buildings

MDPI

Article

The Effect of Adding *Phragmites australis* Fibers on the Properties of Concrete

Meheddene Machaka [1], Jamal Khatib [1,2,*], Safaa Baydoun [1], Adel Elkordi [1,3] and Joseph J. Assaad [4]

1 Faculty of Engineering, Beirut Arab University, Beirut P.O. Box 11-5020, Lebanon; m.mashaka@bau.edu.lb (M.M.); safaa.baydoun@bau.edu.lb (S.B.); a.elkordi@bau.edu.lb (A.E.)
2 Faculty of Science and Engineering, University of Wolverhampton, Wolverhampton WV1 1LY, UK
3 Department of Civil Engineering, Faculty of Engineering, Alexandria University, Alexandria 21511, Egypt
4 Faculty of Engineering, University of Balamand, Al Kourah P.O. Box 100, Lebanon; joseph.assaad@balamand.edu.lb
* Correspondence: j.khatib@bau.edu.lb

Abstract: Nowadays, the increasing demand for concrete is causing serious environmental impact including pollution and waste generation, rapid depletion of natural resources, and increased CO_2 emission. Incorporating natural fibers in concrete can contribute toward environmental sustainability. This paper is concerned with the use of natural fibers obtained from the plant species *Phragmites australis* (PA). The plant is invasive, and rapidly grows abundantly along rivers and waterways, causing major ecological problems. This research is part of a wide range investigation on the use of natural fibers produced from the stem of PA plants in concrete. Using a machine, plant stems were crushed into fibers measuring 40 mm in length and 2 mm in width, and treated with 4% NaOH solution for 24 h. A total of four concrete mixes were prepared with varying additions of treated fibers, ranging from 0% to 1.5% (by volume) with water to cement ratio of 0.5% (by volume). Concrete specimens were tested at 3, 7, and 28 days. Testing included compressive strength, density, total water absorption, and capillary water absorption. The results show that incorporating PA natural fibers reduces the water absorption by total immersion and capillary action by up to 45%. Moreover, there is a negligible decrease in concrete density and strength when fibers were added. It is concluded that adding up to 1.5% natural PA fibers to concrete is a feasible strategy to produce an eco-friendly material which can be used in the production of sustainable building material with adequate mechanical and durability performance.

Keywords: natural fibers; concrete; *Phragmites australis*; capillary water absorption; sustainability

check for updates

Citation: Machaka, M.; Khatib, J.; Baydoun, S.; Elkordi, A.; Assaad, J.J. The Effect of Adding *Phragmites australis* Fibers on the Properties of Concrete. *Buildings* **2022**, *12*, 278. https://doi.org/10.3390/buildings12030278

Academic Editor: Zhenjun Yang

Received: 19 December 2021
Accepted: 21 February 2022
Published: 1 March 2022

1. Introduction

Concrete is one of the most used materials worldwide in the field of building construction. Consequently, using natural and renewable resources, such as plant fibers and waste materials which require minimal processing, in concrete will contribute towards eco-friendly and sustainable construction and emission reduction [1–11]. Plant fibers can be extracted from different parts of plants without extensive processing before use. In fact, natural fibers were used in some applications in the construction field early in the 19th century [12]. Later, synthetic fibers began to be used in concrete due to their superior effects on its properties. However, due to scarcity in raw material and high energy consumption, attention is drawn again towards natural plant fibers [13,14]. These fibers, with their abundant supply in nature, represent a promising sustainable approach to environmental protection, energy saving, and resource conservation. Research shows that using such fibers in concrete can have a significant improvement on concrete properties, including making it more tensile and ductile [15,16]. The primary advantage of using fibers in concrete is represented by the significant improvement in concrete properties and its relatively low cost [17]. Furthermore, using Natural Fiber Reinforced Composite (NFRC) will contribute towards a healthier and more sustainable environment [18]. In addition, the use of fibers in concrete will reduce the size and number of cracks, and produce concrete with better resistance to flexure, impact stresses, and many other physical and mechanical properties. In addition, it will reduce the cost of construction and maintenance [19,20]. Nevertheless, one of the main concerns about using plant fibers in concrete is their effect on its performance, especially its durability [21–23]. The durability of concrete depends mainly on its ability to resist the penetration of external aggressive agents, such as chloride ions, sulfate, oxygen, and carbon dioxide. Therefore, reducing the rate of water penetration into concrete will reduce or delay the ingress of these substances. Water or fluid ingress can be examined by determining the permeability, and water absorption by total immersion and capillary action [24–26]. These properties can give an indication about the pore network in the concrete matrix or microcracks that can provide a transport path for water or aggressive agents. Sorptivity is an index of moisture transport into unsaturated specimens, and is an important index of concrete durability [25–27].

The principle chemical composition of plant fibers is mainly lignocellulose (cellulose, hemicellulose, and lignin), with varying proportion of these constituents, depending on plant species and developmental stage of plant, among other factors [28]. Furthermore, plant fibers have low density and high specific properties. However, the hydrophilic nature and weak moisture resistance of plant fibers represent a major disadvantage for their application in construction [16]. Therefore, alkali treatment has been frequently used to modify the inherent properties of fibers, overcome their limitation for specific application, and enhance their tensile strength and roughness [15]. In addition, the alkali treatment method, which is also named Mercerization, is a common fiber treatment chemical method which is extensively used by researchers [29,30]. While this treatment partially eliminates lignin and hemicellulose, it entirely removes pectin, wax, and other organics from the fibers' surface. After this treatment, cellulose molecules become exposed, promoting the connection between the fiber and matrix [15]. Geremew et al. [31], in their research about alkali treatment of natural Palm fibers, conclude that the method of treatment that produces the higher tensile strength with the required roughness was obtained by treating the fibers for a duration of 24 h in a solution of 4% sodium hydroxide. The modulus of elasticity and percentage of elongation were not significantly affected by the treatment process [8,32,33]. Therefore, in the current investigation, it was decided to use this treatment method.

Phragmites australis (PA) is one of the most worldwide distributed plant species. It is a tall, fast growing perennial plant that can grow to a height of over 4 m. It has broad, pointed leaves of 15–60 cm length and 1–6 cm width, and dense, fluffy, gray or purple flower heads of 15–40 cm. PA is found on every continent, especially around river basins [34,35]. Owing to its fast growth capacity and unique properties, the plant has been frequently used since ancient times in various construction applications [36]. The plant is considered invasive, causing nuisance to farmers and people who live by rivers. Sometimes the plants are cut and burnt in the open air, which causes pollution. Therefore, using the fibers produced from these plants in concrete and other construction applications would offer economic and environmental benefits [35]. Normally, synthetic and expensive fibers are used to improve the tensile properties and control cracks in concrete. Instead, using natural and less expensive fibers of abundant and fast growing plant species such as PA in concrete production can be of high economic and sustainable benefits to the environment and to humans. Interestingly, PA is also used worldwide in both natural and constructed wetland systems in the removal of various pollutants of water and wastewater, due to its high capacity to uptake and bio-accumulate nutrients, heavy metals, and a wide array of other pollutants [35]. After phytoremediation by PA, the plant has the potential to be used as a source of high value products, such as biofuel and construction material, contributing the economic and sustainable management of water pollution and wastewater, as well as the production of sustainable concrete [36,37]. Since it does not absorb water or moisture due to its silicon covering, the stem, in particular, is used in the construction of walls, partitions, fences, roof hatching, and as an insulation material [38,39]. Further, heat treatment of

Phragmites samples have shown that drying at 120–160 °C increases its flexural strength and the technical elasticity limit, highlighting the potential of *Phragmites* in the production of cost-effective lightweight concrete blocks and as feedstock for construction materials [40].

