AMERICAN UNIVERSITY OF BEIRUT

ASSESSING THE HYBRIDIZATION EFFECT OF FIBERS ON THE MECHANICAL PROPERTIES AND DURABILITY OF CONCRETE

by
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ABSTRACT
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Title: Assessing the Hybridization Effect of Fibers on the Mechanical Properties and Durability of Concrete.

Fiber-reinforced concrete has gained wide attention in the past years. The need for a high-performance and ductile construction material led to the advance in research and application of fibrous concrete. Fibers are short filaments that can be natural, metallic, glass, or polymers (like polypropylene or polyvinyl alcohol). The addition of one type of fibers could improve the performance of concrete. Yet, the incorporation of more than one fiber type in the concrete mixture can create a synergetic effect that could further enhance concrete's properties. A multi-phase research program was conducted at the American University of Beirut to study fiber-reinforced concrete. The first phase examined the properties of single-fiber-reinforced concrete with variable fiber types and dosages. Four master students worked on that phase and reported the results in their theses. Based on the findings of the first phase, a second phase was designed in which seven mixtures incorporating different combinations of hybrid fibers were tested for: (1) mechanical properties including compressive strength, splitting tensile strength, flexural strength, and elastic modulus; (2) durability properties including resistance to rapid freezing and thawing, thermal conductivity, and water absorption; and (3) shear strength, bond strength, and ductility of the mode of failure of structural members. The fiber types included in the study are Basalt (B), Steel (S), Polyvinyl alcohol (PVA), Polypropylene Econo-Net (PP), and Glass (G). Test results of the hybrid fiber-reinforced concrete mixtures were analyzed and compared with the plain concrete and single fiber concrete mixtures. This thesis reports on Parts 1 and 2 of the above-described scope. Results indicated that whereas hybridization of fibers imposed a negative effect on the compressive strength, however it significantly enhanced the tensile and flexural strengths and remarkably improved the durability of the tested concrete specimens.

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ABBREVIATIONS

ACI – American Concrete Institute

PP – Polypropylene

PVA – Polyvinyl Alcohol

SF – Steel Fibers

GF – Glass Fibers

BF – Basalt Fibers

PPF – Polypropylene Fibers

HFRC – Hybrid Fiber Reinforced Concrete

SFRC – Single Fiber Reinforced Concrete

HBPFRC – Hybrid Basalt Polypropylene Fiber Reinforced Concrete

ECC – Engineered Cementitious Composites

GFRC – Glass Fiber Reinforced Concrete

PPFRC – Polypropylene Fiber Reinforced Concrete

FRC – Fiber-reinforced Concrete

HGPRC – Hybrid Glass Polypropylene Reinforced Concrete

UHPC – Ultra-High-Performance Concrete

ASTM – American Society for Testing and Materials

HRWR – High Range Water Reducer

CHAPTER 1

INTRODUCTION AND BACKGROUND REVIEW

Concrete is the most used construction material worldwide [1]. It has a relatively low cost, abundant raw materials, and significant strength in compression [2]. However, concrete is weak in tension and characterized by a brittle nature, which can lead to catastrophic failure scenarios. Hence, it is vital to add ductile materials like steel reinforcing bars to counteract the effects of these drawbacks. Steel reinforcement can resist tensile stresses and enhance the ductility of the concrete to avoid brittle failures, thus rendering the structures safer. Meanwhile, due to the detrimental consequences of steel corrosion, a concrete cover must be attained, which makes it harder to resist surface shrinkage cracks [2].

Other materials that have been incorporated into concrete are fibers. The ACI committee classifies these fibers as steel, glass, polymeric, and natural [3]. The outcome of this addition is known as Fiber Reinforced Concrete. The most common types of fibers added to the concrete are steel, basalt, glass, polypropylene, polyethylene, and polyvinyl alcohol as illustrated in Figure 1 below.

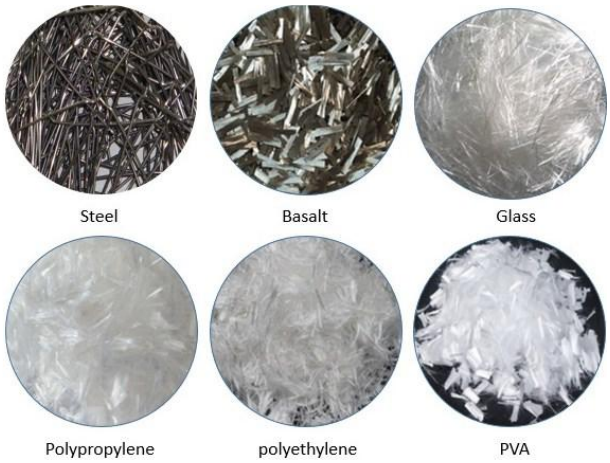


Figure 1: Some types of Fibers

As the necessity of the addition of fibers into concrete increases, the value of the research on fiber-reinforced concrete increases. A group of 4 master students began researching and experimenting on single-fiber reinforced concrete at the American University of Beirut. They aimed to study the effectiveness of different types of fibers on the properties of normal-strength concrete. To accomplish this objective, they chose five different types and aspect ratios of fibers including steel (13mm and 30mm), basalt, glass, PVA, and PP (Mighty-Mono and Econo-Net). Using these types of fibers, 13 different mixtures with variable fibers and superplasticizer dosages were created. Each mixture was tested for the mechanical, durability, and structural properties of concrete. The results of these tests were compared to a control sample that did not contain any type of fiber.

They concluded that upon the addition of fibers, greater dosages of superplasticizers were needed to maintain an acceptable consistency. In addition, they particularly emphasized the responses of duplicate specimens of basalt, steel, PP, and PVA having similar fiber dosages. Table 1 below summarizes the different single-fiber reinforced concrete mixtures created with their corresponding fibers and superplasticizer dosages.

Table 1: Single fiber reinforced concrete mixtures variables

Fiber Type	Fiber %	HRWR dosage (% by weight of cement)	Slump (cm)
Control	-	0.25	19.5
PVA	0.25	1	21
PVA	0.5	2.5	15.5
Glass	0.25	1.5	18.5
Basalt	0.25	1.5	20.5
Basalt	0.35	2	17.5
Steel (13 mm)	0.25	0.25	21.5
Steel (13 mm)	0.5	1	19.5
PP (Mighty-Mono)	0.25	1.25	18.5
PP (Mighty-Mono)	0.35	1.5	19
Steel (30 mm)	0.25	0.75	20
Steel (30 mm)	0.5	1.5	17
PP (Econo-Net)	0.25	1	20
PP (Econo-Net)	0.35	1.5	20.5

After analyzing the data of the tests performed, they concluded that the difference in fiber type and dosages significantly affects the mechanical, durability, and structural properties. In regards to the mechanical properties, they deduced that steel (30 mm) with a dosage of 0.5% had the best impact on the compressive strength of concrete where it increased by 19.0%. However, PP (Mighty-Mono) at 0.35% yielded the greatest reduction in compressive strength. Meanwhile, they reported that steel (30 mm) with a dosage of 0.5% had the most impact on the modulus of elasticity increasing it by 23.2%. Similarly, PP (Mighty-Mono) at 0.35% had the worst effect on elastic modulus. Furthermore, among all fibers, glass with 0.25% yielded the greatest improvement in tensile strength with an increase of 34.2%. On the contrary, 0.35% PP (Econo-Net) decreased the tensile strength the most. Nevertheless, they concluded that all the single fibers had a good impact on the flexural strength. The fibers that yielded an improvement greater than 90% were PP (Econo-Net) at 0.25%, steel at 0.5%, PP (Mighty-Mono) at 0.25% and 0.35%, basalt at

0.25%, and glass at 0.25%. In regards to durability, steel (30 mm) having a dosage of 0.5% had the best impact on the water absorption where it decreased by 46.0%. However, 0.25% glass increased the water absorption by a maximum of 44.0%. Moreover, mixtures of 0.25% and 0.35% PP (Mighty-Mono), 0.35% basalt, and 0.25% and 0.5% PVA yielded the best resistance to freezing and thawing.

Concerning the structural properties, they deduced that 0.5% steel (30 mm) had the best impact on shear load where it increased by 44.3%. Meanwhile, 0.25% PP (Econo-Net) showed the highest improvement in shear ductility followed by 0.25% PVA with a ratio with respect to control of 6.83 and 3.99, respectively, and basalt showed the least improvement with a ratio of 1.09 with respect to the control. Furthermore, 0.5% steel (30mm) showed the worst impact on displacement ductility with no improvement (decreased by 0.1%). However, 0.25% PP (Econo-Net) showed the highest impact on displacement ductility with an improvement of 117% followed by 0.25% glass with an improvement of 87.8%. In addition, for pullout bond test, 0.5% PVA showed the highest impact followed by 0.25% PP (Econo-Net). However, 0.25% PP (Mighty-Mono) showed the worst impact on pullout bond strength.

1.1. Recent research on hybrid fibers

Steel fibers are the most popular fibers used in both research and practical applications because they are efficient [2]. Since steel fibers are highly rigid, they significantly improve concrete's strength and limit cracks' propagation in concrete [4]. Steel fibers also enhance concrete's fracture load and toughness [5]. Nevertheless, SF can easily rust, have a high cost, and drastically affect the slump and consistency of concrete [2, 5]. Some researchers suggest that basalt fibers can be a good alternative to steel fibers.

Basalt ores are melted at approximately 1400 ℃ and drawn to form basalt fibers [4]. They are characterized by excellent mechanical and physical properties like superior tensile strength (can reach 200-5000 MPa) [6, 5, 4], high-temperature and chemical stability [6, 5, 4], high elastic modulus (can reach 93-115 GPa) [4], and excellent deformation performance [5, 6]. On the other hand, polypropylene fibers possess a low elastic modulus [4]. But PP fibers are flexible, significantly enhancing concrete's ductility [4]. Furthermore, PP fibers are becoming popular because they are lightweight [5, 2], easily dispersed in concrete [5, 2, 4], and have good resistance to corrosion and aggressive chemicals [5, 2, 4]. Meanwhile, PVA fibers have a low ultimate strain and greater elongation at break. They have good corrosion, frost, and thermal resistance [7]. Glass fibers were realized in the 1940s. However, at first, it was difficult to mix GF with concrete due to the low alkali resistance to corrosion of GF. Then, in the mid-1960s, improved alkali-resistant GFs were made using high levels of zirconium dioxide. But in the early 1980s, a new generation of fiber composites evolved and provided substantially improved tensile, flexure, and impact strengths [8].

The addition of a single type of fiber can improve the performance of concrete. However, the action of single fibers cannot provide all-sided enhancement on the properties of concrete [2]. The integration of different types of fibers into the same concrete mixture to form what is known as Hybrid Reinforced Concrete can conquer the limitations of single-fiber reinforced concrete. Mixing several types and sizes of fibers will provide a positive hybrid effect because fibers will complement each other’s advantages [2, 7]. In the paper of Fu et al., they mentioned that the flexural strength and toughness and fracture energy of hybrid fiber-reinforced concrete was better than those of single fiber-reinforced concrete [4]. Moreover, some researchers believe that mixing

fibers with different moduli of elasticity, strengths, and sizes will further enhance the strength and toughness of concrete [5]. Rigid fibers with high elastic modulus can bear higher stresses, whereas flexible fibers can improve the ductility of concrete [9, 4]. Short fibers will act during the early loading stages where the micro-cracks start appearing to improve peak strength; then, long fibers will bridge the wider cracks as the loading increases to enhance the toughness and post-load region [6, 5, 2]. The bottom line is that hybrid fibers' synergetic effect will upgrade the strength and fracture performance of concrete better than single-fiber reinforced concrete.

1.1.1. Basalt & Polypropylene

Different researchers have studied the effect of mixing BF and PPF. The research work of Deng et al., Liang et al. and Shi et al. proved that incorporating a mixture of micro basalt and macro polypropylene fibers has a better impact on the flexural and load-bearing performances of concrete than the action of each alone [6, 5, 2]. Similarly, Fu et al. deduced that adding micro basalt and PP fibers improves the mechanical behavior of concrete [9]. The advantage of the mixture of BF and PPF is that each fiber will have a different role during the different loading or fracture phases.

BFs have relatively high elastic modulus compared to PPF; hence, they can resist larger tensile stresses. Moreover, during the early stages of concrete, micro BFs can inhibit the development and propagation of micro-cracks due to plastic shrinkage and temperature deformation [6, 5]. Thus, BFs reduce both the number and size of the cracks. However, since the basalt fibers have a low fracture elongation rate, the fibers will break or pull out once the macro-cracks appear during the loading stage. On the contrary, macro-PP fibers possess a high elongation capacity that allows them to bridge wide

cracks. The bridging effect of fibers allows the concrete beams to maintain some bearing capacity and a long load-bearing time after the appearance of cracks [6, 5, 2]. Among the different mixtures of mono basalt, mono PP, and hybrid BF and PP prepared by Deng et al., HBPFRC showed the highest increase in flexural strength equal to 42.5%. Moreover, HBPFRC showed improved flexural ductility compared to plain concrete. The failure modes of HBPFRC transformed from brittle failure to ductile failure [6]. The enhancement effect of the hybrid fibers on concrete's deformation and ductility performances is more significant than the effects of each fiber alone [9].

Meanwhile, Liang et al. deduced that the fracture energy and toughness of HBPFRC are superior to that of plain concrete. However, they negated the idea of indefinitely increasing fiber content because the fracture toughness stops improving significantly after a certain amount of fibers [5]. Shi et al. investigated the effect of BF and PP on the compressive strength of concrete. The tests targeted C30 and C60 grade mixtures. They found that the hybrid mixture of basalt and polypropylene increases the compressive strength by approximately 10% and 20% respectively [2]. With increasing compressive loading, the specimen will commence developing cracks in the weakest zone of the concrete. The fibers will start stretching and debonding at the fiber-matrix interfaces, which reduces the crack-tip stress concentration. Particularly, the fibers will act as transfer bridges of the stress, which will slow local crack propagation and hence decrease the chances of sudden collapses of concrete [2]. Shi et al. also observed that fracture patterns of HBPFRC are more likely similar to patterns 3 and 4 illustrated in Figure 2 below.

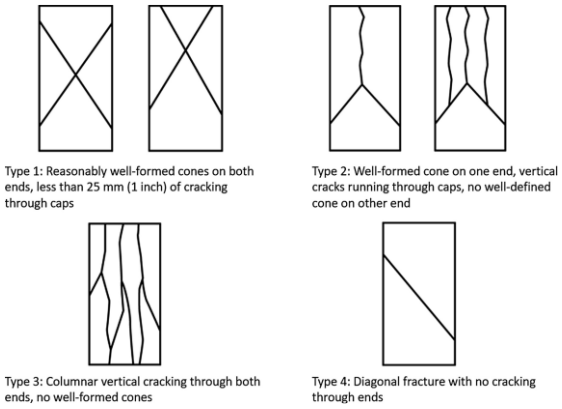


Figure 2: Typical compressive failure patterns of concrete cylinders

Fu et al. also focused on the effect of BF and PP on the integrity of destroyed concrete. They observed that the integrity of destroyed samples of HBPFRC under uniaxial loading is better, and specimens showed less spalling on the corners. Moreover, the specimens contained more fine cracks compared to plain concrete [9].

1.1.2. Basalt and PVA

The basalt and PVA fibers each have advantageous effects on hardened concrete, hence combining these two types of fibers will further enhance the properties of concrete as proved by some researchers. In the paper written by Su et al., they deduced that the hybridization effect on reinforced concrete is positive [7]. Zhen-bo et al. studied the effect of Basalt and PVA mixture in engineered cementitious composites (ECC) at elevated temperatures. They concluded that partially replacing the PVA with basalt fibers increases the compressive residual toughness which alleviates the brittleness behavior of concrete failure at 400℃. Moreover, the presence of basalt fiber in the mixture improves the tensile strength up to a temperature of 200℃ and aids in delaying the sharp reduction of the strength at 400℃. The partial replacement of PVA will also yield a lower cost

material because the basalt fibers are cheaper than PVA [10]. In the work of Ozkan et al., the hybrid basalt and PVA significantly enhanced the flexural strength by 19% when compared to the mono PVA mixture in ECC [11].

The hybrid mixture is also superior relative to plain concrete. Su et al. results presented an increase in compressive strength, splitting tensile strength, and flexural strength by 40.06%, 42.58%, and 37.3% respectively when adding 0.3% volume ratio of basalt, 0.2% volume ratio of PVA, and 5% volume ratio of rubber [7]. Jalal et al. studied the effect of basalt and PVA on the first crack toughness and flexural toughness. For an equal volume ratio of 0.3% and 0.6% for each of the BF and PVA, the first crack toughness increases by 54% and 56%, the flexural toughness improves by 8% and 12%, and the maximum deflection upsurges by 74% and 81%, respectively [12]. In addition, they observed that the load-deflection curve of BF and PVA hybrid mixture concrete extends beyond the peak load with a large deflection before failure [12]. This favorably enhances the ductility of the concrete.

The synergetic effect of basalt and PVA is similar to that of BF and PP. At the earlier stages of loading, the concrete matrix will bear the load. As the loading increases, micro-cracks will initiate and propagate within the matrix. Basalt fibers with high elastic modulus will bear the main load and inhibit the propagation of these cracks. However, with the further increase of the load, the micro-cracks will develop into larger cracks where the action of basalt fiber becomes minimal. PVA fibers will bridge the larger cracks which cumulatively improve the mechanical properties of concrete [7, 10, 11].

1.1.3. Polypropylene and PVA

Maheswaran et al. compared the shear performance of hybrid-engineered cementitious composite beams containing a mixture of polypropylene and PVA to mono steel, PVA, and polypropylene ECC beams. The results revealed a significant increase in the failure strain of hybrid ECC. The failure strain of the PVA and PP mixture was 0.008 greater than the values of steel, PVA, and PP which were 0.0041, 0.0038, and 0.0031 respectively. Moreover, the hybrid mixtures of fibers resulted in effective lateral confinement, leading to a larger lateral expansion when compared to mono fibers. The PVA and PP-ECC showed larger lateral bulging without sudden collapse [13]. Furthermore, the addition of PVA and PP fibers increased the critical shear crack angle to 58.9 degrees compared to 35.9 degrees and 46.4 degrees for PP and steel fibers respectively. The hybridization effect is more effective in restraining the propagation of the major shear diagonal crack where the hybrid PVA and PP inhibited the further opening and widening of the shear crack. The flexural cracks initiated the failure of the hybrid ECC beams which failed due to the combined flexure-shear mode. The addition of hybrid fibers improved the toughness of the beams, and the failure was more ductile compared to the mono ECC specimens [13].

Lin et al. discovered both positive and negative confounding effects of hybrid ECC in their research work. The hybridization of PVA and PP fibers inhibits the initiation and development due to their bridging effect, which positively affects the tensile strength of ECC specimens. Their results revealed that the ultimate tensile strain and strength of PP and PVA fibers increased significantly. In the PP and PVA specimens having a 1% volume ratio of PVA, the addition of 0.5%, 1%, and 1.5% of PP improved the tensile strength by 9.46%, 21.1%, and 57.7% respectively, and increased the ultimate tensile

strain by 22.1%, 59.3%, and 69.0% respectively [14]. However, the incorporation of PVA and PP led to a lower compressive strength when compared to mono PVA ECC which resembled a negative confounding effect. The uneven dispersion of the fibers can create more porosity in the mixture which increases the initial defects in the matrix leading to reduced compressive strength. In addition, the elastic modulus of PP fibers is less than that of the PVA fibers, so the replacement of the higher elastic modulus fibers with lower modulus fibers will reduce the ability of the specimen to resist more stresses and thus reduce the compressive strength. Furthermore, both PVA and PP and PVA ECC specimens experienced a decrease in their elastic moduli with the increase in fiber volumetric ratios [14].

Lin et al. also studied the effect of hybridization on impact loading. The addition of PP and PVA improved the impact resistance of the specimens. For the 1% PVA ECC specimens, the addition of 0.5%, 1.0%, and 1.5% increased the first crack impact strength of the specimens by 80%, 180%, and 240% respectively. It also improved the impact strength by 233%, 543%, and 586% respectively [14].

1.1.4. Polypropylene and Glass

Different researchers concluded that mixing concrete with PP and glass fibers can enhance concrete's compressive strength. In the research done by Munir et al., the compressive strength of PP and glass HFRC was greater than ordinary concrete. However, Munir et al. observed that the effect of fibers on the improvement of compressive strength is more significant for the 28-day strength than the 3- and 7-day strength [15]. In another research done by Ahmed et al., the concrete containing a hybrid mixture of PP and GF showed improved compressive strength in comparison with

ordinary concrete. The mixture containing 0.9% GF and 0.9% PPF yielded a 34.14% increase in the prism uniaxial compressive strength [16]. Similarly, in the work of Liu et al., the compressive strength of GFRC, PPFRC, and hybrid FRC increased by 4.36%, 5.84%, and 9.35% respectively, compared to ordinary concrete, which proves that the hybridization effect is better than the effect of the single fibers [17].

The mixture of GF and PP fibers positively impacts the shear strength of concrete. Ahmed et al. noted that the samples containing fibers possess higher shear strengths than the reference mixture. They also observed that the increase in GF content yielded a significant enhancement in the shear strengths. The mixture containing 0.45% of each GF and PP resulted in the maximum increase in direct shear strength approximately equal to 34%. However, they suggested that the quantity of PP fibers should be within a reasonable range because the extra PP might lead to nonuniform distribution of fibers which affects the shear strength negatively [16].

GF and PPF succeeded in improving the splitting tensile strength of tested specimens. The addition of GF and PPF improved the interfacial bonding between the fibers and the matrix. In the work by Ahmed et al., the hybrid fiber concrete mixtures presented an improved splitting tensile strength compared with the single PPF mixtures that demonstrated over a 45% decrease in the splitting tensile strength [16]. The GF and PPF also enhanced the flexural strength of concrete. The hybrid fibers bridged the micro-cracks in the tension zone which improved the modulus of rupture of concrete compared to ordinary samples [16]. Liu et al. observed that the flexural strength of fiber-reinforced concrete containing glass, PP, and a mixture of both increased by 16.58%, 17.9%, and 20.3%, respectively compared to ordinary concrete [17]. Desai et al. noted that all mixtures containing hybrid GF and PPF demonstrated an improvement in flexural

strength with a maximum increase of about 62% for the mixture containing 0.5% of GF and 0.5% of PPF [18].

Another positive effect of the hybridization of GF and PPF is the reduction in the permeability of concrete. The addition of fibers to the concrete matrix stiffens the mixture, reduces the settlement of aggregates, and decreases bleeding which reduces the ease of the flow through the material [16]. Liu et al. studied the migration of chloride in GFRC, PFRC, and HGPRF. The fibers' presence reduced chloride migration depth in the concrete samples. When the fiber volume fraction was 1.5%, the depth of chloride migration was reduced by 10.9%, 21.7%, and 23.3% for GFRC, PFRC, and hybrid GPFRC respectively compared to ordinary concrete. Likewise, the charge passed through the fiber-reinforced concrete decreased by 6.77%, 11.3%, and 20.15% respectively [17].

1.1.5. Steel and Polypropylene

The hybridization effect of SF and PPF positively affects the bond strength of unconfined and confined recycled aggregate concrete. In the research of Gao et al., they mixed SF and PPF with unconfined and confined concrete mixtures. Stirrups with a spacing of 40mm and 80mm were used to confine the concrete. They observed that the unconfined specimens experienced a splitting failure. Due to the lack of confinement in the specimens, the cracks developed and propagated rapidly reaching the surface of the concrete, resulting in the complete splitting of the sample. On the contrary, the unconfined specimens that contained SF underwent splitting–pullout failure. The presence of SF effectively inhibited the initiation and development of cracks [19].

The incorporation of SF and PPF has successfully improved the ultimate bond strength and residual strength of unconfined concrete specimens. The ultimate bond

strength of specimens having a volume ratio of SF of 0.5%, 1.0%, and 1.5% increased by 3.41%, 7.47%, and 12% respectively compared with unconfined specimens without SF. Likewise, the ultimate bond strength of mixtures containing PPF volume ratios of 0.05%, 0.1%, and 0.15% improved by 1.51%, 3.46%, and 2.04% respectively compared with unconfined specimens without PPF [19]. The SF and PPF have a positive effect on the confined specimens too. For the stirrups spacing of 80mm and 40mm and the same steel volume ratios, the ultimate bond strength increased by 4.85%, 6.68%, and 8.97% for 80mm and 2.59%, 5.48%, and 5.69% respectively for 40mm. Similarly, for the same PPF volume ratios, the same variable improved by 1.26%, 5.2%, and 3.57% for 80mm and 1.36%, 4.17%, and 3.35% respectively for 40mm spacing [19]. Furthermore, Gao et al. noticed that the bond strength of unconfined specimens with SF of 1.0% and 1.5% was approximately equal to that of well-confined specimens without SF and with a volume of 0.5% SF respectively. This reveals that SF can compensate for the bond strength loss in unconfined specimens [19].

Deng et al. noted that SF and PPF build stronger interfaces in the UHPC matrix and improve the failure pattern. UHPC would fail in an extremely brittle manner accompanied by an explosion at the peak stress. However, when fibers are added, the width of the initial main crack formed when the load reaches its maximum was smaller. Moreover, due to the bridging effect of the fibers, the crack propagated into multiple micro-cracks which prevent the fragmentation of the concrete specimens [20]. With the addition of discrete SF, the specimens showed a reduction in the elastic modulus. And with the addition of higher volume ratios of PPF, the specimens experienced a decrease in compressive strength [20].

Regarding the stress-strain response, the hybrid fibers yielded more ductility in the post–peak behavior of UHPC [20, 22]. When the crack develops, the added fibers consume more energy to surpass the interface friction needed to pull out the fibers from the matrix, thus significantly improving the toughness of UHPC [20, 21]. Deng et al. focused on the positive impact of adding PPF to the steel fiber-reinforced UHPC. PPF enhances the chemical adhesion and the friction resistance between SF and the matrix, improving SF's interfacial bonding property. The addition of 0.1% of PPF could increase the pull-out peak load, residual load, and pullout energy of SF by about 40%, 35%, and 50% respectively [20].

