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Determination of Some Selected Mechanical Properties of Recycled Aluminium Alloy Modified with Micro- And Nano-Sized Additives

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ABSTRACT

The growing demand for sustainable materials has intensified interest in recycled aluminium alloys, which present a more energy-efficient alternative to primary aluminium production. However, recycled aluminium typically suffers from diminished mechanical properties due to the presence of impurities and microstructural irregularities. This study explores the influence of nano- and micro-sized reinforcements (black powder, graphite, and waste glass) on the mechanical performance of recycled aluminium alloys. Aluminium was mixed with 6%, 8%, and 10% weight fractions of each reinforcement, and processed using the sand casting technique to produce composite samples. The composites were evaluated for their physical, metallurgical, and mechanical properties. Results indicate that nano-scale reinforcements enhanced hardness, impact strength, and tensile strength relative to their micro-scale counterparts. The highest hardness (84.36 HV) was achieved with 10% nano-glass (GL10), while 8% nano-black powder (BP8) yielded the highest impact strength (18.67 J). Additionally, 10% nano-graphite (G10) produced the highest tensile strength (103 MPa), surpassing the micro-reinforced equivalent (78 MPa). These findings confirm the potential of nano-reinforced recycled aluminium alloys for use in high-performance engineering applications.

INTRODUCTION

Aluminium alloys are widely utilised in industries such as automotive, aerospace, and construction due to their lightweight nature, corrosion resistance, and favourable mechanical properties (Schlesinger, 2021; Davis, 2020). However, the primary production of aluminium via the Hall-Héroult process is highly energy-intensive, consuming approximately 186 MJ/kg and contributing significantly to carbon emissions (International Aluminium Institute [IAI, 2023). In contrast, recycled aluminium alloys require only 5-10% of the energy needed for primary production while maintaining comparable mechanical properties (Capuzzi and Timelli, 2022), making them an attractive alternative for sustainable material development. Despite the benefits of recycling, recycled aluminium often contains impurities and structural inconsistencies, which adversely affect hardness, tensile strength, and impact resistance (Modaresi and Müller, 2022). Therefore, this research focused on reinforcing the recycled aluminium with glass powder (GL), graphite powder (black powder B). These reinforcements enhance aluminium alloys by refining the microstructure, improving load transfer efficiency, and introducing strengthening mechanisms that contribute to better mechanical stability. Despite this, recycled aluminium alloys often suffer from diminished mechanical integrity due to the presence of impurities such as iron, silicon, and oxide inclusions introduced during the collection, melting, and casting processes (Al-Refaie *et al*., 2023).

The effectiveness of these reinforcements largely depends on their particle size, as nano-sized reinforcements offer a higher surface area-to-volume ratio, improved particle-matrix interactions, and enhanced grain refinement compared to their micro-sized counterparts (Huang *et al*., 2023). However, while nano-reinforcements generally enhance mechanical properties more effectively than micro-sized additives, limited research has directly compared the performance differences between nano- and micro-sized reinforcements in recycled aluminium matrices (Zhao *et al*., 2024; Wang *et al*., 2022). Understanding the structure-property relationship between reinforcement size and mechanical performance is critical for optimising composite design and ensuring the long-term stability of aluminium-based materials.

To address these mechanical limitations, researchers have explored the use of reinforcements, particularly micro and nano-additives, to improve the strength, hardness, ductility, and impact resistance of recycled aluminium matrices. Reinforcement strategies involve the dispersion of high-performance materials such as graphite powder (a form of carbon with excellent lubricating and thermal properties), black powder (carbonaceous by-product with potential strengthening properties), and glass powder (amorphous silica-based additive) into the aluminium matrix (Gupta and Singh, 2023; El-Kady *et al*., 2022). These additives enhance mechanical performance by improving load transfer, introducing dislocation barriers, and refining grain structure through heterogeneous nucleation. One of the most critical factors influencing the performance of such composites is the size of the reinforcement particles. Nano-sized particles, owing to their large surface area-to-volume ratio, offer better dispersion and stronger interfacial bonding with the matrix. These properties contribute to grain refinement, load transfer efficiency, and overall mechanical reinforcement (Huang *et al*., 2023). For example, nano-graphite and nano-glass additives have been shown to improve hardness and tensile strength more effectively than their micro-sized counterparts (Zhao *et al*., 2024; Wang *et al*., 2022). However, nanoscale particles may also lead to challenges such as agglomeration and difficulty in uniform distribution during casting, which can adversely affect the final properties if not properly managed.

