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Processing of Recycled Cement Sacks as Cellulose Pulp into Pervious Concrete

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Abstract - *This study proposes and validates a methodology for incorporating cellulose fibres (CF) from recycled cement sacks into pervious concrete. The process involves mechanically converting the sacks into pulp and pre-saturating them to ensure integration into the mix. The CF obtained was evaluated in terms of composition, and its performance was assessed through rheology and the mechanical and permeability properties of pervious concrete at three dosages (3.9, 5.8, and 7.7 kg/m³). A straightforward mechanical procedure was established to produce the CF, requiring a minimum pre-saturation period of 12 hours to secure adequate mix flowability and paste coating uniformity. XRF and XRD tests confirmed that the treatment reduced cement residues, although traces of chlorine remained. Saturated CF did not compromise matrix fluidity, ensuring an adequate coating. Additionally, CF improved permeability by up to 32.9% without compromising strength, acting as an internal curing agent and enhancing long-term compressive strength up to 10.4%. CF also strengthened matrix–aggregate bonding, improved post-crack integrity, and promoted a more ductile failure mode. In conclusion, processing cement sacks into cellulose fibres provides a practical and sustainable solution for improving cohesion and permeability in pervious concrete while maintaining mechanical performance. This approach supports sustainable construction by valorising packaging waste and offers a method adaptable to industry, depending on local conditions.*

Keywords: Pervious concrete, Recycled cement sacks, Cellulose fibres, Internal curing, Sustainable construction.

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1. Introduction

Pervious concrete contains little or no fine aggregate, with a highly porous and interconnected structure. This facilitates water infiltration, promoting aquifer recharge and reducing surface runoff, contributing to flood prevention [1]. Its capacity to absorb water also helps mitigate the urban heat island effect [2]. However, its use is often restricted due to the brittleness of the binder matrix, which limits mechanical performance under high loads [3]. To address this limitation, fibre reinforcement has been widely explored to enhance the mechanical properties of pervious concrete [4]. Various types of fibres have been studied, including synthetic [5-9], metallic [8, 10-12], carbon [13] and organic fibres [14, 15]. Synthetic fibres such as polypropylene and polyethylene have shown significant improvements in strength [5, 16], although some, like polyester, may reduce permeability [6]. Metallic fibres, while effective in increasing strength, may cause clumping at high dosages and are susceptible to corrosion [10-12]. Carbon fibres can increase strength by up to 40% but often reduce permeability [13]. Organic fibres can enhance strength but may compromise the rheological behaviour and permeability [14].

Organic fibres obtained from discarded cement sacks have gained attention as sustainable alternatives

[17-21], particularly considering that paper-based waste accounts for 26% of global landfill content [22], and cement production generates approximately 2.59 kg of paper waste per tonne of cement, mainly from sacks [23]. These fibres can be incorporated into cementitious materials as strips or as pulp. When used as strips, they tend to be less effective due to their limited dispersion capacity within the matrix [18], leading to weak zones and potential obstruction of drainage channels in pervious concrete. In pulp form, however, the sacks are transformed into cellulose microfibres that disperse more uniformly and interact more effectively with the matrix, improving both rheological and mechanical performance [17, 19, 20], including enhanced tensile and compressive strength in pervious concrete without significantly compromising its permeability [14], depending on several factors, including dosage, curing time, and pre-treatment method employed for CF addition. For instance, excessive fibre content leads to agglomeration and poor dispersion, negatively affecting workability [17, 18]. In other cases, if the fibres are not pre-saturated, their high absorption capacity undesirably alters the water-to-cement ratio, but fully saturated fibres may delay early hydration and reduce early-age strength but later contribute to internal curing and microstructural development through gradual water release and nucleation effects [24, 25]. The effective use of fibres in a saturated condition is difficult to achieve through conventional mix design, which typically assumes that the water held by fibres can be treated in the same way as the moisture content of aggregates. This approach fails to consider the characteristics of fibres, namely their sensitivity to ambient humidity and their high capacity to retain water over time. As a result, traditional procedures often struggle to ensure the desired balance between workability and mechanical performance. A more suitable alternative is to develop methods that recognise these specific fibre–matrix interactions, facilitating their incorporation in a form that maximises both their technical benefits and their sustainability potential. In this context, cellulose pulp obtained from recycled cement sacks offers a promising pathway.

The present study proposes a straightforward methodology for incorporating cellulose fibres from recycled cement sacks into pervious concrete, considering their incorporation as pulp. The method is first evaluated in terms of the quality of cellulose fibres obtained and then validated in the cementitious matrix and the pervious concrete by assessing mechanical and hydraulic performance at 7 and 28 days of age.

2. Materials

Type I Portland cement was used, composed mainly of 61.2% CaO and 20.7% SiO_2. Regarding its physical properties, it exhibits a Blaine specific surface of 3620 cm^2/g, a density of 3.14 g/cm^3, and an initial setting time of 122 minutes. No plasticiser additives were used.

