engineering proceedings

MDPI

Proceeding Paper

Recycled Composite Panels for Sustainable Interior Architecture: Density, Water Absorption, and Capillary Action †

Klodjan Xhexhi [1,*], Blerim Nika [2], Ledian Bregasi [1], Ilda Rusi [1], Sonia Jojic [3] and Nikolla Vesho [1]

[1] Architecture and Engineering Department, Faculty of Architecture and Desing, Polis University, 1051 Tirana, Albania; ledian_bregasi@universitetipolis.edu.al (L.B.); ilda_rusi@universitetipolis.edu.al (I.R.); nikolla_vesho@universitetipolis.edu.al (N.V.)
[2] Applied Research Department, Faculty of Research and Development, Polis University, 1051 Tirana, Albania; blerim_nika@universitetipolis.edu.al
[3] Art and Design Department, Faculty of Architecture and Desing, Polis University, 1051 Tirana, Albania; sonia_jojic@universitetipolis.edu.al
* Correspondence: klodjan_xhexhi@universitetipolis.edu.al; Tel.: +355-689018124
† Presented at the 2nd International Conference on Engineering, Technology, and Applied Science Innovations (ICETASI 2026), Zakynthos, Greece, 24–26 September 2026.

Abstract

This study evaluates the physical performance of recycled wood- and plastic-based composite panels made from pine, olive, and beech wood and plastic granules, bonded with a cement-based adhesive (CBA). Density, water absorption, and capillarity tests were performed on panels of 25 × 25 × 2 cm. The tests were conducted after 12, 24, and 48 h in accordance with EN ISO 15148. Three samples per category were analyzed using ANOVA. Results indicate that olive-based panels recorded the lowest dry density (0.495 g/cm^3) and the lowest average capillary rise (17 cm), while plastic-based panels showed the highest capillary rise (25 cm) and higher water absorption (up to 43.96%). Pine panels exhibited the highest moisture content (up to 52.56%), whereas beech panels had moderate capillary rise (20 cm) and lower moisture variation. Despite their relatively low bulk density and favorable aesthetic qualities, olive and beech panels demonstrated reduced strength, limiting their structural application. Overall, the results indicate that these composite panels are more suitable for indoor non-structural architectural uses, such as decorative elements and suspended ceiling systems.

Keywords: composite recycled panels; wood and plastic granules; cement-based adhesive; density; water absorption; capillary action; indoor panels

1. Introduction

Wood–plastic composites (WPCs) have been widely used as sustainable alternatives to traditional building materials, as they combine the benefits of wood fibers with the formability of polymers. These composites are composed of up to 80% recycled wood materials and thermoplastic polymers, promoting the reuse of industrial waste and reducing the environmental impact of building material production [1].

One of the key factors limiting the use of WPCs in various applications is their sensitivity to moisture. The water absorption of WPCs is directly influenced by the percentage of the wood component and the structure of the composite phase and follows a Fickian diffusion model [2]. Increased water ingress can cause deformations, degrade mechanical properties, and compromise material performance.

Check for updates

Academic Editor: Konstantinos Poirazidis

Published: 10 November 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Water transport mechanisms in composite materials are multifaceted and include hygroscopic absorption and capillary action, which cause moisture to rise and spread in the microporous structure of the material. These two phenomena have significant implications for the durability and integrity of the manufactured panels [3].

To understand these phenomena, the present study examines the physical properties of composite recycled panels (CRPs) composed of wood granules (pine, oak, and olive) and recycled plastics, combined with cement-based adhesive (CBA) binders, focusing on the density, water absorption, and capillary rise under controlled laboratory conditions. This approach provides an important basis for understanding the potential of these materials in non-structural architectural applications and sustainable indoor building systems.

2. Literature Review

WPCs are composed of wood particles and plastic material, combined in a composite matrix to create products with improved physical and mechanical properties. These composites are widely used in the construction industry for non-structural applications such as facade panels, floors, and interior elements due to their durability, recyclability, and superior elastic properties [4].

Water absorption is one of the key limitations that has attracted significant attention in the literature on wood–plastic composite materials. As wood fibers have hygroscopic hydroxyl groups that absorb water through hydrogen bonds, water absorption into the composite increases proportionally with the wood content and can lead to deformation, dimensional swelling, and deterioration of the mechanical properties of the panel [5]. Experimental studies have demonstrated that water absorption and swelling are influenced by the capillary network and material microstructure [6].

The water absorption of composite materials is also influenced by the interface between the wood fibers and the plastic matrix. When the adhesion between these phases is weak or non-uniform, water can easily penetrate the structure, increase capillary rise, and deteriorate the physical properties of the panel [7]. Improving the interfacial bonding through the use of coupling agents has been shown to reduce water absorption and swelling of the material, thus improving the overall durability of the composite in humid conditions [8].

Studies have also emphasized the importance of the formation of microporous structure in composites: smaller cells and microstructure result in faster and more intense capillary formation. This phenomenon directly affects the water sensitivity and hygroscopic behavior of composites. This behavior has been widely observed in composites and natural fiber materials [9].

Authors in [10] studied the development of WPCs with the aim of reducing water absorption, focusing on improving the material composition and the interface between the wood and plastic phases. The authors report that water absorption is significantly influenced by the wood content and particle distribution in the plastic matrix. The results indicate that optimizing the composite composition and using appropriate treatments can lead to a significant reduction in water absorption, improving the dimensional stability and overall performance of the material in humid conditions.

