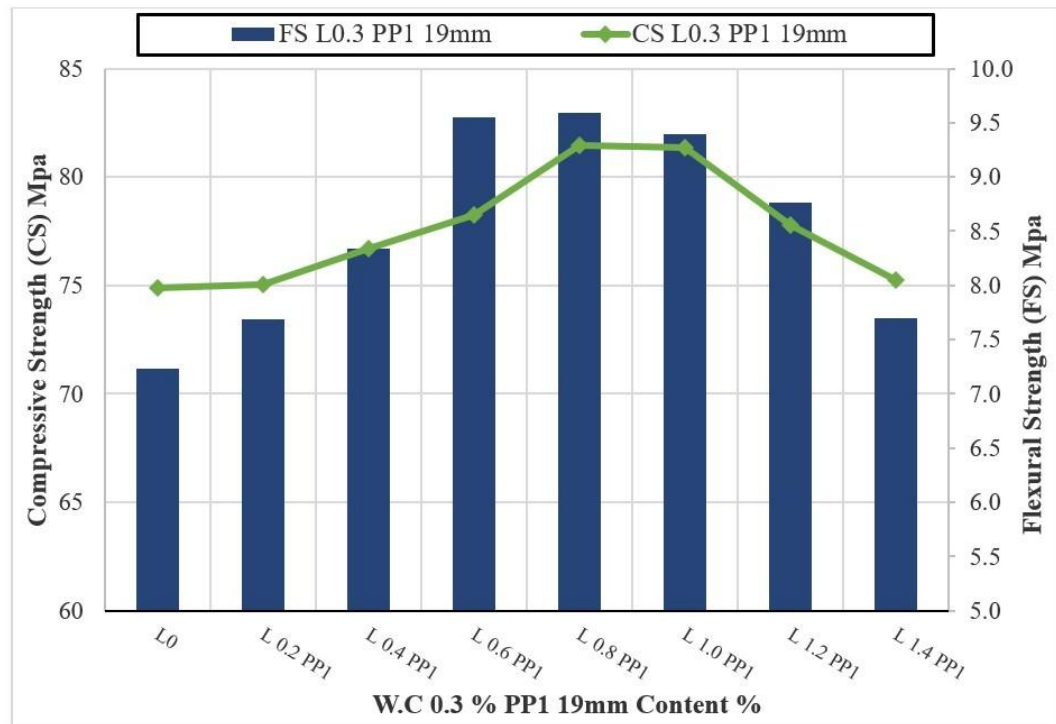
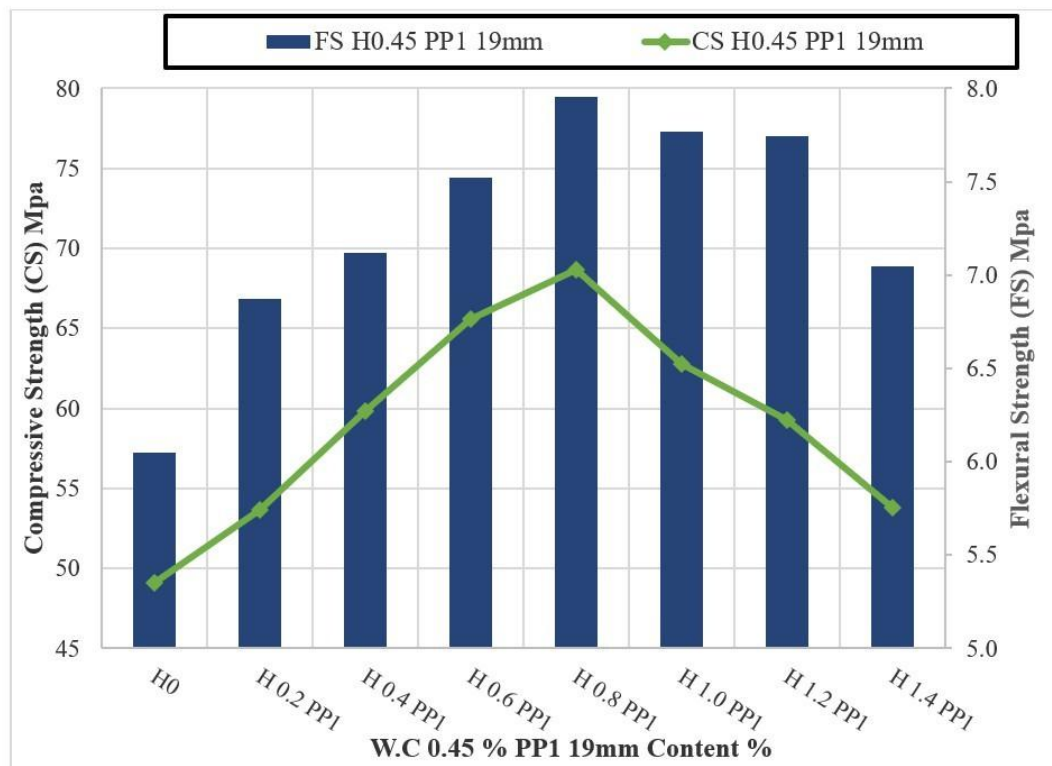


