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# Sustainable production of mortar with partial replacement of the fine aggregate by powdered carton packs

## Produção sustentável de argamassa com substituição parcial do agregado miúdo por embalagens cartonadas trituradas

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**ABSTRACT**

Post-consumer carton packaging has the potential to be utilized as raw material in the manufacturing of new products. This research analyzed the performance of partially replacing fine aggregate with Powdered Carton Packaging Waste (PCPW) in mortar development through of collection, preparation, and milling of carton packaging, as well as the characterization of raw materials. Reference and experimental compositions were defined, followed by the execution of technological tests and analysis of the results. X-Ray Fluorescence (XRF) and Scanning Electron Microscopy (SEM) were used to characterize the by-product, PCPW, through chemical analysis. A reference ratio of 1:6 between the volume of cement and fine aggregate was adopted, while Experimental Compositions were determined with substitutions of 5%, 10%, and 15% of the aggregate volume with PCPW. These compositions were molded and tested using five cylindrical specimens per composition. The produced material exhibited consistency within normative parameters. The strengths of the three compositions with replacement fell within the range of 7.57 MPa, 6.52 MPa, and 6.07 MPa, respectively. Water Absorption by Immersion showed satisfactory results. SEM analysis of the fractured surfaces revealed the presence of empty spaces and microfissures in the samples with the highest percentages of PCPW.

**Keywords:** Waste recycling; Byproducts; Clean production.

**RESUMO**

Embalagens cartonadas pós-consumo têm potencial para serem utilizadas como matéria-prima na fabricação de novos produtos. Esta pesquisa analisou o desempenho da substituição parcial de agregado miúdo por Resíduos de Embalagens Cartonadas em Pó (RECP) no desenvolvimento de argamassas por meio da coleta, preparo e moagem de embalagens cartonadas, bem como a caracterização de matérias-primas. Foram definidas composições de referência e experimentais, seguidas da execução de testes tecnológicos e análise dos resultados. Técnicas de Fluorescência de Raios X (XRF) e Microscopia Eletrônica de Varredura (MEV) foram utilizadas para caracterizar o subproduto, RECP, por meio de análise química. Foi adotada uma relação de referência de 1:6 entre o volume de cimento e agregado miúdo no traço de referência, enquanto as Composições Experimentais foram determinadas com substituições de 5%, 10% e 15% do volume de agregado por RECP. Estas composições foram moldadas e testadas utilizando cinco corpos de prova cilíndricos por composição. O material produzido apresentou consistência dentro dos parâmetros normativos. As resistências das três composições com reposição ficaram na faixa de 7,57 MPa, 6,52 MPa e 6,07 MPa, respectivamente. A absorção de água por imersão apresentou resultados satisfatórios. A análise por MEV das superfícies fraturadas revelou a presença de espaços vazios e microfissuras nas amostras com maiores percentuais de RECP.

**Palavras-chave:** Reuso; Subprodutos; Produção limpa.

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## 1. INTRODUCTION

Since the change from nomadic life to community life, circa 10,000 BC, the production of new materials has been intensified. This process has been accelerated after the Industrial Revolution. With the increment of new technologies, a great diversity of new materials can be produced, among them, carton packs, which were consolidated when Europe experienced problems with milk conservation after the Second World War [1].

Composite packages are extremely versatile and useful in the conservation of dairy products, juices and processed vegetables; however, post-consumption, after fulfilling its purpose (to protect the food), it needs a final destination, so that its life cycle is closed. In general, carton packages have three materials in their composition: cellulose, polyethylene and aluminum, distributed with little variation, around 75%, 20% and 5%, respectively. Each component has a purpose. Paper adds strength; plastic repels water and provides thermal insulation; metal serves as a barrier to oxygen, microorganisms and light. Together, in the proper configuration, they form a package that gives the stored food a long life [2].