The above promising findings have attracted an increasing interest to investigate the incorporation of Phragmites fibers in concrete mixtures. In a study by Shon et al. [37], the physical, mechanical, and thermal properties of a mortar mixture containing PA fibers growing in Kazakhstan were examined. Fibers were prepared by using an automated crusher after open-air drying, and added at three proportions (i.e., 2%, 4%, and 6%) to mortar mixtures. Although the use of fibers in mortar mixture did not improve both compressive and flexural strengths compared to the plain mixture (0% fibers), the authors concluded that the addition of fibers had the advantage to produce a significant decrease in heat loss due to the lower thermal conductivity and higher porosity to density ratio. To this end, research about fibers, and precisely about natural fibers, shows that adding fibers at higher percentages than 2% can cause serious reduction in concrete workability, strength, and durability. For this purpose, it is preferable to use fibers in moderate percentages between 1% and 2% of the concrete volume [41]. Thus, there is still a need for more research regarding the effect of the incorporation of PA fibers on concrete properties, given the variations existing in PA ecotypes and incorporation proportions [42]. For this purpose, this study examines the effect of the incorporation of 0.5, 1.0, and 1.5% fibers of PA stems harvested from Bekaa Valley, Lebanon, on the mechanical properties and durability of concrete including density, compressive strength, ultrasonic pulse velocity, and absorption by total immersion and capillary rise.

2. Experimental Methodology

2.1. Materials

The PA plant material was obtained from the Bekaa Valley in Lebanon, where it grows in abundance along the river and waterways (Figure 1). Using a machine, plant stems were used to prepare natural fibers measuring 40 mm in length and 2 mm in width. The dimensions of the fibers were based on a previous study [15]. After that, the fibers were treated by 4% NaOH solution for 24 h, as previously described by Machaka et al. [15]. The fibers were then washed, dried, and stored in polyethylene bags ready for use. The bulk density of PA fibers was approximately 665 kg/m^3. While the fine aggregate used was a natural sand with a maximum size of 5 mm, the coarse aggregate was prepared with crushed limestone, with a maximum size of 19 mm. The grading of aggregate conformed to ASTM C33 and C136.The physical properties of both fine and coarse aggregates are shown in Table 1. The cement used is PA-L 42.5, which conforms to EN 197 European norms (CEM II/A-L) and to Lebanese standards (LIBNOR).

Figure 1. *Phragmites australis* (PA) from Bekaa Valley, Lebanon.

Table 1. Properties of coarse and fine aggregates.

Aggregate (Type)	Bulk Density	Absorption %	Fineness Modulus (FM)
Fine aggregate (Natural sand)	2.63	1.07%	2.85
Coarse aggregate (Crushed stone)	2.57	2.00%	NA

2.2. Mix Proportions

In total, three concrete mixes of PA-0.5, PA-1.0, and PA-1.5 were prepared with 0.5%, 1.0%, and 1.5% of PA fibers (by volume). These mixes had a proportion of 1 (cement): 2.1 (fine aggregate): 2.6 (coarse aggregate) by weight and water to cement ratio (W/C) at 0.5 in all mixes. A mix of 0.0% fibers (PA-0.0) was also prepared as a control. Table 2 shows the details of all concrete mixes.

Table 2. Details of concrete mixes.

Mix Code	Fiber (% by Volume)	W/C	Quantities (Kg/m^3)				
			Cement	Water	Fine Aggregate	Coarse Aggregate	Fiber
PA-0.0 (Control)	0	0.5	370	185	790	965	0.00
PA-0.5	0.5	0.5	370	185	790	965	3.33
PA-1.0	1.0	0.5	370	185	790	965	6.65
PA-1.5	1.5	0.5	370	185	790	965	9.98

2.3. Mixing and Specimen Preparation

The coarse aggregate was first placed in the mixer, followed by the addition of PA fibers, and then mixed for one minute in order to prevent the balling effect of the fibers. Then, the fine aggregate and the cement were introduced to the mix, and the mixing was resumed for two more minutes until a homogenous dry mix was obtained. The water was then slowly poured onto the dry materials and the mixing continued until a homogenous concrete mix was achieved. Following this step, concrete specimens were prepared using steel molds, and compacted using a vibrating table. For each mix, six cubes of 100 mm in size and 12 prisms of dimensions 100 mm × 100 mm × 50 mm were cast. The cubes were used to determine the density, compressive strength, and ultrasonic pulse velocity (UPV). The prisms were used to determine the water absorption by total immersion and capillary rise. All specimens were cured in water at 20 °C, and testing was conducted at the ages of 3, 7, and 28 days.

2.4. Testing Methods

The compressive strength test was conducted according to ASTM C 31, C 39, C 192, and C 617. The density and UPV testing conformed to ASTM-C642 [43] and ASTM-C597 [44], respectively.

Prior to the total water absorption and capillary water absorption tests, specimens were removed from water, and dried in the oven at 80° until specimens reached a constant dry weight (w_d). This normally took approximately 48 h. For the absorption by total immersion, the specimens were totally immersed in water, and the weight (w_w) of specimens were determined at 5 min, 10 min, 20 min, 1 h, 2 h, 4 h, 24 h, and 48 h. The total water absorption ($TWA\%$) was calculated as follows:

$$TWA\% = 100 \times \left(\frac{w_w - w_d}{w_d} \right) \quad (1)$$

ASTM C1585 [45] was used to conduct the capillary water absorption. The dry specimens were sealed on all sides, except the side touching the water, as shown in Figure 2.

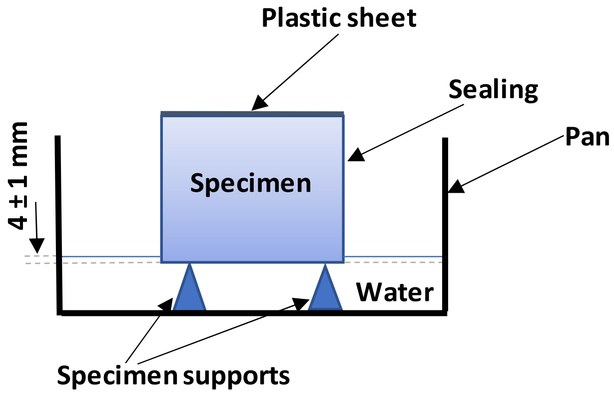

Figure 2. The schematic diagram of the capillary absorption test.