Figure 5.4. Flexural strength at W/C = 0.45



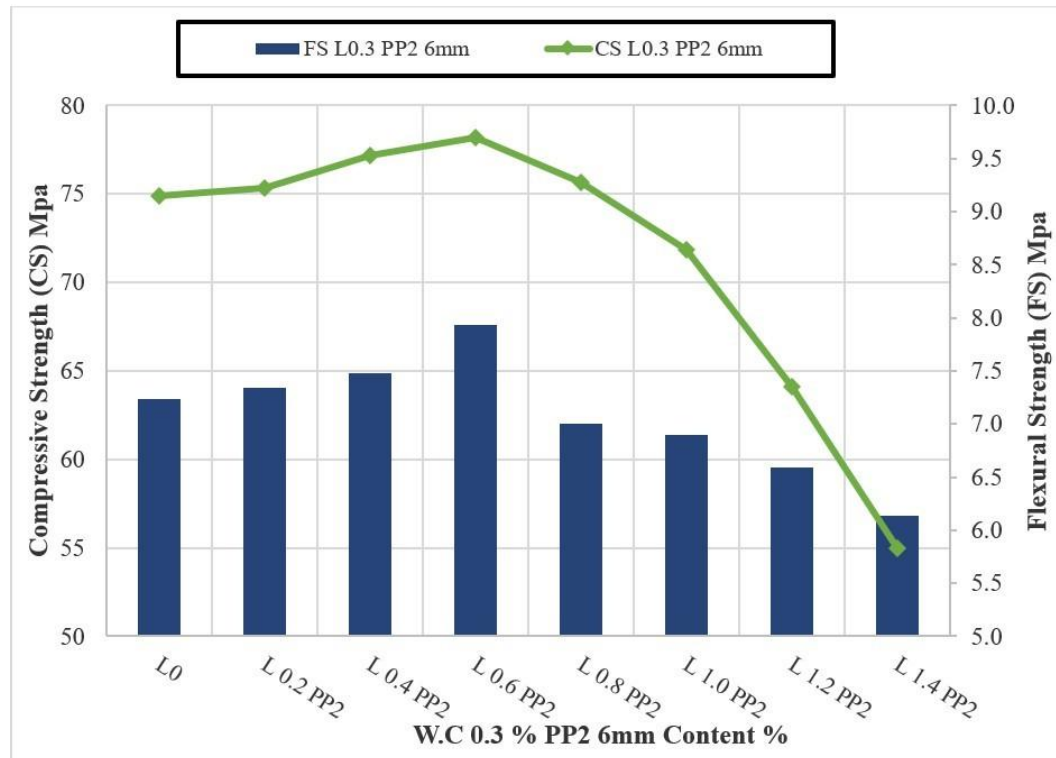
(a)

Figure 5.5. Compressive vs Flexural strength for 0.3 % W.C for PP1 19mm



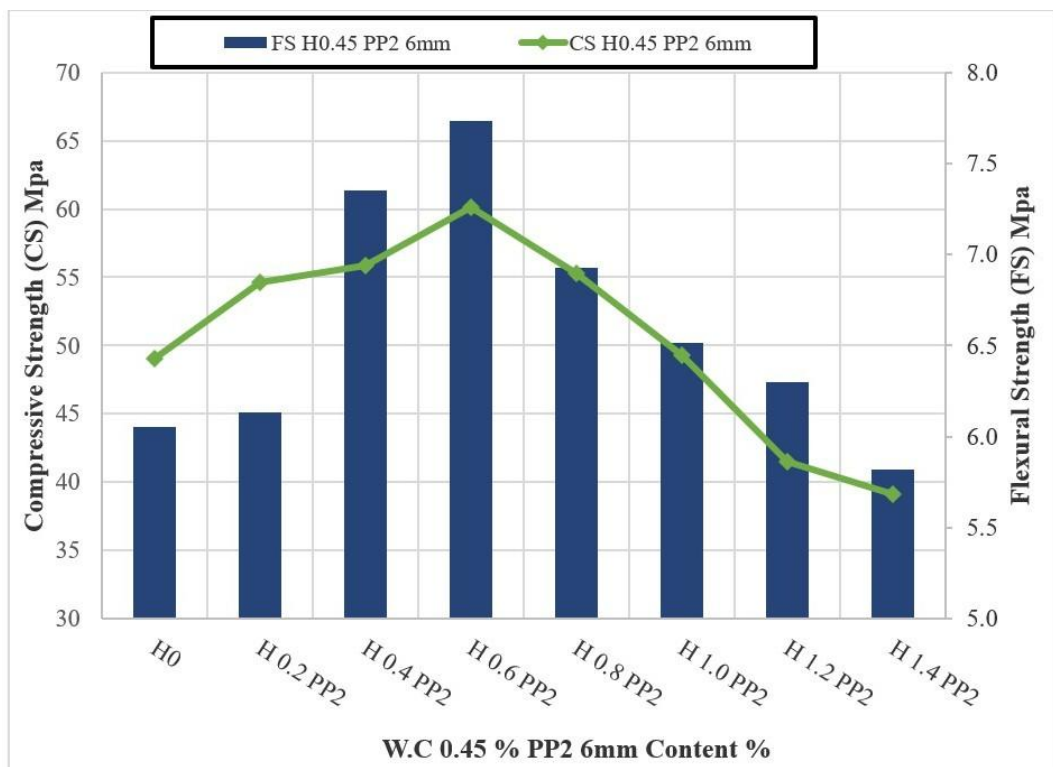
(b)

