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The Effect of Hollow Glass Microsphere (HGM) and Iron Sand Volume Fraction on the Hardness and Wear Rate (Tribological Properties) of Composite Train Brake Blocks

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Abstract. *This research addresses the wear susceptibility of pure polymer composites in railway brake blocks and the lack of studies on the synergistic effect of iron sand and Hollow Glass Microsphere (HGM) fillers under the SNI 8832:2019 standard. The study evaluates the impact of HGM volume fraction variations on composite hardness and wear rate. A quantitative experimental approach was employed using hand lay-up fabrication, combining an epoxy resin matrix, 15% iron sand, and varying HGM fractions (10%, 15%, 20%). Mechanical characterizations involved Shore D Durometer and Pin-on-Disc Tribometer tests. Results showed that HGM addition caused a statistically insignificant decrease in hardness, remaining well within the SNI 8832:2019 standard range. Conversely, increased HGM significantly reduced the specific wear rate, drastically improving wear resistance. In conclusion, while meeting hardness limits, the composite's excessively high wear resistance requires further compositional modification to function ideally as a consumable friction material.*

Keywords - *Composite brake block, hardness, Hollow Glass Microsphere, iron sand, specific wear rate*

INTRODUCTION

A composite is a multiphase material system created through the combination of two or more materials with distinctly different characteristics [1]. It is also an advanced engineered material composed of a macroscopic structural combination between a matrix phase, which acts as a binder, and a reinforcement phase, which serves as a mechanical load-bearing element [2], [3]. The primary constituent components of this material include fibers and a matrix, wherein the fibers act as the main reinforcing framework within the composite system. Meanwhile, the matrix functions as a binding agent tha unifies and locks the fibers in place to prevent positional shifting [4], [5].

The material design and composite engineering, selection of material types, volume fractions, and the distribution of these two phases are specifically tailored to achieve superior mechanical properties suited for the targeted application. One of the most widely utilized classifications of composite materials in the industry is Polymer Matrix Composites (PMC). The utilization of polymer matrices, such as epoxy or polyester resins, offers design advantages including a high strength-to-weight ratio, excellent corrosion resistance, and significantly more efficient manufacturing processes compared to metals [6]. Despite possessing structural advantages and design flexibility, pure polymer composite materials intrinsically exhibit weaknesses in their surface mechanical properties, particularly when subjected to mechanical stresses such as continuous frictional interactions.

These surface weaknesses in the polymer matrix directly implicate the material's high susceptibility to wear, which is the phenomenon of mass or volume loss caused by dynamic frictional interactions with harder counter-surfaces [7]. To address these tribological issues, modifying the composite structure through material design approaches, such as the addition of particulate fillers into the polymer matrix, has become a highly crucial engineering solution. The presence of reinforcing elements within the composite structure functions as load-bearing elements capable of uniformly distributing frictional stresses. The synergy between the reinforcement phase and the matrix has been empirically proven to be highly effective in minimizing the direct contact area between the soft polymer matrix and abrasive surfaces, as well as inhibiting the rate of material erosion or debris detachment during the friction process [8].

Fundamentally, the fabrication techniques for composite materials can be classified into two primary methods: the open-mold process and the closed-mold process. The open-mold approach encompasses five technical variations, including contact molding (or hand lay-up), vacuum bagging, pressure bagging, spray-up, and filament winding. Meanwhile, the closed-mold process is divided into three specific techniques: compression molding, injection molding, and continuous pultrusion [9]. Among all these techniques, hand lay-up is the most commonly applied method. The high frequency of utilizing this method is based on its operational characteristics as the most practical and straightforward lamination technique [10]. Furthermore, this approach offers several comparative advantages, such as eliminating the need for specialized instrumentation during the fabrication stages, and the capability to produce lightweight materials with optimal corrosion resistance [11].

Railway brake blocks represent one of the composite application components that are currently undergoing continuous development. The braking system in railway rolling stock is a crucial aspect that ensures the operational safety of public transportation. Historically, railway brake blocks were dominated by cast iron materials; however, current technological trends are shifting towards the use of composite materials to pursue operational efficiency. Composite brake blocks offer advantages in the form of lighter weight, reduced noise levels during braking, and a minimized risk of sparking that could trigger fires in operational areas [12]. Along with the increasing frequency of railway trips in Indonesia, the demand for durable brake block spare parts that comply with local standards has become highly urgent.