The depth of water was 4 ± 1 mm above the submerged face in order to maintain the supply of water to the specimens (Figure 2). The weight of the water absorbed (w_a) after 1 min, 3 min, 5 min, 10 min, 20 min, 30 min, 1 h, 2 h, 4 h, 24 h, and 48 h was recorded. The weight absorbed versus the square root of curing time was plotted, and the slope of the initial part of the curve was taken to represent the sorptivity index S [45,46] as follows:

$$S = \frac{\Delta w_a}{\Delta \sqrt{t}} \tag{2}$$

3. Results and Discussion

The results presented below describe the properties of concrete mixes prepared with PA fibers being a potential resource material for the production of sustainable and green concrete. The plant material used was collected from Bekaa Valley in Lebanon, where PA is highly abundant, and may be considered an invasive species for its highly capacity to tolerate Mediterranean conditions and high levels of water pollution [34]. The tested PA fibers were exposed to alkali treatment to alleviate their hydrophilic property and to promote their incorporation in the cement matrix. Alkali treatment is well recognized to remove lignin, pectin, and hemicellulose, thus exposing cellulose molecules and roughening of the surface of fibers while enhancing their bonding in the matrix and the mechanical properties of the composite material [15,31,47]. Alkali treatment increases the tensile and flexural properties, as well as the durability of fibers [48]. It is also considered as an efficient and economic approach for the treatment of different natural fiber types [15,49–54].

3.1. Density

Figure 3 shows the fresh concrete densities of mixes with 0.5%, 1.0%, and 1.5% of PA fibers as compared to the control mix (0.0% fibers) and. The results show that adding fibers slightly decreased the fresh density of concrete. This decrease was approximately 2%, 4%, and 5% when using 0.5%, 1.0%, and 1.5% of PA fibers, respectively. This may be due to the lack of full compaction and the creation of voids in the presence of fibers and the lower density of fibers. Nevertheless, this decrease would allow for the assumption that the addition of PA fibers up to 1.5% has a promising potential in the production of lightweight concrete [42]. It could be noted that the addition of the fibers did not considerably decrease density, as the values of mixes still fell within the range of concrete manufactured from granite chippings that is between 2300 and 2500 kg/m^3 [54].

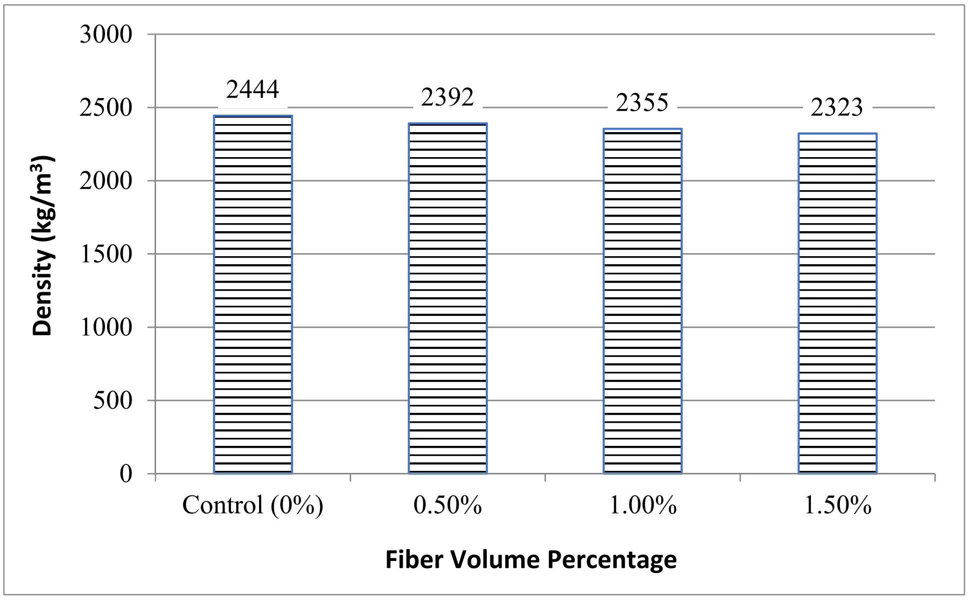

Figure 3. The effect of PA fibers at 0.5%, 1.0%, and 1.5% additions on densities of concrete mixes as compared to the control mix (0.0% PA).

3.2. Compressive Strength

Figure 4 shows the effect of adding PA fibers on compressive strength of concrete for the four mixes at 3, 7, and 28 days of curing. At three days of curing, adding up to 0.5% of PA fibers did not affect the compressive strength. Using 1% and 1.5% fibers caused a reduction of 13% and 33%, respectively. At seven days of curing, the compressive strength for mixes with and without fibers is similar. The trend is similar at 28 days of curing, with the exception of the mix with 0.5% fibers, where there is a slight reduction in compressive strength. The compatible resistance to compressive stress observed with fiber–concrete mixtures with the control (0.0% PA) may be due the alkali pre-treatment of fibers enhancing their binding forces and adhesion within the concrete matrix. These findings are in agreement with the results obtained elsewhere [15,16]. However, these results are not consistent with those of untreated PA fibers and cement mixes reported by Shon et al. [37], where a decrease in strength was observed. In the latter study, the addition of fibers to the mixture at 2%, 4%, and 6% resulted in proportional deceases in compressive strengths, with the lowest value being obtained with 6.0% PA, indicating a 57% strength reduction compared to the control mixture (0% PA). This was attributed to the interlocking strength between the fibers and cement that was significantly lower than that between the cement particles. It was also indicated that the lack of bonding and slipping action between the fibers themselves at higher fractions may also play a role. Consequently, both the proportion of PA fibers and pretreatment are among the factors that should be well considered in the preparation of PA fiber and concrete mixtures.

3.3. Ultra-Pulse Velocity

Ultrasonic pulse velocity (UPV) testing of concrete can detect the presence of voids, cavities, cracks and defects, honeycombing, or other discontinuities [55]. Table 3 shows the guidelines for qualitative assessment of concrete based on UPV test results [44].

Figure 5 shows the UPV values for concrete at 3, 7, and 28 days of curing. There is a small reduction, up to 10%, in UPV in the presence of PA fibers at three and seven days of curing. At 28 days of curing, the UPV values are similar. All UPV values at 7 and 28 days are above 4 km/s, indicating a very good to excellent concrete quality (Table 3).

