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Original Article

An Experimental Investigation on Effect of Rubber Particle Size on Composite Railway Sleeper Mechanical Strength and Vibrational Damping Properties

Mbatha Abednigo Jabu[1], AA Alugongo[2], NZ Nkomo[3]

[1,2,3]*Vaal University of Technology, Department of Industrial Engineering & Operations Management and Mechanical Engineering, Private Bag X021, Vanderbijlpark, 1900, South Africa.*

[3]*Corresponding Author : nkosilathin@vut.ac.za*

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Abstract *- Railway sleepers are being subjected to increased mechanical and vibrational forces as trains get progressively faster and heavier over time. There is a need to develop sustainable railway sleepers that can withstand these dynamic and static forces. Composite materials with rubber particles as filler material are potential railway sleeper materials with high vibrational damping properties. The rubber particles used can originate from waste tyres, creating a sustainable disposal method for the ever-growing challenge of tyre disposal. The purpose of this work is to investigate the mechanical strength and vibrational damping of rubber particle sizes of 150 and 300µm in composite railway sleepers. The experiment design followed varied the rubber particle mass fraction from 5 to 20%. The hand layup method was used to fabricate composites. The methodology involved testing the composite tensile, compression and flexural strength. Thereafter, the fabricated composite's LEED hardness and vibrational damping were determined. The experimental results showed that the composite consisting of 150 µm rubber particles had a maximum tensile strength of 8.86 MPa, compressive strength of 36.52 MPa, and flexural strength of 23.37 MPa at 10%, 5%, and 5% rubber particle loading, respectively. The highest hardness was obtained at 20%, giving the value of 659 Leeb. There is still a need for further study to investigate the effect of 75-micron rubber particles on the structural strength of the composite to withstand shock forces that are applied by heavily loaded trains.*

Keywords *- Composite, Railway sleeper, Rubber particles, Structural strength, Vibrational damping.*

1. Introduction

The railway sleepers are beams found underneath the railway tracks [1]. The railway sleepers tend to lose their structural integrity over time as heavily laden trains use the railway track. Furthermore, there is ever-increasing vibration stress in railway lines trains designed to travel ever faster [2]. The railway sleepers and sleeper pads are located beneath the railway and assist in vibrational damping [3], [4]. However, these railway pads tend to wear out easily and detach from their mounts on the track system due to numerous factors, such as environmental damage and looseness of the fastening system [5]. The primary tasks of the ballasts are to provide constant flexible vertical support and to increase track damping [6]. There is a need to develop a more robust railway track system that can handle the advancements in train technology. The primary purpose of railway sleepers is to absorb the track vibrations while maintaining the necessary mechanical strength properties. However, the sleepers in current use are being subjected to very high stresses, necessitating the redesign and use of novel materials to ensure their durability. As the number of vehicles on the roads increases yearly, so are the scrap tyres generated.

The waste tyres generated annually are approximately one billion [7]. Small vehicles normally go through a set of tyres every two years. Hence, this indicates the magnitude of the problem in the disposal of these waste tyres. The waste tyres are normally incinerated or dumped in landfills [8]. Tyres that are incinerated as the preferred disposal method tend to produce black smoke during combustion, which mostly contains hazardous gases such as sulfides of hydrogen and carbon, carbon monoxide, nitrogen oxides and other volatile oxides. When one ton of waste tyres is burned, it produces roughly 270 kg of soot and 450 kg of poisonous gas [9]. Furthermore, smoke released during combustion can harm human organisms and the environment [9]. The increasing number of vehicles necessitates effective and environmentally friendly methods of disposal of waste tyres [10]. A study by Samsuri (2010) [11] states that the disposal of waste tyres requires expensive and specialized machines to avoid environmental pollution. However, finding alternative uses for waste types can have significant economic benefits due to their availability. A study by Imbernon et al. (2016) [12] shows other potential end uses for waste tyres, such as homemade sandals, decoration ornaments, chairs, and tables.

Using scrap rubber as a filler in polymer and cement-based composites has become a fascinating and trending research area [1, 2, 3]. This interest can be attributed to rubber particles potentially improving the mechanical and vibrational damping properties in composite materials; moreover, using waste rubber particles in this manner is environmentally friendly. Various research has been done on the possible uses of waste rubber as a reinforcement material in a polymer matrix or as a rubber matrix [3]. Partial replacement of fine aggregate in concrete railway sleepers with rubber particles has also been explored and has shown potential. However, the incorporation of rubber particles in concrete sleepers tends to reduce compressional strength substantially. However, adding silica fume to the concrete composite improves the compression strength [16]. Increasing the size and content of rubber particles has been shown to increase the damping ratio significantly [2, 13]. There is a need to design a durable railway sleeper that will be able to cope with the magnitude of stresses introduced by ever-faster and heavier trains. The use of rubber particles has the ability to enhance the vibrational damping while reducing the environmental footprint of waste tyres. In this study, waste rubber tyres will be utilized as filler material in a polymer-based polymer to fabricate and test a composite for use as a railway sleeper.