Previous literature reviews (state of the art) indicate rapid development in the use of polymers as friction composite matrices. The use of epoxy resin has been extensively investigated due to its robust ability to bind fillers and its superior corrosion resistance [13]. The addition of fillers such as iron sand has also been carried out to enhance the hardness and thermal stability of brake pads, wherein these metal particles play a role in withstanding extreme frictional loads [14]. On the other hand, the integration of microsphere material technologies, such as Hollow Glass Microspheres (HGM), has begun to be explored in polymer composite engineering. HGM is known to significantly reduce the material density, and its shell fragments, when crushed on the friction surface, can act as a solid lubricant that affects the wear rate [15].

Although various studies exist regarding the separate uses of iron sand and HGM, an analytical gap remains regarding the synergistic effects of combining iron sand as a functional filler with varying volume fractions of HGM, specifically for railway brake block applications. The majority of prior research has focused more on flexural properties or general automotive brake pad applications without referring to stringent railway standards [16]. No in-depth studies have yet been found that analyze how the interaction between the porosity induced by HGM and the hard particles of iron sand affects the material's compliance with the SNI 8832:2019 standard, particularly concerning the parameters of hardness and specific wear rate.

This research is essential to conduct in order to produce locally-based brake block materials capable of balancing mechanical strength with tribological durability. By targeting a formulation that is lightweight yet maintains standard-compliant hardness, it is expected to reduce the maintenance burden on train wheels caused by uneven material wear. Therefore, this study explicitly aims to evaluate the effect of HGM volume fraction variations (10%, 15%, and 20%) on the hardness properties and tribological characteristics (wear) of the composite brake blocks, and to verify the results against the testing requirements limits of the national standard for railway composite brake blocks.

METHODS

This research was conducted through a series of structured experimental stages encompassing material preparation, specimen molding, mechanical-tribological characteristic testing, and the final data feasibility analysis. Each stage was designed to obtain repeatable and precise test results. The primary material investigated and utilized as the binding matrix constituent was epoxy resin mixed with a hardener. Iron sand powder and Hollow Glass Microsphere (HGM) microparticles were employed as functional reinforcing agents (fillers). The manufacturing equipment utilized included glass/silicone specimen molds, a digital analytical balance for precise measurement of the composite volume fractions, measuring cylinders, and a mechanical stirring device to ensure the homogeneity of the matrix and filler mixture.

