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Improving Structural Performance of Reinforced Concrete Beams with Phragmites Australis Fiber and Waste Glass Additives

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Abstract: The construction industry has seen a growing emphasis on the use of sustainable materials in recent years. This is driven by various factors, including a desire to reduce environmental impact, improve indoor air quality, and promote the health and well-being of building occupants. One sustainable material that is being increasingly utilized in construction is natural fibers. Phragmites australis fibers, in particular, are renewable, biodegradable, and have a low carbon footprint. The present study aims to evaluate the impact of Phragmites australis fibers on the behavior of reinforced concrete beams. Five concrete mixes were utilized in the experiment, with the control mix having a 1:1.5:3 ratio of cement to sand to coarse aggregate by weight. The other four mixes incorporated Phragmites australis fibers at 0%, 0.5%, 1%, and 1.5% of the volume of the mix, with cement replaced by 10% glass by weight. The water-to-cement ratio was set at 0.4 for all mixes. Concrete cubes, cylinders, and prisms were prepared to determine mechanical and physical properties, while reinforced concrete beams were used to assess structural performance. The results of the experiment showed that the addition of Phragmites australis fibers slightly decreased the compressive and tensile strength of the concrete compared to the control mix. However, the inclusion of 0.5% Phragmites australis fibers enhanced the split tensile and flexural strength of the concrete. In terms of reinforced concrete beams, the maximum load-bearing capacity was realized for the mix with 10% glass and 0% Phragmites australis fibers. However, the highest ductility index and deflection were achieved for the mix with 10% glass and 0.5% Phragmites australis fibers. Therefore, the use of Phragmites australis fibers can improve the structural performance of concrete.

Keywords: concrete; waste glass; Phragmites australis; compressive strength; structural performance; flexural strength; split tensile strength

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1. Introduction

Sustainability is a comprehensive approach that takes into account the environmental, social, and economic impacts of building construction [1–3]. The utilization of sustainable materials has gained prominence in recent years as a means of reducing the ecological impact of construction practices by curbing the use of materials that are damaging to the environment, such as non-renewable materials or those with high carbon footprints. Sustainable materials can also enhance indoor air quality by limiting the use of materials that emit harmful chemicals or toxins, leading to improved health and well-being of building occupants [4,5]. Furthermore, such materials are frequently more robust and long-lasting than conventional materials, and their application can help minimize the need for future repairs and replacements, ultimately resulting in long-term cost savings [4]. In addition, the employment of locally-sourced and sustainable materials can have a positive effect on the local economy and communities [6–8]. The incorporation of sustainable materials in building construction has the potential to improve energy efficiency by increasing thermal mass, leading to improved insulation and better regulation of indoor temperatures [9–11]. One promising area of research involves the use of natural fibers in concrete, which has the potential to enhance the strength and durability of concrete while simultaneously reducing its environmental impact [12–15]. Specifically, natural fibers can be employed to replace synthetic fibers such as steel and polypropylene, which are typically utilized in concrete reinforcement [16,17]. Notably, the addition of hemp fibers to concrete has been shown to enhance its compressive strength and reduce cracking [18,19]. For instance, concrete with 2% hemp fibers exhibited compressive strength that was approximately 10% higher than that of concrete without hemp fibers, and also exhibited a reduction of about 50% in the occurrence of cracking [20,21]. Additionally, the use of hemp fibers in concrete improved its flexural strength and toughness, as demonstrated by a flexural strength increase of about 18% in concrete with 2% hemp fibers compared to concrete without hemp fibers [22]. Another study found that the incorporation of hemp fibers improved the tensile strength, flexural strength, and toughness of concrete, with concrete containing 1% hemp fibers exhibiting a tensile strength that was approximately 7% higher than that of concrete without hemp fibers and a flexural strength that was approximately 15% higher than that of concrete without hemp fibers [23].

The use of natural fibers in concrete has also been investigated extensively, including jute, bamboo, and banana fibers. In particular, the addition of jute fibers to concrete has been shown to enhance its compressive strength, flexural strength, and toughness while also reducing the occurrence of cracking. A study demonstrated that concrete with 2% jute fibers had compressive strength that was approximately 10% higher than that of concrete without jute fibers [24]. Similarly, the incorporation of bamboo fibers in concrete has been shown to improve its compressive strength, flexural strength, and toughness. Another study reported that concrete with 2% bamboo fibers had compressive strength that was approximately 5% higher than that of concrete without bamboo fibers and also exhibited a flexural strength improvement of about 15%. Moreover, concrete with 1% bamboo fibers exhibited compressive strength that was about 5% higher than that of concrete without bamboo fibers and also exhibited an increase of about 10% in ductility [25,26].

Phragmites Australis (PA), also known as a common reed, is a perennial grass that typically grows in wetland areas and can reach heights of 15 ft. (4.6 m) or more. The plant's thick, vertical stalks produce broad, pointed leaves that are 6–23.6 in. (15–60 cm) long, 0.4–2.4 in. (1–6 cm) wide, flat, and glabrous. The flower heads are dense, fluffy, gray, or purple, and all parts of the plant can be used for various purposes. In construction, the stems of the PA plant are primarily used. This species has been explored as a renewable, biodegradable, and abundant source of natural fibers for use in concrete. A study conducted by Machaka et al. [27] revealed that the addition of 1.5% PA fibers to concrete enhanced its capillary and water absorption properties.

Alternatively, concrete without cement is a relatively new technology that has been introduced to provide environmental benefits. This process involves fully replacing Portland cement with an alumina–silicate material that contains alkaline reagents to improve concrete properties. The demand for cement shares a directly proportional relationship with economic growth due to the need for infrastructure development, leading to an increase in cement production [28]. The manufacturing of cement is a significant source of air pollution, and in 2007, it was reported that cement production was responsible for 5% of total greenhouse gas emissions [29]. Given these reasons, it is essential to identify eco-friendly alternatives to cement that can help mitigate the environmental impact of cement production and prevent environmental degradation [30–33].

The substitution of cement with supplementary cementitious materials (SCMs), such as fly ash, silica fume [34–36], slag, limestone fines [37–39] and others, has been proposed as an effective solution for reducing the environmental impact of concrete production [40–43]. Numerous studies have explored the use of SCMs in concrete, including the use of waste glass as a replacement for cement [44–46]. However, recent research by Ouldkhaoua et al. [47] has revealed that the use of cathode-ray tube (CRT) glass in concrete may reduce its compressive strength. Conversely, Bawab et al. [48] reported that concrete containing 10% CRT glass had increased elastic modulus, compressive strength, and flexural strength. Several additional properties of CRT glass concrete have also been investigated.

The addition of CRT glass to concrete has been found to decrease drying shrinkage, as CRT glass particles absorb less water [49–51]. However, the addition of CRT glass to concrete has also been found to increase expansion values by minimizing resistance to the alkali-silica reaction (ASR) [52,53]. The structural performance of strengthened concrete beams incorporating glass waste has been studied by various researchers. Hama et al. [54] investigated the structural capacity of reinforced concrete beams incorporating waste glass powder as a cement replacement up to 15% and found that the reference beams' load capacity was lower for beams containing 10% and 15% waste glass, respectively. Another study found a reduction in the flexural strength and ductility factor of strengthened concrete beams when glass was used as fine particles or coarse aggregates [55].

Recent research has provided evidence to suggest that natural fibers could serve as a sustainable substitute for traditional synthetic fibers in concrete, with some studies indicating that their incorporation could enhance the strength and durability of concrete [56–58]. However, the feasibility of using natural fibers in concrete production on a larger scale requires further research. Notably, the use of fibers derived from the Phragmites australis plant as reinforcement in concrete is still an emerging area of investigation. Hence, the objective of the present study is to investigate the effect of incorporating waste glass as a cement replacement with natural fibers from the Phragmites Australis plant on the performance of reinforced concrete (RC) beams. The mechanical properties of concrete, such as compressive strength, ultrasonic pulse velocity (UPV), split tensile strength, and flexural strength, will be examined. The structural performance of RC beams incorporating Phragmites Australis fibers and waste glass will also be investigated. These results will be used to provide recommendations for practicing engineers and future research.

