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Original Article

Mechanical Performance and Feasibility of Recycled Rubber Fiber-Reinforced Geomembranes for Lightened Slab Buildings

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Abstract - *Construction demands solutions that improve durability and reduce environmental impact, and the use of recycled rubber is an alternative aligned with these objectives. However, there is little evidence on its application in geomembranes for lightweight slabs and its effect on structural and hydraulic performance. This study evaluated high-density polyethylene geomembranes reinforced with recycled rubber fibers, integrated in lightweight slabs, by means of permeability, tensile, adhesion, and durability tests according to ASTM standards, in addition to a cost analysis. The results showed reductions in water penetration from 39-42 mm to 25 mm and in the permeability coefficient from 10^{-11} m/s to 10^{-12}–10^{-13} m/s, with sustained improvements up to 91 days, in addition to an increase in the modulus of rupture by an average of 47%. The slight cost increase of 10% is offset by the increased durability, making it a sustainable technical solution for environments with high moisture exposure.*

Keywords - *Durability, Geomembranes, Lightweight Slabs, Recycled Rubber, Waterproofing.*

1. Introduction

The deterioration of the lightweight slab nowadays is occurring due to ambient conditions. In this case, the humidity tends to seep into the inner layers of material, altering your mechanical behavior and the evolution of small cracks. On the other hand, the final disposal of End-Of-Life Tires (ELTs) constitutes a global environmental challenge due to their slow degradation, increasing volume, and potential to release polluting compounds [1]. Among the recovery strategies, the recovery of rubber fibers and particles from NFU has gained interest due to their potential to be reincorporated into cementitious and polymeric matrices, contributing to the circular economy and reducing the use of virgin raw materials [2, 3].

The incorporation of recycled rubber in concretes and mortars has been shown to improve energy absorption, ductility, and impact resistance, in addition to reducing the density of the material, which is advantageous for structural elements where self-weight is critical [4, 5]. However, their addition can also decrease compressive strength and elastic modulus, effects that can be mitigated by surface treatments or combinations with reinforcing fibers [6, 7]. In parallel, metallic and textile fibers recovered from NFU have shown promising results as reinforcement in cementitious composites and geosynthetics, improving tensile strength, crack control, and durability under severe conditions [8]. This approach is especially relevant in the development of reinforced geomembranes, where the integration of fibers can optimize mechanical and functional properties, broadening their field of application [9].

In the context of lightweight slabs, where the reduction of self-weight and the optimization of structural behavior are priorities, the application of geomembranes with recycled rubber fibers presents a double benefit: structural lightening and the use of waste with added value. Despite the advances in the use of recycled rubber in construction, the literature lacks studies that specifically address its integration in geomembranes for lightened slabs, which justifies the relevance and innovation of the present research.

Besides, it has been proven that using glass reinforcement in concrete improves the compression resistance, reaching 70 MPa, and the flexion resistance, 7.94 MPa, at 28 days. To achieve this, the size and length of the glass fibers must be precisely controlled to maximize their effects [10].

The use of the tire dust particles, despite contributing a flexible microstructure, helps the durability in the face of fatigue and best performance in the face of acoustic and thermal capacity [11, 12]. Besides, it is of vital importance to reduce the influence of the external agents in the mechanical behavior of the structural elements, as it is not possible to manipulate the external conditions for the material to material for guarantee the duration of the foreseeable useful life and advantageous contributions during the time in service.

2. Literature Review

Based on recent investigations related to improving the mechanical properties of concrete, as shown in Table 1.

Table 1. Recent literatures

[13]	Concrete structures were reinforced using recycled plastic fibres.	The results showed that improving the compressive and flexural strengths, reducing shrinkage and cracking, was achieved using a dose of 1% of the cement mass.
[14]	Synthetic polypropylene fibres with diameters of 1 mm and lengths ranging from 30 to 60 mm were used.	Using a dosage of 0.5%, improvements in tensile and compressive strength of 14.2% and 15.5%, respectively, were obtained.
[15]	This investigation replaces the aggregate with rubber at percentages of 10%, 20%, and 30%.	It was found that the compressive strength of concrete containing added rubber decreased more than that of conventional concrete. This caused internal residual stresses due to hydrostatic pressure.
[16]	The performance of the concrete was improved using a modified synthetic propylene fibre.	Although improvements were achieved in terms of flexural strength, ductility, and energy absorption, resistance to freeze-thaw cycles was compromised.
[17]	Rubber was used as a surface treatment, replacing some of the aggregates at proportions of 5%, 10% and 15% by weight.	The findings of this partial substitution experiment show that the mechanical properties of the concrete were negatively impacted when the substitution was less than 5%.
[18]	Plain concrete with C30, C40, and C50 strength ratings was made using recycled rubber and spiral steel fibre.	Initially, the results showed an improvement in mechanical strength. However, as the amount of spiral steel fibre increased, the strength decreased. This led to the conclusion that the toughness of the concrete is best achieved with an appropriate dose of rubber particles.
[19]	Reinforced concrete is used in combination with rubber and polymer fibers to enhance crack resistance.	The integration of this compound shows an increase in the Tensile strength. Compression and flexion with values of 38%, 29% and 66%, respectively; However, it poses the challenge of optimising the number of iterations in the rubber–polymer system, because it counts a big utility potential for the sustainable infrastructure.
[20]	The experimental material, metakaolin, was utilised in proportions of 10% and 20% as concrete reinforcement, specifically in the form of ring fibres and strip fibres, respectively.	The evaluation process entailed a comparison of the influence on the shape of the disposable material, wherein the strip fibres exhibited a greater flexural toughness of approximately 24% in comparison to the annular fibres. Furthermore, the substance exhibited a cracking and ion penetration reduction effect.
[21]	The utilisation of crushed glass fibres and plastic waste as reinforcing materials has been demonstrated to enhance the performance of the concrete, particularly concerning its flexural strength.	An optimal combination was identified, with proportions of 15% fiberglass and 10% plastic waste, which increased compressive and flexural strength at each stage of curing. This helps to mitigate waste materials.
[22]	Plastic and glass waste were used as a partial substitute for aggregates in C25 concrete. A series of tests was conducted to assess various	The substitution of arid in the concrete around 10% produces an increase in the compression with values of 12.55% and 6.44% at 7 and 28 days, respectively.