Similarly, authors in [11] studied how WPC materials absorb water, focusing on the absorption rates and moisture transport mechanisms. Their research indicates that the absorption varies based on the microporous structure of the material and the orientation of the wood particles during the injection process. The authors highlight the importance of capillarity and the wood–plastic interface in the distribution of moisture within the material, suggesting that controlling these factors is essential to improve the durability of composites in construction applications.

https://doi.org/10.3390/engproc2026167016

A previous study [5] describes the physical and mechanical characteristics of WPCs made from recycled panel wood powder and polypropylene. The authors observed that WPCs produced with recycled content behave differently from traditional composites when exposed to moisture and expansion because of the differences in the structure of the wood phase. Furthermore, the quality of the particle structure and the wood–plastic interface have a direct effect on water transport and material stability.

Authors in [12] analyzed composite panels manufactured from recycled wood particles and an epoxy matrix, focusing on their performance in sustainable ventilated facade applications. The study examined the moisture response, mechanical properties, and fire behavior, demonstrating that recycled materials can offer comparable performance to conventional composites when the composition and production process are controlled. The authors emphasized the importance of hygroscopic behavior and moisture transport in the long-term performance of the panels, contributing to the development of composite materials with low environmental impact for contemporary architecture [12].

Authors in [13] presented a comparative analysis of the hygroscopic behavior of natural wood, focusing on water absorption, moisture content, and capillary action in different species such as fir, pine, beech, and oak. The study indicates that anatomical differences and wood density directly affect water transport mechanisms, providing an important scientific basis for the evaluation of wood-based materials in construction and architectural applications [13]. Similarly, authors in [14] analyzed the water absorption and capillary action of various construction materials, including bricks and panels used as exterior cladding of buildings. The study highlights the role of material composition and porous structure in water absorption, emphasizing the importance of material selection for the hydrothermal performance and durability of the facades [14].

3. Methodology

3.1. Materials

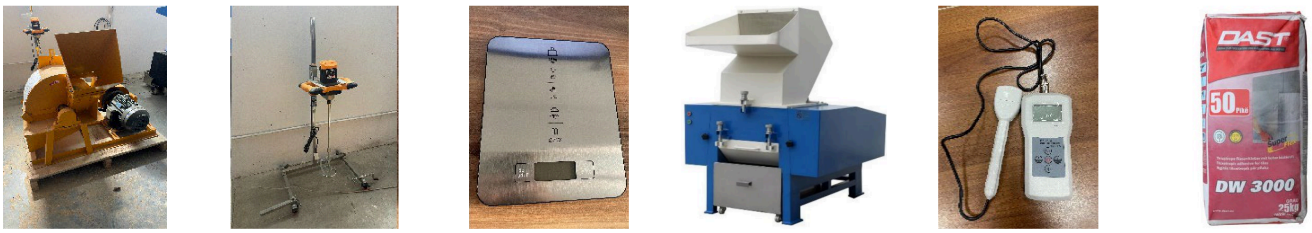
Recycled wood granules from pine (Pinus spp.), beech (Quercus spp.), and olive (Olea europaea) were used in this study, as well as recycled plastic granules from plastic bottles. The materials were obtained from post-consumer wood and plastic waste, which were cleaned and pre-processed before experiments. The wood was crushed into uniformly sized granules to ensure homogeneity during mixing and pressing. CBA was used as a binder. For each type of material (wood and plastic), separate mixtures were prepared for comparative analysis.

The CBA from "Dast sh.a." which is an Albanian-German joint venture, used in this study typically exhibits a bulk density of approximately 1300–1600 kg/m^3 and a specific gravity of around 2.6–3.1, consistent with Portland cement-based materials. It is characterized by a fine particle size (generally <100 µm), which ensures good workability and homogeneous mixing with recycled granules. These properties contribute to improved bonding within the composite matrix while significantly influencing the density and moisture behavior of the panels.

3.2. Panel Production

Recycled wood was crushed in a wood crushing and grinding machine for sawdust, as seen in Figure 1a. The manufacture company for this product is "Anyang Aols Machinery Equipments Co., Ltd.", Anyang, China. Raw materials were logs, branches, and wood waste. The final size of the particles is 3–5 mm for each type of wood. On the other hand, plastic bottles were crushed in the plastic crushing machine called a Shredder with a uniform particle size of 3–5 mm, as shown in Figure 1d. The crushing machine (Shredder) was manufactured by Furui Machinery Co., Ltd. (Xinxiang, Henan, China). The machine

mechanically reduced the plastic waste into smaller fragments through a blade-based crushing mechanism, facilitating subsequent processing and material reuse. The weight of the particles was measured using an EV023 digital scale, as shown in Figure 1c, for the same volume ($25 \times 25 \times 1$ cm $= 625$ cm^3), as seen in Table 1. Its margin of error is 1 g. The manufacture company for this product is "Emos spol. s r.o.", P˘rerov, Czech Republic. Wood pellets and recycled plastic were mixed separately for each type of material with the use of a power agitator, as shown in Figure 1b, and CBA as shown in Figure 1f; water was added in controlled proportions for each sample until a homogeneous mass was achieved, as presented in Table 1. The manufacture company for this product is "Yichang Yuanheng Technology Co., Ltd.", Yichang, China. The mixer type is a homogenizer dispersion blender mixer, and the max. loading volume (L) is 200 L. The application scope is for high-viscosity products, and the power (kW) is 1.8 kW. The range of spindle speed (r.p.m) is 1–1650 r.p.m. For each sample, the mixture was placed in wooden molds and pressed to form square panels measuring $25 \times 25 \times 2$ cm. The pressing was carried out under controlled laboratory conditions, ensuring uniform thickness and density for all samples. The mix design and the exact quantity of the ingredients for each sample are presented in Table 1.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 1. Equipment used in the experiment: (**a**) wood crushing–grinding machine for sawdust; (**b**) power agitator with support; (**c**) EV023 digital scale; (**d**) plastic crushing machine (Shredder); (**e**) hygrometer; (**f**) CBA (Dast).