2. Materials and Methods

2.1. Materials

The experimental materials used in this study comprised Portland cement type I (PA-L 42.5 N) from Sibline manufacture, Lebanon, with a density and specific gravity of 1440 kg/m^3 and 3.15, respectively. The cement properties are illustrated in Tables 1 and 2, respectively. Waste glass obtained from broken glass windows was crushed using a proctor machine and sieved through a No. 200 sieve (75 µm) (Figure 1). The waste powder glass (WPG) had a specific gravity and density of 2.51 and 1241 kg/m^3, respectively. Siliceous sand with a maximum grain size of 2.3 mm was used, with a fineness modulus of 2.8 and a specific gravity of 2.65. The coarse aggregates used had a density of 2480 kg/m^3, a specific gravity of 2.8 and water absorption of 2.3%. The natural fibers utilized in this study were obtained from the Phragmites australis (PA) plant. The plant's stems were collected, cut into 3 cm lengths and 2 cm widths using a mechanical machine, and had an aspect ratio of 19. It should be noted that the chosen length of PA fibers (3 cm) has many reasons, such as insulation purposes, whereas the optimal fiber length ranged between 1 and 3 cm [59]. I will definitely take this as a reference when discussing the fiber length of PA fibers in my manuscript. The PA fibers had a density of approximately 665 kg/m^3. In order to improve the adhesion properties of the PA fibers with the matrix and decrease their hydrophilic character, a 24-h chemical treatment using NaOH was applied to these fibers (Figure 2). The use of NaOH solution is based on previous work conducted by Machaka et al. [27] in Beirut Arab University lab and on previous studies investigated by many authors [22,23,25,26,60]. The superplasticizer used is ViscoCrete from Sika company in Lebanon. It recovers workability retention and permits a large decrease in water content since we are adding natural fibers in the mixture. The percentage of addition varies between 0.2–1% liter by weight of cement. ASTM C136-21, [61] is used in this study for sieve analysis test. This method describes the procedure for performing a sieve analysis on both fine and coarse aggregates. For this experiment, a range of sieve sizes including 0.075 mm, 0.3 mm, 0.6 mm, 1.18 mm, 2.36 mm, 4.75 mm, 6.3 mm, 9.5 mm, 12.5 mm, and 19 mm were utilized for sieve analysis. The sieve analysis was performed on sand, crushed glass, and coarse aggregates, with particle sizes ranging from 19 mm to 0.075 mm. Additionally, the particle size distribution sheet for cement was obtained from the cement manufacturer located in Sibline, Lebanon. The particle size distribution for the cement, sand, glass, and coarse aggregate is presented in Figure 3.

Table 1. Chemical composition of cement.

Tested Element	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	L.O. I	Na_2O+0.658*K_2O	Free Lime	CT
Content (%)	18.53	3.93	3.06	61.78	1.74	2.92	0.18	0.47	6.3	0.48	0.49	0.046

Table 2. Physical properties of cement.

Initial setting time (min)	232
Final setting time (min)	282
Blaine surface area (Cm^2/g)	3998
Soundness (mm)	0
Water Demand (%)	27

(a) (b)

Figure 1. Waste glass: (**a**) pieces of glass; (**b**) fine aggregate/particles of glass (75 µm).

2.2. Mix Proportions

This study evaluated five concrete mix designs. The first mix served as the control mix, with 0% WPG and 0% PA. Its cement–water–sand aggregate's mass proportions were 1:0.4:1.5:3. For the remaining four mix designs, 10% of the cement was replaced with waste powder glass (G) in all mixes. The percentages of Phragmites australis (PA) fibers added to the mixes were 0%, 0.5%, 1%, and 1.5%. Varying concentrations of superplasticizer (SP) were added to the mixtures to maintain a consistent slump (180 ± 20 mm). The essential design details of the concrete mixes are presented in Table 3. Mixes were designated MxG-yPA, where x and y denote the percentages of waste powder glass and PA, respectively.

Figure 2. Treated PA fibers with NaOH solution.

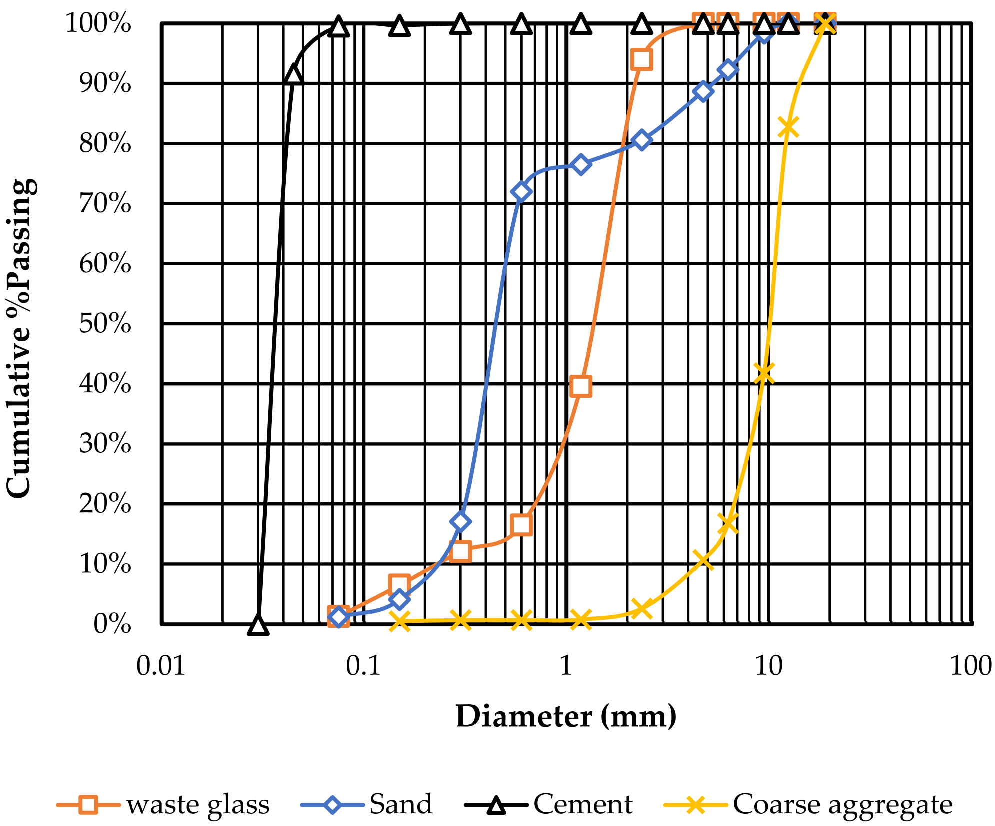

Figure 3. Particle size distribution for cement, sand, and waste glass.

Table 3. Mix proportions.

Mix Designation	Quantity kg/m^3						
	Cement	Sand	Coarse Aggregates	Water	WPG	PA	SP
M0%G-0%PA	425	637	1274	170	0	0	1
M10%G-0%PA	382	573	1147	153	42	0	1
M10%G-0.5%PA	382	573	1147	153	42	3	2
M10%G-1%PA	382	573	1147	153	42	7	2
M10%G-1.5%PA	382	573	1147	153	42	10	2

2.3. Reinforced Concrete (RC) Beam Design

Reinforced concrete (RC) beams were constructed with dimensions of 100 mm in width, 200 mm in height and 1000 mm in length, following the American Concrete Institute (ACI 380-19) code. All beams were designed to fail in flexure mode. Equations (1) and (2) were used to calculate the area of the main reinforcement as follows:

$$A_S f_y = 0.85 f'_c ab \tag{1}$$

$$Mn = A_S f_y \left(d - \frac{a}{2} \right) \tag{2}$$

where A_s represents the area of steel reinforcement, f_y represents the yield strength of the reinforcement, f'_c represents the compressive strength of concrete, a represents the depth of the stress block, b represents the width of the beam, and Mn represents the nominal moment. It was determined that the required area of reinforcement bars was 100 mm^2. Accordingly, two mild steel bars with an 8 mm diameter were selected as the main (bottom) reinforcement, and two mild steel bars with a diameter of 6 mm were chosen as top reinforcement. The bottom and top reinforcement remained the same for all concrete mixes.

2.4. Sample Preparations

The concrete samples were prepared using steel molds based on the table of mix proportions. Prior to casting, the molds were thoroughly cleaned and lubricated. The compressive strength of the samples was determined using cubes with dimensions of 100 × 100 × 100 mm^3, while their ultra-pulse velocity (UPV) and density were also evaluated using these cubes. Cylinders with diameters of 100 mm and lengths of 200 mm were cast to determine the split tensile strength, and prisms with dimensions of 100 × 100 × 400 mm^3 were employed to assess the flexural strength. The structural performance was evaluated using beams measuring 100 × 200 × 1000 mm^3. The slump of each mix was measured before casting. Six cubes, three cylinders, three prisms, and one beam were cast for each mixture. After casting, the specimens were cured in water at 20 °C for a period of 28 days. Wet burlap was used to wrap the beams, which were stored in the laboratory room at 25 °C and 65% relative humidity until testing.

