International Journal of Engineering and Techniques - Volume 10 Issue 3, June 2024

RESEARCH ARTICLE OPEN ACCESS

Experimental Investigation on Compressive test Properties of FRC Mortars with Polyvinyl Alcohol (PVA) Fibers

Diptikar Behera [1] (D.B.) , Kuang-Yen Liu [2] (K-Y. L.), Ratnakar Behera [3] (R.B)
[1,2] Department of Civil Engineering, National Cheng Kung University, Tainan 701, Taiwan
Email : diptiharibol@gmail.com , kyliu@gs.ncku.edu.tw
[3] Department of Mechanical and Computer-aided Engineering, National Formosa University, Yunlin 632, Taiwan
Email: ratanbbsrk@gmail.com

Abstract:

The study investigated the impact of Polyvinyl Alcohol (PVA) fibers on cementitious composite materials (mortars) compressive strength. It encompassed a comprehensive analysis of various properties derived from compressive tests, including stress-strain curves, ultimate strength, ultimate strain, maximum strain, modulus of elasticity, secant modulus, and toughness. The research also examined fracture patterns, correlating them with mortar properties. Two series of specimens were utilized for the study. The first series comprised three 50-mm cubic specimens of plain mortars, while the second series included three 50-mm cubic specimens and a 75-mm by 150-mm cylindrical mortar specimen reinforced with PVA fibers. The compressive tests were conducted using a universal testing machine (UTM) after 14 days of mortar age. During the initial two days of this period, specimens were wrapped in plastic sheets to ensure adequate humidity for curing. Subsequently, they were submerged in a curing tank until one day before testing. Before testing, the specimen surfaces were coated with gypsum to ensure uniform stress distribution during the compressive test. The addition of PVA fibers proved beneficial, resulting in a 46.88% increase in compressive strength (fc'), as well as improvements of 40.49% and 58.25% in the modulus of elasticity (E) and secant modulus (Esec), respectively.

Keywords: Stress-strain curve, ultimate strength, maximum strain, modulus of elasticity, secant modulus, and toughness.

I. INTRODUCTION

Concrete stands out as the most crucial construction material globally, with its usage steadily rising across all nations and regions. This trend owes to its widespread availability and cost-effectiveness, straightforward production methods, and versatile applications in various building and infrastructure projects. Despite its advantages, concrete's primary drawback lies in its brittleness, lower tensile strength, and susceptibility to cracking. To address these limitations, incorporating dispersed fibers is pivotal in advancing concrete-like materials. [1]. The advancement of concrete and cement-based Technology has fueled the expansion of fiber-reinforced concrete (FRC) and fiber-reinforced cementitious composites (FRCC). Fiber-reinforced concrete (FRC) is a structural concrete that has increased ductility and decreased microcracking due to the addition of steel or polymer fibers. At the same time, FRCC material is characterized by a high-strength cement-based mortar with tiny aggregates (usually no more than 2.5 mm) and adding one or more types of fibers. **[2].** Glass, carbon, polyvinyl, polyolefin, waste fiber materials, and polypropylene are among the basic fiber types, along with steel and synthetic fiber. Figure 1.0 depicts BISFA's general fiber classification. These fibers impact the mechanical properties of FRC members, individually and in combination. These mechanical properties influence the type, content, and geometry of fibers. In cementitious composites, adding fibers significantly improves reinforced concrete members' mechanical and dynamic properties. The enhancement level achieved was determined by the type and dosage of fiber used compared to plain concrete. Fiber reinforcement provides adequate tensile strength, energy dissipation capacity, and toughness. Shear, punching, and flexure are significantly increased by the level of enhancement accomplished. **[3]** Polyvinyl alcohol (PVOH) is a water-soluble synthetic polymer, PVA or PVAL. It is effective at film-forming emulsifying and has adhesive properties. It is odorless, non-toxic, and resistant to grease, oils, and solvents. It is ductile but highly flexible and is a potent oxygen and aroma barrier. **[4].** PVA is unique among polymers (chemical compounds made up of monomers) because it is not formed in polymerization reactions from single-unit precursor molecules known as monomers. PVA fibers are incredibly versatile in cementitious applications due to their exceptional crack resistance, high modulus of elasticity, superior tensile strength, molecular solid bonding abilities, and resistance to alkali, UV radiation, chemicals, fatigue, and abrasion. They are distinguished by their ability to form molecular bonds with mortar and concrete, which are significantly more potent on average than other fibers. Instead, PVA is created by dissolving another polyvinyl acetate (PVAc) polymer in an alcohol (e.g., methanol) and treating it with an alkaline catalyst like sodium hydroxide. The resulting hydrolysis, known as "alcoholysis," removes the acetate groups from PVAc molecules while preserving their long-chain structure. When the reaction is allowed to complete, the product is highly soluble in water but insoluble in nearly all organic solvents. Incomplete removal of the acetate groups yields resins that are less soluble in water but more soluble in certain organic liquids. **[5-7]**

Polyvinyl alcohol fibers (PVA or vinylon fibers) are high-performance reinforcement fibers from polyvinyl alcohol and are widely used in concrete and mortar. Fiber (in mortar and concrete) is a minor reinforcing material with specific properties. They could be circular or flat. The aspect ratio is a valuable parameter commonly used to describe fibers. The aspect ratio of a fiber is the ratio of length to diameter. Other important aspects, such as density, modulus of elasticity, and tensile strength, are frequently described. **[8-10]**. PVA fibers are ideal for various cementitious material applications due to their superior crack-fighting properties, high modulus of elasticity, excellent tensile and molecular bond strength, and high alkali, U.V., chemicals, fatigue, and abrasion resistance. PVA fibers are unique in that they can form a much stronger molecular bond with mortar and concrete than other fibers. **[11-13]** Because these fibers are refined and dispersed into monofilament fibers, they are less likely to be visible on finished surfaces. Their diameters determine how visible they are to each other. Similarly, the smaller the fiber, the more fibers there are for any given unit of measure, making it more likely to choke mixes at higher dosage rates. As a result, PVA with a larger diameter in higher doses is more flowable than their smaller counterparts **[14-15].**

High-diameter PVA (e.g., PVA 100s) is preferred over its smaller counterparts (e.g., 7's and 15's) due to their ease of use. Because of their length, these are the most visible PVA fibers on finished surfaces. Perfect for use in flowable (SCC) ECC concrete mixtures. PVA fibers can reinforce artisan concrete objects, such as countertops, architectural concrete elements, concrete furniture, and other applications. The adverse effects of using PVA on mortar (PVA-FRCC) or concrete (PVA-FRC) are caused primarily by the PVA's properties. Aside from reducing workability, PVA fibers, known as the hairball effect, tend to clump and bind to one another during mixing. The secondary negative impact results from Table 1. below contain the parameters of PVA fibers used by **Yew et al. (2015) [2]** and **Devi et al. (2017) [8]**in their research (2015):

Table 1. Parameters of PVA Fibers used in previous research

Parameter	Yew et al.	Devi et al.
Material	Polyvinyl Alcohol	Polyvinyl Alcohol
Length	30 mm	6 mm
Filament diameter	660 microns	18 microns
Specific gravity	1.3	1.3
Tensile strength	800 MPa	1280 MPa
Flexural strength	23 Gpa	36 Gpa
Melting point	225° C	-
Color	Yellow	-
Water absorption	<1% by weight	-
Alkali resistance	Excellent	-