	parameters, including setting time, workability, and mechanical strength.	Replacing arid in a 20% production reduction in 14.35% and 0.73% to 7 and 28 days, respectively.
[23]	In the field of construction and building materials, granulated rubber obtained from tire waste has been used.	The influence of granulated rubber was found to have a mitigating effect on cracking in the concrete; however, the mechanical properties and adhesion were reduced in the self-compacting concrete. Nevertheless, empirical models have been proposed for its simulation.
[24]	In this study, sulfuric acid was used as an intermediate agent in the interaction between rubber particles and cement paste. Rubber dosages ranging from 0% to 30% were used to evaluate its effectiveness as a partial replacement for fine aggregate in the material composition.	An enhancement in the adhesion between the rubber particles and the cement paste was identified, resulting in an augmented deformation capacity in the concrete when compared to conventional concrete.
[25]	This study evaluated the exhaustive flexural behavior of rubberized concrete for beams, with dosages of 10% and 20%, due to the existence of uncertainties in various studies.	Beams incorporating 10% rubber exhibited a decline in moment capacity of up to 13% and a 10% reduction.
[26]	The physical and mechanical properties of concrete hardened with plastic macrofibres from packaging waste were studied as a necessary sustainable solution to the unusual increase in waste.	A reduction in compressive and flexural strength was observed in comparison to traditional concrete; however, a significant enhancement in the toughness of the concrete was evident. This toughened concrete can be regarded as a post-crack resistant material, thereby contributing to the promotion of the circular economy.
[27]	The present study evaluated the mechanical behaviour of concrete with the addition of Polyterephthalate Fibres (PET) for a concrete with a tensile strength of 20 Megapascals (MPa), utilising dosages ranging from 2 % to 8% by weight.	An increase in compressive strength of 23 MPa was achieved for a 2% PET dose, and for flexural strength of 3.19 MPa, 6% was used. However, it is recommended to use a dose no greater than 4% to meet the requirements of traditional con.

The research does not mention other properties of concrete, such as resistance to moisture or aggressive environments. Therefore, we would like to highlight the effect of this geomembrane on durability. In addition, during its useful life, the concrete slab is subject to bending, so it is necessary to evaluate its effect. Besides, it is mentioned [18] that properly recycling rubber can improve the strength of concrete.

3. Materials and Methods

3.1. Recycled Rubber Fiber

Fibers from end-of-life tires were used, whose properties are shown in Table 2, obtained by mechanical shredding and separated by particle size to achieve an average length of 20 ± 5 mm and an approximate diameter of 1 mm. Before incorporation, the fibers were washed with pressurized water to remove impurities and metallic particles, and dried at 60°C for 24 h, following previous conditioning recommendations to improve fiber-matrix adhesion [28].

The polymeric matrix required consisted of bicomponent epoxy resin (resin and hardener) with an initial viscosity of 850 mPa · s at 25 °C. The mixture was prepared in a 2:1 ratio by weight, according to the manufacturer's data sheet, and cured at 25 ± 2 °C for 48 h. This procedure was performed under the guidelines of ASTM D638 for polymeric composites [29].

Table 2. Tire component properties

Tire components (elastomer)	Tensile strength PSI	Elongation %	Density gr/cm3
Vulcanized natural rubber	2.5-3.5	750-850	0.93
SBR (styrene butadiene rubber)	0.2-3.5	400-600	0.94
Neoprene	3-4	800-900	1.25
Silicone	0.6-1.3	100-500	1.1-1.6

3.2. Lightened Slab

The design corresponds to a unidirectional structural system formed by T-type joists and lightening cassettes, designed according to the criteria of Standard E.060 “Reinforced Concrete” and the recommendations of ACI 211 for the design of mixtures. Three samples were made to obtain a better analysis of the good structural performance and adequate compatibility with the recycled rubber geomembrane.

The dimensions of the system were adjusted for the laboratory tests, taking a reduced modulus, but preserving the actual on-site configuration. Table 3 shows the main specifications of the concrete used, where it had a design strength f'c=210kg/cm², while the longitudinal reinforcement was made with Ø 1/2“ steel bars in the joists and temperature reinforcement in the compression layer with Ø 1/4” bars every 25 cm. The steel cover was 2 cm in the specimens.

Table 3. Main specifications of the one-way lightweight slab

Element	Technical Specification
Coffer dimensions	30 × 60 × 15 cm
Joist geometry	Core: 10 cm; Skid: 5 cm
Concrete	f'c = 210 kg/cm²
Reinforcing steel	Ø 1/2" bars in joists
Temperature steel	Ø 1/4" bars @ 25 cm
Coating	2 cm
Subfloor	1:3 mortar 2.5-4 cm, with slope

The sampling was non-probabilistic because there was influence and manipulation in selecting the sample. Select the sample of a one-way lightweight slab with a concrete f´c=210Kg/cm2, excluding other slabs of f´c=210Kg/cm2 or other types like the rigid or lightweight bidirectional, for example, in place of the aleatory selection with the intention of getting the results set out in the hypotheses. In other words, only the sample that is appropriate for this research was chosen with respect to its attributes, characteristics, predominance, and the representation of a general population.

3.3. Recycled Rubber Geomembrane

The geomembrane used is a waterproof geosynthetic made from High-Density Polyethylene (HDPE) and cylindrical fibers of recycled rubber from end-of-life tires. This composition combines the high impermeability and weather resistance of HDPE with the flexibility and resilience provided by rubber.

Table 4. Feature and technical details

Feature	Technical detail
Base polymer	High-Density Polyethylene (HDPE)
Recycled reinforcement	Cylindrical Recycled Rubber Fibers
Thickness	1.5 mm
Surface	Smooth
Elongation	Greater than 300%
Dimension	Rolls up to 15 m wide × 61 m long
Joint	Thermal Welding
Location on the slab	Between the compression layer and the subfloor

Its formulation includes additives such as carbon black (protection against UV radiation), oils and vulcanizing agents (to improve durability and internal cohesion), as well as stabilizers to resist thermal variations. The surface finish is smooth, facilitating the installation of the underlayment and avoiding the accumulation of humidity on the surface.