2. Methodology

2.1. Details of Materials

In this research, rubber particles of two sizes, 150 µm and 300 µm used in the composite fabrication. The resin used was polyester.

2.2. Composites Fabrication

The hand layup fabrication method was used. A gel coat was used to impact smoothness and even finish the composite. A sample of the rubber particles used is shown in Figure 1. The rubber particle volume fraction used varied from 5 - 20 % for both the 150 and 300 µm particles. The moulds used in the test specimen fabrication were of dimensions 22,5 cm x 22,5 cm.

2.3. Mechanical Properties of Composite

The tensile strength test was carried out following ASTM D3518/D3518M-18, which uses a sample size of 250 mm long and 25 mm wide, having a gauge length of 150 mm. An INSTRON model 3369 was used to carry out the test, as shown in Figure 2.

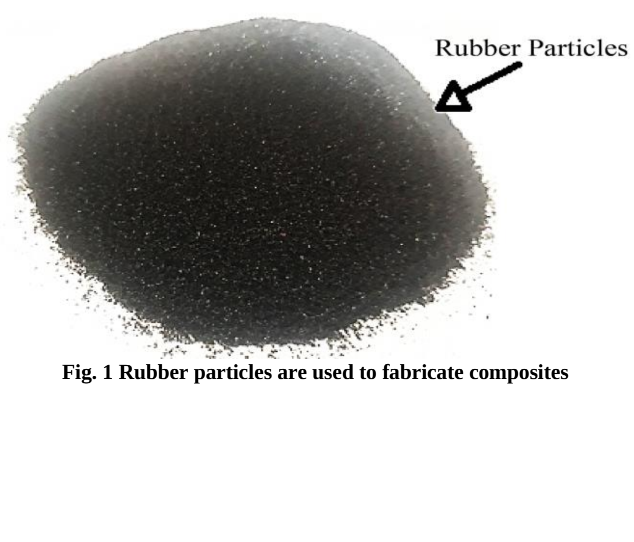

Fig. 1 Rubber particles are used to fabricate composites

Fig. 2 UTM (universal testing machine)

A Static load cell of 5 kN was used. The machine was operated at a continuous speed of 5 mm/s with a gauge length of 150 mm.

2.3.1. Compressional Strength

The test was carried out following ASTM D3410/D3410M [7], which uses a sample size of 140 mm long and 13 mm wide, having a gauge length of 13 mm. The compressive strength was calculated as shown in Equation 1.

$$C = \frac{F}{A} \tag{1}$$

Where C is compression strength (MPa), F is applied force (N), and A is the area (m^2)

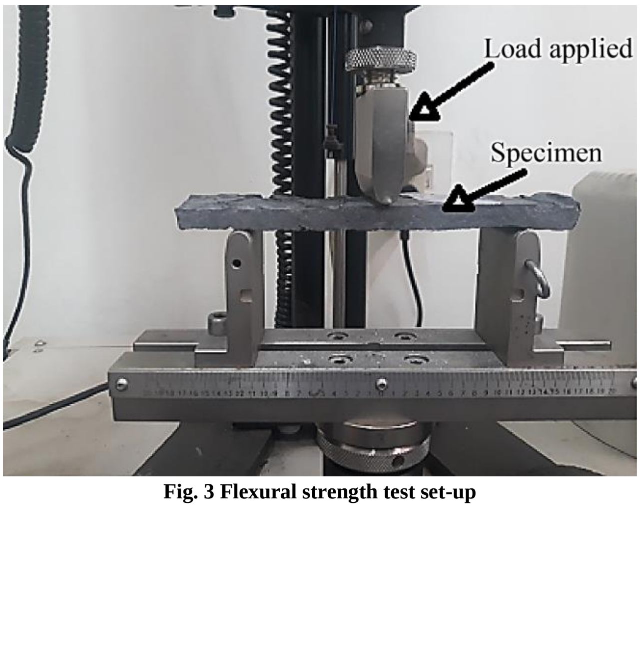

Fig. 3 Flexural strength test set-up

2.3.2. Flexural Strength

The flexural strength test followed the ASTM D8058-19 [8] standard. An INSTRON model 3369 universal testing machine was used. The three-point bending test method, as shown in Figure 3, was followed.