Fiber-reinforced cementitious composites (FRCC) are composite materials with superior material properties that make them suitable for structural applications, such as high tensile strength and significantly increased flexibility compared to conventional concrete. A large proportion of cement must be used to manufacture FRCC to achieve distinct ductility characteristics.**[16]** To address concrete's inherent brittleness, extensive research has been conducted on developing high-ductility fiber-reinforced cementitious composites (FRCCs). Several types of FRCCs incorporating metallic, polymeric, carbon, glass, nylon, and waste tire fibers have been successfully developed and applied for infrastructure (i.e., buildings, tunnels, and bridges) due to their ability to limit crack propagation and widening via fiber bridging. Furthermore, (ultra-)high-performance fiber-reinforced cement composites exhibiting strain- or deflection-hardening behavior with the formation of multiple microcracks have been developed in recent years, and several relevant studies are currently underway. This special issue provides a comprehensive overview of FRCCs, including mechanical behaviors, strengthening performance, and structural implications under various loading conditions (quasistatic, impact, blast, and fire). **[2]** Vinyl acetate is used as a monomer in the commercial production of polyvinyl alcohol (PVA). Completely hydrolyzed PVA has properties different from those of partially hydrolyzed PVA. Its abundance of hydroxyl groups significantly influences PVA's properties. PVA's semicrystalline nature is caused by hydrogen bonding between its chains. PVA has various morphologies for pharmaceutical, biomedical, and other applications. For example, PVA gel beads could be used in water filtration systems. The high optical quality of PVA films is helpful in optical sensors and devices. Polymeric nanofiber membranes are used in many applications, including batteries, filter materials, biomedical scaffolds, fuel cells, and osmotic power plants. **[17].** PVA fiber-reinforced cementitious materials offer enhanced durability compared to plain concrete, especially when managing crack widths up to 100 µm after undergoing wet-dry or freeze-thaw cycles. PVA fibers possess high tensile strength and strain capacity, exhibiting a unique strain-hardening property that controls crack width by forming multiple fine cracks. These short fibers improve relatively thinner cement-based elements' flexural and tensile behavior. Additionally, PVA-reinforced cement-based composites can be produced without relying on micromechanical design approaches, making them suitable for practical applications **[18]**. PVA-FRCC (polyvinyl alcohol-fiber reinforced cementitious composites) materials have excellent tensile strain-hardening properties, which can significantly improve the structure's bearing and deformation capacity. PVA-FRCC beams assume plane sections remain plane and steel bars are deformation-compatible with the PVA-FRCC materials. PVA-FRCC beams also show apparent deflection hardening and high flexibility compared to R.C. beams, with ultimate deflections 2.4-3.1 times those of R.C. beams. **[19-20]**

II. MATERIALS AND METHODOLOGY

A. Tools and Materials

Below are the primary tools and materials that were used in this experiment:

Concrete Mixer Digital Scale Cube Mold Cylinder Mold UTM

Cement Sand Superplasticizer

Water PVA Fiber Gypsum

Fig. 1 Tools and Materials

B. Mix Design

1. The quantities of each material used in this experiment have been determined, as shown in Table 2. This experiment contains seven specimens, divided into two series. The first series comprises three cubic specimens of plain mortar (50mm). The second series includes three cubic specimens (50mm) and a cylinder mortar specimen (75mm x 150mm) reinforced with PVA fiber.

Table 2. Material Contents

Specimens	Cement (g)	Sand (g)	Superplasticizer (g)	Water (g)	PVA Fiber (g)
Pure Mortar (Series 1)	455	455	9	159	-
PVA Reinforced Mortar (Series 2)	2348	2348	23	822	16

This experiment's mix design can be calculated based on the material used. The mix design used in this experiment is cement 2.7 and sand 2.7, water 1, and superplasticizer up to 1% by weight of cement, as needed. The PVA-reinforced mortar has a 0.5% PVA-to-specimen volume (Vf) ratio.

C. Methodology

The mortars (with or without fiber) were made in the laboratory with a small concrete mixer to ensure that all materials were mixed thoroughly and left as little residue as possible in the machine. After casting in the mold, each mortar is wrapped in a plastic sheet for 48 hours to ensure proper humidity for hardening. The mortars were then placed in the curing tank for 11 days. The specimens were removed from the curing tank the day before testing (13th day), ensuring they were dry for testing. The specimens are subjected to a compressive test on a universal testing machine (UTM) for 14 days. Before testing began, the specimens' surfaces were covered with gypsum to ensure equal stress on the surface during the compressive test.

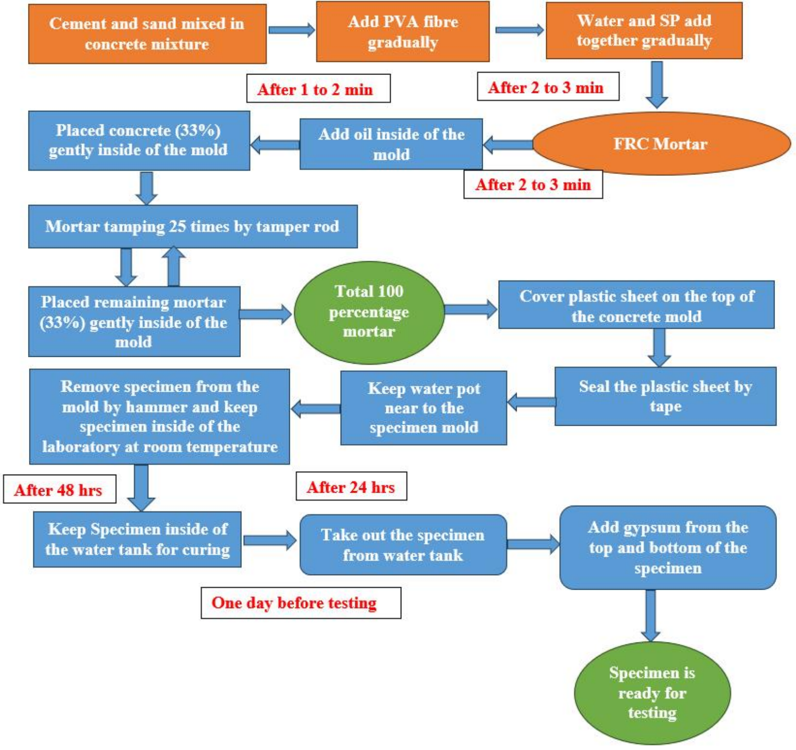
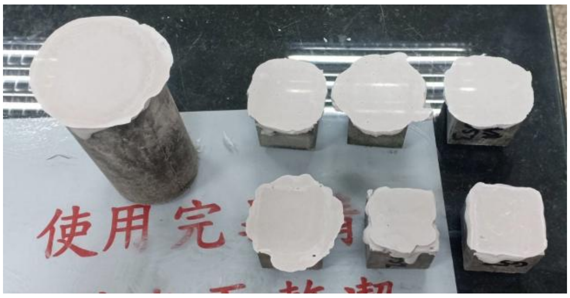


Figure-2 Mixing to testing process of FRC mortar specimen

Fresh specimens cast in molds

Two days old specimen in the curing tank

13-days old specimens



14-day-old specimens are ready for testing

III. RESULTS AND DISCUSSION

A. Test Results

The UTM (Universal Testing Machine) was used to measure the load and deformation of the specimens. The stress-strain curve is then calculated and shown in Figures 4–7. Figures 8–12 show a comparison chart of mortar properties. Figure 13 depicts one example of how the stress-strain curve was corrected to achieve the linear stage—figures 14 and 15 show failure profiles.

