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IMPROVING MECHANICAL AND PHYSICAL PROPERTIES OF WOOD-PLASTIC COMPOSITES USING NATURAL RUBBER LATEX SLUDGE WASTE

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Abstract: *The disposal of synthetic materials and industrial by-products has become a pressing environmental issue, particularly in the wood and polymer sectors. This study investigated the feasibility of utilising natural rubber latex sludge waste as a reinforcing filler in wood-plastic composites (WPCs). The influence of latex sludge content (20-40 wt%) and particle size (≤149 µm, 149-400 µm, and 400-707 µm) on the mechanical, thermal and physical properties of WPCs were examined. The WPC panels were fabricated via twin-screw extrusion followed by hot compression moulding. The morphological analysis revealed that finer sludge particles enhanced interfacial adhesion and homogeneity. The thermal analysis demonstrated that the addition of latex sludge marginally improved the thermal stability of WPCs, with optimal performance observed at intermediate particle size. Higher sludge content increased the modulus of rupture but reduced the stiffness and hardness, attributed to the elastic nature of the sludge. Using finer latex sludge particles significantly improved WPC flexural strength and hardness, while reducing water absorption due to better matrix packing and decreased hydrophilicity. These findings highlighted the potential of latex sludge as a value-added filler in WPCs, offering an innovative approach to waste valorisation and material enhancement for sustainable industrial applications.*

Key words: *wood-plastic composites, fresh latex pond, rubberwood, polypropylene, statistical methods.*

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1. Introduction

The increasing environmental concerns associated with the disposal of non-biodegradable synthetic materials and industrial waste have led to a global shift towards sustainable alternatives in materials engineering. Wood-plastic composites (*WPCs*) have emerged as promising environmentally friendly candidates owing to their capacity to incorporate lignocellulosic materials into thermoplastic matrices, thereby reducing the dependency on virgin plastics while simultaneously valorising agricultural and forestry residues [9, 21]. *WPCs* offer an advantageous balance of low density, low cost, reduced water absorption, recyclability, reasonable strength and stiffness [6, 18], making them suitable for applications in the construction, automotive, and packaging sectors.

However, despite the growing popularity of *WPCs*, limitations in their mechanical and physical properties result from the inherent incompatibility between hydrophilic natural fibres and hydrophobic polymer matrices. To address this, researchers have explored the use of coupling agents and novel fillers that improve interfacial adhesion and composite homogeneity. Khamedi et al. [14] revealed that higher amounts of coupling agent (maleic anhydride) and lower amounts of reinforcement material improved the mechanical properties of *WPCs*, while Rao et al. [19] employed maleated olefins and silane coupling agents based on recycled wood flour and polyethylene to improve *WPCs*, which enhanced the compatibility and interfacial adhesion between the constituents [24]. Wang et al. [22] used biochar and carbon as reinforcing filler in *WPCs*. They found that the addition of biochar and carbon improved *WPC* dimensional stability and weathering performance.

One potentially underutilised and valuable waste is natural rubber latex sludge, a by-product generated in significant quantities by rubber processing industries. Thailand exports 35% of the rubber produced worldwide as concentrated latex, block rubber, and rubber smoke sheet [17]. Rubber latex sludge, rich in inorganic components such as magnesium oxide, phosphorus pentoxide, and residual rubber is often discarded, contributing to environmental pollution and waste management challenges [13]. Incorporating this waste into plastic composites would provide a viable recycling strategy and also introduce novel functionalities due to the rubbery nature and fine particulate structure of the sludge.

The mechanical reinforcement efficiency of latex sludge in *WPCs* remains largely unexplored, particularly in relation to critical influences such as filler content and particle size. Most existing studies on *WPCs* focused on conventional fillers like wood flour, rice husk, or bamboo fibres [4, 5, 7], with limited attention given to industrial by-products such as latex sludge. The moisture sensitivity of *WPCs* is a significant barrier to their broader application, especially in outdoor or humid environments. Therefore, a systematic investigation into how latex sludge waste impacts the mechanical strength, thermal stability, and water resistance of *WPCs* is important for both material design and waste valorisation.

