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Comparison of water absorption rates in roofing substrates treated with different surface coatings

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Abstract: Roofing systems are constructed with a variety of materials and require specific inclinations based on the roof's typology, shapes, and dimensions. However, these systems are vulnerable to various forms of degradation. In Brazil, there is a lack of common use of treatments to decrease water absorption and to improve the durability and performance of roofing systems. This research focused on determining the water absorption rates of clay, concrete, and fiber-cement roofing using two different types of treatments that aim to reduce water absorption. The methodology involved analyzing the cyclical wetting and drying of the coverings over a 12-day period. A simulation of rainfall was applied to the roofing systems for 45 minutes with and without the use of two different treatments: silane-siloxane and acrylic paint based on acrylic resin. The results showed that untreated roofing substrates absorbed a higher percentage of water than the treated coverings. Additionally, when analyzed with acrylic paint, the coverings demonstrated a lower water absorption rate when compared to those treated with silane-siloxane. It can be concluded that the application of water repellent or acrylic paint treatments to clay, concrete, and fiber-cement coverings can reduce their permeability and decrease the rate of water absorption. Furthermore, acrylic paint treatments appear to be a more effective option than water repellent or untreated roofs.

Keywords: Roofing materials. Water absorption. Treatment methods. Permeability. Durability.

1. Introduction

In Brazil, clay, concrete, and fiber-cement tiles are the most prevalent roofing materials for residential buildings (Costa, 2017). However, due to exposure to various weather elements such as water, sunlight, and

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moisture, the roof is susceptible to rapid deterioration (Araújo, 2021). Protective measures must be taken to mitigate the effects of external degradation.

A study conducted by Rangel et al. (2018) emphasizes that excessive water absorption by roofing substrates can increase the weight of the roof, compromising its structure and safety. In addition, water infiltration can impair thermal and acoustic insulation, impacting the comfort of occupants and increasing energy costs. Excessive humidity also creates a favorable environment for the growth of fungi, bacteria, and other microorganisms, harming both the occupants' health and the building's durability (Garcia, 2015). In regions with high rainfall, excessive water absorption can increase the risk of leaks and drips, harming the residents' quality of life (Reis et al., 2017). Given these issues, it is necessary to adopt measures to minimize water absorption by roofing substrates and ensure building protection. It is also essential to conduct comparative analyses to identify the most suitable surface treatments for each type of roofing substrate, considering factors such as effectiveness, cost-effectiveness, and durability.

A suitable roofing system should guarantee waterproofing, avoiding leaks and drips. To improve this characteristic, hydrophobic treatments and acrylic paint can be used, which reduce water absorption by the roofing substrate and, consequently, improve the system's performance. Hydrophobic treatments are chemical compounds that have the property of repelling water and thus prevent its penetration into a certain material. They are widely used to protect porous surfaces, such as concrete, bricks, and roofs, against damage caused by water infiltration, being an effective solution to prevent problems such as humidity, mold, and material deterioration over time (Silva, 2016). Acrylic latex paints are used in external environments due to their impermeability, durability, and higher water resistance.

According to Bezerra, Dantas, and Trindade (2010), the city of Porto Velho experiences abundant rainfall, with a pluviometric regime defined during a rainy period between October and April, with monthly precipitation ranging from 228.9 mm to 329.6 mm, and a dry period between June and September, with precipitation ranging from 38.7 mm to 107.7 mm. It can be observed that for most of the year, the pluviometric rates are high, resulting in elevated humidity levels. Therefore, it is necessary to take actions to minimize the effects of water absorption, especially in roofing substrates.

In order to evaluate the performance of two types of treatments for roofing substrates (hydrophobic and acrylic paint), in relation to water absorption over a predetermined period, this study aimed to compare the behavior of these treatments on different types of roofing substrates, such as clay, concrete, and fiber-cement. The specific objectives were:

- Characterize clay, concrete, and fiber-cement tiles regarding their geometrical properties;
- Analyze the visual appearance of clay, concrete, and fiber-cement tile surfaces when treated with two different treatments;
- Determine the water absorption rate in treated and untreated concrete, clay, and fiber-cement tiles over a period of up to 45 minutes for twelve days.

2. Theoretical Background

The roof is the component responsible for covering and protecting the interior area of a building. This element is composed of several components, which have the function of supporting and fixing the roofing substrate and, in addition, transmitting the roof's forces to the structural elements. Each type of material requires a specific roof structural system, which is exposed to any failures resulting from the substrate (COSTA, 2017).

The NBR 15575-1 standard (ABNT, 2021) serves as a benchmark for evaluating the performance and durability of roof substrates. It outlines general requirements for housing systems in terms of their behavior in use, regardless of the constituent materials and construction system used. Part 5 of the same standard, NBR 15575-5 (ABNT, 2021), specifies the requirements for roofing systems, addressing concepts that are generally not considered in specific prescriptive standards, such as the durability of systems and building maintenance, and user requirements. Furthermore, NBR 15575-5 (ABNT, 2021) describes the performance levels of watertight substrates, stating that they should meet the recommendations of no appearance of adherent droplets, moisture stains of up to 25% of the roof substrate area at the intermediate level, and no moisture stains at the superior level.