In the construction procedure, the geomembrane was laid 14 days after the slab was poured, once the initial curing was completed. It was laid on the clean and leveled surface, fixed by heat welding, and ensured a minimum overlap of 10 cm at each joint. Subsequently, the mortar subfloor (2.5-4 cm) was placed with a slope towards the drain, and finally, the final finish (ceramic floor or other covering) was applied. In addition, Figure 1 shows the samples with and without a membrane that were subsequently tested.

Fig. 1 Membrane and non-membrane samples used in the investigation

3.4. Permeability Test

A test was carried out to quantify the permeability obtained from Darcy's equation, in addition, a test was proposed to determine the permeability of the slabs, which includes the comparison of the water permeability of a conventional unidirectional lightened slab with a unidirectional lightened slab with a geomembrane based on HDPE recycled rubber of 1. 5mm thick based on the water penetration depth at 7, 35 and 91 days after being applied, this permeability was evaluated by the water absorption method by immersion, following ASTM D570 [29]. The specimens (50 × 50 × 5 mm) were immersed in distilled water at 23 °C for 24h, and the mass variation was determined with an analytical balance of ±0.001g accuracy.

To corroborate the permeability behavior of the structures with respect to water, the permeability coefficient obtained from Darcy's equation (equation 1) was used for both cases, also called the water permeability of concrete for structures.

$$K_W = \frac{V.l}{A.\Delta h_w.t} \quad (1)$$

Where: "V" is the volume of water passing through at time t in m^3, "l" is the thickness of the slab in meters, "A" is the area penetrated in m^2, "Δh_w" is the piezometric height in meters, "t" is the time in seconds, and. "K_w" is the coefficient of water permeability in m/s.

Once the permeability is determined, this value is taken as a reference [9] to determine if indeed the HDPE geomembrane reduces the permeability of the ribbed slabs in one direction, based on the following table on the permeability coefficient.

Table 5. Coefficient of water permeability in concrete

Determination	Units	Permeability		
		Low	Average	High
Water permeability coefficient	m/s	<10^-12	10^-12- 10^-10	>10^-10
Penetration depth	mm	<30	30- 60	>60

The concrete aggregate is formed by heterogeneous components, which can be conventional limestones; however, when immersed with rubber fibers, it leads to different interfaces during the setting time. In the fresh state, the appearance of air is expected to occur the appearance of air due to low adhesion with this material. As a consequence of this, a longer setting time increases the porosity of a material, making it much lighter.

3.5. Bending Test

The flexural behavior of the lightweight slabs was evaluated by the three-point flexural test method, following the guidelines of ASTM C78/C78M-18 [30]. The specimens consisted of representative segments of the slab with and without geomembrane, with dimensions adapted to the universal testing machine. The load was applied at a controlled rate of 0.05 MPa/s until failure, and the maximum load and displacement at the midpoint were recorded. From these data, the Modulus Of Rupture (MR) was calculated according to the equation established by the standard. This test made it possible to determine the influence of the geomembrane on the flexural bearing capacity, considering the transfer of stresses between the compression layer and the reinforcement. Figure 2 shows the test carried out on the sample with a membrane. The control groups were the standard samples to which they were subjected to the same conditions as the samples with geomembrane reinforcement.

To calculate the modulus of rupture manually, the location of the failure shall be taken into account. If the failure is located within the middle third of the span, the modulus of rupture shall be calculated using NTP-339.078, 2012, as shown in equation 2.

Fig. 2 Flexural test of the sample with a membrane

$$M_r = \frac{P.L}{B.H^2} \quad (2)$$

Where: "P" is the maximum ultimate load indicated by the testing machine expressed in N, "L" is the free span between supports expressed in mm, "b" is the average width of the beam at the failure section expressed in mm, 'H' is the average height of the beam at the failure section expressed in mm, and "M_r" is the modulus of rupture expressed in MPa.

3.6. Durability Test

Durability was evaluated by accelerated humidity-heat cycles, following ASTM D5229 [31], with the objective of simulating service conditions in humid environments or thermal variations. The specimens were subjected to 20 cycles, each consisting of 8 h of immersion in water at 40 ± 1 °C and 16 h of oven drying at 60 ± 1 °C. Before and after aging, the mass of the specimens was recorded, and mechanical properties were evaluated by compression and tensile tests to determine the relative loss of performance. In addition, possible visual changes such as discoloration, cracking, or swelling were observed.

3.7. Cost of Materials

The unit price analysis of each component corresponding to the lightened slab subheading was carried out based on the performance obtained in the field and the prices based on the cost journal corresponding to the geographical area and the market. In addition, the volume of concrete required for a waffle slab in 1 direction was 0.25 m², as well as the required formwork area, the weight in kg for the steel, and the quantity in units of roofing bricks with dimensions of 30x60x15cm.

Table 6. Cost of materials

Item	Description	Und.	Metered	Price $/.	Partial $/.
1	Concrete (fc) = 210 kg/cm² slabs	m^3	0.03	88.18	2.65
2	Standard formwork and stripping for slabs	m^2	0.2	16.50	3.30
3	Steel (fy) = 4200 kg/cm² slabs	kg	2.74	1.37	3.76
4	15x30x50 Cassette brick in place	und	1	2.13	2.13
5	1.5mm HDPE geomembrane, 1m²	m^2	0.25	4.77	1.19
Direct cost					**13.03**

4. Results

4.1. Cost Comparison

A cost analysis was carried out to compare the cost associated with the execution of lightened slabs with and without a geomembrane based on recycled rubber fibers. The results, shown in Figure 3, show that the average cost of the slab without geomembrane was $11.83/11.83, while with geomembrane it reached $/$13.03 for the same surface. This difference corresponds to an absolute increase of $/1.20, equivalent to 10% more than the conventional solution. Although the incorporation of the geomembrane implies a slight increase in the initial cost, this additional cost is justified by the significant improvements in impermeability and durability observed in the tests, which in the long term can translate into lower maintenance and repair costs.