Chi et al. proved that adding SF and PPF improves the ultimate strength of concrete. The experiments showed that as the volume ratio of PPF increased from 0.05% to 0.1% with a constant SF volume fixed at 0.5%, the compressive strength increased by 11.1%. However, they noticed that when the PPF volume exceeded 0.15%, the compressive strength started decreasing [22]. In another experiment by Shan and Zhang, the compressive strength, splitting tensile strength and axial tensile strength of hybrid SF and PPF concrete improved by 25%, 27%, and 39% respectively. However, single SF concrete with the same steel ratio yielded lower percentages of 12%, 15%, and 18% respectively [23].

Wang et al. examined the effect of the hybridization of SF and PPF on the air content in concrete. They discovered that hybrid SF and PPF would reduce air content and air void size compared to ordinary concrete [24]. The ordinary concrete had an air void of 2.28% divided among three groups of voids: (1) 1.16% of large air voids, (2) 0.6% of medium air voids, and (3) 0.52% of small air voids. The percentages indicated that ordinary concrete was mainly formed of large voids. However, upon the addition of 0.1%

fixed PPF and SF ratios of 0.5%, 1.0%, 1.5%, and 2.0%, the air content reduced by 1.22%, 2.27%, 1.23%, and 0.61% respectively, and the size of the air voids decreased. In addition, upon increasing the PPF content from 0.1% to 0.2%, the content of small air voids increases from 1.41% to 1.48% [24]. Furthermore, the mixture of SF and PPF changed the shape of the air voids where the roundness of the quasi-circular air voids became smaller. The hybrid fibers reduced harmful pores by 56.4% and increased the percentage of harmless pores [24]. These pores become helpful in the freezing and thawing of concrete where they aid in the release of expansion energy of water when frozen. The hybrid fibers would inhibit the decrease in compressive and splitting tensile strength during the early F-T cycles. However, after 100 cycles, SF and PPF showed a negative impact on the compressive strength of concrete; unlike the splitting tensile strength that increased significantly when the content of SF exceeded 1.0% [24].

1.1.6. Steel and PVA

According to Liu et al., the PVA and steel fibers do not significantly affect the compressive strength of the hybrid fiber cementitious composites. However, they greatly improve the peak strain, compressive toughness, and post-peak ductility of the composite because they can effectively restrain the formation of large cracks after post-peak loading. Liu et al. noted that the compressive strength of the ECC-containing fibers was 10% lower than non-fibrous cementitious composites.

Nevertheless, the bridging effect of SF and PVA fibers improves the deformation capability of the material. The peak strain of hybrid ECC increased by 104% to 167% compared to non-fibrous cementitious composites [25].

According to Liu et al., the flexural strength of hybrid fiber-reinforced concrete was higher than that of plain concrete [26]. The addition of 1.5% SF and 0.5% PVA almost doubled the flexural strength compared to plain concrete. They noted that the increase in SF has a positive effect on the bending strength; however, mixing additional PVA could impose a negative effect on the bending strength. Steel fibers can enhance the flexural peak load of the concrete, unlike PVA which has little influence on the peak load. However, PVA can improve the capacity of the matrix to bear additional loads in the post-peak stage which means improved flexural toughness and ductility [26]. In the experiment done by Li et al., the hybrid mixtures with the greatest volume ratio of SF presented the highest increase in the ultimate flexural load compared to the plain concrete equal to 22.7% [27].

PVA and SF have a positive effect on the tensile strength of concrete. The failure nature of SF could result in higher tensile strength. SFs tend to pull out from the mixture instead of being broken which consumes more energy and thus improves the tensile strength [26]. In addition, the capability of SF to withstand additional crack bridging loads without breaking would enhance the post-peak performance and toughness of concrete. On the other hand, PVA can improve the crack resistance of the matrix. Liu et al. noticed that the presence of PVA would create multiple microcracks at the tip of the main macrocrack before the final failure. This increases energy dissipated and thus improves the toughness and integrity of the concrete [26].

1.2. Research significance and objectives

This research project drives attention toward a novel material known as fiber-reinforced concrete. Based on the results of the first phase of the project, single fibers

proved to be effective in enhancing the properties of concrete. However, although one type of single fiber can yield the best enhancement on a specific property, it can damage or have no effect on other properties. For instance, although 0.25% glass had the best impact on the splitting tensile strength, flexural strength, and displacement ductility, it had the worst effect on the compressive strength and water absorption. Similarly, 0.25% PVA had a positive impact on the resistance to freezing and thawing, shear ductility, and pull-out strength; however, it did not significantly affect the elastic modulus and had the least performance on the tensile strength. The novelty of HFRC stems from this problem. Mixing different types of fibers could impose a greater improvement on the properties of concrete. The fibers dosages and types that had relatively the best performances in the first phase will be mixed to create seven HFRC mixtures. The effect of hybridization will be tested for the mechanical, durability, and structural properties. The aim of this project is to study the impact of hybridization on the plain concrete, and to examine the impact of incorporating different types of fibers on the performance of SFRC. The intention is to choose an optimum hybrid mixture that will have the best impact on the properties of concrete. This thesis will particularly focus on the negative and positive confounding effects of hybridization on the mechanical and durability properties of concrete.

CHAPTER 2

EXPERIMENTAL PROGRAM AND METHODS

2.1. Experimental Program

2.1.1. Materials Properties and Mixture Preparation

Ordinary ASTM C150 Type I Portland cement was used in the concrete mixtures. The aggregates used were composed of crushed limestone coarse aggregates with a maximum nominal size of 20 mm and SSD specific gravity of 2.68, medium aggregates with a maximum nominal size of 10 mm, crushed sand with a specific gravity at SSD of 2.56, and natural sand with specific gravity at SSD of 2.59. The absorption capacity of each type of aggregate was tested to correct for the batching weights of the mixture design. Table 2 below shows the results of the absorption capacity of the aggregates. Meanwhile, Figure 3 below shows the types of the used fibers while their specifications are listed in Table 3 below.

Table 2: Absorption capacity of the different types of aggregates

Material	**SSD (Kg/l)**	**Absorption Capacity**
Coarse Aggregate (20 mm)	2.68	1.5%
Medium Aggregate (10 mm)	2.68	0.8%
Natural Sand	2.56	0.8%
Crushed Sand	2.56	3.1%

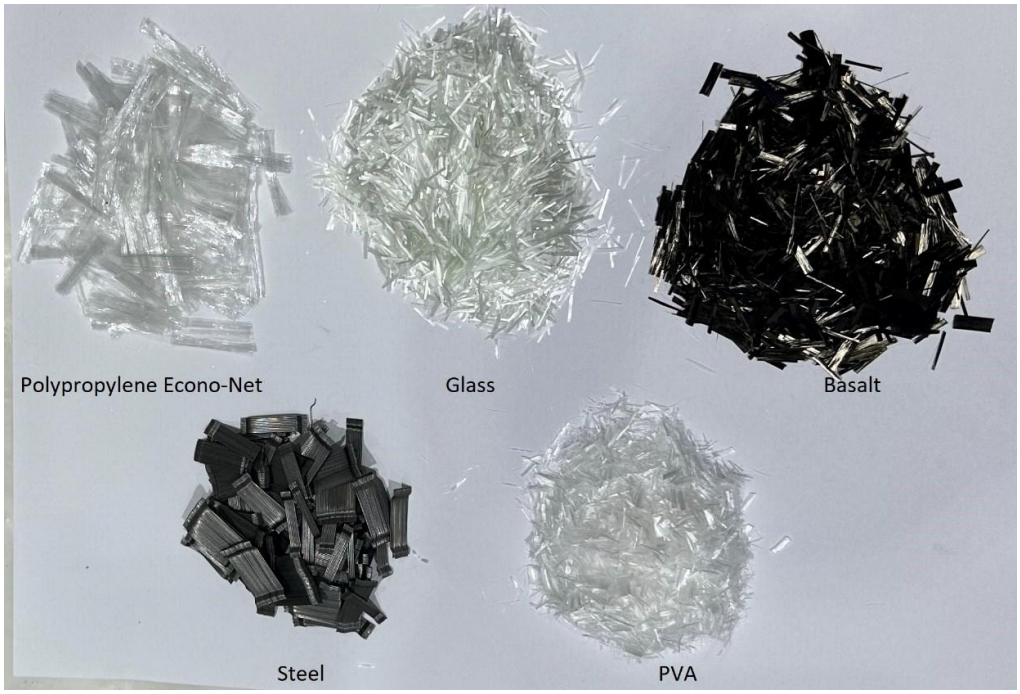


Figure 3: Types of fibers used

Table 3: Fibers Specifications

Fiber	Density (Kg/m3)	Tensile Strength (MPa)	Length (mm)	Diameter (µm)
PVA	1300	1600	8	37
PP (Econo-net)	910	570 - 660	38	900
Basalt	2670	2900 - 3100	12	17
Glass	2700	1700	12	13
Steel (30mm)	7850	1100 - 1600	30	998

The targeted compressive strength after 28 days was 35 MPa, and the slump desired was above 12 cm. The batching weights of the materials were calculated taking into consideration the absorption capacity of the aggregates used. Table 4 below presents the batching weights.

Table 4: Batching weights of the mixture design

Material	Batching Weight (Kg)
Cement	400
Water	222
Coarse Aggregates	401
Medium Aggregates	606
Crushed Sand	240
Fine Sand	451
Superplasticizer	1 (0.25% of Cement)

2.1.2. Mixtures Used

The concrete mixture should be workable and pumpable with a slump above 12 cm. To decide on the dosage of the superplasticizer to be added to the hybrid fiber-reinforced concrete mixtures, different trial batches were tested as shown in Figure 4. In addition, the used superplasticizer was a naphthalene-based high-range water-reducing (HRWR) superplasticizer complying with ASTM C494 Type F, Sikament NN-LB as shown in Figure 5. The consistency of concrete was measured using the slump test as per ASTM C 143/C143M [28] as shown in Figure 6. The slump of the mixture is a key factor in this research program because the mixture should remain pumpable and workable. Fresh concrete is added and rodded in a mold shaped like the frustum of a cone. The cone is then removed and the concrete is allowed to subside. The slump represents the distance between the original and the subsided position.

Table 5 presents the seven different concrete mixtures used in the research program, the superplasticizer dosages used for the mixtures, and the achieved slump values.

Figure 4: Trial batches preparation

Figure 5: HRWR

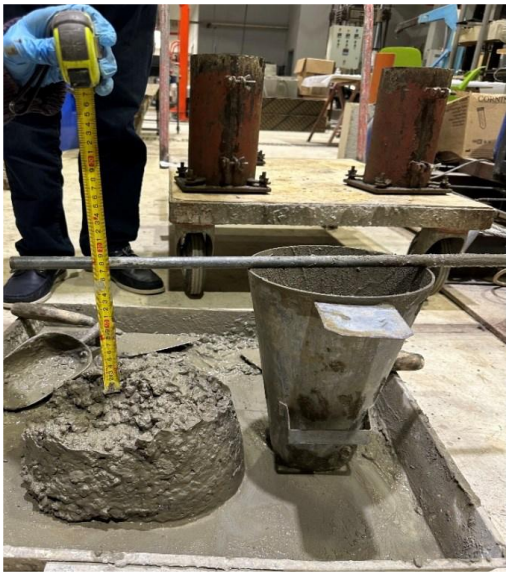


Figure 6: Slump test

Table 5: Superplasticizer dosage and slump value for the seven different concrete mixtures

	Fiber %	Superplasticizer % of cement content	Slump (cm)
Control	-	0.25	19.5
Steel and PVA	0.5 Steel and 0.25 PVA	1.75	15
Basalt and PVA	0.25 Basalt and 0.25 PVA	2.75	10.5 to 12.5
PP and PVA	0.25 PP and 0.25 PVA	2.25	14
Basalt and PP	0.25 Basalt and 0.25 PP	2.75	14
Steel and PP	0.5 Steel and 0.25 PP	1.5	14.5 to 17
Glass and PP	0.25 Glass and 0.25 PP	2	10
PP and PVA	0.125% PP and 0.125% PVA	0.75	15

2.1.3. Test Schedule

Concrete specimens were tested for their hardened mechanical and durability properties. For each tested property, two replicates were prepared to assure the reliability of the results obtained. Table 6 below summarizes the tests along with the specimens' dimensions and numbers.

Table 6: Conducted tests and specimens data

Test	Number of specimens	Sample Dimensions (mm)
Compressive strength	40 cylinders	150x300
Flexural strength	14 standard beams	75x100x400
Tensile Strength	14 cylinders	150x300
Modulus of Elasticity	21 cylinders	150x300
Resistance to Freezing and Thawing	14 standard beams	75x100x400
Absorption Capacity	14 prisms	75x100x400
Thermal Conductivity	14 plates	300x300x40

2.1.4. Formwork Setup and Preparation of Molds

Plywood molds were prepared for the standard beams (75x100x400mm) used to perform the flexural and resistance to freezing and thawing tests (Figure 7), and 300x300x40 mm plates were used to perform the thermal conductivity test (Figure 8). Meanwhile, 150x300 mm steel cylinder molds shown in Figure 9 were used to cast the concrete cylinders needed for the compressive strength, tensile strength, and modulus of elasticity tests.

Figure 7: Molds for flexural and resistance to freezing and thawing tests

Figure 8: Molds for the thermal conductivity test

Figure 9: Steel cylinders

2.1.5. Concrete Mixing, Casting, and Curing

An electric drum mixer was used to prepare the mixtures in the lab as shown in Figure 10. The mixer used had the freedom to control the mixing speed. The batching procedure consisted of different steps as follows:

- Step 1: The material for each batch was weighed and prepared
- Step 2: The aggregates were first put in the mixer with a portion of the mixing water.
- Step 3: Fibers were added to the mixer and mixed properly for around 1 minute to ensure well dispersion of fibers in the mixture and no cumulated fiber available.
- Step 4: Cement was added to the mixture with water and mixed to get a homogeneous mixture, then HRWR was added and mixed for around 3 minutes until achieving a homogeneous workable mixture.

Before casting concrete, all molds were coated with oil as shown in Figure 11 to ensure that concrete will not stick to the molds.

Figure 10: Mixer used

Figure 11: Coating molds with oil

After the mixture was ready for casting, casting started and all samples were cast in three layers where a 50 HZ electric vibrator was used to compact each layer and remove all entrapped air pockets, which will also help to improve the bond between concrete and steel and achieve a smoother concrete finishing. Figure 12 shows the vibrator used and Figures 13 and 14 show the molds before and after casting respectively.

Figure 12: Vibrator

Figure 13: Molds before casting

Figure 14: Molds after casting

Specimens were removed from the molds and placed in the curing room the next day after casting. Curing is a very important factor that should be done in order to resist

early shrinkage and to achieve the required 28 days strength. All samples were placed in water containers in the curing room as shown in Figure 15.

Figure 15: Samples under curing in the curing room

2.1.6. Cylinders Capping

Cylinders prepared for compression and modulus of elasticity tests were capped to provide a smooth and flat surface in order to ensure that the test is performed accurately. Capping with Sulphur was done using the capping machine as shown in 16. The view of the capped cylinder is shown in 17.

Figure 16: Capping machine and sulfur used

Figure 17: Capped cylinders

2.2. Testing Procedures

2.2.1. Mechanical Properties

The compressive strength was tested according to ASTM C39/C39M [29]. A compressive force is exerted on a 15x30cm cylinder until failure. Then the compressive strength is obtained by dividing the maximum axial force over the section area of the cylinder. Figure 18 illustrates the setup of a compressive strength test.

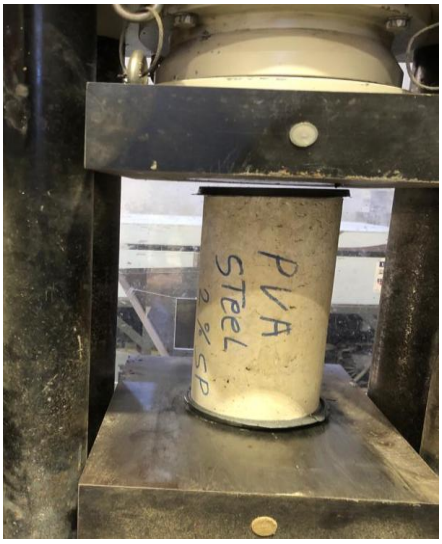


Figure 18: Compressive strength test

The Splitting tensile strength test was performed according to ASTM C496/C496M [30]. The testing machine used conforms to the requirements of ASTM C39/C39M. The machine exerts a diametrical compressive force along the length of the concrete cylinder until failure as shown in Figure 19. Then the strength is obtained by dividing the maximum load resisted over appropriate geometrical factors.

Figure 19: Splitting tensile strength

The elastic modulus is tested and calculated based on ASTM C469 [31]. A compressometer is attached to the 150x300 mmm concrete cylinder. Then, the testing machine complying with ASTM C39/C39M exerts a compressive force on the cylinder as shown in Figure 20 up until 40% of its ultimate force.

Figure 20: Modulus of elasticity test

The flexural strength is tested using the center point loading according to ASTM C293/C293M [32]. A force is exerted at the center of the concrete beam having the following dimensions (75x100x400 mm) as presented in Figure 21. The load at failure is divided by appropriate geometrical properties to obtain the modulus of rupture.

Figure 21: Flexural strength test

2.2.2. Durability Properties

To assess the durability of hybrid fiber-reinforced concrete, specimens representing the seven different concrete mixtures listed in Table 4 above were tested for water absorption, resistance to rapid freezing and thawing, and thermal conductivity.

The water absorption test was conducted according to ASTM C1585 [33]. 50 mm thick prisms were cut from the standard concrete beams (75x100x400 mm), then the specimens were coated with epoxy excluding one face through which water would be absorbed as shown in Figure 22. Each specimen was then put in contact with water, and the mass was recorded at specific durations set by ASTM C1585.

Figure 22: Preparation of prisms for water absorption test

The resistance of concrete to freezing and thawing was conducted as per ASTM C666/C666M [34]. The test specimens are concrete beams with dimensions 75x100x400 mm, same as those used for the flexural strength test. The saturated concrete specimens were placed in the freezing and thawing apparatus shown in Figure 23. After no more than 36 cycles, the thawed specimens were removed and tested for fundamental transverse frequency as illustrated in Figure 24. The specimens were scrutinized for any visible defects. And as per ASTM C666/C666M, each specimen was subject to rapid freezing and thawing cycles until its fundamental transverse frequency reached 60% of its initial frequency, or until the cycles reached up to 300 cycles.

Figure 23: Resistance to freezing and thawing test specimens

Figure 24: Testing for the transverse fundamental frequency

The thermal conductivity test complied with ASTM C177 [35]. The test measures the heat flux and associated test conditions for flat specimens which generally have low thermal conductivity. The concrete specimen should be flat and smooth, and it has dimensions of 300x300x40 mm. Figure 25 shows the thermal conductivity test machine.

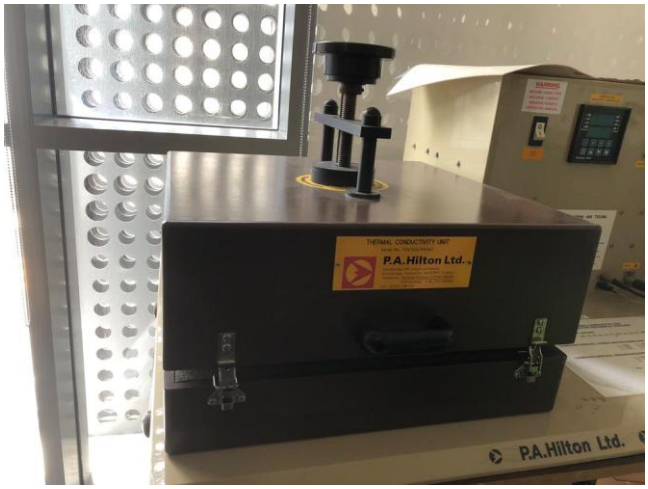


Figure 25: Thermal conductivity test machine

CHAPTER 3

TEST RESULTS AND ANALYSIS

This chapter discusses and analyzes the results obtained from the study of the effect of hybridization of fibers on the mechanical properties and durability of concrete. The analysis will commence by presenting the results of the SFRC study done, proceed by analyzing the results of the different hybrid mixtures, and conclude by comparing the results of the SRFC and HFRC.

3.1. Workability

The incorporation of different combinations of hybrid fibers significantly affected the workability of the concrete. The dosages of the superplasticizer added for HFRC mixtures to attain slump values higher than 10 cm are significantly greater than that of normal concrete (0.25%) as shown in Table 5.

The mixtures which required the highest superplasticizer percentage of 2.75% were the 0.25% basalt + 0.25% PVA and 0.25% basalt + 0.25% PP mixtures. The mixture of 0.25% PP and 0.25% PVA had the second-highest superplasticizer percentage equal to 2.25%. Meanwhile, the percentage of superplasticizer added to the mixture of 0.25% glass and 0.25% PP was 2% accounting for a slump of 10 cm. It is worth noting that when using superplasticizer dosages higher than 2%, the mixture of glass and PP segregated and bled. Nevertheless, the mixture of 0.25% steel and 0.25% PVA needed 1.75% to attain a slump of 15cm, and the mixture of 0.25% steel and 0.25% PP required a superplasticizer dosage of 1.5% to attain slump values that range between 14.5 to 17 cm. The lowest superplasticizer percentage was added to the mixture of 0.125% PP and

0.125% PVA and achieved a slump value equal to 15 cm. However, all the used dosages of the superplasticizer were below the maximum dosage permitted by the manufacturer.

PP fibers can form a network structure in the concrete matrix which reduces the ease with which coarse aggregates move; and thus, reduces the mobility of the mixture [2, 5]. In addition, the cement paste would adhere to the outer surface of the fibers reducing the flowability of the mixture. This phenomenon amplifies with fibers with greater surface area and elements for the same volumetric ratio like basalt and PVA [2, 5].

3.2. Single Fiber Reinforced Concrete Results

Table 7 below summarizes the results of the mechanical properties of the SFRC mixtures tested in Phase 1 of the AUB project. The numerical value in each cell represents the value of the strength obtained while the percentage value in parenthesis represents the change in the studied property compared to the control mixture with no fibers.

Table 7: Results of the single fiber mixtures

Mixtures	Compressive Strength at 7 days [MPa]	Compressive Strength at 28 days [MPa]	Tensile Strength at 28 days [MPa]	Flexural Strength at 28 days [MPa]	Elastic Modulus at 28 days [GPa]
Control	26.4	43.6	2.75	5.06	29.8
0.25% PP	30.9	49.2 (12.8%)	3.29 (19.6%)	11.1 (119.0%)	30.9 (3.7%)
0.25% Glass	26.7	42.0 (-3.7%)	3.69 (34.2%)	9.97 (97.0%)	31.9 (7.0%)
0.25% Basalt	32.0	48.5 (11.2%)	3.57 (29.8%)	10.5 (107.7%)	30.1 (1.0%)
0.25% PVA	26.4	43.2 (-0.9%)	2.99 (8.7%)	8.75 (72.9%)	29.0 (-2.7%)
0.5% Steel	35.1	51.9 (19.0%)	3.41 (24.0%)	10.4 (106.1%)	36.7 (23.2%)

3.2.1. Compressive Strength

The compressive strength of the single fiber mixtures was tested after 7 and 28 days.

3.2.1.1 Compressive Strength at 7 Days

Figure 26 shows the results of the compressive strength of single fibers at 7 days. The compressive strength increased from 26.4 MPa for the control specimen to a maximum of 35.1 MPa when adding 0.5% steel fibers, an increase of 33%. Moreover, the compressive strength increased to reach 32.0 MPa and 30.9 MPa when adding 0.25% basalt and 0.25% PP. They account for the improvements of 21.2% and 17.0%, respectively. Meanwhile, the effect of the addition of 0.25% glass was negligible. The strength increased slightly to reach 26.7 MPa which accounts for a 1.13% improvement. Likewise, the compressive strength remained constant at 26.4 when adding 0.25% PVA. The general trend was that none of the single fibers led to a reduction in the compressive strength at 7 days.

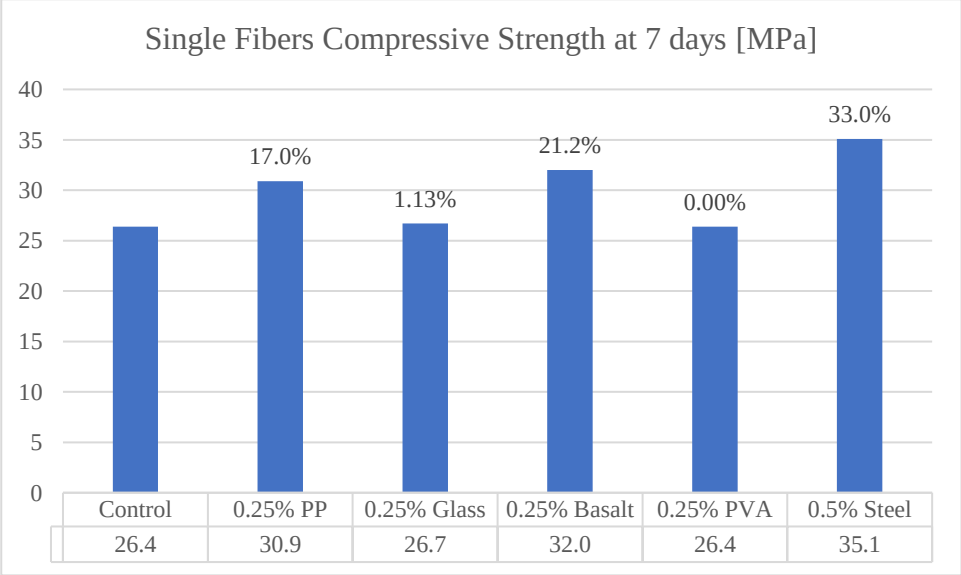


Figure 26: Seven days compressive strength values of the single fiber mixtures

3.2.1.2 Compressive Strength at 28 Days

Figure 27 shows the compressive strength of the single fiber mixtures at 28 days. The compressive strength increased from 43.6 MPa for the control mixture with no fibers to a maximum of 51.9 MPa when adding 0.5% steel fibers, an increase of 19.0%. The addition of 0.25% PP and 0.25% basalt increased the compressive strength to 49.2 MPa and 48.5 MPa which improved the strength by 12.8% and 11.2%, respectively. Meanwhile, the effect of the addition of 0.25% PVA was almost negligible where the strength decreased slightly to reach 43.2 MPa (0.89% reduction). On the other hand, the compressive strength decreased from 43.6 MPa to the lowest of 42.0 MPa when adding 0.25% glass, a reduction of 3.7%.