2.1 Action of water on buildings

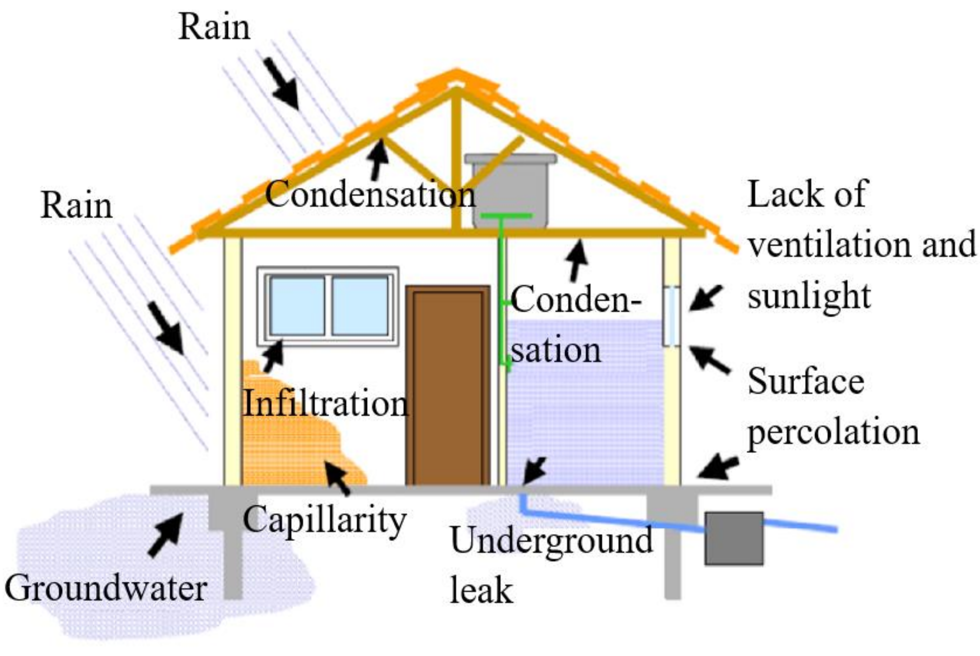
Heavy rainfall or extended periods without rain are common causes of hydrology-related engineering problems in the construction industry, according to Bezerra et al. (2010). The building's roof is the first point of contact with water, heat, and humidity, making regular maintenance critical to assessing the condition and effectiveness of the roof substrates, thereby preventing external factors from compromising the rest of the building.

Furthermore, according to the NBR 15575-5 (ABNT, 2021), water infiltration causing runoff or dripping is prohibited during the useful life of a roof system, whether caused by poor design, lack of maintenance, or insufficient waterproofing treatment.

According to Coutinho (2018), inadequate design and construction of a roof can result in several issues, such as roof substrate displacement, ruptures, unnecessary expenses from purchasing new materials, discomfort to users due to infiltration problems, and failure to meet the project's expected lifespan. Moisture can hasten the deterioration of roof substrates in buildings, resulting from exposure to the sun and rain, leading to problems such as staining, mold, mildew, algae, cracks, efflorescence, among others. Therefore, it is crucial to treat the roof systems, which are directly exposed to solar radiation, rain, humidity, and winds, to extend their lifespan (Souza, 2008).

According to Araújo and Souza (2022), the most common problems in constructions arise from water penetration in different parts of the building and can become severe if not addressed. As a consequence, moisture can appear and develop in various forms, such as: construction moisture, which develops through the construction stages; absorption and capillary moisture, which occurs by the absorption of water from the soil, which moves through capillarity to walls, floors, and structures; infiltration moisture, resulting from rainwater; condensation moisture, caused by air humidity and water vapor, depending on the time of year; and accidental moisture, caused by leaks in the installations (Figure 1).

Figure 1 – Water action on the external surfaces of a building.



Reference: Pozzobon (2007).

Water plays a crucial role in both the functionality of the roof and the performance of its materials. Proper identification of the roof's slope is essential to ensure a safe and thermally comfortable coverage. Incorrect installation with an inadequate slope leads to improper drainage of rainwater, which, coupled with wind action, can cause issues like infiltration (Junior, 2019). It is worth noting that kinetics refers to the water absorption capacity of porous materials, which depends on factors such as the quantity, structure, pore dimensions, and surface wettability. Larger pore dimensions lead to greater connectivity between pores, resulting in higher water absorption capacity. Wettability, on the other hand, is linked to the surface free energy, characterized by the contact angle formed between water and the solid. Higher wettability corresponds to reduced contact angles (Coelho, 2019).