This research offers new information about the feasibility of using natural rubber latex sludge waste as a functional filler in *WPCs*. The influences of latex sludge content and particle size on the mechanical properties (modulus of rupture, modulus of elasticity, hardness) and physical behaviour (water absorption) of polypropylene-based composites reinforced with rubberwood flour were evaluated. The novelty of this study lies in the dual approach of enhancing composite performance while simultaneously utilising an industrial waste, contributing to sustainable material innovation. The results offer practical insights into composite formulation and also broaden the material base for high-performance *WPCs* using bio-derived waste.

2. Materials and Methods

2.1. Materials

Polypropylene (*PP*) granules, marketed under the tradename 1100NK with a melt flow index of 11 g/10 min at 230°C, were procured from IRPC Public Company Limited (Rayong, Thailand). Rubberwood sawdust, used as the reinforcing material, was supplied by Plan Creations Co., Ltd., located in Trang, Southern Thailand. Latex sludge waste derived from the rubber latex industry, specifically from fresh latex ponds, was utilised as the filler material in *WPCs*. The sludge was collected from a rubber glove manufacturing facility in Songkhla, Southern Thailand. The sludge was processed through industrial-scale techniques such as drying, grinding, and sieving. These processes are well-established and scalable, allowing for the practical utilisation of latex sludge in the production of *WPCs* at industrial level. Maleic anhydride grafted polypropylene (*MAPP*), obtained from Sigma-Aldrich (Missouri, USA), was employed as a coupling agent to improve the interfacial adhesion between the PP matrices, the wood-based reinforcement and the latex sludge filler.

2.2. Composite Processing

The latex sludge waste and rubberwood sawdust were pre-processed before the fabrication of the *WPC* samples. Latex sludge waste, derived from a fresh latex pond, was oven-dried at 120°C for 48 hours to reduce the moisture content to 1-2% and subsequently ground into a fine powder using a hammer mill. The latex sludge flour (*LSF*) was then sieved and categorised into three particle size ranges: *1)* retained between 25 and 40 mesh (400-707 μm), *2)* retained between 40 and 100 mesh (149-400 μm), and *3)* passed through 100 mesh (≤149 μm). Similarly, rubberwood flour (*RWF*) was sieved using a 40-mesh screen and dried at 110°C for 8 hours.

The *WPC* production involved two main stages. In the first stage, *WPC* pellets were prepared by melt-blending the *LSF* and *RWF* with *PP* and *MAPP* using a twin-screw extruder (Model CTE-D25L40, Chareon Tut Co., Ltd., Samut Prakan, Thailand). The WPC blend formulations are presented in Table 1. The extruder consisted of seven heating zones, with temperatures maintained between 165 and 185°C from the feed section to the die. The screw rotation speed was held constant at 50 rpm. The extruded strands were subsequently pelletised using a cutting machine. In the second stage, the *WPC* pellets were oven-dried at 110°C for 8 hours to minimise moisture content (1-2%), then moulded into panels using a hot compression moulding machine. The moulding process was carried out at 190°C and 1000 psi for 15 minutes to form panels with dimensions of 200 mm (width) × 250 mm (length) × 4.8 mm (thickness). These panels were then machined into test specimens of appropriate dimensions for mechanical and physical characterisation in accordance with the American Society for Testing and Materials (ASTM) standards.

Formulation of wood-plastic composites in the experiment Table 1

Sample code	Particle size [μm]	*PP* [wt%]	*RWF* [wt%]	*LSF* [wt%]	*MAPP* [wt%]
R50	-	46	50	-	4
LR30L20	400-707	46	30	20	4
LR20L30		46	20	30	4
LR10L40		46	10	40	4
MR30L20	149-400	46	30	20	4
MR20L30		46	20	30	4
MR10L40		46	10	40	4
SR30L20	≤149	46	30	20	4
SR20L30		46	20	30	4
SR10L40		46	10	40	4

Note: PP: Polypropylene; RWF: Rubberwood flour; LSF: Latex sludge flour; MAPP: Maleic anhydride-grafted-polypropylene; wt%: Percent by weight.