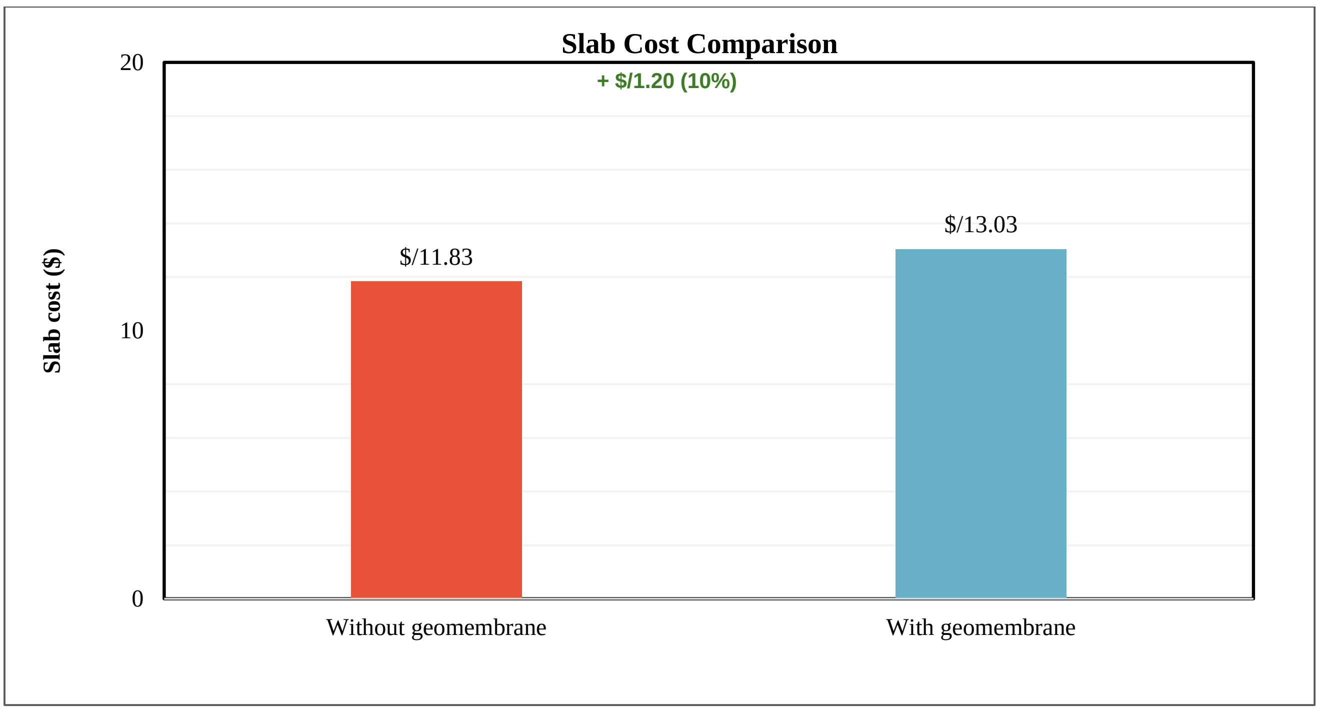
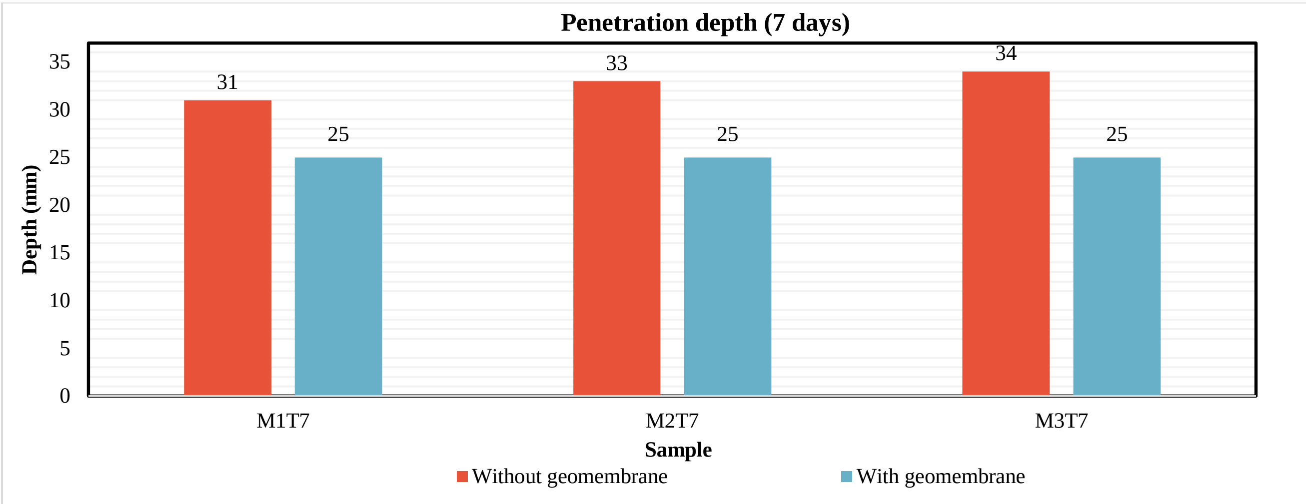