Figure 5.6. Compressive vs Flexural strength for 0.45 % W.C for PP1 19 mm



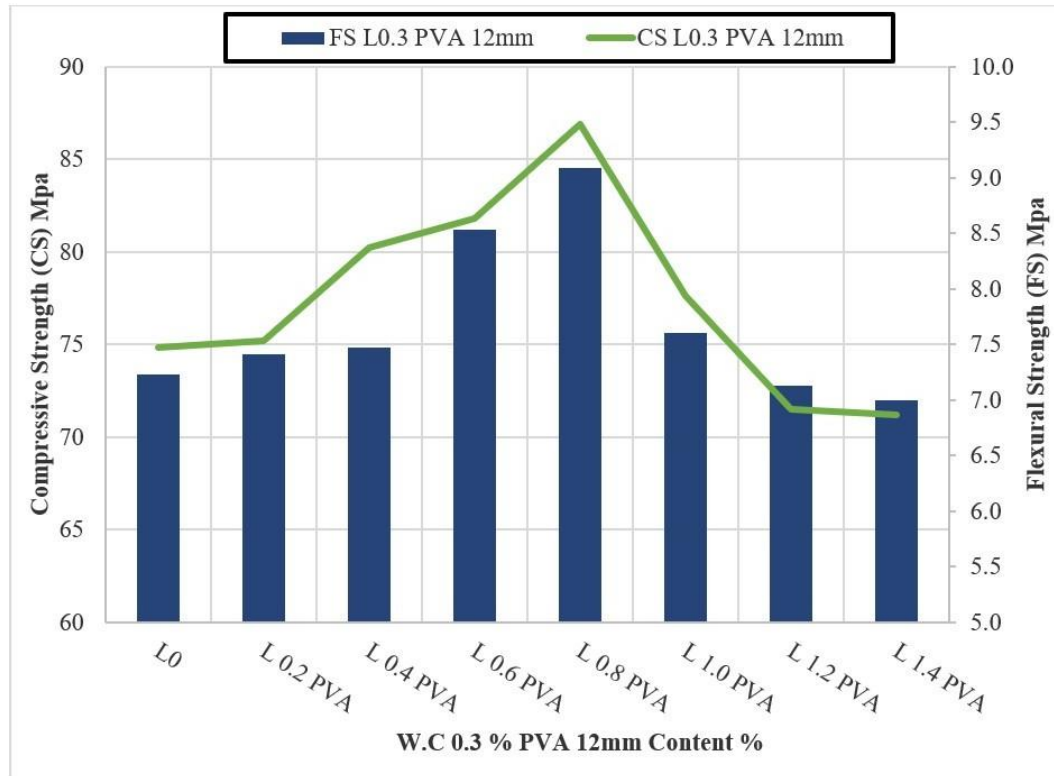
(c)

Figure 5.7. Compressive vs Flexural strength for 0.3 % W.C for PP2 6mm



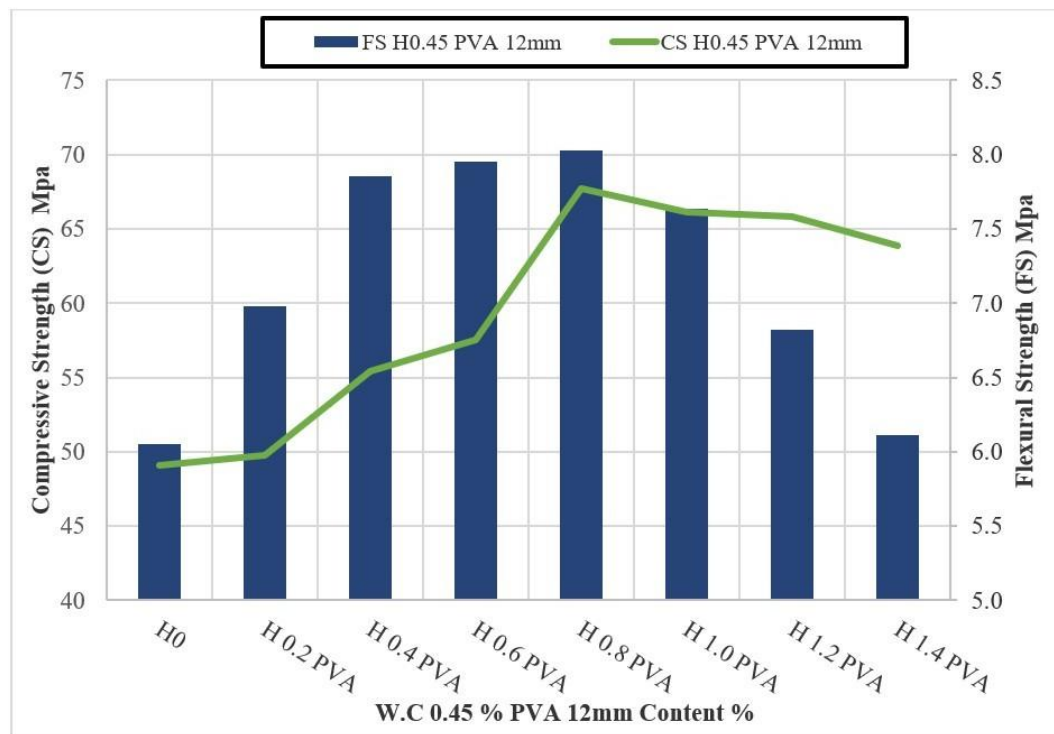
(d)

Figure 5.8. Compressive vs Flexural strength for 0.45 % W.C for PP2 6mm



(e)

Figure 5.9. Compressive vs Flexural strength for 0.3 % W.C for PVA 12 mm



(f)

Figure 5.10. Compressive vs Flexural strength for 0.45 % W.C for PVA 12 mm

At a 0.3%, (W/C) ratio, the specimens achieved higher compressive strengths (CS), ranging from (71.20 MPa to 86.90 MPa) , and flexural strengths (FS) reaching up to 9.59 MPa. These improvements are attributed to the denser internal structure of the mixes, with fewer pores and stronger bonding between structure particles. As a result, the structure was better able to carry loads and resist cracking.

Conversely, mixes with a 0.45% (W/C) ratio showed lower strengths. Compressive strength (CS) dropped to as low as 39.10 MPa, and flexural strengths (FS) peaked at just 8.03 MPa. This decline is likely due to the increased more voids into the structure, resulting in weaker internal cohesion and poorer load transfer.

While the mixes with 0.45% (W/C) showed slightly better workability and showing slightly greater flow values by (about 1 to 2 cm). These results give us the importance of maintaining a low water content when aiming to achieve high strength and durable cementitious composites.