2.3. Analytical Methods
2.3.1. Thermal Analysis

Thermogravimetric analysis (*TGA*) was carried out using a Perkin Elmer instrument (TGA-7, USA) to evaluate the thermal stability of *WPCs* filled with varying contents and particle sizes of latex sludge. The analysis was performed over a temperature range of 50 to 600°C, with a constant heating rate of 10°C per minute under a nitrogen atmosphere. WPC powder (5-10 mg) was tested and the degradation temperatures were reported as the onset temperatures corresponding to the initial weight loss.

2.3.2. Morphological Analysis

A Field Emission Scanning Electron Microscope (FE-SEM) (Model FEI Apreo, FEI Company, Oregon, USA) operating at an accelerating voltage of 20 kV was employed to examine the fractured surfaces, interfacial characteristics, and filler distribution within the plastic matrices. Before the FE-SEM analysis, all the *WPC* specimens were oven-dried at 50°C for 24 hours. Subsequently, the cross-sectional surfaces were gold-coated to prevent electrostatic charging and micrographs were captured at a magnification of 3,000×.

2.3.3. Statistical Analysis

Statistical evaluations of the mechanical and physical properties of the *WPCs* were carried out using one-way analysis of variance (ANOVA), followed by Tukey's multiple comparison test. The influence of varying contents and particle sizes of latex sludge on *WPC* properties was examined, with all analyses conducted at a significance level of 5% (α = 0.05).

2.4. Characterisation

2.4.1. Flexural Tests

The flexural properties, including modulus of rupture (*MOR*) and modulus of elasticity (*MOE*), of the WPCs were assessed using a standard mechanical universal testing machine (Model NRI-TS500-50, Narin Instrument Co., Ltd., Samut Prakan, Thailand). The three-point bending test was performed in accordance with the ASTM D 790-17 standard [3], employing a crosshead speed of 2 mm/min and a support span of 80 mm. Rectangular specimens with dimensions of 13 mm (width) × 100 mm (length) × 4.8 mm (thickness) were tested at 25°C, with five replicates conducted for each formulation. The resulting data were averaged to determine the *MOR* and *MOE*.

2.4.2. Hardness Test

The hardness of the *WPCs* was evaluated in accordance with the ASTM D 2240-15 standard [1], employing Shore D Durometer scales (Model GS-702G, Teclock Corporation, Nagano, Japan). Tests were conducted at 25°C using specimens with nominal dimensions of 20 mm (width) × 20 mm (length) × 4.8 mm (thickness), with five replicates performed for each formulation.

2.4.3. Water Absorption Measurement

The water absorption (*WA*) behaviour of the *WPCs* was assessed through a short-term immersion test conducted over a 24-hour period, in accordance with the ASTM D 570-98 standard [2]. Five specimens were extracted from the *WPC* panels and preconditioned by oven-drying at 50°C for 24 hours to minimise the initial moisture content. Each specimen, with dimensions of 13 mm (width) × 26 mm (length) × 4.8 mm (thickness), was then immersed in distilled water maintained at 25°C. Before immersion, the initial mass of each sample was recorded. After 24 hours, the specimens were removed from the water, gently blotted to eliminate surface moisture, and promptly weighed to determine the water uptake. The percentage of water absorbed was calculated using Equation (1).

$$WA_t(\%) = \frac{W_t - W_0}{W_0} \cdot 100 \qquad (1)$$

where:
W_0 is the initial dry mass [g];
W_t – the wet mass after immersion [g].

3. Results and Discussion

3.1. Morphological Analysis of the WPCs

Figure 1 presents FE-SEM images illustrating the effect of both the content and particle size of natural rubber latex sludge on the morphological structure of *WPCs*. The control sample (Figure 1a) had a smooth fracture surface with large interfacial gaps between the *RWF* and the polypropylene matrices, indicating poor compatibility and weak interfacial adhesion. By contrast, Figure 1b shows that the incorporation of *LSF* (400-707 µm) resulted in a rougher morphology with visible voids and poor particle dispersion. As the particle size decreased, improved morphological characteristics were observed. Figure 1c, with medium-sized particles (149-400 µm), shows a more compact structure with better filler dispersion and reduced gaps, suggesting enhanced interfacial adhesion. The most uniform morphology was seen in Figure 1d, with fine particles (≤149 µm) well dispersed within the matrix, forming a dense and homogeneous structure. The presence of more pronounced micro-fractures was attributed to stronger interfacial bonding, which resisted cracks by debonding and instead promoted tearing of the wood fibre. Results suggested that reducing the particle size of latex sludge improved the compatibility, homogeneity, and structural consistency of the *WPCs*.