There are some notes for the calculation of the raw data:

a. For f'_c - ε relation curves, the shape factor for cube specimens is 0.83, so the data can be compared among all specimens.

b. The raw strain data were modified to obtain the linear stage of the stress-strain curve, as shown in Figure 13.

c. The acceleration of gravity is assumed to be 9.80665 m/s^2.

Table 3. Test Result Summaries

No.	**Specimen**	**Max Load (N)**	**A (mm^2)**	**f'_{cu} (MPa)**	**Avg. f'_{cu} (MPa)**	**ε_u**	**Avg ε_u**	**$\varepsilon_{fracture}$**	**Avg $\varepsilon_{fracture}$**
1	Pure Mortar Cube (1)	100616	2500	33.40	35.92	2.64 %	2.24%	3.10%	2.71%
2	Pure Mortar Cube (2)	82572	2500	27.41		2.08 %		2.64%	
3	Pure Mortar Cube (3)	141412	2500	46.95		2.00 %		2.40%	
4	PVA Reinforced Mortar Cube (1)	165732	2500	55.02	51.94	1.78 %	2.02%	2.76%	2.77%

5	PVA Reinforced Mortar Cube (2)	148669	2500	49.36		2.15 %		2.76%	
6	PVA Reinforced Mortar Cube (3)	154945	2500	51.44		2.13 %		2.78%	
7	PVA Reinforced Mortar Cylinder	243989	4418	55.23	55.23	0.89 %	0.89%	0.98%	0.98%

No.	Specimen	E (MPa)	Avg. E (MPa)	E_{sec} (MPa)	Avg. E_{sec} (MPa)	$E_{toughness}$ (MPa)	Avg. $E_{toughness}$ (MPa)
1	Pure Mortar Cube (1)	1482.50		1265.33		0.55	
2	Pure Mortar Cube (2)	1682.83	2273.79	1320.52	1642.86	0.43	0.50
3	Pure Mortar Cube (3)	3656.05		2342.75		0.53	
4	PVA Reinforced Mortar Cube (1)	3848.44		3084.26		0.87	
5	PVA Reinforced Mortar Cube (2)	2520.41	3194.47	2297.86	2599.83	0.77	0.80
6	PVA Reinforced Mortar Cube (3)	3214.57		2417.38		0.75	
7	PVA Reinforced Mortar Cylinder	6930.51	6930.51	6219.36	6219.36	0.28	0.28

B. Discussion

The addition of 0.5% PVA fiber to the matrix increased the overall ultimate compressive strengths (f'cu) of both cubes and cylinders by 46.88% (from 35.92 MPa to an average of 3 x 51.94 MPa and 55.23 MPa). If we only look at the cube specimens, the overall ultimate compressive strength increase is 44.60%.

Based on cube specimens, the ultimate strain (εu) decreased by 9.82% from 2.24% to 2.02%. This condition, combined with the increase in ultimate compressive strengths, indicates that the specimens' secant modulus increases significantly at the ultimate strength.

Fiber-reinforced mortar's maximum strain (εfracture) decreases, potentially indicating reduced ductility. However, this is not true because the specimens were not fractured. Instead, the UTM's compression tests were halted to protect the machine. As a result, the ductility of the specimens in this experiment is difficult to calculate. However, this axial test is not the best way to determine FRCC ductility; a uniaxial tensile test may produce a more accurate ductility result.

The modulus of elasticity (E) and secant modulus (Esec) show a significant increase of 40.49% (from 2273.79 MPa to 3194.47 MPa) and 58.25% (from 1642.86 MPa to 2599.82 MPa) based solely on cube specimens. The amount of energy that the specimens can absorb before fracture, also known as the modulus of toughness, increases by 60%. In this experiment, all 1% superplasticizers were used in both series mixtures to make the comparison fair. The PVA-reinforced mix is consistent, whereas the plain mortar mix is slightly wet. This is due to the addition of fiber; PVA significantly reduces the workability of a mixture. The low difference between specimens can be attributed to the fiber-reinforced mortar's excellent consistency, whereas the difference between plain mortar specimens is significant. The results for these parameters are ignored because of the significant difference in strain and all modulus between the cylinder and cube specimens. Various factors, including shape, testing speed, and reloading, can cause this. In this study, the cylinder specimen was reloaded because the first cylinder loading produced insufficient strength compared to the previously tested cube counterparts.

From the fracture pattern, it is seen that the cylinder specimen has the slightest crack. This is because the machine stopped before the specimen fracture, which can answer the deficient value of the maximum strain. The PVA-reinforced cube specimens also show less damage than the plain counterparts, which also answers the low value of the maximum strain.

The cylinder specimen shows a few narrow cracks, the PVA-reinforced cube specimens show some wide compression cracks, while the plain cube specimens show a crush due to the compression. Again, this indicates that the plain cube specimens have crushed hard at the maximum strain on the curve while the PVA counterparts still can show more considerable strain if the tests are to be continued.