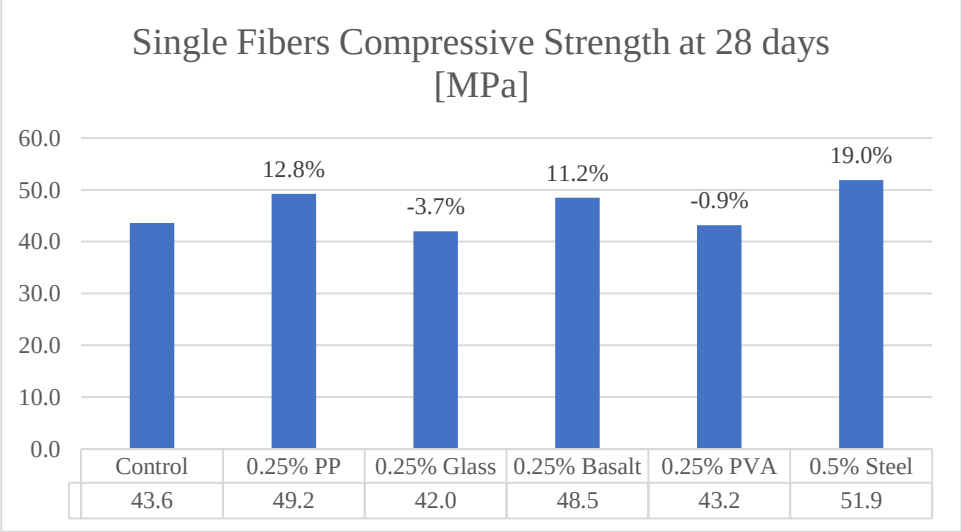


Figure 27: 28-day compressive strength of single fibers

3.2.2. Splitting Tensile Strength

All the single fiber mixtures presented in Figure 28 succeeded in improving the tensile strength of concrete. The 2.75 MPa tensile strength of the control specimen increased to a maximum of 3.69 MPa upon the addition of 0.25% glass fibers, an

improvement of 34.2%. On the other hand, the single fiber mixture with the least performance relative to the control mixture among the tested fibers was PVA; however, the addition of 0.25% PVA fibers increased the tensile strength from 2.75 MPa to 2.99 MPa with an improvement of 8.73%. Moreover, the incorporation of 0.25% basalt, 0.5% steel, and 0.25% PP increased the tensile strength to 3.57, 3.41, and 3.29 MPa, respectively. These fibers accounted for a tensile strength improvement of 29.8%, 24.0%, and 19.6%, respectively. It was concluded that the fibers play an important role in bridging the tensile cracks, and thus enhancing the tensile strength of concrete.

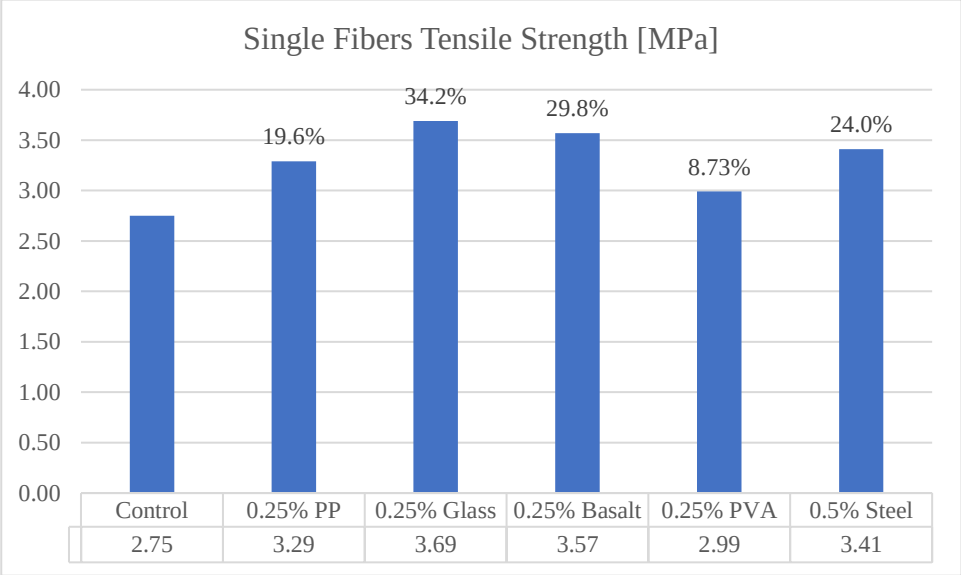


Figure 28: Single fibers tensile strength results

3.2.3. Flexural Strength

Figure 29 illustrates the results of the flexural strength test for the SFRC. The effect of the inclusion of fibers on the flexural strength is remarkable. The flexural strength of the control mixture which is equal to 5.06 MPa almost doubled to the maximum of 11.1, 10.5, and 10.4 MPa upon the addition of 0.25% PP, 0.25% basalt, and 0.5% steel, respectively. Hence, the percentages of improvement in flexural strength were

119%, 108%, and 106%, respectively. Also, the addition of 0.25% glass and 0.25% PVA yielded enhancements in the flexural strength of 97.0% and 72.9%, respectively. The crack-bridging mechanism of fibers aided in improving the flexural strength of ordinary concrete. Moreover, the brittle nature transformed into a ductile behavior.

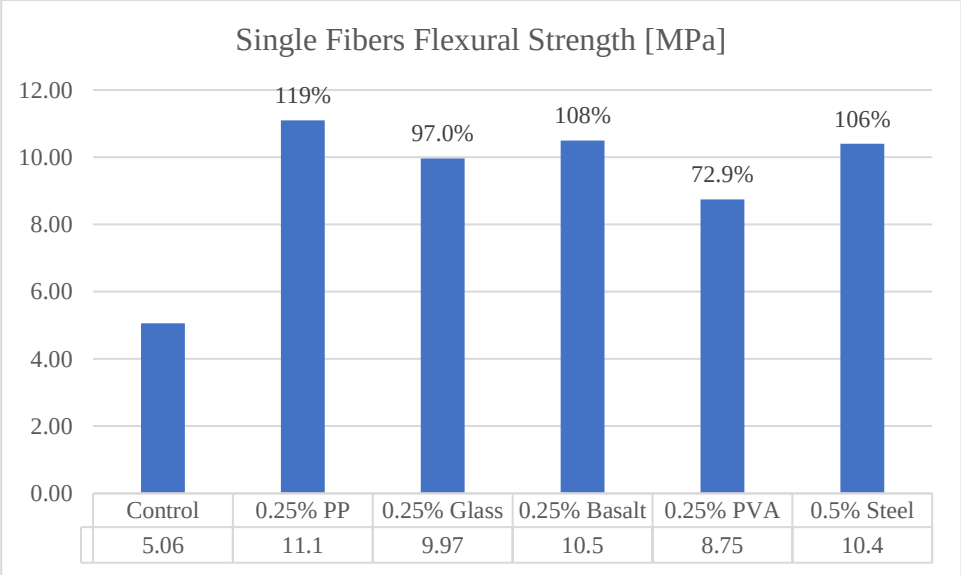


Figure 29: Single fibers flexural strength results

3.2.4. Modulus of Elasticity

Figure 30 below shows the results of the elastic modulus test of the SFRC mixtures. The general trend is that the elastic modulus did not change much when adding the single fibers, except for the case of the steel fibers. Upon the addition of 0.5% steel fibers, the elastic modulus increased from 29.8 to 36.7 GPa, a 23.2% improvement. Meanwhile, the addition of 0.25% glass, 0.25% PP, and 0.25% basalt increased the elastic modulus to 31.9, 30.9, and 30.1 GPa, respectively. These mixtures improved the elastic modulus by 7.05%, 3.69%, and 1.01%, respectively. However, the addition of 0.25% PVA fibers decreased the elastic modulus to 29.0 GPa, a reduction of 2.68%.

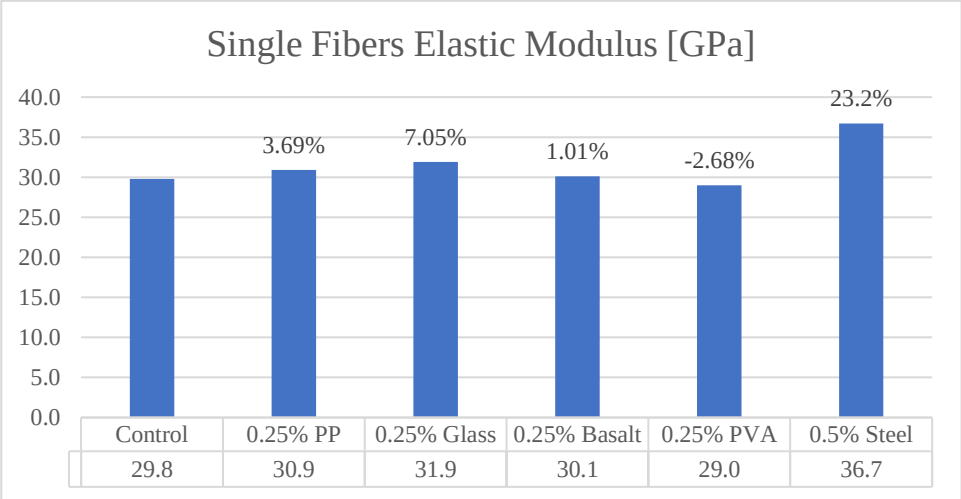


Figure 30: Single fibers elastic modulus test results

3.2.5. Water Absorption

Table 8 summarizes the results of the water absorption tests for the SFRC mixtures. The mixtures containing single 0.5% steel and single 0.25% PP decreased the water absorption of concrete. However, mixtures containing single 0.25% PVA, 0.25% glass, and 0.25% basalt increased the absorption of water. For instance, as shown in Figure 31, the water absorption at 7 days of the concrete increased from 6.11 mm to the highest of 8.80 mm upon the addition of 0.25% glass. Thus, the glass fiber reinforced concrete absorbed 44% more water than the control sample with no fibers. Similarly, the water absorption of PVA and basalt-reinforced concrete increased by 25.5% and 15.2%, respectively. On the contrary, the water absorption decreased from 6.11 mm for the control mixture to the lowest of 3.30 mm upon the addition of 0.5% steel fibers, a reduction of 46%. Likewise, the water absorption of the PP fiber-reinforced concrete decreased by 40.6%.

Table 8: Water absorption results of single fiber reinforced concrete mixtures

Fiber	Absorption [mm]												
	1 hr.	2 hr.	3 hr.	4 hr.	5 hr.	6 hr.	1 day	2 days	3 days	4 days	5 days	6 days	7 days
Control	1.15	1.42	1.56	1.74	1.90	2.07	3.61	4.52	5.04	5.48	5.76	5.97	6.11
0.25% PVA	2.25	3.18	3.70	4.21	4.56	4.92	7.14	7.46	7.54	7.60	7.64	7.64	7.67
0.25% Glass	1.70	2.08	2.61	2.87	3.19	3.45	5.96	7.71	8.41	8.68	8.85	8.80	8.80
0.25% Basalt	1.28	1.64	1.84	2.10	2.36	2.57	4.58	5.56	6.17	6.53	6.85	6.98	7.04
0.5% Steel	0.56	0.57	0.75	0.75	0.82	0.87	1.59	1.98	2.26	2.54	2.90	3.18	3.30
0.25% PP	0.85	1.03	1.09	1.24	1.26	1.36	2.10	2.58	2.90	3.14	3.36	3.49	3.63

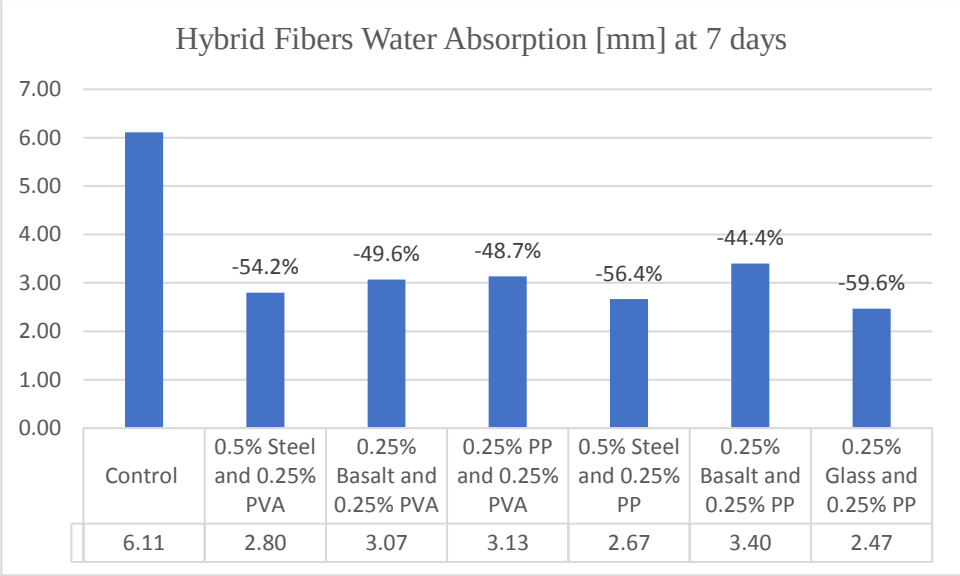


Figure 31: Water absorption of single fiber reinforced concrete [mm] at 7 days

3.2.6. Resistance to Rapid Freezing and Thawing

Table 9 shows the dynamic modulus of elasticity of the single fiber mixtures calculated using the fundamental transverse frequency obtained from the resistance to freezing and thawing test. The results of the mixtures containing 0.25% glass and 0.5% steel were similar to that of the control sample. The dynamic modulus of elasticity ranged from 50.5% to 67.9%, and the samples failed after 108 cycles of rapid freezing and

thawing. Specimens containing 0.25% PP also failed after 108 cycles, but the dynamic modulus of elasticity was 29.0% after 36 cycles. On the other hand, specimens containing 0.25% basalt failed after 144 cycles of freezing and thawing. The best performance was that of specimens containing 0.25% PVA which did not collapse even after 144 cycles.

Table 9: Dynamic modulus of elasticity (%) of single fibers

	Dynamic Modulus of Elasticity Pn (%)		
Fiber	n=36	n=108	n=144
Control	67.9	collapsed	collapsed
0.25% PVA	63.6	23.1	18.1
0.25% Glass	61.1	collapsed	collapsed
0.25% Basalt	81.1	7.84	collapsed
0.5% Steel	50.5	collapsed	collapsed
0.25% PP	29.0	collapsed	collapsed

3.3. Hybrid Fiber Reinforced Concrete Results

Table 10 below summarizes the results of the mechanical properties of the tested HFRC mixtures. The numerical value in each cell represents the value of the strength obtained while the percentage value in parenthesis represents the change in the studied property compared to the control mixture with no fibers.

Table 10: Results of the mechanical properties of the tested hybrid fiber reinforced concrete (HFRC) mixtures

Mixtures	Compressive Strength at 7 days [MPa]	Compressive Strength at 28 days [MPa]	Tensile Strength at 28 days [MPa]	Flexural Strength at 28 days [MPa]	Elastic Modulus at 28 days [GPa]
Control	26.4	43.6	2.75	5.06	29.8
0.5% Steel and 0.25% PVA	21.5 (-18.6%)	34.1 (-21.8%)	3.36 (22.2%)	8.32 (64.4%)	29.3 (-1.70%)
0.25% basalt and 0.25% PVA	26.0 (-1.50%)	35.6 (-18.3%)	3.19 (16.0%)	8.23 (62.6%)	30.0 (0.70%)
0.25% PP and 0.25% PVA	29.1 (10.2%)	38.5 (-11.7%)	3.22 (17.1%)	9.48 (87.4%)	29.5 (-1.00%)
0.5% Steel and 0.25% PP	27.6 (4.50%)	36.9 (-15.4%)	3.05 (10.9%)	10.1 (99.6%)	29.7 (-0.30%)
0.25% Basalt and 0.25% PP	28.5 (8.00%)	38.9 (-10.8%)	3.03 (10.2%)	9.01 (78.1%)	28.3 (-5.00%)
0.25% Glass and 0.25% PP	27.8 (5.30%)	38.8 (-11.0%)	3.29 (19.6%)	10.6 (109%)	29.6 (-0.70%)
0.125% PP and 0.125% PVA	22.6 (-14.4%)	31.8 (-27.1%)	2.88 (4.73%)	9.12 (80.2%)	28.3 (-5.03%)

3.3.1. Compressive Strength

The compressive strength of the HFRC mixtures was tested after 7 and 28 days.

3.3.1.1. Compressive Strength at 7 Days

Figure 32 represents the values of the compressive strength of the control and six HFRC mixtures after 7 days. The 7-day compressive strength of the control sample, equal to 26.4 MPa, increased to the maximum of 29.1 MPa for the binary mixture of 0.25% PP and 0.25% PVA, an improvement of 10.2%. In addition, the incorporation of 0.25% basalt + 0.25% PP, 0.25% glass + 0.25% PP, and 0.5% steel + 0.25% PP improved the compressive strength by 8.00%, 5.30%, and 4.50%, respectively. On the other hand, the incorporation of 0.25% basalt and 0.25% PVA reduced the strength to 26.0 MPa (1.5% reduction). The largest reduction in compressive strength was recorded for the 0.5% steel and 0.25% PVA mixture, whose value was 21.5 MPa, a reduction of 18.6%.

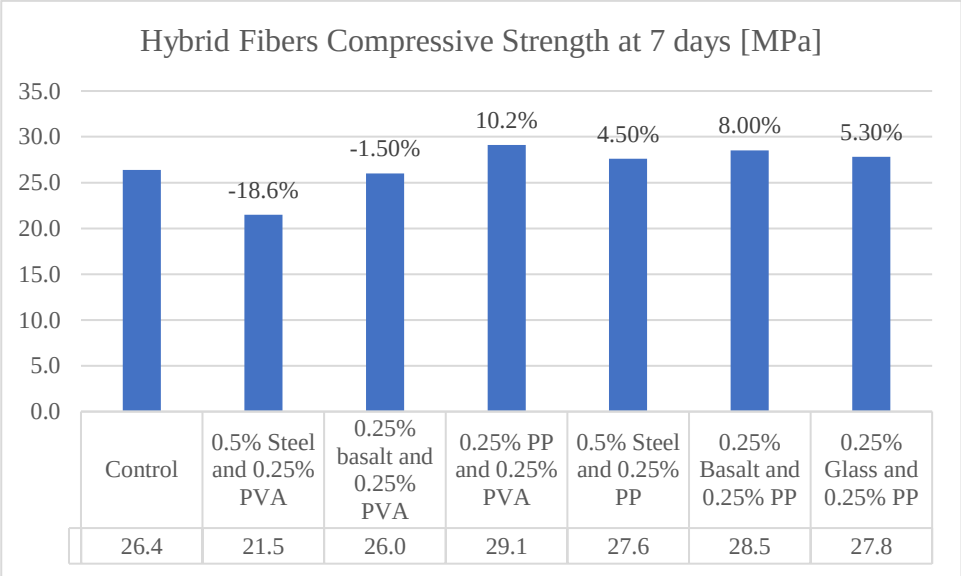


Figure 32: 7-day compressive strength of the tested HFRC mixtures

The effect of the combined addition of 0.5% steel and 0.25% PVA as compared to the action of single 0.5% steel and single 0.25% PVA is shown in Figure 33. The figure also compares the compressive strength of the mixtures to that of the control sample. The incorporation of 0.5% steel and 0.25% PVA negatively affects the 7-day compressive strength when compared to the action of single fibers. The hybrid mixture decreases the 7-day compressive strength by 18.6%. However, the addition of 0.5% steel increased the 7-day compressive strength by 33.0%, and the addition of 0.25% PVA did not affect the strength. Thus, mixing steel and PVA affected the compressive strength negatively.

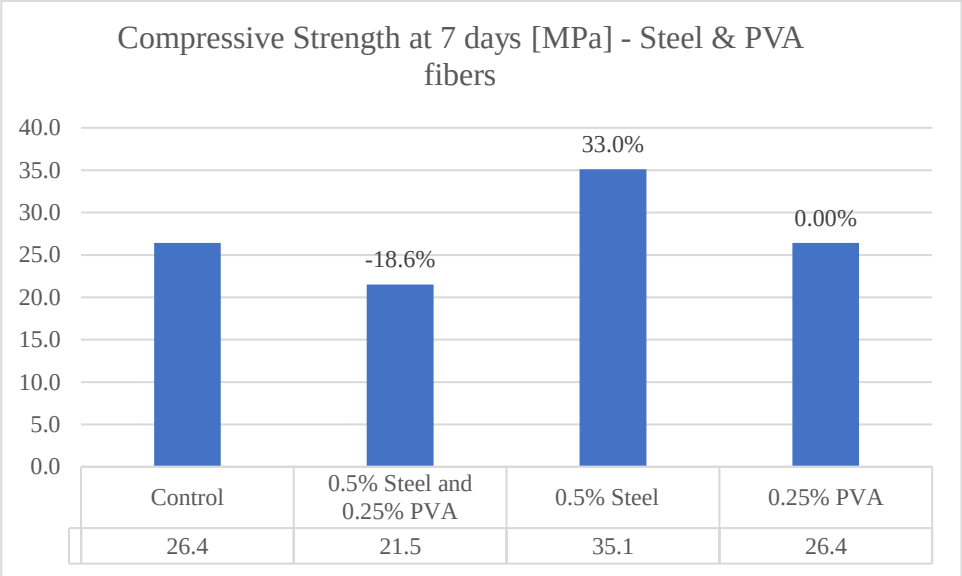


Figure 33: 7-day compressive strength of single vs. hybrid fiber reinforced concrete for steel and PVA fibers

As shown in Figure 34, the combined incorporation of 0.25% basalt and 0.25% PVA has a very similar effect on the control strength as that of the single 0.25% PVA. The hybrid mixture slightly decreased the strength to reach 26.0% (1.50% reduction) whereas the single PVA did not affect the strength at all. However, the performance of the single 0.25% basalt fiber was much better than the control mixture and recorded a 7-day compressive strength of 32.0 MPa (21.2% improvement). Thus, the hybridization negatively affected the 0.25% basalt but did not affect the single 0.25% PVA.

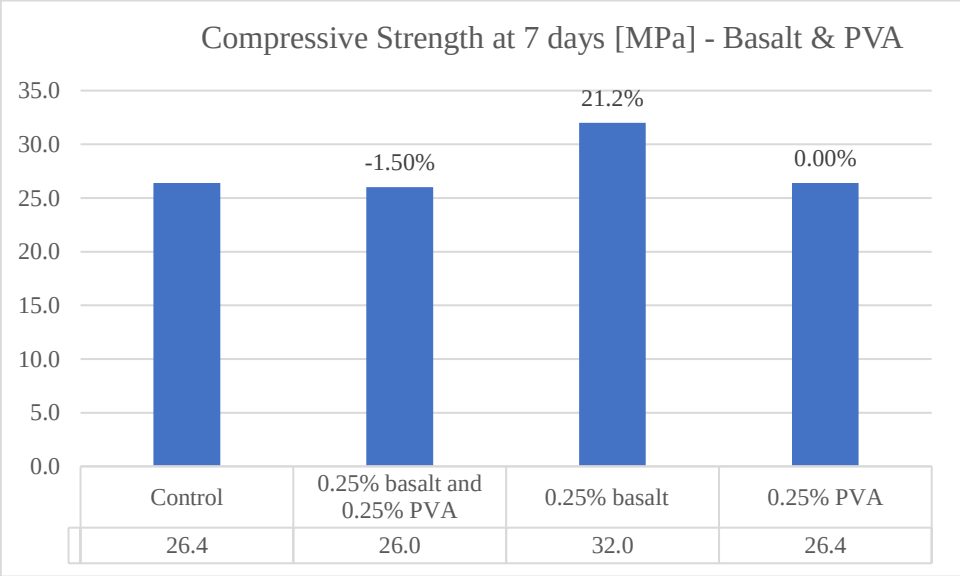


Figure 34: 7-day compressive strength of single vs. hybrid fiber reinforced concrete for basalt and PVA

Figure 35 compares the hybrid PP and PVA fiber mixture with the single PP and single PVA fiber mixtures. The incorporation of 0.25% PP and 0.25% PVA had a positive impact on the performance of the single 0.25% PVA, where the 7-day compressive strength increased from 26.4 MPa to 29.1 MPa (10.2% improvement). However, the impact of the hybrid mixture was negative compared to the performance of the single 0.25% PP fibers. The 7-day compressive strength of the single PP was equal to 30.9 MPa (17.0% improvement), higher than that of the hybrid PP and PVA by 10.2%. Thus, hybridization had a positive impact on the PVA, but it had a negative impact on the single PP.