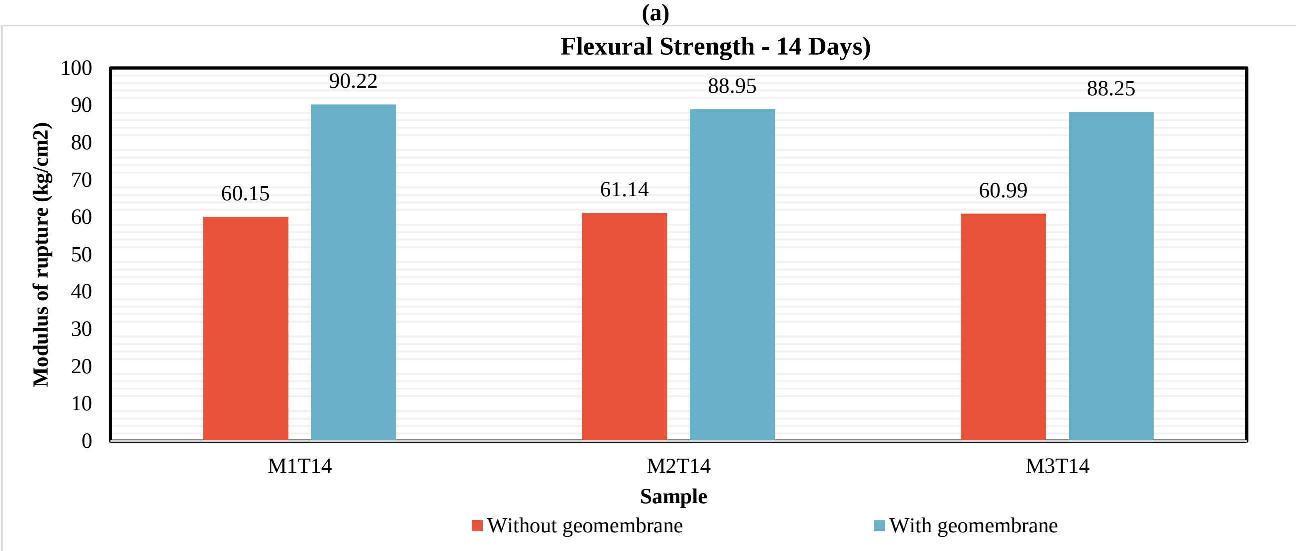
Fig. 3 Sample price comparison

4.2. Bending Test

En la Figure 4(a) shows the evolution of the modulus of rupture obtained in the flexural tests at 7, 14, and 28 days for the slabs with and without geomembrane. At all curing intervals, it is observed that the specimens with geomembrane reached higher values of flexural strength compared to those without geomembrane. At 7 days, the relative increase varies between 47% and 50%; Figure 4(b) shows that at 14 days, the improvement is between 45 % and 50%. The most outstanding behavior is evidenced at 28 days as shown in Figure 4(c), where the samples with geomembrane exceed, on average 47% the resistance of those without geomembrane, reaching values close to 100 kg/cm² compared to the standard samples with resistance of 66-67 kg/cm² in the reference samples. These results suggest that the incorporation of geomembrane not only contributes to a higher flexural load capacity from the early ages but also maintains a sustained growth in strength throughout the curing time, which supports its viability as a reinforcement for structural slabs.



(a)



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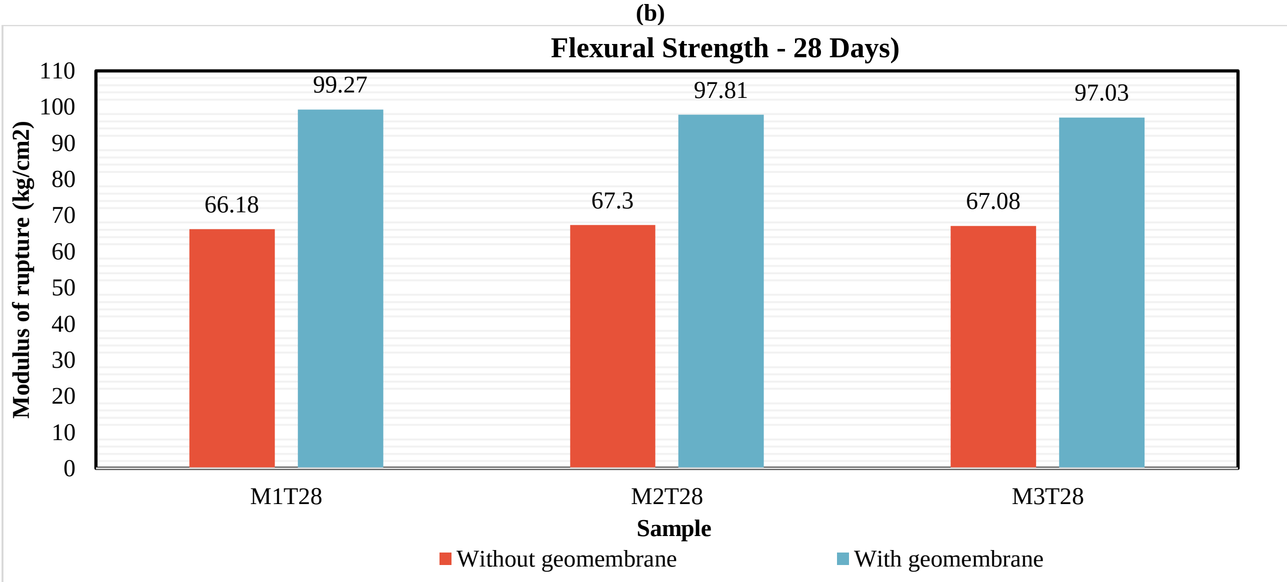


(c)

Fig. 4 (a) Modulus of rupture of samples at 7 Days, 9b) Modulus of rupture of samples at 14 Days, and (c) Modulus of rupture of samples at 28 Days.