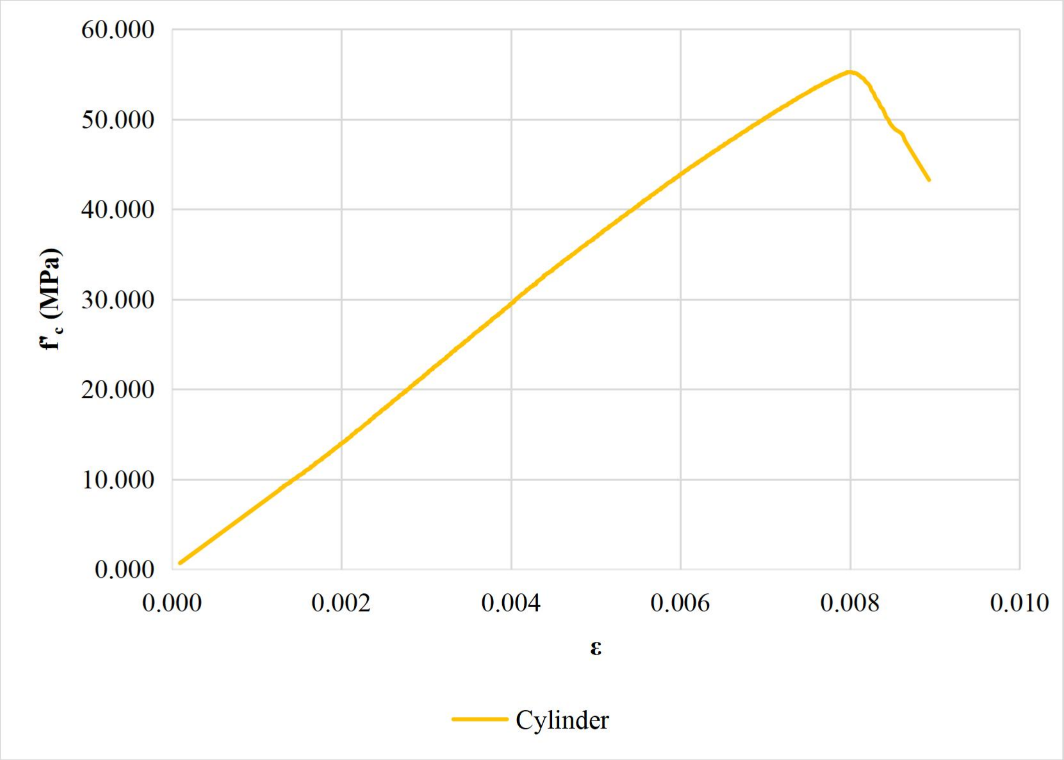


Figure 4. f'_c - ε for PVA Reinforced Mortar Cylinder

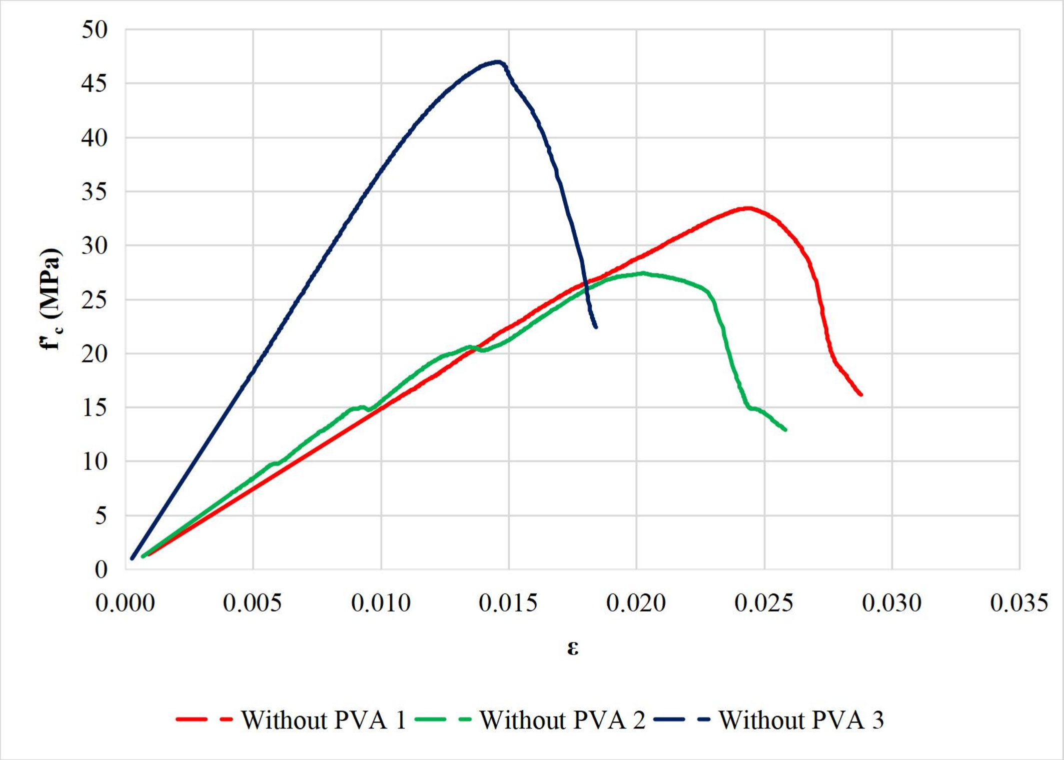


Figure 5. f'_c - ε for Pure Mortar Cubes

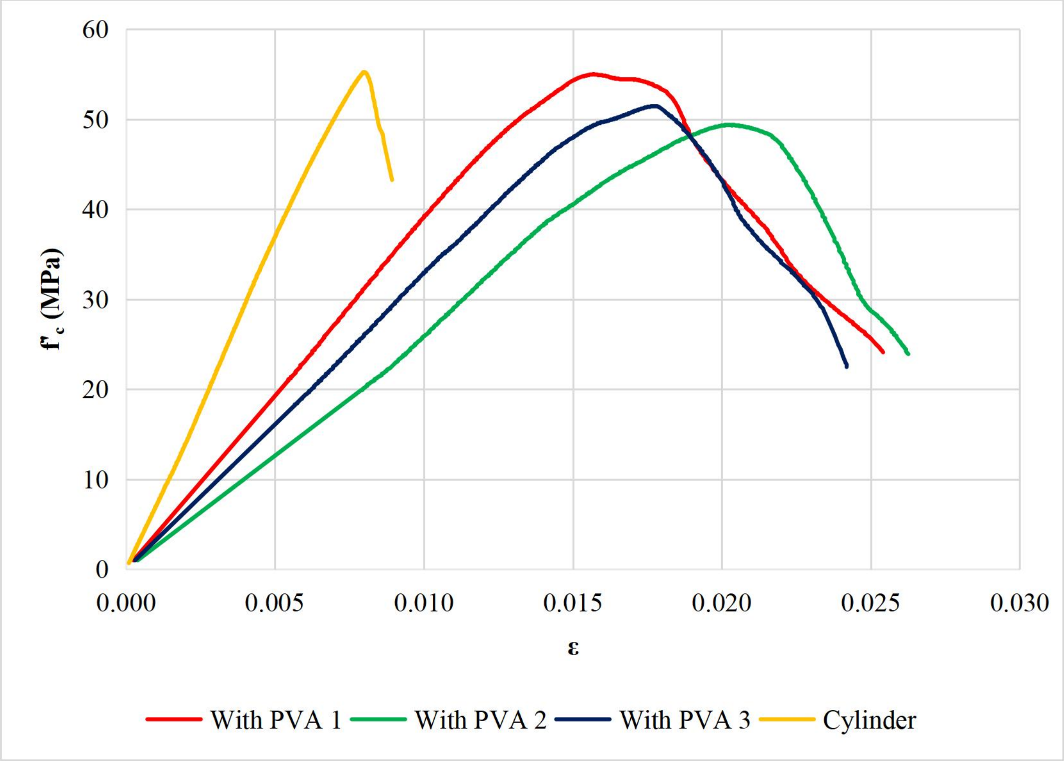


Figure 6. f'c - ε for PVA Reinforced Mortar