Semi-crushed coarse aggregate from alluvial igneous rocks was used in this study. The particle size distribution comprised aggregates retained on the 1/2" and 3/8" sieves in a 75:25 proportion, yielding a 44 % void ratio as specified by ACI 522 [26]. The coarse aggregate presented a specific surface area of 0.15 m^2/kg, a water absorption capacity of 0.95%, a loose unit weight of 1403.3 kg/m^3, a rodded unit weight of 1539.8 kg/m^3, a specific gravity of 2.77, and a moisture content of 0.63%.

The waste cement sacks were supplied by a local company specialising in industrial waste management.

3. Experimental methodology

The experimental program was developed into four steps, as detailed next: (1) Production of cellulose fibres (CF), (2) evaluation of the CF absorption capacity, (3) chemical and physical characterisation of CF, and (4) validation in the cementitious matrix and the pervious concrete.

3. 1. Production of CF and its incorporation in the pervious concrete

A mechanical process was developed to transform discarded cement sacks into cellulose pulp, without resorting to chemical treatments or requiring specialised equipment. Additionally, its incorporation as pulp in the pervious concrete was established. The method was designed to be simple and reproducible, making it suitable for laboratory and field-scale applications.

3. 2. Evaluation of the absorption capacity of CF

To better control the wetting condition of the cellulose pulp in the mixture and to determine the minimum saturation time required for the fibres to act as internal curing agents, the water absorption of CF was evaluated following the Salem & Al-Salami procedure [19]. The CF sheets were manually dispersed in water and moulded into 15 spheres of 2 cm in diameter. These were oven-dried at 110 °C for 12 hours to reach a constant mass. The samples were then immersed in water for various durations (10 seconds to 15 hours), and after each interval, excess water was removed with filter paper before weighing. This was repeated until the weight stabilised.

3. 3. Chemical and physical characterisation of processed CF

To assess the effectiveness of the fibre extraction process in reducing potential residual traces of Portland cement or other contaminants, both X-ray fluorescence (XRF) and X-ray diffraction (XRD) were employed. Additionally, the morphology and dimensions of the CF were analysed using Scanning Electron Microscopy (SEM).

3. 4. Validation in the cementitious matrix and pervious concrete

The incorporation of CF was first validated at the matrix level, observing rheological and compressive strength testing. A mixing process adapted from the conventional cement paste mixing [27] was used to determine the incorporation of CF. CF was incorporated into the mixing water at dosages of 0 (control), 3.9, 5.8, and 7.7 kg/m^3 of cementitious matrix, as recommended by ACI Committee 522 [26]. All mixtures were prepared with a water-to-cement ratio of 0.35.

Rheological properties were assessed through flowability, using the flow table test [28], and actual paste thickness (*APT*) as suggested by Xie et al. [29]. APT reflects the paste's ability to coat aggregates, indirectly indicating adhesion and required volume. It was calculated in millimetres using Equation 1.

$$APT = \frac{M_p}{M_a * \rho_p * S_a} \times 10 \quad (1)$$

Where M_p is the mass of cement paste adhered to the aggregate (g), M_a is the mass of aggregate in SSD condition (g), ρ_p is the paste density (g/cm^3), and S_a is the specific surface area of the aggregate (cm^2/g).

The mechanical strength of the matrix was evaluated by compression test on 5 cm cubic specimens at 7 and 28 days [30].

Pervious concrete was prepared with a constant matrix content of 0.233 m^3 and 1,462.8 kg of coarse aggregate per m^3 of concrete for each CF dosage.

Permeability was assessed at 7 days using a falling head permeameter, following ACI 522 guidelines [26]. Samples were cast in UHMW tubes (10 cm diameter × 20 cm height) to avoid the demoulding process before testing, and the coefficient of permeability (K) was calculated using Equation 2.

$$K = \frac{A_1 h}{A_2 t} ln\left(\frac{h_i}{h_f}\right) \quad (2)$$

Where A_1 is the cross-sectional area of the acrylic tube (cm2), A_2 is the cross-sectional area of the concrete sample (cm^2), h is the sample length (cm), h_i and h_f are the initial and final water levels (cm), respectively, and t is the time for water to drain from h_i to h_f (s).

The mechanical behaviour was evaluated via compressive strength [31] and splitting tensile strength [32] tests on 100 mm × 200 mm cylindrical specimens, and flexural strength [33] tests on 150 mm × 150 mm × 500 mm prismatic beams. All tests were performed at 7 and 28 days of curing.

4. Results and discussion

4. 1. Production of CF and its incorporation in the pervious concrete

Recycled cement sacks were first cleaned to remove surface dust and cement residues, then cut into pieces of approximately 2 × 3 cm in size. The pieces were immersed in water for 48 hours to soften and separate the paper layers. This pre-treated material was subsequently processed in a 1,400 W blender for 40 minutes, yielding a slurry of fine fibres. The wet pulp was spread uniformly on a Raschel mesh and air-dried at ambient temperature for two days. As shown in Figure 1, the dried cellulose fibre (CF) sheets were then collected and stored until use in concrete mixing.