The flexural strength was calculated for each specimen using Equation 2.

$$R = \frac{3PL}{2bd^2} \quad (2)$$

Where R symbolizes the flexural strength of the sample in MPa, P is the breaking load of the specimen in N, L is the length of the span of the sample in mm, b is the width of the sample in mm, and d is the average sample thickness in mm.

2.3.3. LEEB Hardness

Hardness was measured using a model time 5330 hardness tester, shown in Figure 4. The method followed was based on the dynamic rebound principle, and the test was carried out following ASTM A-956 (ASTM A-956 1998).

2.3.4. Vibration Test

A vibration test was carried out using a shaker table. The test followed the ASTM E756 standard (ASTM E756 2009). This test method measures the loss factor, young modulus or shear modulus, and vibration properties of materials. It is accurate over a frequency range of 50 to 5000 Hz over the useful temperature range of materials. The vibration samples used had dimensions of 140 mm x 14 mm x 5 mm and were prepared as shown in Figure 5.

Fig. 4 Time 5330 LEEB hardness tester

Fig. 5 Samples used for vibration and damping test

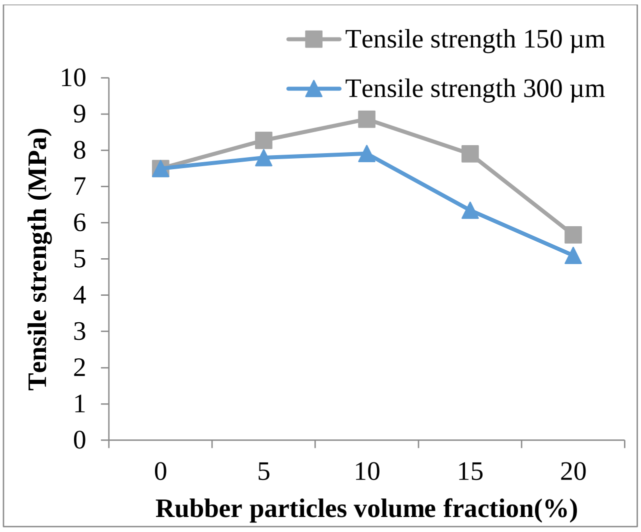

Fig. 6 Effects of varying rubber particle content on tensile strength

The base of the cantilever beam was clamped over a length of 20 mm, with 120 mm free to vibrate.

3. Results and Discussion

The following sections discuss the results obtained for the tensile, compression, flexural strength, hardness, and vibrational analysis.

3.1. Tensile Strength

Figure 6 presents the effects on composite tensile strength of rubber particles of sizes 150 µm and 300 µm.

Figure 6 shows that adding 150 µm rubber particles initially marginally increased the tensile strength. The tensile strength recorded at 5% rubber particle loading was 8.27 MPa. As the volume fraction increased to 10%, there was a slight increase in tensile strength to 8.86 MPa. However, any further addition of rubber particles resulted in a decrease in tensile strength. This is seen with a 15% rubber particle volume fraction, giving a tensile strength of 7.90 MPa. Further increase in rubber particle volume fraction to 20% gave a tensile strength of 5.67 MPa, significantly lower than the control specimen.

Rubber particle sizes of 300 µm gave an initial strength at a 5% volume fraction of 7.80 MPa, as shown in Figure 6. As the rubber particle volume fraction increased to 10%, there was a marginal increase in tensile strength to 7.91 MPa. However, any further addition of rubber particles resulted in a decrease in tensile strength. This is seen with a 15% rubber particle volume fraction, giving a strength of 6.35 MPa. Further increase in volume fraction to 20% gave tensile strength of 5.10 MPa. The 150 µm rubber particle results show that increased rubber particle volume fraction beyond 10% decreases the composites' tensile strength. The results obtained for composite tensile strength are consistent with a study by Abu-jdayil [14]. Abu-jdayil (2016) [14] concluded that increasing rubber particle volume fraction in composites reduces its tensile strength. The highest tensile strength of the composite is realized at a low volume fraction of rubber particles, less than 5%.