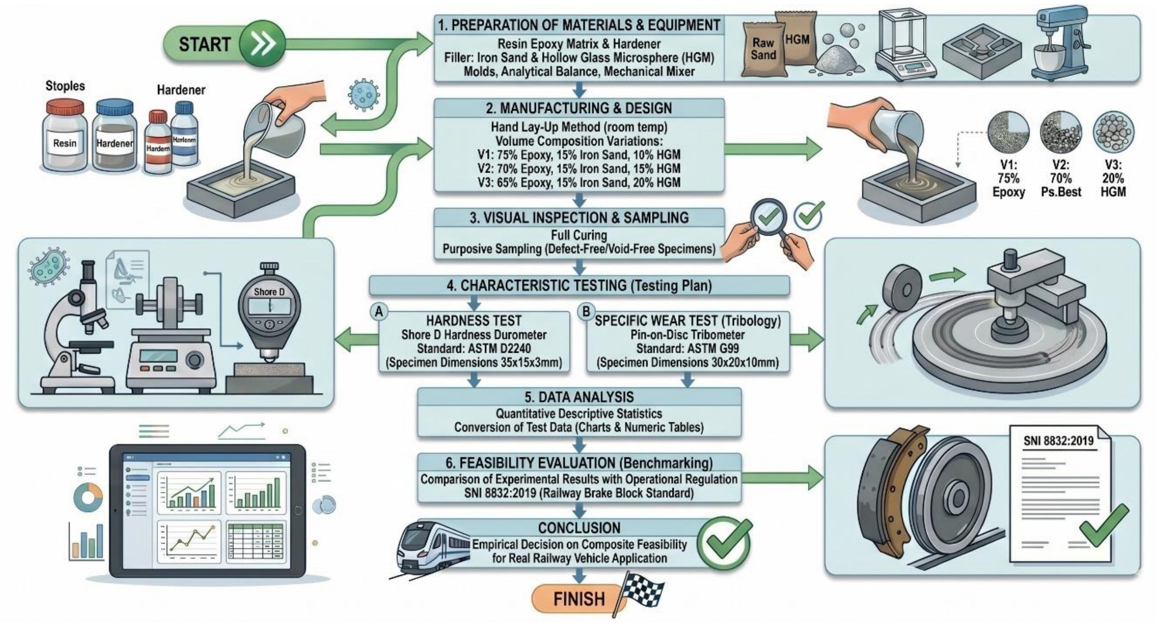

Figure 1. Flow diagram

A. Hand Lay-Up Composite Fabrication Method

The experimental design employed was a quantitative comparative experiment examining the direct effect of varying percentage compositions of the composite constituents. The composite specimens were fabricated using the hand lay-up technique at room temperature without additional pressure (under an atmospheric pressure of 1 atm) until the material was fully cured. The three compositional treatment variations (based on volume ratio) molded were: Variation 1 (75% Epoxy Resin + 15% Iron Sand + 10% HGM); Variation 2 (70% Epoxy Resin + 15% Iron Sand + 15% HGM); and Variation 3 (65% Epoxy Resin + 15% Iron Sand + 20% HGM). The sampling technique was conducted using purposive sampling, wherein the analyzed test specimens were exclusively those that passed visual inspection (possessing precise geometric shapes and free from macroscopic defects such as large voids). The composition ratios of the volume fractions for the durometer hardness test and tribometer test molds are presented in Table 1 and Table 2.

Table 1. Composition Ratio of Volume Fractions for Durometer Hardness Test Molds

No.	Volume Fraction Composition Ratio (%)			Mass (gr)			Mold Volume (cm^3)
	Epoxy Resin	HGM Particles	Iron Sand	Epoxy Resin	HGM Particles	Iron Sand	
1	75	10	15	234	14,4	57,6	240
2	70	15	15	218,4	21,6	57,6	240
3	65	20	15	202,8	28,8	57,6	240

Table 2. Composition Ratio of Volume Fractions for Tribometer Test Molds

No.	Volume Fraction Composition Ratio (%)			Mass (gr)			Mold Volume (cm^3)
	Epoxy Resin	HGM Particles	Iron Sand	Epoxy Resin	HGM Particles	Iron Sand	
1	75	10	15	76,54	4,71	18,84	78,5
2	70	15	15	71,4	7,1	18,81	78,5
3	65	20	15	66,3	9,42	18,84	78,5

B. Testing and Data Acquisition Plan

The testing and data acquisition plan aimed to record two primary dependent variables: surface hardness and specific wear rate values. The composite hardness level variable was measured via indentation using a Shore D Hardness Durometer instrument in accordance with the ASTM D2240 method, and data acquisition was conducted according to Table 3. Samples for this hardness testing were prepared with standard dimensions of 35 mm in length, 15 mm in width, and 3 mm in thickness, as shown in Figure 2. Meanwhile, the tribological property variables were evaluated using a Pin-on-Disc Tribometer mechanical testing machine with reference to the ASTM G99 testing procedure, and data acquisition was conducted according to Table 4. In this wear test, the specific wear rate was quantified based on the parameters of applied compressive load, sliding distance of the friction cylinder, and the volume reduction of the material from the test specimens with dimensions of 30 mm × 20 mm × 10 mm, as shown in Figure 3.

Table 3. Process Parameter Variations for Durometer Hardness Test

Specimen Variation	Nilai Uji Hardness Durometer Test (HRR)		
	Variation Specimen 10% HGM	Variation Specimen 15% HGM	Variation Specimen 20% HGM
A	1A	2A	3A
B	1B	2B	3B
C	1C	2C	3C

Table 4. Process Parameter Variations for Tribometer Test

Specimen Variation	Specific Wear Rate Value (ws) (mm2/kg)		
	Variation Specimen 10% HGM	Variation Specimen 15% HGM	Variation Specimen 20% HGM
A	1A	2A	3A
B	1B	2B	3B
C	1C	2C	3C