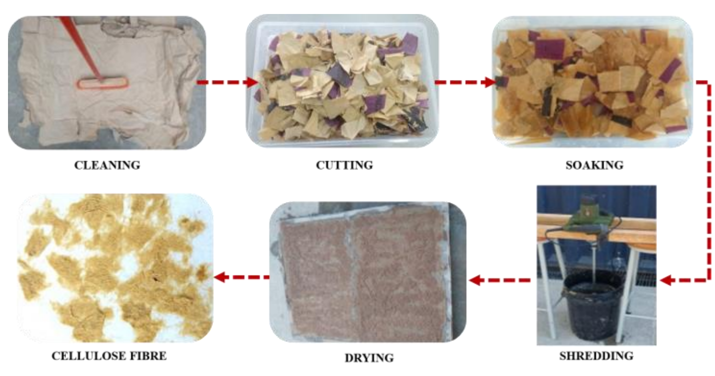

Figure 1. Schematic of the processing to obtain CF.

For the incorporation of cellulose fibres (CF) into pervious concrete, a straightforward and efficient procedure was established. The CF were first pre-saturated with half of the total mixing water for 12 hours, ensuring their stabilisation before mixing. For the preparation of the cementitious matrix, saturation was performed using the total mixing water. In both cases, fibres were dispersed directly in the designated portion of water before incorporation. In the mixer, aggregates were introduced first, followed by half of the mixing water (without fibres), the cement, and finally the remaining water containing the fibres. Mixing was performed at low speed for 120 seconds, paused for 15–30 seconds to scrape the walls, and then resumed at medium speed for 3 minutes. For pervious concrete, the fresh mix was placed in moulds in two layers, each compacted with 20 uniform blows of a Proctor hammer. Specimens were demoulded after 24 hours and cured until the designated test ages (Figure 2). This methodology ensured both consistent fibre dispersion and stable rheological performance, while remaining simple and adaptable for practical applications.

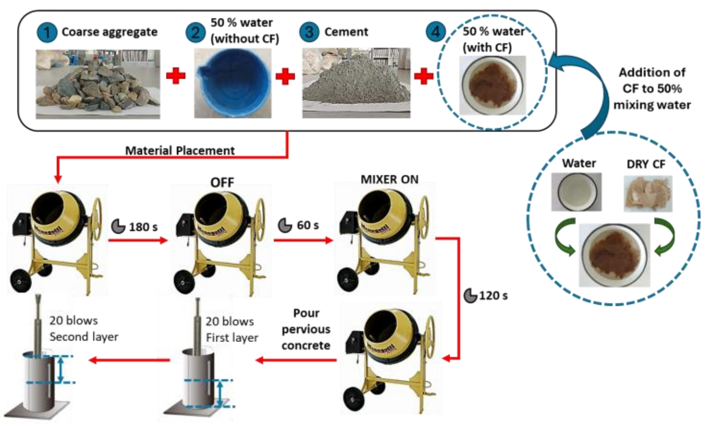

Figure 2. Process of pervious concrete fabrication with CF as pulp.

4. 2 Evaluation of CF absorption capacity

The cellulose fibres demonstrated a pronounced ability to absorb water, a behaviour linked to their hydrophilic nature and the presence of hydroxyl (-OH) groups along the cellulose chains, which readily form hydrogen bonds with water molecules [38]. The absorption behaviour (Figure 3) revealed two distinct phases: an initial, rapid intake reaching roughly 245% of the dry fibre mass within the first 20 minutes, followed by a slower, gradual increase over the next 12 hours, stabilising at approximately 270%. Between 80 and 120 minutes, an apparent plateau was observed, which could be mistakenly interpreted as the point of full saturation. However, the continued gradual increase beyond this stage demonstrates that equilibrium is only reached after about 12 hours, highlighting the slow and progressive nature of the fibre–water interaction. This behaviour confirms that cellulose fibres undergo a two-stage absorption process: an early, fast uptake governed by surface and near-surface porosity, and a subsequent, much slower process associated with deeper pore penetration.

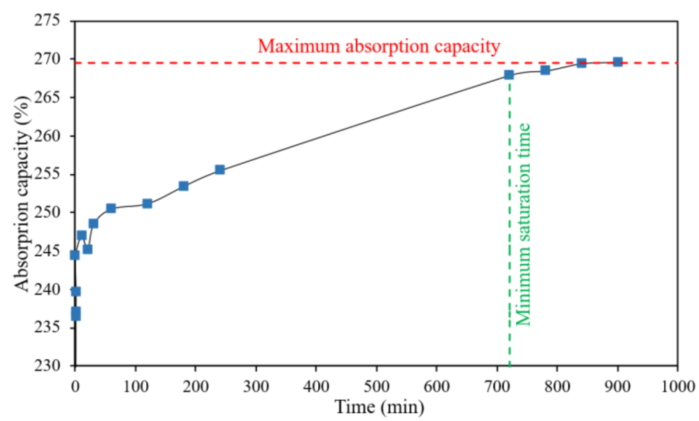

Figure 3. Water absorption capacity rate of processed CF.

