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Original Article

Composite based on recycled polypropylene for use in agricultural installations[1]

Compósito à base de polipropileno reciclado para utilização em instalações agrícolas

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HIGHLIGHTS:
Recycled polypropylene can be effectively employed in rural installations that require safety, efficiency, and high quality.
Using waste polypropylene in a composite instead of cement brings higher physical properties than conventional concrete.
As the brick's voids are filled with polymer, the brick's strength becomes more reliant on the strength of the polymer itself.

ABSTRACT: This study aims to develop an eco-friendly, recyclable, and cost-effective composite material for use in storage sheds and machine workshops. The new composite consists of stone dust and gravel bricks bonded by recycled polypropylene through heat treatment. The main focus of this study is to determine the effects of varying polymer proportions on the resistance and permeability properties of the studied composite, intending to achieve optimal properties, i.e., high resistance and low permeability. To do this, the 2^2 factorial arrangement was employed, comprising four treatments along with three central points, each replicated three times. The data was statistically analyzed at a 95% confidence level from an adapted methodology. This involved tests of compression strength, 3-point bending strength, Los Angeles abrasion, and water absorption by immersion, in which three percentages of polymer content (PC) - 15, 25, and 35% - and aggregates (fine sand, medium sand, and coarse sand - FS, MS, and CS) were used to prepare the composite. The developed composite was deemed suitable for use in storage warehouses and machine workshops, as it presented physical and mechanical appropriate characteristics, i.e., a low water absorption rate and high resistance to compression and abrasion, in addition to being an environmentally friendly composite.

Key words: agricultural sheds, polymer, strength, waste

RESUMO: Este estudo tem como objetivo desenvolver um material compósito ecológico, reciclável e de baixo custo para uso em galpões de armazenamento e oficinas de máquinas. O novo compósito consiste em um bloco de pó de pedra e cascalho unidos por polipropileno reciclado através de tratamento térmico. O foco principal deste estudo é determinar os efeitos de variações nas proporções de polímeros nas propriedades de resistência e permeabilidade do compósito estudado, visando alcançar propriedades ótimas, ou seja, alta resistência e baixa permeabilidade. Para isso, utilizou-se o arranjo fatorial 2^2, composto por quatro tratamentos e três pontos centrais, cada um replicado três vezes. Os dados foram analisados estatisticamente com nível de confiança de 95% a partir de metodologia adaptada. Isso envolveu testes de resistência à compressão, resistência à flexão em 3 pontos, abrasão Los Angeles e absorção de água por imersão, nos quais três porcentagens de teor de polímero (PC) – 15, 25 e 35% – e agregados (areia fina, areia média, e areia grossa – FS, MS e CS) foram usadas para preparar o compósito. O compósito desenvolvido foi considerado adequado para utilização em armazéns e oficinas de máquinas, pois apresentou características físicas e mecânicas adequadas, ou seja, baixa taxa de absorção de água e alta resistência à compressão e abrasão, além de ser um compósito ecologicamente correto.

Palavras-chave: galpões agrícolas, polímero, resistência, resíduo

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Introduction

Implementing alternative materials in rural construction can bring numerous benefits. Firstly, such materials often offer increased affordability, allowing for cost-effective construction. Furthermore, the use of waste as an alternative material has been shown to reduce the impact caused by the high consumption of raw materials and the reduction of disposal areas. This second point is particularly important considering that 75% of all the plastic ever produced in the world has already become waste and an additional 100 million tons are predicted by 2030, if considerable measures are not implemented (WWF, 2019).

The production of Portland cement comes with high levels of energy expenditure and high emission rates of polluting materials (Andrew, 2019). Substitution of cement with polymeric materials can positively impact the production process of concrete, since plastics that were once useful are reused for its production. This reduces the consumption of clinker, which is the main source of pollutant emissions into the atmosphere (Ali et al., 2011). In this replacement, polymetric materials are used as the binding element in the matrix, eliminating the need for hydration or curing of the concrete. This leads to a reduction in the number of production steps, lowering costs and saving water, which itself is a finite natural resource. A common contributor to polymetric waster, polypropylene, has good chemical resistance, adequate mechanical properties, flexibility, and low cost (Javadi et al., 2018; Bensaada et al., 2021).

Due to high production requirements and the need for efficiency, the rural environment is becoming increasingly technologically advanced. Consequently, infrastructure has to keep up with this growth. Considering the need to reuse waste, this study proposes a brick of aggregates bonded by recycled polymers heat treated at low temperatures, resulting in a composite for rural construction suitable for storage sheds and machine workshops.