Moreover, PVA-reinforced composites were found to be more sensitive to changes in the W/C ratio. Their strength dropped more noticeably at a 0.45 W/C ratio, especially when higher fiber dosages were used. As we noted that PP1 and PP2 mixes also showed reductions while the hydrophobic nature of polypropylene helped to slightly reduce the negative impact of excess water.

In Parallel with these results of above, the predictive modeling supported these experimental findings. Gene Expression Programming (GEP) consistently showed that the W/C ratio (X_1) as one of the most influential parameters. The reduction in model accuracy reflected by increased MAPE values in Multiple Linear Regression (MLR) models at higher W/C ratios further reinforces the detrimental effect of excess water on performance.

5.2. Effect of Fiber Content

Fiber content had a clear and measurable impact on the mechanical performance of the cementitious composites studied. As shown in (Figures 5.1 to 5.4), increasing the amount of polymeric fibers whether polypropylene (PP1, PP2) or polyvinyl alcohol (PVA) generally led to higher flexural strength, particularly in the range of 0.6% to 1.0% fiber volume.

At low fiber dosages (0.2–0.6) %, both PP and PVA fibers improved the FS of the mixes. This enhancement can be attributed to the fibers' ability to bridge

microcracks, delay crack propagation, and distribute tensile stresses across the cement matrix. PVA fibers proved more effective because of their higher tensile strength and better bonding with the cement matrix.

For example, the FS peaked at 9.09 MPa in a mix containing 0.8% PVA at a W/C ratio of 0.30 %, while PP1 reached a slightly higher value of 9.55 MPa at a fiber content of 1.0% (see Figures 3.5 and 3.6).

Overall, the optimal fiber content range was found between (0.6 to 1.0) %, where FS was maximized without minimal impact on CS. These findings show the importance of selecting an appropriate fiber dosage % in enhancing tensile and flexural behavior.

However, when the fiber content exceeded 1.0%, some mixes began to show a decline in mechanical performance particularly in CS. At 1.2% and 1.4%, CS dropped noticeably, and FS gains plateaued or even declined slightly. This behavior is likely due to poor fiber dispersion, clumping, and increased entrapped air, all of which reduce the overall integrity of the cement matrix. For detail, the CS dropped to 54.97 MPa for PP2 and to 71.20 MPa for PVA at 1.4% fiber content, despite FS values remaining relatively stable.

For the mixes, the PP2 mixes showed more stable behavior across different dosages but they reached lower peak FS compared to (PP1 & PVA) and the best performance for PP2 was observed at 1.0% fiber volume where the FS reaching 7.93 MPa. While PP2 fibers contributed to crack control, their shorter and stiffer nature may have limited their bridging capacity when compared with the longer PVA and PP1 fibers.

In addition to strength, the post-cracking response also varied with fiber content. Mixes with containing moderate fiber volumes (0.6–1.0) % showed better toughness and energy absorption after peak load, while those which higher volumes led to premature failure due to poor matrix continuity.

These findings were also supported by the GEP modeling results. Fiber content (X_6) consistently appeared as one of the most important input variables in the top performing models. Its role was less linear and more complex, which the GEP approach was able to capture effectively and the MLR models showed reduced accuracy at high fiber volumes, this indicating that linear models struggle to account for the diminishing returns or negative effects of excessive fiber addition.

In summary above tell us that both the experimental and modeling results confirm that fiber content is a critical factor in enhancing the flexural performance of cementitious composites. The best effective range was found between (0.6 to 1.0) % offered the best balance between strength and workability. Higher dosages may seem beneficial in theory but often lead to complications during mixing and a decline in performance due to poor fiber dispersion. Selecting the right fiber content is therefore essential to achieving both mechanical efficiency and practical workability in real-world applications.

In summary, both the experimental and modeling results highlight fiber content as a key factor in improving the flexural behavior of cementitious composites. The most effective range was found between 0.6% and 1.0%, where strength and workability were balanced. Although higher dosages may appear advantageous, in practice they often create difficulties during mixing and reduce performance because of poor fiber dispersion. Choosing the proper fiber content is therefore crucial for achieving mechanical efficiency while maintaining workable mixes in real-world applications.

5.3. Comparison of polypropylene (PP) and polyvinyl alcohol (PVA) Fibers

The comparative evaluation of PP and PVA fibers showed notable differences in how each fiber type affected the mechanical performance of fiber-reinforced cementitious composites. While both fiber types contributed to improved flexural strength (FS) compared to plain mixes, the magnitude and consistency of these improvements depended on (fiber geometry, dosage, and bonding characteristics) with the cementitious matrix (see Figure 5.5 to 5.10).

PVA fibers demonstrated superior performance under most test conditions, especially at intermediate dosages between (0.6 to 1.0) %. As focused, at a W/C ratio of 0.3, the FS reached at 9.09 MPa for a mix containing 0.8% PVA fiber, outperforming all mixes of PP based. This improvement can be attributed to the high tensile of PVA, hydrophilic surface, and strong chemical bond with the cement matrix.

The improved fiber-matrix interaction led to enhanced crack control, distributed cracking, and increased energy absorption, these making that PVA an excellent choice for applications requiring both strength and toughness.

In contrast, PP fibers used in two sizes (PP1 and PP2), also improved the mechanical performance of the composites, though to a lesser extent. The longer, fibrillated PP1 fibers showed better performance than PP2, with a maximum FS of 9.59 MPa at 1.0% dosage under a W/C ratio of 0.3. These fibers effectively bridged larger cracks and contributed to post-cracking load resistance. However, due to have their hydrophobic nature and relatively low modulus of PP fibers limited and weaker their bonds with the cement matrix, which reduced their efficiency under high-stress conditions.

