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Physical and Mechanical Characteristics of Coconut Coir-Based Composite Roof Tiles with Molasses Polyurethane Coating

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ABSTRACT

Lightweight roofing materials based on natural fibers are one alternative for developing more efficient and sustainable building materials. Coconut coir is an abundant agricultural waste product with potential as a raw material for composite roof tiles. This study aims to evaluate the effect of molasses substitution level variation on the physical and mechanical properties of coconut coir-based composite roof tiles coated with polyurethane. Composite roof tiles are produced from coconut coir particles and coated using a polyurethane system with varying molasses substitution level. Physical property testing included density, moisture content, water absorption, and thickness swelling, while mechanical properties were evaluated through flexural testing. All tests were conducted in accordance with JIS A 5908:2003 standards and analyzed using analysis of variance. The results showed that variations in molasses substitution level in the polyurethane coating system did not have a statistically significant effect on the physical and mechanical properties of composite roof tiles. Polyurethane-molasses coating tended to reduce water absorption and thickness swelling compared to uncoated roof tiles, but did not show a consistent pattern of change. The mechanical properties of composite roof tiles were relatively similar across all treatments, indicating that roof tile performance is more influenced by the material's internal characteristics and the compaction process.

Keywords: Citric Acid, Coatings, Coconut Coir, Composite Roof Tiles, Molasses, Natural Fiber

1. Introduction

Indonesia is one of the countries prone to earthquakes due to its geographical location at the meeting point of several major tectonic plates. This condition poses a high risk of building damage and casualties during an earthquake. [1], [2]. One of the main causes of fatalities in earthquakes is being hit by falling debris from collapsed buildings [2]. Conventional roofing materials such as clay tiles, ceramics, and concrete generally have a relatively large mass. Heavy roof mass can increase the fatality rate when building structures collapse [3]. Therefore, choosing lighter roofing materials that still have adequate mechanical strength is an important aspect of earthquake risk mitigation. Composite roof tiles have the potential to be a safer alternative roofing material in earthquake-prone areas.

Composite roofing tiles made from natural fibers have the advantages of being lightweight, structurally strong, and suitable for tropical climates [4]. In addition, the use of natural fibers supports the concept of sustainable development because they come from renewable resources [5]. Natural fibers such as coconut coir, bamboo, kenaf, jute, rice husk, and sorghum have been widely studied as raw materials for composite roof tiles [6]-[10]. Coconut coir, a plentiful by-product of Indonesia's coconut industry, is still rarely used in construction material [11]. The structural components of cellulose, hemicellulose, and lignin found in coconut coir contribute to the material's mechanical strength [12], [13]. Coconut coir is a possible material for use in composite roof tiles because of these qualities [13].

Lignocellulose composite roof tiles still face several obstacles related to their physical and mechanical properties [14]. The hydrophilic nature of natural fibers results in composite roof tiles with relatively high water absorption. High water absorption affects the mechanical strength of the material [15]. Changes in moisture content also affect the dimensional stability of composite roof tiles. Dimensional instability leads to a decline in mechanical performance during use [5]. Exposure to outdoor conditions, such as rain and temperature fluctuations, accelerates the deterioration of the material's physical properties. Efforts to enhance the physical and mechanical properties of composite roof tiles are needed to improve the material's performance and usability [16].

The physical and mechanical properties of composite roof tiles can be improved by applying coating materials. Coating materials reduce water absorption at the material's surface [17]. A decrease in water absorption improves the dimensional stability of roof tiles [18]. Coating also helps improve the bond between material components. This improved bonding increases the mechanical strength of composite roof tiles [19]. Polyurethane is known as a coating material with good adhesion to various substrates [17]. Polyurethane coating systems require modification to improve their efficiency and sustainability [20].