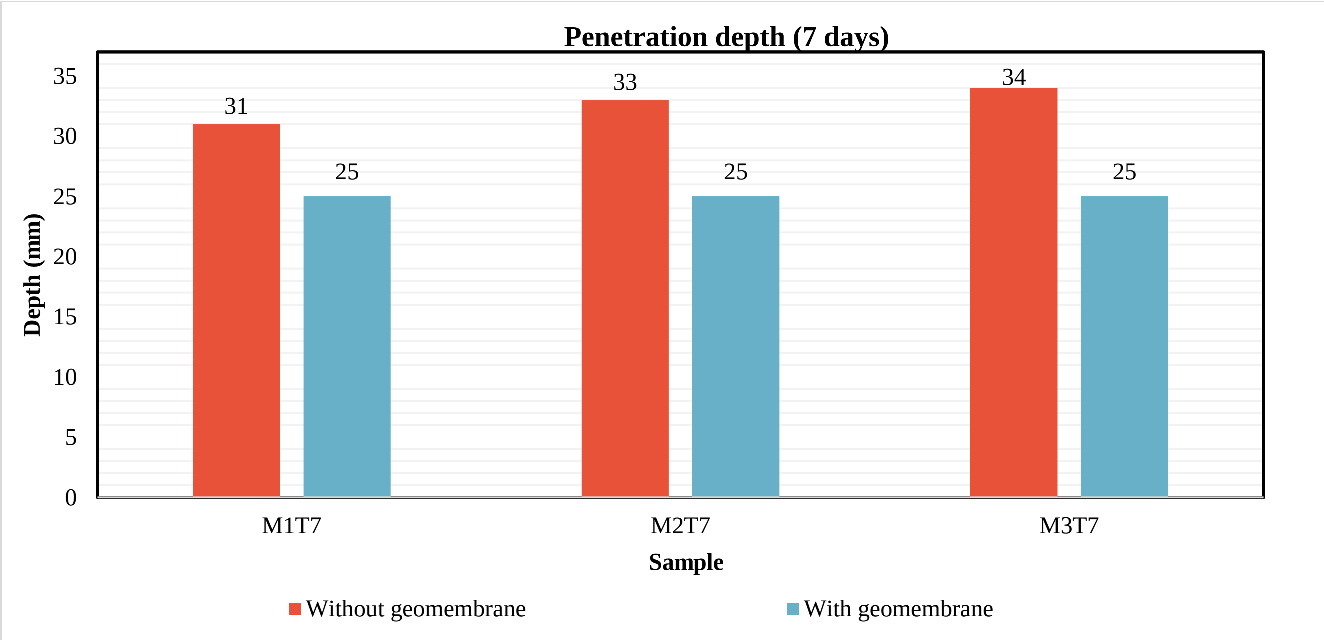
Table 7. ANOVA test on flexural strength

7 days						
Condition	∑ X2	GDL	∑ X2/GDL	F	Prob.	Fcrit
Between groups	630.05	1	630.05	1868.59	0.00	7.71
Within groups	1.35	4	0.34			
Total	631.40	5				
14 days						
Condition	∑ X2	GDL	∑ X2/GDL	F	Prob.	Fcrit
Between groups	1208.14	1	1208.14	1884.77	0.00	7.71
Within groups	2.56	4	0.64			
Total	1210.70	5				
28 days						
Condition	∑ X2	GDL	∑ X2/GDL	F	Prob.	Fcrit
Between groups	1458.57	1	1458.57	1769.18	0.00	7.71
Within groups	3.30	4	0.82			
Total	1461.87	5				

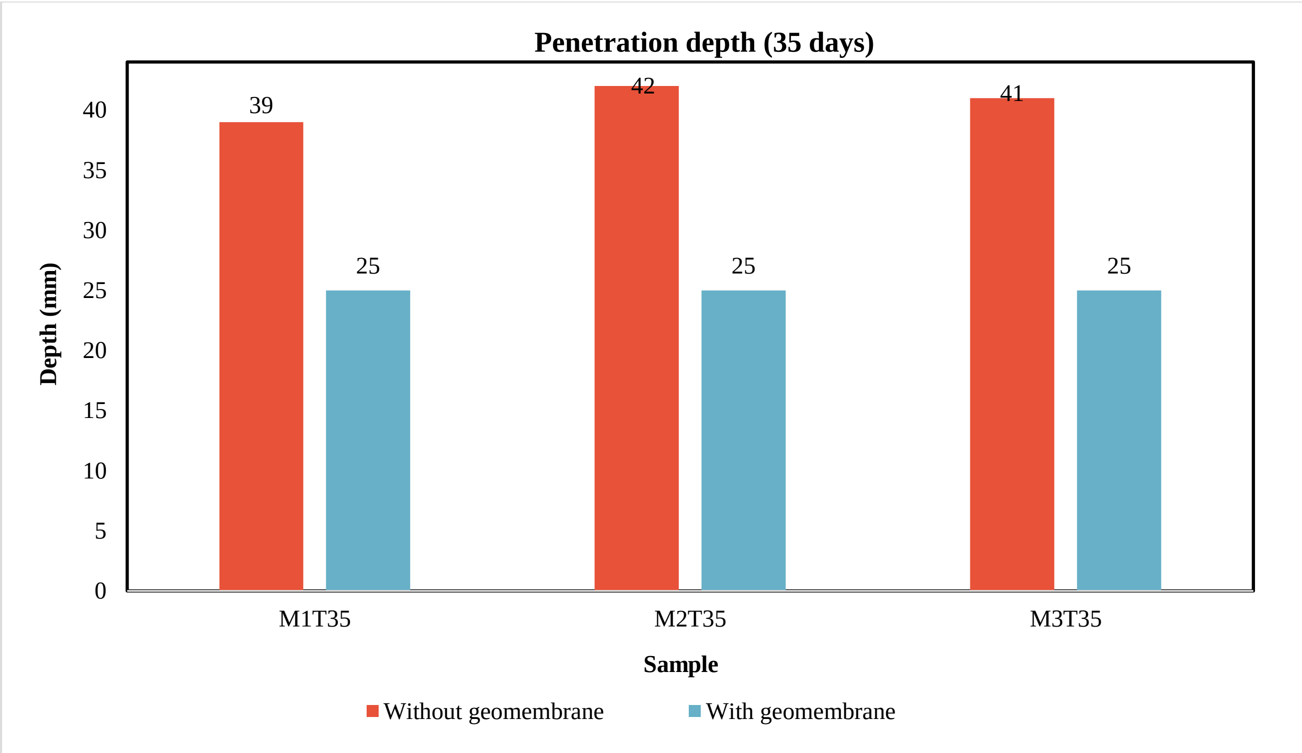
The treatment of the results using the test of ANOVA for verification of the variations of the flexion between every group of samples based on setting time (7, 14, and 31 days), taking the convention of the grade of significance of 0.05, the degree of significance obtained for each case is shown in Table 7.