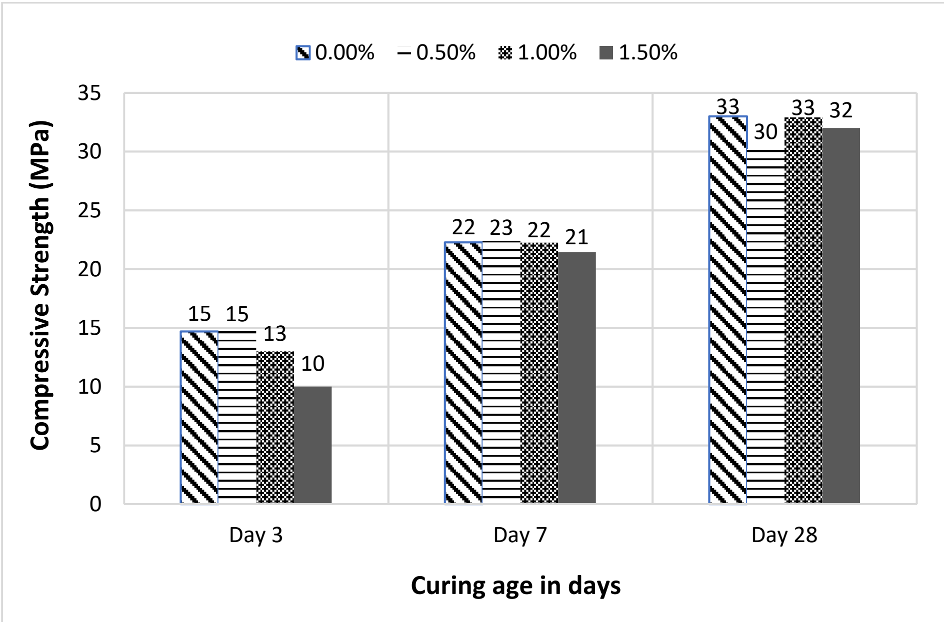

Figure 4. The effect of adding PA fibers on the compressive strength of concrete mixes at 3, 7, and 28 days of curing.

Table 3. Quality of concrete based on UPV value (ASTM C597 2016).

Pulse Velocity	Concrete Quality
>4.0 km/s	Very good to excellent
3.5–4.0 km/s	Good to very good, slight porosity may exist
3.0–3.5 km/s	Satisfactory but loss of integrity is suspected
<3.0 km/s	Poor, and loss of integrity exists.

3.4. Total Water Absorption

Total water absorption (TWA) is one of the concrete properties that affect the durability of concrete. Figure 6 shows the TWA by total immersion of concrete mixes with and without fibers. The TWA of the concrete depends on many factors, including mixture proportions, curing duration, air content, and the presence of chemical and mineral admixtures [56]. The results show that adding PA fibers to the concrete decreases the concrete total water absorption at all ages of curing. This decrease is systematic in that, as the addition of fibers increases, the TWA decreases. The decrease ranges from 21% to 26% for concrete containing 0.5% fibers (PA-0.5), and 35% to 39% for concrete with 1.5% fibers (PA-1.5). This may indicate that the accessible volume of pores is reduced in the presence of fibers as a result of the alleviation of the hydrophilic property of fibers by the alkali treatment, increasing their surface roughness and adhesion in the concrete matrix [57]. The observed decrease in TWA in the tested concrete mixes is fully in line with results reported by Jamshaid et al. [58] on water absorption capacity of the natural cellulosic fiber-reinforced concrete mixes with different plant fibers and varying loading ratios of fibers. Findings revealed that mixes with up to 2% fiber loading ratios had a reduced absorption capacity, as compared to plain concrete, enhancing the durability and stability of mixes.

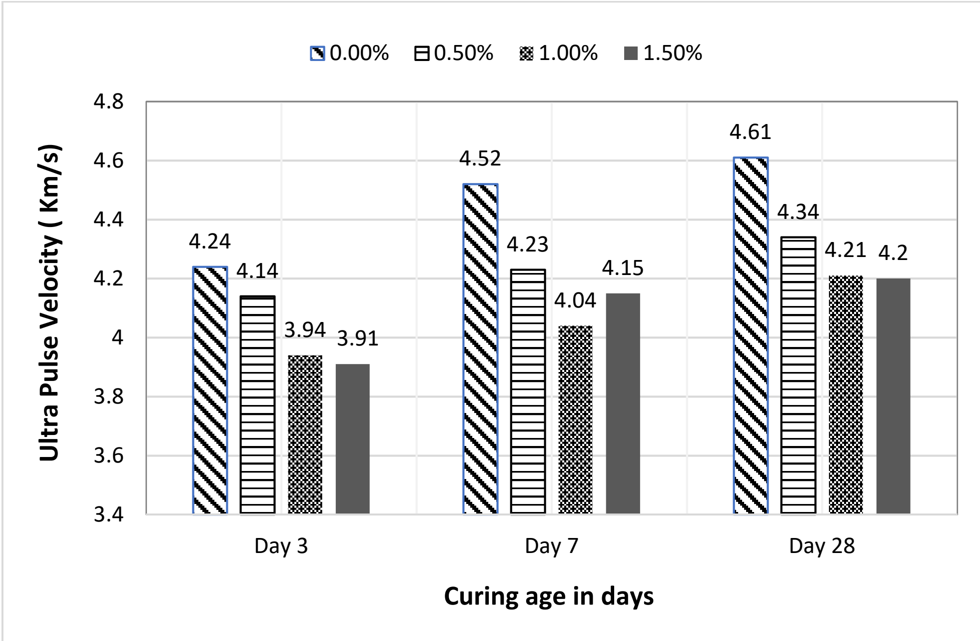

Figure 5. The effect of adding PA fibers on the UPV of concrete mixes at 3, 7, and 28 days of curing.

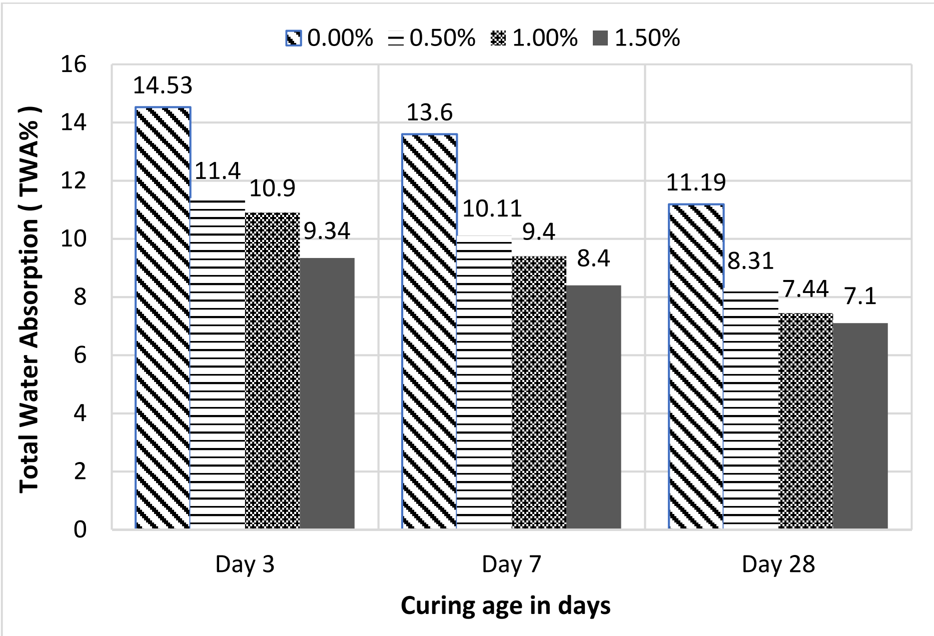

Figure 6. The effect of adding PA fibers on the total water absorption (TWA) of concrete mixes at 3, 7, and 28 days of curing.