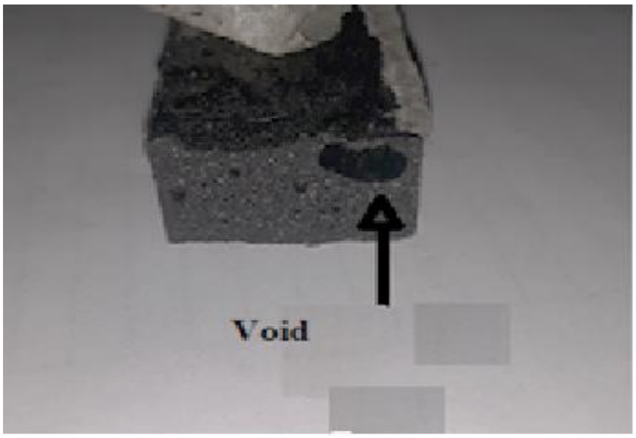

Fig. 7 Failure mode for rubber particles

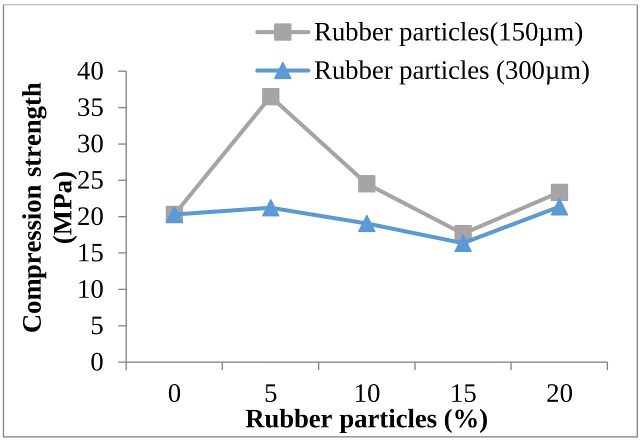

Fig. 8 Effects of rubber particles on composite compression strength

This phenomenon can be attributed to the even distribution of the rubber particles at lower volume fractions, minimizing void formation. The results for 300 µm rubber particles show that an increase in rubber particles' volume fraction lowers the tensile strength of the composites in a similar trend to the 150 µm rubber particles. The composites for 150 and 300 µm containing 20% rubber particles were observed to contain voids, as shown in Figure 7. The presence of the voids could be attributed to the poor dispersal of rubber particles within the composite. Therefore, using rubber particles alone as the filler material is not feasible at percentages exceeding 15%.

The findings in this study align with research by Hisham [19], who reported that an increase in rubber particle volume fraction reduces tensile strength. The workability during composite fabrication is easier at a low volume fraction of rubber particles. Furthermore, composite machining is easier and more accurate at rubber particle volume fractions below 15%. The composites containing higher rubber particle volume fraction greater than 15% took an excess of 48 hours to cure and reach acceptable hardness.

The findings obtained align with the study by Wang (2019) [20], who stated that the smaller the size of rubber particles used, the greater the composite tensile strength. This analogy is attributed to the even dispersion possible with finer rubber particles compared to coarser rubber particles. Furthermore, finer rubber particles have a larger surface area, resulting in enhanced interfacial bonds with the polyester resin.Even though rubber particles of size greater than 300 µm can significantly improve the damping properties of the composite in comparison to rubber particles less than 150 µm, the tensile strength of coarser rubber particles would be adversely affected.

3.2. Compression Strength

Figure 8 presents the effects on compression strength of rubber particles of sizes 150 and 300 µm. Figure 8 shows that for 150 µm rubber particles, the initial composite compressive strength at 5% rubber particle loading is 36.52 MPa. As the rubber particle volume fraction increased to 10%, there was a marginal decrease in compression strength to 24.55 MPa.

Furthermore, any further addition of rubber particles resulted in a reduction of composite compression strength. As observed with 15% rubber particles, the volume fraction gives a strength of 16.36 MPa. Further increase in rubber particle volume fraction to 20% showed an increase in compression strength to 23.35 MPa. Rubber particle sizes of 300 µm gave initial compression strength at 5% of 21.208 MPa. As the particle volume fraction increased to 10%, there was a marginal decrease in compression strength to 19.09 MPa. Furthermore, any further addition of rubber particles resulted in a reduction of compression strength. This is seen with 15% rubber particles, giving a strength of 16.36 MPa. Further increase in volume fraction to 20% increases compression strength to 21.36 MPa. This could be because more catalysts were added to the composite since it was not curing after 24 hours.

Rubber particle sizes of 150 µm decreased composite compressive strength with increased rubber particle volume fraction. This decrease in strength could be attributed to the rubber particles' low hydrophilicity, which gave a weak interfacial. Abu-jdayil (2016) [14] found a similar decrease in composite compressive strength with incremental rubber particle volume fraction. The low volume fraction of rubber particles, less than 5%, enhances the composite compression. This trend could be attributed to the even distribution of the rubber particles in the matrix, creating a robust interfacial bond with the absence of voids.