Due to its composition, this packaging has the potential to be reused in new materials [3]. Unlike its component materials, cellulose, plastic, and aluminum, the packaging does not convert to its original compositions in recycling, but may provide some components when processed [4]. For represents, a considerable proportion of the material, paper has its fibers recovered by pulping in water [5]. Polyethylene can be separated by lamination using solvents such as trichloroethylene, a trichloroethylene: water mixture, toluene, in an environmentally hazardous process [6]. Aluminum recovery via pyrolysis is feasible, despite the low percentage of metal in the composition [7]. For the consumer, packaging always has a negative effect generated by its post-use disposal and this perception is linked to the exorbitant consumption of processed foods [8]. The mixed composition of waste from carton packs makes it unfeasible to use it as a starting material in its own production cycle; it needs processing.

The use of solid waste in construction materials has grown lately [9]. The use of by-products generated in the sector itself is absorbed, as well as the waste from other productive sectors. Residues of various chemical compositions such as ceramics [10], demolition [11], plastics [12], paper [13], mollusk shells [14] high titanium heavy slag powder [15] copper mine tailing [16], graphene oxide/fiber [17], *kraft* papel fibers [18] have been successfully incorporated into the cement matrix. Studies of the incorporation of carton packs in concrete were carried out in order to understand the morphology of the microstructure after the application of radiation doses to the tetra pak lamellas arranged in the matrix [19]. Aiming to improve the mechanical behavior of polymeric mortar applied a radiation dose of 100 to 500 kGy to promote the interfacial coupling of tetra pack particles with the cement matrix [20]. Furthermore, studies carried out at high temperatures or exposure to fire investigated the behavior of cementitious composites with the addition of recyclable materials [21, 22].

The present research studied the behavior of masonry mortars with PCPW incorporation, verifying the technical viability of giving final destination and closure to the by-product cycle of PCPW as an integral part of a new material. The use of this food packaging waste in mortars for laying and covering masonry proposes a clean production route for this widely used cementitious material. The use of this by-product in a cementitious material to replace fine aggregate (river sand) proposes a solution to two problems. Our results showed that it is possible to close the cycle of packaging waste generated by the consumption of processed food products, while reducing the extraction of silicates from the environment.

## 2. MATERIAL AND METHODS

This research is divided into 3 steps: characterization, production and technological tests.

### 2.1. Fine aggregate characterization

In the first step, the fine aggregate was characterized by granulometric analysis. The sample placed on the set of sieves of the normal series 19.00 mm, 9.5 mm, 4.75 mm, 2.40 mm, 1.20 mm, 0.60 mm, 0.30 mm and 0.15 mm was stirred with mechanical assistance for 20 minutes (cf. Figure 1). The determination of the maximum characteristic diameter of the aggregate and the calculation of the fineness modulus was performed based on NBR NM 248 [23, 24].

#### 2.1.1. Powdered carton packaging waste characterization

The packaging used was collected from household waste. The collected material was cleaned with running water to eliminate impurities. Subsequently, the by-product was crushed with the aid of a conventional blender together with water, forming a pulp weighing approximately 2 kg. The pulp obtained from the crushing process was placed to dry at room temperature for 24 h, forming PCPW. The PCPW was characterized by X-Ray Fluorescence (XRF) and Scanning Electron Microscopy (SEM).

**Figure 1:** Sample of fine aggregate.

An XRF analysis was carried out at the Laboratory of the Center for Gas Technologies and Renewable Energy – CTGAS-ER, located in Natal – RN, using the X-ray fluorescence spectrometer – EDX-720 from Shimadzu, with a detection limit of Na (11) to U (92) (>0.001%), applying a semiquantitative method to determine the elements.

The microscopy test was carried out in the laboratory of chemistry of the Federal Institute of Alagoas – IFAL, Maceió, Brazil. A small sample of the fibrous material and the fracture surface of the cylindrical specimen was adhered to a carbon tape and metalized with a thin layer of gold. After sample preparation, the material was investigated using SEM model TESCAN VEGA3.

#### 2.1.2. Mortar production

The raw materials needed for the development of this research were: cement, fine aggregate and PCPW. The cement chosen was CPII–Z–32. The fine aggregate used was medium sand acquired from a local quarry in the municipality of Palmeira dos Índios, in the state of Alagoas, Brazil. The carton packs went through a crushing process (100 g pack/200 mL of water) to obtain a pulp; after drying, the material passed through a sieve with a 4.75 mm opening; and it was then incorporated into the mixture, partially replacing the fine aggregate.