On the other hand, micro-sized reinforcements are easier to process and distribute in molten aluminium but often exhibit weaker particle-matrix bonding due to their lower specific surface area. While they may not achieve the same degree of hardness or tensile strength as nano-reinforcements, micro-sized additives can contribute to improved toughness and impact resistance under dynamic loading conditions (Ramesh *et al*., 2021). The effectiveness of each reinforcement size depends on multiple parameters, including composition, morphology, processing method, and the base alloy's condition.

METHODOLOGY

Materials selection and preparation

The primary material used in this study was recycled aluminium cans, sourced from local scrap yards. The reinforcements included nano and micro-sized battery-derived black powder, graphite, and discarded glass, which were processed and characterized before incorporation into the aluminium matrix. The nano- and micro-sized particles were obtained through high-energy ball milling at 350 rpm for 5 hours, followed by sieving to separate particle sizes (Kumar *et al*., 2022).

Experimental design and sample preparation

The experiments consist of 9 runs conducted in triplicate for each nano- and micro-sized particle as shown in Table 1. Stir casting was used for composite fabrication to ensure uniform distribution of reinforcements. In this case, the recycled aluminium cans were cleaned, degreased, and melted in a pit furnace at 700°C. The molten aluminium was stirred at 250 rpm for three minutes as recommended in previous studies (Huang *et al.*, 2023), while preheated reinforcements (nano/micro black powder, graphite, and waste glass) were gradually introduced. After thorough mixing, the molten metal was poured into preheated (250-300 oC metallic moulds and allowed to solidify. The cast samples were normalised to relieve internal stresses. The aluminium ingot was characterised by XRD and SEM to identify the crystal structure, phases, and morphology of the ingot.

Table 1: Experimental Processing Parameters and Levels

	Aluminium (%)	Glass (%)	Graphite (%)	Black Powder (%)	Code (%)
1	94	6	0	0	GL6
2	92	8	0	0	GL8
3	90	10	0	0	GL10
4	94	0	6	0	G6
5	92	0	8	0	G8
6	90	0	10	0	G10
7	94	0	0	6	BP6
8	92	0	0	8	BP8
9	90	0	0	10	BP10

Mechanical tests

To evaluate the effects of nano- and micro-reinforcements, hardness, tensile and impact tests were conducted. Hardness was measured using the Matsuzawa MMT-X Vickers Hardness Tester, applying a 500 N load with a 10-second dwell time on polished samples (ASTM E92 standard). Three readings were taken per sample, and the average value was recorded. Tensile strength was assessed using an Instron-Series 3369 Universal Testing Machine, following ASTM E8M-13. Samples with a diameter of 1.5 cm and 10 cm length were subjected to axial loading at a strain rate of 10^{-5} s^{-1} until fracture. The Charpy V-Notch Impact Test (ASTM E23) was conducted using a pendulum impact tester, with samples of 10 × 10 × 50 mm, notched at 45° with a depth of 1 mm. The absorbed impact energy was recorded.

RESULTS AND DISCUSSION

The particle sizes for milled black powder, graphite and glass are 2.36 µm in size and 24.6 nm, 3.26 nm and 18.5 nm, respectively. Figure 1 shows the transmission electron micrograph (TEM) for graphite particles, indicating particle sizes ranging between 1.4 nm to 5.8 nm.