2.5. Testing

The compressive strength, split tensile strength, density, and UPV tests were conducted in accordance with appropriate international codes and specifications (ASTM C39 [62], ASTM C496 [63], ASTM C138 [64], and ASTM C597 [65], respectively). The flexure behavior of reinforced concrete (RC) beams was determined using the three-point test, with the beam being tested at 10 kN increments until yielding occurred [48]. At each load, the machine was stopped to measure the central deflection and the strain at different levels. The load at first crack was recorded, and loading continued until failure, with the central deflection being measured [30,48]. The propagation of cracks was observed throughout the test. The test setup for RC beams is depicted in Figure 4a,b, while the testing setup for mechanical properties is illustrated in Figure 5.

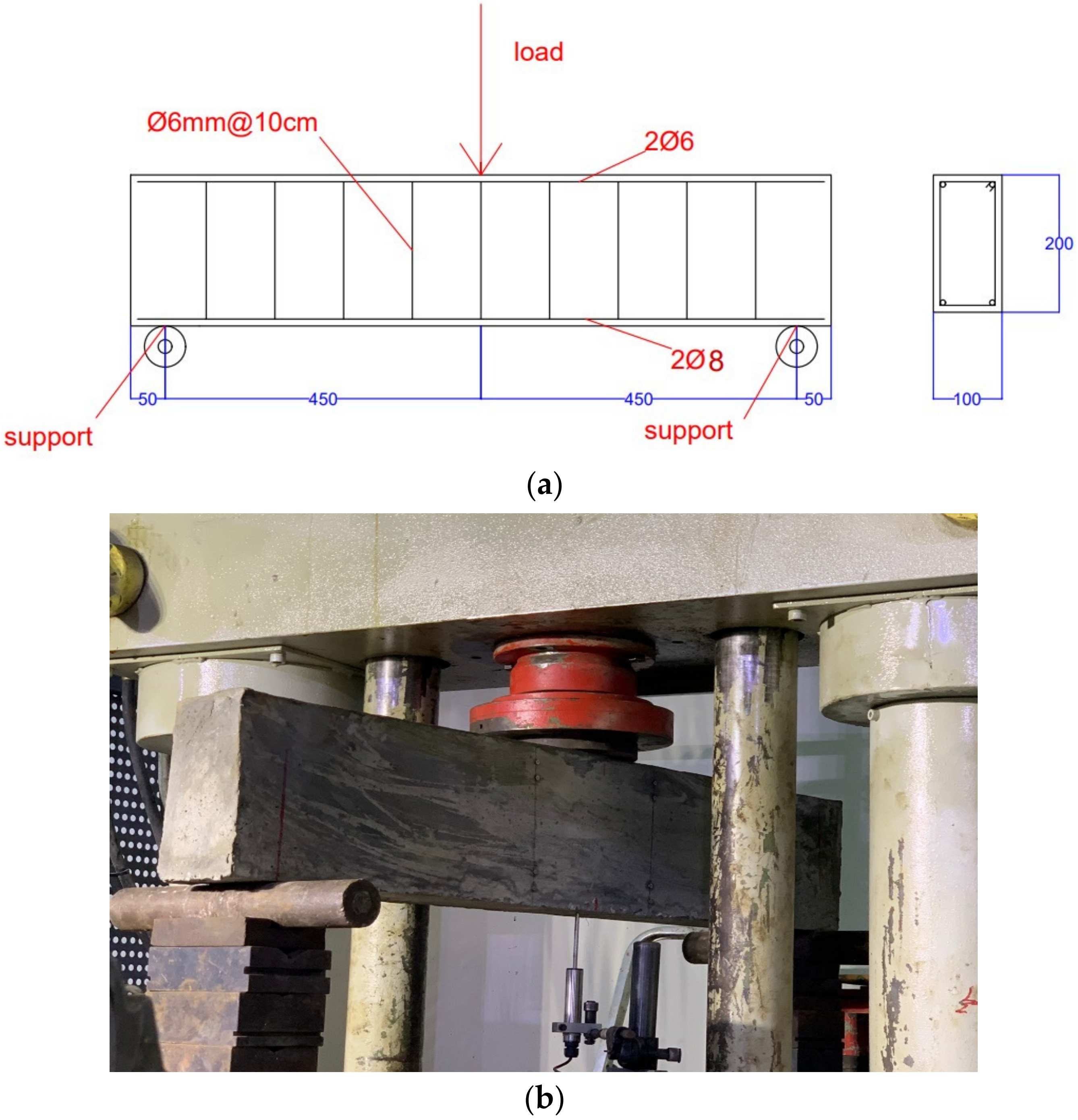

Figure 4. RC beams Testing setup: (**a**) schematic illustration (mm); (**b**) RC beam during testing.

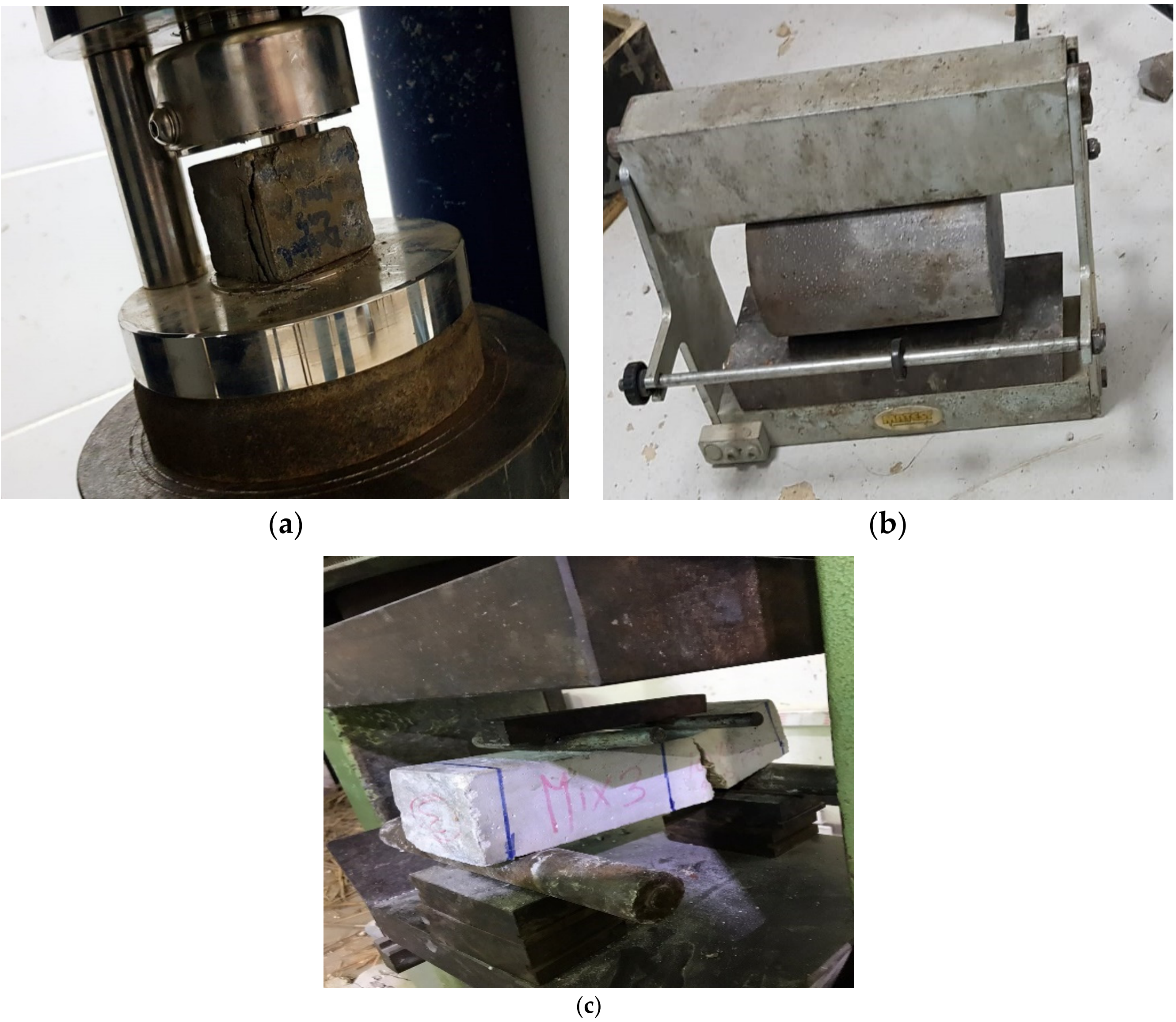

Figure 5. Mechanical testing: (**a**) compressive strength; (**b**) split tensile strength; (**c**) flexural strength.

