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Review Article

Effect of Different Types and Ratio of Fibers on the Tensile Strength of Reinforced Foam Concrete: A Review

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Abstract

Reducing the weight of buildings—particularly dead loads—is one effective way to lower construction costs. Foam concrete offers a viable alternative to conventional concrete for non-structural elements. This paper reviews the impact of incorporating polypropylene, natural fibers, steel fibers from waste tyres, and carbon fibers on the tensile strength of foamed concrete. According to the literature, the polypropylene content varied between 0.2% and 0.8%, with different target densities. Steel fibers extracted from scrap tyres ranged from 0.2% to 0.6%, while carbon fiber and Henequen fiber (natural fiber) were used separately or in combination with polymers in volumetric fractions ranging from 0.5% to 1.5%. The results presented in this paper indicate that tensile strength gradually increased as the volume of fibers increased up to a certain point, suggesting an optimal dosage for enhancing performance.

1. Introduction

Foamed concrete, or cellular lightweight concrete, has a density that varies randomly between 400 and 1850 kg/m3, and an air void is created in the mixture by a foaming agent. Foamed concrete is known for its high flow ability, low cement content, limited aggregate [1, 2], and excellent thermal insulation [3]. The main differences between normal concrete and foam concrete can be related to their composition [4]. Cement is the most common binder in foamed concrete; the types of cement used in foamed concrete are ordinary Portland cement, rapid-hardening Portland cement, calcium sulfate cement, and high-aluminum cement that can be used as a partial constituent or up to 100% of the total binder material [5, 6, 7]. Additional ingredients such as silica fume, fly ash, and lime may also be used, and the ranges vary between 10

-75 % [8, 9, 10]. More materials are added to improve the mixture's uniformity and long-term strength [10]. Since adding a foaming agent produces foam bubbles, which are referred to as contained air voids, the foam agents also control the density of concrete by controlling the pace at which air bubbles form in the cement paste mixture. Common foaming agents include synthetic, protein-based detergents, adhesive resins, hydrolyzed protein, resin soap, and saponin [11]. The best foam agents are synthetic and protein-based. Protein-based foam additives result in a stronger and limited bubble structure that allows a larger air volume and provides a denser air gap network, while synthetic additives generate larger expansions and, thus, smaller densities [12, 13]. The foam agent material significantly influences the properties of fresh and hardened concrete [14]. The excessive volume of foam is reported to result in a decrease in flow [15, 16].

Nevertheless, mixing time dramatically affects the flow. As stated, the longer the mixing time, the higher the entrained air, while extended mixing may result in the loss of air intake by decreasing the air content [13, 17]. The admixture's materials and application determine the water required in foamed concrete. The most effective mixture's homogeneity, quality, and durability govern the water content. [15, 18, 19]. Nambiar and Ramamurthy [15] showed that the mixture was too stiff due to low water content, and the bubbles collapsed during mixing, resulting in increased density.

Similarly, the liquid was too thin for the high water content to hold the bubbles, causing foam separation from the mixture and resulting in increased final density. In terms of the water-cement ratio, it is generally recommended to start from 0.4 to 1.25% or 6.5 to 14% of the desired density [20]. In practice, this type of concrete has become popular in most European and Asian countries. Historically, the Romans first discovered that by binding animal blood and agitating a mixture of small gravel size and coarse sand with heated lime and water, small air bubbles were produced that improved the mixture to be more workable and stable[13, 21]. However, Axel Eriksson invented the first Portland cement-based foamed concrete in 1923 [1, 17]. Richard and Ramli [22] stated that foamed concrete has superior properties, such as low density, which helps minimize structural dead loads, foundation section, labor, transport and execution costs. However, a decrease in the load supported by concrete is observed due to the availability of void particles inside the concrete. This paper reviews the effects of various fiber types used in previous experimental work on the tensile strength of foam concrete. Also, it is an attempt to analyze and discuss the effect of different types of fiber used in previous experimental work on the mechanical properties of foam concrete, especially its tensile strength.