Due to the different conventional mixes for laying mortar, the 1:6 ratio was taken as Reference Composition (RC) in the proportions of volume of cement and fine aggregate respectively, as it is economically and environmentally interesting, for it uses less cement in the mix [25, 26]. Thereafter, three Experimental Compositions (EC) were elaborated, which present, respectively, 5%, 10% and 15% of replacement of the volume of the fine aggregate by shredded carton packaging; they were named EC5, EC10 and EC15.

The compositions produced were submitted to compressive strength, water absorption and consistency index tests.

#### 2.1.3. Compressive strength test

Compression tests were performed based on the technical instructions of NBR 7215 [27]. In this test, cylindrical specimens with a diameter of 50 mm and a height of 100 mm were molded. The molding of the specimens was carried out immediately after preparing the mortar with the mold cleaned, assembled and greased with release agent. The mortar was arranged in four layers of approximately equal heights, with each layer receiving 30 uniform and homogeneously distributed blows with the normal socket.

Afterwards, the test specimens, still in the molds, were placed in the humid chamber of the Construction Materials Laboratory, where they remained for 24 h. After this period, the specimens were demolded, identified and immersed in the tank for the next 27 days (remainder of the curing period).

#### 2.1.4. Water absorption test

The absorption by capillarity test was performed according to recommendations and technical instructions contained in NBR 9779 [28], which simulates the behavior of mortars and hardened concrete in contact with water.

The specimens were submerged in water for 28 days for the curing time and then placed in the oven for a period of 24 h for drying. After this period, they were placed in a container with water so that only 5 mm of the specimen was submerged and in permanent contact with the water. Subsequently, the masses of the specimens were measured at intervals of 3 h, 6 h, 24 h, 48 h and 72 h, returning immediately to the container with water after weighing, as determined by NBR 9779 [28].

#### 2.1.5. Consistency index test

The consistency test was carried out in accordance with NBR 13276 [29] which determines the technical procedures for preparing the mixture and determining the consistency index of the mortar. The mortars were molded in a frusto-conical placed centrally on the flow table for consistency index. The conical mold was filled in three successive layers with approximately equal heights and 15, 10 and 5 strokes were applied in each of them, respectively.

After this process, the spreading diameter of the mortars was measured. They were measured from three diameters taken at pairs of points evenly distributed along the perimeter. The mortar consistency index corresponds to the average of the three measured diameters.

#### 2.1.6. Fracture surface investigation

Fracture surface microscopy was obtained for a better understanding of the material. The specimens were segmented with the aid of a circular saw with a diamond disk to achieve reduced and appropriate dimensions for the test. Then, the samples were subjected to the metallization process, through the deposition of a thin layer of gold.

## 3. RESULTS AND DISCUSSION

Table 1 presents the results obtained in the granulometric analysis of the fine aggregate.

The results, when compared with the granulometric distribution limits of fine aggregate laid down in NBR 7211 [30], shows that the material is within the usable zone. The analysis of Table 1 allowed the calculation of the Fineness Modulus of the sample (= 2.16), reaffirming that the material can be used as a fine aggregate according to the standards laid down in NBR NM 248 [23]. This NBR 7211 establishes a limit between 1.55 and 2.20. Fine aggregate in this same range of use was applied to manufacture mortar with the addition of expanded polystyrene and thermal insulating panels wastes in studies by PASSOS and CARASEK [31]. From the data in Table 1, the granulometric curve was obtained (cf. Figure 2).

**Table 1:** Fine aggregate granulometry test.

| MESH (mm) | RETAINED MASS (%) | ACCUMULATED MASS (%) | CROSSED MASS (%) |
|---|---|---|---|
| 19.00 | 0.00 | 0.00 | 100.00 |
| 9.50 | 0.00 | 0.00 | 100.00 |
| 4.75 | 0.00 | 0.00 | 100.00 |
| 2.36 | 1.87 | 1.87 | 98.13 |
| 1.18 | 9.42 | 11.29 | 88.71 |
| 0.60 | 27.53 | 38.82 | 61.18 |
| 0.30 | 32.02 | 70.84 | 29.16 |
| 0.15 | 21.91 | 92.75 | 7.25 |
| End | 7.25 | 100.00 | 0.00 |