PP2 fibers, being shorter and stiffer, showed relatively consistent but lower flexural performance, with reaching at 7.93 MPa at 1.0% dosage due to their reduced aspect ratio and limited crack-bridging ability likely explain this performance difference. At the same time, the PP fibers generally showed better workability in fresh mixes, especially at higher dosages which is beneficial in large-scale applications where ease of mixing and placement is a critical consideration.

Workability differences between fiber types were also observed. PVA mixes required more careful mixing since they tended to fiber clump together and make them reduce flowability, especially at fiber content above 1.0%. In contrast, for PP mixes, particularly those containing PP2 had maintained better flow characteristics and made them easier to manage in practical applications. However, when fiber dosages exceeded 1%, both fiber types (PVA and PP) mixes showed reduced workability which affecting fiber dispersion and the overall uniformity of the composite. when dosages exceeded 1.0%, affecting fiber dispersion and the overall uniformity of the composite.

The blends of PVA fibers tended to keep a little better flow and density than PP1 when it came to workability and unit weight. PP2, on the other hand, showed the biggest drops. These differences indicate how fiber shape and interaction with the cement matrix affect the results. The smoother dispersion of PVA fibers helped to lessen its negative effect on flow, whereas the coarser texture of PP1 fibers increased internal friction, making it harder to work with but stronger in bending.

In terms of workability and unit weight, the mixes of PVA fibers tended to maintain slightly better flow and density compared to PP1, while PP2 showed the most noticeable reductions which these differences reflect the influence of fiber geometry and interaction with the cement matrix. The smoother dispersion of PVA fibers helped to reduce its negative impact on flow and PP1 fibers rougher texture increases internal friction, leading to lower workability but greater flexural resistance.

In conclusion, while both PP and PVA fibers enhanced the mechanical performance of cementitious composites, PVA fibers provided superior flexural strength, ductility, and durability. Their effectiveness was most evident in the (0.6–0.8) % dosage range under low W/C ratios. PP fibers, on the other hand, offered benefits in terms of cost and workability, making them suitable for non-structural or moderate-performance applications. The selection between these fibers should be based on the specific structural requirements, budget constraints, and practical considerations such as mixability and placement conditions.

5.4. Modeling Discussion

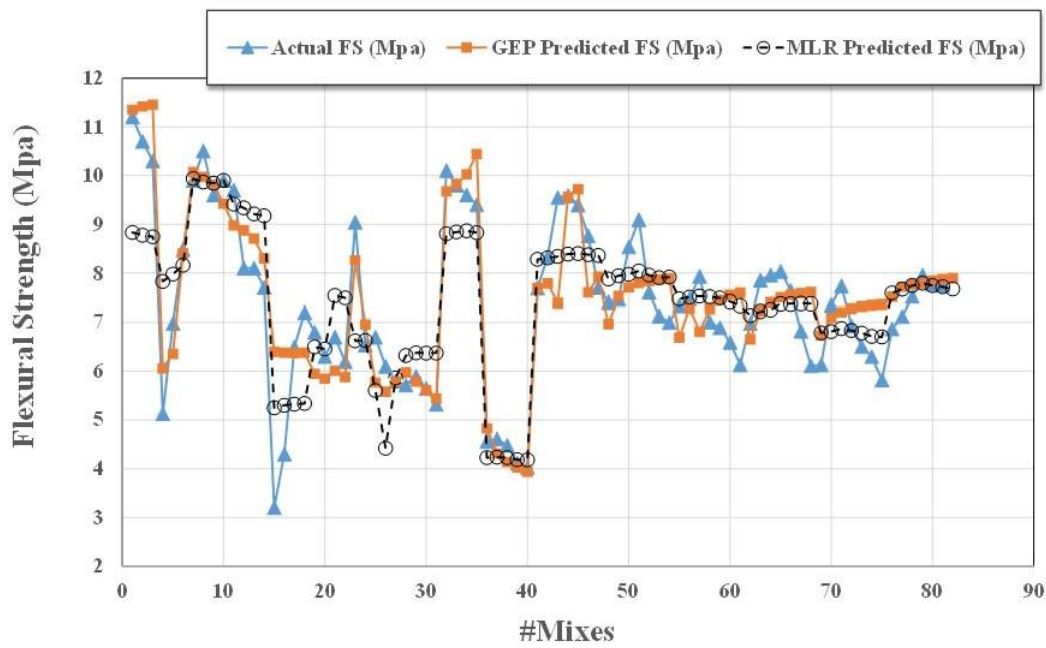


Figure 5.11. Actual vs Predicted FS for GEP and MLR Models (W/B = 0.3–0.45%)