2. Methodology

Several papers from the literature have been collected and studied to show the effect of adding fiber (different types of fiber) on the tensile strength of foam concrete, as presented in Figure 1:

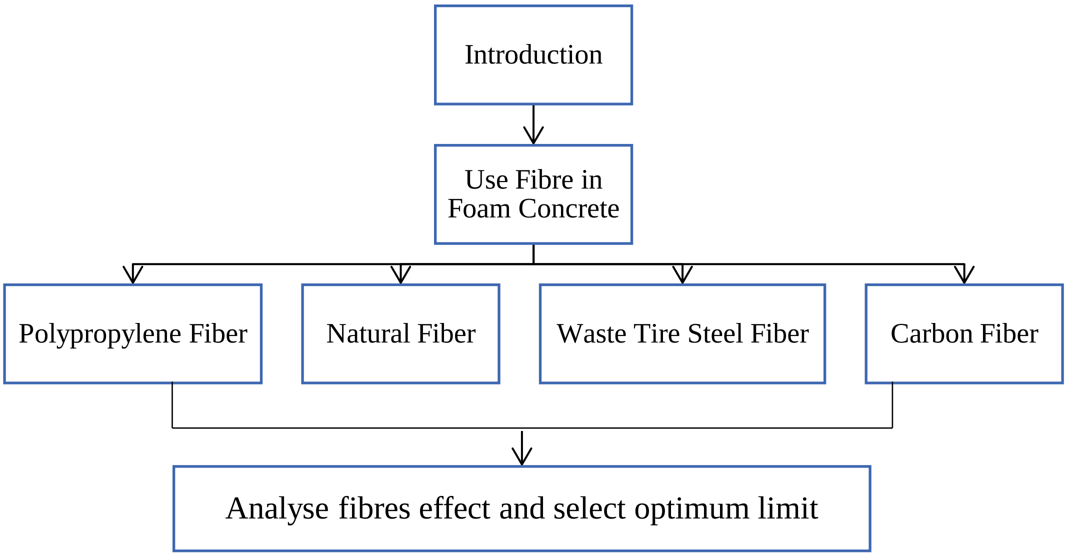

Figure 1. Methodology flow chart

3. Used Fiber in Experimental Works

The fibers used in foamed concrete are either natural or synthetic. The main types are alkali-resistant glass, kenaf, stainless steel, palm oil, and polypropylene fibers [11, 23, 24, 25]. The volume fraction of these fibers ranges from 0.25 to 0.4 percent of the total mix design components [26]. It was previously reported that when foamed concrete was reinforced with polypropylene fibers, significant improvements in mechanical properties and their impact were observed [27, 28]. Fibre reinforcement was later shown to change the standard behavior of foamed concrete from brittle plastic to rigid elastic plastic [28]. Steel fibers have also been used to improve foamed concrete [29]. This work reviewed four types of fibers as described in the following work.

3.1. Polypropylene Fiber

The use of polypropylene fibers (PF) in mixing concrete will take advantage of concrete properties, such as improving the tensile strength and, in particular, the prevention of post-cracking initiated by micro cracking. Several studies have stated that an improvement in the proper mixing of PF will significantly alter the quality of the concrete. These advantages depend on the form and amount of PF blended into a concrete matrix. A modification of the concrete characteristics due to PF mixing occurred due to two phenomena, i.e., the fiber matrix interface and the bridging force going through the crack [30]. The fiber placed into the concrete matrix delays the deterioration processes' beginning by controlling shrinkage and permeability. It will also reduce the expansion of concrete [31]. However, the appropriate ratio of PF volume to foamed concrete is crucial. This concerns the excessive use of PF in modified concrete, such as the excessive inclusion of fly ash to replace Portland cement, which could reduce the strength of concrete. The porosity value can increase due to an excessive PF ratio [32]. Table 1 illustrates the results of different fiber fractions added to foamed concrete. Figure 1 illustrates that adding PP fiber significantly increases the split tensile strength of foamed concrete. This development occurs when the density increases and the foam volume decreases. It suggests that strength is increased exponentially with the change in density or decrease in foam volume. The peaking values of tensile strength due to fiber addition are between 0.2 and 0.3%, and increasing the content beyond that range resulted in a significant decrease in strength.

Table 1. Different polypropylene fiber fraction volume and their strength

Reference	Target density (kg/m3)	PP (%)	Tensile strength (MPa)
Josef et al. [33]	1400	0.28	3.02
	1400	0.21	1.69
	1600	0.28	5.53
	1600	0.21	3.25
	1800	0.28	6.72
	1800	0.21	4.35
Hazlin et al. [34]	1600	0	0.77
	1600	0.05	1.04
	1600	0.10	0.9
	1600	0.15	1.24
	1800	0	1.34
	1800	0.05	1.88
	1800	0.10	1.8
	1800	0.15	1.7
Ashfaque et al. [35]	1400	0	0.69
	1400	0.8	1
	1600	0	1.2
	1600	0.8	1.54
	1800	0	2.6
	1800	0.8	2.1