Recognising this behaviour was critical for defining the incorporation protocol. Introducing the fibres into the mix in a saturated state ensures that they do not compete with the cement paste for available mixing water. Instead, they act as micro-reservoirs, releasing retained moisture progressively during curing. This mechanism supports internal curing, maintains workability, and prevents unwanted changes to the water-to-cement ratio. For these reasons, a pre-saturation period of at least 12 hours in the mixing water was adopted as a key step in the process, ensuring both consistent dispersion and stable rheological performance during mixing. Building on this protocol, the next stage of the study focuses on assessing its influence on the cementitious matrix, particularly in terms of rheological behaviour and compressive strength.

4. 3 Chemical and physical characterisations of CF after processing

The extracted CF exhibited a specific gravity of 1.02 [34] and a moisture content of 7.19% [35]. The structural organic composition of the obtained CF was determined, and the results are presented in Table 1. The high cellulose content confirms its predominance in the recovered fibres, while the low lignin content promotes a more homogeneous dispersion of the fibres within the cementitious matrix.

Table 1. Organic composition of the processed CF.

Component	Quantity (%)
Cellulose	75.40
Hemicellulose	0.70
Lignin	23.88

The results of the XRF analysis are presented in Table 2. Element characteristics of Portland cement were identified, with a notably high calcium content (35.4%), as well as the presence of silicon (1.6%), aluminium (2.6%), and iron (1.1%). These findings suggest that the mechanical process used to obtain the CF produces a significant reduction of cement residues compared to untreated cement bags, unless they are not completely removed. This result matches with other processing proposals of cement bags as cellulose pulp [37]. The substantial chlorine content (35.4%) detected in the fibres does not correspond to the typical composition of Portland cement, indicating the presence of external contaminants or residual compounds acquired by the drinking water used for the treatment process. Given the low dosage of fibres within the cementitious matrix, this amount of chlorine is unlikely to interfere with cement hydration or contribute to significant chloride-induced corrosion, particularly in typical applications of pervious concrete systems.

Table 2. XRF results of processed CF.

Element	Content (%)	Element	Content (%)
Cl	35.4	Si	1.6
Ca	35.4	Fe	1.1
Na	9.8	Sr	0.7
S	6.1	Ti	0.6
Mg	4.1	P	0.2
Al	2.6	Zn	0.2
K	2.1	Cu	0.1

The XRD analysis (Figure 4) identified crystalline phases associated with cementitious residues. Calcite (24%), lime (0.90%), and tricalcium aluminate (0.80%) were detected—compounds typically found in hydrated or carbonated Portland cement products—indicating partial retention of such residues in the fibres. The presence of silica (SiO_2, 13.9%) further supports this interpretation, as it is a common component in clinker.

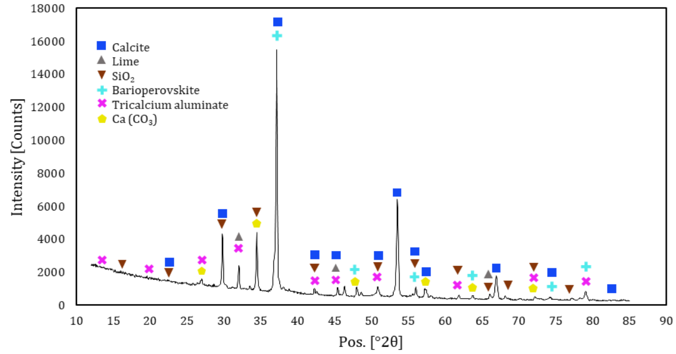

Figure 4. XRD of processed CF.

The SEM micrographs revealed free-lignin fibres, typical of processed cellulose fibres [22], ranging in length from 2.7 mm to 12.5 mm, and a ribbon-like structure with a ribbed surface along its longitudinal axis (Figure 5). Based on their dimensions, the CF were classified as microfibres, with thicknesses between 5 and 10 μm and widths between 30 and 60 μm, resulting in average values of 8 μm and 44 μm, respectively, which yields a form factor greater than 100 [37]. It is also observed that some remaining contaminant particles stayed adhered to the fibres.