After molding, the panels (three panels for each category) were left to cure in a laboratory environment for 3 weeks with a stable temperature (18 °C) and humidity (44%) before performing physical tests, as shown in Figure 2.

Figure 2 shows the CRPs after a curing period of three weeks under controlled laboratory conditions, illustrating their final shape, surface texture, and uniformity. The weight of CBA and water was kept constant for each sample. Additionally, the initial and final dry densities of CRPs were measured to evaluate the volumetric change as a result of moisture loss.



Figure 2. CRPs after a curing period of three weeks.

Table 1. Mix design of the composite panels (mean ± SD, $n = 3$).

CRP	Weight of CBA (g)	Water (g)	Particle Weight (g) for the Same Volume 25 × 25 × 1 cm	Total Initial Weight (g)	Total Weight After Natural Drying (g)
CRP plastic + CBA + water	650	500	124 ± 9	1276 ± 8.5	782 ± 9.5
CRP pine + CBA + water	650	500	114 ± 7.8	1263 ± 7.5	823 ± 8.1
CRP olive + CBA + water	650	500	110 ± 7.35	1258 ± 6.9	619 ± 7.8
CRP beech + CBA + water	650	500	134 ± 8.95	1286 ± 9.2	776 ± 8.7

The experimental data obtained were processed and analyzed using Microsoft Excel (Version 2021, Microsoft Corp., Redmond, WA, USA), and IBM SPSS Statistics for Windows, Version 27.0. IBM Corp., Armonk, NY, USA, enabling comparative evaluation of the results between different composite panel categories. Three samples ($n = 3$) were taken for each category, and the differences between groups were analyzed using the one-way and two-way ANOVA tests to verify the statistical significance of the observed changes.

3.3. Density Determination

The density of the CRPs was determined by measuring the mass and volume of each sample after curing. The mass of granules, CBA, and water was measured with a high-precision laboratory balance, while the volume was calculated using the geometric dimensions of the panels.

The volume of the granules per sample was 25 × 25 × 1 cm = 625 cm^3, and the total volume of the matrix, 25 × 25 × 2 cm, was 1250 cm^3. Density was expressed in g/cm^3 and was used as a basic parameter for comparing panels made from different types of wood and recycled plastic. The Composite Density (CD) was defined as follows:

$$\rho c = (M_{CBA} + M_{granules} + M_{water})/V_{sample} \quad (1)$$

where M_{CBA} is the weight of CBA, $M_{granules}$ is the weight of the granules, M_{water} is the weight of water, and V_{sample} is the volume of the sample (matrix).

Equation (1) is used to standardize density calculation across all samples.

3.4. Measurement of Capillary Action

The capillary action was measured in accordance with the EN ISO 15148 standard [15], which specifies a method for measuring water absorption by capillarity in porous materials. This test simulates capillary absorption from rainwater or moisture in contact with the base, ensuring one-dimensional flow, avoiding hydrostatic pressure (which occurs with deeper immersion), and allowing standardized comparison across materials. The samples were placed in a vertical position and immersed in water to a controlled depth of approximately 1–5 mm. The water was kept at laboratory temperature (~ 20 ± 2 °C). The maximum height of the composite panels was 25 cm. During the test, the capillary rise of water along the surface of the CRPs was measured with a ruler after time intervals of 12, 24, and 48 h. The height of the absorbed water was recorded visually and used to analyze the moisture transport mechanisms in the porous structure of the panels composed of wood and plastic granules.

3.5. Measurement of Water Absorption

The behavior of the CRPs to moisture was examined using the water absorption test. The samples were partially immersed in water at ambient temperature and kept immersed for periods of 12, 24, and 48 h according to the EN ISO 15148 standard [15]. After each time interval, the panels were removed from the water, their surfaces were dried, and the moisture content was measured with a hygrometer at the highest capillary level. Readings were taken three times per sample at both ends and in the middle of the CRPs.

The moisture content was measured with the Inductive Moisture Meter Tester MS310-S, as shown in Figure 1e. The manufacture company for this product is "Tsingtao Toky Instruments Co., Ltd.", Qingdao, China. Measuring range: 0–99%. Operating conditions: temperature: 0–60 ◦C and humidity: 5–90%. Accuracy: ±0.5 (main moisture range). The equipment is suitable for the measurement of moisture content in concrete, wood, paper, timber, bamboo, cardboard, and textiles.

4. Experimental Results and Analysis

4.1. Density Results

CD before and after natural drying was calculated using (1). The findings are presented in Table 2 and Figures 3 and 4.

Table 2. CD before and after natural drying of the CRPs (mean ± SD, $n = 3$).

CRP	Total Initial Weight of the Composite Panel (g)	Total Weight of the Composite Panel After Drying (g)	Volume of the Matrix (m^3)	Initial Density (gcm^{-3})	Density After Natural Drying (gcm^{-3})
CRP plastic + CBA + water	1276 ± 8.5	782 ± 9.5	1250	1.021 ± 0.007	0.626 ± 0.008
CRP pine + CBA + water	1263 ± 7.5	823 ± 8.1	1250	1.010 ± 0.006	0.658 ± 0.006
CRP olive + CBA + water	1258 ± 6.9	619 ± 7.8	1250	1.006 ± 0.006	0.495 ± 0.006
CRP beech + CBA + water	1286 ± 9.2	776 ± 8.7	1250	1.029 ± 0.007	0.621 ± 0.007