The 300 µm rubber particle results show that increased rubber particle volume fraction negatively affects the composite compression strength. However, there is a moderate increase in composite compression strength between 15 and 20% rubber particle volume fraction. The results align with a study by Abu-jdayil (2016) [14], who stated that the compression strength progressively reduces when you increase rubber volume fraction in composites. The low volume fraction of rubber particles enhances the mechanical strength of the composites due to the even distribution of the rubber particles in the matrix, creating a solid interfacial bond with the absence of voids. From Figure 8, it was observed that composite compression strength decreases with an increase in the size of rubber particles. The 300 µm rubber particles had a generally lower compressive strength than the 150 µm rubber particles. Smaller rubber particles have a larger surface area than bigger rubber particles, which increases the matrix bond. An increase in composite rubber particle volume fraction positively affects the composite flexibility, elasticity, and damping properties [2].

However, stress transfer is low due to the weak bond strength that exists between the rubber particles and the resin. A study by Wang (2019) [20] aligns with a current study that finer rubber particles as composite fillers give higher composite compression strength than coarser rubber particles. This analogy is attributed to the even dispersion possible for finer rubber particles within the composite. Furthermore, the larger surface area presented by finer rubber particles increases their bond strength compared to the coarser rubber particles [21].

The workability in the composite fabrication was easier at a low volume fraction of rubber particles of less than 15%. Furthermore, composite cutting was more straightforward for these specimens. The composites containing higher rubber particle volume fraction greater than 15% did not cure quickly and took an excess of 48 hours to reach acceptable hardness.

3.3. Flexural Strength

Figure 9 presents the effects of varying rubber particle volume fractions on the composite flexural strength. Figure 9 shows that for 150 µm rubber particles, the composite flexural strength at a 5% rubber particle volume fraction is 20.37 MPa above the control specimen, which had a flexural strength of 19.00 MPa. As the fibre volume fraction was increased to 10%, there was a marginal decrease in flexural strength to 19.84 MPa. However, any further addition of rubber particles beyond 10% resulted in a decrease in flexural strength, as observed with a 15% rubber particles volume fraction giving a flexural strength of 15.30 MPa. Further increase in volume fraction to 20% gave a flexural strength of 12.60 MPa.

Rubber particle sizes of 300 µm had an initial strength of 18.98 MPa at 5% rubber particle loading. As the rubber particle volume fraction increased to 10%, flexural strength decreased to 18.00 MPa. However, further addition of rubber particles beyond 10% decreased flexural strength, as observed with a 15% rubber particle volume fraction giving flexural strength of 12.60 MPa. Further increase in rubber particle volume fraction to 20% gave flexural strength of 5.80 MPa.

The results of 150 µm rubber particles suggest that a low volume fraction of less than 5% must be used in a composite to maximize flexural strength. The trend observed in Figure 9 for 150 µm rubber particles shows that an increase in rubber particle volume fraction decreases the flexural strength of the composite. The reduction in flexural strength can be attributed to the low rubber particle hydrophilicity, which gives a weak interfacial bond with the resin.