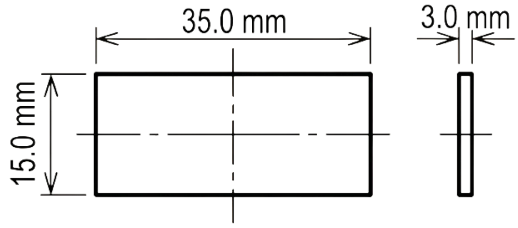

Figure 2. Specimen Design for Durometer Hardness Test

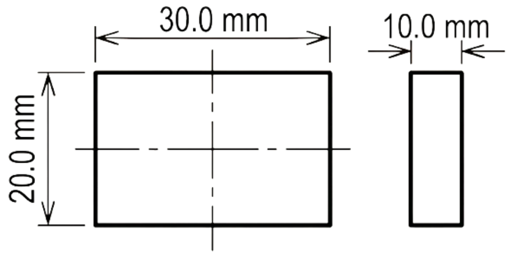

Figure 3. Specimen Design for Tribometer Test

C. Data Analysis

Data analysis was performed using a quantitative descriptive statistical model to observe the patterns and correlation trends regarding the impact of the HGM addition percentage as the independent variable on the mechanical performance of the specimens. The average values of the raw test data from each variation were converted and presented in graphical and numerical tabular formats. Subsequently, a direct comparative analysis (benchmarking) was conducted against the operational regulatory threshold values of the Indonesian National Standard for railway composite brake blocks, specifically the SNI 8832:2019 standard document. This standard comparison served as the primary foundation for drawing empirical conclusions regarding the feasibility of applying the composite to actual railway rolling stock.

RESULTS AND DISCUSSION

A. Results and Discussion Surface Hardness Properties Analysis (Macroscopic Indentation)

Material hardness represents the composite's surface resistance to local plastic deformation induced by compressive forces (indentation). The visual representation of the specimens from the durometer hardness test is shown in Figure 4. Meanwhile, the graphical representation of the hardness trends derived from the Shore D Hardness Durometer testing is presented in Table 5 and Figure 5.

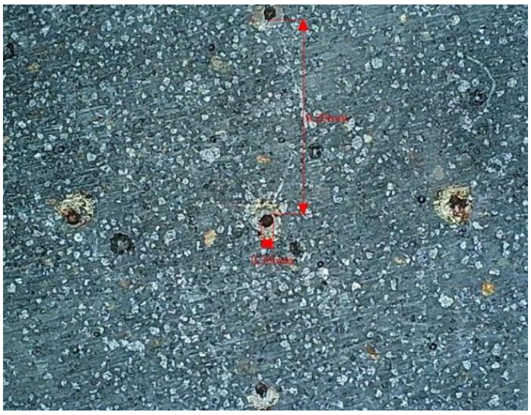

Figure 4. Specimens from the Durometer Hardness Test

Table 5. Durometer Hardness Test Values

Specimen Variation	Nilai Uji Hardness Durometer Test (HRR)		
	10% HGM	15% HGM	20% HGM
A	100	99,2	98
B	102,5	102	99,2
C	110	105	100,5

Table 6. Analysis of Variance of the Effect of HGM Volume Fraction on Composite Hardness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	2	36.78	18.39	1.49	0.299
Error	6	74.12	12.35		
Total	8	110.90			

Composite hardness testing with variations in the addition of Hollow Glass Microspheres (HGM) volume fractions of 10%, 15%, and 20% was conducted, with each variation undergoing three testing replications. Based on descriptive statistical calculations, the average hardness values (HRR) exhibited a decreasing trend with the incremental addition of the HGM volume fraction. The average hardness values were 104.17 (standard deviation 5.20) for the 10% fraction, 102.07 (standard deviation 2.90) for the 15% fraction, and 99.23 (standard deviation 1.25) for the 20% fraction, respectively.

To verify the significance of this decreasing trend, a One-Way Analysis of Variance (ANOVA) was performed. The ANOVA test results yielded an F-value of 1.488 and a P-value of 0.298. Since the significance value (P-value) was greater than the margin of error threshold ($\alpha = 0.05$), the Null Hypothesis (H0) failed to be rejected. This affirms that the variation in HGM volume fractions within the 10% to 20% range does not exert a statistically significant difference on the composite's hardness values.

Although no statistically significant difference was found, the decreasing trend in average hardness with the addition of the HGM fraction can be explained through the structural mechanism of its constituent materials. As elucidated by Ferreira et al. (2022)[17], the incorporation of HGM particles into a composite matrix is fundamentally applied to reduce the overall material density. However, the hollow structure of the HGM particles at their core, combined with their thin glass walls, renders this reinforcement phase susceptible to deformation or fracture when subjected to external compressive or indentation loads [17], [18].