Figure 7 shows the correlation between the compression strength and TWA of concrete mixes containing 0.0, 0.5, 1.0, and 1.5% PA fiber additions at different curing ages. There exists a strong inverse linear correlation between the compressive strength and TWA, indicated by the R^2 values of all the mixes (>0.97). The equations presented in the Figure allow the prediction of the compressive strength of the amount of TWA at different curing ages, which is crucial for the detection of the durability of mixes.

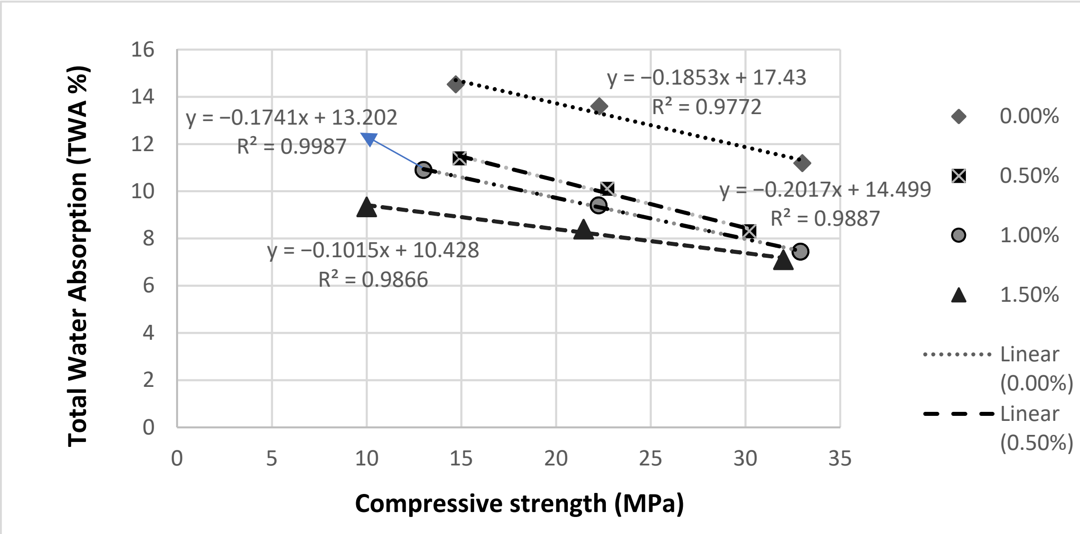

Figure 7. Correlation between compressive strength and total water absorption at different curing ages.

3.5. Capillary Water Absorption

Figure 8 shows the sorptivity index (water absorption by capillary action) of the four concrete mixes with different additions of PA fibers. The capillarity water absorption represented by the term named the sorptivity index, which is the rate of absorption during the first 20 min of water absorption test by capillary action, as described before in Equation (2). The results indicate that adding PA fibers decrease the sorptivity index of the concrete. As the percentage of fibers increases, the sorptivity index decreases. This is similar to the trend observed for water absorption by total absorption. At three days of curing, the decrease in sorptivity index ranged from approximately 47% to 58% at 0.5% and 1.5% fibers addition, respectively. The corresponding reduction at seven days of curing was 18% to 32%, and that at 28 days was 31% to 42%, respectively. The percentage decrease in sorptivity index is clearly presented in Figure 9 for mixes with and without PA fibers at 3, 7, and 28 days of curing. The decrease is in agreement with results reported by Kaplan and Bayraktar [59] for concrete containing up to 2% natural fiber additions. This may indicate that fibers at specific ratios may reduce concrete porosity [60].

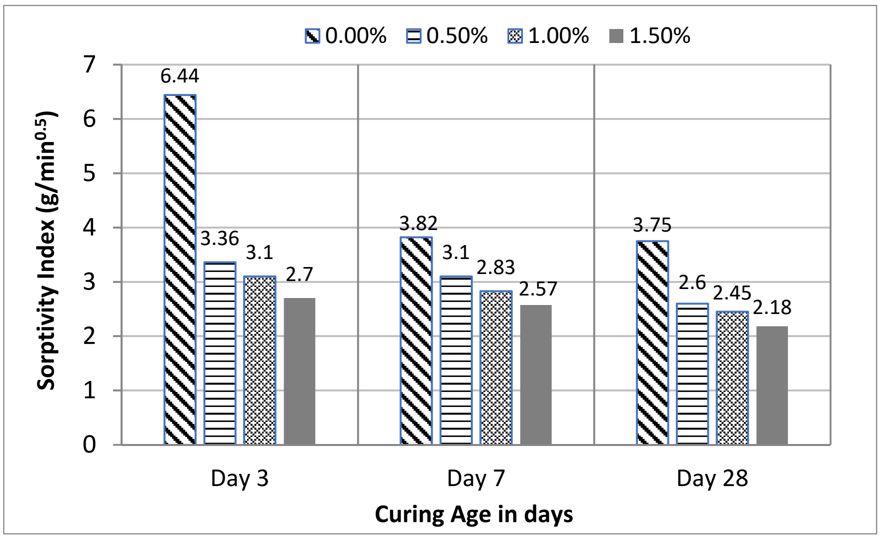

Figure 8. The effect of adding PA fibers on the sorptivity index of concrete mixes at 3, 7, and 28 days of curing.

Figure 10 shows the correlation between the compression strength and sorptivity index of concrete mixes containing 0.0, 0.5, 1.0, and 1.5% PA fiber additions at different curing ages. The graph suggests that as the compressive strength increases the sorptivity decreases. With the exception of the control mix, there is a strong linear relationship with R^2 values above 0.91. The trend in the results is similar to those reported in Figure 7.