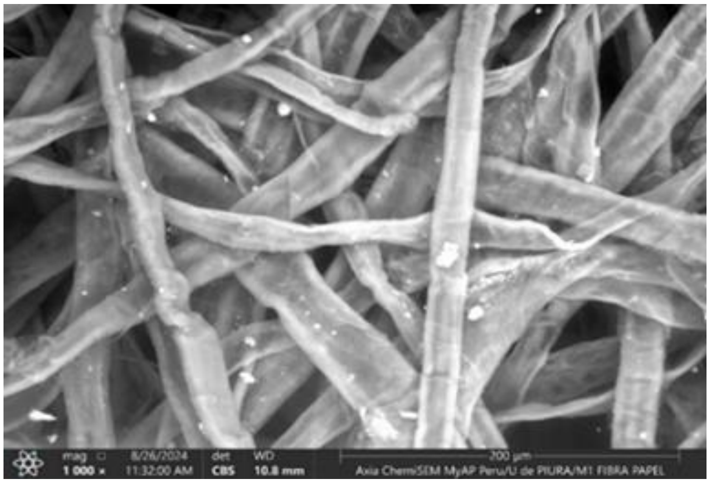

Figure 5. CF morphology and texture by SEM micrographs [37].

This simple mechanical procedure enabled the consistent extraction of cellulose fibres without the use of chemical treatments or specialised equipment. The process proved effective in producing homogeneous fibres suitable for further incorporation into cementitious matrices for pervious concrete.

4. 4 Validation in the cementitious matrix

The validation of CF dispersion in the cementitious matrix was examined through rheological tests. Mixtures containing 3.9, 5.8, and 7.7 kg/m^3 of CF were evaluated in terms of flowability and APT, as shown in Figures 6a and 6b.

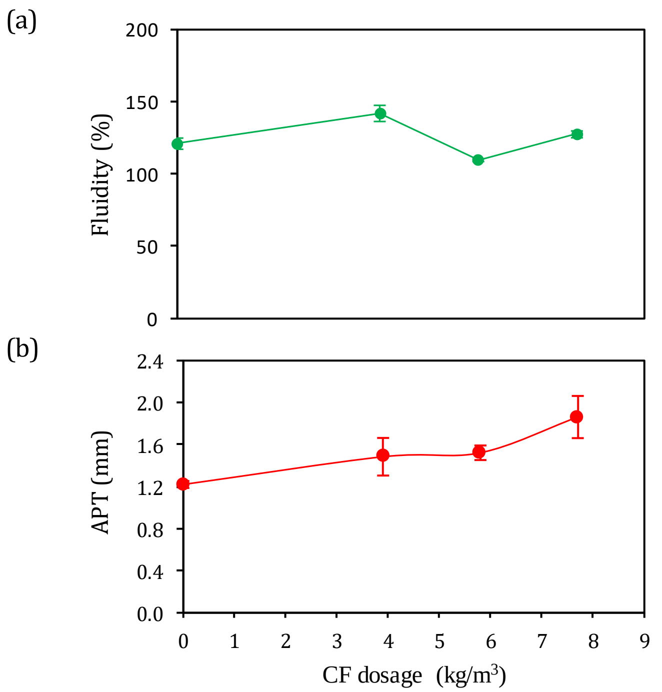

Figure 6. Rheological properties of the matrix containing CF (a) Fluidity and (b) APT.

A general improvement in flowability (Figure 6a) was observed across all fibre-reinforced mixes, with the highest value recorded at 3.9 kg/m^3 (142%), followed by 127.5% at 7.7 kg/m^3 and 109.7% at 5.8 kg/m^3, relative to the control. This indicates that the pre-saturated CF acted as micro-bridges between particles, enhancing distribution and reducing localised friction while entering the mix without extracting water from the paste. At lower dosages, the fibres promoted lubrication and particle dispersion, whereas at higher contents, a slight reduction in flowability occurred, likely due to fibre entanglement and increased particle-to-particle contact, which raised local viscosity [39]. This contrasts with previous studies, in which the absence of a controlled CF saturation process resulted in a 30–40% reduction in workability [17, 22, 24]. In the present study, however, no such decrease was observed, even at the highest dosage, thereby eliminating the need for plasticising admixtures to maintain adequate fresh-state performance. These findings suggest that applying the correct saturation time and method, without adjusting the mixing water, not only preserves the intended water-to-cement ratio and the cohesion of the mix but also simplifies mix design by avoiding the use of additional chemical components, while still achieving fresh-state properties equal to or superior to those of the control. Furthermore, the relatively small standard deviations (ranging from 1.0% to 5.6%) confirm that variations between replicates were minor, reinforcing the reliability of the observed trends.

APT values also increased with CF addition, rising from 1.22 mm in the control matrix to 1.49 mm at 3.9 kg/m^3, 1.52 mm at 5.8 kg/m^3, and 1.86 mm at 7.7 kg/m^3 (Figure 6b). This progressive growth suggests the formation of a thicker and more continuous paste film around the aggregates, which likely enhances coating uniformity and the cohesion of the fresh mix. As shown in Figure 7a, aggregates without fibre present a more dispersed and less cohesive paste, with particles appearing more separated. In contrast, Figures 7b, 7c and 7d, corresponding to mixes with CF, reveal a denser and more cohesive bond between paste and aggregates. The fibres act as reinforcement, helping to hold the mix components together; however, at higher dosages, some degree of agglomeration becomes evident (marked in red circles), likely due to the interconnected fibre network reducing particle mobility. Such improvements in paste distribution and stability can have direct implications for the performance of pervious concrete, as they promote stronger matrix–aggregate bonds.