4.3. Permeability Test

In Figure 5(a), corresponding to the 7-day test, the slabs without geomembrane recorded penetration depths of 31 mm (M1T7), 33 mm (M2T7), and 34 mm (M3T7), while the slabs with geomembrane maintained a constant value of 25 mm, achieving reductions of 19 to 24%. Figure 5(b), at 35 days, shows a similar trend, but with more marked differences: the slabs without geomembrane reached between 39 mm and 42 mm (M1T35, M2T35, and M3T35), compared to the uniform 25 mm of the slabs with geomembrane. Finally, Figure 5(c), which shows the penetration depth at 91 days, shows that the slabs without geomembrane reached values of 48, 50, and 49 mm, surpassing the slabs with geomembrane that obtained 25 mm in all the samples.



(a)



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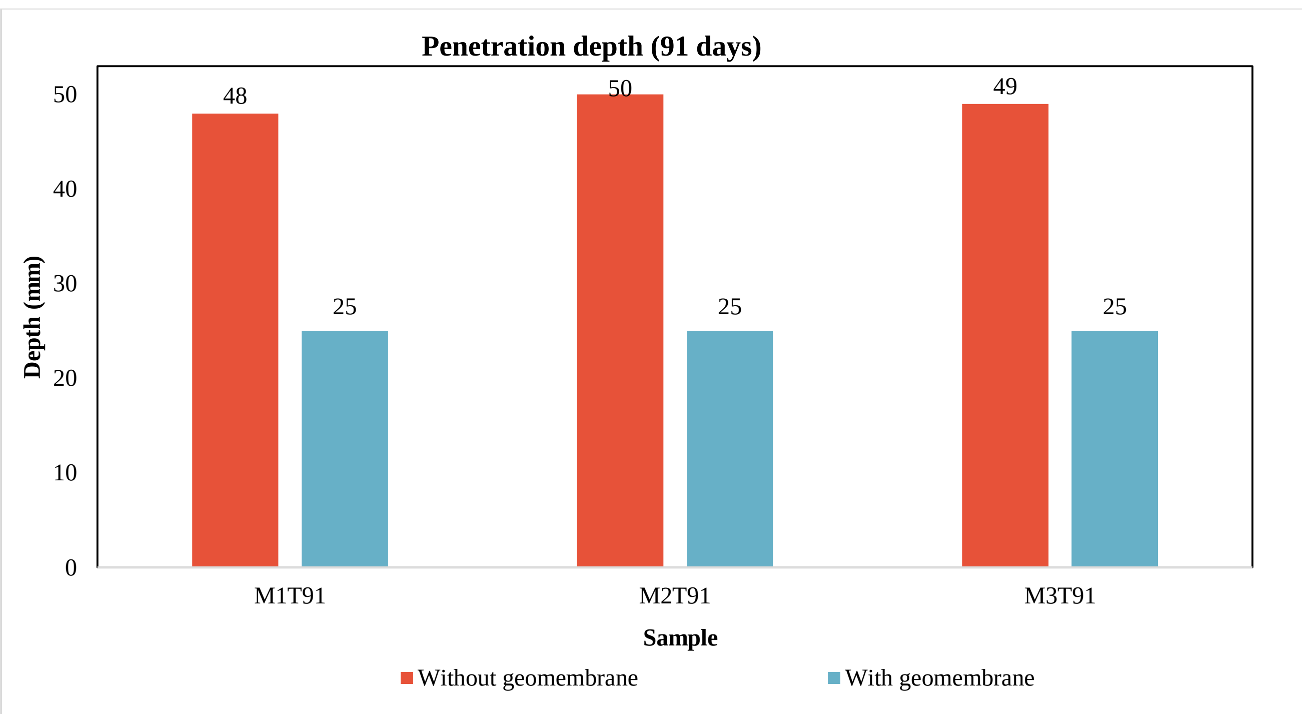

(c)

Fig. 5 (a) Penetration depth of samples at 7 days, (b) Penetration depth of samples at 35 days, and (c) Penetration depth of samples at 91 days.

Similar to the Flexural Strength test, the results were treated using the ANOVA test to verify the variations in the permeability of material between every sample group in function of the time of setting (7, 35, and 91 days), taking the significance level convention of 0.05, the degree of significance obtained for every case is shown in Table 8.

Table 8. ANOVA test in the permeability test

Condition	∑ X2	GDL	∑ X2/GDL	F	Prob.	Fcrit
7 days						
Condition	∑ X2	GDL	∑ X2/GDL	F	Prob.	Fcrit
Between groups	88.17	1	88.17	75.57	0.00	7.71
Within groups	4.67	4	1.17			
Total	92.83	5				
35 days						
Condition	∑ X2	GDL	∑ X2/GDL	F	Prob.	Fcrit
Between groups	368.17	1	368.17	315.57	0.00	7.71
Within groups	4.67	4	1.17			
Total	372.83	5				
91 days						
Condition	∑ X2	GDL	∑ X2/GDL	F	Prob.	Fcrit
Between groups	888.17	1	888.17	5329.00	0.00	7.71
Within groups	0.67	4	0.17			
Total	888.83	5				

Figure 6 compares the evolution of the permeability coefficient in lightened slabs with and without a geomembrane based on recycled rubber fibers, evaluated at 7, 35, and 91 days of curing. In the control group (without geomembrane), the values remain in the order of 10^{-11} m/s, with minimal variations over time, reflecting a limited capacity to resist the passage of water even at advanced ages. In contrast, slabs with geomembrane register coefficients between one and two orders of magnitude lower (10^{-12} to 10^{-13} m/s) and show a decreasing trend as the age of the concrete increases. This substantial reduction is evidence of the sweeping effect of the geomembrane, which acts in conjunction with the hydration process to close the internal capillary network, decreasing pore connectivity and, therefore, permeability. The results suggest that the inclusion of this material not only improves the initial impermeability but also optimizes long-term durability against continuous exposure to moisture, becoming a viable and sustainable alternative for structural elements exposed to aggressive conditions.