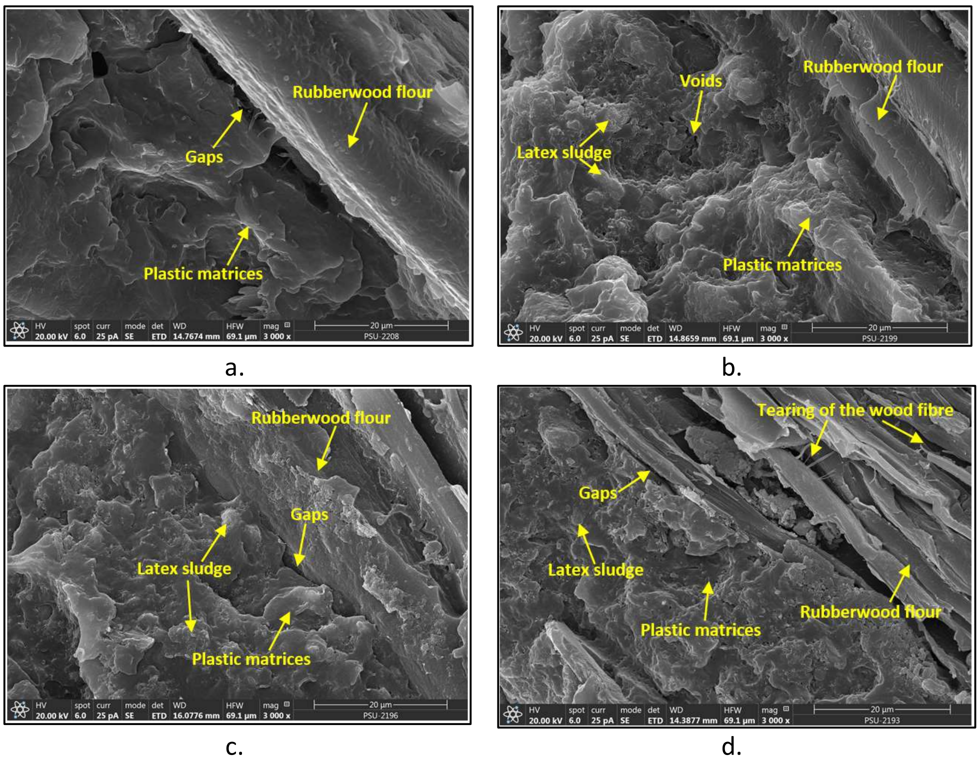

Fig. 1. *FE-SEM images of WPCs prepared with the following formulations: a. R50; b. LR30L20; c. MR30L20; d. SR30L20*

3.2. Thermal Stability of the WPCs

Thermogravimetric analysis (*TGA*) and derivative thermogravimetric (*DTG*) curves for the *WPCs*, prepared using particle sizes of 400-707 µm, 149-400 µm, and ≤149 µm, are presented in Figures 2a and 2b. Figure 2a shows that the thermal stability of the *WPCs* was not significantly influenced by *LSF* particle size. *WPCs* incorporating sludge particles smaller than 149 µm (denoted *S*) displayed the lowest thermal stability, followed by those containing particles in the 400-707 µm range (denoted *L*), while the highest thermal stability was found in *WPCs* with particle sizes between 149 and 400 µm (denoted *M*). Srivabut et al. [20] also reported that the addition of smaller particles reduced the thermal resistance of *WPCs*, consistent with our results demonstrating decreased thermal stability for *LSF* particles ≤149 µm. Further analysis revealed that *WPCs* incorporating latex sludge exhibited greater thermal stability compared to composites reinforced with only *RWF* (R50). This enhancement was attributed to the complex organic structure of the natural rubber residues in the sludge, which contributed to char formation and reduced the volatility of the degradation products [13].