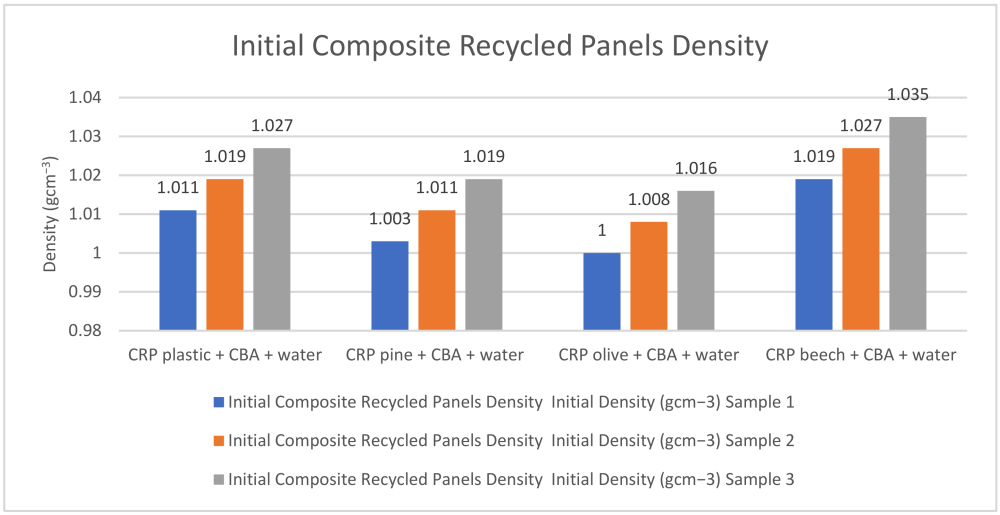


Figure 3. Initial density of the samples.

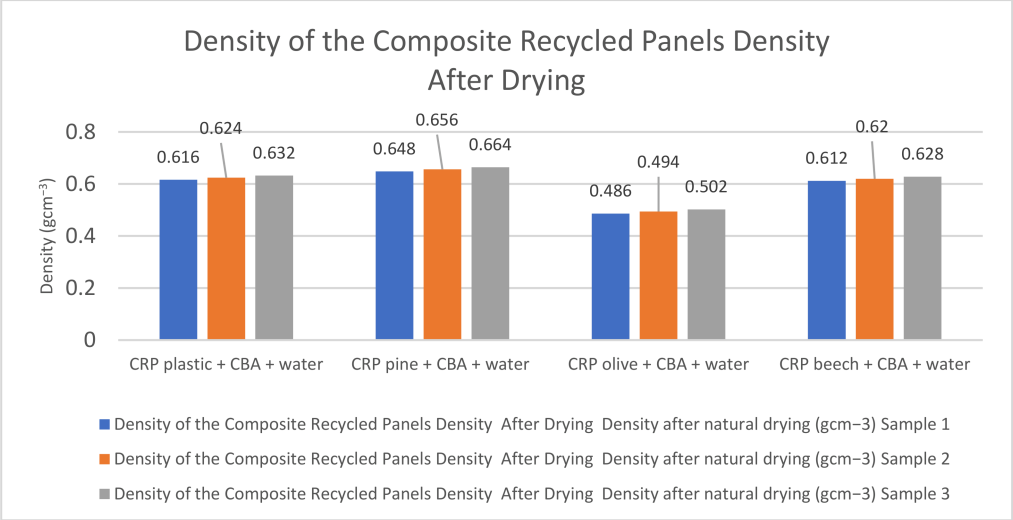


Figure 4. Density of the CRPs after drying.

Statistical analysis of the results was performed using IBM SPSS Statistics 27 through the One-Way ANOVA test, with a 95% confidence level ($p < 0.05$). For each panel category, three samples were analyzed, and the results were used to compare the average densities between groups before and after the drying process. The ANOVA test assessed the variation between and within groups to determine whether the observed differences are statistically significant. The results show the differences in density between panels produced from composite materials and the structure of the granules, while the use of the 95% confidence level ensures a statistically consistent interpretation of the experimental data.

While the volume of the matrix was kept constant for all the samples, the CRPs exhibited an initial density of more than 1 g/cm^3, indicating a compact structure with reduced internal porosity and a density slightly higher than water, mainly due to the contribution of CBA, moisture content, and recycled granules within the mold volume. Beech CRPs exhibited the highest initial density (1.019–1.095 g/cm^3). In this case, all the panels are expected to sink in water due to their density exceeding that of water.

If the density is higher than 1 g/cm^3, the panel may have better compressive strength but may have lower thermal insulation compared to very light wood-based composites or plastic composites. The higher the density of the composite, the higher the compressive strength tends to be. The panel tends to be relatively compact and has fewer air voids (lower porosity).

The significant decrease in the density of the CRPs after drying is attributed to the removal of free and bound water from the internal porous structure of the panels, while their volume remains unchanged. Since density is defined as the ratio of mass to volume ($\rho = m/V$), the reduction in mass without a proportional shrinkage of the volume leads to a decrease in the average density of the material. In the case when the final density is less than the density of water (~1.0 g/cm^3), the panels may float according to Archimedes' principle since the buoyant force becomes greater than the weight of the body. This suggests the presence of higher porosity and residual air within the composite matrix, elements that directly reduce the density of the material. Such behavior is typical for wood-based materials and wood–polymer composites, where micro-voids and gaps in the contact area between the granules and the binder, as well as incomplete compaction of the matrix, can significantly affect the physical performance and hydrostatic behavior of the material.

The analysis of the initial and post-drying density for CRPs with CBA + water and different components (plastic, pine, olive, beech) shows that the differences are due to both the nature of the filler material and its interaction with water and the binding matrix.