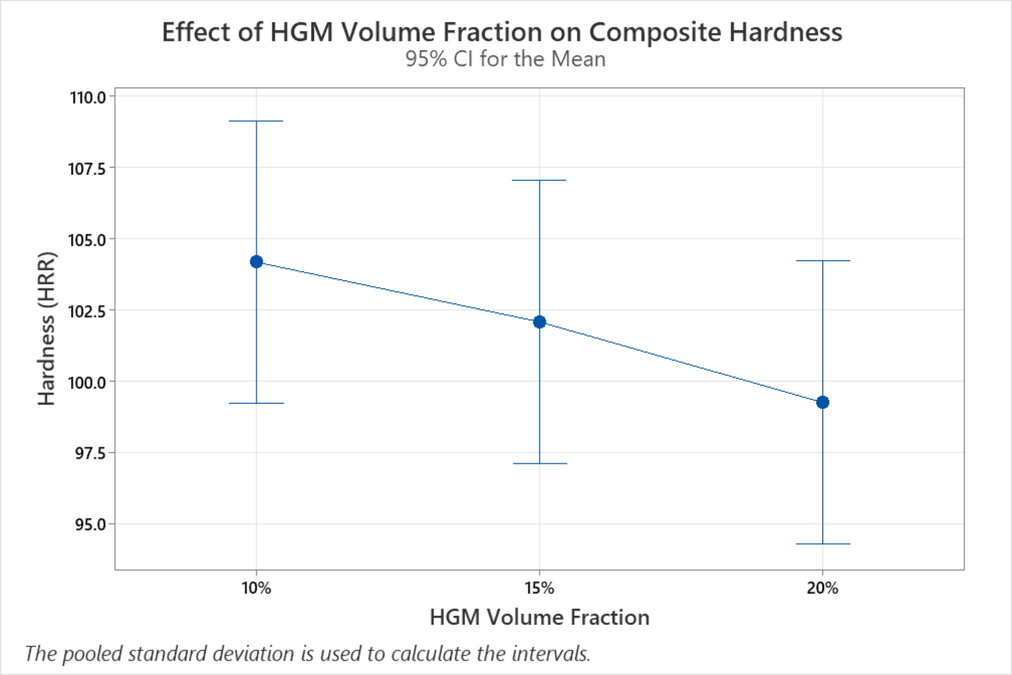

Figure 5. Effect of HGM Volume Fraction on Composite Hardness

Furthermore, Aruniit et al. (2012) [18] proposed that an increase in the volume fraction of the added hollow particles directly correlates with a greater accumulation of microscopic voids within the composite system. The presence of this void volume automatically reduces the total area of the solid matrix responsible for optimally withstanding the penetration load from the indenter, leading to a tendency for the material's surface hardness values to decrease. On the other hand, the statistical insignificance (P-value > 0.05) is heavily influenced by the high variance range of the data among replications within the treatment groups, particularly in the 10% fraction, which ranges from 100.00 to 110.00 HRR. The fluctuation of hardness values at different test points indicates the probable occurrence of non-uniform HGM particle distribution within the matrix. This phenomenon aligns with the findings of Patankar et al. (2009)[19], where the agglomeration tendency in glass microsphere particles can cause certain areas of the specimen to become denser, while other areas weaken due to a high concentration of voids at a single point. This uneven distribution condition is strongly suspected to trigger the fluctuations in hardness value readings and obscure the actual effects of the overall volume fraction ratio increase.

Based on the analytical results, it can be concluded that the addition of HGM volume fractions up to 20% decreases the absolute average hardness value of the composite due to the structural characteristics of its hollow particles. Nevertheless, this decrease is not statistically proven to be significant due to the large data variance, which indicates potential particle agglomeration within the composite matrix. This finding of decreased hardness is highly consistent with the theoretical mechanics model of syntactic foams proposed by Hassan et al and Salleh [20], [21], which states that a deterministic increase in the porosity fraction will weaken the polymer's surface rigidity. Additionally, this phenomenon reinforces the study by Setiawan et al. [22], which asserts that the addition of hollow particles degrades the static mechanical properties of polymer composites.