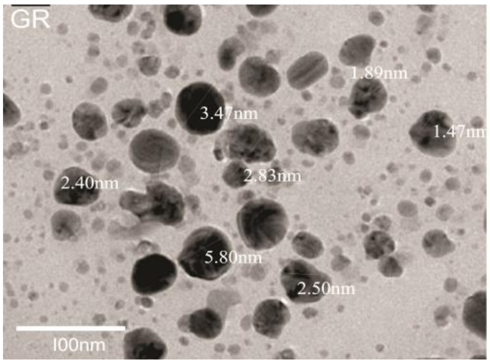

Figure 1: TEM image of graphite nanoparticles

Figure 2 shows the XRD of the Al ingot having the highest peak representing the primary phase. This is expected since aluminium is the major component of the beverage cans (Mackenzie and Reeve, 2022). The presence of $Zn_{0.69}Ti_{0.31}$ suggests an intermetallic compound or solid solution involving zinc and titanium. However, Zn-Ti is an unusual phase in standard can alloys, but it could have been introduced through coating or foreign materials during the melting process (Smith *et al*., 2021).

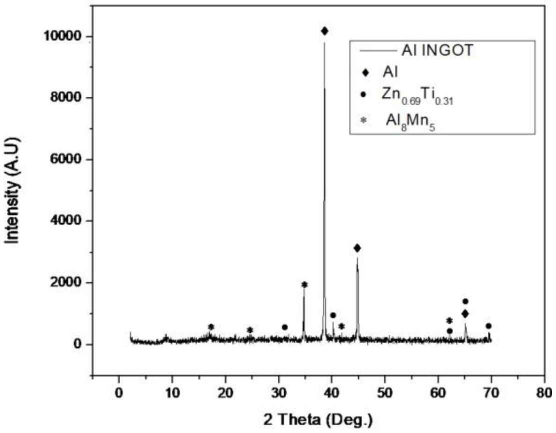

Figure 2: XRD of Al ingot

It is evident from the SEM micrograph as shown in Figure 3 that the Al ingot contains several phases, as indicated by the different colours of the various regions (light, dark, and white regions), which is consistent with findings from studies on phase distribution in aluminium alloys (Zhao *et al*., 2020). The SEM micrograph of the recycled aluminium ingot reinforced with micro- and nano-sized additives (Figure 3) reveals a rough, heterogeneous surface with embedded particles and clusters, indicating the presence of black powder, graphite, and glass reinforcements. The distribution of these particles, while generally effective, shows signs of agglomeration, suggesting incomplete dispersion likely due to processing limitations. Visible cracks, voids, and porosity across the matrix highlight potential thermal stresses and gas entrapment during solidification, which may affect the overall mechanical integrity. However, areas showing good interfacial bonding between the matrix and additives suggest improved hardness and strength, though the presence of surface defects could compromise ductility and fatigue resistance. Overall, the microstructure demonstrates the potential benefits and challenges of using recycled aluminium with nano/micro reinforcements for enhanced mechanical performance.

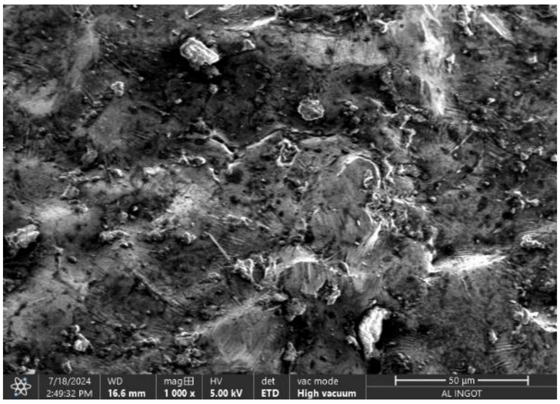

Figure 3: SEM micrograph of Aluminium ingot

Effects of graphite, glass and black powder addition on hardness

Figure 4 presents the hardness values of recycled aluminium composites reinforced with nano- and micro-sized additives (graphite, glass, and black powder), highlighting the influence of both particle size and reinforcement concentration (0%, 6%, 8%, and 10%). A consistent trend was observed in which nano-sized reinforcements generally outperformed their micro-sized counterparts in enhancing hardness. For nano-graphite, the hardness increased progressively from 65.83 HV at 0% to 67.53 HV (6%), 72.80 HV (8%), and peaked at 87.70 HV at 10%. In contrast, micro-graphite showed a marginal increase at 6% (64.93 HV) and 8% (68.16 HV), followed by a decline to 64.13 HV at 10%. Nano-glass also exhibited a steady increase, from 65.83 HV (0%) to 72.68 HV (6%) and 80.86 HV (8%), followed by a slight decrease to 72.80 HV at 10%. Micro-glass showed higher initial gains, reaching 78.86 HV (6%) and peaking at 84.18 HV (8%), before reducing to 71.76 HV (10%).