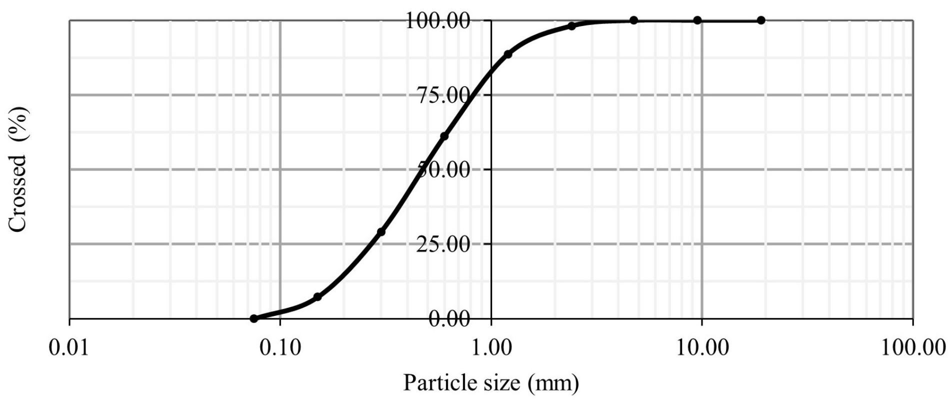


**Figure 2:** Fine aggregate granulometric curve.

According to NBR 6502 [24] – Soils and Rocks, the material used as fine aggregate is in the same size range as medium sand, since it was observed that about 60% of the grains had diameters varying from 0.20 mm to 0.60 mm.

The characterization of the composition of PCPW by X-Ray Fluorescence is shown in Table 2.

According to the chemical composition of PCPW, presented in Table 2, a great part of the sample of the PCPW consists of calcium, silicon and aluminium oxides. In similar studies, CaO, $SiO_2$ and $Al_2O_3$ compounds also appear as predominant in alternative materials incorporated in mortar, such as, for example, the bakelite sample, which presented more than 90% of CaO in the studies [32]. The high concentration of calcium oxide and silica can be considered favorable for the application of PCPW as a raw material for making mortar, as the presence of such minerals can contribute to the percentage of calcium coming from the cement in the mixture [14].

Scanning Electron Microscopy on samples of PCPW with 150× (**A**) and 458× (**B**) magnifications are shown in Figure 3.

Regarding the microstructure of the PCPW, the presence of random fibers is observed; they are intertwined, taking the form of a mesh. This formation may be responsible for preventing the cement matrix of the mortar from occupying spaces between the fibers, directly contributing to the increase of empty spaces inside the material, affecting its properties [33].

The SEM technique did not allow us to evaluate the average length of the PCPW, due to its great variability; however, it showed that the arrangement is fibrous (cf. Figure 4).

The fibrous aspect contributes to the variation in workability of material, as they help to increase the cohesion of the mortar through the anchoring mechanism, which consequently reduces the consistency index, requiring greater consumption of water in the mixture [34]. However, the production of mortars replaced with PCPW in the proposed percentages did not compromise its consistency, which was maintained in the margin used in other studies [25, 26, 31]. Table 3 presents the average values obtained in the compressive strength test.

From Table 3, it can be observed that replacing sand by PCPW in the mortar compromised its Compressive Strength (CS), causing a reduction of the average values obtained. In relative terms, if compared with the reference composition, EC5, EC10 and EC15 showed a reduction in CS of 31.31%, 40.82% and

**Table 2:** X-ray fluorescence of the PCPW.

| Oxides | CaO | $SiO_2$ | $Al_2O_3$ | $SO_3$ | $Fe_2O_3$ | $K_2O$ | $TiO_2$ | ZnO | MnO | SrO | CuO | $ZrO_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (%) | 49.79 | 22.76 | 21.05 | 2.21 | 2.12 | 0.81 | 0.76 | 0.28 | 0.07 | 0.07 | 0.06 | 0.02 |