Molasses is a by-product of the sugar industry that contains reactive organic compounds [21]. These compounds have the potential to be used as additives in polyurethane-based coating systems [22]. The addition of molasses can increase the interfacial interaction between the coating and the composite roof tile substrate [23]. Hatakeyama [24] reported that the addition of molasses to polyurethane is thought to reduce water absorption. The test was conducted on polyurethane foam with molasses as an additive, and it was found that water absorption decreased with increasing molasses substitution level. Studies on the use of polyurethane-molasses coatings on composite roof tiles are still limited. The impact of this coating on the mechanical and physical characteristics of composite roof tiles made of coconut coir has not been widely reported.

This study was therefore designed to develop coconut coir-based composite roof tiles, incorporating a polyurethane-molasses coating to enhance material performance. Water absorption and dimensional stability were evaluated to characterize the composite roof tiles physical properties, while load-bearing capacity was assessed to determine their mechanical performance, all in accordance with the JIS A 5908:2003 standard. The results of this study provide information on the effect of coatings on the physical and mechanical properties of roof tiles. This study aims to evaluate the effect of molasses substitution level variation on the physical and mechanical properties of coconut coir-based composite roof tiles coated with polyurethane.

2. Materials and Methods

2.1. Materials and Tools

The main ingredient used is coconut coir obtained from the CV. Polatique, Indonesia. Other complementary ingredients include molasses from PTPN XII (East Java), citric acid from PT Digdaya Indo Karya (Bogor), polyol, and MDI (methylene diphenyl diisocyanate). The equipment used includes digital scales, a chipper (Pallmann, Germany), ring flaker (Pallmann, Germany), sieve, mixer, spray gun (Meiji, Japan), hot press, pH meter, viscometer, caliper, oven, 30 cm × 30 cm deckle box, Teflon sheet, iron plate, and brush. Mechanical property testing was performed using a Universal Testing Machine (Shimadzu 50 kN, Japan).

2.2. Preparation of Raw Materials

Coconut coir is chopped with a chipper until it is reduced in size. The chopped husks are then ground using a ring flaker to obtain more uniform particles. The coconut coir particles are then sieved using a 4-mesh sieve, with the retained fraction retained on a 20-mesh sieve. The particles that pass through the 4-mesh sieve and are retained on the 20-mesh sieve are used as raw material for composite roof tiles. The coconut coir particles are dried in an oven at 60–80 °C until they reach a moisture content of about 5%.

2.3. Adhesive Manufacturing

The adhesive is prepared by mixing a 59% concentrated citric acid solution with molasses containing 65% solids [25]. The molasses is then diluted to a solution concentration of 59%. The citric acid solution and molasses are mixed in a 50:50 ratio (w/w) to obtain a homogeneous adhesive.

2.4. Manufacture and Conditioning of Composite Roof Tiles

Composite roof tiles are made from coconut coir particles as the raw material, with a target density of 0.8 g/cm³. Coconut coir particles are mixed with a prepared citric acid-molasses adhesive at a 50:50 (w/w) ratio. The adhesive is sprayed evenly onto the particles' surface using a spray gun (Meiji, Japan) inside the mixer. The mixture is then dried in an oven at 100 ± 3 °C for 10 minutes as a pre-drying step to reduce the particles' moisture content. The dry mixture is then molded using a 30 cm × 30 cm deckle box with a target thickness of 0.6 cm. The pressing process is carried out in a hot press at 200 °C and 5 MPa for 10 minutes. The resulting composite roof tiles are then conditioned at room temperature (20 ± 2 °C) for one week before testing.

2.5. Coating Composite Roof Tiles

The coating was applied by preparing a polyurethane formulation containing methylene diphenyl diisocyanate (MDI) and a polyol. Molasses was added to the polyurethane system as a modifying component with varying concentrations of 0%, 10%, 20%, and 30% according to the composition in Table 1 [24]. The MDI content was maintained at 50% in all formulations, while molasses progressively replaced the polyol component; therefore, the combined proportion of polyol and molasses remained at 50%. Accordingly, the polyol content decreased from 50% to 20% as the molasses substitution level increased from 0% to 30%. Uncoated samples were used as controls (U). The coating weight on the composite roof tiles was set at 110 g/m². The coating mixture was homogenized until a uniform mixture was obtained. The coating solution was then applied evenly to the composite roof tile surface using a brush. The coated roof tiles were dried for 24 hours at room temperature until the coating hardened, then stored at room temperature before undergoing physical and mechanical testing.