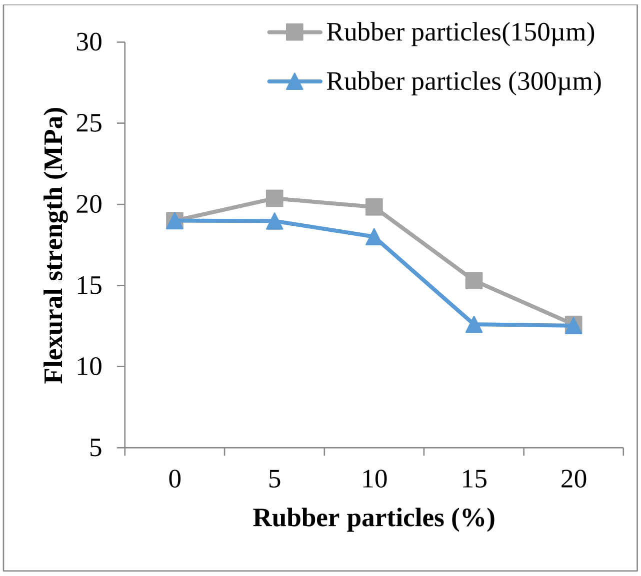

Fig. 9 Effect of rubber particles on composite compression strength

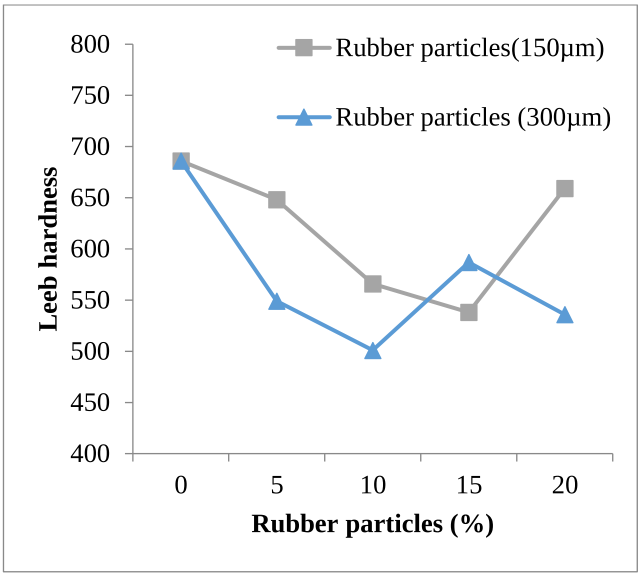

Fig. 10 Effect of 150 and 300 µm rubber particles on the composite hardness

Rachchh et al. (2018) [22] showed a similar trend to the current study that an increase in rubber particle volume fraction decreases the composite flexural strength due to insufficient bond strength to polyester resin. The results shown in Figure 9 for 300 µm show that rubber particles of less than 5% must be used to maximize the flexural strength as the composite strength decreases when the rubber particle volume fraction is increased.

This was attributed to low rubber particle hydrophilicity and weak interfacial bond between rubber particles and resin. The results obtained in Figure 9 align with a study by Abu-jdayil (2016) [14] and Meesit (2017) [2]. They reported that increasing composite rubber particle loading increases the composite flexibility and elasticity. The composites with a more significant rubber particle volume percentage greater than 15% took longer to cure and required more than 48 hours to obtain an acceptable hardness.

3.4. LEEB Hardness

Figure 10 shows the effects on the composite hardness of rubber particles of sizes 150 and 300 µm.Figure 10 shows that for 150 µm rubber particles, the initial Leeb hardness at 5% is 648. As the rubber particle volume fraction increased to 10%, there was a marginal decrease in hardness to 566. Further addition of rubber particles beyond 5% resulted in a decrease in composite hardness, as observed with composite containing 15% rubber particles, giving a hardness of 538. However, a further increase in volume fraction to 20% resulted in an increase in hardness to 659 MPa.

Composite containing 300 µm rubber particles gave Leeb hardness at 5% rubber particle loading of 549. As the rubber particle volume fraction increased to 10%, there was a marginal decrease in hardness to 501. However, further addition of rubber particles to 15% resulted in an increase in composite hardness to 587. Further increase in rubber particle volume fraction to 20% gives a composite hardness of 536. The results for 150 µm present that an increase in rubber particle volume fraction from 5% to 15% decreases the composite hardness. However, the hardness increases at 20% particle volume fraction to 660. This could be a result of adding excess catalyst at higher particle volume fractions to ensure composite cures.

The results for 300 µm present that an increase in rubber particle volume fraction from 5% to 10% decreases the composite hardness. On the other hand, there is an increase in composite hardness at a rubber particle volume fraction of 15%. However, further addition of rubber particles to 20% loading decreases the composite hardness due to the presence of voids.

The current study shows that composites fabricated from 300 µm rubber particles have a lower hardness than composites made with 150 µm rubber particles. The larger rubber particles of sizes 300 µm are inefficiently dispersed and result in low hardness. Smaller rubber particles of 150 µm are rougher and have larger specific areas that enhance the matrix bond with the polyester resin and, hence, have higher hardness[21].

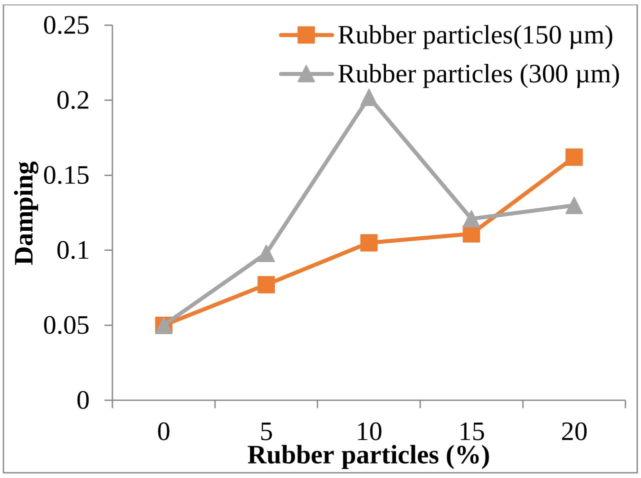

Fig. 11 Effect of rubber particles on vibration and damping properties

3.5. Vibrational Damping

Figure 11 shows the effects of rubber particle loading on the vibration and damping properties. Figure 11 indicates that for 150 µm rubber particles, the initial damping at 5% is 0.077. As the rubber particle volume fraction increased to 10%, there was a marginal increase in damping to 0.105. Further addition of rubber particles beyond 10% resulted in a decrease in composite damping, as observed with composite containing 15% rubber particles, giving a damping of 0.111. Further increase in rubber particle volume fraction to 20% resulted in a slight rise in damping to 0.162.