Material and Methods

The experiments were carried out at the Laboratory of Materials and Structures Testing (Laboratório de Ensaios de Materiais e Estruturas - LABEME) at the Universidade Federal da Paraíba - UFPB in João Pessoa city (7° 07' 54" S 34° 53' 03" W and 33 m altitude) - from February to May 2023.

The experimental program consisted of collecting and characterizing the material, understanding the interaction between the materials, the production of the composites, and the characterization of their properties. For this study, a 2^2 factorial arrangement was used, totaling four treatments plus three at the central point, with three replicates. The data was statistically analyzed using the Statistica 5.0 program, from StatSoft, at $p \leq 0.05$. Table 1 presents the matrix that describes the treatments in this study.

In the nomenclature, the first number refers to the percentage by mass of recycled polypropylene used to mix the composite, while the letters CS, FS, and MS refer to the types of aggregate used, corresponding to coarse sand, fine sand, and medium sand, respectively. For these compositions, stone dust and gravel were used in proportions of 1/3, 2/3 or 1/2, varying as desired. For example, for the coarse sand (CS) combination, 1/3 of stone dust aggregate and 2/3 of gravel aggregate was used.

Table 1. Matrix of encoded and real values of treatments, where: CS - Coarse sand; FS - Fine Sand; MS - Medium sand; and PC - Percentage of polymer content

Treatments	Nomenclature	X_1	X_2 Encoded values	Real values	
				PC (%)	Aggregates
1	15_CS	-1	-1	15	CS
2	35_CS	+1	-1	35	CS
3	15_FS	-1	+1	15	FS
4	35_FS	+1	+1	35	FS
5	25_MS_1	0	0	25	MS
6	25_MS_2	0	0	25	MS
7	25_MS_3	0	0	25	MS

The 25% polypropylene treatments will only be tested with medium sand, as they will be following the experimental plan presented here, representing the three analyzes at the central point.

The grain size distribution (GSD) curves are shown in Figure 1. The different sands were selected to explore the role of grain size on the strength and water absorption properties of the composites.

The collection of polypropylene residue was carried out at the company Plast Man in the city of Campina Grande, Paraíba state, Brazil, which uses the material in the "cut pasta" format (Figure 2A), resulting from the melting of plastic materials for packaging, lids, and labels. The stone dust aggregate (Figure 2B) was acquired in the trade from quarries, where it is sold or donated due to its high availability as it is a waste material. Similarly, gravel aggregate (Figure 2C) was purchased from local businesses and is found in rivers within the region.

The manufacturing process for each mixture will now be described. Firstly, a predetermined mass of dry sand is manually mixed with a predetermined mass of polypropylene, such that a desired polymer content of either 15, 25, or 35% is attained. Equipment was developed and built for better heating of the polymer, as well as improved molding, mixing, and compacting of the bricks (Miranda et al., 2024). A manual mold was used where the temperature causes the polypropylene to melt and bind to the aggregate particles, thus shaping the brick. The machinery consisted of a temperature controller, a temperature sensor, a controller activation key, and three ceramic-plate-type electrical resistances located at the bottom of the mold, and on the larger sides, as shown in Figures 3A, B and C.