Despite the decreasing trend in hardness, another crucial finding is that the lowest hardness value (100 HRR at 20% HGM) remains within the safe tolerance limit range of the SNI 8832:2019 standard (70–105 HRR) [12]. The retention of the hardness value at this relatively high level can be explained by the stress transfer mechanism contributed by the 15% iron sand matrix. Dense iron particles, which possess a high modulus of elasticity, absorb the majority of the compressive load from the epoxy matrix, preventing the material from becoming excessively soft [23]

B. Tribological Characteristics and Specific Wear Rate Mechanism

The tribological properties of the composite were evaluated using a Pin-on-Disc Tribometer instrument to measure the specific wear rate. A low specific wear rate indicates the material's excellent resistance to abrasive frictional forces. The fluctuation trend of this wear rate can be visually observed in Table 7 and Figure 7.

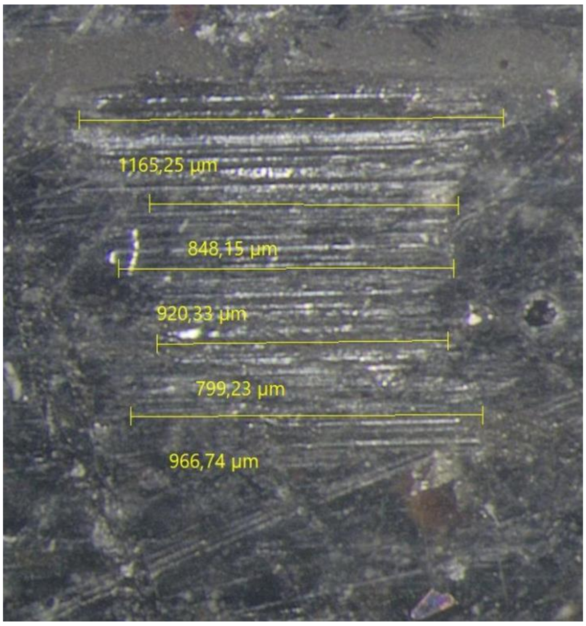

Figure 6. Specimens from the Tribometer Test

Table 7. Tribometer Test Values

Specimen Variation	Specific Wear Rate Values (ws) (mm2/kg)		
	10% HGM	15% HGM	20% HGM
A	1,284585 x 10^{-6}	1,26342 x 10^{-7}	1,02562 x 10^{-7}
B	6,19956 x 10^{-7}	2,50824 x 10^{-7}	1,16952 x 10^{-7}
C	8,16618 x 10^{-7}	4,12638 x 10^{-7}	1,97059 x 10^{-7}

Table 8. Analysis of Variance of the Effect of HGM Volume Fraction on Specific Wear Rate Values

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	2	0.000000	0.000000	11.01	0.010
Error	6	0.000000	0.000000		
Total	8	0.000000			

Ased on statistical calculations using the One-Way Analysis of Variance (ANOVA) test, the varied additions of the Hollow Glass Microspheres (HGM) filler volume fraction were proven to exert a highly significant effect on the specific wear rate of the composite material ($p\text{-value} = 0.010 < \alpha = 0.05$). Experimental results demonstrated a distinct negative correlation, wherein increasing the HGM percentage from 10% to 20% consistently reduced the composite's specific wear rate from its highest point at an average of 9.05 x 10^{-7} mm²/kg down to 1.38 x 10^{-7} mm²/kg. This drastic reduction in the wear rate provides empirical proof that the presence of hollow microparticles (HGM) mechanically and actively contributes to enhancing the overall wear resistance of the composite material.