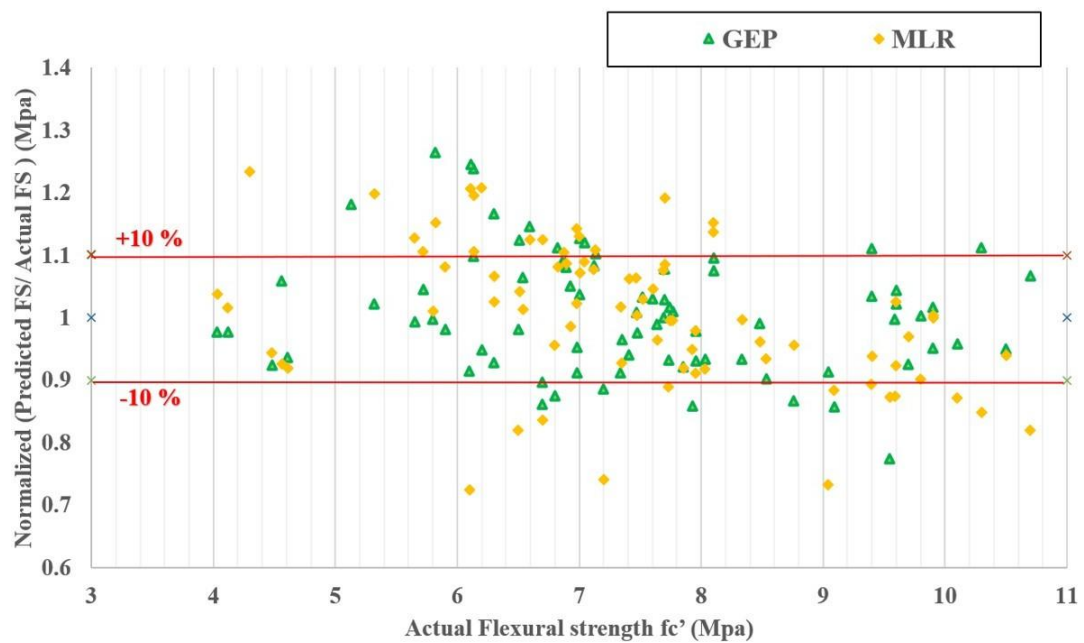


Figure 5.12. Comparison of Normalized Predicted to Actual Flexural Strength (FS)

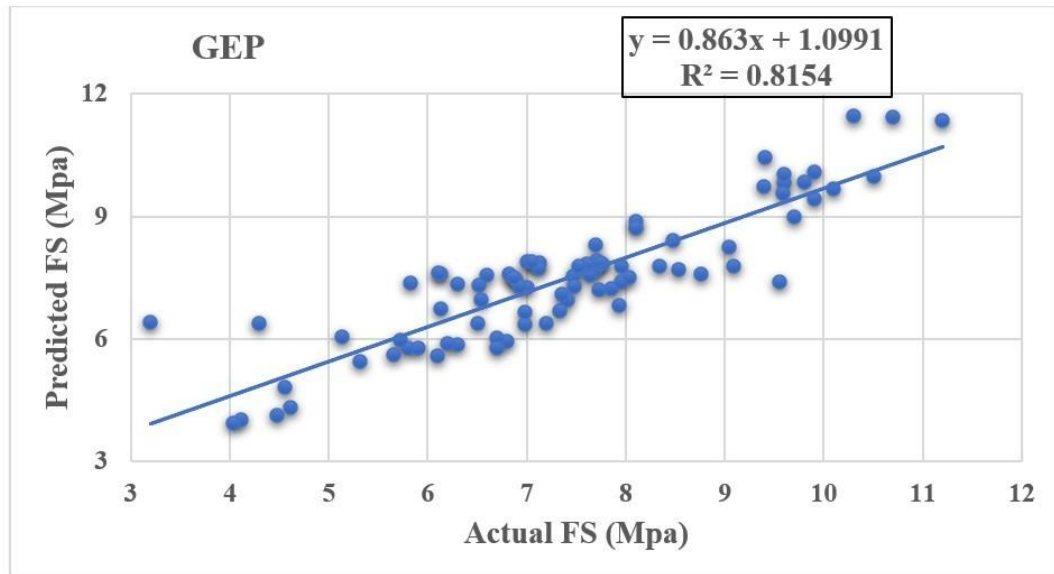


Figure 5.13. Regression Plot for GEP Models

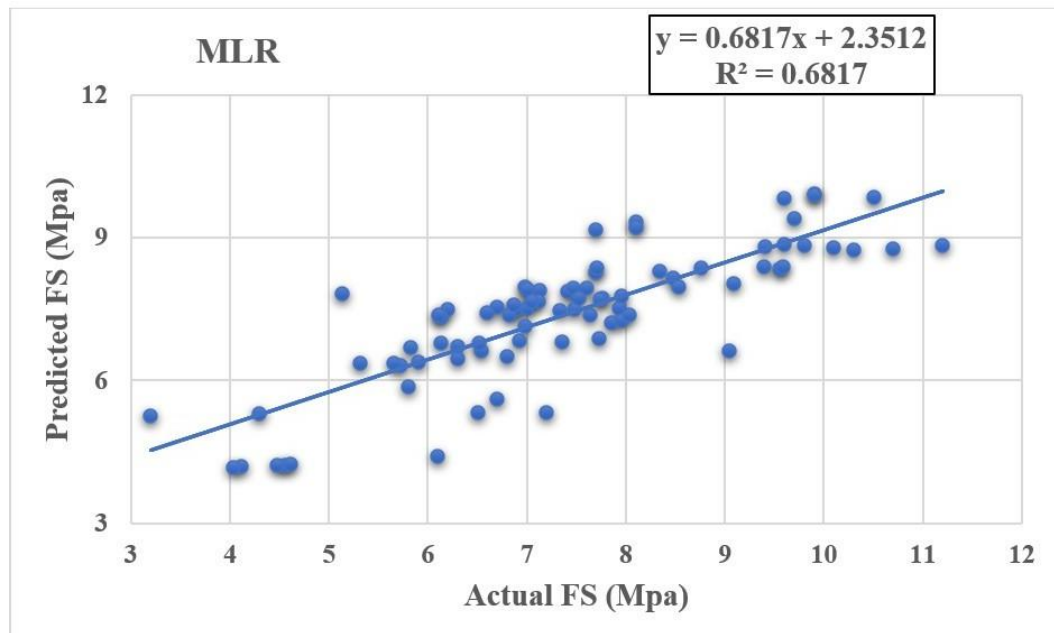


Figure 5.14. Regression Plot for MLR Models

The GEP model proved particularly effective in capturing the nonlinear and complex interactions between variables. The best performing GEP model utilized eight genes, integrating a broad function set including basic arithmetic operations, square roots, logarithmic, and exponential functions. This configuration achieved a coefficient of determination (R^2) of 0.90 for the training dataset and 0.74 for the validation set, indicating strong predictive capacity and generalizability (see Table 4.6 and Figures 5.11, 5.12 & 5.13) with MAPE values of 5.57% and 13.19%, respectively demonstrating strong predictive capacity and reliability across the dataset.