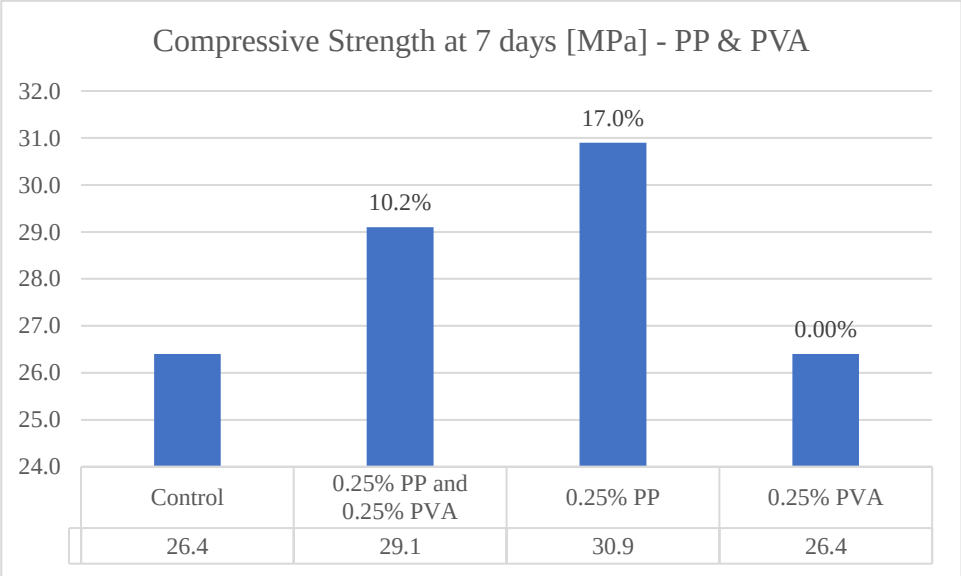


Figure 35: 7-day compressive strength of single vs. hybrid fiber reinforced concrete for PP and PVA

According to Figure 36, the effect of the hybrid Steel and PP mixture on the 7-day compressive strength was negligible when compared to that of the single steel and single PP fibers. The hybrid mixture improved the strength by 4.50%. On the other hand, the single steel fibers increased the strength to 35.1 MPa (33.0% improvement), and the single PP fibers increased the strength to 30.9 MPa (17.0% improvement). Hence, although the hybrid steel and PP mixture did not negatively affect the control sample, it negatively affected the performances of the single steel and PP fibers.

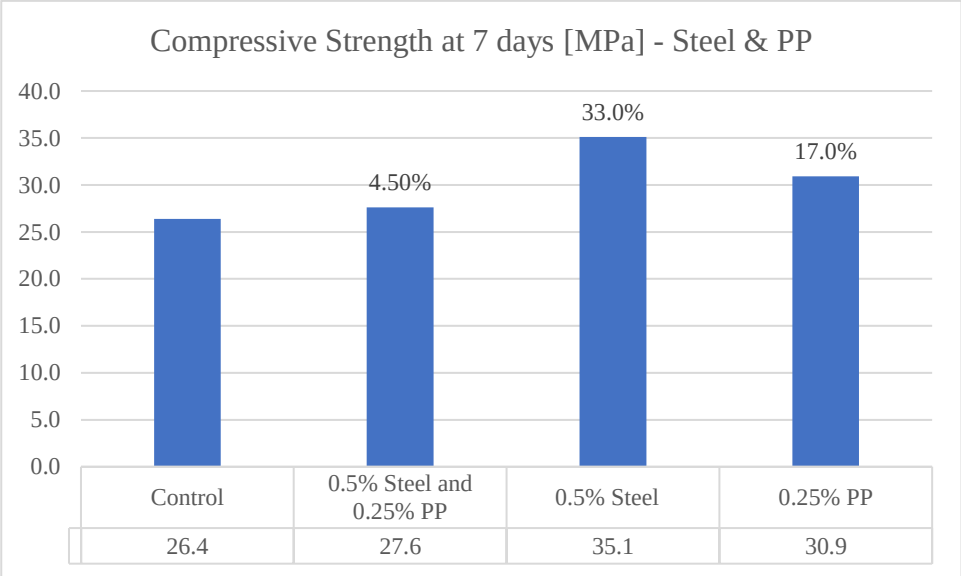


Figure 36: 7-day compressive strength of single vs. hybrid fiber reinforced concrete for steel and PP

As shown in Figure 37, the hybrid mixture of basalt and PP improved the 7-day compressive strength by 8.00%. However, the 7-day compressive strength of the hybrid basalt and PP was less than both the strengths of the single basalt and single PP. The addition of single 0.25% basalt increased the strength to 32.0 MPa (21.2% improvement), and the addition of single 0.25% PP increased the strength to 30.9 MPa (17.0% improvement). Hence, the performance of the single basalt and single PP on the 7-day strength was better than that of the hybrid mixture.

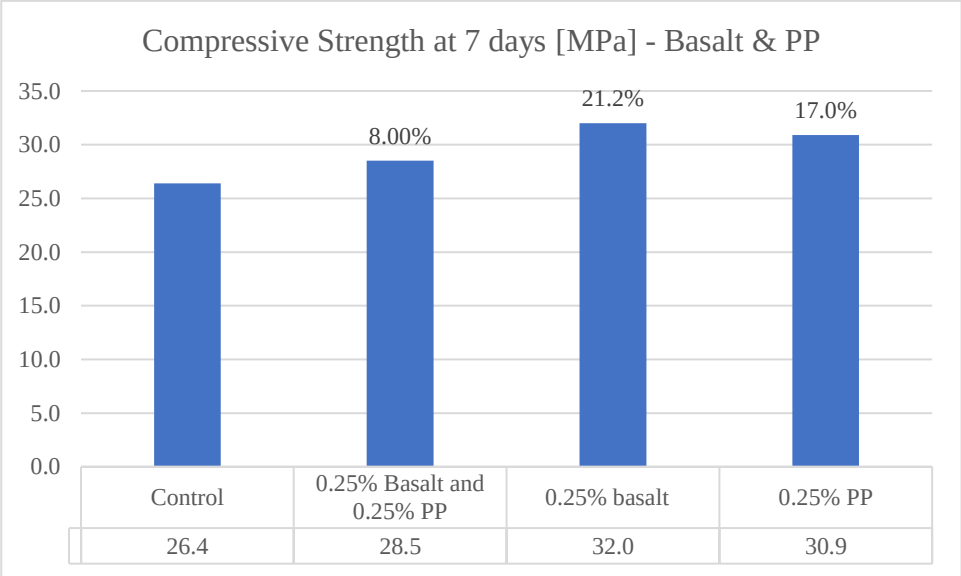


Figure 37: 7-day compressive strength of single vs. hybrid fiber reinforced concrete for basalt and PP

As shown in Figure 38, the hybrid mixture of 0.25% glass and 0.25% PP increased the 7-day compressive strength to 27.8 MPa (5.30% improvement). The strength of the hybrid mixture was greater than that of the single 0.25% glass mixture equal to 26.7 MPa. The effect of the single glass fibers was negligible (1.13% improvement). On the other hand, the strength of the hybrid mixture was smaller than that of the single PP mixture equal to 30.9 MPa (17.0% improvement). Hence, the hybridization negatively affected the impact of the single 0.25% PP fibers on the 7-day strength, but positively affected the impact of the single glass fibers.

In other words, the hybridization of fibers negatively affected the impact of steel, basalt, and PP fibers on the 7-day compressive strength. However, it had a good impact on PVA and a negligible impact on glass fibers.

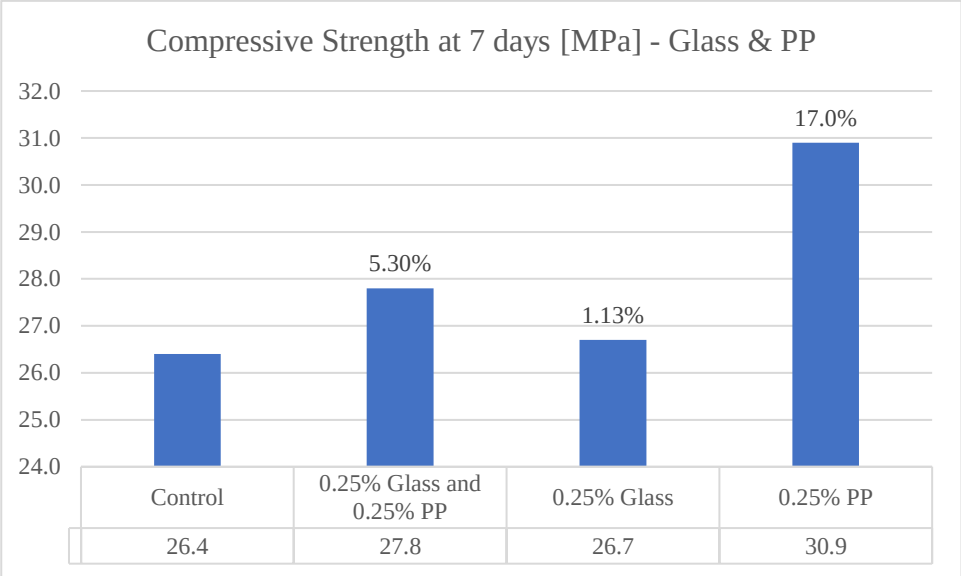


Figure 38: 7-day compressive strength of single vs. hybrid fiber reinforced concrete for glass and PP

3.3.1.2. Compressive Strength at 28 Days

Figure 39 summarizes the 28-day compressive strength values for the hybrid fibers. Unlike the single fibers, none of the hybrid fiber mixtures improved the compressive strength of ordinary concrete. The greatest drops in the compressive strength equal to 21.8% and 18.3% are associated with the addition of 0.25% steel + 0.25% PVA (34.1 MPa) and 0.25% basalt + 0.25% PVA (35.6 MPa). The compressive strengths of the remaining hybrid mixtures in ascending order are equal to 36.9, 38.5, 38.8, and 38.9 MPa for the mixtures of 0.5% steel + 0.25% PP (15.4% reduction), 0.25% PP + 0.25% PVA (11.7% reduction), 0.25% glass + 0.25% PP (11.0% reduction), and 0.25% basalt + 0.25% PP (10.8% reduction), respectively.

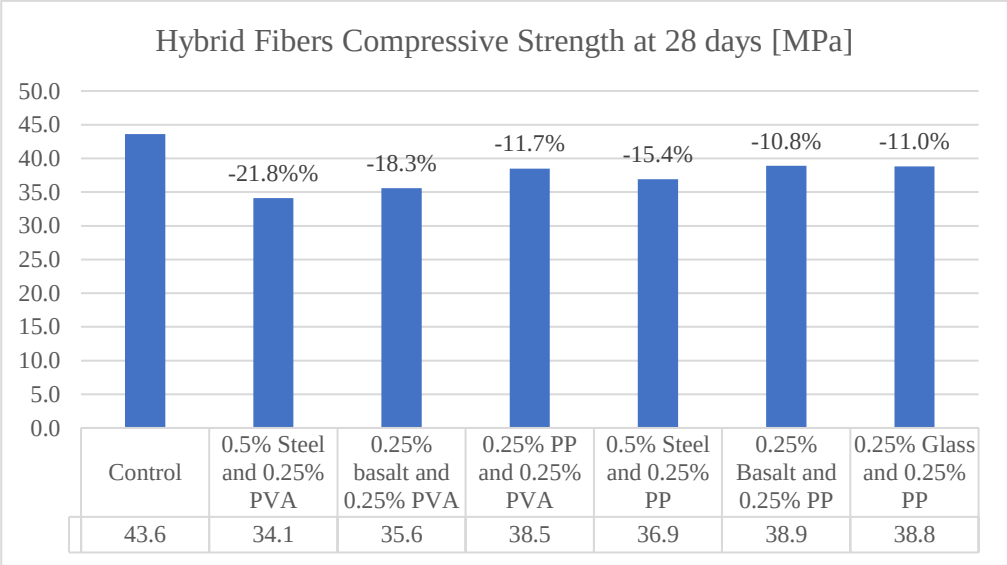


Figure 39: 28-day compressive strength for hybrid fibers

Figure 40 compares the hybrid mixture of steel and PVA to the single mixture of steel and single mixture of PVA. The binary combination of steel and PVA negatively affected the 28-day compressive strength when compared to the single fiber mixtures. The addition of hybrid steel and PVA decreased the compressive strength by 21.8% (34.1 MPa). On the contrary, the addition of single steel fibers improved the compressive strength by 19.0% (51.9 Mpa), and the addition of 0.25% had a negligible effect on the compressive strength (a reduction of 0.90%). Thus, the hybridization of fibers negatively affected the compressive strength.

In an experiment done by Liu and Han, the addition of 1.0% PVA reduced the peak load by 7%; however, when adding 1.0% PVA with 1.0% steel, the peak load decreased by 10.7% [25].

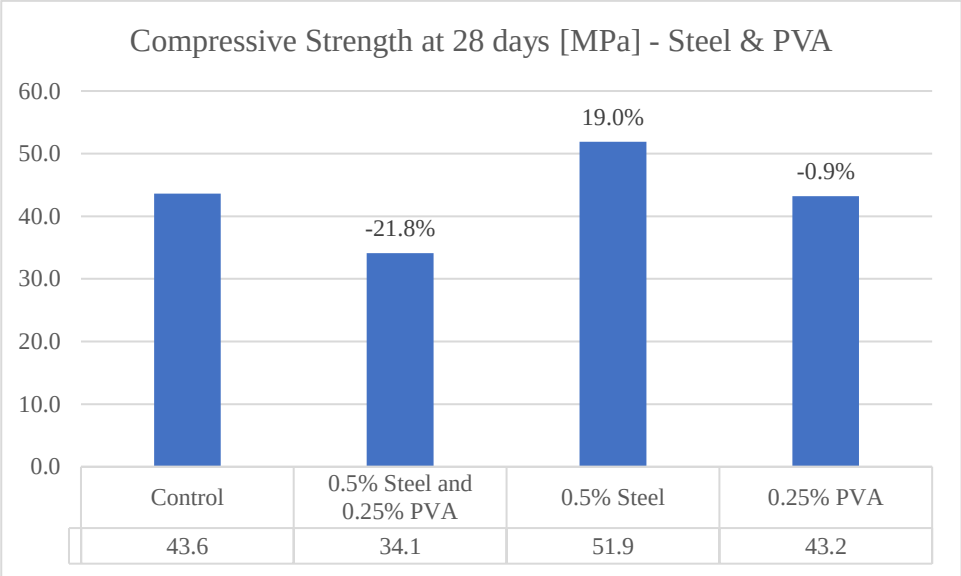


Figure 40: 28-day compressive strength of single vs. hybrid reinforced concrete for steel and PVA

As shown in Figure 41, the incorporation of a hybrid mixture of basalt and PVA negatively affected the action of single basalt and single PVA mixtures. The incorporation of 0.25% basalt and 0.25% PVA reduced the compressive strength by 18.3%. meanwhile, the addition of single 0.25% basalt enhanced the compressive strength by 11.2%, and the addition of 0.25% PVA did not affect the compressive strength (a reduction of 0.90%).

According to Jalal et al., the mixture of 0.3% basalt and 0.3% PVA reduced the compressive strength by 7.3% [12]. Similarly, in the experiment done by Özkan and Demir, the compressive strength of a mixture of PVA and basalt was 21.0% lower than the mixture of pure PVA [11].

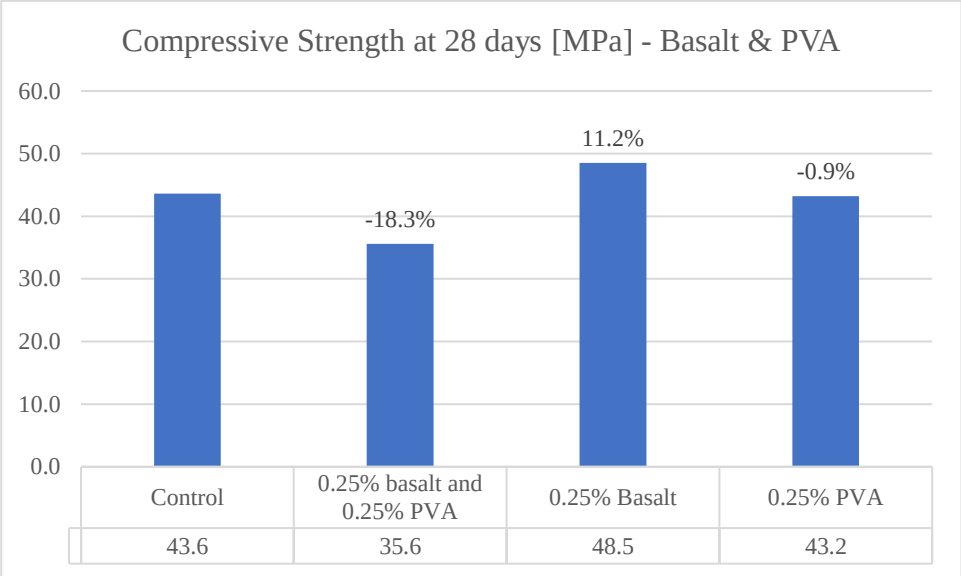


Figure 41: 28-day compressive strength of single vs. hybrid reinforced concrete for basalt and PVA

Figure 42 compares the performance of hybrid mixture of PP and PVA to that of single PP and single PVA mixtures. The addition of hybrid 0.25% PP and 0.25% PVA reduced the compressive strength by 11.7%. However, the addition of single 0.25% PP enhanced the strength by 12.8%, and the addition of 0.25% PVA had a negligible effect. Hence, the hybridization negatively affected the performance of single PP and PVA mixtures.

According to Lin et al., when they added 0.5%, 1.0%, and 1.5% of PP fibers to a constant ratio of 1.0% PVA fibers in the engineered cementitious composites, the compressive strength decreased by 6.73%, 10.6%, and 35.7% [14].

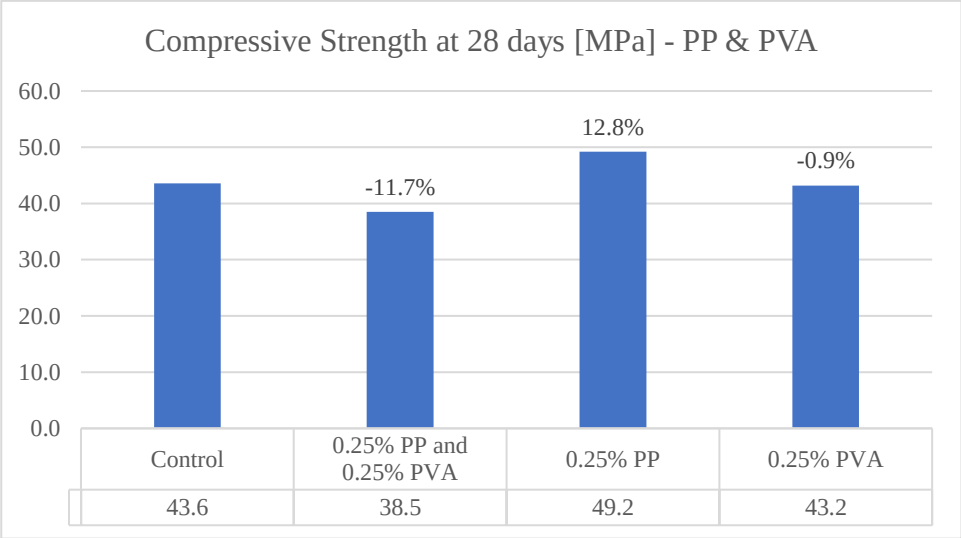


Figure 42: 28-day compressive strength of single vs. hybrid reinforced concrete for PP and PVA

According to Figure 43, the hybrid combination of 0.5% steel and 0.25% PP decreased the compressive strength by 15.4%. On the other hand, the single mixture of 0.5% steel improved the compressive strength by 19.0%, and the single mixture of 0.25% PP enhanced the compressive strength by 12.8%. Therefore, the hybridization negatively affected the performance of single steel and single PP mixtures.

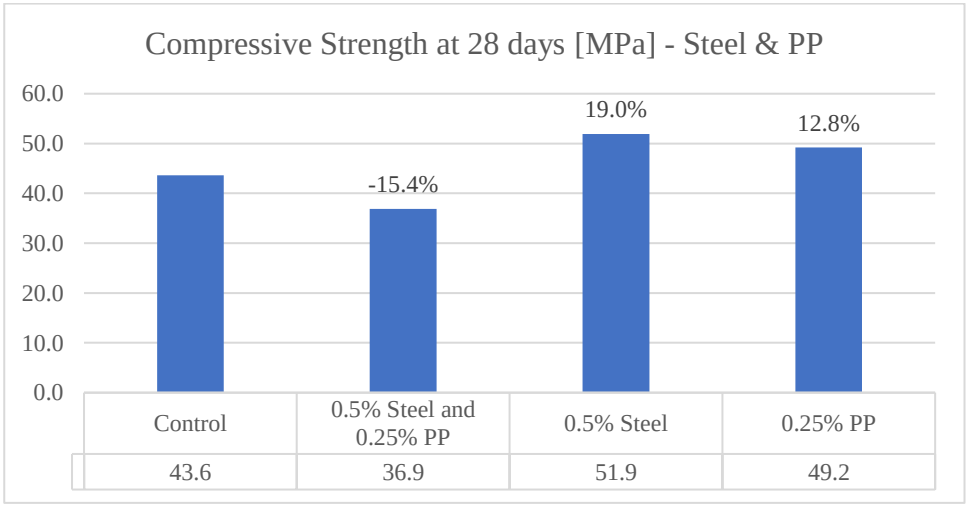


Figure 43: 28-day compressive strength of single vs. hybrid reinforced concrete for PP and steel

Similarly, Figure 44 shows the negative impact of the hybrid basalt and PP mixture on the compressive strength. The binary combination of 0.25% basalt with 0.25% PP reduced the compressive strength by 10.8%. Meanwhile, the addition of single 0.25% basalt and single 0.25% PP mixtures enhanced the compressive strength by 11.2% and 12.8%, respectively.

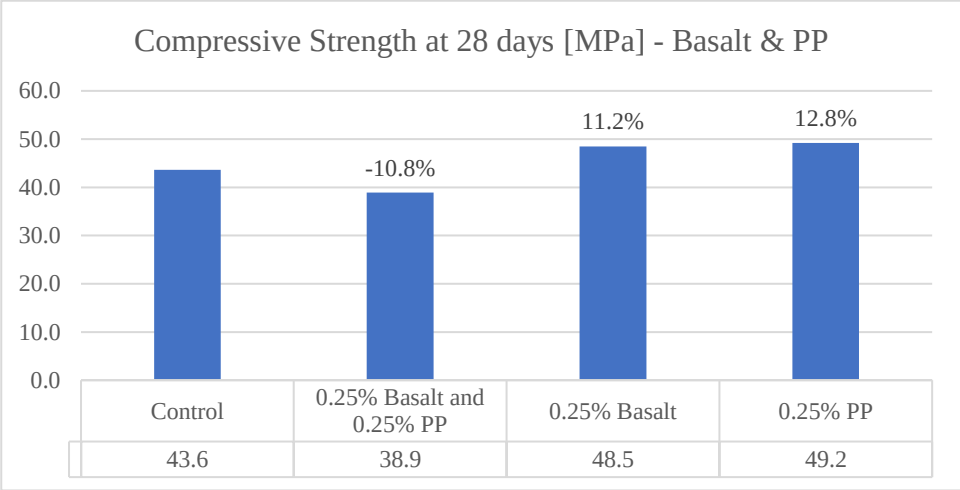


Figure 44: 28-day compressive strength of single vs. hybrid reinforced concrete for PP and basalt

According to Figure 45, the compressive strength of the hybrid 0.25% glass and 0.25% PP mixture decreased the compressive strength by 11.0%. However, the incorporation of a single 0.25% PP improved the strength by 12.8%, and the addition of single 0.25% glass did not impact the compressive strength (a reduction of 3.7%). Hence, the hybridization negatively affected the action of single PP and single glass fibers.

In the experiment done by Ahmad and Jia, the addition of 1.35% GF improved the compressive strength by approximately 55%, the addition of 1.35% PP reduced the strength by about 22%, but the addition of 1.35% GF and 1.35% PP further reduced the compressive strength by approximately 48% [16].

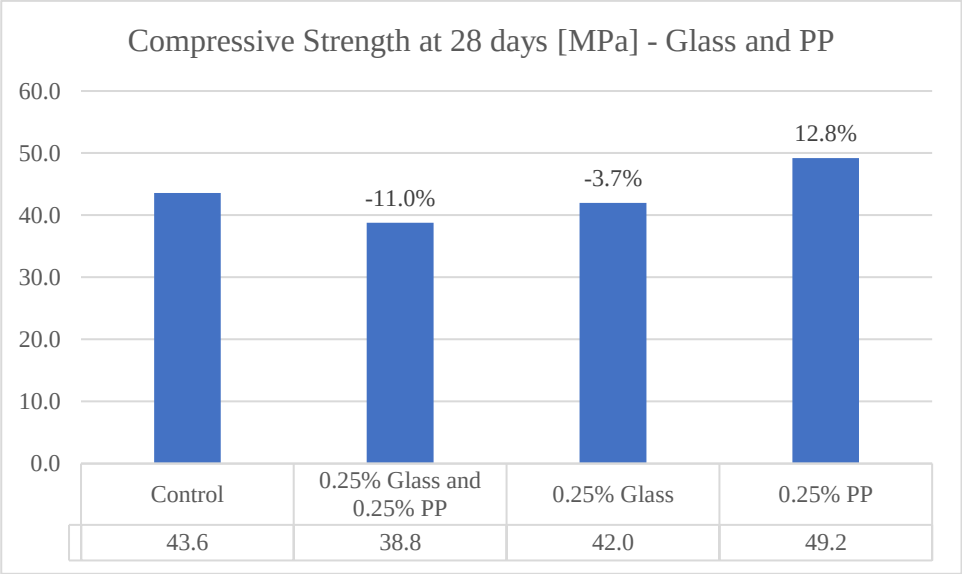


Figure 45: 28-day compressive strength of single vs. hybrid reinforced concrete for PP and glass

Overall, the hybridization of fibers negatively affected the performance of all the single fibers on the 28-day compressive strength. Upon the addition of an equal volumetric fraction of a second type of fiber, the volume of fibers in the mixture doubles. This could be a reasonable cause of the reduction in the compressive strength of ordinary concrete. As the volume of fibers increases, it becomes more difficult to achieve a uniform distribution of the fibers. The uneven distribution of fibers will increase the initial defects in the microstructure of concrete thus reducing the compressive strength [12, 14, 16, 25]. Correspondingly, the addition of 0.25% PVA to steel and basalt reduces the compressive strength more than the addition of 0.25% PP. For the same volumetric ratio of PP and PVA, the number of PVA fibers added would be much greater than the number of PP fibers added because of the smaller dimensions of the PVA fibers. Thus, the defect introduced by the PVA fibers is more than that introduced by PP fibers.