The initial density is higher due to the presence of water in the structure, while after drying, a significant decrease is observed as a result of water evaporation and an increase in effective porosity. Olive CRPs have the lowest density values after drying (around 0.486–0.502 g/cm^3), while pine and alder CRPs exhibit higher values. The plastic CRPs tend to maintain higher stable densities, since plastic is not hygroscopic. Pine and beech, as species with a more homogeneous structure, show intermediate behavior, while olive CRPs have a lower dry density, which can be explained by their denser, heterogeneous physical structure, larger pores and vessels, as well as the natural oil content. These factors affect adhesion to the matrix and create micro-voids during drying. This increases the internal porosity and decreases the final density of the olive-based composite.

To reinforce CRPs, it is advisable to place a plastic mesh on their back before installation. It was observed that CRPs made of plastic and pine dried faster under the same laboratory conditions than olive or beech CRPs. The olive-based panels exhibited the highest fragility and brittleness and required the longest drying time after mixing. The beech-based panels showed comparatively lower fragility and a shorter drying period, followed by the plastic-based panels.

4.2. Results of Capillary Action

The results of the capillary rise during 12, 24, and 48 h are presented in Table 3 and Figure 5.

Table 3. Capillary action during partial immersion in water of the CRPs (mean ± SD, $n = 3$).

Samples	Capillary Rise After 12 h (cm)	Capillary Rise After 24 h (cm)	Capillary Rise After 48 h (cm)
Plastic CRP	25.0 ± 0.0	25.0 ± 0.0	25.0 ± 0.0
Pine CRP	17.0 ± 1.0	22.0 ± 1.0	25.0 ± 0.0
Olive CRP	11.0 ± 1.0	16.0 ± 1.0	24.0 ± 1.0
Beech CRP	15.0 ± 1.0	20.0 ± 1.0	25.0 ± 0.0

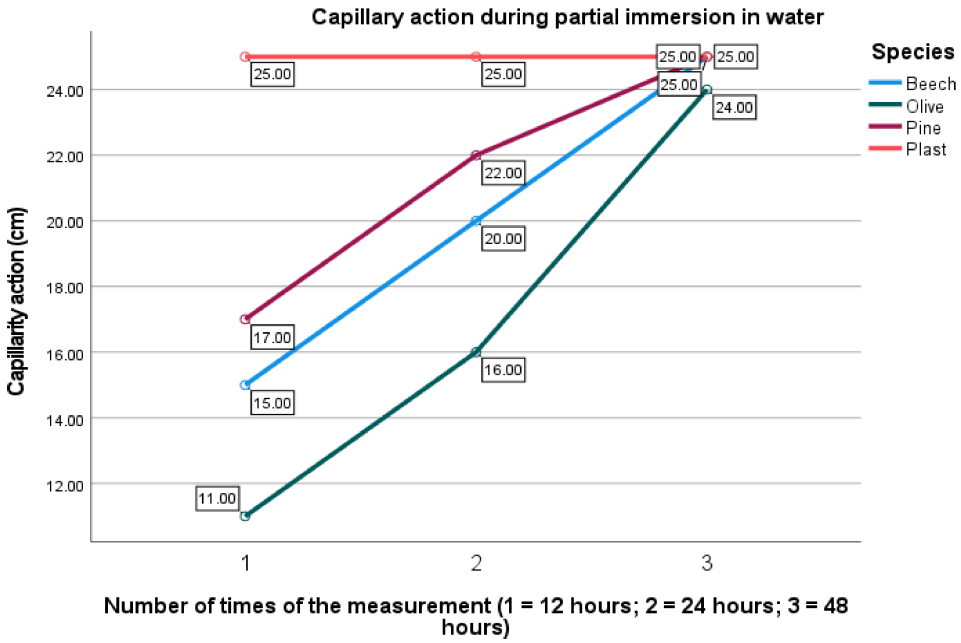


Figure 5. Capillary action during partial immersion in water of the CRPs ($n = 3$).

The results of the capillarity test show a progressive increase in water absorption with increasing exposure time (12 h, 24 h, and 48 h) for all CRPs, as presented in Table 3 and Figure 5. Statistical analysis was performed using a General Linear Model (GLM) in SPSS to assess the effect of time and material type on capillarity. The results indicate a statistically significant effect of exposure time ($F \approx 18.6$; $p < 0.001$), confirming that capillarity increases significantly with time. The plastic CRPs presented the highest capillary rise (up to the height of the panel) due to the presence of micro-voids and interfacial areas between the plastic granules and the binder matrix, which create pathways for capillary rise. In contrast, the olive CRPs exhibited the lowest capillary rise (around 11–24 cm) due to the denser fiber structure and the natural oil content, which reduce water absorption.

4.3. Water Absorption Results

Figure 6 shows how the measurements were performed using the hygrometer. Meanwhile, the results of water absorption using a hygrometer are presented in Table 4 and Figure 7.



Figure 6. Moisture content measurement with a hygrometer of the CRPs when partially immersed in water.

