Mechanical and damping properties of composite rubber with waste crumb rubber tire and silica sand

Emeraldo Gabriel Putra¹, Henricus Priyosulistyo¹,*, Danna Darmayadi¹,²
¹Department of Civil and Environmental Engineering, Universitas Gadjah Mada (UGM), Yogyakarta, Indonesia. ²Department of Civil Engineering, Universitas Islam Sultan Agung, Semarang, Indonesia
E-mail: *priyo.ugm@ugm.ac.id

Abstract. The use of waste crumb rubber tire to reduce earthquakes impact on buildings is one of promising environmentally friendly solutions. Waste rubber tire will increase with the increasing number of vehicles. The purpose of this research is to study the mechanical and damping properties of waste rubber tire containing silica sand. Eleven different composites were produced with variation of the amount of waste rubber tire from 0, 25 and 50-per hundred rubber towards rubber compound based on their weight. The local silica sand consists of 10-phr, 20-phr, 30-phr, and 40-phr will be added on rubber compound containing 25 and 50-phr waste rubber tire respectively. Tensile strength, modulus of elasticity, shear modulus, and damping properties will be tested and researched. Composites of waste rubber tire with silica sand have lower tensile strength and modulus of elasticity with the addition of silica content. The shear modulus increased by loading silica sand and reached a maximum at filling of 40-phr. The damping properties also increased with the addition of silica sand and waste rubber tire, with the highest damping properties reached 10.40% on 40-phr silica sand and 25-phr waste rubber tire from the natural rubber damping properties of 3.10%. This study provides an overview of the effect of waste rubber tire and the interaction of silica sand on rubber properties experimentally.

1. Introduction
Based on data from BMKG during the year of 2015 at least 4,300 earthquakes had occurred with magnitudes greater than 3 on the Richter scale. According to [1] during the month of August 2019 there were 673 earthquakes and 22 of them had magnitudes above 5 on the Richter Scale. Building structures that are built without taking into account earthquake loads can certainly be dangerous because they can be damaged or even collapse. Many retrofitting methods have been developed, such as the addition of shear wall and steel bracing [2] or stiffness reduction with base isolation system [3]. Natural frequency and damping ratio of the structure could also be increased by adding viscoelastic dampers [4].

Rubber tire can be divided into two types based on their use, such as rubber tire that can be reused into vulcanizing and rubber tire that can not be reused because of considerable damage. In Europe, the use of reusable rubber was only 19% of 3,251,000 tons and only 5% of 3,251,000 was used in civil engineering [5]. The large number of waste rubber tire that cannot be used anymore causes the need for several methods to recycle, and one of the simplest and most used methods is to convert waste rubber tire into crumb [6].
Research on the mechanical properties of rubber and silica sand composites with varying grain size and amount (pphr) indicated that the more the amount of silica sand and the larger the grain size, the value of hardness will increase but the highest tensile strength, elongation, and compression set was obtained when mixing between rubber and silica sand with smallest grain size and loading [7]. The mechanical properties of natural rubber reinforced with silica from rice husk and carbon black also showed an increase in tensile strength, abrasion resistance, compression set, and hardness as carbon black increased [8].

[9] showed that the addition of silica fume and modified silica fume increased the level of tensile strength, modulus of elasticity, tear strength, and hardness than the natural rubber composites alone. Type and loading of silica also influenced the dynamic mechanical properties of rubber [10]. Optimum mixture of carbon black or silica in natural rubber showed that the average of mechanical strength (tensile strength, tearing strength, abrasion resistance, crack growth resistance, heat resistance, and grinding resistance) reached good values when the silica mixture was 20 and 30-phr [11]. Using silica also increased fatigue resistance and rolling resistance but decreased the modulus of elasticity and heat buildup on carbon black silica composite rubber [12]. The damping ratio calculated based on the logarithmic decrement method of a rubber and sand composites had also been studied by [13]. Several sizes of grains of sand were mixed with rubber material including mesh 4, mesh 20, and mesh 60 mixture. The results concluded that the damping ratio also increased with the addition of sand material, and the highest damping ratio was obtained in a rubber mixture with fine and coarse grained sand.

The properties tested in this study were ultimate tensile strength ($\sigma$), modulus of elasticity (E), shear modulus (G), and damping ratio ($\zeta$). These properties can be used to design environmentally friendly composite rubber material for buildings in reducing the earthquake impact or dynamic response. Rubber is a type of viscoelastic polymer, which is a material that can deform long after being exposed to a load and return to its original shape slowly after the load is removed. This nature of rubber which when exposed to small loads can deform long enough, impact on the low tensile strength but has a high elongation. The shear modulus or modulus of rigidity is a parameter that indicates the level of stiffness of the rubber material. The shear modulus of practical rubber compounds can be varied about 0.2 to 0.8 MPa, and could be even larger by filler increase to about 1-5 MPa [14]. Study reported that viscoelastic material was effective in reducing dynamic response and damage to structure. The damping ratio of reinforced concrete structure which is 5.06% can be increased to 6.92% with the addition of viscoelastic dampers based on [4].