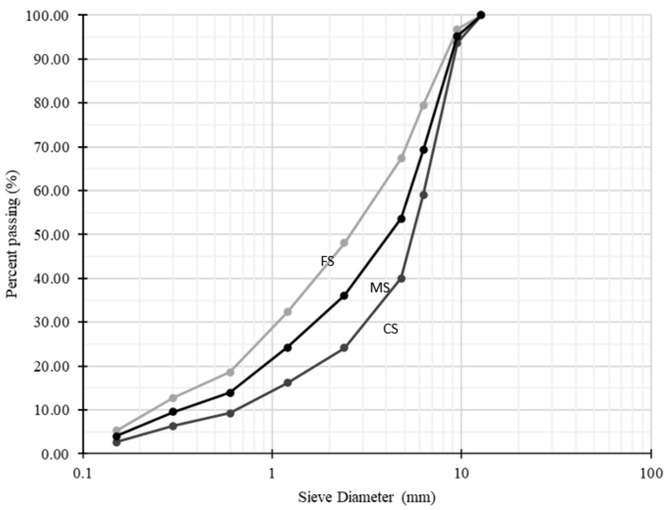

Figure 1. Grain size distribution curves of aggregates used

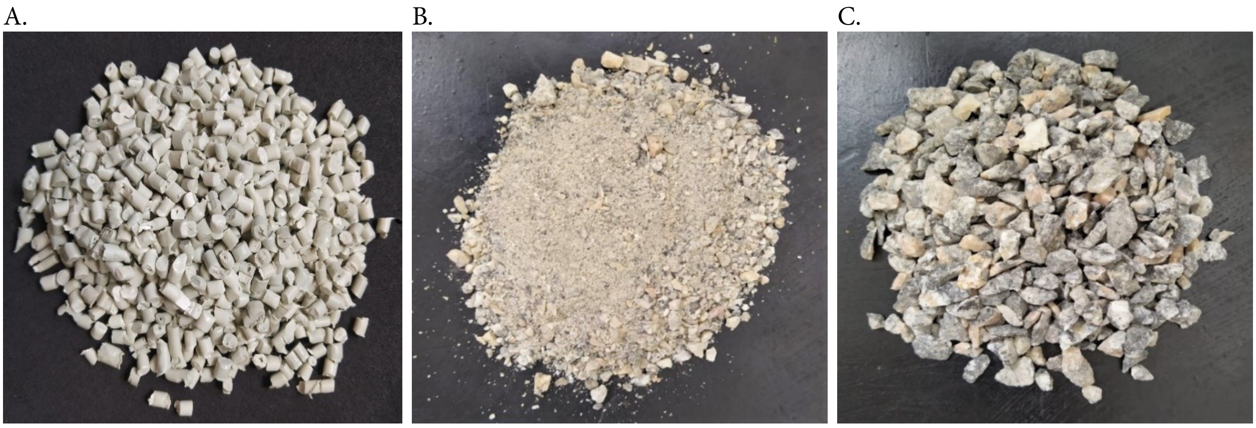

Figure 2. Waste polypropylene (A) and aggregates used: stone dust (B) and gravel (C)

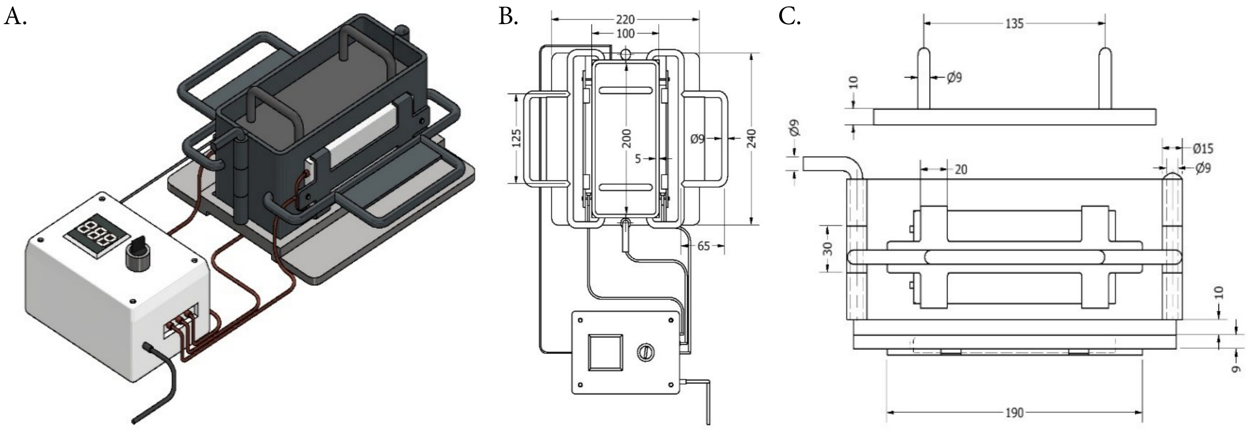

Figure 3. Custom-made apparatus scheme (A), upper view (B), and front view (C). The measurements of length and diameter are in mm

Initially, the equipment is turned on until the desired internal temperature for melting the polymer is reached (about 180 °C). After pouring the cold mixture into the hot mold, the equipment is covered and left for 15 min while the material heats up and begins to melt. After this step, the mixture inside the mold is manual mixed to homogenize the composite. With adequate agglutination of the particles and melting of the polypropylene inside the metallic mold, another 15 min are necessary for adequate accommodation of the mixture in the metallic mold. During this step, the press is driven through the lid, applying force and minimizing the volume of voids in the brick. After that, the equipment can be turned off and allowed to cool down so that the brick can harden and be removed from the mold without segregation, voids, surface marks, or brittleness. A brick is shown in Figure 4.

Following NBR 13279 (ABNT, 2005a), a 3-point bending test was performed, in which the bricks were cut to dimensions of 4 × 4 × 16 cm and tested at a rate of 50 N/s, analyzing the tension which causes it to fail in shear bending (Figure 5A). Finally, each brick is subjected to a compressive strength test, following NBR 13279 (ABNT, 2005a), in which each half of the brick previously broken under tension is broken in compression at 500 N/s (Figure 5B).