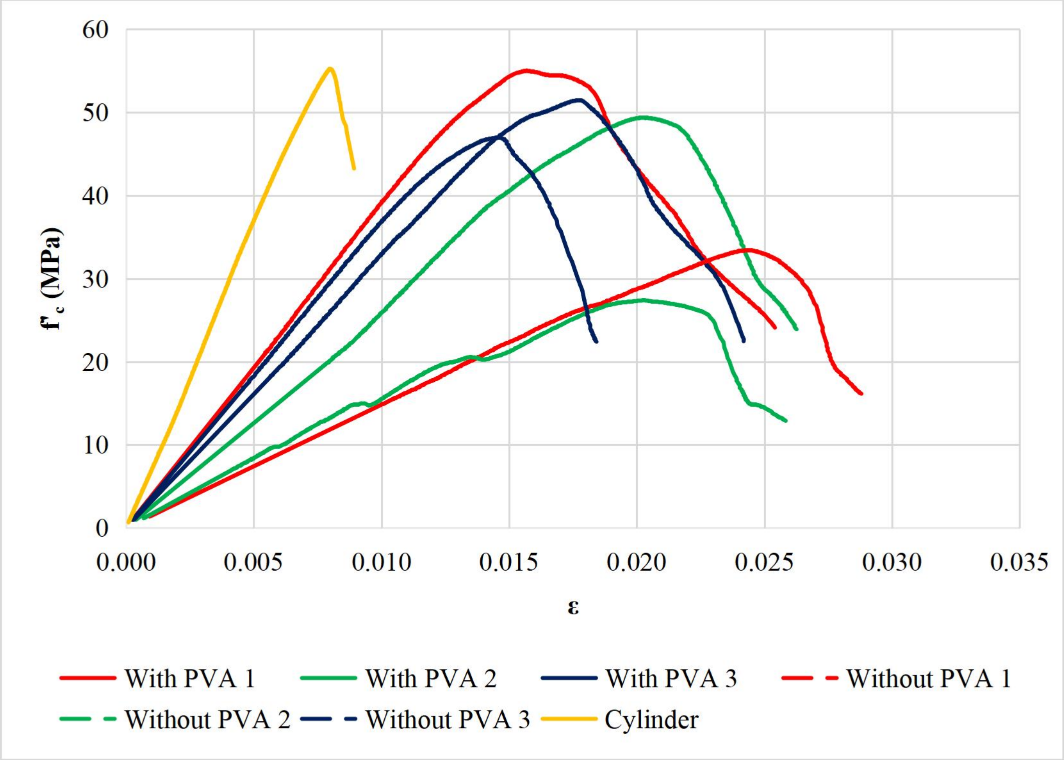


Figure 7. f'c - ε for All Specimens

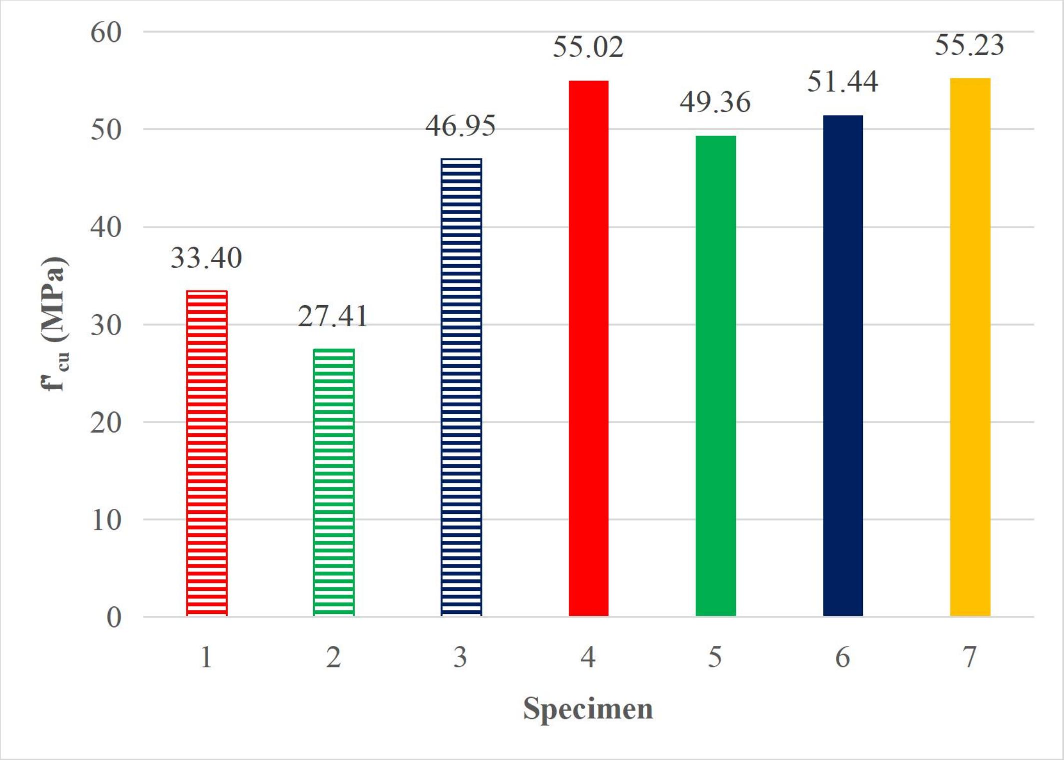


Figure 8. Maximum stress (f'_{cu})

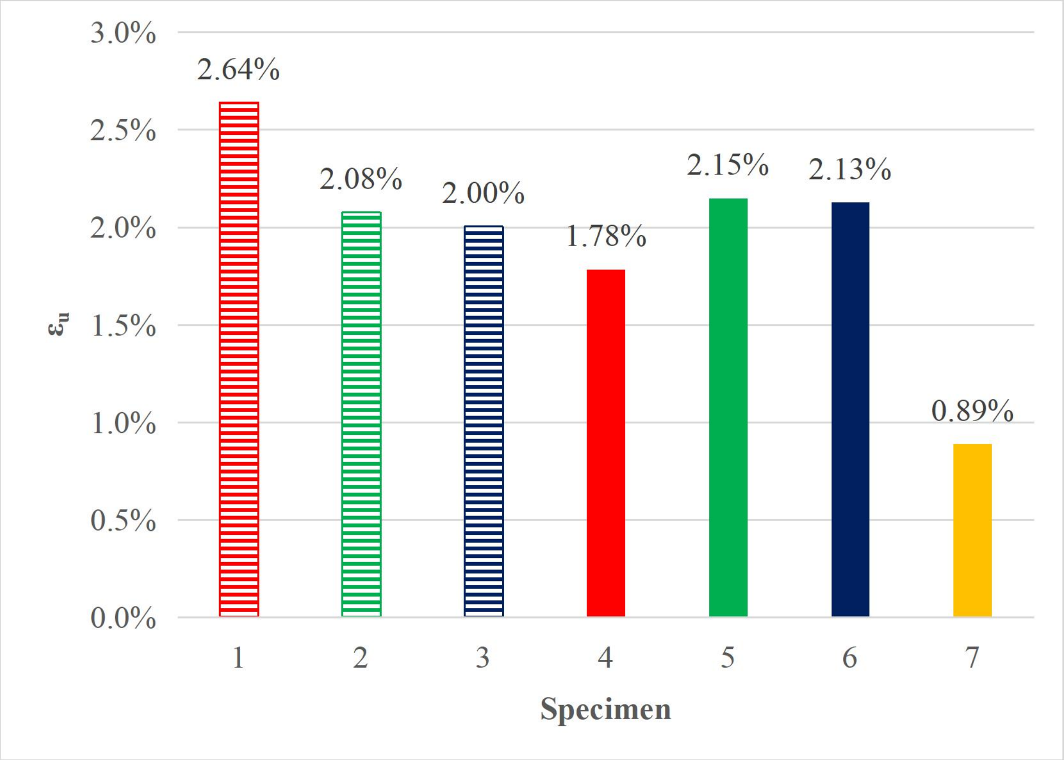


Figure 9. Ultimate strain (ε_u)