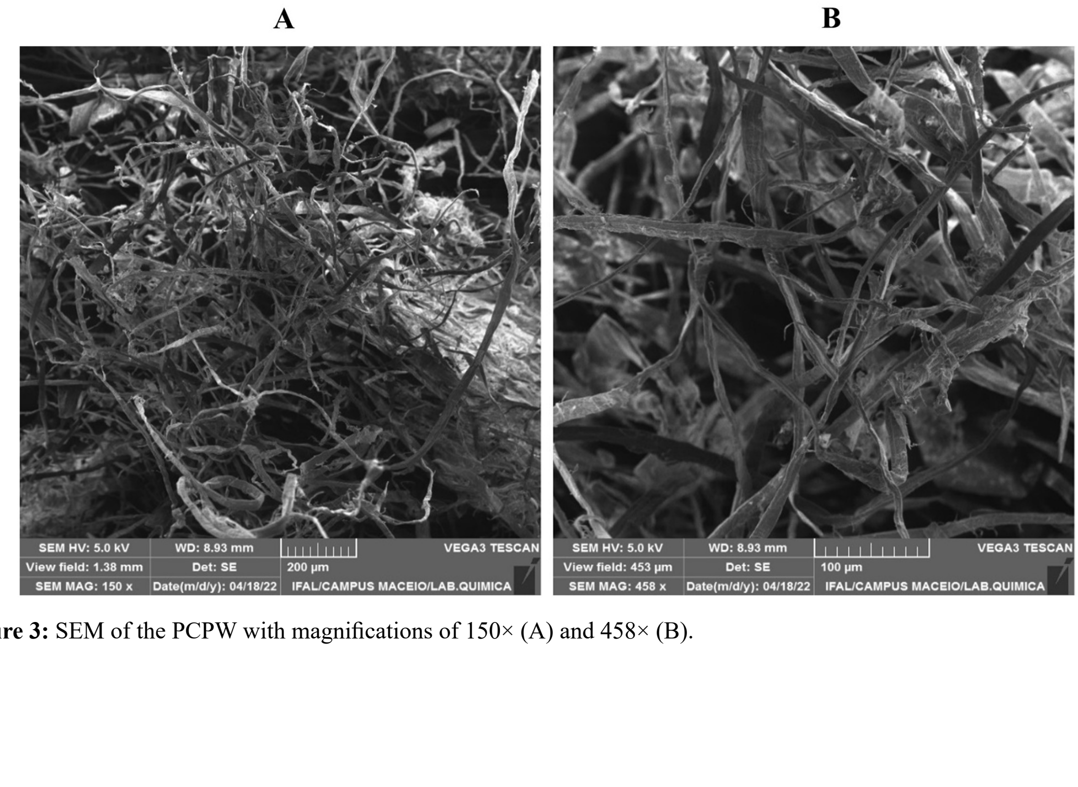


**Figure 3:** SEM of the PCPW with magnifications of 150× (A) and 458× (B).

44.95%, respectively. The replacement of conventional fine aggregate by PCPW caused the material to lose strength possibly due to the propagation of cracks. The configuration of the arrangement of fibers in the matrix – random and intertwined – prevents the entry of material, forming empty spaces. Thus, the adhesion between the cement matrix and the aggregates is impaired in compositions with replacement [35]. Immersion water absorption values for the mortar are shown in Table 4.

From Table 4, it can be verified that replacing sand by PCPW in the mortar contributed to the increase of water absorption in the samples and promoted an increase in average values. The increases were 12.87%, 41.45% and 33.90%, respectively, when compared to the reference composition. Similarly, also observed an increase in absorption values in mortars with higher replacement rates compared to the standard recipe [35].

Figure 5 shows SEM images, with magnification at a scale of 500 µm, of the fracture surfaces in the cylindrical specimen of RC (A), EC5 (B) and EC10 (C).