3.3.2. Splitting Tensile Strength

Figure 46 illustrates the results related to the hybrid fiber mixtures. Similar to the case of SFRC, all the hybrid fiber mixtures enhanced the tensile strength of ordinary concrete. When mixing 0.5% steel with 0.25% PVA, the tensile strength increased from 2.75 MPa to the highest of 3.36 MP, a 22.2% improvement. Moreover, the addition of 0.25% glass to 0.25% PP, and the addition of 0.25% PVA to 0.25% PP and 0.25% basalt enhanced the tensile strength by 19.6%, 17.1%, and 16.0% where the control sample's strength increased to reach 3.29, 3.22, and 3.19 MPa, respectively. Meanwhile, the addition of 0.25% PP to 0.5% steel and 0.25% basalt increased the tensile strength to 3.05 and 3.03 MPa accounting for improvement equal to 10.9% and 10.2%, respectively.

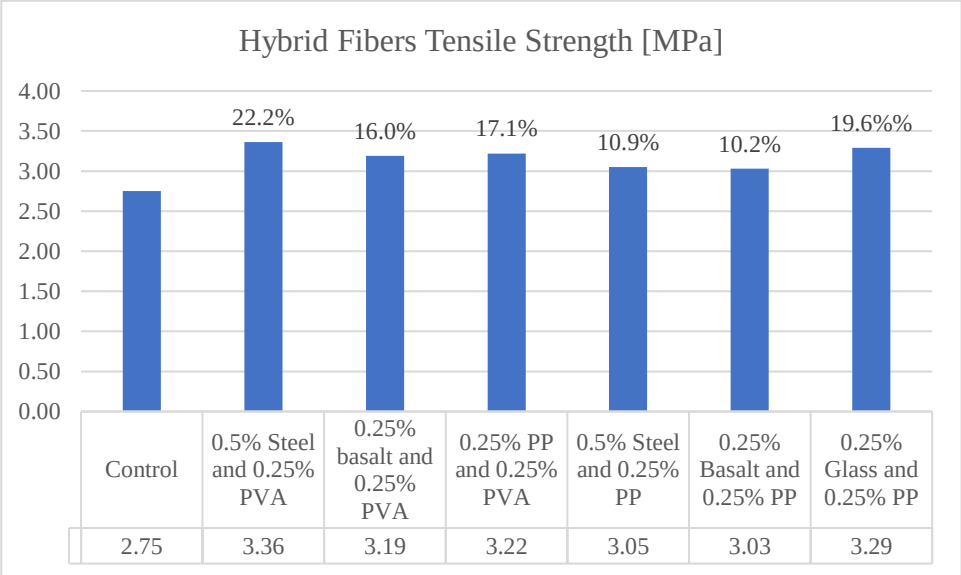


Figure 46: Hybrid fibers tensile strength

According to Figure 47, the addition of hybrid 0.5% steel and 0.25% PVA enhanced the tensile strength by 22.2%. similarly, the addition of 0.5% steel improved the tensile strength by 24.0%, which is close to that of the hybrid mixture. However, the addition of single 0.25% PVA improved the tensile strength by 8.73%. Thus, the

hybridization positively affected the performance of single PVA, but it had no effect on the performance of single 0.5% steel.

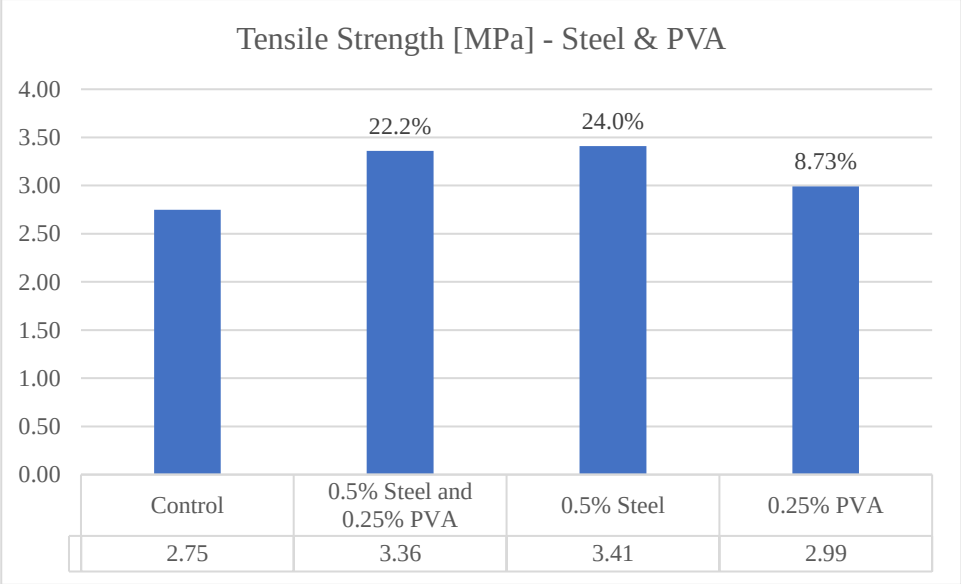


Figure 47: Tensile strength of single vs. hybrid reinforced concrete for steel and PVA

According to Figure 48, the incorporation of binary combination of 0.25% basalt and 0.25% PVA enhanced the tensile strength by 16.0%. however, the addition of single 0.25% basalt improved the tensile strength by 29.8%, and the addition of 0.25% PVA improved the strength by 8.73%. Hence, the hybridization negatively affected the action of 0.25% basalt, but it positively affected the action of single PVA fibers.

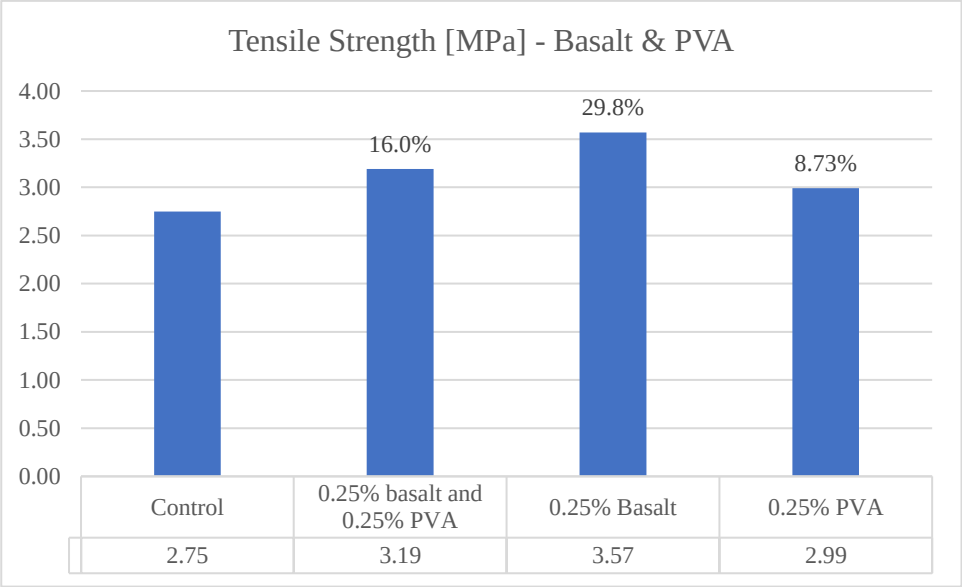


Figure 48: Tensile strength of single vs. hybrid reinforced concrete for basalt and PVA

According to Figure 49, the tensile strength of the hybrid mixture of 0.25% PP and 0.25% PVA increased by 17.1%. Meanwhile, the tensile strength of the single 0.25% PP mixture increased by 19.6% which is close to 17.1%, and the strength of the single 0.25% PVA increased the strength by 8.73%. Thus, the hybridization did not have a significant effect on the performance of single PP fibers, but it enhanced the performance of single PVA fibers.

According to Lin et al., the control sample, the samples containing 1.0% PVA, and the samples containing 1.0% PP and 1.0% PVA yielded tensile strengths equal to 4.34, 4.44, and 5.60 MPa, respectively. The action of a single PVA improved the tensile strength by 2.3%, and the action of the hybrid PP and PVA enhanced the strength by 29.0% [14].

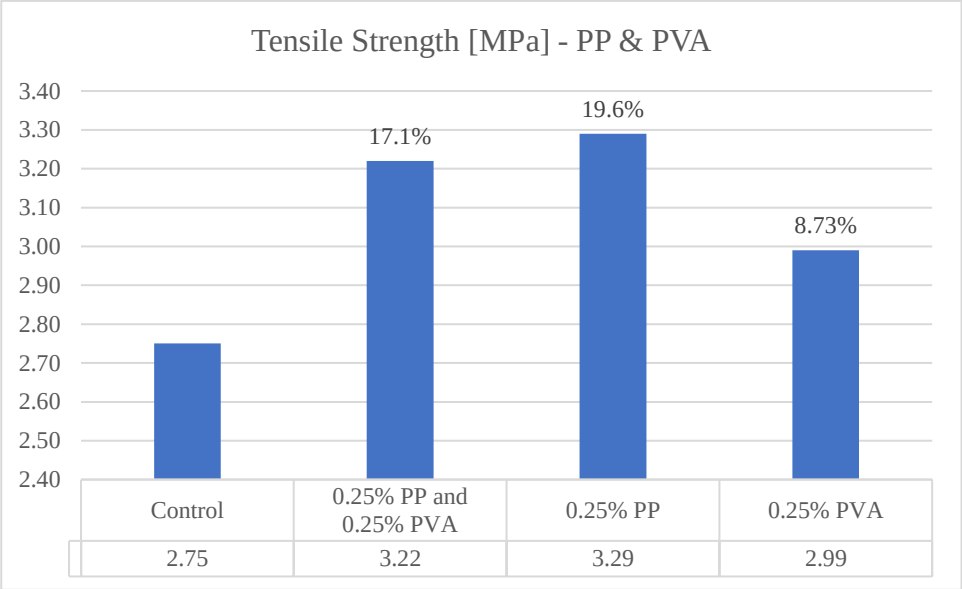


Figure 49: Tensile strength of single vs. hybrid reinforced concrete for PP and PVA

As shown in Figure 50, the tensile strength of the hybrid 0.5% steel and 0.25% PP mixture improved by 10.9%. Meanwhile, the tensile strength of the single 0.5% steel improved by 24.0%, and the strength of single 0.25% PP increased by 19.6%. Thus, the hybridization of fibers negatively affected the performance of single steel and PP fibers.

In an experiment done by Shang and Zhang, the incorporation of 0.4% steel fibers and 0.15% PP fibers improved the tensile strength by 8.87% where the strength increased from 3.27 MPa to 3.56 MPa [23].

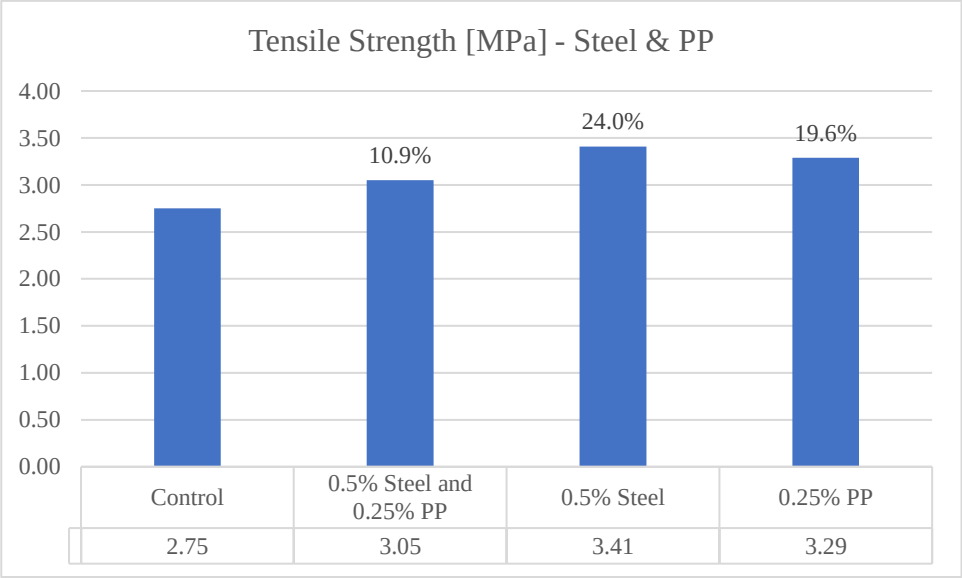


Figure 50: Tensile strength of single vs. hybrid reinforced concrete for PP and steel

As shown in Figure 51, the addition of hybrid 0.25% basalt and 0.25% PP improved the tensile strength by 10.2%. However, the addition of single 0.25% basalt enhanced the strength by 29.8%, and the addition of single 0.25% PP improved the strength by 19.6%. Thus, the hybridization of basalt and PP negatively affected the performance of single PP and basalt mixtures.

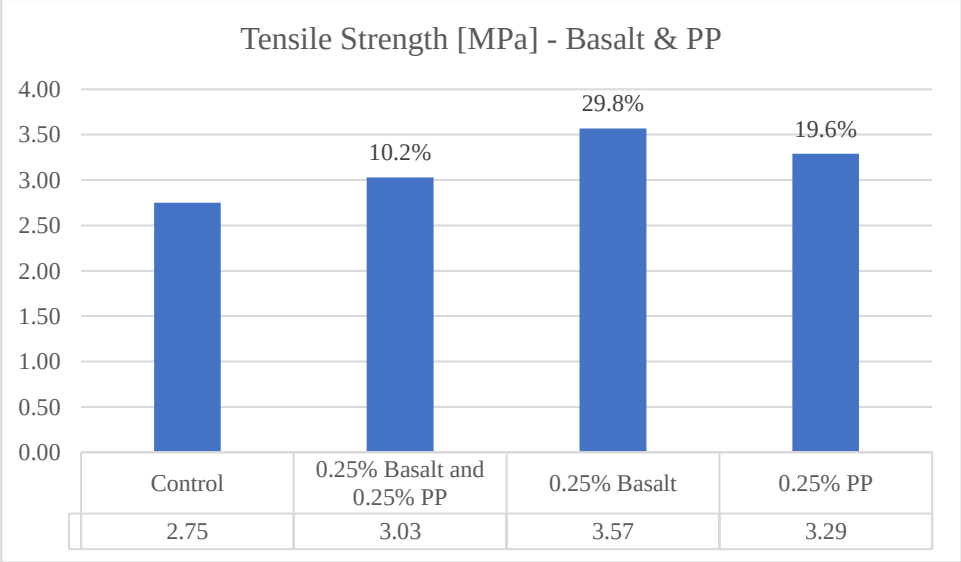


Figure 51: Tensile strength of single vs. hybrid reinforced concrete for PP and basalt

Figure 52 shows that the tensile strength of hybrid 0.25% glass and 0.25% PP improved by 19.6%. Whereas, the addition of single 0.25% glass improved the strength by 34.2%, and the addition of single 0.25% PP enhanced the strength by 19.6%. Thus, the hybridization of glass and PP negatively affected the action of single glass fibers, but it did not affect the action of single PP fibers. Overall, the hybridization of fibers had the best impact on the performance of single PVA on the tensile strength.

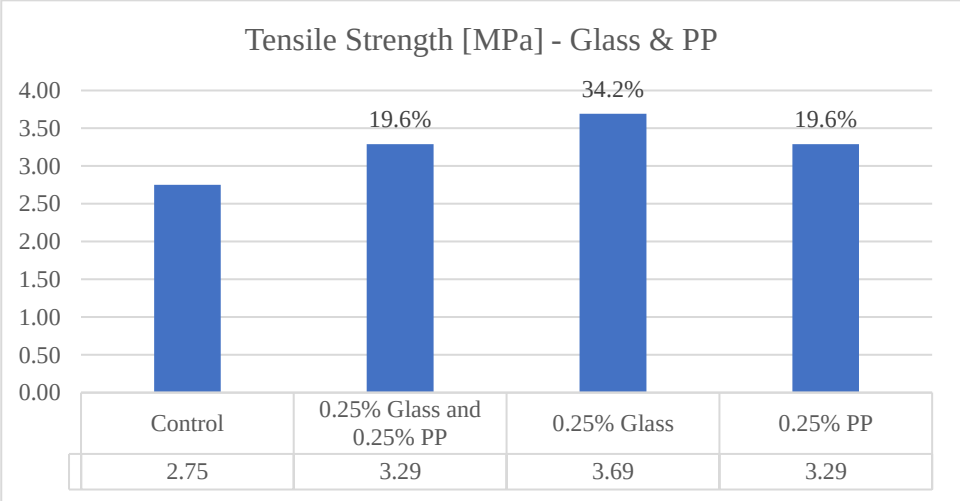


Figure 52: Tensile strength of single vs. hybrid reinforced concrete for PP and glass

Fibers yield an enhanced tensile strength when added to ordinary concrete because they are characterized by relatively high tensile strengths. In addition, the fibers with high elastic modulus like steel and basalt tend to resist stresses more than the fibers with relatively lower elastic modulus.

It is well known that ordinary concrete is weak in tension. Thus, tensile stresses can easily generate tensile cracks that may lead to failure. When introducing fibers to the concrete mixture, the fibers will inhibit the initiation and propagation of these cracks; thus, improving the tensile strength capacity of concrete [27]. Unlike the case of ordinary concrete, when the first crack in the fiber-reinforced concrete appears, there will not be a

brittle failure. However, more microcracks will appear, and the width of the cracks will widen continuously until the fibers pull out or rupture [14]. Meanwhile, it can be observed that the difference in dimensions of the mixed fibers affects the tensile strength. It is advisable to mixture micro polymeric type of fibers with macro fibers that possess high tensile strength. For instance, when the steel fibers having a diameter of 998 µm and length of 30 mm are mixed with PVA that have a diameter of 37 µm and length of 8 mm, the tensile strength improves more than when the steel fibers are mixed with PP fibers that have similar dimensions including a diameter of 900 µm and length of 38 mm. This is because, at the initial stages of the loading, the microfibers will inhibit and resist the formation of microcracks. Then, through the continuous loading phase, these microcracks will develop into macrocracks that will be resisted and bridged by the macro-fibers. Figure 53 shows the way the fibers are bridging the cracks.

Figure 53: Crack bridging effect of fibers

3.3.3. Flexural Strength

Similar to the SFRC, all the hybrid mixtures had a positive effect on the flexural strength of ordinary concrete as shown in Figure 54. The flexural strength of the ordinary concrete 5.06 MPa doubled to reach a maximum of 10.6 and 10.1 MPa when mixing

0.25% PP with 0.25% glass and 0.5% steel, respectively, a 109% and 99.6% improvement. Meanwhile, the flexural strength increased from 5.06 MPa to reach 9.48, 9.01, 8.32, and 8.23 MPa for the hybrid mixtures of 0.25% PP and 0.25% PVA, 0.25% basalt and 0.25% PP, 0.5% steel and 0.25% PVA, and 0.25% basalt and 0.25% PVA, respectively. Accordingly, the percentages of improvement in flexural strength are 87.4%, 78.1%, 64.4%, and 62.7%.

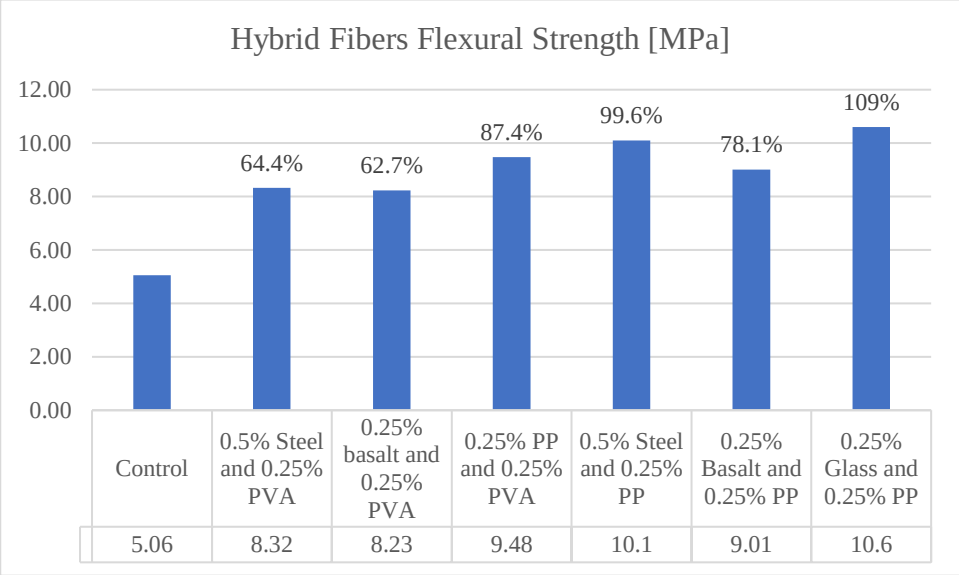


Figure 54: Hybrid fibers flexural strength test results

According to Figure 55, the addition of the binary mixture of 0.5% steel and 0.25% PVA improved the flexural strength by 64.4%. Meanwhile, the addition of single 0.25% PVA improved the flexural strength by 72.9%, and the addition of 0.5% steel improved the strength by 106%. Thus, the hybridization negatively affected the performance of steel and PVA.

In the experiment performed by Liu et al., the specimens that incorporated a mixture of 1.5% of steel fibers and 0.5% of PVA fibers had a flexural strength equal to 7.65 MPa almost double that of the plain concrete equal to 3.93 MPa [26].

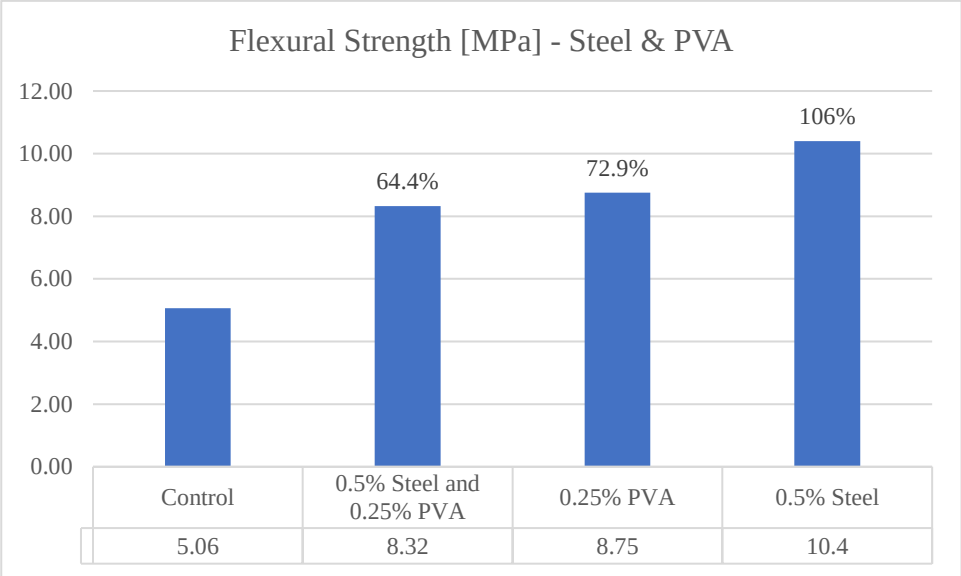


Figure 55: Flexural strength of single vs. hybrid reinforced concrete for steel and PVA

According to Figure 56, the flexural strength of hybrid 0.25% basalt and 0.25% PVA improved by 62.7%. However, the flexural strength of single 0.25% basalt mixture improved by 108%, and the strength of single 0.25% PVA improved by 72.9%. Thus, the hybridization negatively affected the performance of single basalt and PVA fibers.

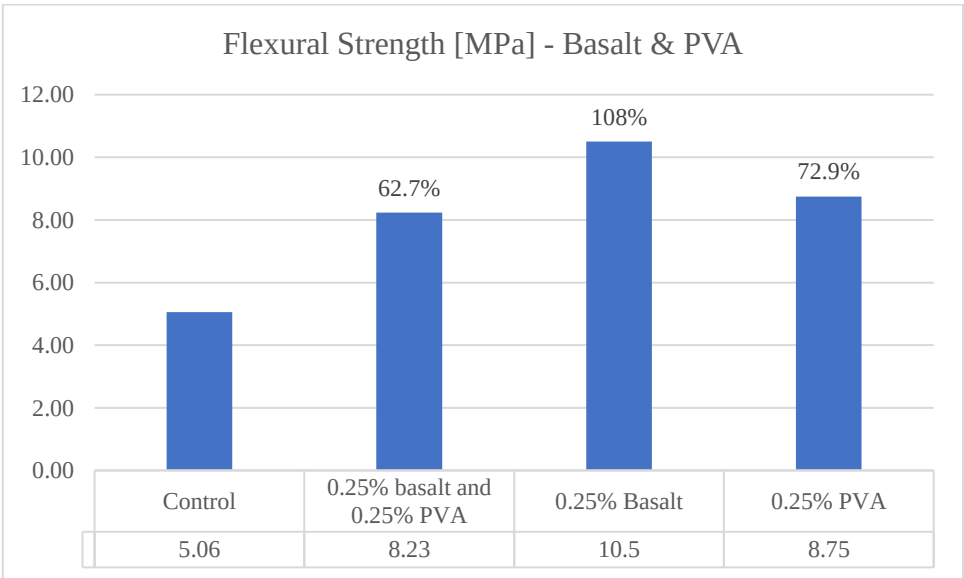


Figure 56: Flexural strength of single vs. hybrid reinforced concrete for basalt and PVA

As shown in Figure 57, the incorporation of hybrid 0.25% PP and 0.25% PVA enhanced the flexural strength by 87.4%. Meanwhile, the addition of single 0.25% PP enhanced the flexural strength by 119%, and the addition of 0.25% PVA enhanced the strength by 72.9%. Thus, the hybridization positively affected the performance of single PVA fibers, but it negatively affected the performance of single 0.25% PP.