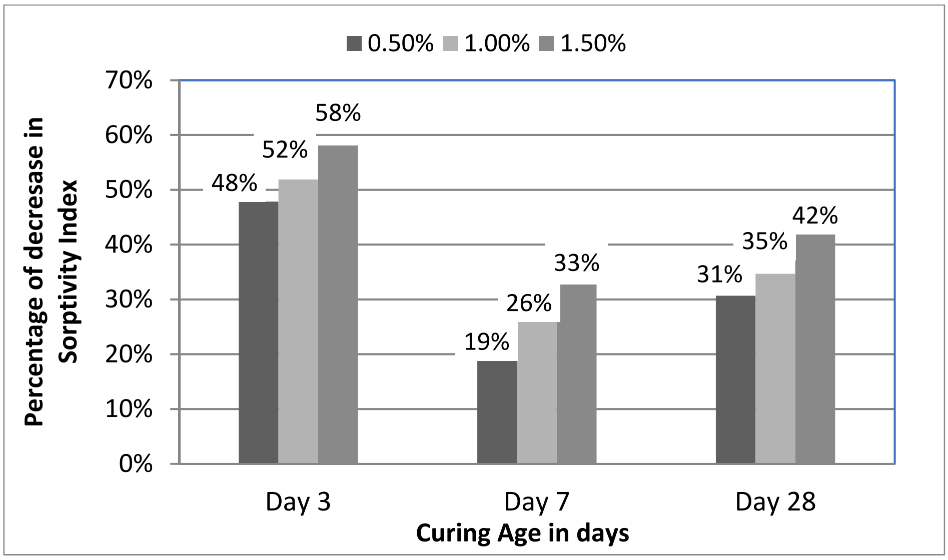

Figure 9. The effect of adding PA fibers on the percentage decrease in the sorptivity index of concrete mixes at 3, 7, and 28 days of curing.

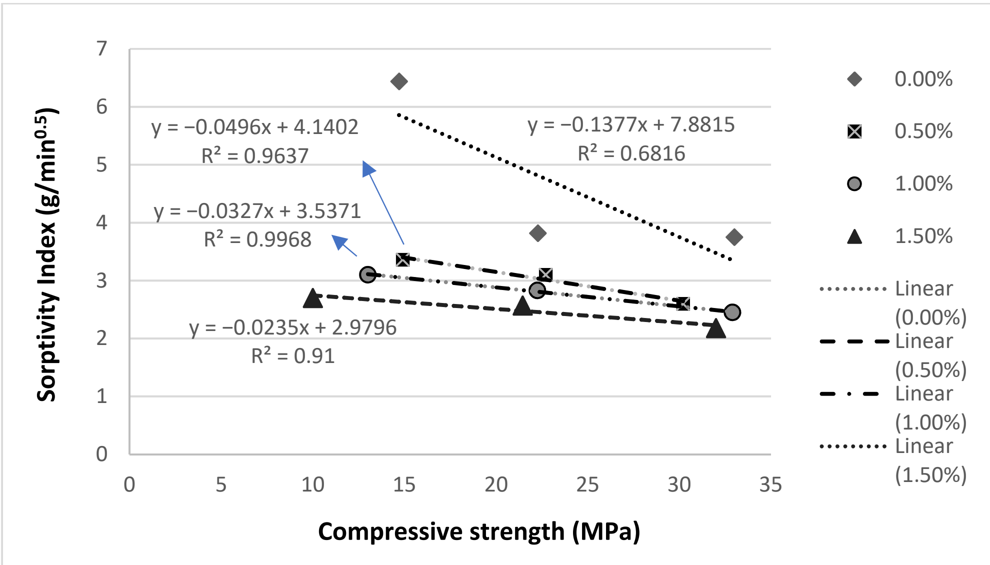

Figure 10. Correlation between compressive strength and sorptivity index at different curing ages.

4. Conclusions

Natural fibers of abundant and fast growing plant species such as PA have the potential to be incorporated in concrete mixes for the production of sustainable building materials with enhanced mechanical and durability performance. The present experimental study examined the effect of adding PA natural fibers on the concrete properties which included density, compressive strength, UPV, TWA by total immersion, and sorptivity index by capillarity. The following conclusions may be drawn from the current investigation:

The density of concrete is slightly reduced by up to 5% in the presence of fibers, possibly due to the lower density of fibers combined with the lack of complete compaction and the possible creation of isolated pores.

There is a decrease in compressive strength in the presence of fibers. During the early ages of curing (i.e., 3 days), this decrease is 34% at 1.5% fibers addition. However, at later curing ages (i.e., 28 days), there is only a slight or negligible decrease in compressive strength when fibers are added to the concrete mix.

Similarly to those of the compressive strength, the UPV values are slightly reduced in the presence of fibers. This may be due to the creation of isolated voids in the concrete. Beyond seven days of curing, the UPV values are above 4 km/s indicating a good quality concrete.

The TWA by total immersion and by capillary rise (sorptivity index) are decreased in the presence of increasing amounts of PA fibers. This decrease is apparently not associated with an increase in compressive strength or UPV. This may be justified that although the presence of PA fibers may have caused the discontinuity of pores causing their isolation.

Finally, adding PA fibers to the concrete mix can produce concrete with adequate mechanical properties, and may improve the durability if the ingress of water is reduced (i.e., less water absorption by total immersion and capillary action). More investigation should be conducted on the long-term performance of concrete with PA fibers in order to assess the durability of concrete and impact of fibers on its structure.

Author Contributions: Conceptualization, J.K. and M.M.; methodology, J.K.; validation, J.K., S.B., A.E. and J.J.A.; formal analysis, M.M.; investigation, J.K. and M.M.; resources, A.E.; data curation, M.M.; writing—original draft preparation, M.M.; writing—review and editing, J.K., S.B. and J.J.A.; visualization, J.K.; supervision, J.K. and A.E.; project administration, J.K. and A.E.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. El-Darwish, I.; Kurdi, A.; Mahmoud, H.; El-Kair, H.A. Mechanical properties and durability of Portland cement concrete incorporating ground steel making slag. *AEJ Alex. Eng. J.* **1997**, *36*, 1–14.
2. El-Kurdi, A.A.; Abdel-Hakam, A.; El-Gohary, M.M. Study the effect of silica fume, polypropylene fibre, steel fibre, limestone powder and bentonite on the fire resistance of concrete. *Int. J. Res. Anal. Allied Sci. Eng.* **2014**, *1*, 13–29.
3. Herki, B.A.; Khatib, J.M. Valorisation of waste expanded polystyrene in concrete using a novel recycling technique. *Eur. J. Environ. Civ. Eng.* **2017**, *21*, 1384–1402. [CrossRef]
4. Khatib, J.M.; Mangat, P.S.; Wright, L. Sulphate resistance of blended binders containing FGD waste. *Proc. Inst. Civ. Eng. (ICE)-Constr. Mater.* **2008**, *161*, 119–128. [CrossRef]
5. Khatib, J.M.; Kayali, O.; Siddique, R. Dimensional change and strength of mortars containing fly ash and metakaolin. *J. Mater. Civ. Eng.* **2009**, *21*, 523–528. [CrossRef]
6. Khatib, J.M.; Wright, L.; Mangat, P.S. Effect of fly ash–gypsum blend on porosity and pore size distribution of cement pastes. *Adv. Appl. Ceram.* **2013**, *112*, 197–201. [CrossRef]
7. Khatib, J.M.; Mangat, P.S.; Wright, L. Mechanical and physical properties of concrete containing FGD waste. *Mag. Concr. Res.* **2015**, *68*, 550–560. [CrossRef]
8. Khatib, J.M.; Machaka, M.M.; Elkordi, A.M. Natural fibers 5. In *Handbook of Sustainable Concrete and Industrial Waste Management: Recycled and Artificial Aggregate, Innovative Eco-Friendly Binders, and Life Cycle Assessment*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 85–107.
9. Mangat, P.S.; Khatib, J.M.; Wright, L. Optimum utilisation of FGD waste in blended binders. *Proc. Inst. Civ. Eng.-Constr. Mater.* **2006**, *159*, 119–127. [CrossRef]
10. Sonebi, M.; Ammar, Y.; Diederich, P. Sustainability of cement, concrete and cement replacement materials in construction. In *Sustainability of Construction Materials*; Woodhead Publishing: Sawston, UK, 2016; pp. 371–396.