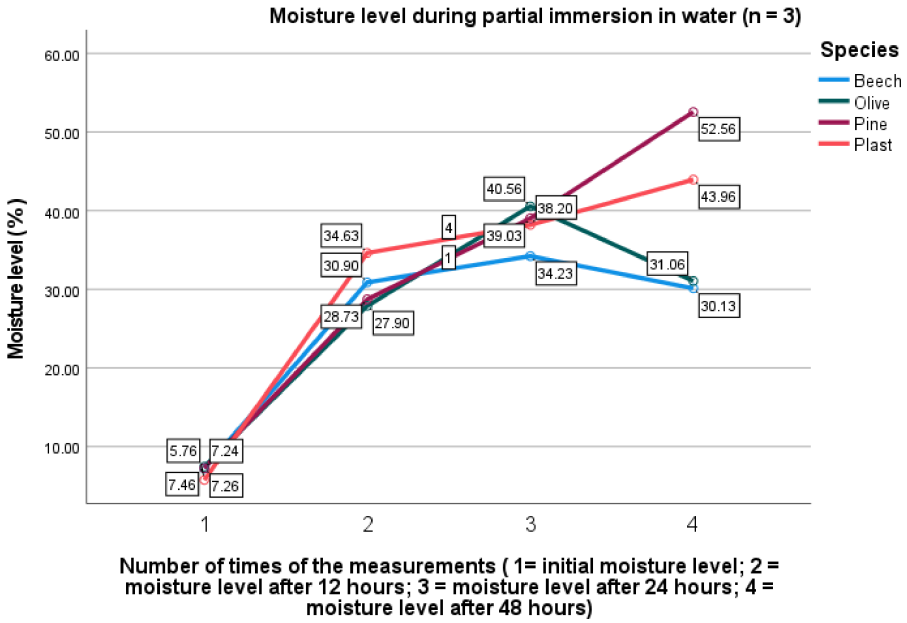


Figure 7. Moisture content during partial immersion in water ($n = 3$).

Table 4. CRP's moisture content during partial immersion in water (mean ± SD, n = 3).

Samples	Moisture Content Before Partial Immersion (%)	Moisture Content for 12 h (%)	Moisture Content for 24 h (%)	Moisture Content for 48 h (%)
Plastic CRP	5.76 ± 0.21	34.63 ± 1.02	38.20 ± 0.94	43.96 ± 1.31
Pine CRP	7.26 ± 0.25	28.73 ± 1.10	39.03 ± 1.28	52.56 ± 1.42
Olive CRP	7.46 ± 0.18	27.90 ± 0.95	40.56 ± 1.20	31.06 ± 1.05
Beech CRP	7.24 ± 0.22	30.90 ± 1.15	34.23 ± 0.98	30.13 ± 1.02

A repeated-measures ANOVA was performed to evaluate the effect of immersion time and material type on the moisture content of the composite panels. The results indicate that immersion time has a statistically significant effect on the moisture content (Greenhouse–Geisser-corrected: $F = 11364.54$, $p < 0.001$, $\eta^2 = 0.999$), indicating a significant increase in moisture content over time.

A statistically significant interaction between immersion time and material type was also observed ($F = 406.30$, $p < 0.001$, $\eta^2 = 0.993$), indicating that the water absorption rate varies depending on the recycled material used in the composite panels.

The between-subjects test also showed significant differences between materials ($F = 32.53$, $p < 0.001$, $\eta^2 = 0.924$). Bonferroni post hoc comparisons showed that panels produced with pine and recycled plastic granules showed higher moisture absorption compared to beech-based panels ($p < 0.01$). By contrast, the differences between beech and olive were not statistically significant ($p > 0.05$). Overall, the results indicate that both the immersion time and the type of recycled material have a significant effect on the water absorption behavior of composite panels.

The CRPs containing olive granules exhibited the highest initial moisture content (7.46%) before drying, as seen in Table 4 and Figure 7. This may be attributed to the physical structure and relatively high porosity of olive particles, which are able to retain more moisture during mixing. Also, the presence of natural oils and organic components (extractives) in olive wood can affect the interaction with the bonding matrix and the diffusion of water within the material structure. However, over the extended test period, a slight decrease in the moisture content was observed in the olive and beech CRPs. This can be attributed to the capillary pores approaching saturation and the hydrophobic properties of extractives and lignin, which limit further water penetration and stabilize the moisture content in the composite structure. The ambient temperature during testing may also have influenced the drying, as exposing the panel surface to air at room temperature promotes the gradual evaporation of moisture from the upper layers of the panel.

5. Results and Discussion

The data obtained from the density, water absorption, and capillary action tests were comparatively analyzed for each type of CRP. The analysis aimed to identify the influence of wood type, the presence of plastic granules, and the mixture characteristics on the hygroscopic and physical behavior of the panel and evaluate their potential for use in indoor non-structural architectural applications. The overall results are presented in Table 5 and Figure 8.

The results presented in Table 5 and Figure 8 suggest significant differences in the behavior of the CRPs depending on the type of granules used. Olive and beech CRPs exhibited lower capillary rise (17 cm and 20 cm) and average moisture content compared to the plastic and pine CRPs, which can be attributed to a higher degree of compaction of these materials and the lower interaction with water. In particular, the recycled olive particles contain natural organic compounds and oils that can increase the hydrophobic

character of the material and limit the capillary rise. Furthermore, olive CRPs also exhibited the lowest dry density (0.495 g/cm^3), which suggests the presence of a porous structure after drying and evaporation of water from the composite matrix. These results indicate that the physical and chemical characteristics of the filler material play an important role in influencing capillary rise, moisture uptake, and final density of the composite panels.

Table 5. Overall results.