According to ASTM C1167 (ASTM, 2022), clay roof tiles intended for use as roof covering must exhibit durability and appearance to ensure a weather-resistant surface. This standard covers three classes of clay roof tiles with varying degrees of weather resistance, where the maximum water absorption per unit of material ranges from 8 to 15%. As per NBR 15310 (ABNT, 2009), water absorption of roofing substrates is defined as the ratio of the mass of water absorbed by the specimen saturated in water to its dry mass.

2.2 Surface treatment on roofs

The NBR 9575 (ABNT, 2010), which deals with the selection and design of waterproofing, states that a hydrophobic product is intended to repel water by reducing the wetting angle of the pores of a specific substrate. It can be added to the material or applied onto it. Hydrophobic agents do not alter the surface of materials nor form films, which directly reduce the pore angles and result in a decrease in water absorption (Coelho, 2019).

The most commonly used hydrophobic agents in the construction industry for reducing water penetration are silicone-based, which have a low surface tension (less than 24 mN/m). The product reduces the pore angles of the material surface without forming a film and does not visibly modify the surface appearance. It reduces capillary forces and water penetration, resulting in less impact on vapor permeability and good adhesion to siliceous materials. The most widely sold hydrophobic agents in Brazil are silicone-based, including silanes, siloxanes, siliconates, and mixtures of silanes and siloxanes (Maranhão and Loh, 2010).

In addition, there are silicone-based and water-based hydrophobic agents available in various types and specifications. According to Freire (2018), silicone is a chemically inert substance that is resistant to decomposition by heat, water, or oxidizing agents. Its covalent bonds are apolar, making it suitable for use as a hydrophobic agent.

Silicones are commonly used as hydrophobic materials due to their inorganic component's stability against degradation agents, as explained by Maranhão and Loh (2010). Silanes are the simplest form of silicones, while siloxanes have a shorter time to create hydrophobic surfaces. Siliconates are water-based and provide intermediate hydrophobicity. The mixture of silane and siloxane is suitable for granite, which has fewer and smaller pores, but may contain substances that are harmful to workers' health.

Coelho (2019) stated that a surface treated with a hydrophobic agent repels water, preventing it from remaining in the substrate. Additionally, any remaining water droplets evaporate more quickly due to their small angles, facilitating the evaporation process. The application of hydrophobic agents must adhere to the guidelines outlined in NBR 9575 (ABNT, 2010), which detail the basic criteria for applying products that make the material surface impermeable. The substrate that receives this treatment should be clean, dry, and preferably without fissures to ensure the product's effectiveness.

Acrylic paint is a synthetic, water-soluble, quick-drying paint that can be applied in thin or thick layers on both interior and exterior walls. Due to the presence of acrylic resins in its formulation, it offers a higher degree of impermeability, durability, and resistance compared to latex paints. Additionally, the resin in its formulation forms a transparent film on the applied surface, which is washable and recommended for porous materials to prevent premature deterioration and discoloration, reducing the penetration of dirt, grease, and fluids (Pereira and Siqueira, 2019).

According to Araújo (2021), acrylic paint is a product that is used to waterproof certain building materials. Solvent-based acrylic paint has a higher gloss and durability, while water-based versions are odorless and easier to apply. The finish of acrylic paint can be glossy or matte, and it can be colorless or colored. Once applied, it forms a film that facilitates the flow of water.

The application of acrylic paints should follow the NBR 9575 (ABNT, 2010), which specifies basic criteria for the application of products aimed at making the material surface waterproof. The standard requires detailed procedures from cleaning to product drying. The surface receiving this treatment must be clean and dry, preferably without cracks, to ensure the product's efficiency.