Table 1. Formulation of Polyurethane–Molasses Coating

Formula	Material		
	MDI (%)	Polyol (%)	Molasse (%)
U	-	-	-
0	50	50	0
10	50	40	10
20	50	30	20
30	50	20	30

2.6. Testing the Physical and Mechanical Properties of Composite Roof Tiles

The physical and mechanical properties of composite roof tiles were tested in accordance with JIS A 5908:2003 [26]. The physical properties tested included density, moisture content, water absorption, and thickness swelling using samples measuring 5 cm × 5 cm × 0.6 cm. In comparison, the mechanical properties included modulus of elasticity and rupture, measured on samples 20 cm × 5 cm × 0.6 cm. Moisture content was determined by oven-drying at 103 ± 2 °C for 24 hours, while water absorption and thickness swelling were determined by immersion for 24 hours. Modulus of elasticity and modulus of rupture tests were conducted using the three-point bending method with a Universal Testing Machine at a loading rate of 10 mm/minute. All physical and mechanical property values were calculated based on the equations specified in the JIS A 5908:2003 standard [26].

2.7. Statistical Analysis

The test data were analyzed using one-way analysis of variance (ANOVA) at the 5% significance level. Duncan's multiple-range test was performed when the ANOVA indicated significant differences. All statistical analyses were performed using SPSS software.

3. Results and Discussion

3.1. Density and Moisture Content

The density value of coconut coir-based composite roof tiles with varying molasses substitution level in the polyurethane coating system ranges from 0.71 to 0.82 g/cm³. The density of uncoated roof tiles (U) is 0.78 g/cm³, whereas the density of composite roof tiles coated with polyurethane without molasses (0%) is somewhat lower at 0.75 g/cm³. The maximum density, 0.82 g/cm³, was obtained with the addition of 10% molasses, suggesting that the coating system can successfully fill voids and compact the roof tile structure at this concentration. On the other hand, when the molasses substitution level was raised to 20%, the density decreased to 0.71 g/cm³, the lowest value of all treatments. At a molasses substitution level of 30%, the density increased again to 0.73 g/cm³, although it was still lower than in the treatment without molasses and at 10%. In general, all density values obtained were close to the target density of 0.8 g/cm³ and within the range required by JIS A 5908:2003 [26].

The results of the analysis of variance (ANOVA) showed that variations in molasses substitution level in the polyurethane coating formulation had a significant effect on the density of composite roof tiles ($p < 0.05$) (Table 2). This was confirmed by Duncan's multiple-range test, as indicated by the letter notation differences in the Figure 1, where the 10% molasses substitution treatment (MDI:polyol = 50:40:10) was significantly different different from the treatments with 0%, 20%, and 30% molasses substitution. In contract, the uncoated treatment (U) did not differ significantly from the 0%, 20%, and 30% treatments. These results indicate that the effect of the coating formulation on density was not associated with a systematic concentration-dependent trend, but rather with the specific formulation at the 10% molasses substitution level. These differences in density may be associated with changes in the coating formulation, particularly coating viscosity and pore-filling efficiency during application and subsequent drying [27]. Therefore, the 10% molasses substitution treatment resulted in a density that differed significantly from the other coated formulations, although this result should not be interpreted as an optimum condition.