In the case of black powder, nano-reinforced samples showed an increase in hardness to 74.70 HV at 6%, a drop to 55.43 HV at 8%, and a slight recovery to 64.50 HV at 10%. Similarly, micro-black powder yielded values of 74.53 HV (6%), 54.93 HV (8%), and 69.90 HV (10%). Notably, graphite-reinforced samples with 10% nano-graphite (G-10 NANO) achieved the highest hardness value of 87.70 HV, significantly outperforming the corresponding micro-graphite sample (G-10 MICRO) at 64.13 HV. The superior hardness observed in nano-reinforced samples may be attributed to the formation of nano-ceramic phases that impede dislocation motion, enhancing the matrix strength. The decrease in hardness at higher micro-reinforcement levels is likely due to agglomeration and poor interfacial bonding, consistent with the findings of Kumar *et al*. (2022). Furthermore, the observed decline in black powder-reinforced composites beyond 6% nano-reinforcement supports earlier conclusions by Chen and Liu (2022), who reported that excessive ceramic additions in aluminium matrices could introduce brittle phases, thereby diminishing mechanical performance. This difference may be attributed to the higher surface area-to-volume ratio of nanoparticles, which improves bonding with the aluminium matrix and refines the grain structure (Huang *et al*., 2023). Similar findings were reported by Zhang *et al*. (2023), who observed that nano-scale ceramic reinforcements in aluminium composites led to the formation of hard intermetallic phases that improved wear resistance and hardness.