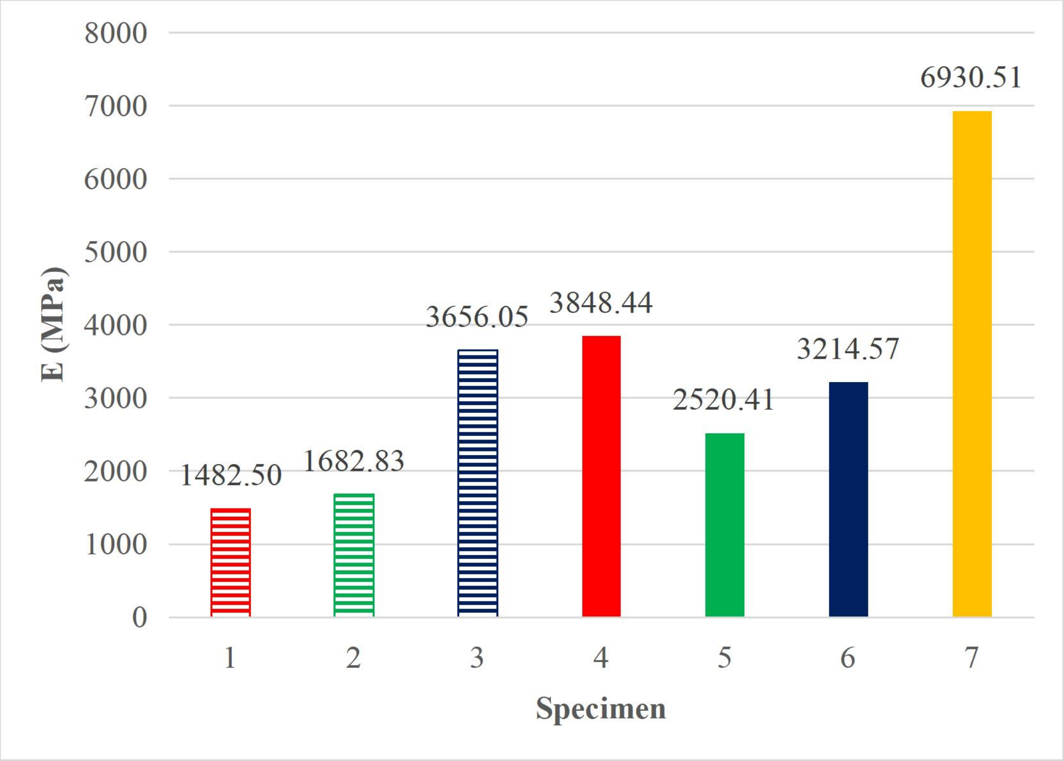


Figure 10. Young's Modulus (E)

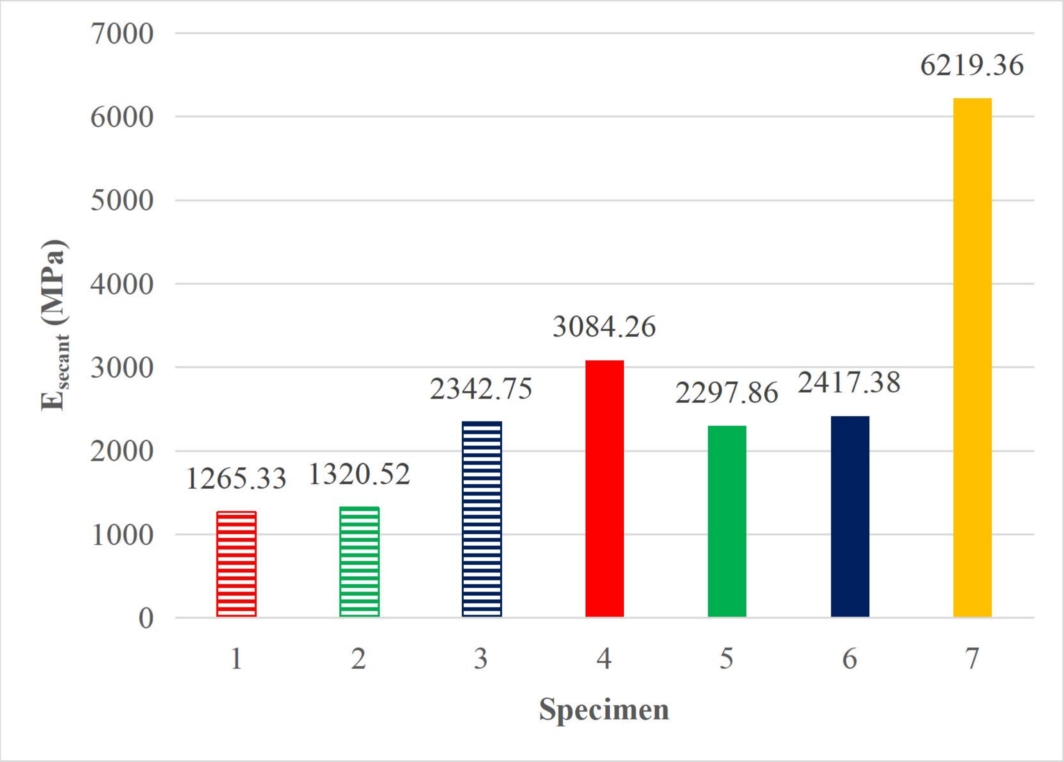


Figure 11. Secant Modulus (E_{sec})

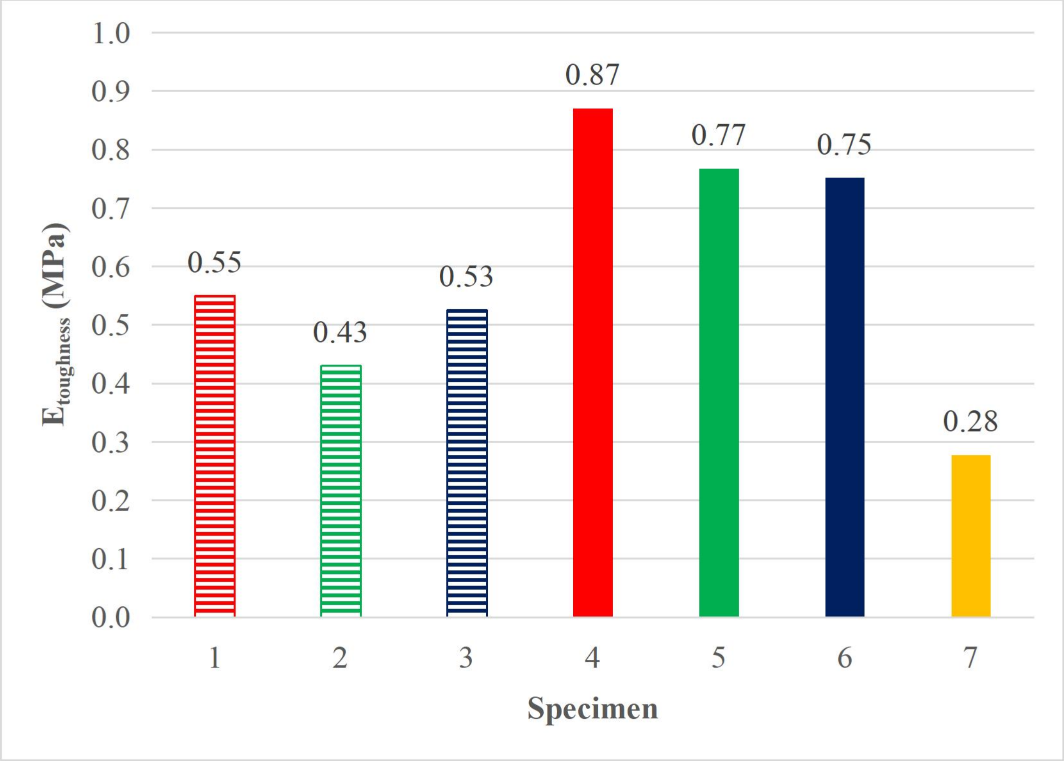


Figure 12. Modulus of Toughness ($E_{toughness}$)