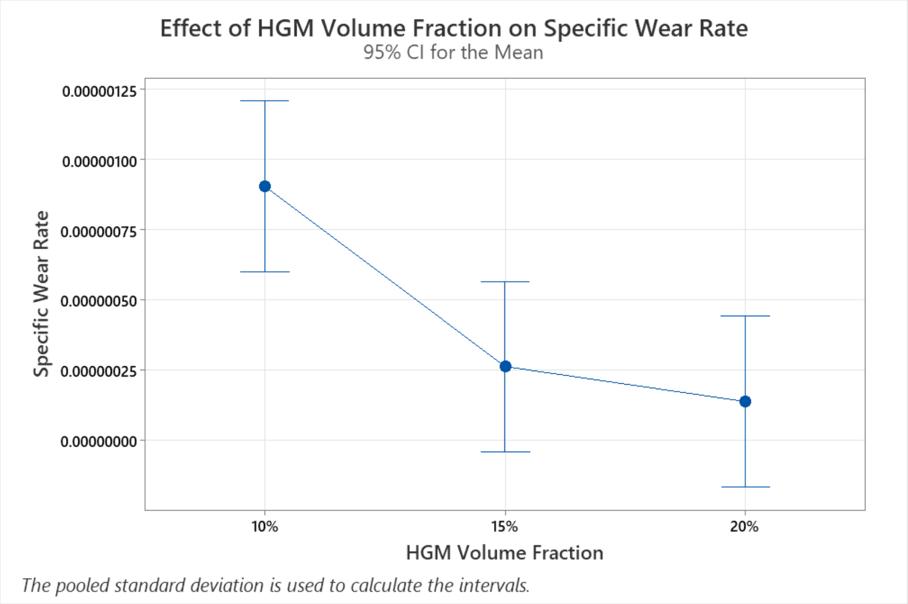

Figure 7. Effect of HGM Volume Fraction on Specific Wear Rate

This phenomenon of increased wear resistance can be explained through the load-bearing mechanism of the filler particles distributed within the matrix. Polymer matrices (such as epoxy) fundamentally possess relatively low wear resistance and are prone to degradation when directly subjected to frictional stress [7]. However, as the HGM particle volume fraction increases up to 20%, the direct contact area between the relatively soft matrix surface and the abrasive plane progressively decreases. Frictional loads are effectively borne by the glass microsphere particles, which inherently possess significantly higher mechanical properties and hardness levels compared to the binding resin [24]. The addition of these spherically-morphologized reinforcing particles also minimizes the release of material debris caused by friction, which serves as a primary indicator of a reduced specific wear rate in polymer composites [8].

The third-body lubrication mechanism facilitated by these crushed microspheres confirms the empirical findings previously published by Bello et al. [20] and Fahri et al. [25] regarding the modification of polymer friction coefficients using glass powder additives. However, when evaluated from the perspective of railway rolling stock engineering, this finding of increased wear resistance actually reveals a crucial application gap. The resulting wear rate value (which is in the extreme order of 10^{-7} mm^2/kg) indicates that this composite is overly resistant to friction and fails to comply with the minimum wear threshold permitted by the SNI 8832:2019 standard (which mandates wear rates to fall within the range of 10^{-4} to 10^{-3} mm^2/kg) [12].

In the engineering principles of braking systems, brake block materials are designed as sacrificial materials tasked with absorbing kinetic energy in the form of heat and the shedding of brake dust. If a brake block possesses excessive wear resistance, as observed in the trend of this study, the abrasive energy will conversely be transferred to the surface of the train wheels. Wear on steel train wheels is a highly avoided condition since wheels are not consumable components and their operational maintenance costs are extremely high [26]. Consequently, the findings of this study substantiate the necessity for reformulation by adding friction-reducing agents, such as graphite, to ensure the "sacrificial" rate of the brake block material ideally conforms to the SNI profile.

CONCLUSION

Based on the research findings corresponding to the initial objectives, it can be concluded that the addition of varying volume fractions of Hollow Glass Microspheres (HGM) to the brake block polymer composite results in a reduction in material hardness, although this decrease is not statistically significant. Conversely, regarding tribological characteristics, the incorporation of HGM particles has been proven to significantly enhance the overall wear resistance of the material, as evidenced by the decline in specific wear rate with an increasing percentage of HGM. Feasibility verification against railway standards indicates that the hardness level of this composite successfully complies with the safe tolerance limits specified by SNI 8832:2019. However, wear testing reveals a critical discrepancy: the composite material is excessively resistant to friction, thereby failing to meet the minimum wear threshold of the SNI 8832:2019 standard, which dictates that brake blocks should ideally function as sacrificial materials during frictional contact.

As a recommendation for future studies, engineering modifications to the composite's composition or formulation are highly advised. Adjustments—such as re-evaluating the resin binder ratio, reducing the percentage of hard reinforcements like iron sand, or introducing novel additive materials—are necessary to decrease the material's wear resistance. This step is essential to ensure that the wear rate of the brake block increases to align with the operational standards mandated by SNI, without posing any risk of abrading or damaging the railway wheel components.

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