3. Results and Discussion

3.1. Density

Figure 6 presents the density of plain concrete and PA fiber-reinforced concrete with powder glass at 28 days. There is no big difference between specimens with and without PA fibers. The density of all mixtures is almost the same. As shown, the density slightly increased with the addition of 10% G without PA fibers but then began to decrease with the addition of 0.5%, 1%, and 1.5% PA fibers. The primary cause for this slight decrease is the use of PA fibers in cement-based materials, which can result in reduced compaction due to the added volume of fibers in the mix. As fibers occupy space, they may generate more voids within the material, thereby lowering the overall density of the structure [66]. This was mentioned in previous study by Song et al. [67]. This study held the view that the presence of jute fiber in concrete leads to a decrease in its density when compared to concrete that does not contain reinforced fiber. Another factor contributing to the reduction in compaction when utilizing a higher proportion of PA fibers in concrete is "balling", a phenomenon in which the fibers in the mix clump together, creating small balls or clumps of fibers [66]. These fiber clumps occupy space within the mix, creating voids or spaces. These voids can actually reduce compaction within the mixture. Compaction refers to the process by which the particles within a mixture are pressed together, reducing the amount of space between them. This can lead to a denser and more solid mixture, which may not always be desirable. The voids created by the clumps of PA fibers can help prevent excessive compaction, allowing for a more porous and breathable mixture. Balling can be more severe with higher fiber contents in the mix because more fibers can clump together. Furthermore, the type and size of the fibers used, as well as the mixing and curing conditions, can all influence balling [68].

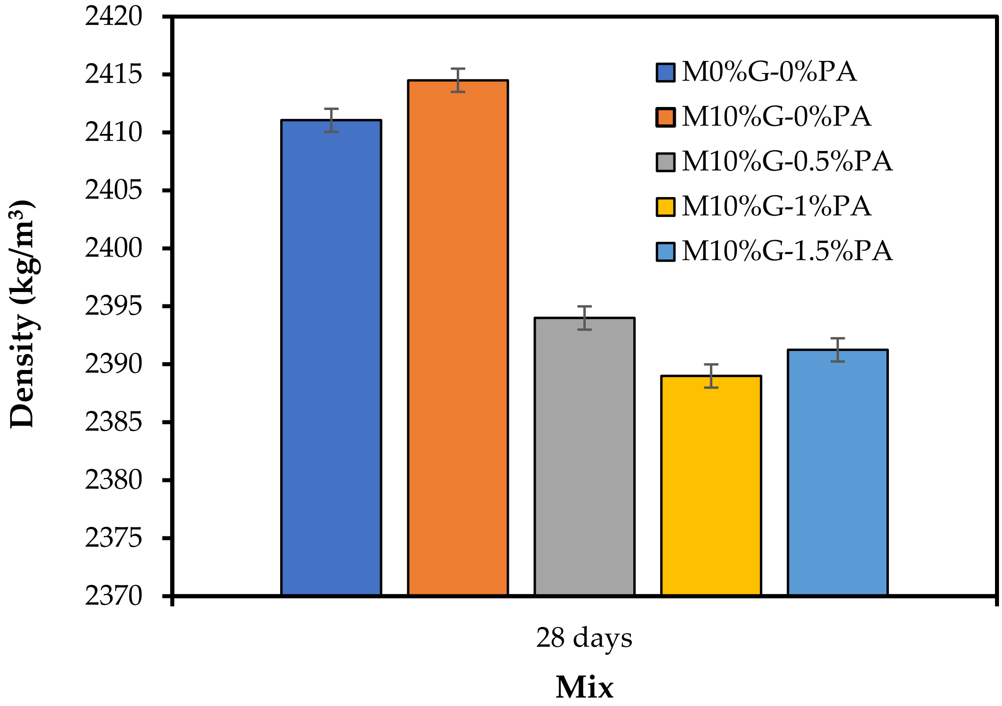

Figure 6. Density for cubes with powder glass and PA fibers (6 cubes/mix).

3.2. UPV

To validate the density results obtained from our experiment, we compared them with the ultrasonic pulse velocity (UPV) measurements and found that the two sets of data were in good agreement, confirming the accuracy of our density measurements. Figure 7 illustrates the effect of incorporating powder glass and PA fibers on the UPV of various cubes at different curing ages. The results indicate that the addition of 10% G without PA fibers leads to a slight increase in UPV at all curing ages. However, the UPV gradually decreases with the addition of 0.5, 1, and 1.5% PA fibers. This phenomenon can be attributed to the generation of voids, which is promoted by the presence of PA fibers, resulting in a decrease in pulse velocity. The voids or spaces in the material act as an obstacle to the passage of the mechanical impulse, thus decelerating the velocity of the pulse [69]. As the proportion of PA fibers in the mix increases, the number of voids in the material also increases, leading to a decrease in pulse velocity. Additionally, the type and size of fibers, the orientation and distribution of fibers within the material, and the curing conditions of the material also affect the pulse velocity [70]. It should be noted that all UPV values at 28 days exceed 4 km/s, indicating excellent to very good concrete quality [65].

3.3. Compressive Strength

In Figure 8, the compressive strength of various concrete cubes mixtures containing powder glass and PA fibers is presented. It can be observed that the incorporation of 10% powder glass fibers slightly increases the compressive strength, while the addition of 0.5%, 1%, and 1.5% PA fibers causes a decrease in compressive strength. This enhancement is attributed to the pozzolanic reaction of powder glass, which can improve the strength and durability of the concrete through the formation of additional cementitious compounds, such as calcium silicate hydrate (C-S-H) [39]. As shown, the compressive strength at 28 days decreases by 9.77%, 9.8%, and 13.8%, respectively, for the different levels of PA fibers as compared to the control mix. Zakaria et al. [71] conducted a study that revealed a similar trend in which the compressive strength of concrete increased when 0.5% of jute fiber was used. This was also found to be the case of concrete with nylon and jute fibers [72], once the percentage of nylon and jute fibers in the concrete mixture exceeded 1%, the strength decreased due to increased air spaces and porosity resulting from poor compaction of a large number of fibers in the mixture. Moreover, Bheel et al. [73] found that the compressive strength of concrete increased up to 1% when the amount of human hair was increased, after which it began to decrease. This reduction is due to the lower interlocking strength between the PA fibers and cement, as well as the lack of bonding and sliding action between the fibers at high friction. Therefore, the selection of the appropriate proportion of PA fibers and any pretreatment used in creating mixtures of PA fibers and concrete is crucial [74]. It is noted that the relationship between these results and the UPV values is significant, as a decrease in UPV due to voids correlates with a reduction in compressive strength (Figure 9). Therefore, there is a direct correlation between the UPV values and the compressive strength of the material, whereby a decrease in UPV indicates the presence of voids and a decrease in compressive strength. The correlation between compressive strength and ultrasonic pulse velocity (UPV) has been extensively studied. It has been found that this correlation follows a normal exponential relationship with a high correlation coefficient, as reported in previous literature by Khatib et al. [39,47]. For example, Khatib et al. [39] found that the coefficient of determination for pastes and mortars was reported to be 0.91 and 0.93, respectively.