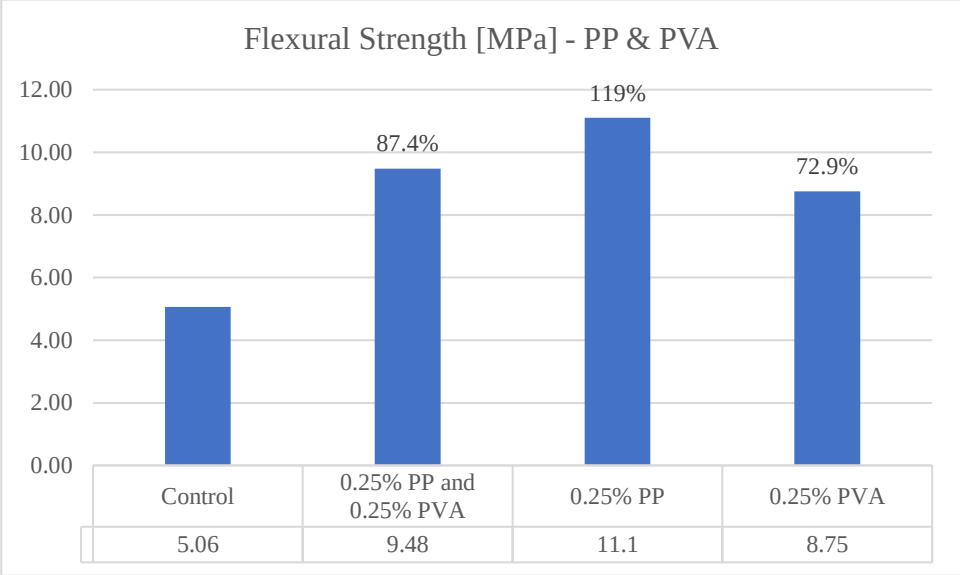


Figure 57: Flexural strength of single vs. hybrid reinforced concrete for PP and PVA

According to Figure 58, the addition of hybrid 0.5% steel and 0.25% PP mixture improved the flexural strength by 99.6%. Meanwhile, the addition of 0.5% steel improved the strength by 119%, and the addition of single 0.25% PP improved the strength by 106%. Hence, the hybridization did not significantly affect the performance of single steel and PP fibers.

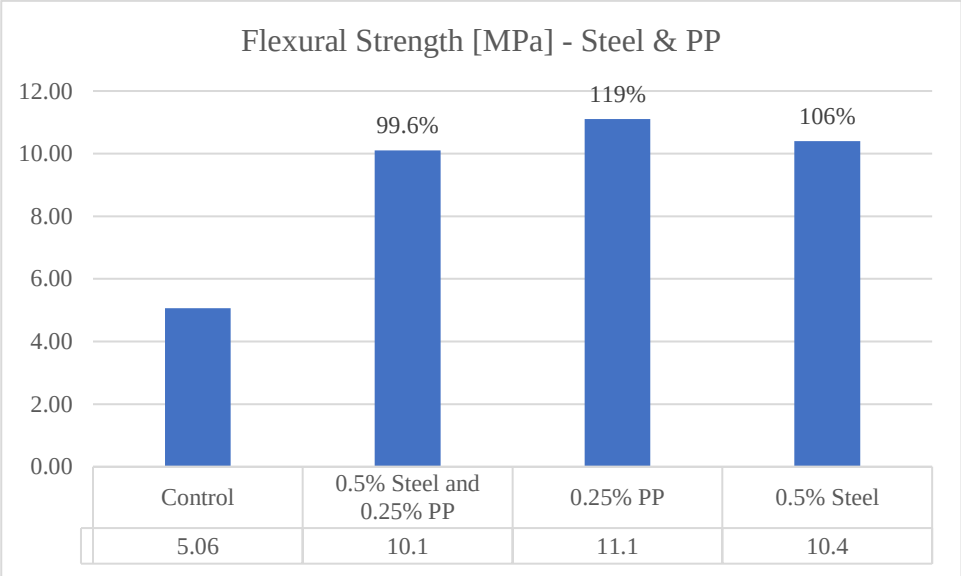


Figure 58: Flexural strength of single vs. hybrid reinforced concrete for steel and PP

According to Figure 59, the flexural strength of hybrid 0.25% basalt and 0.25% PP mixture enhanced by 78.1%. However, the flexural strength of single 0.25% PP enhanced by 119%, and the strength of single 0.25% basalt improved by 108%. Therefore, the hybridization negatively affected the single basalt and PP fibers.

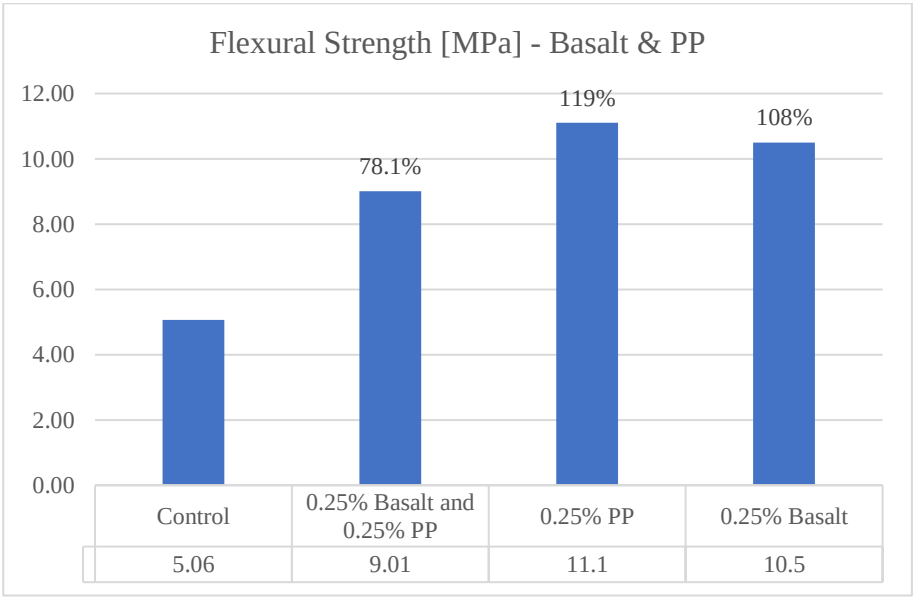


Figure 59: Flexural strength of single vs. hybrid reinforced concrete for basalt and PP

As shown in Figure 60, the incorporation of binary glass and PP mixture improved the flexural strength by 109%. Meanwhile, the addition of 0.25% PP improved the strength by 119%, and the incorporation of 0.25% glass enhanced the strength by 97.0%. Thus, the hybridization did not have a significant effect on the single PP and glass fibers.

According to Dersai et al., the mixture of 0.5% glass and 0.5% PP increased the flexural strength from 3.98 MPa to 6.45 MPa, accounting for an improvement of 62.1% [18].

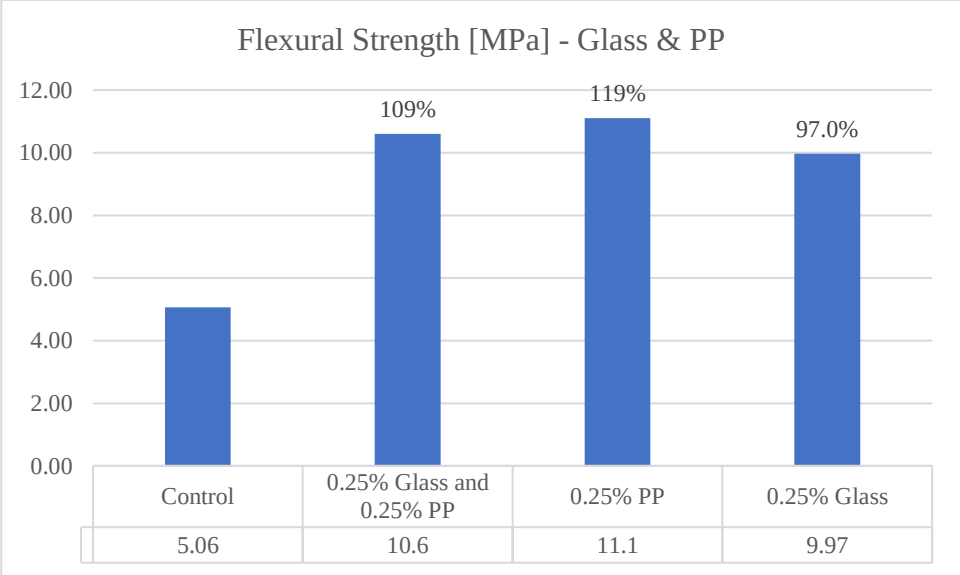


Figure 60: Flexural strength of single vs. hybrid reinforced concrete for glass and PP

Similar to the tensile strength property, the main mechanism that improves flexural strength is the crack-bridging effect of the fibers. In the absence of fibers, the crack generated from the loads will rapidly propagate through the whole section of the beam leading to a brittle behavior [6]. The beam will fail and cut into two halves. Figure 61 below shows the flexural failure of the control sample of this project. The crack propagated through the whole depth of the beam cutting it into two pieces. However, in the case of fiber-reinforced concrete, the fibers will bridge the crack that generates in the

tension zone [16]. Thus, the crack will not propagate through the whole section and lead to a brittle failure. The beam would still possess some bearing capacity after the generation of the crack [6]. Figures 62 and 63 below show the flexural failure of fiber-reinforced concrete and the crack-bridging action of the fibers.

Figure 61: Flexural failure of control beam (no fibers)

Figure 62: Flexural failure of fiber-reinforced concrete

Figure 63: Crack bridging mechanism of fibers

3.3.4. Modulus of Elasticity

Figure 64 shows the results of the modulus of elasticity test of the HFRC. The trend was also similar to the SFRC, the hybrid fibers did not impose a noticeable effect on the elastic modulus of ordinary concrete. The percentages of change of 0.25% basalt and 0.25% PVA, 0.5% steel and 0.25% PP, 0.25% glass and 0.25% PP, 0.25% PP, and 0.25% PVA, and 0.5% steel and 0.25% PVA were almost negligible ranging from a maximum of 0.671% improvement to a maximum reduction of 1.68%. Furthermore, the addition of 0.25% basalt and 0.25% PP yielded the lowest elastic modulus of 28.3 GPa, a 5.03% reduction.

In the experiment performed by Fu et al., the mixture of 0.1% basalt and 0.1% PP increased the modulus of elasticity of ordinary concrete by approximately 2.35% [4]. Furthermore, according to Deng et al., the elastic modulus of ultra-high-performance concrete decreased upon the addition of hybrid steel and PP fibers [20]. In addition, Lin

et al. deduced that the hybrid mixture of PVA and PP fibers reduced the elastic modulus [14].

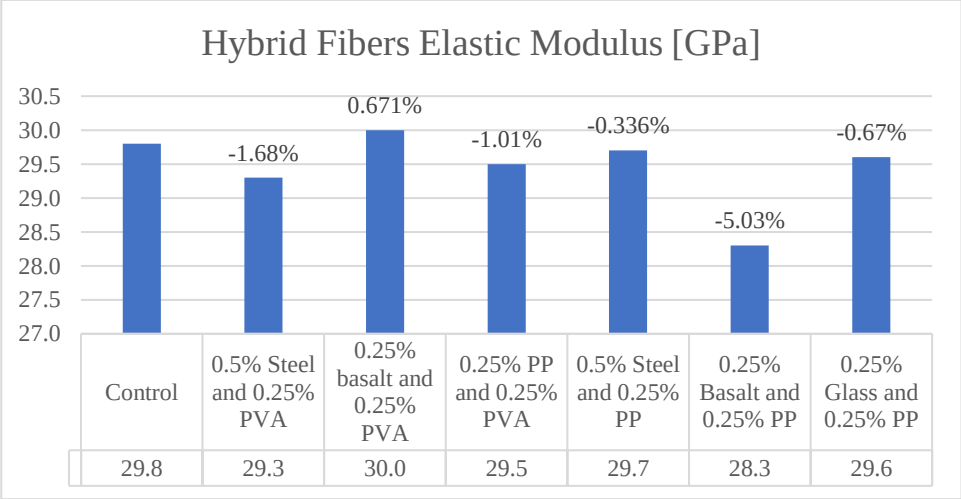


Figure 64: Hybrid fibers elastic modulus test results

As shown in Figure 65, the elastic modulus of the hybrid 0.5% steel and 0.25% PVA mixture reduced by a negligible 1.68%. Similarly, the addition of single 025% reduced the elastic modulus by a negligible 2.68%. Meanwhile, the addition of single 0.5% steel increased the elastic modulus by 23.2%. Thus, the hybridization did not have an effect on the action of single PVA fibers, however, it negatively affected the performance of single steel fibers.

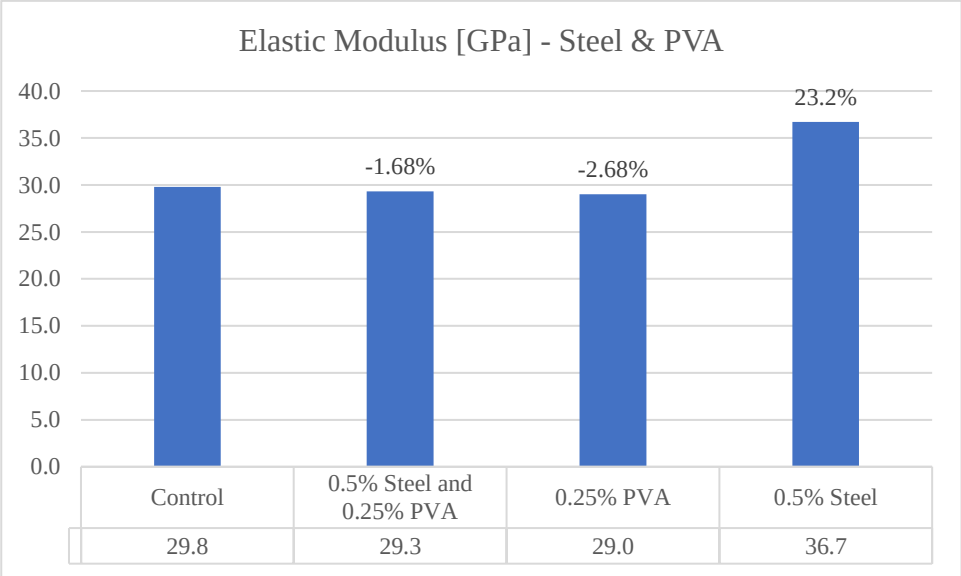


Figure 65: Elastic modulus of single vs. hybrid fiber reinforced concrete for steel & PVA

According to Figure 66, the elastic modulus of the hybrid 0.25% basalt and 0.25% PVA mixture improved by 0.67%. Moreover, the addition of single 0.25% basalt improved the modulus of elasticity by 1.01%, and the addition of 0.25% PVA reduced the modulus by 2.68%. Thus, the hybridization did not affect the single basalt and PVA fibers.

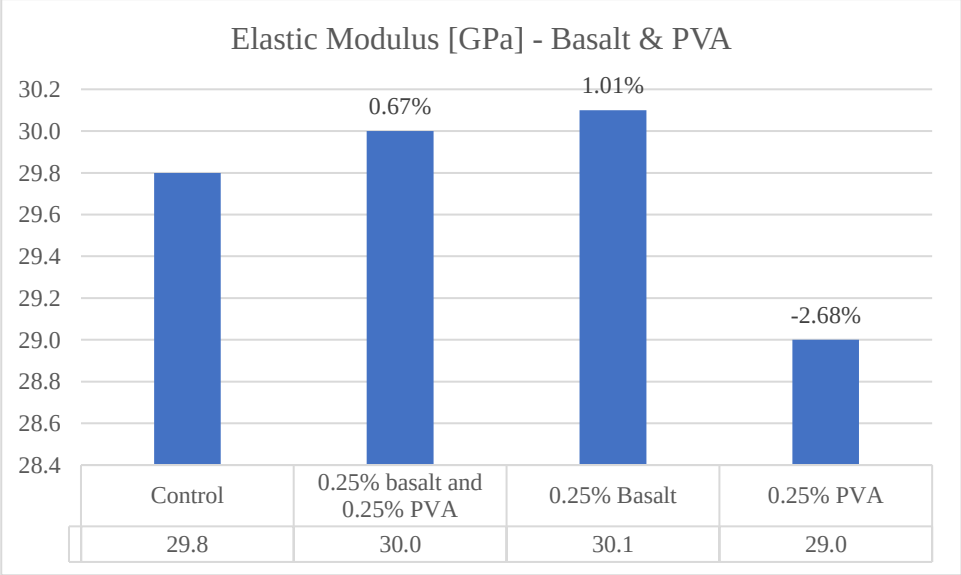


Figure 66: Elastic modulus of single vs. hybrid fiber reinforced concrete for basalt & PVA

As illustrated by Figure 67, the elastic modulus of the hybrid 0.25% PP and 0.25% PVA mixture reduced by a negligible 1.01%. Furthermore, the addition of single 0.25% PP increased the modulus of elasticity by 3.69%, and the addition of 0.25% PVA reduced the modulus of elasticity by 2.68%. Hence, the hybridization did not affect the performance of single PP and PVA fibers.

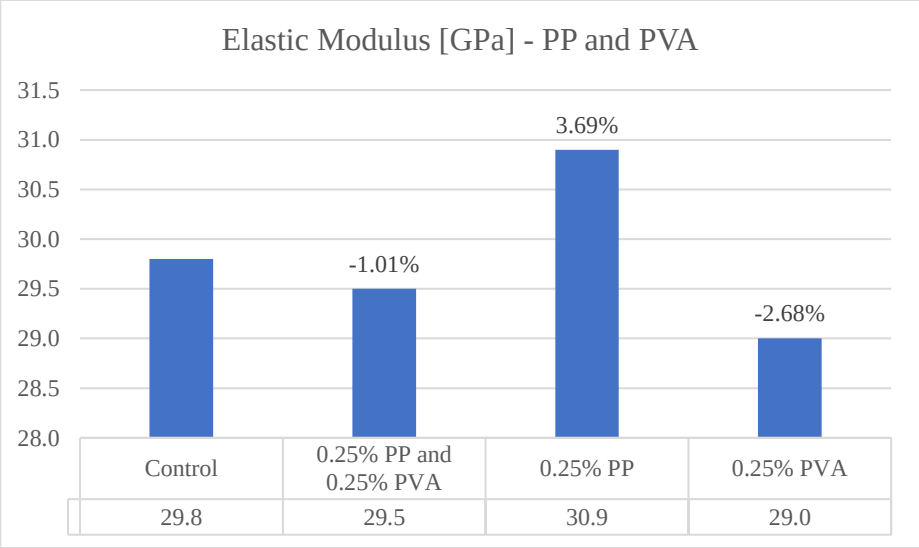


Figure 67: Elastic modulus of single vs. hybrid fiber reinforced concrete for PP & PVA

Figure 68 shows that the elastic modulus of hybrid 0.5% steel and 0.25% PP mixture reduced by a negligible 0.34%. Meanwhile, the addition of single 0.25% PP increased the modulus of elasticity by 3.69%, but the addition of single 0.5% steel improved the modulus of elasticity by 23.2%. Hence, the hybridization negatively affected the performance of single steel fibers, but it had no effect on the single PP fibers.

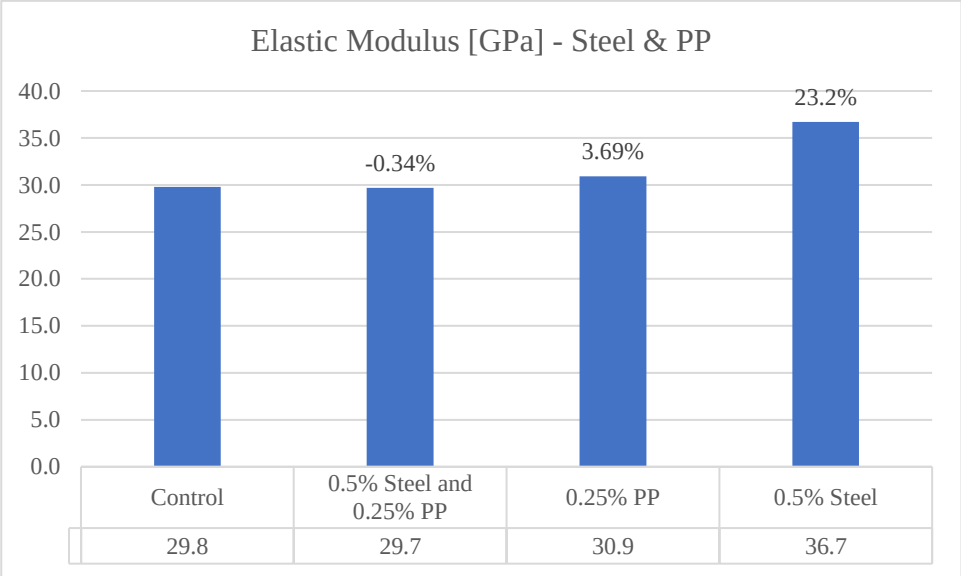


Figure 68: Elastic modulus of single vs. hybrid fiber reinforced concrete for steel & PP

Figure 69 shows that the addition of hybrid 0.25% basalt and 0.25% PP reduced the modulus of elasticity by 5.03%. Meanwhile, the addition of single 0.25% PP increased the elastic modulus by 3.69%, and the addition of single 0.25% basalt increased the elastic modulus by 1.01%. Therefore, the hybridization did not affect the performance of single basalt and PP fibers.

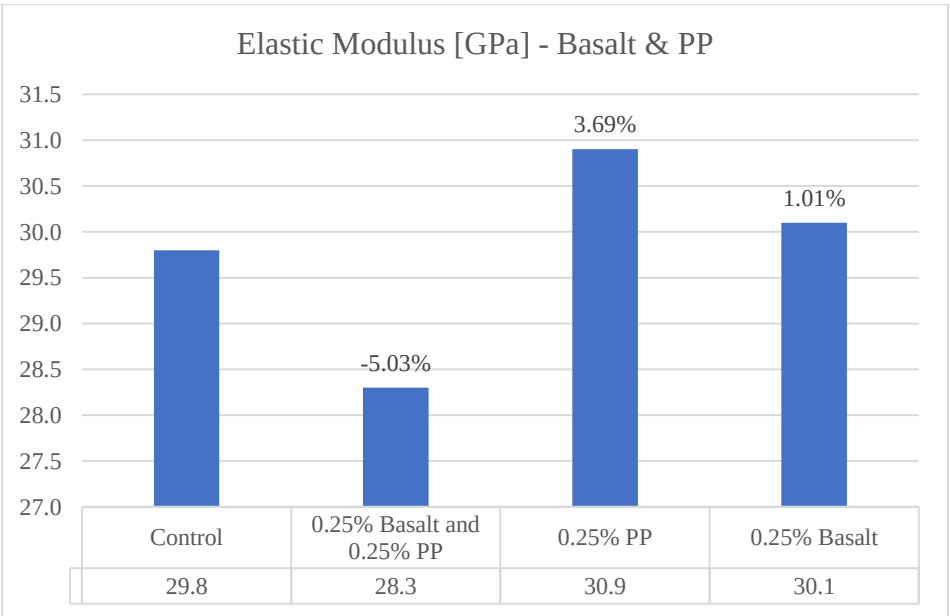


Figure 69: Elastic modulus of single vs. hybrid fiber reinforced concrete for PP & basalt

As shown in Figure 70, the elastic modulus of hybrid 0.25% glass and 0.25% PP mixture reduced by a negligible 0.67%. Meanwhile, the addition of single PP fibers increased the modulus by 3.69%, and the addition of single glass fibers increased the elastic modulus by 7.05%. Therefore, the hybridization had no impact on the single PP and glass fibers.

The hybridization of fibers negatively affected the performance of single steel fibers. Meanwhile, the hybridization did not significantly alter the impact of the other types of single fibers. The general trend is that the fibers have a neutral effect on the elastic modulus except for single steel fibers.