Infiltration tests were carried out following the guidelines of NBR 9778 (ABNT, 2005b). Firstly, the mass of each brick was measured. Secondly, each brick is immersed in filtered tap water at room temperature, as shown in Figure 6. Thirdly, each brick is removed from submersion after 24 hours and its mass is measured before it is resubmerged. The mass of each brick is also measured 48 and 72 hours into the submersion duration.

Figure 4. Polymer bonded brick

Following this, each brick is removed from the water bath and left to dry completely.

Lastly, the Los Angeles abrasion test aims to determine the potential resistance to degradation of concrete by impact and abrasion. The standard used for this test was the C1747M-13 (ASTM C1747M-13, 2013).

Three pre-weighed samples were inserted into the Los Angeles abrasion cylinder without loads for 500 revolutions. After the revolutions, the resulting material was sieved on a 25 mm sieve and the material retained on it is weighed. The lost mass is divided by the initial mass of the three specimens and multiplied by 100. The lost mass is interpreted as a percentage of the original mass. Figure 7 shows a test step.

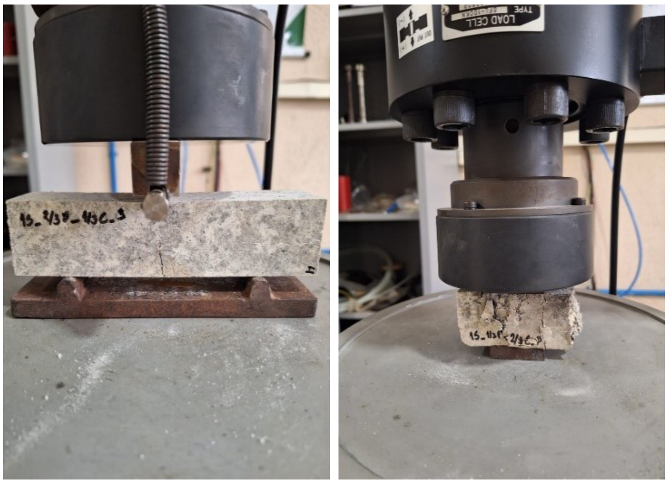

Figure 5. Bricks being tested at 3-point bending (A) and compression (B)

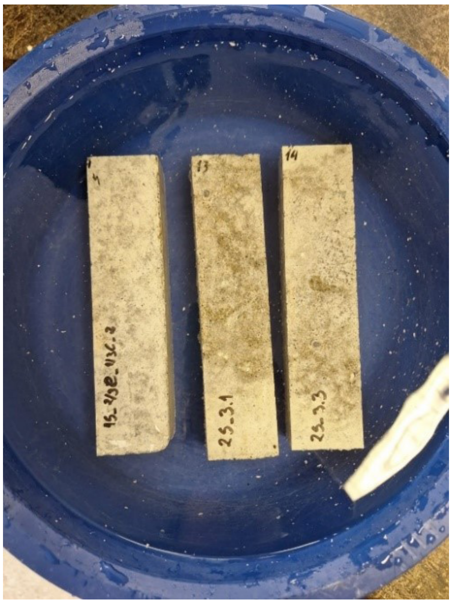

Figure 6. Immersion stage in the infiltration test

Figure 7. Execution of the Los Angeles abrasion test (A) and final weighing stage (B)

The data obtained were statistically evaluated using analysis of variance (ANOVA) to verify whether there are differences at the 5% level of significance between the evaluated composites. The level of significance observed was given through the p-value, as well as the F test and Tukey's test ($p \leq 0.05$).

Results and Discussion

The f_L values for the manufactured bricks are shown in Figure 8, where each data bar corresponds to a mean of three bricks. Note that the granulometric composition played a significant role in the results, showing that stone dust in greater quantity responds to better tensile behavior in bending.

The flexural toughness of the composites increases as the ratio of stone dust content increases. Adding recycled polypropylene can effectively improve the flexural tensile strength, reaching an average of 5.41 MPa. This value is consistent with the study by Gao et al. (2023), who varied the water/cement ratio, number of recycled aggregates, and steel fibers in the composition of the composite, showing that the flexural tensile strength had a range between 5.12 and 7.5 MPa.