This study also conducted Scanning Electron Microscopy-Energy Dispersive X-Ray test to see the addition effect of waste rubber tire crumb in the rubber compound according to topography and morphology of the surface of the analyzed sample [15], while the Energy Dispersive X-Ray (EDX) test shows an indication of the constituent elements of the sample [16].

2. Materials and Experimental Procedure

2.1. Materials

In this study Ribbed Smoked Sheets (RSS) natural rubber in accordance with Styrene Butadiene Rubber (SBR) synthetic rubber was used as main component of rubber compound. Waste rubber tire with grain size 0.15 mm (mesh 100) was obtained from shredded rubber truck tires. Natural rubber and waste rubber tire were obtained from the home industry in Semarang and can be seen in Figure 1. The white local silica sand material was used and graded as fine aggregate based on ASTM C33 standards. Grain size 1.18 mm (mesh 16) was the largest grain size used in silica sand and the most granular size of 600 $\mu$m (mesh 30) was 78%, so that mechanical crushing was needed in order to obtain gradations in accordance with the standard. After crushing and sieving, percentage of silica sand was determined based on grain size as in Table 1 with notation: $CP$: Cumulative percent retained, $PR$: Percent retained used, $CU$: Cumulative percent retained.
used. The fine modulus of silica sand with a value of 2.816 was still included in the ASTM grain fine modulus criteria, which is between 2.3 - 3.1.

| Sieve         | CP [17] (%) | PR (%) | CU (%) |
|---------------|-------------|--------|--------|
| 9.5 mm (3/8-in) | 0           | 0      | 0      |
| 4.75 mm (No. 4) | 0 – 5       | 0      | 0      |
| 2.36 mm (No. 8) | 0 – 20      | 0      | 0      |
| 1.18 mm (No. 16) | 15 – 50     | 34.2   | 34.2   |
| 600 µm (No. 30) | 40 – 75     | 26.3   | 60.5   |
| 300 µm (No. 50) | 70 – 95     | 26.3   | 86.8   |
| 150 µm (No. 100) | 90 – 100   | 13.2   | 100.0  |

**Table 1:** Silica sand percentage used

![Figure 1](image1.png)

**Figure 1:** Rubber compound (a), waste crumb rubber tire (b), and silica sand (c)

2.2. Mixture proportions

In this study rectangular test specimen were used in 2 different sizes, there were: 17 cm × 22 cm × 2 mm for tensile test, and 10 cm × 10 cm × 2.5 cm for shear test and determination of damping ratio. Each of these sizes was made according to a mixture of rubber compound, waste rubber tire, and silica sand namely WR0, WR1, WR2, WR3, WR4, WR5, WR6, WR7, WR8, WR9, WR10, dan WR11 with a mixture in accordance written on Table 2. The mixing of silica sand, compound rubber, and waste rubber tire were based on the weight measured using scales in per hundred rubber (phr), for example in specimen WR4 the amount of waste rubber tire and silica sand respectively were 125 gram and 50 gram on 500 gram rubber compound. WR meaning waste rubber was used as specimen code in this study to represent the mixing formula.

2.3. Mixture procedure and curing

The process of making test specimens were carried out at the Polytechnic ATK Yogyakarta. In this study, two-roll mill machines were used in the mixing process and press molding machine with molds from steel were used for the curing process as in Figure 2 (a). First of all, the rubber compound was mixed with waste rubber tire using the two-roll mill that can be seen on Figure 2 (b) while controlling the temperature so it didn’t get too hot. Then the rubber was taken away from the machine in the form of sheets to be cut according to the size of the mold and then given silica sand according to the mixture that has been prepared as in Figure 2 (c). After the mixing process, the compound rubber was then heated and molded through the press molding
Table 2: Mixture constituent for 10cm × 10cm × 2,5cm test material

| Sample name | Rubber compound (-phr) | Waste rubber tire (-phr) | Silica (-phr) |
|-------------|------------------------|--------------------------|---------------|
| WR1         | 100                    | 0                        | 0             |
| WR2         | 100                    | 25                       | 0             |
| WR3         | 100                    | 50                       | 0             |
| WR4         | 100                    | 25                       | 10            |
| WR5         | 100                    | 25                       | 20            |
| WR6         | 100                    | 25                       | 30            |
| WR7         | 100                    | 25                       | 40            |
| WR8         | 100                    | 50                       | 10            |
| WR9         | 100                    | 50                       | 20            |
| WR10        | 100                    | 50                       | 30            |
| WR11        | 100                    | 50                       | 40            |

machine. Based on the results of rheological tests, it was found that the rubber material reaches optimum curing (tc90) at a heating time for 3 minutes 19 seconds with a temperature of 160°C. After molding, the rubber was then cooled to room temperature before testing.