The symbolic output of the model consistently highlighted the dominant influence of the W/C ratio (X_1) and fiber content (X_6) across multiple genes, affirming their critical role in determining mechanical performance. Notably, the model also identified significant nonlinear relationships, especially when fiber content exceeded 1.0%, where strength gains began to plateau or decline.

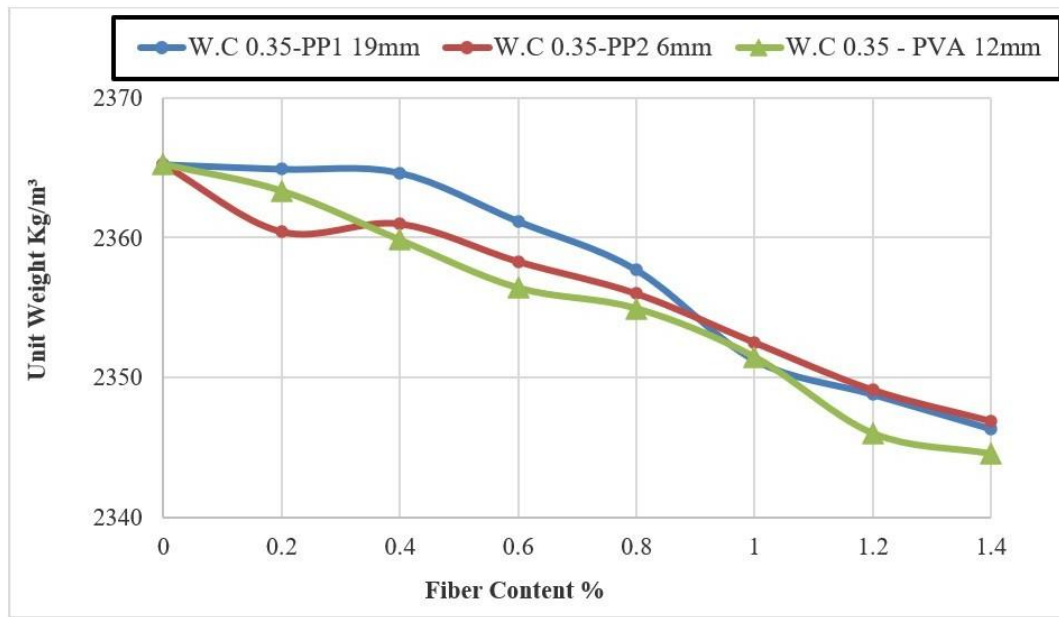
In comparison, the MLR model, although simpler and faster to compute, yielded lower predictive performance. It achieved (see Table 4.5 & Figure 5.14) a training R^2 of 0.68 and a validation R^2 of 0.52, with noticeably higher MAPE values. MLR was particularly ineffective at the extremes of the dataset. The discrepancy between predicted and actual FS values was especially noticeable for mixes with high PVA fiber content or low W/C ratios, where nonlinear behavior dominates.

Additionally, residual analysis for both models confirmed that GEP provided a more balanced prediction range with minimal overfitting. Residuals in the GEP model were symmetrically distributed around zero, while the MLR model exhibited a tendency to underpredict high-strength mixes and overpredict low-strength ones.

As illustrated in Figure 5.12 (Normalized Prediction vs. Actual FS), most GEP predictions fell within a $\pm 10\%$ error range, while MLR exhibited more scatter and several outliers. This clearly demonstrates that GEP, with its evolutionary symbolic regression capabilities, outperforms linear models for modeling the behavior of fiber-reinforced cementitious composites.

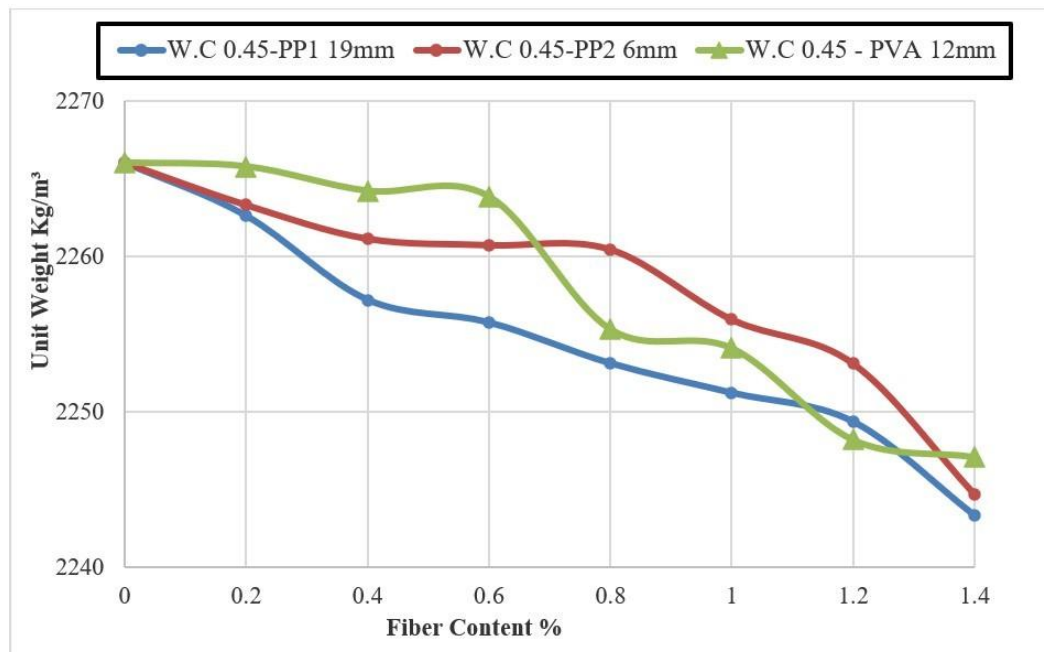
In conclusion, predictive modeling, especially using GEP, proved to be a powerful tool for flexural strength estimation in polymeric fiber-reinforced composites. These models not only support experimental observations but also offer engineers a data driven framework for optimizing mix designs with greater efficiency and confidence.