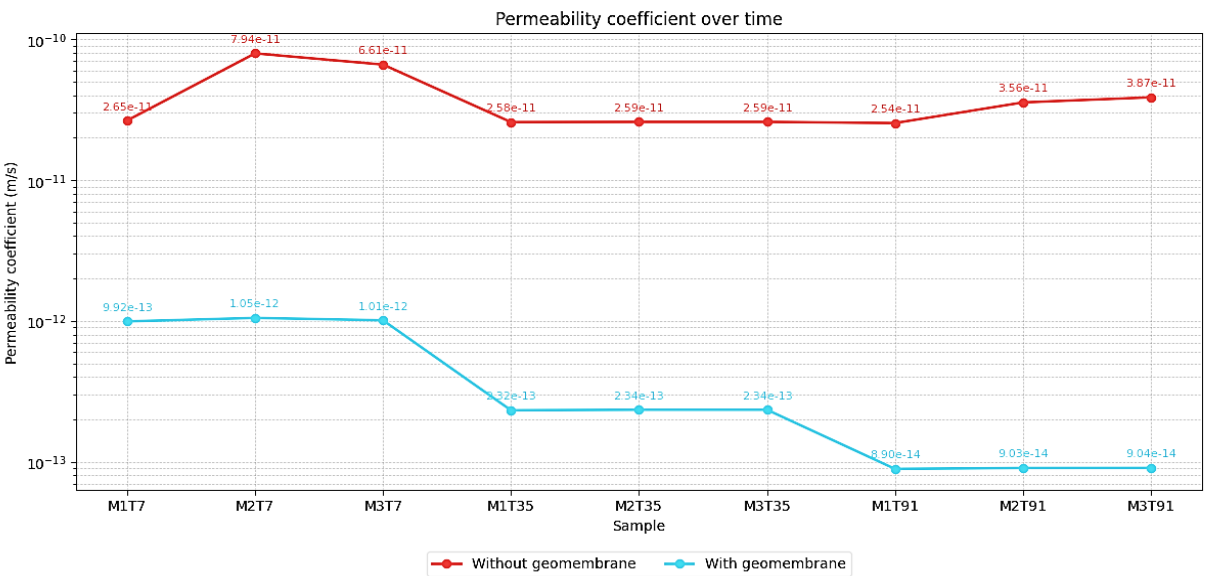

Fig. 6 Coefficient of permeability over time

5. Discussion

Regarding testing costs, our study reported a price of around $/$11.83 per sample of slab without geomembrane and $/$13.03 per sample of slab with geomembrane. These values can be compared with the reference prices of tests published in the document Lista de Precios 2024 - Laboratorio de Ensayo de Materiales de Construcción (LEMC), Universidad de Piura UDEP, where it is indicated that the compressive strength test of concrete specimens has a cost of $/$4.27 per unit [32]. This comparison shows that our costs per slab specimen are at a higher level, which may be justified by a higher complexity of the test or by the incorporation of additional elements such as the geomembrane; however, it confirms that we are within the medium-high range of Peruvian academic prices, reinforcing the economic feasibility of our experimental methodology.

For the evaluation of permeability, the methodology is based on the constant head method, applied to composite materials similar to those under study. In previous research, this method has been extensively compared to the head-drop method in permeable concrete; the results indicate that the constant head method offers advantages in terms of accuracy in samples with sustainable aggregates [33]. In addition, a systematic analysis highlights the adaptability of different permeability characterization methods in shale reservoirs [34]. Complementarily, studies on recycled rubber concrete indicate that the improvement in impermeability is also due to the optimization of the interfacial transition zone between particles and matrix [35].

Regarding the bending test, the three-point method was used to determine the modulus of rupture of the material, which allowed an effective evaluation of its behavior under transverse loads. In the specialized literature, three configurations of bending tests are recognized: four-point, biaxial, and three-point bending, each with its own advantages [36]. Furthermore, in layered composites, the modulus measured by bending is influenced by the surface layers, whereas tensile strength reflects the overall behavior [37]. Additionally, it has been shown that the three-point test is more sensitive to detect debonding failures in recycled fiber-reinforced materials [35].

An important consideration is the improvement of the flexion resistance of around of 52% in the transition of 14 and 28 days to comparison of the use of fiberglass as reinforcement [10] because this, when used with a volume dosage of 1%, the contribution increase to the 23%, On the other hand, the significance of the permeability test on the membrane cuts the capillarity that forms in the concrete despite the increase in porosity [38]. Likewise, a continuity of permeability is shown in the samples with geomembrane for different ages; beyond 91 days, the material is constantly susceptible to the changes in the ambient conditions, causing cracks that occur between 3-5 mm/year, making the material more permeable [39].

The main idea behind using rubber as an extra material in concrete is that it should be used as a flat configuration (geomembrane). However, various studies [17] show that when used in fibres or particles, it has a negative effect on how things behave mechanically; only some dosages make things better [16].

6. Conclusion

The implementation of geomembranes reinforced with recycled rubber fibers in lightweight slabs showed outstanding performance in terms of waterproofing and durability. The results showed that, after 35 days of curing, the average water penetration depth was reduced from 40.5 mm in the conventional system to a constant 25 mm in the slabs with geomembrane, which represents an improvement of 38%. Likewise, the permeability coefficient decreased from values in the order of 10^{-111} m/s to ranges between 10^{-12} and 10^{-13} m/s for 7 and 35 days, maintaining this difference even at 91 days, which helps to obtain a sweeping effect of the polymer-rubber composite, optimizing the resistance to moisture migration and favoring the useful life of the structural element in environments with the presence of precipitation.

Regarding the mechanical properties, the modulus of rupture showed an average increase of about 46.71% at 7 days, 47.19% at 14 days, and 46.64% at 28 days, reaching 100 $^{kg/cm2}$ when using the reinforced geomembrane, which indicates a higher bearing capacity in bending attributable to the interface between the compression layer and the membrane. In addition, this effect is complemented by the substantial improvement in waterproofing and the reduction of the risk of cracking due to external agents. On the economic side, the approximate 10% cost overrun (additional $/ 1.20 per 0.25 m^2) is considered reasonable in view of the potential to minimize maintenance interventions and prolong service life. Overall, the results position this solution as a technically and environmentally viable alternative for projects that demand high moisture performance and long-term durability.

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