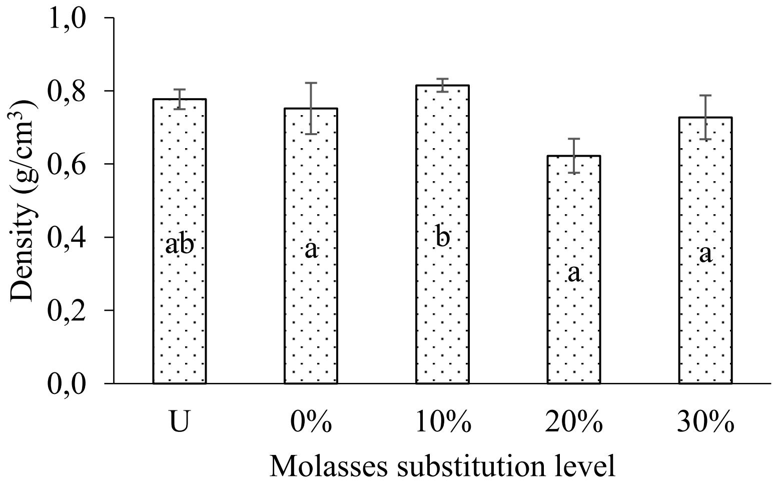

Figure 1. Density of Coconut Coir–Based Composite Roofing Tiles

Table 2. Statistical Analysis (ANOVA) of Physical and Mechanical Properties

Properties	ANOVA
Density	0,016**
Moisture content (MC)	0,076ns
Water absorption (WA)	0,203ns
Thickness swelling (TS)	0,137ns
Modulus of elasticity (MOE)	0,985ns
Modulus of rupture (MOR)	0,680ns

nsnot significance, **highly significant difference.

The moisture content of the coconut coir-based composite roof tiles ranged from 7.29 to 9.79% across the tested coating treatments (Figure 2). The lowest mean moisture content was observed in uncoated roof tiles (U) at 7.29%, while the highest occurred in polyurethane-coated roof tiles without molasses (0%) at 9.79%. Substitution levels of 10% and 20% molasses yielded mean values of 8.97% and 9.38%, respectively, before decreasing to 8.18% at the 30% level. As a result, there was no obvious pattern of rising or falling moisture content as the molasses level increased. Rather than being a systematic impact of the addition of molasses, the observed variations might represent heterogeneity among the replicate specimens. However, every tested value stayed below the JIS A 5908:2003 maximum moisture content.

The moisture content of composite roof tiles was not significantly affected by changes in the molasses substitute amount in the polyurethane coating system, according to ANOVA results ($p > 0.05$) (Table 2). Thus, the differences among treatments were insufficient to demonstrate a systematic effect of coating formulation on the final moisture content. The relatively narrow variation may instead reflect the greater influence of the drying, pressing, and conditioning conditions on moisture equilibration [28]. Furthermore, it is not likely that the polyurethane-molasses coating on the roof tiles' surfaces will have a direct impact on the material's internal moisture content. Usually, the coating system acts as a surface layer without changing the roof tile structure's moisture distribution [29].