Taken together, the flowability and APT results demonstrate that the proposed fibre incorporation method not only avoids the loss of workability reported in previous studies but also contributes to improved paste cohesion and aggregate bonding. This behaviour provides a sound basis for examining whether such rheological benefits translate into enhanced compressive strength in the hardened state.

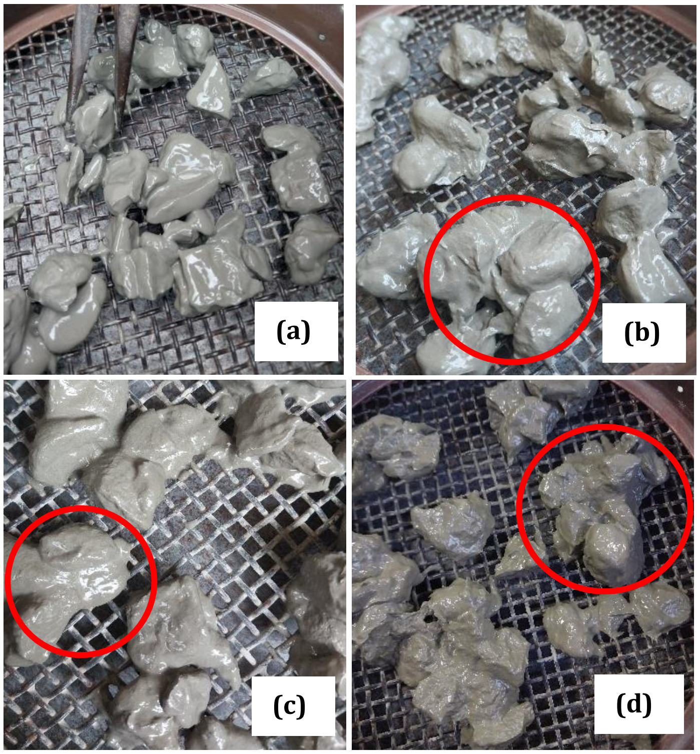

Figure 7. Coated aggregate in the APT test (a) Control, (b) 3.9CF, (c) 5.8CF and (d) 7.7CF. Agglomerations of aggregates are marked in red circles.

The compressive strength of the matrices with CF was also evaluated (Figure 8). At 7 days, a moderate reduction in strength was observed compared with the control (58.4 MPa), with values ranging from 48.8 MPa at 3.9 kg/m^3 to 59.1 MPa at 7.7 kg/m^3. This early-age decrease may be associated with a slight delay in hydration kinetics caused by the presence of saturated CF, which, while not absorbing water during mixing, can influence the initial rate of hydration reactions and nucleation [25]. The magnitude of variability between results was similar at each age, although the overall spread was slightly larger at 28 days. At 28 days, most CF mixes exceeded the control strength (61.1 MPa), with 3.9 kg/m^3 achieving 67.9 MPa—an 11% increase—confirming that CF incorporation does not impair long-term performance and, at specific dosages, can enhance it. The trend also indicates that beyond a certain fibre content, strength gain tends to stabilise rather than increase further. These findings confirm the effectiveness of the proposed CF saturation and incorporation method, ensuring that fibres act as an internal curing resource capable of gradually releasing retained water and facilitating continued hydration and microstructural development. Overall, the results at the matrix level validate the method as a viable strategy for enhancing cementitious systems, thereby providing a solid foundation for its subsequent evaluation in pervious concrete.

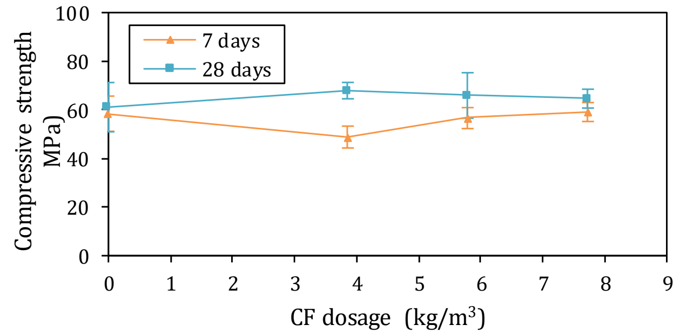

Figure 8. Compressive strength of the matrix containing CF.

4. 5 Validation in pervious concrete

The performance of pervious concrete incorporating saturated CF was assessed by measuring permeability and mechanical properties. As shown in Figure 9, the inclusion of CF led to an improvement in permeability, yielding values of 18.6, 22.2 and 20.2 mm/s for 3.9, 5.8 and 7.7 kg/m^3, respectively, all above the control sample (16.7 mm/s). The highest value, obtained at 5.8 kg/m^3, represented a 32.9% increase, while 3.9 and 7.7 kg/m^3 produced improvements of 11.4% and 21.0%, respectively.