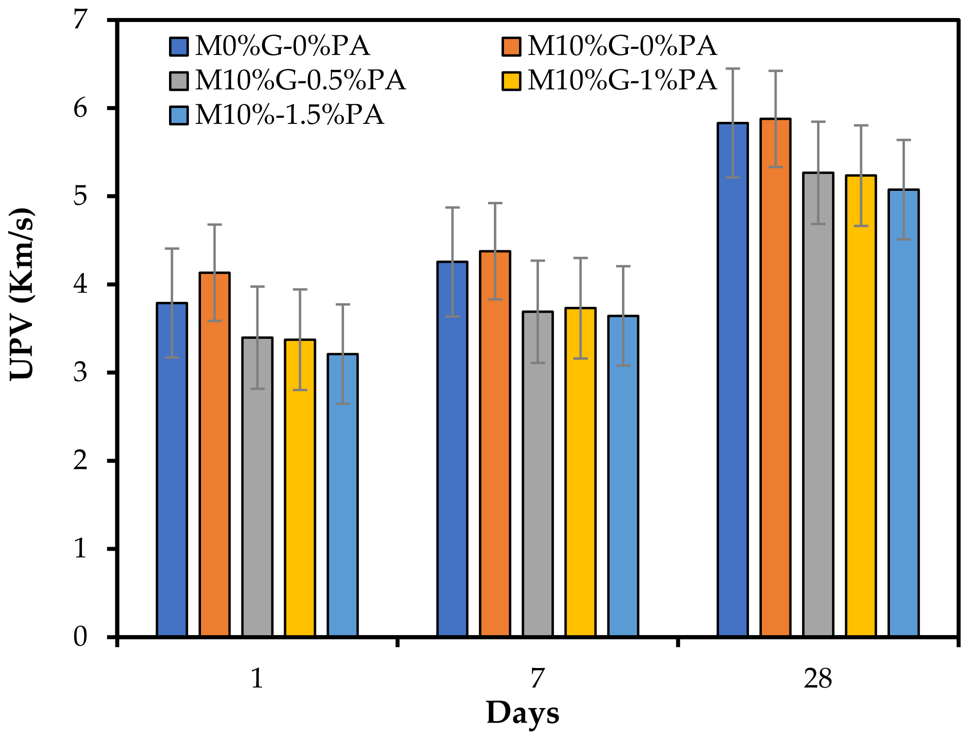

Figure 7. UPV for cubes with powder glass and PA fibers (6 cubes/mix).

3.4. Split Tensile Strength

The split tensile strength results for plain concrete and PA fiber-reinforced concrete are presented in Figure 10. The data indicate that the addition of PA fibers enhances the split tensile strength of plain concrete, with the highest increase observed at fiber volume fractions of 0.5% (13.33%). However, the strength improvement diminishes as the fiber volume fraction increases, which may be due to segregation issues arising from inadequate compaction of mixtures with higher fiber volumes. These results are consistent with those of Darshan et al. [75], where the split tensile strength of M-sand concrete (C2) reinforced with 0.5% sisal fiber exhibits an improvement in strength when compared to conventional concrete (C1). Specifically, at 7 days, the split tensile strength of C2 with 0.5% sisal fiber increases by 29.41% compared to C1, while at 28 days, the strength of C2 with 0.5% sisal fiber increases by 24% compared to C1. It has been observed that the strength of the composite increases almost linearly with the volume percentage of fibers when segregation is prevented [76]. This effect can be partly attributed to the NaOH treatment of PA fibers, which can enhance their interaction with the cement matrix [77]. Treatment with NaOH can increase the surface roughness of the fibers, improving their mechanical interlocking with the matrix [77]. This, in turn, can promote better fiber distribution and orientation within the matrix, leading to improved mechanical properties such as increased compressive strength and decreased pulse velocity. Furthermore, NaOH treatment can also alter the chemical composition of the fiber surface, facilitating better chemical bonding between the fibers and the matrix, thus further contributing to the superior performance of the fibers in cement-based materials [78]. The addition of 10% powder glass without PA fibers resulted in similar outcomes in terms of both compressive strength and split tensile strength. This suggests that the presence of powder glass may have compensated for the lack of fibers in terms of enhancing the material's strength and resistance to splitting forces.

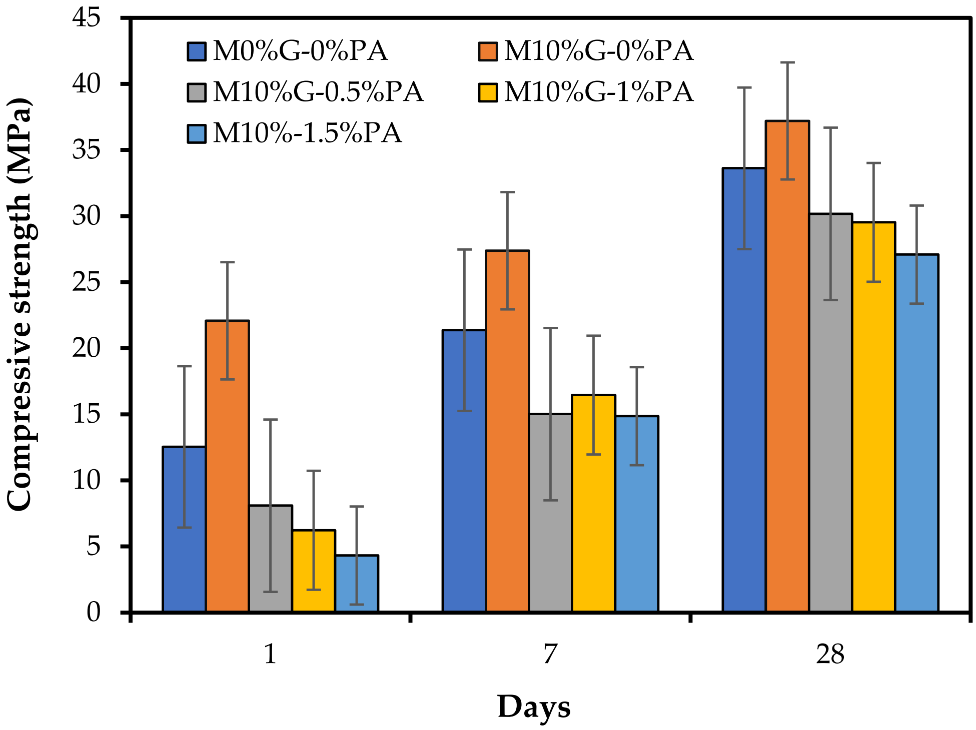

Figure 8. Compressive strength for cubes with powder glass and PA fibers (6 cubes/mix).

3.5. Flexural Strength

In Figure 11, the flexural strength of prisms with and without fibers is presented. The results indicate that the inclusion of PA fibers enhances the flexural strength of plain concrete, with the greatest increase observed at a fiber volume fraction of 0.5% (16%). The outcomes of this experiment are related to a previous study by Islam et al. [79]. The results of this research indicate that incorporating 0.5% and 1.0% coir fibers in normal strength concrete (NSC) leads to improved performance in flexural strength. Furthermore, the inclusion of 0.5% coir fiber in high-strength concrete (HSC) results in improved flexural and tensile strengths. In both types of concrete, the addition of coir fibers leads to increased ductility and toughness. This enhancement is attributed to the high pozzolanic reactivity of cement, which promotes the formation of additional C-S-H gel [80]. The increased formation of C-S-H gel leads to a less dense hydration product around the fibers, which reduces the embrittlement of the composite and increases its ductility [81]. Additionally, the inclusion of PA fibers reinforces the matrix by acting as small reinforcing bars, which help to transfer stress and enhance the overall performance of the material. The PA fibers contribute to the enhancement of flexural strength in several ways, including increasing the toughness of the matrix, providing confinement to the concrete, and improving the bond strength between the fibers and the matrix, which results in more efficient load transfer and increased strength of the material [76,82,83]. In fact, when a composite material is subjected to stress, cracks may form in the matrix material that surrounds the fibers. These cracks can propagate and ultimately lead to the failure of the material. However, when natural fibers such as PA fibers are present, they can help to prevent these cracks from propagating by acting as bridges across the crack faces. These fibers are able to distribute the stress more evenly, which helps to reinforce the matrix and prevent further cracking. This bridging effect is particularly important in enhancing the tensile and flexural strengths of composite materials. The bridging effect also helps to improve the toughness and ductility of the material, making it more resistant to fracture and deformation [83].