3. Materials and Methods

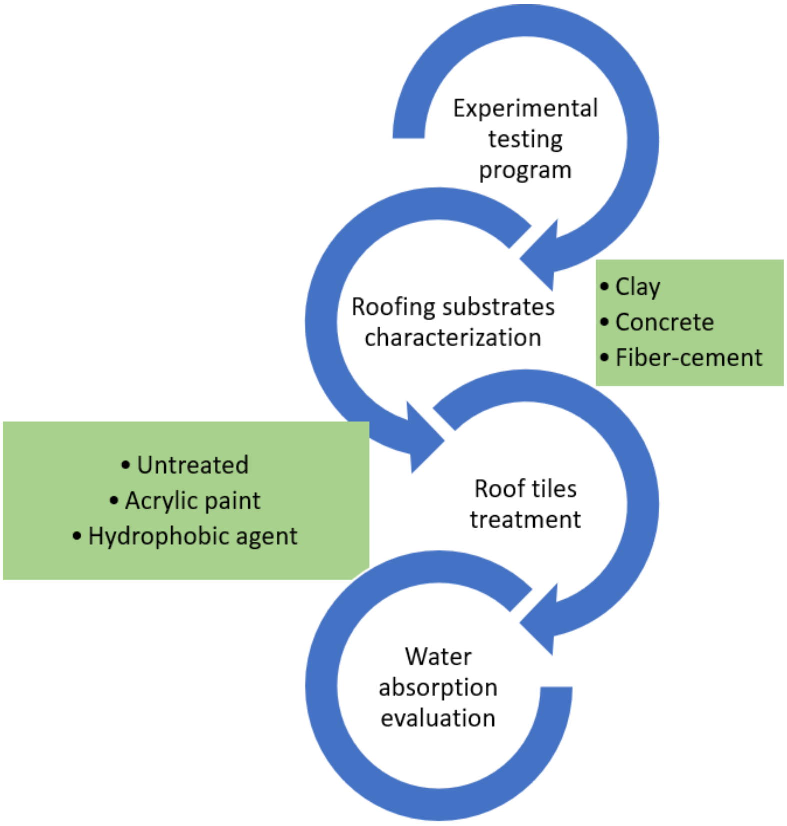
3.1 Materials

For the research, nine roofing substrates of each type - concrete, clay, and fiber-cement - were used. The roofing substrates were divided into three groups and received treatment with a hydrophobic solution based on silane and siloxane, an acrylic paint composed of water-soluble acrylic resins, or no treatment. The concrete tiles had an average length of 42 cm, width of 37.9 cm, and thickness of 2.4 cm. The clay roof tiles had an average length of 41.7 cm, width of 29.5 cm, and thickness of 1.5 cm. The fiber-cement tiles were cut to similar dimensions as concrete, with an average length of 42.2 cm, width of 41 cm, and thickness of 0.4 cm. The surface treatments were carried out according to the manufacturer's instructions.

3.2 Methods

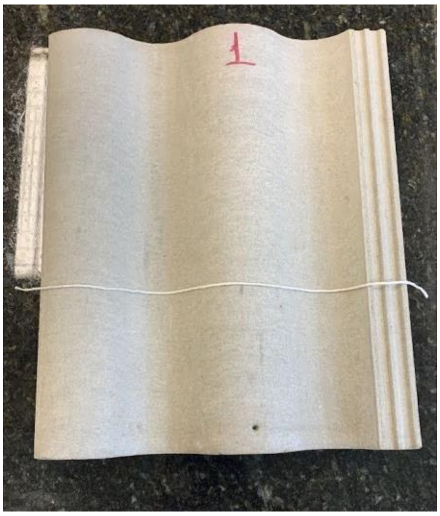
The experimental program followed the flowchart presented in Figure 2.

Figure 2 – Experimental program flowchart.



To determine the mass and dimensions (width, length, and thickness) of each specimen, the roofing substrates were prepared and geometrically characterized as shown in Figure 3. The characterization was conducted using a string and digital calipers.

Figure 3 - Using string to assist measurements.



To reduce water absorption, the specimens were treated with a silane-siloxane-based hydrophobic solution recommended by the manufacturer for clay, concrete, and fiber-cement tiles. Another treatment involved applying an acrylic paint with water-soluble resins, which has a high solids content and provides a glossy finish, offering excellent waterproofing and thermal insulation. This product also prevents algae growth by preventing water retention in the pores of treated roofing substrates. It is worth noting that this treatment complies with NBR 11702 (ABNT, 2019) specifications.

Figure 4 - Acrylic paint application.

To simulate a realistic rain scenario, a prototype roof system with metal profiles (Figure 5) and a 33% slope was used to subject both treated and untreated roofing substrates to water absorption. This adaptation allowed for the comparison of different roof treatment techniques. To create artificial rain, a hose with small holes was used to distribute small amounts of water, aiming to closely imitate real precipitation. ASTM C1167 (ASTM, 2022) and ASTM C373 (ASTM, 2018) standards recommend water absorption testing using heavy tiles that are immersed in boiling water for 5 hours. The heating is then turned off, and the samples remain immersed in water for an additional 24 hours to saturate. After this procedure, excess moisture on the sample surfaces is removed with a damp cloth, and their mass is measured again. However, this characterization method does not reflect the real-world use of roofing systems exposed to cycles of rain and sun. Therefore, this study proposed a laboratory simulation of rain.

Figure 5 - Roofing substrates exposed to the rain simulator: a) Lateral view of the roof; b) Front view of the roof.

In the absorption determination stage, the procedures of the TC 116-PCD standard (RILEM, 1999) were adapted for this study. Values were calculated at time intervals of 0, 15, 30, and 45 minutes using the difference between the roofing substrate's mass at time zero and its mass at the analyzed time. To obtain the absorption in grams per square centimeter, it was necessary to determine the contact area of water with each specimen. It was considered that the entire width of the roofing substrates was exposed to water, but the length was not completely exposed, except for the elements located at the top, which were fully exposed due to the overlap of the roofing substrate. The water absorption at each time interval was calculated using Equation 1 (adapted from RILEM, 1999), which takes into account the mass of water absorbed, in grams, by the contact area in square centimeters:

$$Water\ absorption = \frac{Mx - M0}{Ac} \tag{1}$$

Where:

Water absorption = absorption of the specimen, in g/cm²;

Mx = mass of the roofing substrate at the analyzed time (x), in grams;

M0 = mass of the roofing substrate at the analyzed time (x), in grams.