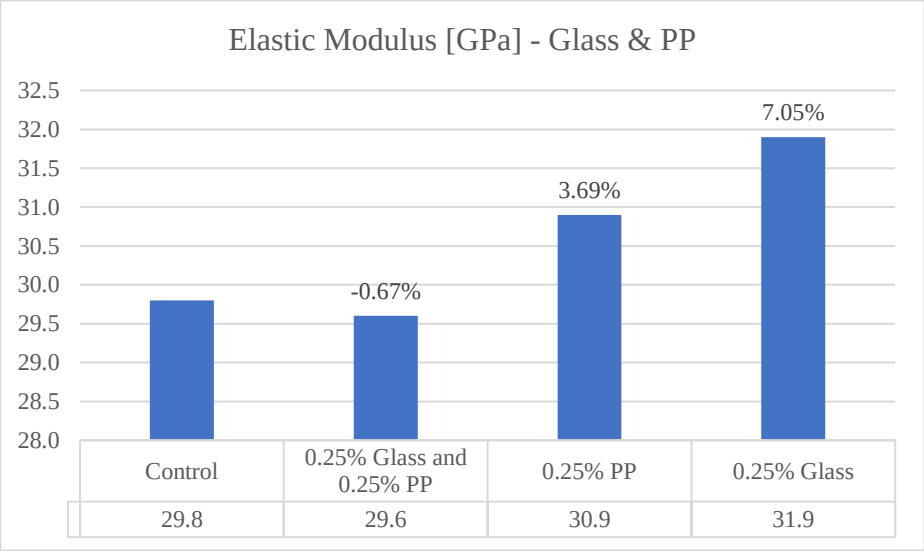


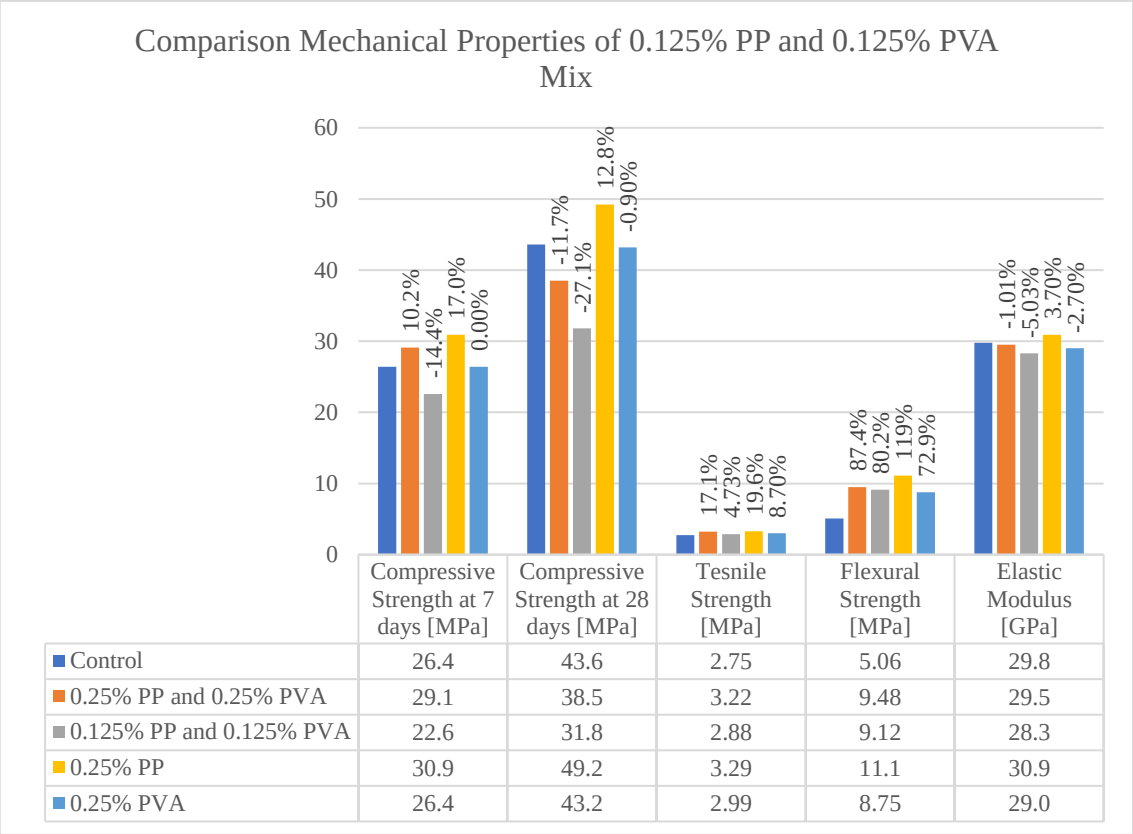
Figure 70: Elastic modulus of single vs. hybrid fiber reinforced concrete for PP & glass

The elastic modulus of a material represents its deformation resistance in the elastic damage-free stage. In this elastic stage, there would be no generation of cracks due to exerted loads. When these cracks initiate, the concrete moves to the plastic range. Thus, the crack-bridging mechanism of fibers is essential for plastic deformation, which means that fibers would not affect the elastic stage of the concrete, and thus, have no impact on the elastic modulus [4].

3.3.5. The Mixture of 0.125% PP and 0.125% PVA

Since the single fiber mixtures of PP and PVA had a fiber dosage of 0.25% each, an additional mixture was cast in which the sum of the hybrid fibers' dosages equaled the dosage of the single fiber which was 0.25%. The mixture was performed by adding 0.125% of PP and 0.125% of PVA fibers, and it was tested for mechanical properties including compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity. Figure 71 summarizes the results of the different tests of this mixture. Additionally, the figure compares the mechanical properties of the 0.125% PP and 0.125% PVA mixture with the control sample, the hybrid mixture of 0.25% PP with 0.25% PVA, the single 0.25% PP, and the single 0.25% PVA.

From the figure, the compressive strengths of 0.125% PP and 0.125% PVA both at 7 (22.6 MPa) and 28 days (31.8 MPa) were lower than that of the control (26.4 and 43.6 MPa), hybrid 0.25% mixture (29.1 and 38.5 MPa), and single PP (30.9 and 49.2 MPa) and single PVA (26.4 and 43.2 MPa). Meanwhile, the tensile strength of 0.125% PP and 0.125% PVA (2.88 MPa) was smaller than that of the 0.25% PP and PVA mixture (3.22 MPa), single 0.25% PP (3.29 MPa), and single 0.25% PVA (2.99 MPa). However, the tensile strength was greater than that of the control sample (2.75 MPa) accounting for a 4.73% improvement. Concerning the flexural strength, the mixture of 0.125% PP and 0.125% PVA improved the strength by 80.2% (9.12 MPa) more than that of a single 0.25% PVA equal to 72.9% (8.75 MPa). But the improvement was less than that of the hybrid 0.25% mixture equal to 87.4% (9.48 MPa) and the single PP equal to 119% (11.1 MPa). Nevertheless, the mixture of 0.125% PP and 0.125% PVA reduced the elastic modulus by 5.03% which was similar to the effect of hybrid 0.25% mixture (reduction of 1.01%), single PP (improvement of 3.70%), and single PVA (reduction of 2.70%).



	Compressive Strength at 7 days [MPa]	Compressive Strength at 28 days [MPa]	Tesnile Strength [MPa]	Flexural Strength [MPa]	Elastic Modulus [GPa]
Control	26.4	43.6	2.75	5.06	29.8
0.25% PP and 0.25% PVA	29.1	38.5	3.22	9.48	29.5
0.125% PP and 0.125% PVA	22.6	31.8	2.88	9.12	28.3
0.25% PP	30.9	49.2	3.29	11.1	30.9
0.25% PVA	26.4	43.2	2.99	8.75	29.0

Figure 71: Mechanical properties of 0.125% PP and 0.125% PVA mixture

3.3.6. Water Absorption

This section discusses the effect of fiber hybridization on the durability of ordinary concrete.

Unlike SFRC, all the hybrid fibers had a positive impact on the water absorption of ordinary concrete. The water absorption capacity was almost reduced by half for all the mixtures of hybrid fibers at 7 days as shown in Figure 72 and Table 11. The reduction of the water absorption capacity ranged from 44.4% for the hybrid mixture of 0.25% basalt and 0.25% PP up to 59.6% for the hybrid mixture of 0.25% glass and 0.25% PP. According to Ahmed and Jia, the addition of 0.45% glass and 0.45% PP fibers reduced the air permeability of concrete by approximately 42.0% [16]. In the experiment performed by Liu et al., the addition of hybrid 0.75% glass and 0.75% PP fibers reduced

the migration depth of chloride ions by 23.3% when compared to ordinary concrete [17]. In addition, they noted that the addition of hybrid GF and PP decreased the total charge passed through the concrete by 20.15% [17].

Table 11: Water absorption results of hybrid fibers

	Absorption I [mm]						
Fibers	**1 hr.**	**2 hr.**	**3 hr.**	**4 hr.**	**5 hr.**	**6 hr.**	
Control	1.15	1.40	1.60	1.70	1.90	2.10	
0.5% Steel and 0.25% PVA	1.00	1.07	1.13	1.27	1.33	1.60	
0.25% Basalt and 0.25% PVA	1.33	1.33	1.33	1.47	1.47	1.47	
0.25% PP and 0.25% PVA	1.27	1.27	1.47	1.60	1.67	1.67	
0.5% Steel and 0.25% PP	1.20	1.20	1.20	1.27	1.27	1.33	
0.25% Basalt and 0.25% PP	0.93	1.13	1.33	1.53	1.87	2.07	
0.25% Glass and 0.25% PP	0.93	1.07	1.07	1.33	1.47	1.53	
Fibers	**1 day**	**2 days**	**3 days**	**4 days**	**5 days**	**6 days**	**7 days**
Control	3.61	4.52	5.04	5.48	5.76	5.97	6.11
0.5% Steel and 0.25% PVA	2.00	2.20	2.27	2.33	2.47	2.67	2.80
0.25% Basalt and 0.25% PVA	1.73	2.53	2.53	2.67	2.67	2.93	3.07
0.25% PP and 0.25% PVA	2.13	2.47	2.60	2.67	2.93	3.00	3.13
0.5% Steel and 0.25% PP	1.67	2.20	2.20	2.33	2.33	2.60	2.67
0.25% Basalt and 0.25% PP	2.47	2.73	2.73	2.87	3.13	3.20	3.40
0.25% Glass and 0.25% PP	1.73	2.00	2.00	2.20	2.27	2.33	2.47

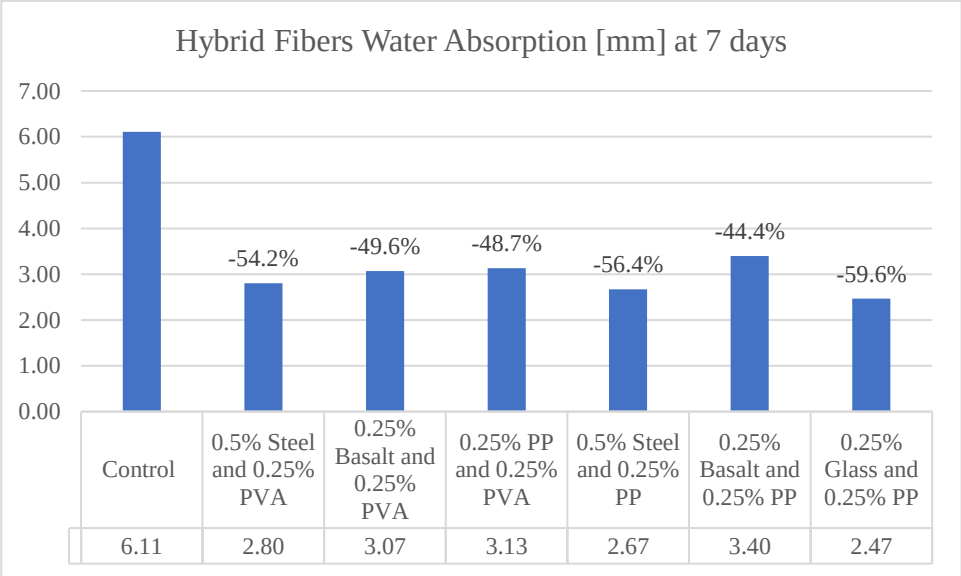


Figure 72: Water absorption of hybrid fibers ay 7 days

Figure 73 shows that the water absorption at 7 days of the hybrid 0.25% PVA and 0.5% steel mixture decreased by 54.2%. However, the water absorption of the single 0.25% PVA mixture increased by 25.5%, and the water absorption of the single 0.5% steel mixture reduced by 46.0%. Thus, the hybridization positively affected the single PVA and steel fibers.

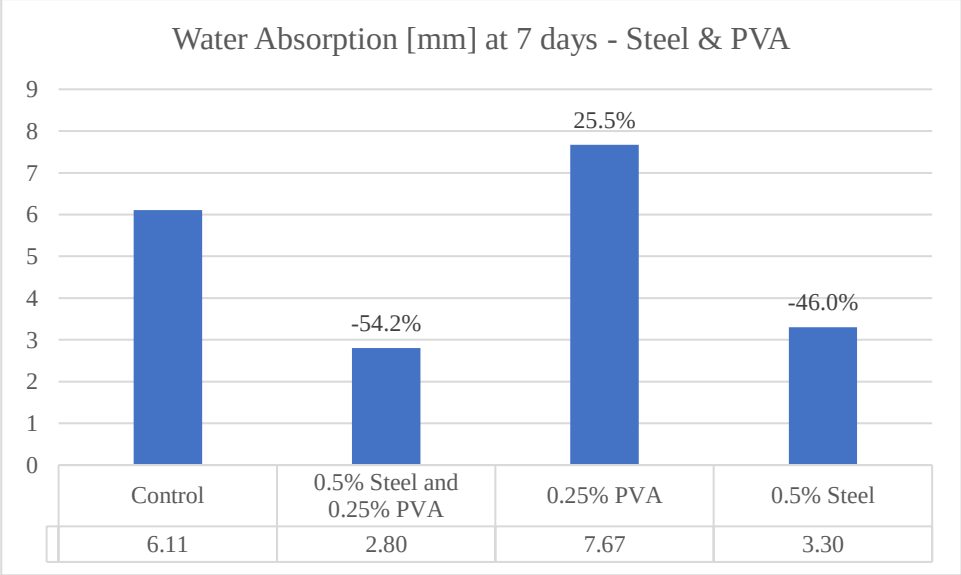


Figure 73: Water absorption of single vs. hybrid fiber reinforced concrete for steel & PVA

As shown in Figure 74, the addition of hybrid 0.25% basalt and 0.25% PVA mixture reduced the water absorption by 49.8%. Whereas, adding single 0.25% basalt increased the water absorption by 15.2%, and adding single PVA fibers increased the absorption by 25.5%. Therefore, the hybridization significantly improved the water absorption of the single PVA and basalt fibers.

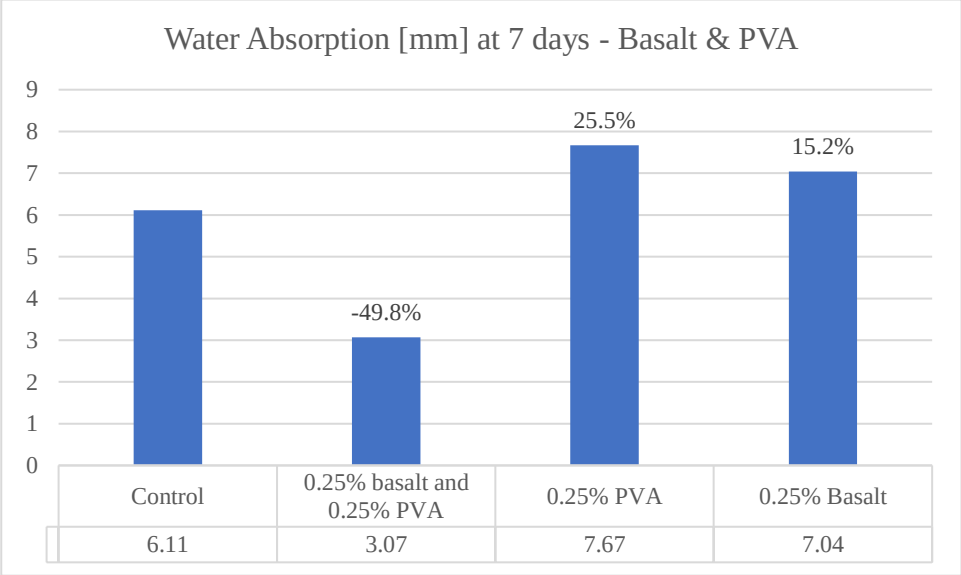


Figure 74: Water absorption of single vs. hybrid fiber reinforced concrete for basalt & PVA

According to Figure 75, the incorporation of hybrid 0.25% PP and 0.25% PVA reduced the water absorption by 48.8%. Meanwhile, the addition of single 0.25% PVA increased the absorption by 25.5%, and the addition of 0.25% PP reduced the absorption by 40.6%. Thus, the hybridization positively affected the performance of single PP and PVA fibers.

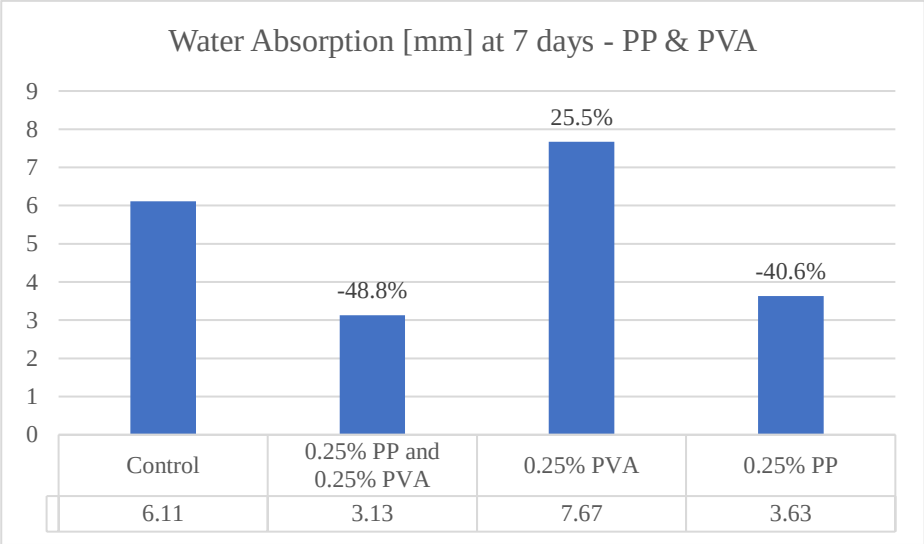


Figure 75: Water absorption of single vs. hybrid fiber reinforced concrete for PP & PVA

Figure 76 shows that the water absorption at 7 days of the hybrid 0.5% steel and 0.25% PP reduced by 56.3%. Meanwhile, the water absorption of the single 0.5% steel reduced by 46.0%, and the absorption of single 0.25% PVA reduced by 40.6%. Hence, the hybridization had a positive impact on the single steel and PP fibers.

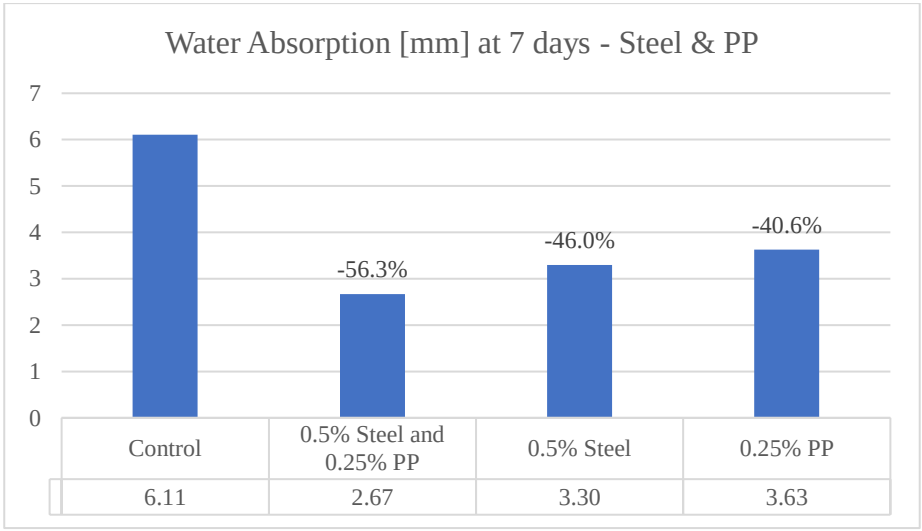


Figure 76: Water absorption of single vs. hybrid fiber reinforced concrete for PP & steel

According to Figure 77, the addition of binary 0.25% basalt and 0.25% PP reduced the water absorption by 44.4%. However, adding single 0.25% basalt increased the absorption by 15.2%, and adding single 0.25% PP reduced the absorption by 40.6%. Hence, the hybridization positively affected the single basalt and PP fibers.

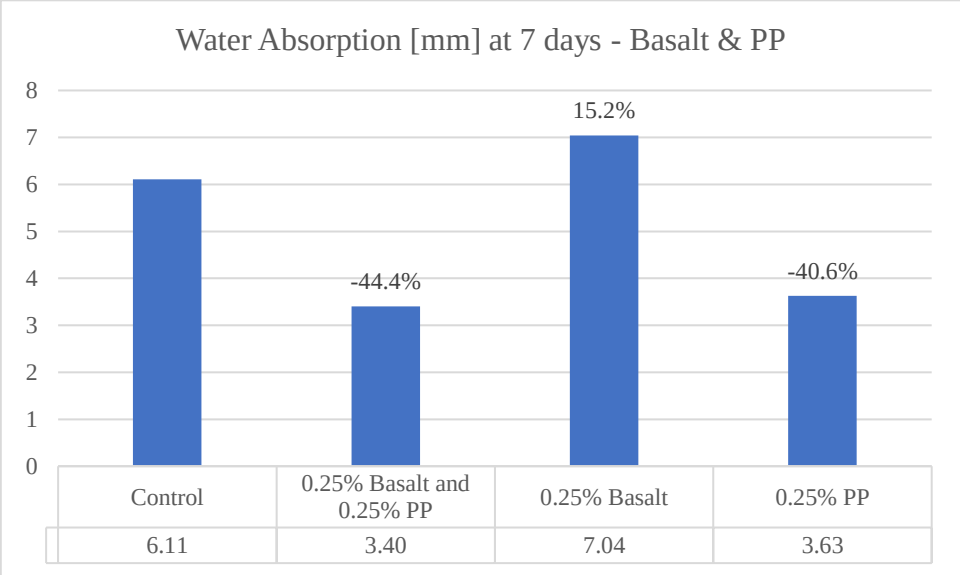


Figure 77: Water absorption of single vs. hybrid fiber reinforced concrete for PP & basalt

Figure 78 shows that the water absorption at 7 days of the hybrid 0.25% glass and 0.25% PP reduced by 59.6%. Whereas, the addition of single 0.25% glass increased the absorption by 44.0%, and the addition of single 0.25% PP reduced the absorption by 40.6%. Hence, the hybridization positively affected the performance of glass and PP.

The hybridization of fibers positively impacts the action of all types of single fibers, especially basalt, PVA, and glass. It is remarkable that upon the addition of 0.25% PP, the glass performance changes from the worst in the SFRC to the best among the HFRC.

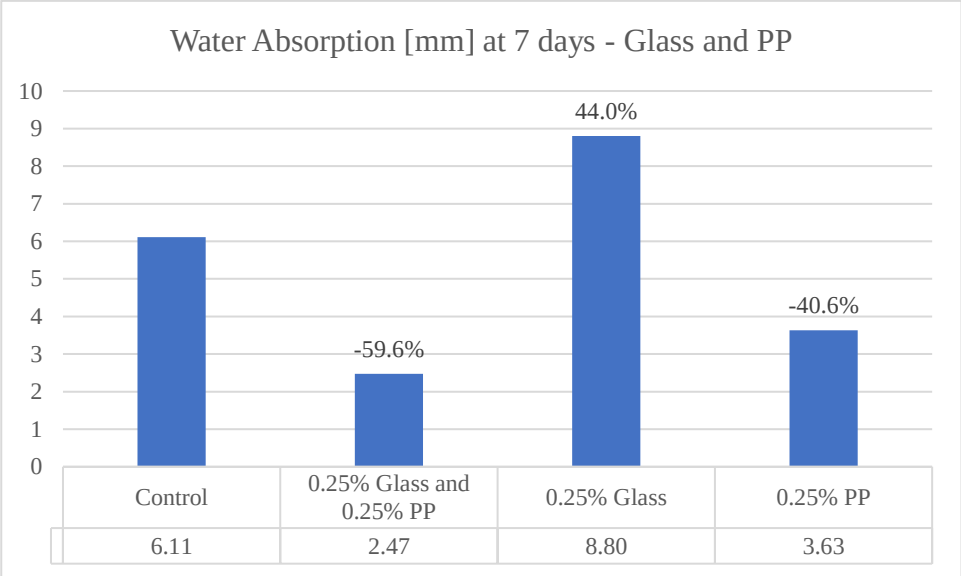


Figure 78: Water absorption of single vs. hybrid fiber reinforced concrete for PP & glass

The addition of fibers to ordinary concrete would stiffen the matrix, reduce bleeding, and decrease the settlement of the aggregates. Thus, the presence of fibers reduces the ease of flow in the concrete [16]. Moreover, it is expected that fibers would retain the water in the cement binder; hence, they reduce the occurrence of shrinkage cracks and produce a more solid and compact material [16].

3.3.7. Resistance to Freezing and Thawing

Table 12 summarizes the dynamic modulus of elasticity results of the hybrid mixtures. Note that the resistance to freezing and thawing test for the hybrid fibers proceeded up until 324 cycles of freezing and thawing. The reason behind this was that ASTM requires that the test continues until the dynamic modulus of elasticity of the sample reaches 60% of its initial values, or until the cycles reach up to 300 cycles, whichever occurs first.

The resistance to freezing and thawing of the hybrid mixtures was significantly better than that of the single fibers. The hybrid mixtures containing 0.25% PP with 0.25%

PVA and 0.5% steel with 0.25% PP failed after 180 cycles. Meanwhile, their dynamic moduli of elasticity reached less than 60% after 108 cycles. The mixture containing 0.25% basalt and 0.25% PVA fails after 324 cycles; however, its dynamic modulus of elasticity reduced to less than 60% after 108 cycles. On the other hand, mixtures containing 0.5% steel with 0.25% PVA, 0.25% PP with 0.25% glass, and 0.25% basalt with 0.25% PP resisted 324 cycles of freezing and thawing cycles. The dynamic modulus of elasticity of basalt and PP reduced to less than 60% after 324 cycles, whereas the moduli of glass with PP and steel with PVA remained greater than 60% even after 324 cycles. In other words, mixtures of 0.5% steel with 0.25% PVA and 0.25% glass with 0.25% PP delivered the best performance.

Table 12: Dynamic modulus of elasticity (%) for hybrid fibers

	Dynamic Modulus of Elasticity Pn (%)									
Mixtures	**n=0**	**n=36**	**n=72**	**n=108**	**n=144**	**n=180**	**n=216**	**n=252**	**n=288**	**n=324**
control	100	68.0	-	-	-	-	-	-	-	-
0.5% Steel and 0.25% PVA	100	97.4	97.4	89.9	87.5	85.2	80.4	80.4	75.8	69.1
0.25% Basalt and 0.25% PVA	100	70.9	64.5	48.7	45.2	35.2	23.9	25.0	25.0	1.73
0.25% PP and 0.25% PVA	100	89.9	71.3	55.0	53.0	1.69	-	-	-	-
0.5% Steel and 0.25% PP	100	94.9	67.3	48.0	42.7	1.35	-	-	-	-
0.25% Basalt and 0.25% PP	100	97.4	94.7	87.0	84.5	77.1	65.7	65.7	61.4	53.2
0.25% Glass and 0.25% PP	100	100	100	97.4	97.4	90.0	83.0	80.6	71.6	63.2

Niu et al. noted that as the fiber content of steel and PVA increases, the dynamic modulus of elasticity of concrete increases [37]. Wang et al. reported that the hybrid

mixture of steel and PP fibers increased the percentage of smaller voids with respect to larger pores [24]. In addition, and as cited by Wang et al., Sun et al. reported that the mixture of 1% steel, 0.25% PVA, and 0.25% PP reduced the percentage of harmful pores and increased the percentage of harmless pores [24, 38].