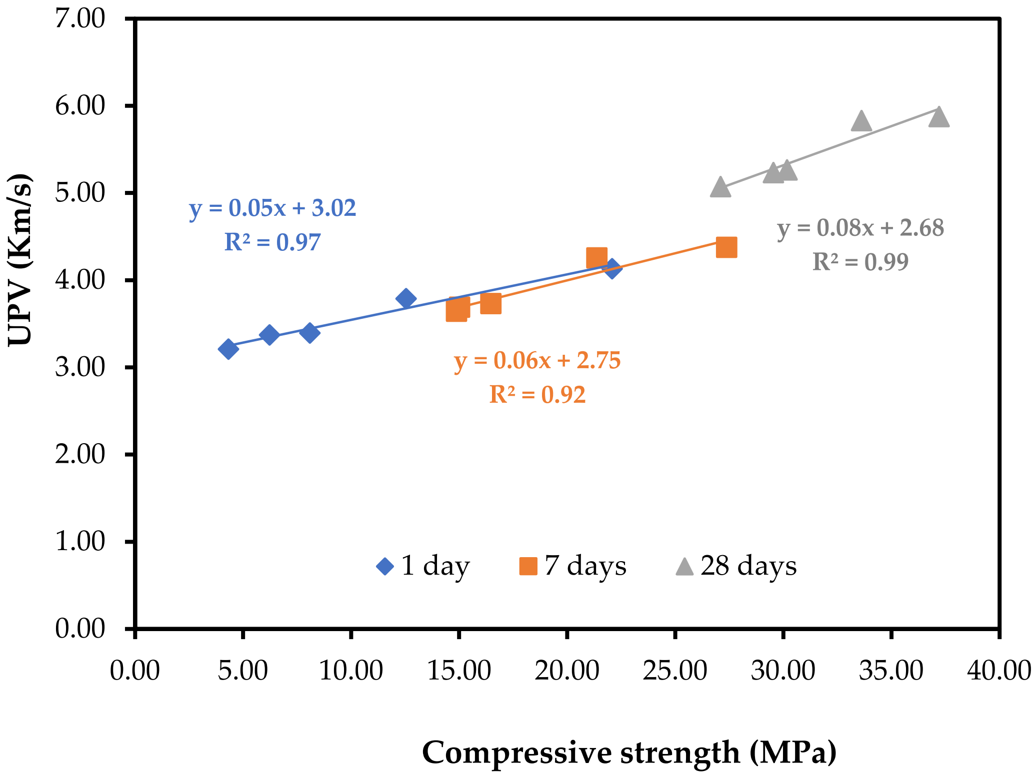

Figure 9. Correlation between UPV and compressive strength at different curing ages.

3.6. Behavior of Reinforced Concrete Beams

Figure 12 presents the Load deflection curves for all the RC beams tested. The beam containing 10% powder glass and 0% PA exhibited the best performance in terms of both ductility and load capacity. The maximum load capacity for this beam was slightly higher, around 20%, than the control beam (0%G, 0%PA). As for the other beams, the load capacity increased compared to the control beam, with the increase ranging from 1.6% to 2.9%. However, a slight decrease of 1.2% was observed in Beam 3 (10%G, 0.5%PA). The data for load deflection are summarized in Table 4. The highest yield and failure deflection were observed in Beam 3, indicating that the incorporation of 0.5% PA fibers improved the ductility of the concrete. This improvement is mainly attributed to the application of chemicals to PA fibers, which improves the connection between the fibers and the polymer matrix, resulting in increased roughness on the fiber surface and stronger bonding. This leads to a reduction in cracks and shrinkage during drying. Moreover, the addition of dry, pre-treated PA fibers into the mix results in lower shrinkage during drying.

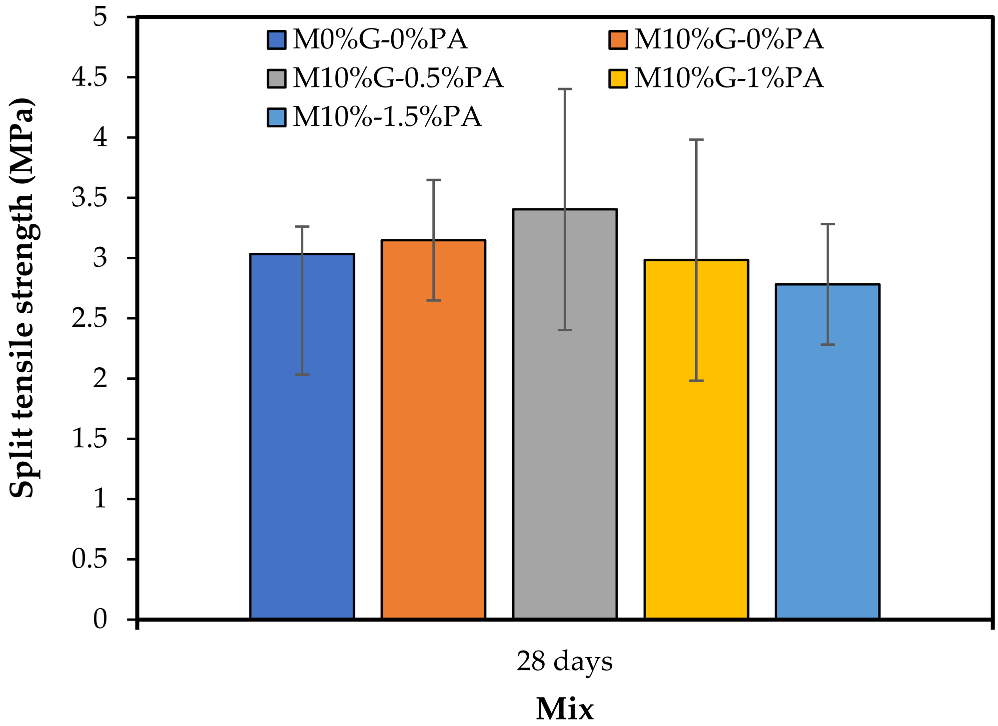

Figure 10. Split tensile strength for cylinders with powder glass and PA fibers (3 cylinders/mix).

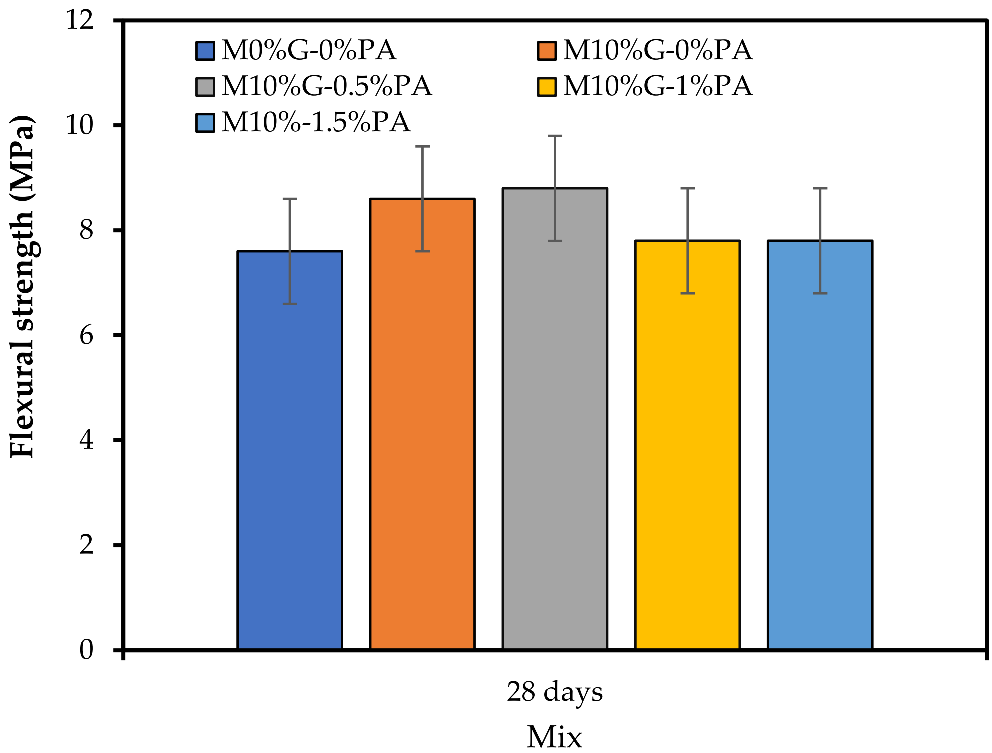

Figure 11. Flexural strength for prisms with powder glass and PA fibers (3 prisms/mix).