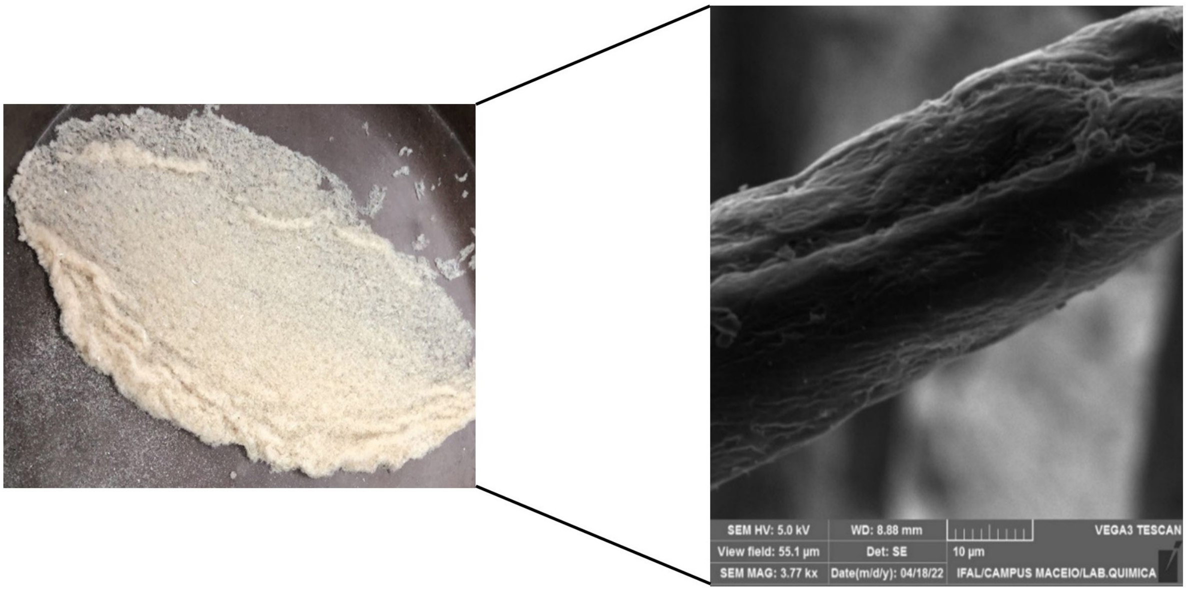


**Figure 4:** SEM of the PCPW with magnifications of 3770×.

**Table 3:** Average values of consistency indices.

| COMPOSITION | *CONSISTENCY INDEX (mm) |
|---|---|
| RC | 203.0 ± 1.5 |
| EC5 | 201.3 ± 1.2 |
| EC10 | 197.3 ± 0.9 |
| EC15 | 187.7 ± 1.7 |

*The Shapiro-Wilk test was performed for each composition at a significance level of 5%, taking into account three measurements (n = 3). All compositions had a p-value > 0.05, so the data are normally distributed.

**Table 4:** Average values of immersion water absorption.

| COMPOSITION | *IMMERSION WATER ABSORPTION (%) |
|---|---|
| RC | 4.29 ± 0.15 |
| CE5 | 4.84 ± 0.16 |
| CE10 | 6.07 ± 0.22 |
| CE15 | 5.74 ± 0.11 |

*The Shapiro-Wilk test was performed for each composition at a significance level of 5%, taking into account three measurements (n = 3). All compositions had a p-value > 0.05, so the data are normally distributed.

The presence of empty spaces inside the mortar can reduce the adhesion between the cement matrix and the aggregates, resulting in a decrease in mechanical resistance and increase in water absorption. Thus, it is reasonable to associate performance loss of the material with an incorporation of PCPW. Aiming to better understand the arrangement of the microstructure of the mixture with PCPW, a magnification of 231× was obtained for EC5 (cf. Figure 6).

Analyzing Figure 6, it was possible to verify the presence of fissures in the regions close to the empty spaces, corroborating with the thesis that the increase of empty spaces contributes to the propagation of cracks, and consequently reduces the mechanical strength of the samples. On the other hand, it is possible to observe the irregular arrangement of the fibers in the EC10 composite (cf. Figure 7).