11. Wang, W.; Wei, W.; Gao, S.; Chen, G.; Yuan, J.; Li, Y. Agricultural and aquaculture wastes as concrete components: A Review. *Front. Mater.* **2021**, *8*, 762568. [CrossRef]
12. Faruk, O.; Bledzki, A.K.; Fink, H.P.; Sain, M. Biocomposites reinforced with natural fibres: 2000–2010. *Prog. Polym. Sci.* **2012**, *37*, 1552–1596. [CrossRef]
13. Çomak, B.; Bideci, A.; Bideci, Ö.S. Effects of hemp fibres on characteristics of cement based mortar. *Constr. Build. Mater.* **2018**, *169*, 794–799. [CrossRef]
14. Dawood, E.T.; Ramli, M. Durability of high strength flowing concrete with hybrid fibres. *Constr. Build. Mater.* **2012**, *35*, 521–530. [CrossRef]
15. Machaka, M.M.; Basha, H.S.; ElKordi, A.M. The effect of using fan palm natural fibres on the mechanical properties and durability of concrete. *Int. J. Mater. Sci. Eng.* **2014**, *2*, 76–80.
16. Machaka, M.; Elkordi, A.; Ghanem, H.; Khatib, J.; Baalbaki, O. Selected properties of concrete containing palm fibres. In Proceedings of the 3rd International Conference on Bio-Based Building Materials, Belfast, UK, 26–28 June 2019; pp. 279–286.
17. Pacheco-Torgal, F.; Jalali, S. Cementitious building materials reinforced with vegetable fibres: A review. *Constr. Build. Mater.* **2011**, *25*, 575–581. [CrossRef]
18. Banthia, N. Current innovations in fibre reinforced concrete. In Proceedings of the 3rd ACF International Conference-ACF/VCA, HoChiMinh, Vietnam, 11–13 November 2008.
19. Mello, E.; Ribellato, C.; Mohamedelhassan, E. Improving concrete properties with fibers addition. *Int. J. Civ. Environ. Eng.* **2014**, *8*, 249–254.
20. Sanjay, M.R.; Madhu, P.; Jawaid, M.; Senthamaraikannan, P.; Senthil, S.; Pradeep, S. Characterization and properties of natural fiber polymer composites: A comprehensive review. *J. Clean. Prod.* **2018**, *172*, 566–581. [CrossRef]
21. Ghanem, H.; Zollinger, D.; Lytton, R. Predicting ASR aggregate reactivity in terms of its activation energy. *Constr. Build. Mater.* **2010**, *24*, 1101–1108. [CrossRef]
22. Ghanem, H.; Zollinger, D.; Lytton, R.; Ghanem, N. Determining ASR characteristics using dilatometer method. *Constr. Build. Mater.* **2012**, *36*, 1008–1015. [CrossRef]
23. Machaka, M.; ElKordi, A. Experimental study of the effect of adding fan palm fibres on concrete durability exposed to severe environments. In Proceedings of the 2nd International Conference on Bio-Based Building Materials, Clermont-Ferrand, France, 21–23 June 2017.
24. Amriou, A.; Bencheikh, M. New experimental method for evaluating the water permeability of concrete by a lateral flow procedure on a hollow cylindrical test piece. *Constr. Build. Mater.* **2017**, *151*, 642–649. [CrossRef]
25. Hall, C. Water sorptivity of mortars and concretes: A review. *Mag. Concr. Res.* **1989**, *41*, 51–61. [CrossRef]
26. Wright, L.; Khatib, J.M. Sustainability of desulphurised waste materials in construction. In *Sustainability of Construction Materials*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2016; pp. 685–720.
27. Wang, H.; Sun, X.; Wang, J.; Monteiro, P. Permeability of concrete with recycled concrete aggregate and pozzolanic materials under stress. *Materials* **2016**, *9*, 252. [CrossRef] [PubMed]
28. Sathishkumar, T.; Navaneethakrishnan, P.; Shankar, S.; Rajasekar, R.; Rajini, N. Characterization of natural fiber and composites—A review. *J. Reinf. Plast. Compos.* **2013**, *32*, 1457–1476. [CrossRef]
29. Hashim, M.Y.; Roslan, M.N.; Amin, A.M.; Ahmad Zaidi, A.M.; Ariffin, S. Mercerization treatment parameter effect on natural fiber reinforced polymer matrix composite: A brief review. *J. Mater. Metall. Eng.* **2012**, *6*, 1382–1388.
30. Kalia, S.; Kaith, B.S.; Kaur, I. Pretreatments of natural fibers and their application as reinforcing material in polymer composites—A review. *Polym. Eng. Sci.* **2009**, *49*, 1253–1272. [CrossRef]
31. Geremew, A.; De Winne, P.; Demissie, T.A.; De Backer, H. Treatment of natural fiber for application in concrete pavement. *Adv. Civ. Eng.* **2021**, *2021*, 6667965. [CrossRef]
32. Machaka, M.; Basha, H.; Chakra, H.A.; Elkordi, A. Alkali treatment of fan palm natural fibres for use in fibre reinforced concrete. *Eur. Sci. J.* **2014**, *10*, 186–195.
33. Machaka, M.; ElKordi, A. The effect of using fan palm natural fibres on the impact resistance of concrete. In Proceedings of the 1st International Turkish World Engineering and Science Congress, Antalya, Turkey, 7–10 December 2017; pp. 472–479.
34. Amacha, N.; Karam, F.; Jerdi, M.; Frank, P.; Viala, E.; Hussein, D.; Kheireddin, S.; Baydoun, S. Assessment of the efficiency of a pilot constructed wetland on the remediation of water quality—Case study of Litani River, Lebanon. *Environ. Pollut. Clim. Chang.* **2017**, *1*, 119. [CrossRef]
35. Milke, J.; Gałczyńska, M.; Wróbel, J. The Importance of Biological and Ecological Properties of *Phragmites australis* (Cav.) Trin. Ex Steud., in Phytoremendiation of Aquatic Ecosystems—The Review. *Water* **2020**, *12*, 1770. [CrossRef]
36. Rezania, S.; Park, J.; Rupani, P.F.; Darajeh, N.; Xu, X.; Shahrokhishahraki, R. Phytoremediation potential and control of *Phragmites australis* as a green phytomass: An overview. *Environ. Sci. Pollut. Res.* **2019**, *26*, 7428–7441. [CrossRef]
37. Shon, C.-S.; Mukashev, T.; Lee, D.; Zhang, D.; Kim, J.R. Can Common Reed Fiber Become an Effective Construction Material? Physical, Mechanical, and Thermal Properties of Mortar Mixture Containing Common Reed Fiber. *Sustainability* **2019**, *11*, 903. [CrossRef]
38. Jiménez-Espada, M.; Herrero-Adán, D.; González-Escobar, R. Characterization of Mechanical and Hygroscopic Properties of Individual Canes of Reed. *Materials* **2021**, *14*, 2193. [CrossRef] [PubMed]