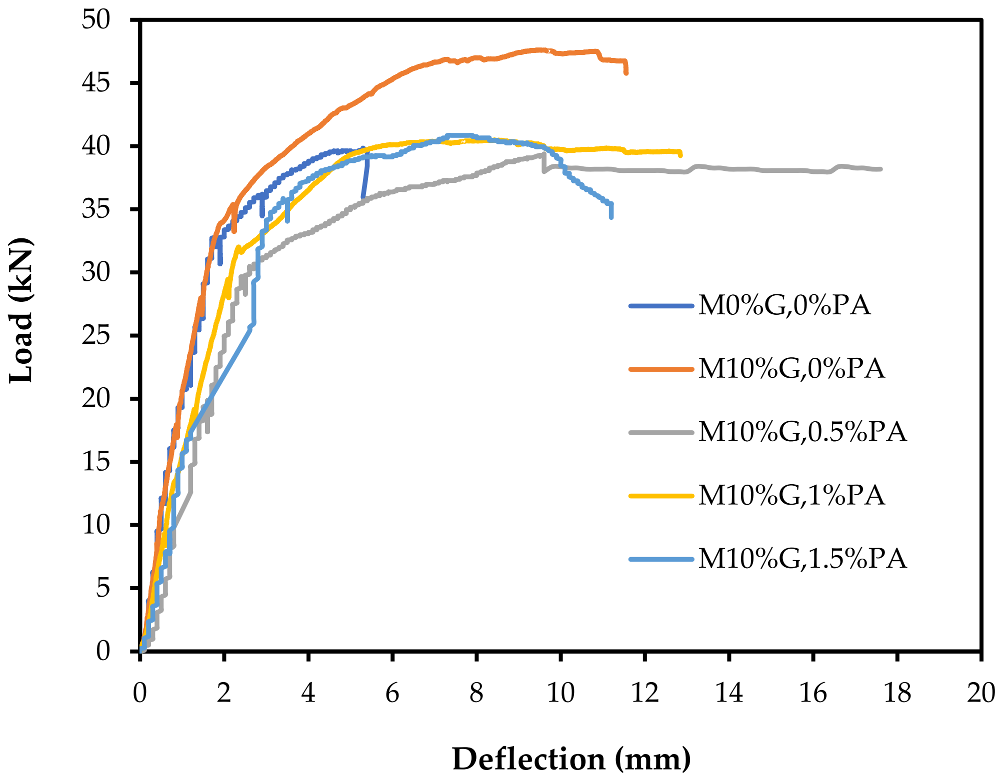

Figure 12. Load deflection for RC beams with powder glass and PA fibers.

Table 4. Load deflection data for all RC beams.

	Maximum Load (P_{max}) (kN)	Deflection at Yield (γ_y) (mm)	Deflection at Failure (γ_u) (mm)	Ductility Index (γ_u/γ_y)
B1:0%G, 0%PA	39.8	1.8	5.4	3.0
B2: 10%G, 0%PA	47.6	1.7	11.6	6.8
B3: 10%G, 0.5%PA	39.4	2.5	17.6	7.0
B4:10%G, 1%PA	40.5	2.3	12.8	5.7
B5:10%G, 1.5%PA	40.9	3.0	11.2	3.7

The crack pattern for all the beams is shown in Figure 13. The failure of all the beams was due to flexure, with varying numbers of cracks. Beam 3 exhibited the most cracks due to its greater ductility compared to the other beams. PA fibers are not brittle like synthetic fibers and are more flexible. Thus, they can absorb more energy before failure. Furthermore, the addition of PA fibers improves the overall strength and stiffness of the beam, delaying the onset of cracking, which, in turn, increases the ductility of the beam. PA fibers have good compatibility with the matrix, improving the interfacial bonding between the fibers and the matrix, leading to more homogeneous stress distribution, reducing stress concentrations, and increasing ductility.

The strain distribution of the beams was analyzed by adding demec points at different depths, as shown in Figure 14. The strain distribution along the depth of the beam at different load increments is shown in Figure 15 for Beam 1 (0%G, 0%PA), Beam 2 (10%G, 0%PA), Beam 3 (10%G, 0.5%PA), Beam 4 (10%G, 1%PA), and Beam 5 (10%G, 1.5%PA). As demonstrated in the data, as the applied load increases, the strain on the beam also increases. Beam 2 exhibited the lowest strain values among the other beams tested, which is directly related to its higher ultimate load, as shown in Table 4 (47.61 kN). This suggests that Beam 2 has a higher resistance to deformation and is able to withstand greater loads before failure. The higher ultimate load of Beam 2 can be attributed to its superior strength and stiffness, which could be the result of using powder glass. The inclusion of powder glass in the concrete can help to reduce the occurrence of cracking by providing additional support for the concrete matrix. These findings are consistent with a previous study by Bawab et al. [48].

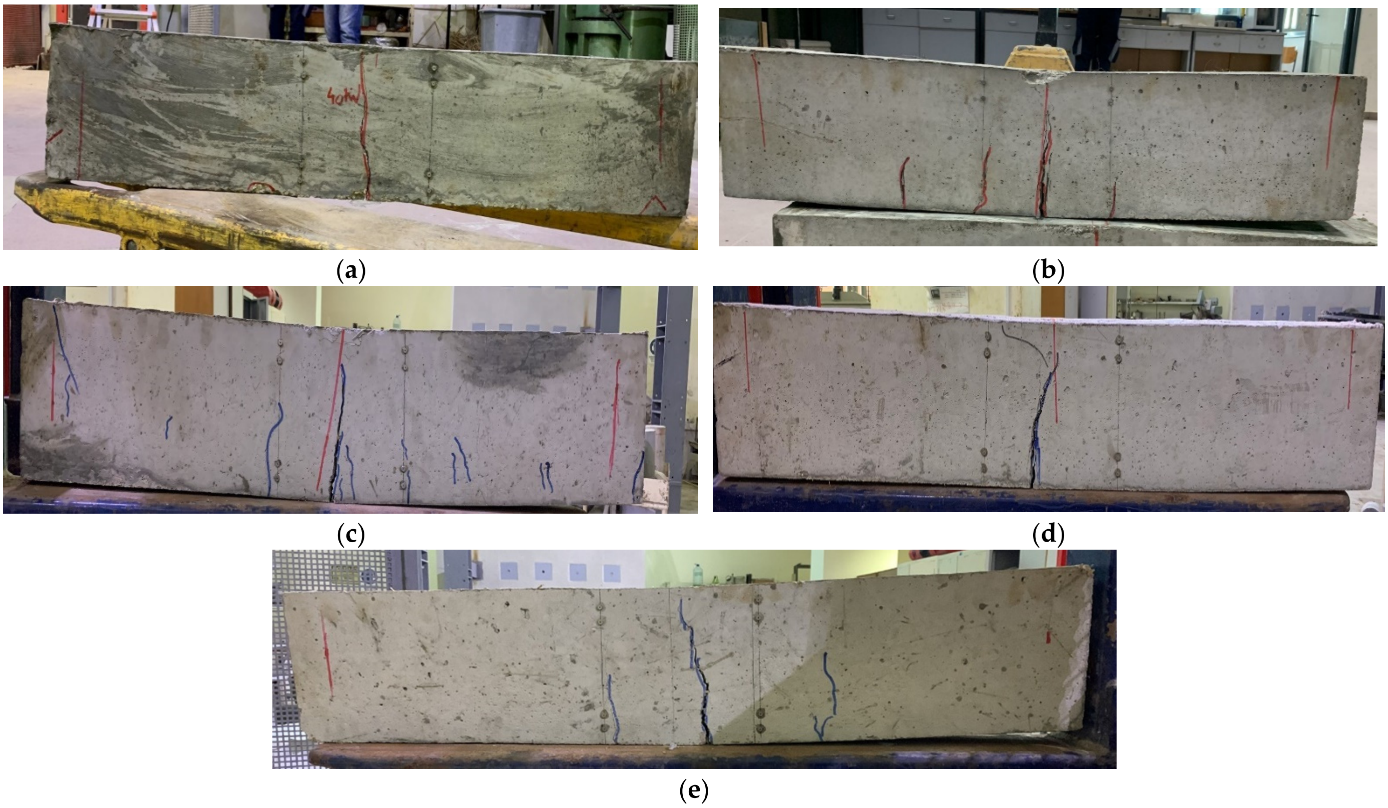

Figure 13. Cracks patterns; (**a**) B1: 0%G, 0%PA; (**b**) B2:10%G, 0%PA; (**c**) 10%G, 0.5%PA; (**d**) = 10%G, 1%PA; (**e**) 10%G, 1.5%PA.