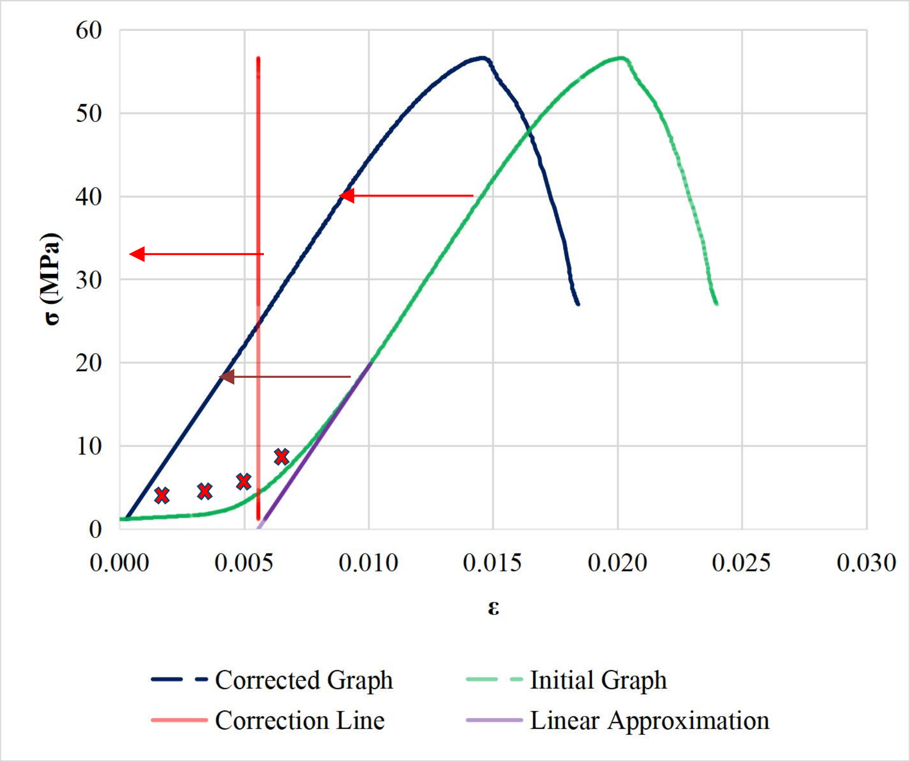


Figure 13. Example of Graph Correction

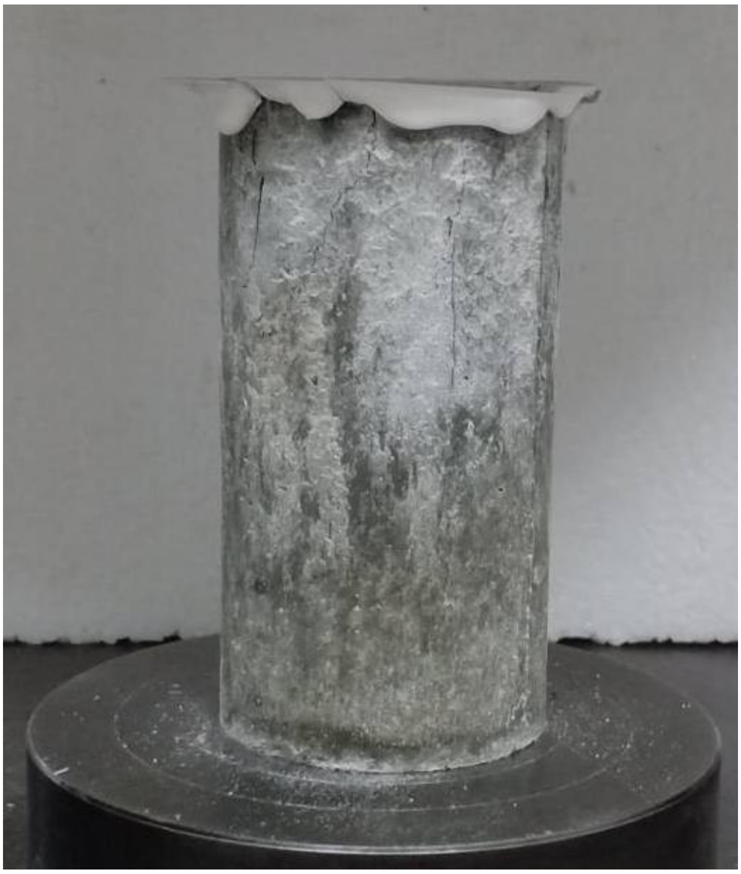
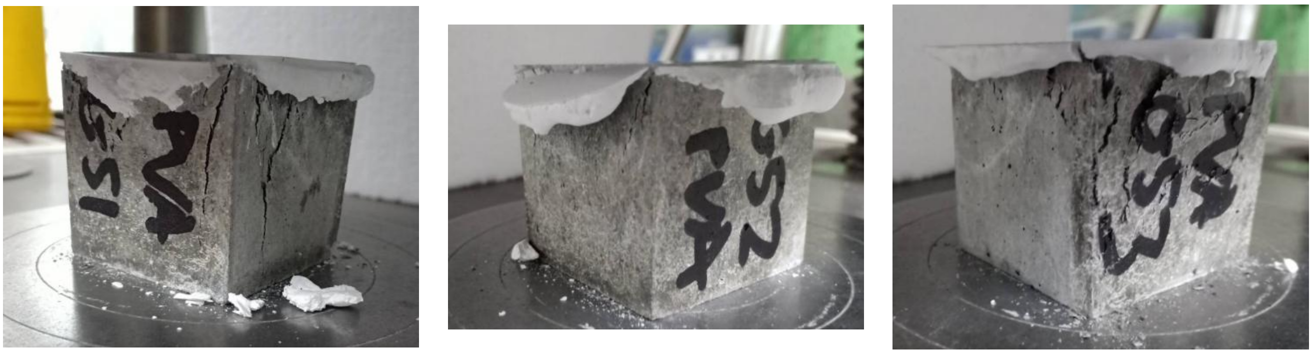


Figure 14. PVA Reinforced Mortar Cylinder

Pure Mortar Cube 1

Pure Mortar Cube 2

Pure Mortar Cube 3



PVA Reinforced Mortar Cube 1 PVA Reinforced Mortar Cube 2 PVA Reinforced Mortar Cube 3

Figure 15. Cube Mortars Failure Profiles

IV. CONCLUSION

In this study, the effects of PVA (Polyvinyl Alcohol) fibers on compressive strength cementitious materials (mortars) were investigated. The following properties are obtained from a compressive test: stress-strain curve, ultimate strength, ultimate strain, maximum strain, modulus of elasticity, secant modulus, and toughness. The fracture patterns were also investigated and found to be related to the mortar's properties.