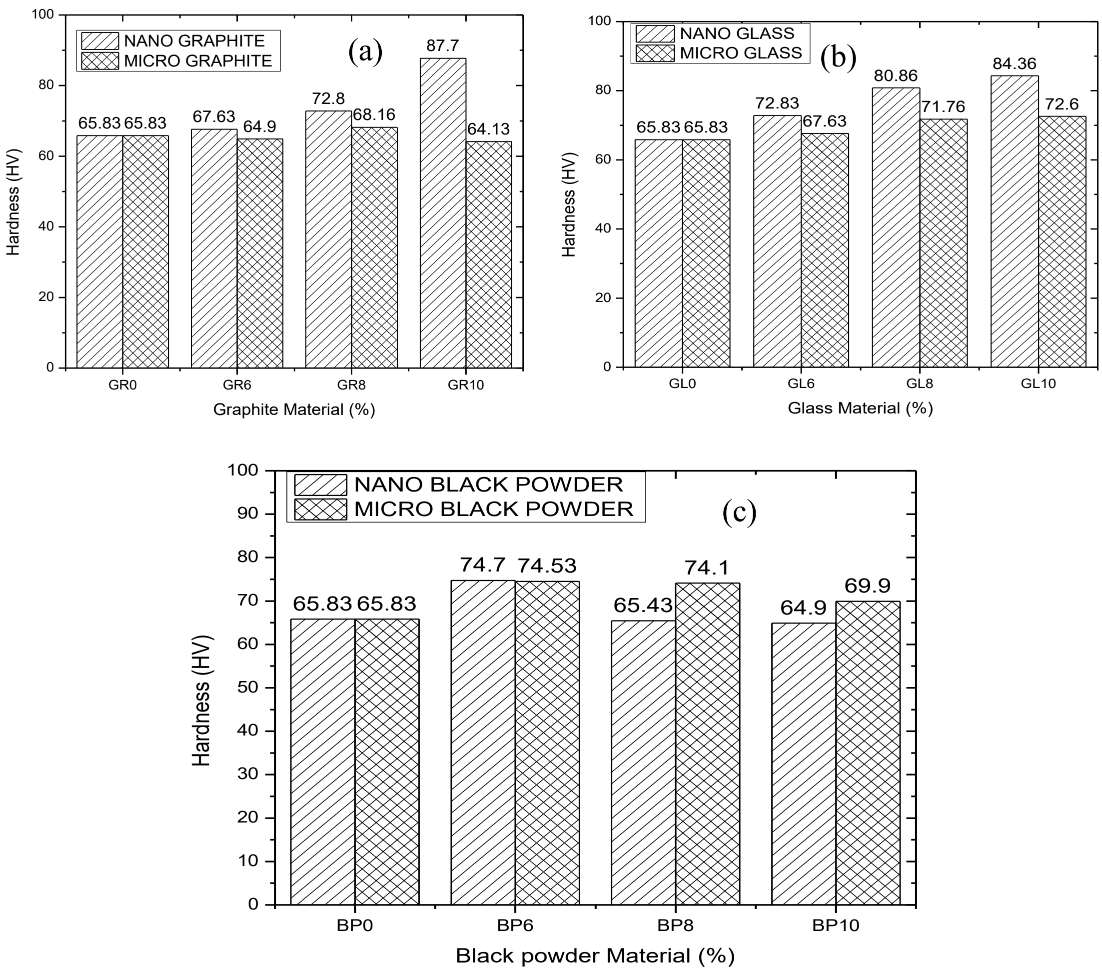

Figure 4: Hardness values of aluminium alloy modified with micro and nano-sized (a) graphite (b) glass and (c) black powder.

Impact strength analysis

Figure 5 presents the impact strength values of recycled aluminium composites reinforced with nano- and micro-sized graphite, glass, and black powder additives at varying concentrations (0%, 6%, 8%, and 10%). For graphite-reinforced composites, nano-graphite showed a progressive increase in impact strength, from 13.42 J at 0% to 15.33 J (6%), 16.55 J (8%), and reaching 17.20 J at 10%. In contrast, micro-graphite reinforced samples increased from 13.42 J (0%) to 14.86 J (6%), 14.93 J (8%), and 15.27 J (10%). Notably, the 10% nano-graphite sample (G-10 NANO) outperformed its micro counterpart (G-10 MICRO), which recorded 15.27 J, demonstrating the superior stress distribution and fracture toughness imparted by nano-carbon reinforcements. This observation is consistent with findings by Zhang *et al*. (2023), who reported enhanced energy dissipation in nano-reinforced aluminium matrices.