5.5. Effect of Flow and Unit Weight



(a)

Figure 5.15. Unit Weight of Mixes at (a) W/C 0.30 %



(b)

Figure 5.16. Unit Weight of Mixes at (b) W/C 0.45 %

The flow values and unit weights of the mixes were measured for two W/C ratios (0.30 and 0.45). The results are presented in Table 4.2 and Figures 5.15 & 5.16.

- ♦ At $W/C = 0.30$, the flow of the control mix (L0) was 20.0 cm, decreasing gradually with fiber dosage. For PP1 mixes, the flow dropped from 19.0 cm at 0.2% to 14.5 cm at 1.4%, showing the strongest reduction. PP2 and PVA mixes showed slightly better workability compared with PP1 and flows in the range of 15.0–20.0 cm.
- ♦ At $W/C = 0.45$, the flow was naturally higher, with the control mix (H0) reaching 22.0 cm. Fiber addition again reduced flow, although the effect was less severe than at the lower W/C ratio. For example, the flow of PP1 mixes decreased from 21.0 cm at 0.2% to 15.0 cm at 1.4% fiber content, while PP2 and PVA mixes remained slightly higher flow values at the same dosages.

The unit weight of mixes also reflected the influence of fiber type and dosage:

- ♦ At $W/C = 0.30$, unit weights ranged between 2344.55 and 2365.23 kg/m^3 . The reduction with increasing fiber dosage was modest but noticeable for particularly in (PP2 and PVA) mixes with fiber content above 1.0%.
- ♦ For $W/C = 0.45$, the control mix (H0) recorded 2266.01 kg/m^3 , with fiber-reinforced mixes ranging from 2243.30 to 2265.77 kg/m^3 . The decline was again more visible at higher dosages.

Overall, the results confirm that fiber addition reduces workability (flow) more strongly than density. PP1 fibers consistently caused the largest drop in flow, while PVA fibers maintained slightly better consistency. Nevertheless, the effect on unit weight was minor compared to the significant improvements observed in strength properties, as discussed earlier.

6. CONCLUSION

This study obtainable a comprehensive experimental and analytical evaluation of the mechanical behavior of polymeric fiber-reinforced cementitious composites, with particular focus on the effects of water to cement (W/C) ratio and fiber content using (polypropylene PP1 and PP2, and polyvinyl alcohol PVA).

Key conclusions drawn from the results are:

- ♦ The lower W/C ratio of 0.3 consistently delivered higher mechanical performance comparing with 0.45, due to improved matrix compaction and reduced porosity.
- ♦ Fiber adding between 0.6% and 1.0% by volume showed most effective in developing flexural strength while calculating compressive strength. especially between 0.6% and 1.0%, significantly developed flexural strength due to the crack-bridging and ductility-development properties of the fibers. PVA fibers out achieved PP fibers in terms of mechanical properties, owing to their better tensile strength and stronger chemical bond with the cementitious matrix. Beyond 1.0%, mechanical properties gains plateaued or declined, likely due to fiber cluster, abridged workability, and poor distribution.
- ♦ At high fiber dosages (1.4%), compressive strength has a tendency to decrease due to poor distribution and workability issues, though flexural strength remained relatively high.
- ♦ PP vs. PVA Performance: PVA fibers consistently outdone PP fibers in terms of flexural strength, post crack behavior, and ductility, due to their higher tensile strength and better bonding with the matrix.
- ♦ However, PP fibers, particularly PP2, offered better workability and are more cost effective for applications not requiring high ductility.
- ♦ Gene Expression Programming (GEP) showed to be a highly effective analytical tool, completing with an R^2 of 0.87 for Test and 0.72 for validation, outdoing the simpler Multiple Linear Regression (MLR) model, which completed an R^2 of 0.68.

Overall, this research confirms that the integration of optimized W/C ratio, fiber dosage, and appropriate fiber type can significantly improve the mechanical behavior of cementitious composites and predictive models developed especially GEP provide engineers with powerful tools to tailor mix designs for performance, enabling more efficient and durable applications in structural concrete systems.

7. RECOMMENDATIONS

Based on the outcomes of this study, the following suggestions are proposed to guide future investigations and extend the current findings:

1. Evaluation of Fiber Dispersion and Orientation: Future studies should investigate fiber distribution and alignment within the matrix, using microscopic imaging or digital analysis, to clarify the effects of clustering or alignment on mechanical performance at higher dosages.
2. Investigation of Intermediate Water-to-Binder Ratios: Examining additional W/B ratios (e.g., 0.35 or 0.40) may provide more balanced insights into optimizing both workability and strength.
3. Exploration of Alternative Fiber Types and Configurations: Research should include other fibers such as polyethylene (PE), aramid, recycled materials, or modified shapes (e.g., crimped, twisted) to broaden the understanding of fiber reinforcement.
4. Assessment of Long-Term and Durability Properties: Beyond 28-day strengths, studies should address fatigue, shrinkage, freeze–thaw resistance, and chemical durability for real-world applicability.
5. Application of Advanced Modeling Techniques: Future work may benefit from advanced machine learning methods (e.g., neural networks, random forests) to improve predictive accuracy and handle larger datasets.

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RESUME

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