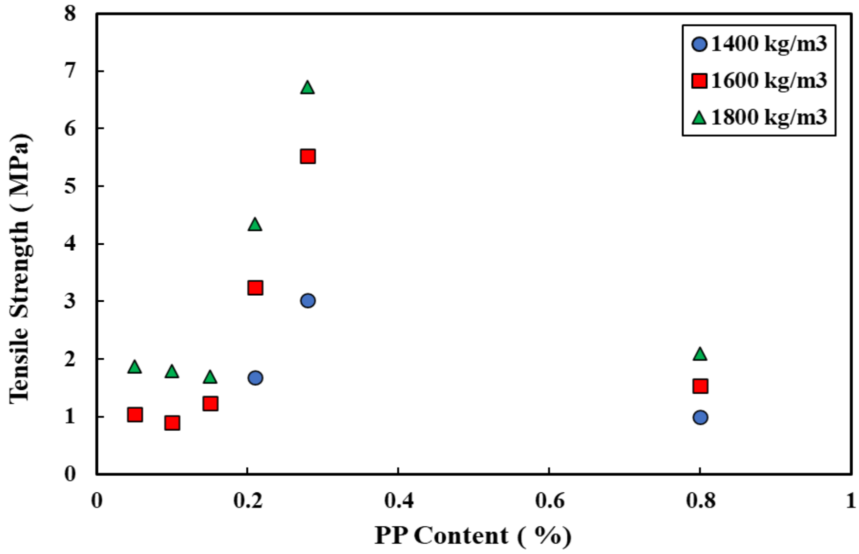

Figure 2. Relation between polypropylene fiber and tensile strength of different foamed concrete density

3.2. Natural Fiber (Henequen)

Metallic and synthetic fibers are the most common reinforcing fibers [36, 37]. However, the use of natural fibers as reinforcements have become increasingly common. The interest in materials reinforced with natural fibers is growing because materials can be made with good mechanical properties, low density and low cost. In addition, natural fibers are biodegradable and reusable, which promotes sustainability [38, 39, 40], an issue that is becoming progressively important. In certain implementations, these fibers could replace synthetic fibers, as synthetic fibers leave a larger environmental footprint. Several experiments have been performed on cement-based materials reinforced with natural fibers, including sisal, coir, jute, and Kraft pulp. These studies have shown that the flexural, impact, tensile, and compressive strengths and toughness of cement-based materials are enhanced by using these fibers [41, 42, 43].

Natural fibers are extremely susceptible to the alkalinity of the cement matrix, which results in the deterioration of the fibers and a decrease in the flexibility and deformation capability of the fibers due to the friction associated with their mineralization [44]. Poor degradation resistance of lignin and hemicellulose in highly alkaline environments can decrease the integrity and stability of the cell wall of natural fibers in cement-based materials [45]. Polymer coating, chemical treatment or thermal treatment of fibers will increase the durability of natural fiber-reinforced cement materials [45, 46, 47]. Foamed concrete strengthened with natural fibers has rarely been investigated. Mahzabin et al. [48] found that foamed concrete had a density of 1,250 kg/m3 by adding 0.45 % of kenaf fiber, and showed a significant improvement in compressive strength relative to unreinforced foamed concrete. Mydin et al. [49] examined the mechanical properties of foamed concrete with a density range of 800–1250 kg/ m3 reinforced with coir fiber at a fraction volume of 0.2 and 0.4 percent. They observed that fiber reinforcement enhanced the tensile, compressive, and flexural strengths and impact resistance of foamed concrete. Liu et al. [50] confirmed that applying 0.75 percent of sisal fiber to foamed concrete enhanced the shrinkage efficiency and the mechanical properties of the material.

Henequen is the main cultivated species of Agave for fiber production in the Yucatan Peninsula in Mexico. It withstands droughts better than sisal [51] and can rise in semi-arid, rocky and nutritionally low soils. Castilo et al. [52] conducted a study on foamed concrete modified by Henequen (untreated and treated) fiber, summarized in Table 2. The result presented in Figure 2 for the henequen fiber reinforced concrete shows that the peak strength was observed for the mixtures with 1 and 1.5 % treated fibers content, which was increased by about 98 % relative to the plain foamed concrete. The tensile strength was higher for the 0. 5% untreated Henequen relative to the same amount of treated Henequen fiber. However, by normalizing the strength relative to the density of foamed concrete, it can be noticed that for a fiber content of 0. 5%, treatment had no influence on the tensile strength.