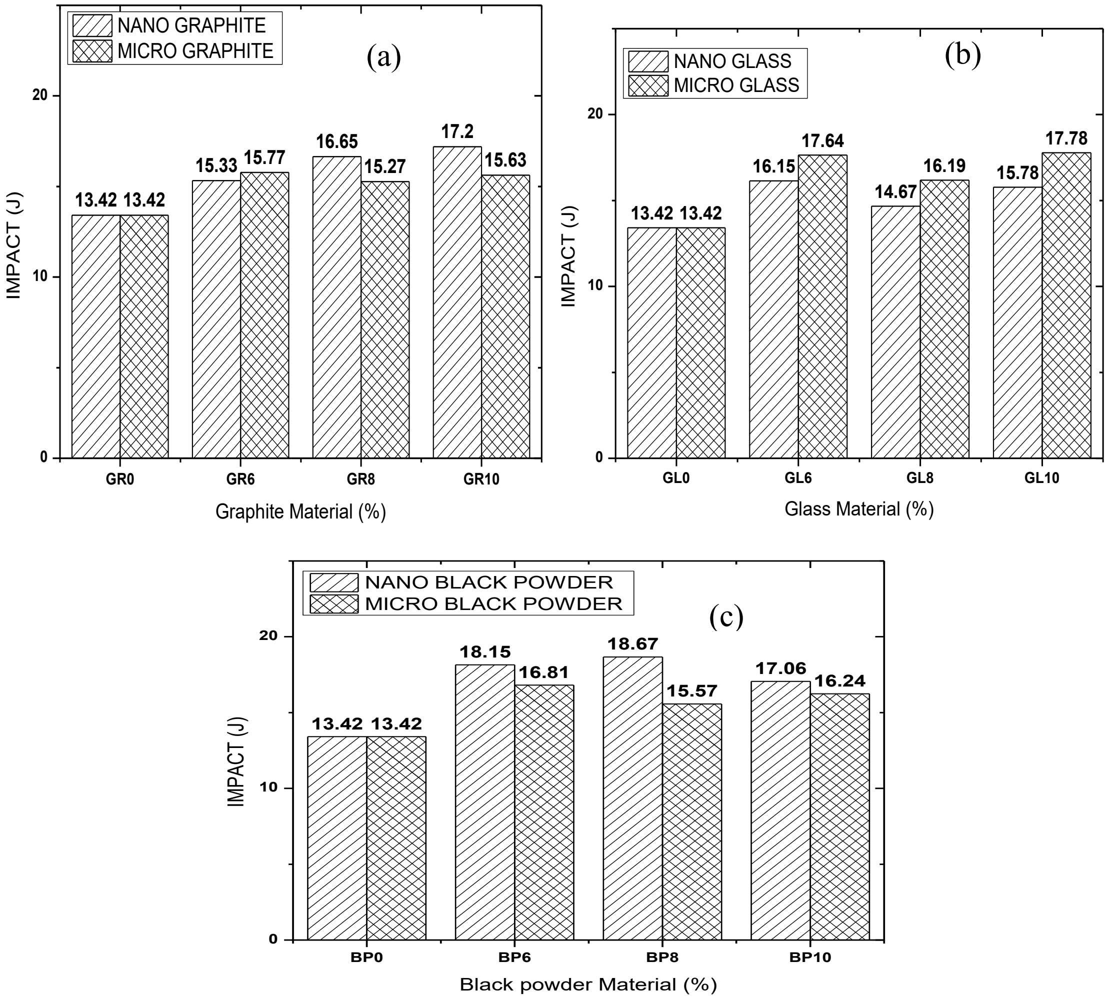

Figure 5: Impact strength of aluminium alloy modified with micro and nano-sized (a) graphite (b) glass and (c) black powder.

For glass-reinforced composites, nano-glass exhibited impact strengths of 13.42 J (0%), 16.15 J (6%), 17.64 J (8%), and 17.78 J (10%), while micro-glass yielded lower values of 13.42 J (0%), 14.29 J (6%), 14.57 J (8%), and 15.19 J (10%). Interestingly, at 8% reinforcement, micro-glass (GL-8 MICRO) slightly outperformed 10% nano-glass (GL-10 NANO), suggesting that excessive nano-glass content may contribute to embrittlement, as previously observed by Kim *et al*. (2023), where nano-scale oxide particles were found to induce hard but brittle phases at higher concentrations. Black powder-reinforced composites demonstrated the highest impact performance overall. Nano black powder achieved 13.42 J (0%), 18.15 J (6%), peaking at 18.67 J (8%), before slightly decreasing to 17.06 J at 10%. Micro black powder followed a similar trend, with values of 13.42 J (0%), 15.97 J (6%), 15.32 J (8%), and 16.24 J (10%). The superior impact strength of the 8% nano black powder composite (M-8 NANO) reflects enhanced grain refinement and suppression of crack propagation mechanisms, aligning with the findings of Choudhury *et al*. (2023), who attributed such improvements to the barrier effects of uniformly dispersed nanoparticles.

Overall, these results confirm that nano-reinforcements significantly improve the impact resistance of recycled aluminium composites, though optimal concentrations must be maintained to avoid adverse effects such as brittleness, especially with high nano-glass content.

Tensile strength analysis

Figure 6 presents the tensile strength of cast aluminium alloy composites reinforced with nano- and micro-sized graphite, glass, and black powder at varying concentrations. For graphite-reinforced composites, nano graphite exhibited a tensile strength increase from 80.96 MPa at 0% to a peak value of 108.642 MPa at 10%. In contrast, micro graphite displayed a lower range, with tensile strengths varying from 56.44 MPa at 8% to 78.584 MPa at 2%. The superior performance of nano graphite, particularly at 10% (G-10 NANO), which recorded 103 MPa, confirms its capacity to enhance mechanical strength. This improvement is attributed to the refinement of grain boundaries and improved stress transfer efficiency, as supported by Hernandez *et al*. (2024).