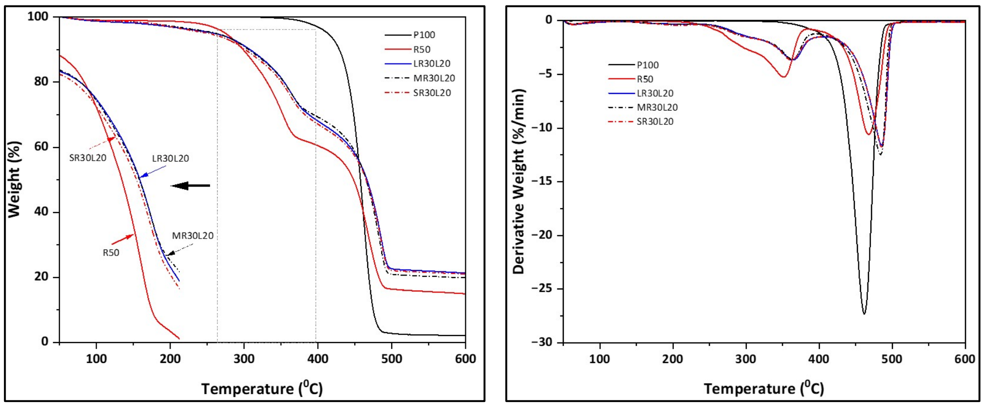

Fig. 2. *Curves of (a.) TGA and (b.) DTG for WPCs containing different latex sludge contents and particle sizes*

Figure 2b shows that the decomposition behaviour of the *WPCs* was characterised by two degradation peaks. For *WPCs* without latex sludge (R50), the first peak was recorded at 249°C, with the maximum rates of weight loss (*DTG*) occurring at 351°C. This stage corresponded to the thermal degradation of wood constituents such as hemicellulose, cellulose, and lignin [8, 12]. Similarly, for *WPCs* incorporating *LSF* with particle sizes of 400-707 µm, 149-400 µm, and ≤149 µm, the first degradation peak was observed at 273°C, with peak *DTG* values recorded at 368, 369, and 362°C respectively, associated with the decomposition of the natural rubber in the latex sludge and the wood components [11]. In the second step, the decomposition of *PP* and *MAPP* for *WPCs* with and without *LSF* occurred at 418-433°C with *DTG* in the range of 364-488°C. Results indicated that variations in *LSF* particle size did not impact the thermal stability of the *WPCs*.

3.3. Flexural Properties of the WPCs

The effect of latex sludge content and particle size on the modulus of rupture (*MOR*) and modulus of elasticity (*MOE*) of the *WPCs* is shown in Figures 3 and 4 respectively. The findings indicated that increasing the latex sludge content from 20 to 40 wt% resulted in an increase in *MOR* but a decrease in *MOE*. This opposing trend implied that while the incorporation of latex sludge enhanced the resistance of *WPCs* to flexural failure, it concurrently reduced their rigidity under bending loads. Likewise, the observed increase in *MOR* with greater sludge content was attributed to the energy-absorbing characteristics of the rubbery phase derived from natural latex residues. The *MOR* values of *WPCs* containing latex sludge were higher than composites reinforced with only *RWF* (R50), suggesting a synergistic reinforcing effect when latex sludge was combined with rubberwood flour. The presence of natural rubber in the latex sludge enhanced interfacial bonding within the *WPC* structures, thereby increasing their load-bearing capacity [11]. Nevertheless, owing to the inherently more rigid nature of *RWF*, *WPCs* reinforced with *RWF* exhibited a higher modulus [15].