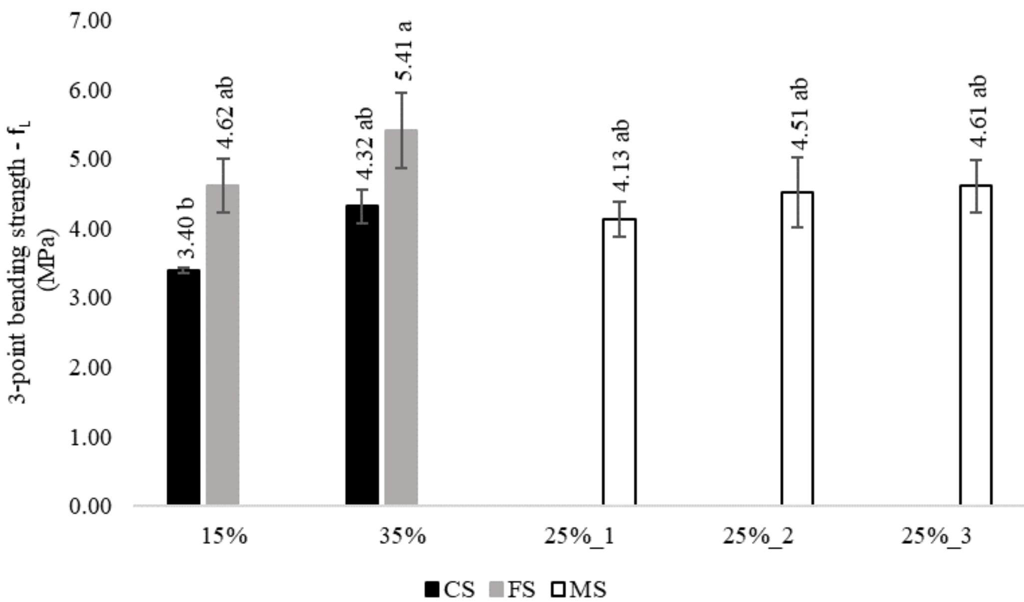

Figure 8. 3-point bending strength of the polymer bricks. On the x-axis, 15 and 35% are the polymer content by weight; 25%_1, 25%_2, and 25%_3 also represents the polymer content, but are the replications 1, 2, and 3 according to the statistical arrangement. The mean values are compared by Tukey's test at $p \leq 0.05$. The vertical error bar represents one standard deviation

Through analyzing the variables that influence the result of flexural tensile strength tests, Niaki et al. (2022) found that the type and content of polymer used, as well as the quantity and size of aggregates, are key factors controlling the flexural tensile strength of these composites. The flexural tensile strength measurements from this study ranged from 0.18 to 76.10 MPa, with an average of 10.62 MPa. It is therefore possible to state that the results of the flexural tensile strength tests performed in this study are within expectations, in accordance with Niaki et al. (2022).

The ANOVA results for the 3-point point bending strength tests are presented in Table 2. According to the F test applied, these results indicate that the polymer and fine content were statistically significant with a probability of 98.2 and 99.74%, respectively.

The compression strength results for the polymer concretes are presented in Figure 9. For concrete with more recycled polypropylene (35%), the compression strength is in the range of 19–20 MPa, while for concrete with less PC, the values are between 14 and 17 MPa. Thus, the compressive strength for polymer concrete is controlled by the polypropylene ratio. In the case of the polymer concrete with 15% PC, the strength decreases by up to 20% when more gravel is added relative to stone dust. However, bricks with a PC of 25 and 35% displayed similar compressive strengths of about 17–18 MPa.

The studies by Lee et al. (2015) and Romero et al. (2018) demonstrated that so-called polymeric concrete made with plastic, which completely replaces the cementitious binder, is already a reality. Their studies investigated the viability of molding polymeric concrete bricks using high temperatures to ensure full melting of the polymer in the mixture, as well as observing the regenerative ability of sand bound by polymers. These studies become very significant in the justification of this study, as it validates the hypothesis that a composite containing plastic melted together with aggregates can be a viable alternative for modern construction in several aspects. For example, those studies achieved a compressive strength of up to 12.9 MPa, which is surpassed by the current study where a compressive strength of approximately 20 MPa was achieved.

Figure 9 shows that the encapsulation of particles occurs more efficiently when greater quantities of stone powder are present in the mixture. This is explained by increased wettability between the components, which provides superior mechanical resistance as the stone powder particles are small. Therefore, the involvement and encapsulation of inorganic particles by polypropylene happens more effectively, as in Azeko et al. (2023) and Miranda et al. (2024). When talking about the addition of plastic to the mix, other studies, such as that carried out by Salaou et al. (2021), achieved compressive strength levels of 7 MPa when using 0.23% polypropylene fiber in the mixture, while for studies using polymer as the mixture binder, strengths of 8 MPa were achieved (Miranda et al., 2017).

The ANOVA results for compressive strength test are presented in Table 3. These results indicate that only the polymer content was statistically significant at a probability of 99.97%, according to the F_t test applied.

On the other hand, the influence of aggregates on the properties of composites must also be taken into account.