39. Honoré, M.; Lecompte, T.; Pimbert, S. Properties of *Phragmites australis* for insulating concrete application. *Constr. Technol. Archit.* **2022**, *1*, 332–338.
40. Dosdall, R.; Jülich, W.; Schauer, F. Impact of heat treatment of the water reed *Phragmites communis* Trin. used for thatching on its stability, elasticity and resistance to fungal decomposition. *Int. Biodeterior. Biodegrad.* **2015**, *103*, 85–90. [CrossRef]
41. Harle, S.; Dhawale, V. Comparison of Different Natural Fiber Reinforced Concrete. *Int. J. Eng. Sci. Res. Technol.* **2014**, *3*, 605–607.
42. Pude, R.; Banaszuk, P.; Trettin, R.; Noga, G. Suitability of Phragmites for lightweight concrete. *J. Appl. Bot. Food Qual.* **2005**, *79*, 141–146.
43. *ASTM C642-12*; Standard Test Method for Density, Absorption, and Voids in Hardened Concrete; Annual Book of American Society of Testing and Materials. ASTM International: West Conshohocken, PA, USA, 2012.
44. *ASTM C597-16*; Standard Test Method for Pulse Velocity through Concrete; Annual Book of American Society of Testing and Materials. ASTM International: West Conshohocken, PA, USA, 2016.
45. *ASTM C1585-13*; Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. ASTM International: West Conshohocken, PA, USA, 2013.
46. Patel, V.N. Sorptivity Testing to Assess Durability of Concrete against Freeze-Thaw Cycling. Master's Thesis, McGill University, Montreal, PQ, Canada, August 2009.
47. Lai, P.; Zhi, X.; Shen, S.; Wang, Z.; Yu, P. Strength and Damping Properties of Cementitious Composites Incorporating Original and Alkali Treated Flax Fibers. *Appl. Sci.* **2019**, *9*, 2002. [CrossRef]
48. Bisen, H.B.; Hirwani, C.K.; Satankar, R.K.; Panda, S.K.; Mehar, K.; Patel, B. Numerical study of frequency and deflection responses of natural fiber (Luffa) reinforced polymer composite and experimental validation. *J. Nat. Fibers* **2018**, *17*, 505–519. [CrossRef]
49. Aluco, O.G.; Yatim, J.M.; Kadir, M.A.A.; Yahya, K. A review of properties of bio-fibrous concrete exposed to elevated temperatures. *Constr. Build. Mater.* **2020**, *260*, 119671. [CrossRef]
50. Momoh, E.O.; Osofero, A.I. Use of oil palm broom fibres for eco-friendly concrete. In Proceedings of the 5th Conference on Sustainable Construction Materials and Technologies, London, UK, 15–17 July 2019.
51. Ajouguim, S.; Stefanidou, M.; Abdelouahdi, K.; Waqif, M.; Saâdi, L. Influence of treated bio-fibers on the mechanical and physical properties of cement mortars. *Eur. J. Environ. Civ. Eng.* **2020**, 1–15. [CrossRef]
52. Sanal, I.; Verma, D. Construction materials reinforced with natural products. In *Handbook of Ecomaterials*; Springer: Berlin/Heidelberg, Germany, 2019; Volume 3, pp. 2119–2142.
53. De Klerk, M.D.; Kayondo, M.; Moelich, G.M.; de Villiers, W.I.; Combrinck, R.; Boshoff, W.P. Durability of chemically modified sisal fibre in cement-based composites. *Constr. Build. Mater.* **2020**, *241*, 117835. [CrossRef]
54. Oriola, F.O.P.; Afolayan, J.O.; Sani, J.E.; Adamu, Y. Estimating the shear strength of sisal fiber reinforced concrete. *Niger. J. Technol. (NIJOTECH)* **2019**, *38*, 557–565. [CrossRef]
55. Rehman, S.K.U.; Ibrahim, Z.; Memon, S.A.; Jameel, M. Nondestructive test methods for concrete bridges: A review. *Constr. Build. Mater.* **2016**, *107*, 58–86. [CrossRef]
56. Ghanem, H.; Machaka, M.; Khatib, J.; Elkordi, A.; Baalbaki, O. Effect of palm fibres addition on absorption characteristics and mechanical properties of concrete. In Proceedings of the Fifth International Conference on Sustainable Construction Materials and Technologies (SCMT5), London, UK, 14–17 July 2019; Volume 2.
57. Li, Y.; Mai, Y.-W.; Ye, L. Sisal fibre and its Composites: A review of recent developments. *Compos. Sci. Technol.* **2000**, *60*, 2037–2055. [CrossRef]
58. Jamshaid, H.; Mishra, R.K.; Raza, A.; Hussain, U.; Rahman, M.L.; Nazari, S.; Chandan, V.; Muller, M.; Choteborsky, R. Natural Cellulosic Fiber Reinforced Concrete: Influence of Fiber Type and Loading Percentage on Mechanical and Water Absorption Performance. *Materials* **2022**, *15*, 874. [CrossRef]
59. Kaplan, G.; Bayraktar, O.Y. The effect of hemp fiber usage on the mechanical and physical properties of cement based mortars. *Res. Eng. Struct. Mater.* **2021**, *7*, 245–258. [CrossRef]
60. Rostami, V.; Shao, Y.; Boyd, A.J. Durability of concrete pipes subjected to combined steam and carbonation curing. *Constr. Build. Mater.* **2011**, *25*, 3345–3355. [CrossRef]