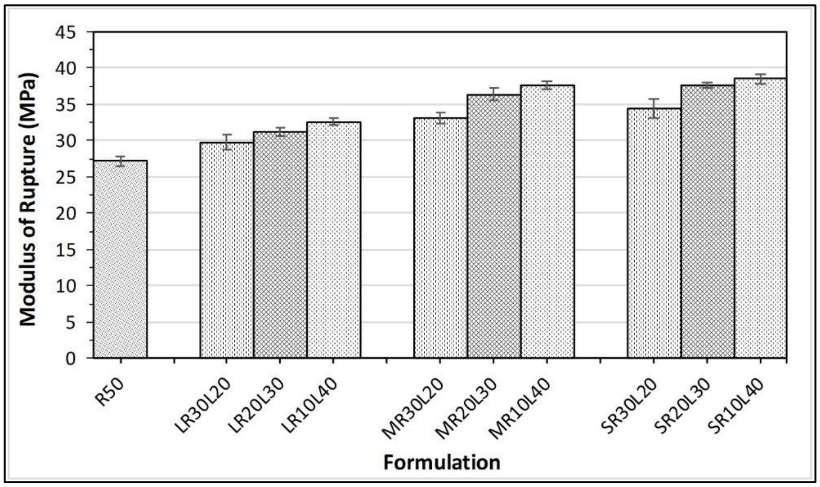

Fig. 3. *Effect of latex sludge content and particle size on the modulus of rupture of WPCs*

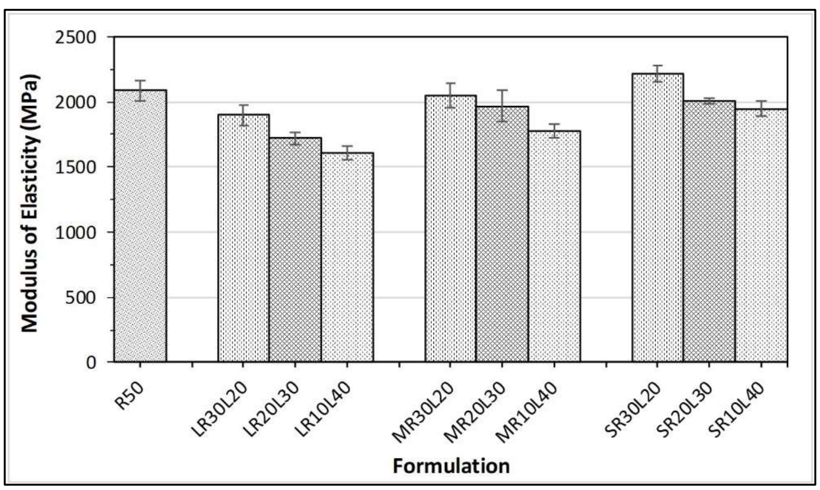

Fig. 4. *Effect of latex sludge content and particle size on the modulus of elasticity of WPCs*

Figures 3 and 4 revealed that reducing the particle size of the latex sludge considerably improved the *MOR* and *MOE* of the *WPCs* by facilitating efficient stress transfer and minimising interfacial defects [11]. The highest values for both properties were recorded in *WPCs* incorporating latex sludge particles smaller than 149 µm (*S*), followed by those with particles in the 149-400 µm range (*M*), with the lowest values in *WPCs* containing particles sized 400-707 µm (*L*). This trend correlated well with the FE-SEM observations in Figure 1, showing that *WPCs* with finer sludge particles (SR30L20) had a more compact and homogeneous morphology, with fewer interfacial voids and better filler dispersion compared to *WPCs* containing larger particles (e.g., LR30L20), where poor dispersion and visible gaps were evident. Zhou et al. [23] highlighted that decreasing filler particle size typically improved *MOR* and *MOE* due to better dispersion and reduced stress concentration. The ANOVA results (Table 2) confirmed that latex sludge content and particle size significantly ($p < 0.05$) affected the *MOR* and *MOE* of the *WPCs*. No statistically significant difference in *MOR* was found between WPCs containing 20 and 30 wt% *LSF* (both denoted with suffix *A*), whereas a significant increase in *MOR* was observed when the *LSF* content was increased from 30 wt% (suffix *A*) to 40 wt% (suffix *B*). Similarly, *WPCs* produced with sludge particles in the 400-707 µm range (suffix *a*) displayed significantly lower *MOR* than those with 149-400 µm particles (suffix *b*), while no statistically significant difference in *MOR* was found between *WPCs* containing 149-400 µm and <149 µm particles (both denoted as suffix *b*).