PVA fibers are ideal for various cementitious material applications due to their superior crack-fighting properties, high modulus of elasticity, excellent tensile and molecular bond strength, and high alkali, U.V., chemicals, fatigue, and abrasion resistance. PVA fibers are unique in that they can form a much stronger molecular bond with mortar and concrete than other fibers.

The mix design used in this experiment is as follows: cement 2.7; sand 2.7; water 1; and, if necessary, superplasticizer up to 1% by weight of cement. The PVA-reinforced mortar has a PVA to specimen volume (Vf) ratio of 0.5%. Using PVA fibers can improve a mortar's compressive strength and stiffness. The following points provide more information about the experiment's outcome:

1. Using PVA fibers is beneficial in increasing compressive strength (fc') by 46.88%.
2. Based on the results of the mortar cube specimens, using PVA fiber increases the value of modulus of elasticity (E) and secant modulus (Esec) by 40.49% and 58.25%, respectively.
3. Using PVA fiber reduces ultimate strain (εu) by 9.82%, based on mortar cube specimens.
4. According to the results of the mortar cube specimens alone, using PVA fiber increases the value modulus of toughness by 60%.
5. Using PVA fiber, the damage pattern experienced by concrete is less visible. This means that the PVA fibers

6 This research will examine the various practical applications in civil engineering practices. Because of their extraordinary strength and performance.

ACKNOWLEDGMENT

The author would like to thank the Department of Civil Engineering, National Cheng Kung University, Taiwan, for supporting this research.

References

1. Brandt, Andrzej. Fiber-reinforced cement-based (FRC) composites after over 40 years of building and civil engineering development. Composite Structures. (2008). doi: https://doi.org/10.1016/j.compstruct.2008.03.006
2. Doo-Yeol, et al. Fiber-Reinforced Cement Composites: Mechanical Properties and Structural Implications. (2018). doi: https://doi.org/10.1155/2018/8395461
3. Del Zoppo, Marta & Di Ludovico, M. & Balsamo, Alberto & Prota, Andrea. Comparative analysis of existing R.C. columns jacketed with CFRP or FRCC. Polymers. (2018). doi: https://doi.org/10.3390/polym10040361
4. Noushini, A.; Samali, B.; Vessalas, K. Effect of polyvinyl alcohol (PVA) fiber on dynamic and material properties of fiber reinforced concrete. Constr. Build. Mater. (2013) doi: https://doi.org/10.1016/j.conbuildmat.2013.08.035
5. Yew, Ming Kun & Mahmud, Hilmi & Ang, Bee & Yew, Ming. Effects of Low Volume Fraction of Polyvinyl Alcohol Fibers on the Mechanical Properties of Oil Palm Shell Lightweight Concrete. Advances in Materials Science and Engineering. (2015). doi: https://doi.org/10.1155/2015/425236
6. Abbass, W.; Khan, M.I. Mechanical properties of Hybrid steel/PVA fiber reinforced high strength concrete. MATEC

Web Conf. (2018). doi: https://doi.org/10.1051/matecconf/201819911005

7. Feng, J.; Sun, W.; Zhai, H.; Wang, L.; Dong, H.; Wu, Q. Experimental Study on Hybrid Effect Evaluation of Fiber Reinforced Concrete Subjected to Drop Weight Impacts. Materials (2018) doi: https://doi.org/ 10.3390/ma11122563

8. Devi, M & Kannan, L & kumar, M.Ganesh & achalam, T.S.Venkat. Flexural Behavior of Polyvinyl Alcohol Fiber Reinforced Concrete. International Journal of Civil Engineering. (2017). doi: https://doi.org/10.14445/23488352/IJCE-V4I6P104

9. Zhang, R.; Jin, L.; Tian, Y.; Dou, G.; Du, X. Static and dynamic mechanical properties of eco-friendly polyvinyl alcohol fiber-reinforced ultra-high-strength concrete. Struct. Concr. (2019) doi: https://doi.org/10.1002/suco.201800247

10. Libre, N.A.; Shekarchizadeh, M.; Mahoutian, M.; Soroushian, P. Mechanical properties of hybrid fiber reinforced lightweight aggregate concrete made with natural pumice. Constr. Build. Mater. (2011) doi: https://doi.org/ 10.1016/j.conbuildmat.2010.11.058

11. Ting-Yu Liu, Peng Zhang, Juan Wang, and Yi-Feng Ling. Compressive Strength Prediction of PVA Fiber-Reinforced Cementitious Composites Containing Nano-SiO_2 Using B.P. Neural Network (2020) doi: https://doi.org/ 10.3390/ma13030521

12. Hassanpour, M.; Shafigh, P.; Bin Mahmud, H. Lightweight aggregate concrete fiber reinforcement—A review. Constr. Build. Mater. (2012) doi: https://doi.org/10.1016/j.conbuildmat.2012.07.071

13. Sudhikumar, G.S.; Prakash, K.B.; Rao, M.S. Effect of Aspect Ratio of Fibers on the Strength Characteristics of Slurry Infiltrated Fibrous Ferrocement. J. Civ. Struct. Eng. (2014) https://www.researchgate.net/publication/301815771

14. Arıoglu, N.; Girgin, Z.C.; Arıoglu, E. Evaluation of Ratio between Splitting Tensile Strength and Compressive Strength for Concretes up to 120 MPa and its Application in Strength Criterion. ACI Mater. J. (2006): https://www.researchgate.net/publication/286689584

15. Majhi, R.K.; Padhy, A.; Nayak, A.N. Performance of lightweight structural concrete produced by utilizing the high volume of fly ash chemosphere and sintered fly ash aggregate with silica fume. Clean. Eng. Technol. (2021) doi:https://doi.org/10.1016/j.clet.2021.100121.

16. Tian, H. & Zhang, Y.X. Tensile Behavior of a Sustainable Fiber Reinforced Cementitious Composite Under Different Strain Rates. (2014). doi: https://doi.org/10.1533/9780081002254.316

17. Aslam, Muhammad & Kalyar, Muhammad & Raza, Zulfiqar. Polyvinyl alcohol: A review of research status and use of polyvinyl alcohol-based nanocomposites. Polymer Engineering & Science. (2018). doi: https://doi.org/10.1002/pen.24855

18. Atahan, Hakan & Tuncel, Erman & Pekmezci, Bekir. The behavior of PVA Fiber-Reinforced Cementitious Composites under Static and Impact Flexural Effects. Journal of Materials in Civil Engineering. (2013). doi: https://doi.org/ 10.1061/(ASCE)MT.1943-5533.0000691

19. Liu, Shuguang & Bai, Ru & Zhang, Ju & Yan, Changwang & Wang, Xiaoxiao. (2019). Flexural load-deflection performance of polyvinyl alcohol fiber reinforced cementitious composite beams—construction and Building Materials. (2019). doi: https://doi.org/10.1016/j.conbuildmat.2019.07.215

20. Labib, Wafa. Fibre Reinforced Cement Composites. (2018). doi: https://doi.org/10.5772/intechopen.75102