The composite, which had 300 µm rubber particles at a 5% rubber particle loading, gave a vibrational damping of 0.098. As the rubber particle volume fraction increased to 10%, there was a marginal increase in damping to 0.202. However, further addition of rubber particles to 15% resulted in a sharp decrease in composite damping to 0.121. Further, an increase in rubber particle volume fraction to 20% gave composite vibrational damping of 0.130.

The fabricated composites from particles size 300 µm have greater damping compared to a composite made with 150 µm rubber particles. A study by Wang (2019) states that larger rubber particles of sizes greater than 300 µm increase damping, but the use of extremely coarse rubber particles tends to lead to a lack of homogeneity in their dispersal [20]. This lack of homogeneity can be attributed to coarse rubber particles having large surface areas, allowing air pockets to ingress into the composite.

The particles of sizes less than 150 µm possess lower vibrational damping as they have a larger specific area that enhances the matrix bond with the polyester resin. Rubber particles size of less than 150 µm have less damping compared to rubber particles greater than 300 µm in size. The rubber particles less than 150 µm have better cohesion than coarse particles, which could help enhance composite properties but decrease damping. Thus, when the size of rubber particles increases, voids within rubber particles also increase. This phenomenon can be attributed to damping increases due to voids within rubber particles and decreases in composite material strength.

It was observed in this study that an increase in rubber particle size and volume fraction leads to an increase in damping. However, rubber particle volume fraction greater than 20% tends to have inherent voids and cracks. A study by Hartwig (2002) reported that these cracks at high rubber particle loading tend to contribute to the damping of the composite material [23]. As the rubber particles' volume fraction was increased beyond 15%, the composite tended to foam surface micro-cracks, which reduced the strength of the composite but improved damping. This phenomenon could be attributed to vibration energy dissipation at the location of cracks under load until composite failure. The development and progression of micro-cracks in polymeric composites have an effect of energy dissipation, improving the composites' fatigue behaviour.

Table 1. Strength parameters of railway sleepers [2,24]

Property	Fabricated composite	Concrete sleeper	Concrete with rubber particles [2,4]
Tensile strength (MPa)	8.86	6.50	3.20
Compression strength (MPa)	36.52	51.20	44.37
Flexural strength (MPa)	20.37	5.60	5.30
Vibrational Damping	0.1050	0.0211	0.0304

4. Composite Application in Railway Sleepers

The mechanical properties of composites have been discussed in table 1. The fabricated composites possess higher tensile and flexural strength than concrete sleepers. However, the compression strength of concrete is higher than that of fabricated composite. The damping of fabricated composites is higher than concrete by 0.0839%.

5. Conclusion

The research findings indicated that the maximum tensile strength of 8.86 MPa was realized at 10% of 150 µm rubber particle content. However, tensile strength reduces after volume fraction exceeding 10% due to insufficient resin and poor stress transfer. The maximum compression strength observed was 36.52 MPa at a 5% rubber particle loading. Further, the addition of rubber particles resulted in a decrease in compressional strength. The maximum flexural strength realized was 20.37 MPa at 5% of 150 µm rubber particle loading; further increase in the volume fraction of rubber particles resulted in a decrease in flexural strength. The highest hardness observed was 659 LEEB. The rubber particles in the composite sleep can help with the absorption of vibrational forces, eliminate the possibilities of crack failure and increase the stability of the railway way track to heavily laden trains. Furthermore, the hybrid composite fabrication increased the damping of the sleeper.