Ac = area of contact of the roofing substrate with water, in cm².

4. Results and Discussion

To evaluate the water absorption of clay, concrete, and fiber-cement tiles, it was necessary to determine the geometric dimensions of all specimens. This was because variations in the geometric dimensions of the samples can affect the absorption results. Some of the analyzed roofing substrates showed variations in their dimensions. According to NBR 13858-2 (ABNT, 2009), concrete tiles should have a length of 420 mm, with a tolerance of plus or minus 2 mm. However, this standard does not specify the total width of the roofing substrate, only the useful width. After the application of different treatments, the roofing substrates were subjected to water exposure tests. During this phase, differences in the behavior of the roofing substrates were observed, as shown in Figure 6. Roofing substrates treated with hydrophobic agents presented hydrophobic properties, while those that received acrylic paint exhibited a protective satin layer, the result of a film formation after the material dried.

Figure 6 - Behavior of clay roofing substrates with different treatments.

Next, water absorption calculations were performed per unit area of contact at 15-minute intervals. These calculations allowed for the observation of the average variation in absorption in g/cm² for each time interval. The results obtained on the first day of testing showed that the samples exhibited the highest values of mass variation due to being completely dry and thus absorbing more water during this period.

When analyzing the water absorption percentage of clay test specimens after 45 minutes of exposure, it was found that untreated roofing substrates had a 9 times higher absorption rate than treated roofing substrates. According to ASTM C373 (ASTM, 2018), typical water absorption in non-porous clay roof tiles is between 0.1% to 0.5%, while porous products may exhibit water absorption in the range of 9% to 15%. According to NBR 15310 (ABNT, 2009), the maximum allowable water absorption in clay roof tiles is up to 20% of their dry weight. It is important to emphasize the significance of clay roof tile treatment to prevent fungal degradation, which, as stated by Ranogajec et al. (2011), occurs in two phases: the first 18 days based on surface characteristics, and after 18 days, based on textural features, where water absorption is a dominant parameter.

When analyzing the percentage of water absorption by the clay specimens after 45 minutes of exposure, it was found that the untreated roofing substrates had a 9 times higher absorption rate than the treated ones. According to ASTM C373 (ASTM, 2018), typical water absorption in non-porous clay roof tiles ranges from 0.1 to 0.5%, while porous products may exhibit water absorption in the range of 9 to 15%. According to NBR 15310 (ABNT, 2009), the maximum allowable water absorption in clay roof tiles is up to 20% of their dry weight. It is important to highlight the importance of treating clay roof tiles due to the degradation caused by fungi, which, according to Ranogajec et al. (2011), occurs in two phases: up to the 18th day, based on surface characteristics, and after the 18th day, based on texture characteristics, where water absorption is a dominant parameter. ASTM 1492-03 (ASTM, 2016) specifies a maximum water absorption by immersion for normal weight concrete tiles of 12.5%. NBR 13858-2 (ABNT, 2009) establishes that the maximum allowable water absorption cannot exceed 10% of the dry weight. Although they had a higher absorption rate compared to treated specimens, the untreated roofing substrates registered an absorption of only 1% in relation to their dry weight.

The ASTM 1492-3 (ASTM, 2016) specifies that for concrete tiles to be deemed acceptable, no free water should form on the underside after 2 hours, and no more than 25% of the visible underside of any roofing substrate should show moisture. The treated fiber-cement tiles showed a higher water absorption rate compared to other types of treated roofing substrates, but still recorded a reduction in absorption when compared to untreated fiber-cement tiles. NBR 7581-1 (ABNT, 2014) sets a maximum absorption rate of 37% for fiber-cement tiles, which is considered high tolerance when compared to other roofing materials. To highlight the average water absorption rates of the analyzed roofing substrates at each time interval, Table 1 uses conditional formatting with dark green shades indicating the lowest absorption rates and reddish shades representing the highest absorptions recorded in the tests.

Table 1 - Average water absorption of roofing substrates over the exposure time.