Samples	Initial Density (gcm^{-3})	Density After Natural Drying (gcm^{-3})	Mean Capillary Rise During 12, 24, and 48 h (cm)	Mean Moisture Content (Initial; 12; 24 and 48 h) (%)
Plastic CRPs	1.021	0.626	25	30.63
Pine CRPs	1.010	0.658	21.33	31.9
Olive CRPs	1.006	0.495	17	26.74
Beech CRPs	1.029	0.621	20	25.62

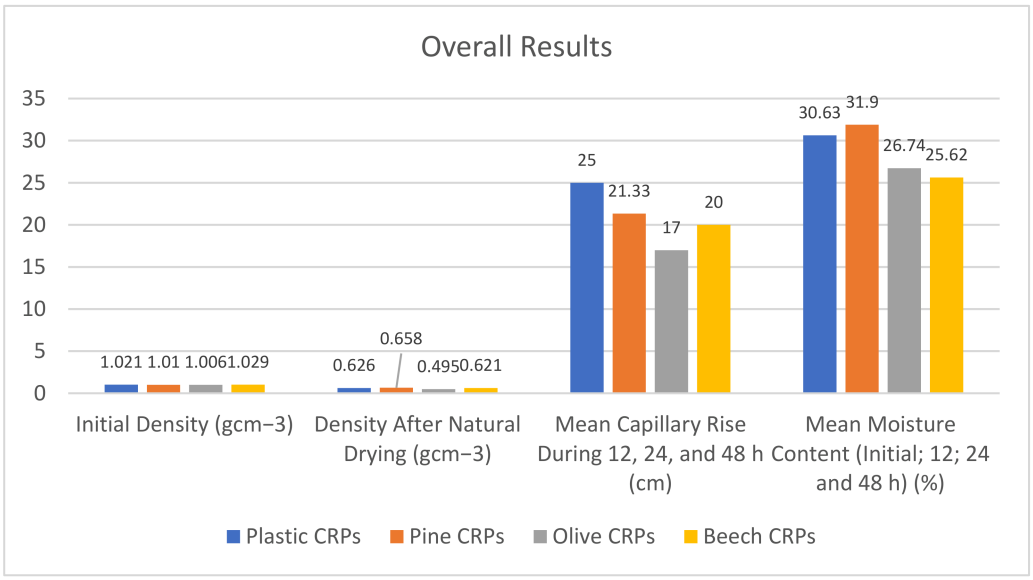


Figure 8. Overall results.

On the other hand, the relatively higher fragility observed in olive and beech CRPs can be attributed to their distinct physical and chemical characteristics, which influence fiber-matrix interaction and moisture response.

Previous studies have shown that beech wood, due to its low extractive content and homogeneous fiber structure, tends to exhibit weaker interfacial bonding within composite matrices, making it more susceptible to moisture-induced swelling and microcrack formation. In contrast, olive wood particles, despite containing natural oils, often exhibit a dense and brittle morphology after grinding, which can create stress concentration zones and promote crack initiation within the composite structure. In both cases, water absorption weakens interfacial adhesion between the lignocellulosic particles and the matrix, accelerating microstructural degradation and reducing overall material integrity. These mechanisms are consistent with established findings on moisture diffusion and interfacial debonding in WPCs under environmental exposure [16].

From an aesthetic point of view, CRPs produced with different granule compositions exhibit distinct visual characteristics, which depend on the nature and color of the filler material. In general, these panels exhibit a relatively uniform and light-toned surface,

creating a soft and even texture. The panel containing pine granules exhibits a slight tonal variation and scattered spots on the surface, which create a natural visual effect, similar to traditional wood-based materials. The panel with beech granules presents a more pronounced texture with a more visible distribution of particles, creating a more dynamic and decorative appearance. However, from an aesthetic point of view, the panel produced with olive granules appears more visually appealing. This panel is characterized by a darker tone and a more natural distribution of the material structure on the surface, creating a visual effect that resembles natural decorative surfaces. The combination of color, texture, and surface heterogeneity gives the olive-based panel a greater potential for use as architectural interior elements and in decorative elements of indoor contemporary design.

One of the main limitations of this study is that only the physical properties of the material were investigated, while the mechanical characteristics were not analyzed. Mechanical tests, such as compressive strength, bending strength, and structural stability, will be the subject of a future study for a more comprehensive evaluation of the performance of these panels.

From a practical design perspective, differences in density and moisture content directly affect the suitability of CRPs for interior applications. Lower moisture absorption and capillary rise, as observed in olive- and beech-based CRPs, indicate better dimensional stability and make them more suitable for interior cladding and furniture. In contrast, higher values in pine- and plastic-based CRPs may require additional surface protection in humid conditions. Density also influences handling, installation, and the perceived material quality in architectural applications.

6. Conclusions

This study developed Composite Recycled Panels (CRPs) using pine, olive, beech, and recycled plastic granules bonded with a cement-based adhesive. The panels were evaluated for density, water absorption, and capillary rise. The results indicate that composite panels made from recycled wood and plastic granules, combined with a cement-based binder, exhibit different physical and visual characteristics depending on the filler material used. CRPs containing olive and beech particles exhibit lower levels of capillarity and moisture content, suggesting improved moisture resistance. In contrast, pine- and plastic-based panels exhibit higher moisture absorption. From an aesthetic point of view, the panel surface shows natural textures and distinct visual variations; in particular, the olive-based panel exhibits a more distinctive decorative appearance due to the pronounced tone and the more natural distribution of particles on the surface. Considering the relatively low density, moisture resistance, and aesthetic qualities, these panels demonstrate significant potential for use in interior spaces, such as suspended ceilings, decorative wall coverings, or lightweight interior design elements, where a combination of low weight, durability, and visual appearance of the material is required.