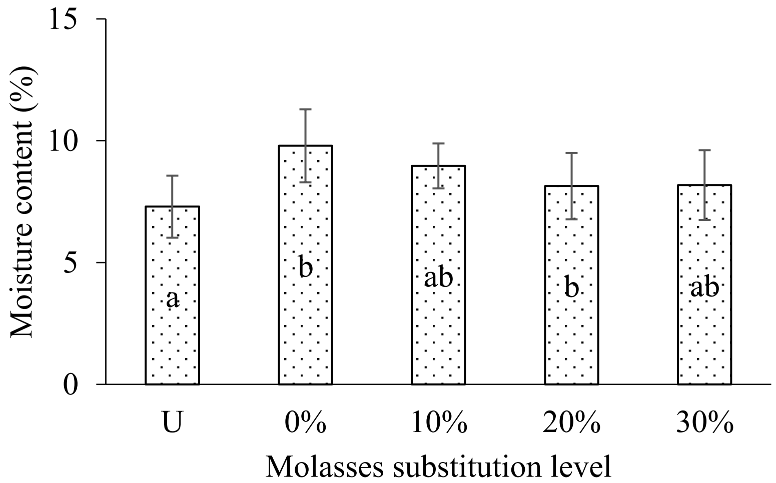

Figure 2. Moisture Content of Coconut Coir–Based Composite Roofing Tiles

3.2. Water Absorption and Thickness Swelling

Across the tested molasses substitution levels in the polyurethane coating system, water absorption in coconut coir-based composite roof tiles ranged between 43.84% and 60.54% (Figure 3). Uncoated roof tiles (U) showed the highest absorption at 60.54%, reflecting the high hydrophilicity typical of unprotected lignocellulosic materials. Applying polyurethane without molasses substitution (0%) reduced water absorption to 50.03%, indicating that the coating provided an initial barrier against water uptake. The lowest value was obtained at 10% molasses substitution (43.84%), followed by an increase to 55.45% at 20% and a subsequent decrease to 48.34% at 30%. Thus, the coating generally reduced water absorption relative to the uncoated control, but the response did not follow a consistent concentration-dependent trend [30].

The results of the analysis of variance (ANOVA) showed that variations in molasses substitution level in the polyurethane coating system did not have a significant effect on the water absorption of composite roof tiles ($p > 0.05$) (Table 2). This indicates that the differences in water absorption values observed between treatments were not statistically significant [31]. These conditions indicate that the hydrophilic nature of coconut coir and the internal structure of composite roof tiles play a more dominant role than variations in coating formulations in determining water absorption capacity [29]. In addition, the polyurethane-molasses coating applied to the roof tiles' surfaces, which is primarily intended to serve as a protective surface layer, is not yet fully capable of inhibiting water diffusion into the material's internal pores [30]. Thus, the coating system used tends to numerically reduce water absorption, but has not yet provided a statistically significant change in the water absorption behavior of composite roof tiles.

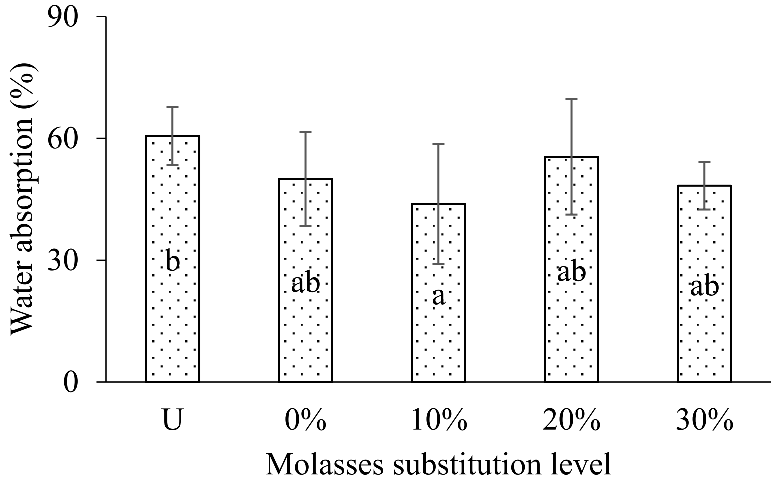

Figure 3. Water Absorption of Coconut Coir–Based Composite Roofing Tiles

The thickness swelling of coconut coir-based composite roof tiles after 24 hours of soaking ranged from 3.82% to 10.38% (Figure 4). Uncoated roof tiles showed the highest thickness swelling of 10.38%, while the application of polyurethane coating without molasses reduced this value to 6.27%. The addition of 10% molasses resulted in the lowest thickness swelling of 3.82%, indicating the coating's ability to limit changes in roof tile dimensions. At molasses substitution level of 20% and 30%, the thickness swelling values increased again to 5.95% and 4.87%, respectively, indicating no consistent downward trend with increasing molasses substitution level. All thickness swelling values obtained were still below the maximum limit required by JIS A 5908:2003, indicating sufficient dimensional stability of the composite roof tiles.