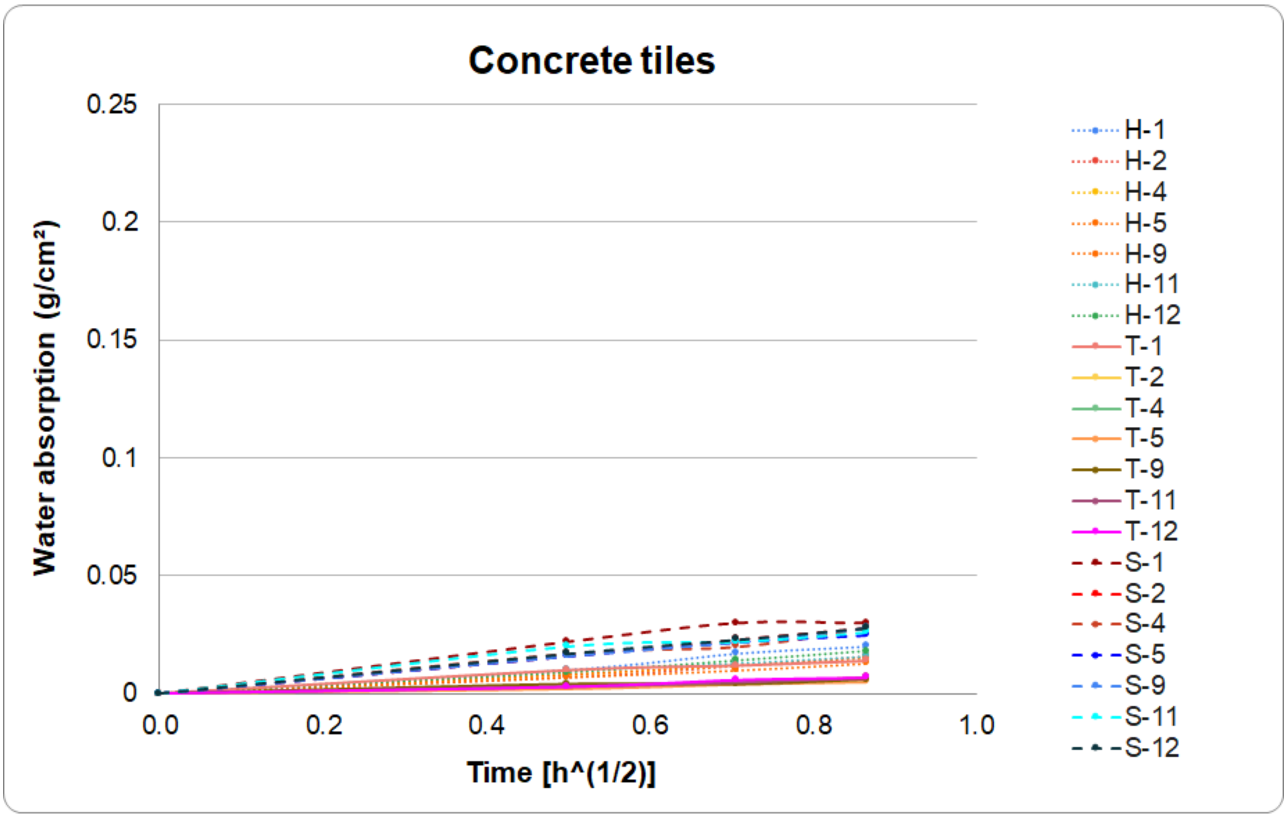
AVERAGE ABSORPTION OF THE ROOFING SUBSTRATES, IN G/CM², FOR EACH DAY OF THE TEST										
Types of roofing tiles		**Concrete**			**Clay**			**Fiber-cement**		
Time (min)		**15**	**30**	**45**	**15**	**30**	**45**	**15**	**30**	**45**
Day	**Surface treatment**									
1	Hydrophobic agent	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.03	0.04
	Acrylic paint	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.02
	Untreated	0.02	0.03	0.03	0.13	0.18	0.24	0.04	0.06	0.07
2	Hydrophobic agent	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.02
	Acrylic paint	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01
	Untreated	0.02	0.02	0.03	0.08	0.13	0.16	0.04	0.05	0.07
4	Hydrophobic agent	0.01	0.01	0.01	0.01	0.02	0.03	0.01	0.02	0.02
	Acrylic paint	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01
	Untreated	0.02	0.02	0.03	0.08	0.13	0.16	0.04	0.06	0.07
5	Hydrophobic agent	0.01	0.01	0.01	0.01	0.02	0.03	0.01	0.02	0.02
	Acrylic paint	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.01
	Untreated	0.02	0.02	0.03	0.09	0.12	0.14	0.04	0.05	0.06
9	Hydrophobic agent	0.01	0.01	0.02	0.00	0.01	0.02	0.01	0.02	0.03
	Acrylic paint	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.01
	Untreated	0.02	0.02	0.03	0.09	0.15	0.18	0.04	0.05	0.06
11	Hydrophobic agent	0.01	0.01	0.02	0.01	0.01	0.03	0.01	0.02	0.02
	Acrylic paint	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01
	Untreated	0.02	0.02	0.03	0.10	0.14	0.17	0.04	0.05	0.06
12	Hydrophobic agent	0.01	0.01	0.02	0.02	0.03	0.05	0.01	0.02	0.03
	Acrylic paint	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01
	Untreated	0.02	0.02	0.03	0.06	0.10	0.13	0.04	0.05	0.06