Figure 79 illustrates the dynamic moduli of elasticity of the hybrid steel and PVA, single PVA, single steel, and control mixture with respect to the number of cycles of freezing and thawing. The performance of the hybrid 0.5% steel and 0.25% PVA is better than the remaining mixtures. The control sample and the mixture of single steel collapsed after 108 cycles. Meanwhile, the mixture of single PVA did not collapse after 144 cycles; but its dynamic modulus of elasticity was reduced to less than 60% after 108 cycles. However, the dynamic modulus of elasticity of the hybrid steel and PVA mixture did not reduce to less than 60% even after 324 cycles of freezing and thawing. The hybridization of steel and PVA improved the performance of single PVA and steel.

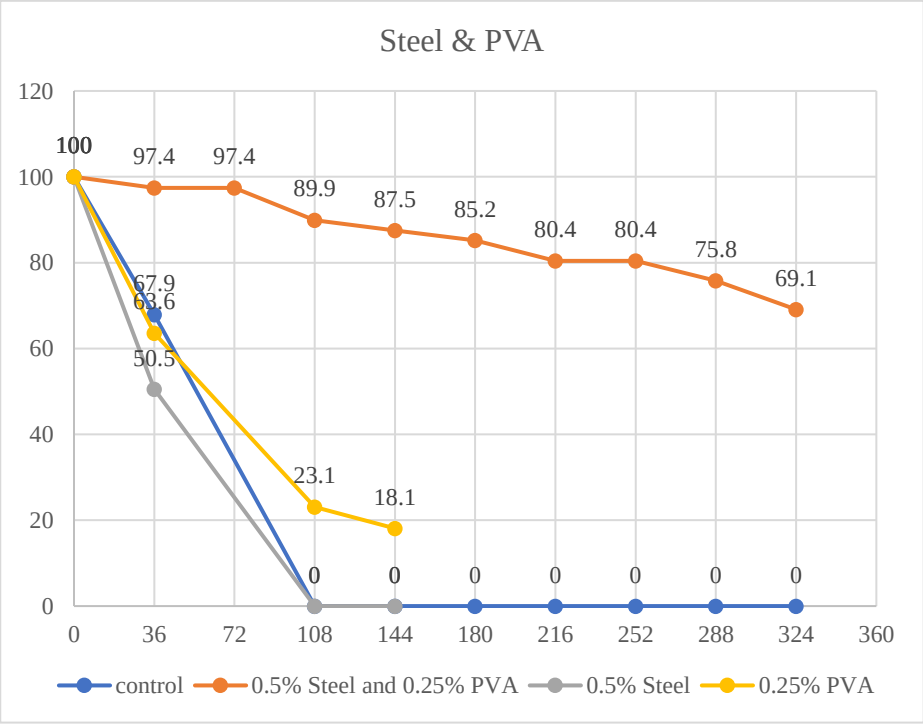


Figure 79: Resistance to freezing and thawing single vs. hybrid reinforced concrete for steel and PVA

Figure 80 compares the dynamic elastic moduli of the control sample, the hybrid 0.25% basalt and 0.25% PVA, the single basalt, and the single PVA samples. The hybrid basalt and PVA mixture had a better performance than the other samples. The control sample was the first to fail after 108 cycles. Then the single basalt failed after 144 cycles. The PVA sample did not fail after 144 cycles, but its modulus reached less than 60% after 108 cycles. Meanwhile, the modulus of the hybrid sample reached less than 60% after 108 cycles, but it remained higher than that of the remaining mixtures until the samples failed after 324 cycles. Hybridization had a positive impact on the performance of single basalt and PVA fibers.

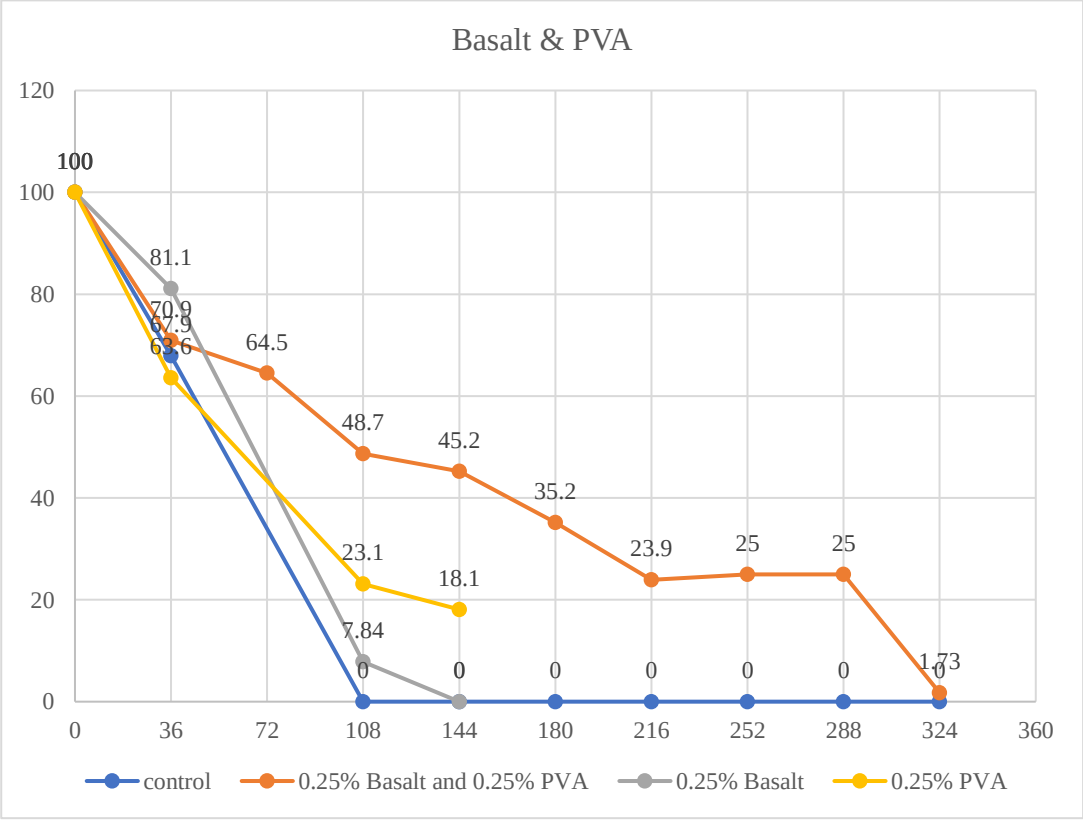


Figure 80: Resistance to freezing and thawing single vs. hybrid reinforced concrete for basalt and PVA

Figure 81 compares the dynamic elastic moduli of the control sample, the hybrid 0.25% PP and 0.25% PVA, the single PP, and the single PVA samples. The hybrid PP

and PVA mixture had a better performance than the other samples. The control sample and the single PP were the first to fail after 108 cycles. The PVA sample did not fail after 144 cycles, but its dynamic modulus reached less than 60% after 108 cycles. Meanwhile, the modulus of the hybrid sample reached less than 60% after 108 cycles, but it remained higher than that of the remaining mixtures until the samples failed after 180 cycles. Hybridization had a positive impact on the performance of single PP and PVA fibers.

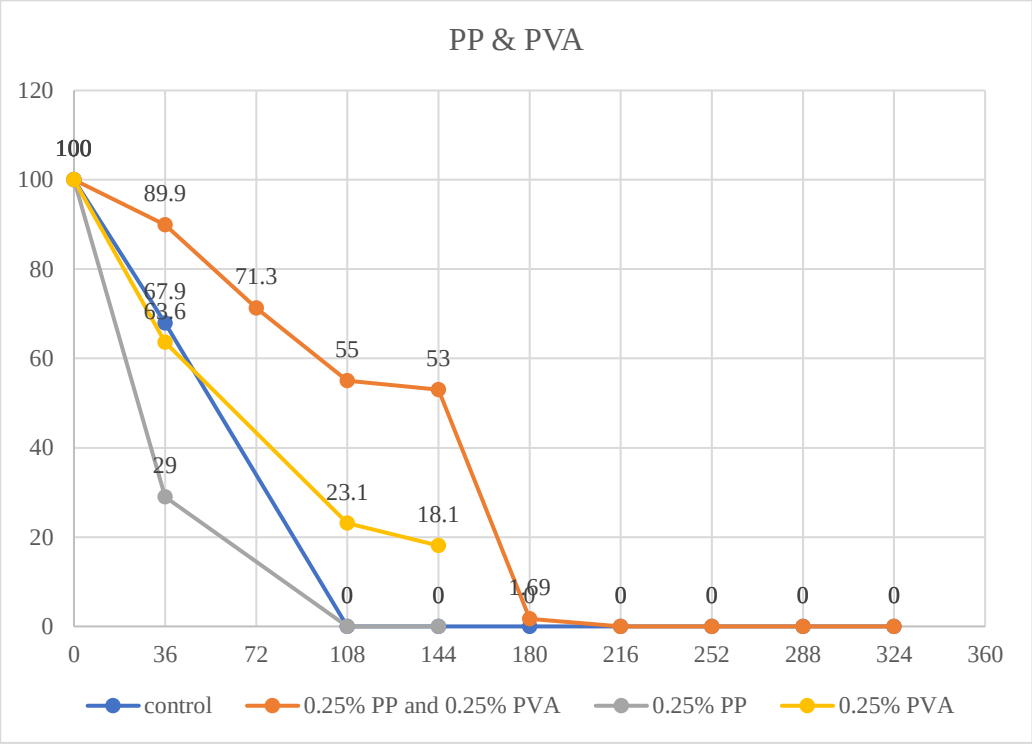


Figure 81: Resistance to freezing and thawing single vs. hybrid reinforced concrete for PP and PVA

Figure 82 compares the dynamic elastic moduli of the control sample, the hybrid 0.25% PP and 0.5% steel, the single PP, and the single steel samples. The hybrid PP and steel had a better performance than the other samples. The control sample, the single PP mixture, and the single steel mixture failed after 108 cycles. Meanwhile, the modulus of the hybrid sample reached less than 60% after 108 cycles, but it remained higher than that

of the remaining mixtures until the samples failed after 180 cycles. Hybridization had a positive impact on the performance of single PP and steel fibers.

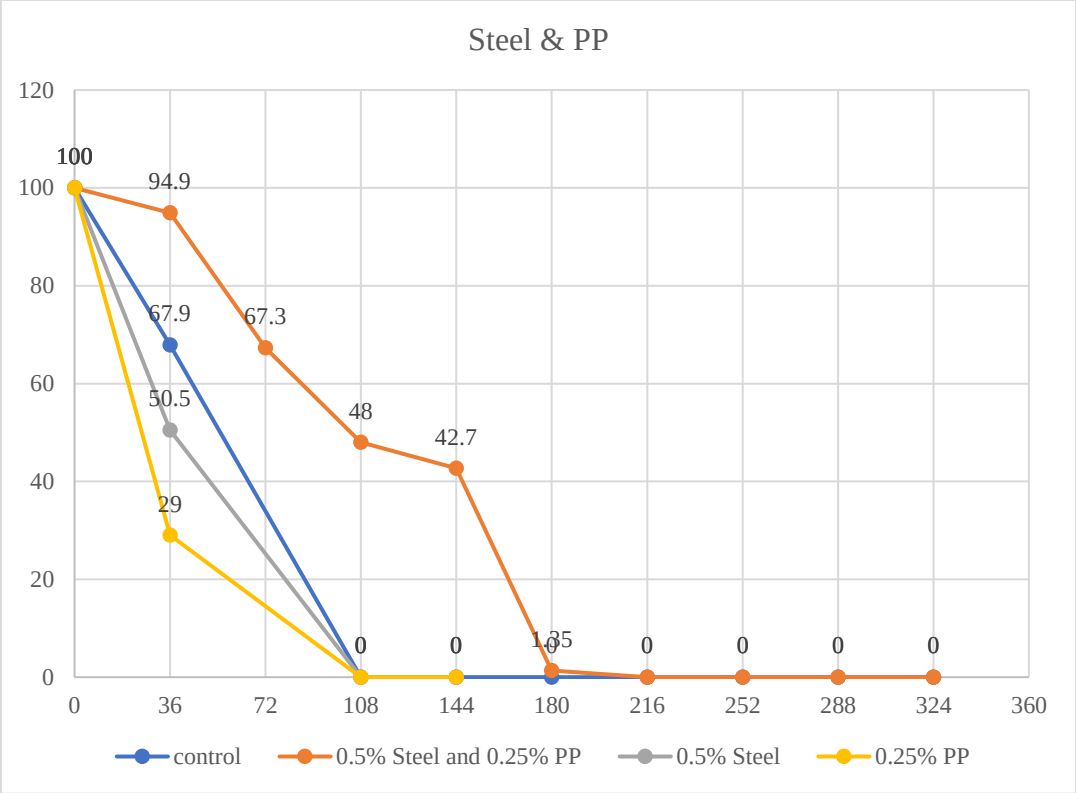


Figure 82: Resistance to freezing and thawing single vs. hybrid reinforced concrete for PP and steel

Figure 83 illustrates the dynamic moduli of elasticity of the hybrid basalt and PP, single PP, single basalt, and control mixture with respect to the number of cycles of freezing and thawing. The performance of the hybrid 0.25% basalt and 0.25% PP was better than the remaining mixtures. The control sample and the mixture of single PP collapsed after 108 cycles. Meanwhile, the mixture of single basalt collapsed after 144 cycles. However, the dynamic modulus of elasticity of the hybrid basalt and PP mixture did not reduce to less than 60% until after 324 cycles of freezing and thawing. The hybridization of basalt and PP improved the performance of single basalt and single PP.

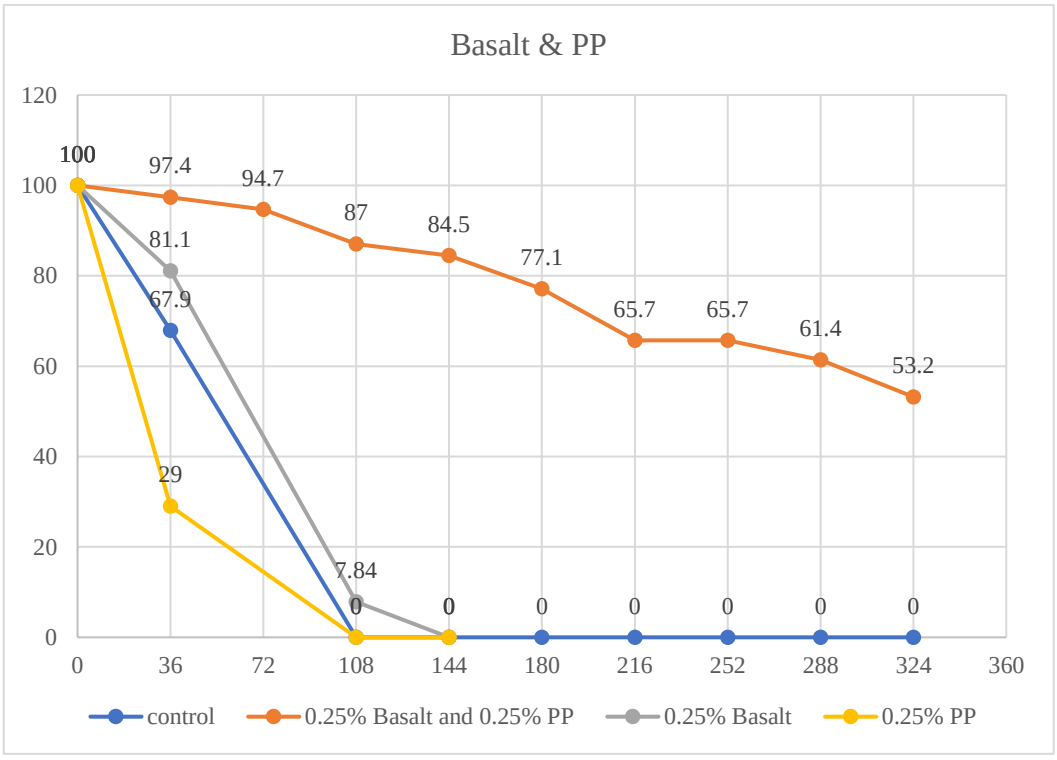


Figure 83: Resistance to freezing and thawing single vs. hybrid reinforced concrete for PP and basalt

Figure 84 shows the dynamic moduli of elasticity of the hybrid glass and PP, single PP, single glass, and control mixture with respect to the number of cycles of freezing and thawing. The performance of the hybrid 0.25% glass and 0.25% PP was better than the remaining mixtures. The control sample, the mixture of single glass, and the mixture of single PP collapsed after 108 cycles. Meanwhile, the dynamic modulus of elasticity of the hybrid glass and PP mixture did not reduce to less than 60% even after 324 cycles of freezing and thawing. The hybridization of glass and PP improved the performance of single PP and single glass fibers.

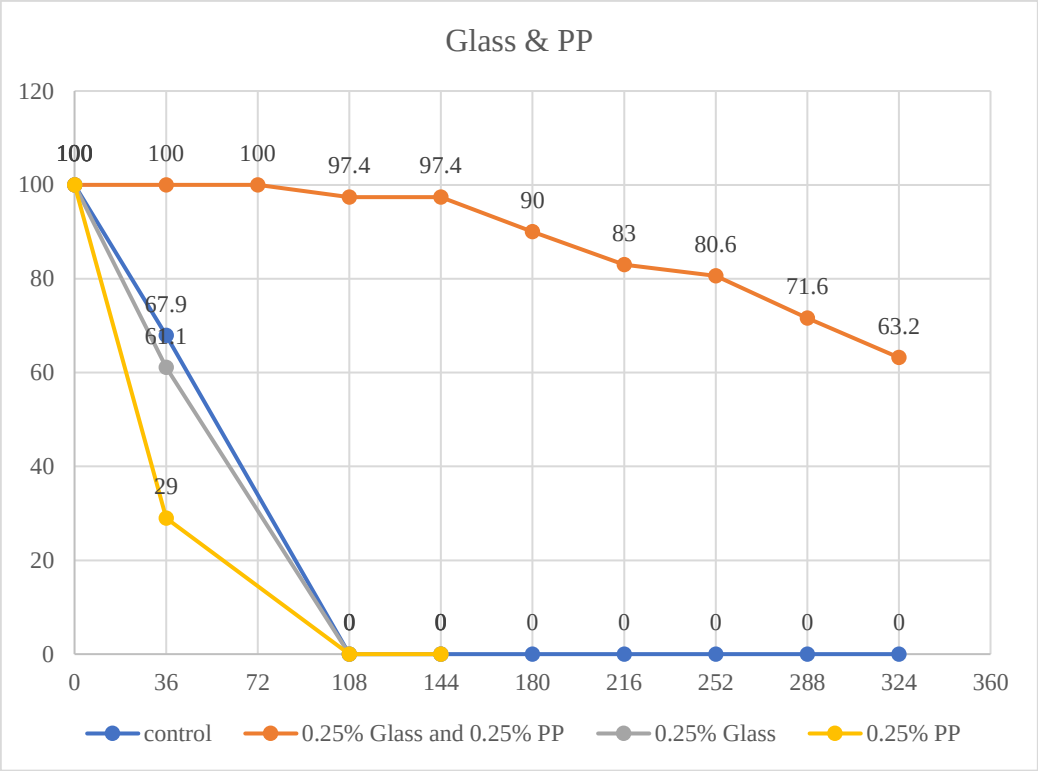


Figure 84: Resistance to freezing and thawing single vs. hybrid reinforced concrete for PP and glass

The two mixtures with the best performance on the tensile strength of concrete yielded the best performance on the resistance to freezing and thawing. When the water freezes in the voids of the concrete, its volume increases which exerts tensile stresses on the concrete. Because concrete is weak in tension, tensile cracks develop and failure occurs. However, when the tensile strength of the concrete is enhanced, the concrete can resist more tensile stresses and cracks, and thus the resistance to freezing and thawing improves.

Furthermore, when the mixed fibers have different dimensions (micro and macro), the resistance to freezing and thawing improves. Smaller fibers like PVA have a higher number of elements per volumetric dosage, they can help in refining the structure of the pores, reducing the number of interconnected pores, and resisting the initiation of micro-

cracks. Then when the micro-cracks develop into macro-cracks, the larger fibers like steel aid in bridging these cracks [24, 37].

3.3.8. Thermal Conductivity

Figure 85 shows the thermal conductivity results of the HFRC. All the hybrid fiber mixtures increased the thermal conductivity of ordinary concrete. The increase in thermal conductivity ranged from the highest of 58.0% for the mixture of 0.5% steel and 0.25% PVA to the lowest of 31.0% for 0.25% PP and 0.25% PVA.

Because steel has high thermal conductivity, the mixtures containing steel fibers including 0.5% steel with 0.25% PVA and 0.5% steel with 0.25% PP had the highest thermal conductivity values equal to 1.48 W/mK and 1.38 W/mK, respectively. The results of the thermal conductivity agreed with that of the water absorption and resistance to freezing and thawing tests. As the number and connectivity of pores decrease, the thermal conductivity increases because the conduction of heat occurs more readily in solid mediums [39]. Since the hybrid fibers decreased the volume of voids and the number of interconnected pores, the heat was conducted faster throughout the concrete.

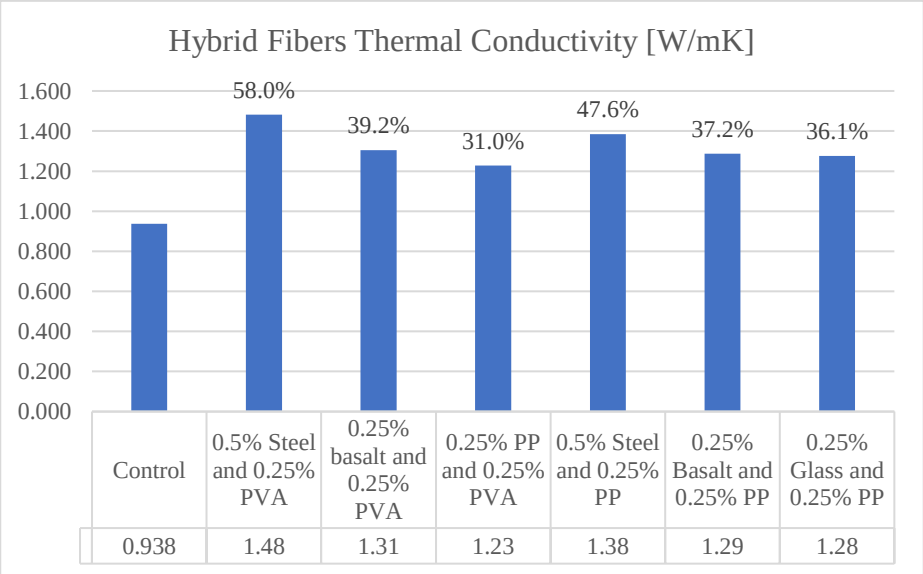


Figure 85: Thermal conductivity [W/mK] results of hybrid fiber

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

The effects of incorporating hybrid fibers in concrete varied from one property to another. The hybridization of fibers imposed negative and positive confounding effects depending on the property of concern.

- The hybridization of fibers reduced the compressive strength of ordinary concrete. In addition, incorporating hybrid fibers negatively affected the performance of SFRC.
- The hybridization of fibers had a positive impact on the tensile strength of ordinary concrete. All the hybrid mixtures enhanced tensile strength. Moreover, the hybridization of fibers had the best impact on the single PVA fibers but did not significantly alter the performance of other fibers. The hybrid mixture that had the best impact on the tensile strength was 0.5% steel and 0.25% PVA.
- The hybridization of fibers positively affected the flexural strength of ordinary concrete. All hybrid mixtures improved flexural strength by almost double. And the performance of the hybrid mixtures was similar to that of the single fibers. The hybrid mixture that had the highest enhancement was the 0.25% glass and 0.25% PP.
- Fibers played an important role in altering the brittle nature of the concrete failure to more ductile behavior.
- Like the case of SFRC, HFRC did not affect the elastic modulus of ordinary concrete. However, the hybridization of fibers negatively affected the impact of single steel fibers on the elastic modulus of ordinary concrete.

- The effect of hybridization on the water absorption and resistance to freezing and thawing tests was remarkable, unlike the performance of the SFRC. Almost all hybrid mixtures reduced water absorption by half. The mixture with the highest reduction was 0.25% glass and 0.25% PP. Moreover, the mixtures that provided the best resistance to freezing and thawing were 0.5% steel with 0.25% PVA and 0.25% glass with 0.25% PP.
- The hybridization of fibers increased the thermal conductivity of ordinary concrete, especially mixtures containing steel fibers.

Based on the performance of the hybrid fibers, the optimum hybrid mixture that improved both the mechanical properties and durability was 0.25% glass with 0.25% PP. However, it is best to use fibers like steel and basalt in single mixtures. On the other hand, it is recommended to introduce other types of fibers to the mixtures containing pure PVA.

When the durability of the concrete to be used is of great importance, it is advisable to use hybrid fibers. Nevertheless, it is not recommended to use HFRC where thermal resistivity is required.

4.2. Future Research

It is recommended to further research and study the effect of the hybridization of fibers on concrete. Different aspects might be studied:

- Study the effects of single and hybrid fibers on ultra-high performance and ultra-high-strength concrete.
- Use hybrid mixtures of the same type of fibers with different dimensions and aspect ratios (the use of micro and macro fibers).

- Study the effectiveness of replacing steel reinforcement with bars that are made up of fibers.
- Study the effects of the addition of pozzolanic materials on the impacts of fibers.

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