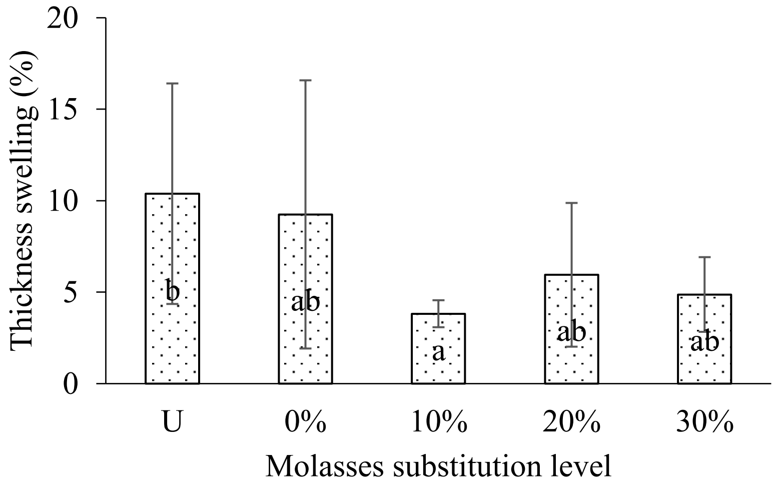

Figure 4. Thickness Swelling of Coconut Coir–Based Composite Roofing Tiles

The thickness swelling of the composite roof tiles was not substantially impacted by the molasses substitution level in the polyurethane coating, according to ANOVA ($p > 0.05$). The lack of a significant effect suggests that variation in coating formulation was insufficient to produce a measurable difference in dimensional change. Rather, the observed thickness swelling may have been more substantially influenced by the pore structure and hygroscopic nature of coconut coir, as well as the degree of compaction during pressing [32]. Increasing the substitution of molasses may also change the surface coverage and viscosity of the coating, which could lead to less uniform film formation [33]. Consequently, increasing the molasses level did not consistently improve resistance to thickness swelling. Although the polyurethane–molasses coating reduced thickness swelling relative to the uncoated condition, the differences among substitution levels were not statistically significant.

3.3. Modulus of Elasticity and Rupture

The modulus of elasticity (MOE) of the coconut coir-based composite roof tiles ranged from 704.83 to 816.64 N/mm² across the tested molasses substitution levels in the polyurethane coating system (Figure 5). The uncoated roof tiles (U) had an MOE of 759.37 N/mm², while polyurethane coating without molasses substitution (0%) resulted in a comparable value of 788.87 N/mm². The highest numerical value was obtained at 10% molasses substitution (816.64 N/mm²), followed by a decrease to 704.83 N/mm² at 20% and a slight increase to 741.74 N/mm² at 30%. Thus, MOE did not show a consistent trend with increasing molasses substitution.

Consistent with this variation, ANOVA indicated that molasses substitution level did not significantly affect MOE ($p > 0.05$). The absence of a significant treatment effect suggests that the coating formulation did not produce a measurable change in flexural stiffness. The observed variation may instead be related to inherent differences in particle composition, interparticle bonding, and compaction within the composite structure [34], [35]. As the polyurethane–molasses formulation was applied primarily as a surface layer, its contribution to the overall flexural stiffness of the roof tiles appears to have been limited.