As shown in Table 1, untreated roofing substrates exhibited the highest absorption rates, with clay roof tiles showing the highest average absorption rate. Compared to untreated fiber-cement and concrete tiles, clay specimens recorded more than double the absorption rate. According to Ranogajec et al. (2011), water absorption in clay roof tiles results in deterioration during exposure to weather conditions. The authors evaluated water absorption in untreated clay roof substrates and found that immersion water absorption for 24 hours varied depending on the firing temperature, which in this study ranged from 900°C to 1020°C, with respective water absorption rates of 10.86% and 8.60%.

However, when analyzing the peaks of lower absorption, it can be observed that treated clay roof tiles showed similar levels to other types of roofing substrates that were also subjected to treatment. This suggests that the treatments were effective on clay roof tiles, demonstrating a peak of efficiency.

Figures 7, 8, and 9 show that untreated roofing substrates had higher water absorption rates than treated ones. It was observed that treatment with acrylic paint was more effective than treatment with hydrophobic agent in all cases, resulting in a clear reduction in water absorption in different types of roofing substrates. However, in the case of concrete tiles, there was little variation in water absorption rates between different treatments, as can be seen in Figure 7.

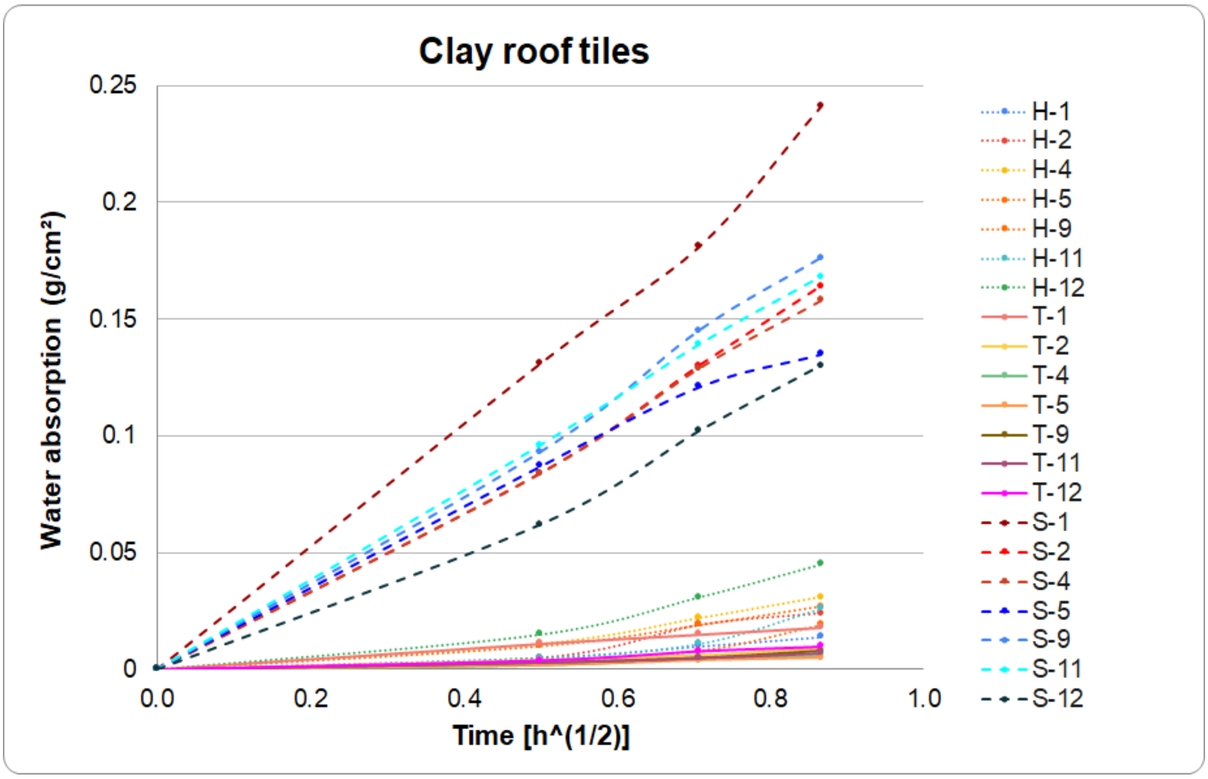
Figure 7 – Trend of water absorption of concrete tiles.



Caption: T: acrylic paint; S: untreated; H: water repellent.

It was observed that untreated clay roof tiles showed an increasing trendline, suggesting that they tend to saturate with less time (Figure 8). On the other hand, roofing substrates treated with acrylic resin showed constant trendlines or small variations over the analyzed periods.