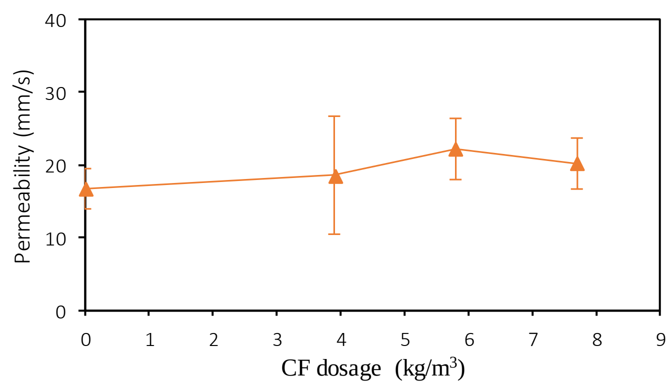

Figure 9. Permeability of the pervious concrete containing CF.

This trend is likely related to the role of CF in pulp form, which enhances matrix cohesion and favours the formation of a thicker and more uniform coating around aggregates. Such a coating helps maintain pore interconnectivity while preventing the cement paste from draining to the bottom and blocking pores. At higher fibre dosages, a slight decrease in permeability was observed, possibly due to fibre entanglement and mix heterogeneity. Despite this reduction, permeability values remained above those of the control, confirming that fibre addition does not compromise the hydraulic function of pervious concrete. The variability of results was generally similar across all fibre dosages, except for 3.9 kg/m^3, which displayed a wider spread.

Figure 10a shows that the incorporation of CF produced measurable though moderate gains in compressive strength, with increases of up to 33.4% at early ages and less than 10.4% at later stages. In CF mixes, the difference between the 7- and 28-day strengths was less marked than in the control mix, with the 7-day values reaching approximately 80% of the 28-day strength. At higher CF contents, the 28-day strength tended to stabilise, whereas the 7-day strength showed a slight decrease, possibly associated with localised heterogeneities introduced by the fibres. The overlapping error bars between 7 and 28 days suggest that these differences may not be statistically significant, reinforcing that CF mainly enhances early-age matrix stability rather than acting as a long-term strength contributor.

A similar pattern was observed for flexural strength (Figure 10b) and splitting tensile strength (Figure 10c). At 7 days, flexural strength reached 2.93 MPa for the 7.7 kg/m^3 CF mixture, while other dosages produced more modest increases. However, for mixtures containing CF, the 7-day and 28-day values were essentially the same, indicating that higher fibre contents did not lead to significant long-term strength gains. In fact, at 28 days, the flexural strength was up to 19% lower than the control, suggesting that excessive CF may introduce local heterogeneities that counteract mechanical efficiency. Splitting tensile strength showed a similar trend: CF mixtures exhibited higher values at 7 days—up to 36% above the control—but these differences diminished by 28 days, with most results converging to the control level, except for the 3.9 kg/m^3 mixture, which maintained a 7.7% improvement.

Overall, these findings indicate that saturated CF contributes to greater matrix stability, improved cohesion and enhanced mechanical performance at early ages, without compromising permeability. However, as the matrix continues to develop its intrinsic strength through hydration, the relative effect of CF becomes less relevant, and at higher dosages, slight mechanical penalties may occur.