Table 2. Analysis of variance (ANOVA) results for 3-point bending strength, where: %PP - Polypropylene; %SD - Stone dust; SS - Squares sum; DF - Degrees of freedom; MS - Mean sum; Fc - Calculated Fisher test; Ft - Tabulated Fisher test; and p - Probability

	SS	DF	MS	F_c	F_t	p
%PP	2.2085	1	2.2085	7.3528	3.5915	0.0180
%SD	4.0256	1	4.0256	13.4026		0.0026
Residual	5.1061	17	0.3003			
Total	11.3403	19				

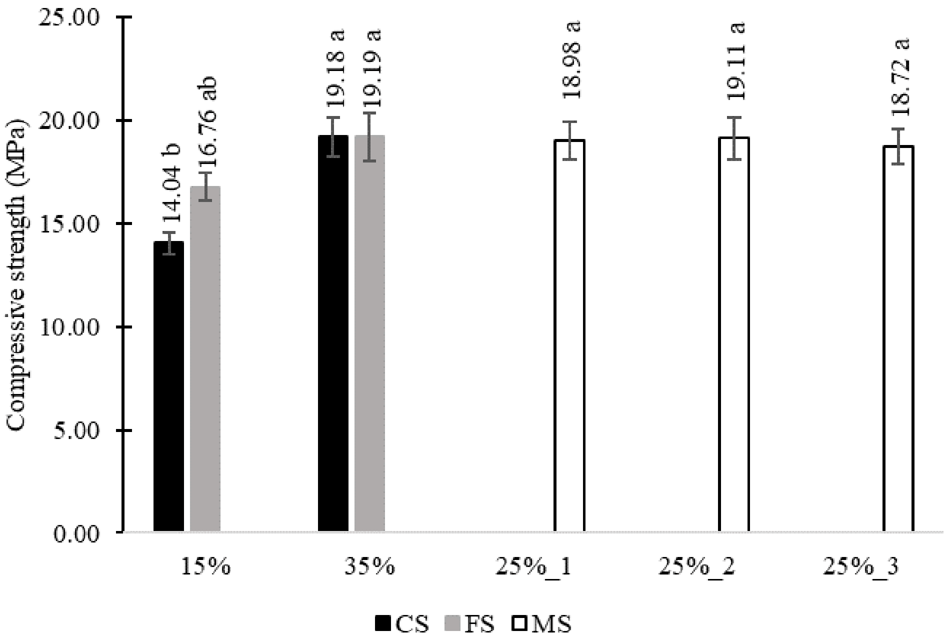

Figure 9. Compressive strength for polymer bricks. On the x-axis, 15 and 35% are the polymer content by weight; 25%_1, 25%_2 and 25%_3 also represents the polymer content, but are the replications 1, 2, and 3 according to statistical arrangement. The mean values are compared by Tukey's test at p ≤ 0.05. The vertical error bar represents one standard deviation

Table 3. Analysis of variance (ANOVA) results for compressive strength, where: %PP - Polypropylene; SS - Squares sum; DF - Degrees of freedom; MS - Mean sum; Fc - Calculated Fisher test; Ft - Tabulated Fisher test; and p - Probability

	SS	DF	MS	F_c	F_t	p
%PP	43.0339	1	43.0339	19.5199	4.3807	0.000295
Residual	41.8876	19	2.2046			
TOTAL	84.9216	20				

According to Jozef et al. (2020), porosity within the composite leads to a decrease in the physical properties of the castings. Therefore, using a greater amount of fine aggregates leads to a more ductile mixture, resulting in improved physical and mechanical properties of the composite, as observed in the results of the water absorbability tests. The evolution of the water absorbability is shown in Figure 10.

The following observations can be made: (i) the water absorbability (w) for all bricks is considerably lower than the maximum permitted by American and Brazilian standards for fired clay bricks, i.e., 20% (ASTM C-62, 2013). Indeed, typical values for fired clay bricks range between w = 14 and 16% (Monatshebe et al., 2019; Moujoud et al., 2023). While in the study by Horsakulthai (2021), permeability has substantially higher values, reaching up to 20% due to the partial replacement of cement by binder in recyclable concrete powder, demonstrating how much the studied composite may be ahead of other eco-friendly composites; (ii) when the brick has 35% of PC, bricks composed of FS absorb more water than analogous bricks composed of CS. A possible explanation is that in FS bricks, a larger amount of mineral surface area is left untouched by the polymer; therefore, water infiltrates the FS brick more easily along unbonded regions. However, for those with a PC of 15%, water absorption was much higher for the CS bricks; (iii) water absorption decreases substantially as the PC increases, as water infiltration is reduced significantly as the content of polymer increases; (iv) the rise in water absorbability with time is negligible. This means that the pervious paths contained in each brick, although small, are readily infiltrated by water, in accordance with Farooq & Banthia (2022).