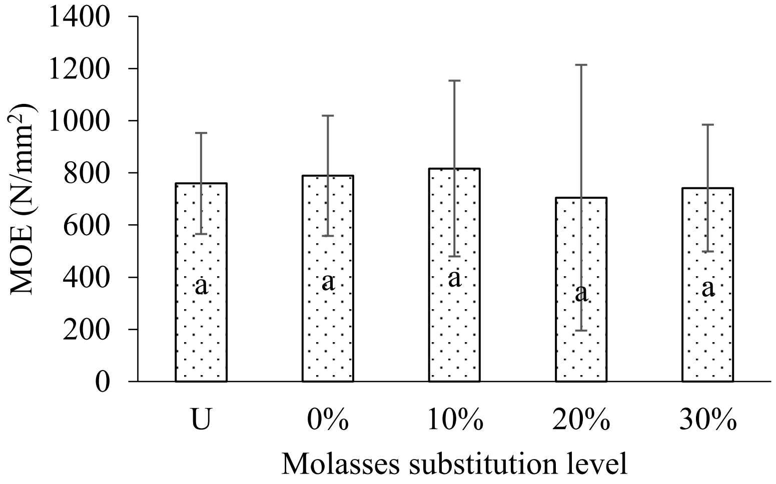

Figure 5. Modulus of Elasticity (MOE) of Coconut Coir–Based Composite Roofing Tiles

Coconut coir-based composite roof tiles with different molasses substitution levels in the polyurethane coating system had moduli of rupture (MOR) ranging from 8.18 to 10.19 N/mm² (Figure 6). Uncoated roof tiles showed the lowest MOR values, whereas polyurethane coatings, with or without molasses, yielded higher MOR values. Treatment with 10% molasses produced the highest MOR value, while at 20% and 30% molasses, the MOR value tended to decrease again. These changes in MOR indicate that molasses addition does not consistently increase the MOR with increasing concentration. All MOR values obtained have met the minimum requirements of JIS A 5908:2003.

Based on analysis of variance (ANOVA), variations in molasses substitution level in the polyurethane coating system did not have a significant effect on the MOR value of composite roof tiles ($p > 0.05$) (Table 2). This condition indicates that the MOR of roof tiles is more influenced by internal material factors, such as the quality of coconut coir particle bonding, particle distribution, and compaction effectiveness during the pressing process [34]-[36]. The polyurethane-molasses coating applied to the roof tile surface is thought to play a greater role in protecting the surface than in increasing the roof tile's load-bearing capacity to the point of breakage. Therefore, although variations in molasses substitution level affected MOR values, these changes were not strong enough to produce statistically significant differences in modulus of rupture.

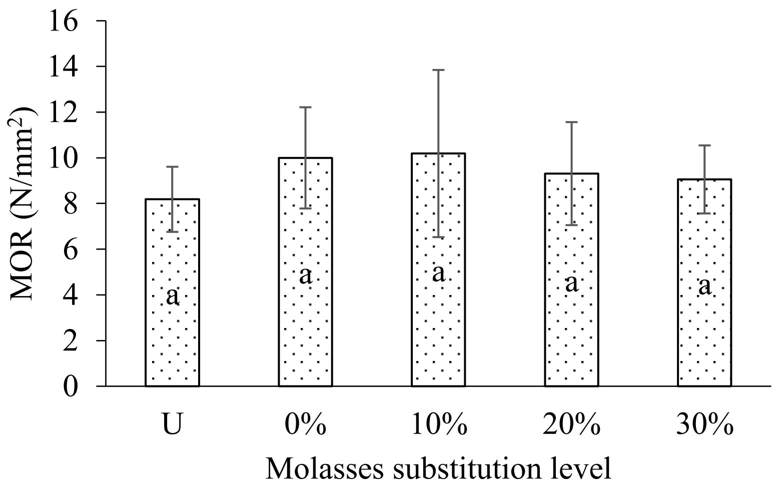

Figure 6. Modulus of Rupture (MOR) of Coconut Coir–Based Composite Roofing Tiles

4. Conclusion

The variation in molasses substitution level in the polyurethane coating system has been evaluated in relation to the physical and mechanical properties of coconut coir-based composite roof tiles. Overall, the coating treatments did not produce a consistent concentration-dependent trend across the evaluated properties. The polyurethane-molasses coating tended to improve several physical properties, particularly by reducing water absorption and thickness swelling compared with the uncoated roof tiles, although the magnitude of improvement varied among treatments. Furthermore, the mechanical properties of composite roof tiles were relatively similar across all treatments, indicating that mechanical performance was more influenced by the material's internal characteristics and compaction process than by variations in the coating formulation.

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