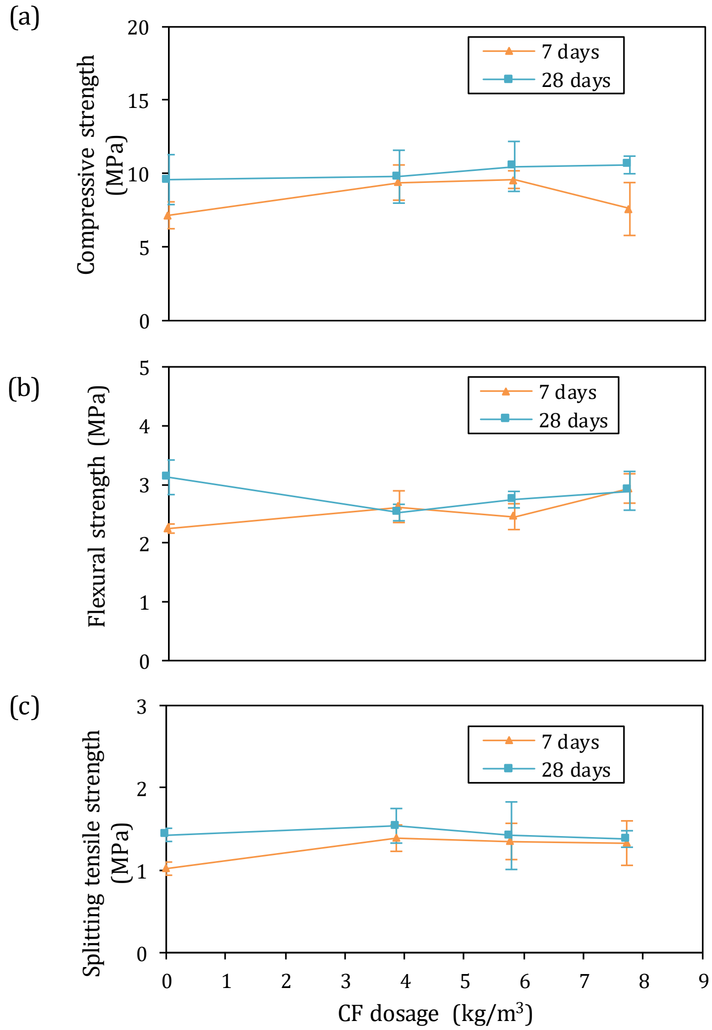

Figure 10. Mechanical properties of the pervious concrete containing CF: (a) compressive strength, (b) flexural strength, and (c) splitting tensile strength.

Further insights were obtained by examining the failure patterns of the pervious concrete specimens (Figure 11). In the control mixture, a brittle failure with clear separation of the fragments and pronounced cracking was observed, indicative of weak bonding between the matrix and aggregates. In contrast, specimens with CF exhibited more controlled crack propagation and retained structural integrity after failure, with reduced fragment separation. This behaviour highlights that CF not only improves early-age cohesion but also contributes to greater ductility and post-fracture integrity, offering residual load-bearing capacity beyond initial cracking.

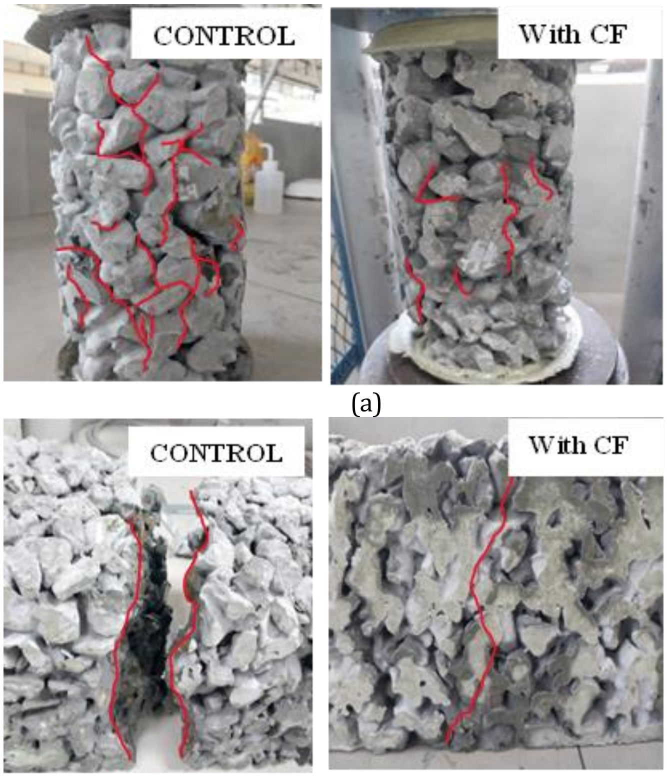

Figure 11. Typical failure pattern observed in pervious concrete in (a) compressive strength and (b) flexural strength.

In summary, the proposed approach proves effective for enhancing early-age performance and durability aspects of pervious concrete, while maintaining permeability above control levels.

5. Conclusion

This study proposed and validated a practical methodology for incorporating recycled cement sacks, processed into cellulose pulp fibres (CF), into pervious concrete. The validation was carried out through the analysis of cementitious matrix rheology and the evaluation of mechanical and hydraulic performance in pervious concrete.

1) The methodology enabled the efficient transformation of waste cement sacks into cellulose fibres suitable for direct use in cementitious systems, without the need for advanced or energy-intensive processing.
2) XRF and XRD analyses showed that the mechanical treatment significantly reduced cementitious residues in the fibres, although crystalline phases such as calcite and tricalcium aluminate remained.
3) Pre-saturated CF improved matrix flowability at moderate dosages by enhancing particle dispersion and lubrication, while excessive contents slightly reduced workability due to fibre entanglement. Regardless of dosage, CF increased the average paste thickness (APT), resulting in a more uniform coating of aggregates and improved pore structure connectivity. Consequently, pervious concrete permeability was preserved, with increases of up to 32.9% at 5.8 kg/m^3.
4) The incorporation of saturated CF caused a modest reduction in compressive strength at early ages but improved 28-day strength by up to 10.4%, confirming their role as internal curing agents that release moisture gradually during hydration.

Overall, the methodology developed in this study for processing cement sacks into cellulose pulp fibres provides a feasible and sustainable route for enhancing the cohesion and hydraulic functionality of pervious concrete, while preserving its mechanical integrity. Further research should evaluate long-term durability and environmental resistance to consolidate the potential of CF as a sustainable construction material.

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