Table 2

Results of statistical analysis in effect of LSF contents and sizes on the mechanical and physical properties for wood-plastic composites

Property	LSF content [wt%]	LSF particle size [µm]			*p*-value
		400-707	149-400	≤149	
MOR [MPa]	20	29.8 Aa	33.2 Ab	34.4 Ab	*0.000**
	30	31.3 Aa	36.4 Bb	37.7 Bb	*0.000**
	40	32.6 Ba	37.6 Bb	38.5 Bb	*0.000**
p-value		*0.029**	*0.023**	*0.031**	
MOE [MPa]	20	1900 Aa	2049 Aab	2216 Ab	*0.036**
	30	1720 Ba	1967 Ab	2004 Bb	*0.000**
	40	1604 Ca	1778 Bb	1947 Bc	*0.000**
p-value		*0.000**	*0.017**	*0.012**	
Hardness (Shore D)	20	76.4 Aa	77.0 Aab	77.5 Ab	*0.034**
	30	76.1 Aa	76.8 Aab	77.3 ABb	*0.041**
	40	75.8 Aa	76.7 Ab	76.9 Bb	*0.019**
p-value		*0.063*	*0.071*	*0.042**	
WA [%]	20	2.04 Aa	1.57 Aab	1.30 Ab	*0.028**
	30	1.74 Ba	1.32 Bb	1.14 Ac	*0.002**
	40	1.49 Ca	1.16 Bb	0.93 Bb	*0.016**
p-value		*0.002**	*0.007**	*0.011**	

*Note: *LSF contents and sizes significantly affected the measured properties at p-value < 0.05. Means within each property with the same letter (suffixes A-C for effect of LSF contents and suffixes a-c for effect of LSF particle sizes) are not significantly different (α =0.05).*

3.4. Hardness of the WPCs

The effect of latex sludge content and particle size on the hardness of *RWF*-polypropylene composites is presented in Figure 5. An increase in latex sludge content from 20 to 40wt% led to a noticeable reduction in hardness, primarily attributed to the inherent softness of the natural rubber component in the sludge, which was less rigid than *RWF* [8]. Substituting a higher proportion of RWF with latex sludge decreased the rigidity of the WPC structure because the higher latex content weakened the surface rigidity [13].

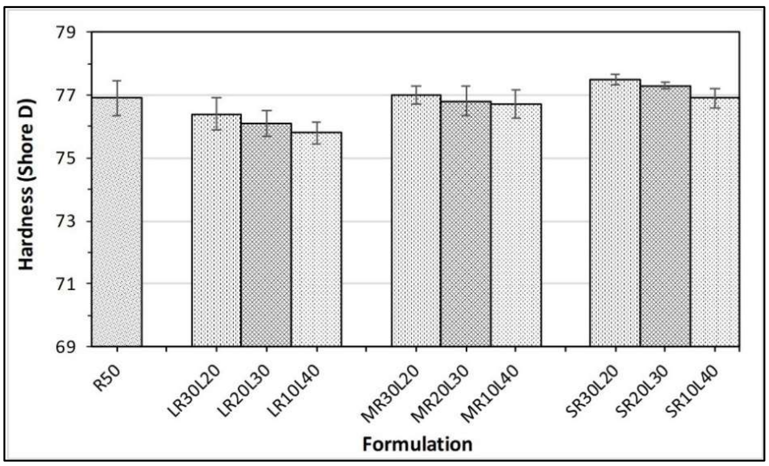

Fig. 5. *Effect of latex sludge content and particle size on the hardness value of WPCs*

WPCs incorporating sludge particles smaller than 149 µm (*S*) exhibited the highest hardness values, followed by those containing particles in the 149-400 µm range (*M*), while the lowest hardness was found in *WPCs* with particle sizes between 400 and 707 µm (*L*). This was attributed to the more uniform distribution of the finer particles within the polymer matrices, which effectively minimised the presence of voids [12]. Incorporating sludge particles smaller than 149 µm yielded higher hardness values compared to composites produced exclusively from polypropylene and *RWF* (R50), suggesting that finer sludge particles contributed to increased composite hardness. Khamtree et al. [16] also mentioned that *WPCs* using finer latex sludge particles maintained or even exceeded the hardness of *WPCs* without latex, emphasising the reinforcing synergy between fine particles and polypropylene matrices.