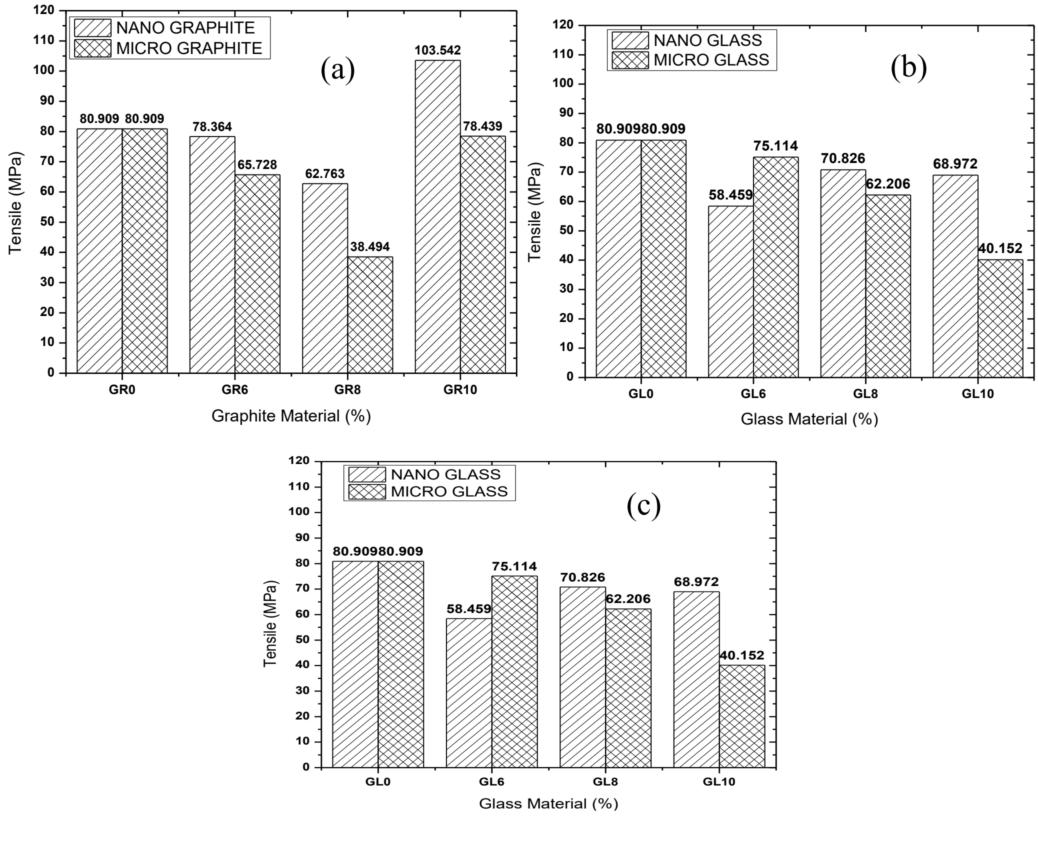

Figure 6: Tensile strength of aluminium alloy modified with micro and nano-sized (a) graphite (b) glass and (c) black powder

CONCLUSIONS

This study investigated the effects of nano- and micro-sized reinforcements—specifically black powder, graphite, and recycled glass powder—on the mechanical properties of recycled aluminium alloys. The results demonstrated that nano-scale reinforcements consistently outperformed their micro-scale counterparts, with notable enhancements observed in hardness, impact strength, and tensile strength, particularly in composites reinforced with nano graphite. The superior performance of nano-sized additives is attributed to their uniform dispersion within the aluminium matrix, stronger interfacial bonding, and their capacity to refine grain structures, thereby improving load transfer and resistance to deformation. Among the reinforcements studied, nano graphite exhibited the most significant improvements across all mechanical parameters.

Despite these advantages, it was observed that excessive incorporation of nano reinforcements may result in decreased ductility, likely due to the formation of brittle phases or particle agglomeration. Therefore, to optimise the mechanical performance of aluminium matrix composites, careful consideration must be given to the selection of reinforcement type, particle size, and concentration. These findings underscore the potential of nano-reinforced recycled aluminium composites for structural and engineering applications where enhanced mechanical properties are desired.

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