Therefore, the incorporation of polypropylene waste in a composite can decrease its susceptibility to expansion, generating greater mechanical resistance and reducing water absorption, since the polymer and the aggregates are inert components and do not incorporate water into their structure. This enables the use of these composites in applications where infiltrated or percolated water are not desired (Akin & Polat, 2022).

The ANOVA results for the water absorption tests (72 hours) are presented in Table 4. These results indicate that the polymer content was statistically significant at a probability

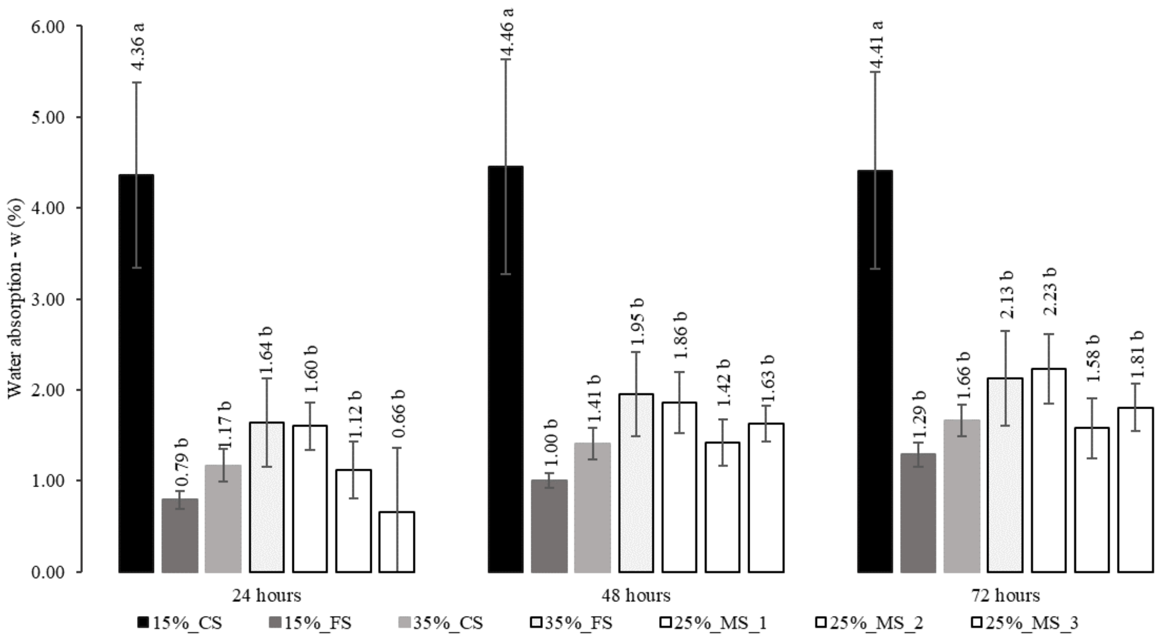

Figure 10. Water absorbability for polymer bricks, where: 15%_CS – coarse sand with 15% of polymer content by weight; 15%_FS - fine sand with 15% of polymer content by weight; 35%_CS - coarse sand with 35% of polymer content by weight; 35%_FS - fine sand with 35% of polymer content by weight; 25%_MS_1 - medium sand with 25% of polymer content by weight repetition 1; 25%_MS_2 - medium sand with 25% of polymer content by weight repetition 2; 25%_MS_3 - medium sand with 25% of polymer content by weight repetition 3. The means are compared by Tukey's test at $p \leq 0.05$. The vertical error bar represents one standard deviation

Table 4. Analysis of variance (ANOVA) results for water absorption, where: %PP - Polypropylene; %SD - Stone dust; SS - Squares sum; DF - Degrees of freedom; MS - Mean sum; Fc - Calculated Fisher test; Ft - Tabulated Fisher test; and p - Probability

	SS	DF	MS	F_c	F_t	p
%PP	2.7436	1	2.7436	6.3495		0.022034
%SD	5.3013	1	5.3013	12.2687	3.1967	0.002728
%PP by %SD	9.6500	1	9.6500	22.333		0.000195
Residual	7.3456	17	0.432			
TOTAL	25.0406	20				

of 97.79%, according to the F test applied. As well as the fine content and the interaction between the two variables, which were statistically significant at a probability of 99.72 and 99.98%, respectively.