The results also indicate that CRPs based on olive and beech granules are more suitable for interior applications where reduced moisture absorption and dimensional stability are required, such as decorative wall claddings and suspended ceiling systems; however, these panels are more fragile due to their distinct physical and chemical characteristics, which influence fiber–matrix interaction and moisture response. Panels incorporating pine and plastic granules, due to their higher water absorption, may be more appropriate for controlled indoor environments with limited exposure to moisture. Furthermore, the relatively low density of all panels supports their use in lightweight architectural elements, facilitating installation and reducing structural load. Future research should focus on improving mechanical performance and durability to expand their applicability in more demanding interior conditions.

https://doi.org/10.3390/engproc2026167016

Author Contributions: Conceptualization, K.X. and B.N.; methodology, K.X. and B.N.; software, K.X. and B.N.; validation, K.X., B.N., L.B., I.R., S.J. and N.V.; formal analysis, B.N., L.B., I.R., S.J.; investigation, K.X. and N.V.; resources, L.B., I.R., S.J. and N.V.; data curation, K.X. and B.N.; writing—original draft preparation, K.X. and B.N.; writing—review and editing, K.X., B.N., L.B., I.R., S.J. and N.V.; visualization, K.X. and B.N.; supervision, K.X. and B.N.; project administration, K.X. and B.N.; funding acquisition, K.X., B.N., L.B., I.R. and S.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the "AKKSHI" (National Agency for Scientific Research and Innovation, Albania), with the project title "Sustainable Panels: Recycling wood, plastic, and glass for ventilated facades" under grant number 938/1 Prot. (Approval Date: 26 June 2025). The APC was funded by the AKKSHI.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are not available due to privacy or ethical restrictions.

Acknowledgments: The authors would like to thank the National Agency for Scientific Research and Innovation (AKKSHI), Albania, for funding and supporting this research.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

CBA	Cement–based adhesive
WPC	Wood–plastic composites
CRP	Composite recycled panel

References

1. Perišić, S.; Kalevski, K.; Grujić, A.; Nedeljković, D.; Stajić-Trošić, J.; Radojević, V. Effect of Moisture on the Mechanical Properties of Wood–Plastic Composites Hybridized with Metal Grid Layers. *Polymers* **2023**, *15*, 4705. [CrossRef] [PubMed]
2. Wang, W.; Guo, X.; Zhao, D.; Liu, L.; Zhang, R.; Yu, J. Water Absorption and Hygrothermal Aging Behavior of Wood-Polypropylene Composites. *Polymers* **2020**, *12*, 782. [CrossRef] [PubMed]
3. Ashori, A.; Sheshmani, S. Hybrid Composites Made from Recycled Materials: Moisture Absorption and Thickness Swelling Behavior. *Bioresour. Technol.* **2010**, *101*, 4717–4720. [CrossRef] [PubMed]
4. Mitaľová, Z.; Mitaľ, D.; Berladir, K. A Concise Review of the Components and Properties of Wood–Plastic Composites. *Polymers* **2024**, *16*, 1556. [CrossRef] [PubMed]
5. Gozdecki, C.; Wilczyński, A.; Kociszewski, M.; Zajchowski, S. Properties of Wood–Plastic Composites Made of Milled Particleboard and Polypropylene. *Eur. J. Wood Prod.* **2015**, *73*, 87–95. [CrossRef]
6. Amirta, J.R.; Suwinarti, W.; Kusuma, I.W.; Wardhani, I.Y. The Physical Properties of Wood-Plastic Composite Produced from Red Meranti (Shorea spp.) Sawdust, Polyethylene and Polypropylene. *J. Biodivers. Environ. Sci.* **2024**, *25*, 121–128.
7. Turku, I.; Keskisaari, A.; Kärki, T.; Puurtinen, A.; Marttila, P. Characterization of Wood Plastic Composites Manufactured from Recycled Plastic Blends. *Compos. Struct.* **2017**, *161*, 469–476. [CrossRef]
8. *ASTM D570-22*; Test Method for Water Absorption of Plastics. ASTM International: West Conshohocken, PA, USA, 2022. [CrossRef]
9. Flores-Hernández, M.Á.; Torres-Rendón, J.G.; Jiménez-Amezcua, R.M.; Lomelí-Ramírez, M.G.; Fuentes-Talavera, F.J.; Silva-Guzmán, J.A.; García Enriquez, S. Studies on Mechanical Performance of Wood-Plastic Composites: Polystyrene-Eucalyptus Globulus Labill. *BioResources* **2017**, *12*, 6392–6404. [CrossRef]
10. Coelho, K.V.; Líbano, E.V.D.G.; Ramos Filho, F.G.; Santos, S.F.; Pereira, P.S.; Bastos, D.C. Development of Wood Plastic Composite with Reduce dwater Absorption. *Int. J. Dev. Res.* **2021**, *11*, 44547–44551.
11. Burgstaller, C.; Renner, K. Water Uptake Behavior of Injection-Molded Wood–Plastic Composites. *J. Compos. Sci.* **2024**, *8*, 61. [CrossRef]

12. Xhexhi, K.; Nika, B.; Bregasi, L.; Rusi, I.; Jojic, S.; Vesho, N. In Pursuit of Sustainable Ventilated Façades: Moisture Response, Mechanical Performance, and Fire Behavior of Recycled Wood Particle/Epoxy Composite Panels. *Sustainability* **2025**, *18*, 226. [CrossRef]
13. Xhexhi, K.; Aliaj, B. Water Absorption, Moisture Content, and Capillarity Action in Wood: A Comparative Analysis of Fir, Pine, Beech, and Oak. *Adv. Eng. Forum* **2025**, *55*, 1–16. [CrossRef]
14. Xhexhi, K.; Aliaj, B. Water Absorption, Capillarity Action, and Materials Composition of Different Bricks and Panels as Part of the External Coating of Buildings. Case Study: Tirana, Albania. *E3S Web Conf.* **2024**, *585*, 01015. [CrossRef]
15. *EN ISO 15148*; Hygrothermal Performance of Building Materials and Products-Determination of Water Absorption Coefficient by Partial Immersion. European Committee for Standardization: Brussels, Belgium, 2003.
16. Väisänen, T. Effects of Thermally Extracted Wood Distillates on the Characteristics of Wood-Plastic Composites. Ph.D. Dissertation, University of Eastern Finland, Joensuu, Finland, 2016.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.