A B C

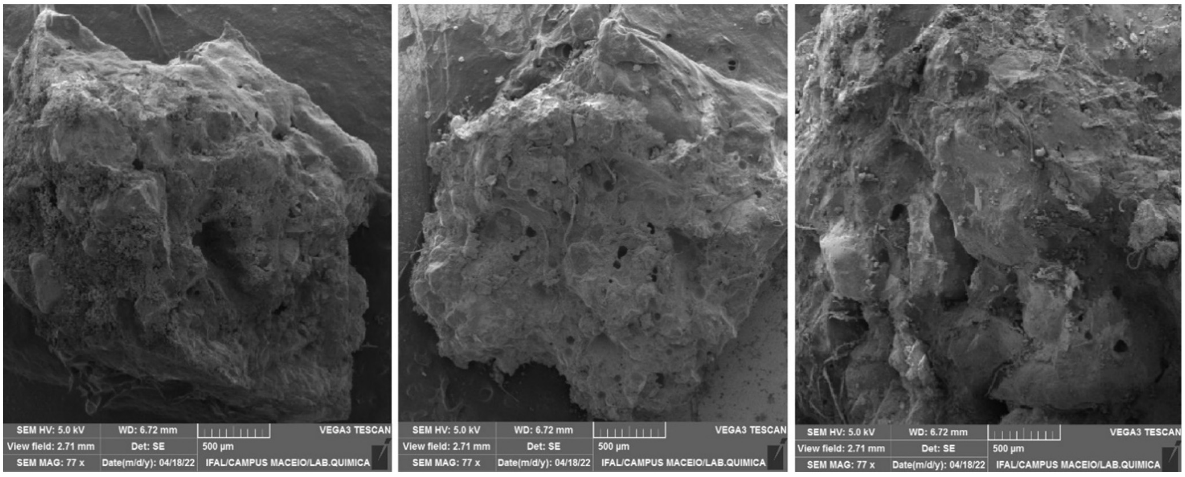

**Figure 5:** SEM of fracture surfaces in the cylindrical specimens of RC, EC5 and EC10.

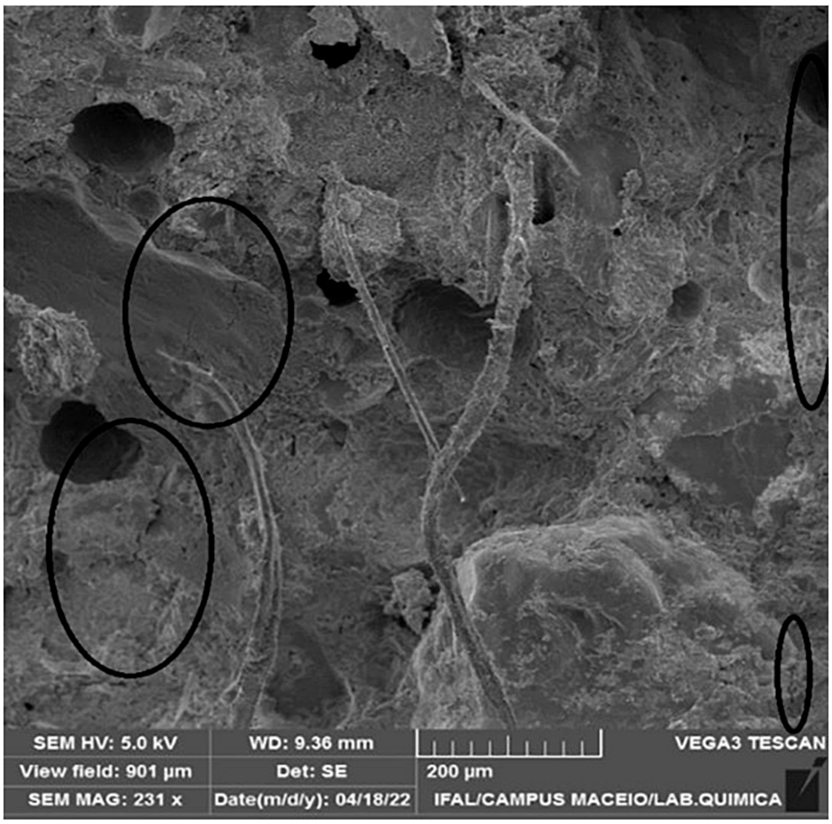


**Figure 6:** SEM image of the fractured surface of CE5 at 231×.

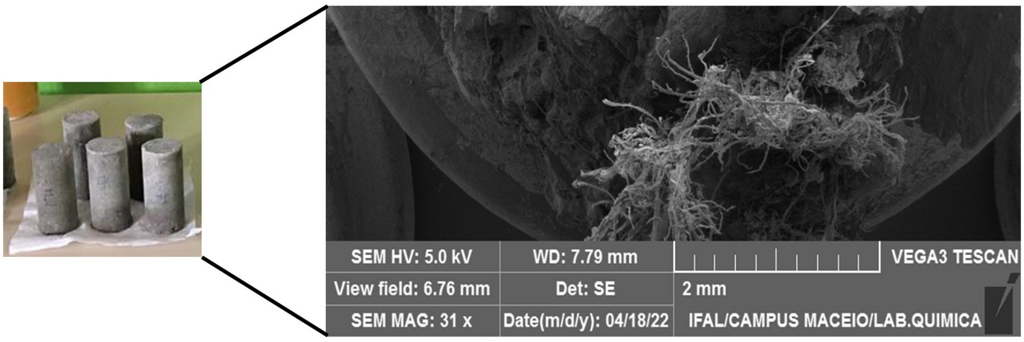


**Figure 7:** SEM image of the fractured surface of CE10 at 31×.

It is noted that, at the microstructure level, the incorporation of PCPW creates points of disintegration between the matrix and the by-product as the percentage of incorporation increases. This behavior can be evaluated based on the nature of the byproduct, which has a high amount of polymers in its composition, which agglomerate in the matrix like webs that compromise adhesion at the interface between the components, forming weaker interaction points that break. However, the addition of fibers to the cementitious composite does not invalidate the use of the PCPW in mortars intended for laying and covering blocks. In accordance with studies already reported [31], the size and distribution of the fibrous material in the cement matrix is viable and proposes a reduction in impacts caused by inadequate disposal of post-use packaging. Studies can be carried out aiming at scale up of production.

The compositions adopted in laying and coating mortar are generally 1:5, 1:6 and 1:7, in the proportions of cement:sand components. This study adopted a composition of 1:6 and evaluated the partial replacement of sand with PCWP in 5%, 10% and 15%, which could reduce the impact, in relation to the reference trace (without replacement), by minimizing extraction of natural resources (sand) in the mixture. The water: cement ratio used was 0.75 in all compositions. The washing water from post-use packaging can be reused in the formulations. The implementation of compositions with 5% and 10% proved to be viable in the laboratory. Unfortunately, scaling to production scale depends on a significant amount of PCPW, which can only be achieved with an efficient waste collection and recycling process of post-use packaging. The challenges in developing of sustainable materials are enormous, because, despite the advances made in the development of new environmentally friendly materials, many countries are stuck in an unsustainable production and consumption logic. We need to create, reformulate and break paradigms.