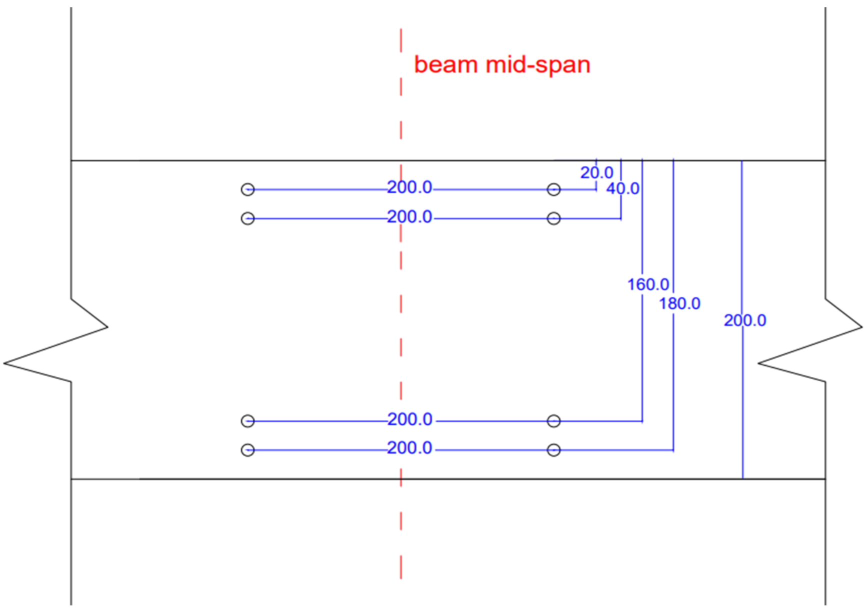

Figure 14. Distribution of demec points on the beam in the tension and compression faces.

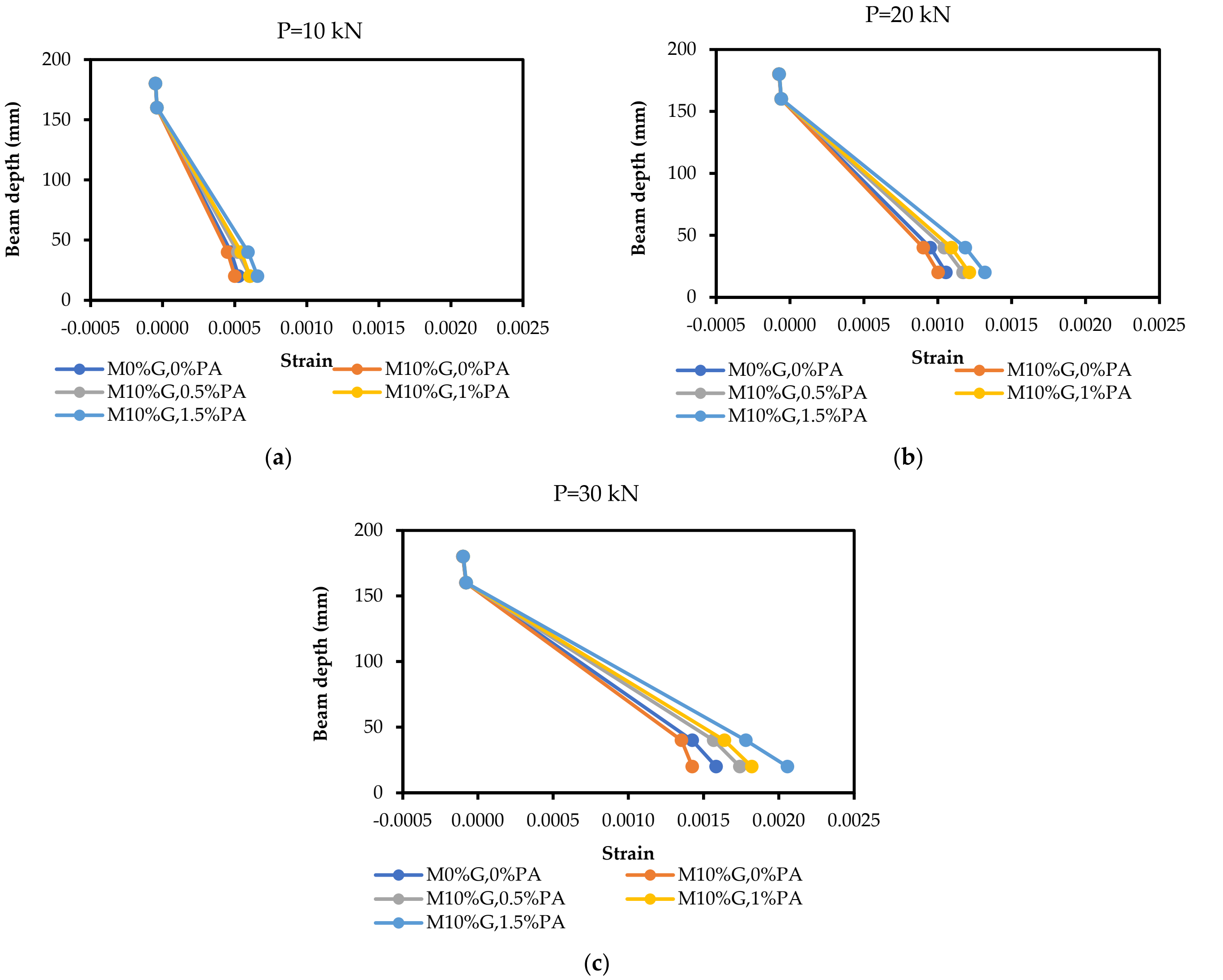

Figure 15. Strain measurements for beams; (**a**) 10kN load incrementation; (**b**) 20kN load incrementation; (**c**) 30 kN load incrementation.

4. Conclusions

The present study investigated the impact of waste powder glass as a cement replacement with natural fibers from the Phragmites australis plant on the performance of reinforced beams. The study evaluated five concrete mix designs, including a control mix with no glass or Phragmites australis (PA) fibers. The mixes contained varying percentages of PA fibers, ranging from 0% to 1.5%, and 10% of the cement was replaced with waste powder glass in all mixes. Superplasticizer (SP) was added to the mixtures to maintain a consistent slump. The mechanical properties of concrete, including compressive strength, ultrasonic pulse velocity (UPV), split tensile strength, and flexural strength, were examined to evaluate the structural performance of reinforced concrete (RC) beams. Based on this study, the following conclusions can be driven:

- The addition of 10% powder glass in the concrete mixture resulted in an increase in density, compressive strength, and split tensile strength in all curing ages;
- The addition of 0.5%, 1%, and 1.5% PA fibers caused a decrease in density and compressive strength but an increase in UPV values, indicating good to excellent concrete quality ranging from 5.08 to 5.83 km/s;
- The incorporation of PA fibers decreased the compressive strength. As PA fibers percentages increased, the compressive strength decreased as well. It is noted that the

highest compressive value was achieved for mix with 10% powder glass with 0% PA fibers (37.2 MPa). There is a high correlation between UPV and compressive strength with high coefficient of determination R^2 of 0.99;

- The addition of fibers may increase the split tensile strength due to the chemical treatment (NaOH) of PA fibers, which promotes better interaction between fibers and matrix, increasing the fiber surface roughness and bonding between them. The highest split tensile value was achieved for the addition of 10% glass with 0.5% PA fibers (3.4 MPa). Same trend was observed for flexural test results. The addition of 10% powder glass and 0.5% PA fibers achieved the highest value (8.8 MPa);
- The load deflection curves showed that the beam containing 10% powder glass and 0% PA fibers had the best performance in terms of load capacity (47.6 Mpa);
- The beam with 10% powder glass and 0.5% PA had the best performance in terms of ductility index (7);
- It is important to consider the proportion of PA fibers and any pretreatment used when creating mixtures of PA fibers and concrete.

Based on the findings of this study, it can be concluded that the addition of powder glass and Phragmites australis fibers can improve the mechanical properties and durability of reinforced beams. These results can have practical implications for the construction industry, where the use of sustainable and eco-friendly materials is increasingly being emphasized. Furthermore, future studies could investigate the effect of different types and proportions of fiber and glass powders on the mechanical and durability properties of reinforced beams. Additionally, further research could explore the potential use of other natural fibers and recycled materials in combination with powder glass as reinforcements in concrete structures. Such studies could lead to the development of novel eco-friendly and sustainable construction materials with enhanced performance and reduced environmental impact.

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