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References

[1] J. Taherinezhad et al., "A Review of Behaviour of Prestressed Concrete Sleepers," *Electronic Journal of Structural Engineering*, vol. 13, no. 1, pp. 1-16, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[2] I.A Carrascal et al., "Dynamic Behaviour of Railway Fastening Setting Pads," *Engineering Failure Analysis*, vol. 14, no. 2, pp. 364-373, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[3] D.P Connolly et al., "Benchmarking Railway Vibrations - Track, Vehicle, Ground and Building Effects," *Construction and Building Materials*, vol. 92, pp. 64-81, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[4] Ryan G. Kernes et al., "Investigation of the Dynamic Frictional Properties of a Concrete Crosstie Rail Seat and Pad and its Effect on Rail Seat Deterioration (RSD)," *Transportation Research Board 91st Annual Meeting*, pp. 1-14, 2011. [Google Scholar] [Publisher Link]

[5] Coenraad Esveld, *Modern Railway Track*, 2nd ed., MRT-Productions, pp. 1-654, 2001. [Google Scholar] [Publisher Link]

[6] Mingjun Li, "Preparation and Damping Properties of (Waste Rubber Powder)/ Hindered Phenol Composites," *Journal of Vinyl and Additive Technology*, vol. 20, no. 4, pp. 225-229, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[7] Martí Nadal et al., "Human Exposure to Environmental Pollutants after a Tire Landfill Fire in Spain, Health Risks," *Environment International*, vol. 97, pp. 37-44, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[8] Mihails Urbans, Inese Vilcane, and Jelena Malahova, "Assessment of Technogenic Risks in Recovering Company for Worn Tyres," *Engineering for Rural Development*, pp. 1616-1622, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[9] M. Nuzaimah et al., "Recycling of Waste Rubber as Fillers : A Review," *IOP Conference Series: Materials Science and Engineering*, vol. 368, pp. 1-9, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[10] A. Bin Samsuri, "A Degradation of Natural Rubber and Synthetic Elastomers," *Shreir's Corrosion*, vol. 3, pp. 2407-2438, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[11] Lucie Imbernon, and Sophie Norvez, "From Landfilling to Vitrimer Chemistry in Rubber Life Cycle," *European Polymer Journal*, vol. 82, pp. 347-376, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[12] S.P. Jani et al., "Machinablity of Hybrid Natural Fiber Composite with and without Filler as Reinforcement," *Materials and Manufacturing Processes*, vol. 31, no. 10, pp. 1393-1399, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[13] Basim Abu-Jdayil, Abdel-Hamid I. Mourad, and Atif Hussain, "Investigation on the Mechanical Behavior of Polyester-Scrap Tire Composites," *Construction and Building Materials*, vol. 127, pp. 896-903, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[14] A. Benazzouk et al., "Thermal Conductivity of Cement Composites Containing Rubber Waste Particles, Experimental Study and Modelling," *Construction and Building Materials*, vol. 22, no. 4, pp. 573-579, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[15] Sakdirat Kaewunruen et al., "Enhancement of Dynamic Damping in Eco-Friendly Railway Concrete Sleepers using Waste-Tyre Crumb Rubber," *Materials*, vol. 11, no. 7, pp. 1-20, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[16] *ASTM, D6641: Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture*, American Society for Testing and Materials, vol. 15.03, pp. 1-13, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[17] *ASTM, D8058-23: Standard Test Method for Determining the Flexural Strength of a Geosynthetic Cementitious Composite Mat (GCCM) Using the Three-Point Bending Test*, American Society for Testing and Materials, vol. 04.13, pp. 1-5, 2019. [CrossRef] [Publisher Link]

[18] Siti Farhana Hisham et al., "Blends of LNR with Unsaturated Polyester Resin from Recycled PET: Comparison of Mechanical Properties and Morphological Analysis with the Optimum Blend by Commercial Resin," *Malaysian Science*, vol. 40, no. 7, pp. 729-735, 2011. [Google Scholar] [Publisher Link]

[19] Jianfeng Wang et al., "Advances in Toughened Polymer Materials by Structured Rubber Particles," *Progress in Polymer Science*, vol. 98, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[20] Xun Lu, Weiwei Wang, and Lin Yu, "Waste Ground Rubber Powder, Waste Ground Rubber Tire Powder/Thermoplastic Vulcanizate Blends: Preparation, Characterization and Compatibility," *Journal of Applied Polymer Science*, vol. 131, no. 3, pp. 131-139, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[21] N.V. Rachchh, and D.N. Trivedi, "Mechanical Characterization and Vibration Analysis of Hybrid E-Glass/Bagasse Fiber Polyester Composites," *Materials Today Proceedings*, vol. 5, no. 2, pp. 7692-7700, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[22] Z. Zhang, and G. Hartwig, "Relation of Damping and Fatigue Damage of Unidirectional Fibre Composites," *International Journal of Fatigue*, vol. 24, no. 7, pp. 713-718, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[23] Kai Wei et al., "Virtual Special Issue Durability of Innovative Construction Materials and Structures Experimental Investigation into Temperature- and Frequency-Dependent Dynamic Properties of High-Speed Rail Pads," *Construction and Building Materials*, vol. 151, pp. 848-858, 2017. [CrossRef] [Google Scholar] [Publisher Link]