## 4. CONCLUSION

The characterization of the fine aggregate showed a fineness modulus equal to 2.16 and a maximum dimension of 1.18 mm. X-ray fluorescence indicates that the residue has more than 90% of its composition made up of calcium oxide (49.79%), silica (22.76%) and alumina (21.05%), as well as significant amounts of carbon not detected by the technique. The presence of intertwined fibers with different lengths and diameters of the order of magnitude of 20 μm was observed in the SEM. With the incorporation of the PCPW, there was a decrease in consistency, an increase in water absorption and a loss of resistance to compression, but the average values meet the current normative standards. SEM of the fracture surface in the cylindrical specimens allowed the observation of an increase in the number of empty spaces in composites with higher substitution levels. It was also possible to verify fissures near the empty regions. This microscopic arrangement must be correlated with the macroscopic behavior of the material. The execution of this study proved relevant in the context of the development of composite materials of environmental interest, aimed at the civil construction sector, certifying the viability of producing mortar with the incorporation of waste from carton packs, contributing to the search for clean environmental technologies. Reuse prevents packaging from accumulating in dumps and landfills. It incorporates carbon into a durable cementitious matrix that is in great demand in the construction industry. Reduces the proportion of fine aggregate (river sand) in the mortar composition, causing less pressure on the extraction of natural resources that are associated with processes of loss of vegetation and habitat, erosion, compaction, sedimentation and contamination.

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