The results obtained from the Los Angeles abrasion resistance tests, in which the bricks demonstrated a high resistance to wearing out, are shown in Figure 11. In addition, there was little variation in the bricks' resistance to abrasion with varying levels of aggregate and polypropylene content. This demonstrates that, regardless of the amount of fines or polymer, the composite was resistant to abrasion, losing little mass (a maximum of 6.44% mass loss and retaining up to 97.63% mass).

The ANOVA results for abrasion resistance test are presented in Table 5. These results indicate that only the polymer content was statistically significant at a probability of 97.84%, according to the F test applied.

This result highlights the applicability of this composite in rural construction, since it is resistant from an abrasive point of view, bringing advantages when working with animals that wear down the floor of their installations, making it more durable and economical by reducing the need for maintenance.

Studies of lightweight polymeric concretes are also being carried out, where they are investigating mechanical properties, as well as the quality, integrity, and durability of the composite (Arruda Filho et al., 2012). In these studies, several advantages in modern engineering are pointed out, where a material with a high strength/weight ratio is required (Heidarnezhad et al., 2020). For this polymeric composite, a 20 × 10 × 5 cm brick weighs around 1.4 kg, while it is known that ceramic building blocks weigh at least 2 kg, with concrete bricks weighing at least 5 kg. Considering that the results of both physical and mechanical resistance were satisfactorily superior relative the results of other bricks used in rural construction, one can see the advantage when discussing the resistance/weight ratio.

Lastly, the properties of a polymeric composite, both physical and mechanical, differ greatly depending on the preparation conditions. For a given type of polymeric brick, the properties depend on the percentage and type of polymer used, the granulometric distribution of the aggregates, the technique used for mixing, the temperatures, how long it takes to melt, the curing conditions, etc. Therefore, it is clear that recycled polypropylene can be applied in any situation that requires safety, efficiency, and quality in agricultural installations.

Conclusions

1. Precast polymer concrete bricks, with a polymer content of 35% by mass using fine sand, reveal the best compressive and flexural strengths, in addition to favorable absorption and abrasion results within the expectations of the literature.

2. The strength of the brick becomes increasingly dependent on the strength of the polymer as the voids are filled with polymer. Conversely, the soil's gradation does play a significant role in the strength of bricks.

3. Therefore, the composite developed here has full capacity for applications in storage sheds and machine workshops, as it presents mechanical and physical characteristics suitable for its use with reduced permeability and satisfactory compression and abrasion resistance, which is required when working with machinery or heavy supply. It is also an environmentally friendly composite.

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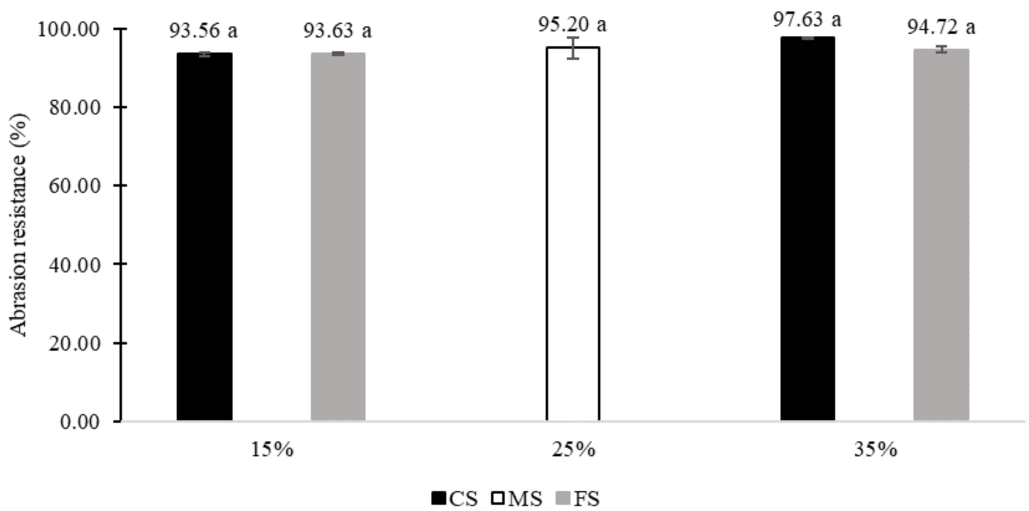

Figure 11. Abrasion resistance of polymeric bricks. On the x-axis, 15, 25, and 35% represent the polymer content by weight. The means are compared by Tukey's test at $p \leq 0.05$. The vertical error bar represents one standard deviation

Table 5. Analysis of variance (ANOVA) results for abrasion resistance

	SS	DF	MS	F_c	F_t	p
%PP	19.9692	1	19.9692	6.8018	4.6671	0.0216
Residual	38.1658	13	2.9358			
Total	58.135	14				

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