3.5. Water Absorption Behaviour of the WPCs

Figure 6 shows the effect of latex sludge content and particle size on the water absorption percentage of the *WPCs*. An increase in latex sludge content from 20 to 40 wt% resulted in a progressive reduction in the absorbed water percentage of the *WPCs*, primarily attributed to the lower hygroscopic nature of the rubber-rich sludge compared to rubberwood flour [14].

Partial substitution of wood flour with latex sludge reduced the hydrophilicity of the *WPC* material. The *WPCs* incorporating latex sludge exhibited significantly lower water uptake than those composed solely of polypropylene and *RWF* (R50). Srivabut et al. [20] reported a similar observation, where rubberwood-latex sludge composites exhibited reduced hydrophilicity relative to wood-only composites, with smaller particle sizes being most effective.

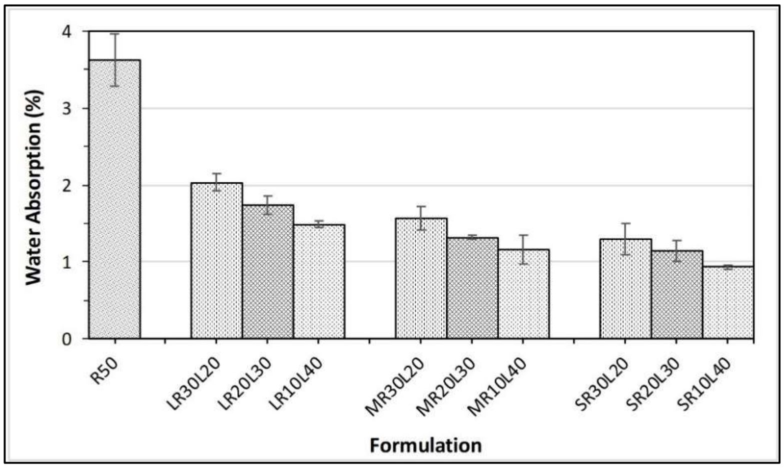

Fig. 6. *Effect of latex sludge content and particle size on the water absorption percentage of WPCs*

Figure 6 also showed that the water absorption behaviour of the *WPCs* depended on sludge particle size. The *WPCs* containing particles smaller than 149 µm (*S*) exhibited the lowest levels of water absorption, followed by those with particle sizes between 149 and 400 µm (*M*), while the highest absorption was recorded for *WPCs* with the largest particles, 400-707 µm (*L*). The findings indicated that finer sludge particles were more effective at filling voids within the polymer matrices, thereby limiting the free volume available for water penetration and improving the resistance of the composite to moisture uptake. Hamzeh et al. [10] also revealed that larger particles compromised matrix-filler interactions and introduced porosity, thereby increasing water absorption.

4. Conclusions

This research demonstrated the potential of *NR* latex sludge waste as a reinforcing filler in PP-based *WPCs*. The combined effects of filler content and particle size were evaluated, with results indicating that sludge waste can serve as an environmentally responsible waste management solution to enhance composite performance. The incorporation of latex sludge promoted effective interfacial bonding and matrix homogeneity, with fine particles providing the most favourable balance between *WPC* mechanical strength, hardness retention, and moisture resistance. The elastic character of the sludge moderated *WPC* stiffness, with the observed improvements in load-bearing capacity and reduced water absorption indicating clear advantages for applications where durability and dimensional stability are critical. Importantly, the findings highlighted the decisive role of particle size control in optimising filler efficiency and offered guidance for industrial-scale processing of sludge-modified *WPCs*. Beyond material performance, our results illustrated a sustainable pathway for valorising an abundant industrial by-product into value-added composites. This approach aligns with circular economy principles and broadens the potential application of WPCs in sectors such as decking, packaging, and construction materials.

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