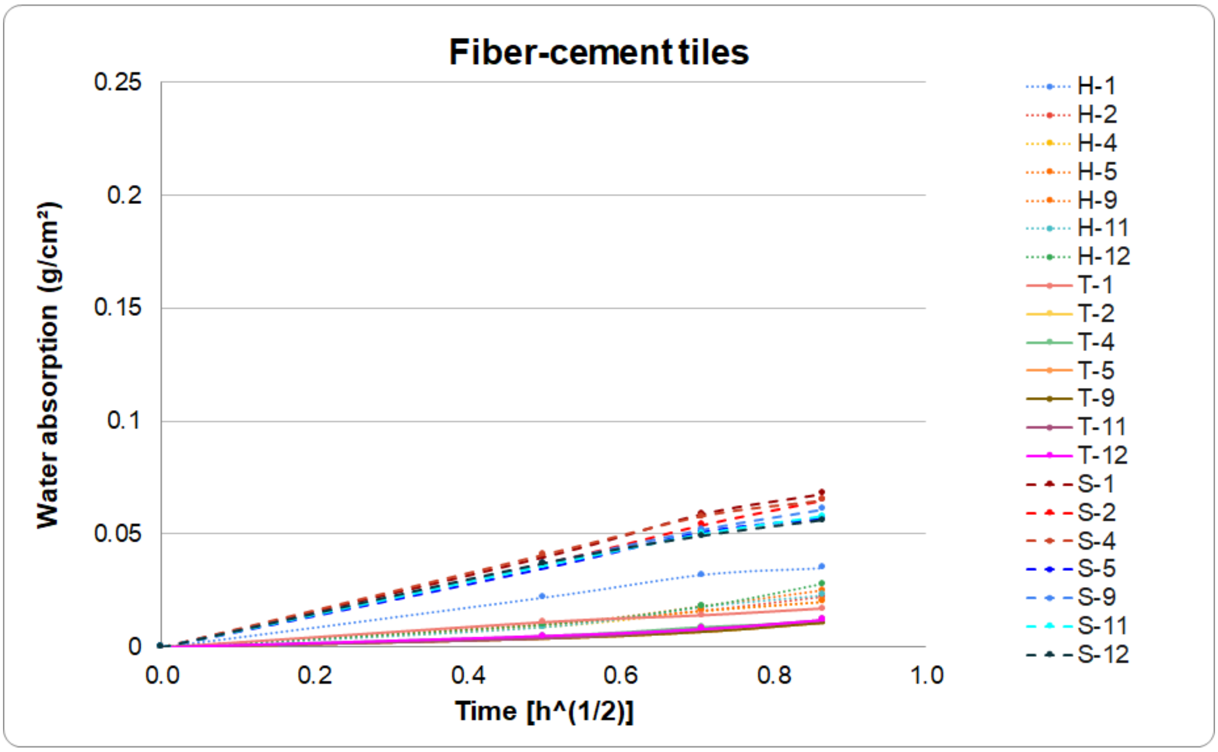
Figure 8 – Average water absorption of clay roof tiles.



Caption: T: acrylic paint; S: untreated; H: water repellent.

In the study, it was found that untreated fiber-cement tiles tend to saturate (Figure 9). However, treatment with acrylic resin was more effective in reducing water absorption when compared to treatment with silane-siloxane.

Figure 9 - Average water absorption of fiber-cement tiles.



Caption: T: acrylic paint; S: untreated; H: water repellent.

The results of the roofing substrates treated with hydrophobic products are in agreement with Carrascosa, Facio and Mosquera (2016). The authors used silica nanoparticles added to a mixture of organic and inorganic silica oligomers in the presence of n-octylamine. Copolymerization between organic and inorganic components produced a hybrid gel with hydrophobic properties adhered to the substrate. The nanoparticles induced a new roughness on the surface, creating a densely compacted coating and thus reducing the water absorption on the surface of clay and fiber-cement tiles, since according to Mukhametrakhimov et al. (2017), surface hydrophobization reduces the total volume of pores and considerably changes the nature of the pore distribution of substrates.

5. Conclusions

The main objective of this article was to evaluate, compare and understand the behavior and efficiency of different treatments applied to the most common types of roofing substrates used in Brazil, in relation to untreated ones, with a focus on water absorption through precipitation simulations that exposed the roofing substrates to situations similar to those found in reality. Therefore, with the analysis of the results following the adopted methodology, it was possible to understand that:

- Clay roof tiles without treatment present significantly higher water absorption compared to fiber-cement and concrete tiles;
- Concrete tiles have low water absorption due to cement hydration during manufacturing, even without treatments;
- Treatments were more efficient in clay roof tiles, with a higher percentage reduction in water absorption than in the other types of roofing substrates;
- Reducing roofing substrate permeability brings numerous benefits, such as preventing construction anomalies caused by water, preventing premature roofing substrate deterioration, improving aesthetics and durability, which extends the lifespan of the roofing system.

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