Table 2. Summary of different mixtures modified with natural fiber [52]

Mixture	Type of Fiber	Fiber content (%)	Tensile Strength (MPa)
C	-	0	0.255
A1	Henequen	0.5	0.283
A2	Henequen	1	0.352
A3	Henequen	1.5	0.398
B1	Treated henequen	0.5	0.272
B2	Treated henequen	1	0.477
B3	Treated henequen	1.5	0.455

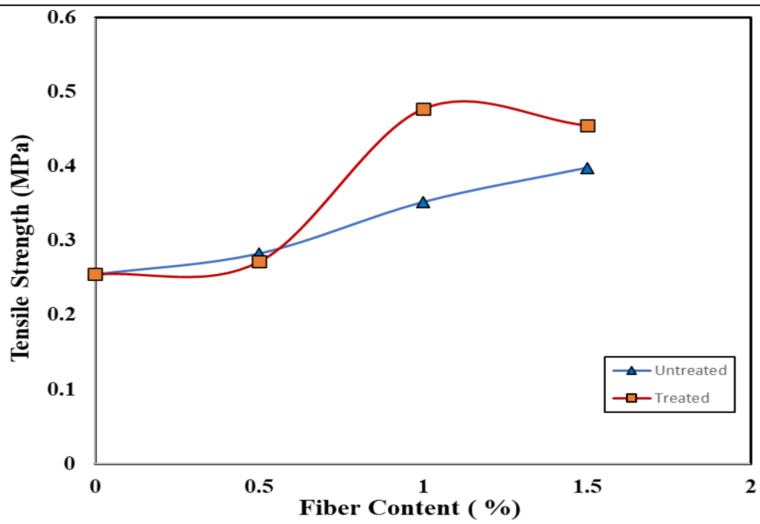

Figure 2. Comparison of tensile strength between treated and untreated henequen fiber (author)

3.3. Waste Tire Steel Fiber

Researchers are starting to investigate the idea of using waste tyres in buildings [53, 54], but little or no study has been conducted on reusing steel fibers in waste tyres. The steel in the tyres is of high strength, consisting of dense, twisted strands known as bead wire, which can be physically removed from the tyre by "debearding" or during the shredding or powder manufacturing process along with the other steel. Including tyre steel strands gives the waste an ecological benefit, ending the high recycling costs and the loss of natural resources [55]. Atoyebi et al. [56] performed a study using waste tire steel fiber, which is illustrated in Table 3. As shown in Figure 3, the tensile strength of all foamed concrete improved with age but decreased with the addition of steel fibers by up to 0.4 % before the fiber became sufficient, as observed in 0.6 % steel fiber where the tensile strength increased accordingly. The tensile strength of the control cylinder was found to be 1.28 MPa and decreased to 1.08 MPa at 0.2 % and 0.49 MPa at 0.4 %. However, the intensity improved back to 0.6 % for 1.46 MPa. This shows that the steel fiber content affects the tensile strength, where the tensile strength of concrete only improves when there is a sufficient quantity of fibers. The inadequate steel fibers adversely affect the bonding of the concrete instead of improving it. This is attributed to a decrease in the porosity of the foamed concrete and an improvement in the mechanical bond strength when the appropriate amount is applied.

Table 3. Summary of different mixtures and fiber fracture content

Sample	Fiber content (%)	Tensile Strength (MPa)		
		7 – days	14 – days	28 -days
1	0	0.85	1.06	1.28
2	0.2	0.74	0.97	1.08
3	0.4	0.4	0.45	0.49
4	0.6	0.66	1.08	1.46

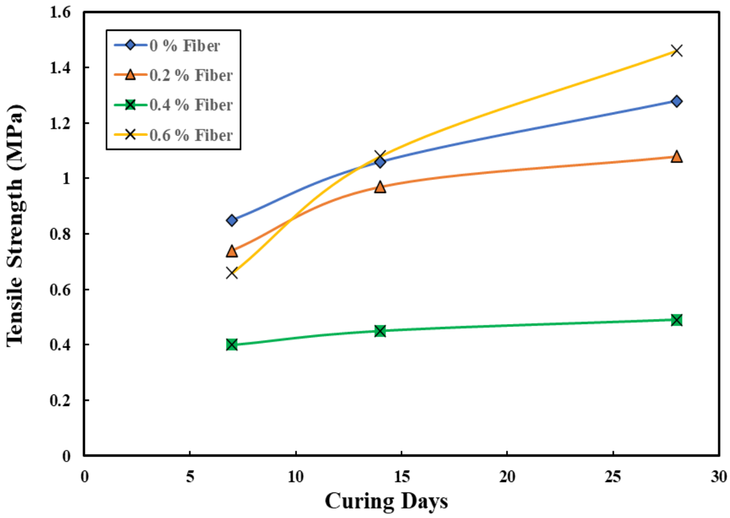

Figure 3. Relation between carbon fiber and tensile strength of foamed concrete at different curing days (author)

3.4. Carbon Fiber

Fibers used in concrete could be categorized into two groups: one is low modulus with high elongation fibers such as polypropylene and polyethylene. This form has high energy absorption properties and does not enhance the compressive strength. The second group is the high-grade modulus with high-strength steel, glass, and carbon fibres, which manufacture solid composites [57]. The combination of different fibers can provide potential advantages in improving concrete properties. Hybrid fibers may reinforce all forms of strains. A combination of low and high-modulus fibers will avoid micro and macro cracks [58].

A study was performed by Abbas et al. [59] on foamed concrete with inducing carbon fiber and a combination of (Carbon + Polypropylene), the results of which are presented in Table 4. Figure 4 shows that carbon fibers in the foamed concrete mixture increase its tensile strength. If the volumetric proportion of carbon fiber increases, the splitting tensile strength of foam concrete rises as well. As a result, the highest value was observed for 1.5 per cent carbon fiber in the foamed concrete mixture, where the improvement was approximately 47 % compared to the reference foamed concrete at 28 days. This is due to the high tensile strength of carbon fibers that can enhance the tensile strength of foamed concrete and the capacity of the fibers to avoid cracks and reinforce the homogeneity of foamed concrete.

On the other hand, the hybridization of 1 % CF with 0.5 % polypropylene increases the tensile strength significantly. The percentage rise of the above case S4 was nearly 53 % compared to the control mixture S0. This could be due to the enhancement in the capacity of foamed concrete through two fibers concerning bridging cracks effectively, where the micro-mechanical mechanism of bridging cracks functions from the stage of damage evolution to beyond final loading.

Table 4. Mechanical property of foamed concrete with different fiber fraction [61]

Mixture	Fiber Content (%)		Tensile Strength (MPa)	Relative strength (%)
	Carbon	PP		
S0	0	0	1.9	100
S1	0	0	2.0	105
S2	0.5	0	2.6	137
S3	1	0	2.8	147
S4	1.5	0	2.9	153
S5	1	0.5	2.1	111
S6	0.5	1	2.0	105

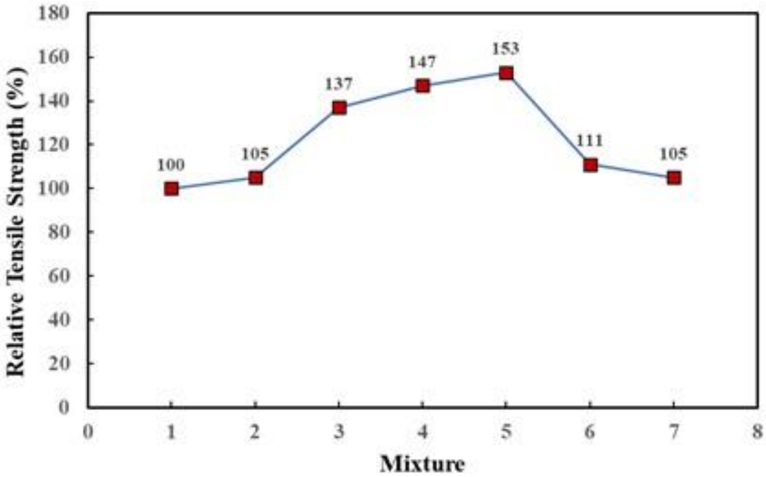

Figure 4. Relative strength of different foamed concrete mixtures

5. Conclusion

The primary objective of this study was to review existing research on the tensile strength of foamed concrete modified with various types of fibers, detailing the materials used in foam concrete and their key properties. The study explored how different fibers enhance the mechanical strength of foamed concrete in its hardened state. The findings from previous research led to several conclusions.

Foamed concrete is commonly used in construction due to its low density, but its compressive strength decreases as density diminishes. Generally, denser foamed concrete exhibits higher compressive strength and fewer voids. Incorporating polypropylene fiber, within a range of 0.2 to 0.5% results in an approximate 5% increase in tensile strength. Foamed concrete with 1% and 1.5% treated henequen fiber demonstrates the highest tensile strength compared to unmodified foamed concrete, attributed to improved fiber-matrix interaction. Conversely, including a small amount of volume waste tyre steel fiber can reduce concrete strength due to the creation of irregularities. However, foamed concrete with 1% carbon fiber shows a notable tensile strength increase of about 44% compared to samples without fiber. Furthermore, hybridizing fibers by adding 1% carbon and 0.5% polypropylene significantly enhances tensile strength by approximately 48% compared to fiber-free samples.

Declaration of Competing Interest The authors declare they have no known competing interests.

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