Figure 2: (a) Sample test molding middle layer, (b) sample test molding all layer, (c) Two Roll Mill, (d) Silica sand added, (e) rubber and silica sand layer in millimetre

3. Testing Procedure
3.1. Tensile test
SNI ISO 37: 2011 standard was used for tensile testing so that the tensile strength and modulus of elasticity of rubber can be obtained. Tensile testing was done by cutting sheet rubber specimen into dumb-bells of the size as in Figure 3 (a). Tensile testing was carried out at the Center
for Leather, Rubber, and Plastics (CLRP) Special Region of Yogyakarta. Calculation of the maximum tensile strength value is obtained from the division between the maximum tensile load and the tensile area. As for the calculation of rubber elastic modulus, it is done by dividing the stress and strain that occurs. The addition of other materials such as waste rubber tire and silica sand can reduce the elasticity of rubber so that the rubber tends to be brittle. The formula for calculating the tensile strength and modulus of elasticity of rubber according to [18] written respectively on Eq. (1) and Eq. (2) as follows:

\[
\sigma = \frac{P}{A_0} \quad (1)
\]

\[
E = \frac{\sigma}{\varepsilon} \quad (2)
\]

where: \(\sigma\) : tensile stress (MPa), \(P\) : maximum tensile load (N), \(A_0\) : tensile area (mm\(^2\)), \(E\) : modulus of elasticity (MPa), and \(\varepsilon\) : tensile strain.

3.2. Shear Test

Shear test was conducted according to SNI 3967-2013 in the form of inclination testing and was carried out at Structure Laboratory Department of Civil and Environmental Engineering Universitas Gadjah Mada. The test configuration can be seen in Figure 4 (b). 10 cm x 10 cm x 2.5 cm was the test specimen size to evaluate the shear modulus. The shear modulus calculation step according to [19] the first is to set the value of the \(F_1\) force, the smallest force chosen between 2% of the maximum force when deforming is 65% thick or 5 kN. Then calculate the \(X_1\) value as the lower limit, then the \(X_2\) value is calculated by adding a deformation of 0.5 thickness. Then the value of the \(F_2\) is calculated on the graph by pulling up until it intersects the graph. The value of the shear modulus is obtained by dividing the force by the area and the slope that can be seen in Eq. (3). Illustration of shear test calculations can be seen in Figure 4 (a).

\[
G = \frac{2(F_2 - F_1)}{A \times n} \quad (3)
\]

where, \(G\) : shear modulus, MPa, \(F_1\) : initial load (5 kN or 2% maximum load at fourth cycle where displacement achieved 65% thick), \(N\), \(F_2\) : load at the intersection point \(X_2\) with the fourth cycle curve, \(N\), \(A\) : cross section area of rubber bearing, mm\(^2\), and \(n\) : plate slope, example if 20% slope is used then enter the value of \(n = 20\).

3.3. Damping Test

Damping properties of this study calculated based on hysteresis energy loop or equivalent viscous damping using Eq. (4) where the hysteretic area of the load-deformation graph is divided by the potential energy in the form of the area of a triangle [20]. The assumption used in calculation was that the dissipated energy is proportional to the stored energy. The damping ratio calculation was done on the shear modulus specimen measuring 10 cm x 10 cm x 2.5 cm in four cycles which are then averaged to obtain the material damping ratio. The illustrative calculations can be seen through Figure 4 (d). The value of \(F_0\) is the maximum load of each cycle, and \(u_0\) is the maximum deformation that occurs in the cycle. Multiplication between \(F_0\) and \(u_0\) is the potential energy value (PE) and the area of the curve is the hysteretic energy (HE) of the viscoelastic polymer material.

\[
\zeta = \frac{1}{2\pi} \frac{A_{\text{hyst}}}{F_0 u_0} \quad (4)
\]

where, \(\zeta\) : damping ratio, % , \(A_{\text{hyst}}\) : area of hysteretic curve, kNmm, \(F_0\) : maximum load at maximum displacement, kN, and \(u_0\) : maximum displacement, mm.
4. Results and discussion

4.1. Tensile properties

The results of the tensile strength of the rubber specimen decreased with the addition of waste rubber tire, as in Figure 5 (a). This happened due to the fact that waste rubber tire was not cross-linked with rubber compound as a result of no addition of vulcanizing elements such as
sulfur during the process of mixing waste rubber tire with rubber compound, so that waste rubber tire only engages mechanically. The addition of 25-phr waste rubber tire to the rubber compound caused the tensile strength to be reduced by 41.353% from the tensile strength value without the addition of waste rubber tire and the addition of 50-phr waste rubber tire caused the tensile strength to decrease by 60.495% from the tensile strength without adding waste rubber tire.

The addition of silica sand to the rubber compound mixture also resulted in a decreased of the tensile strength. The decrease occurred in the addition of silica sand by 10-phr to 30-phr, but there was a slight increase when adding as much as 40-phr. This was due to the addition of silica sand disrupting the bond between rubber so that the rubber becomes more brittle. In addition, large enough silica sand grains can also damage rubber when given a tensile load. The comparison graph of the addition of silica sand to rubber mixture with waste rubber tire as much as 25-phr and 50-phr can be seen at Figure 5 (b). The decrease in tensile strength due to the addition of silica sand by 10-phr, 20-phr, 30-phr, and 40-phr on a rubber compound containing 25-phr waste rubber tires to the tensile strength value of 25-phr used tires successively were 26.145%, 35.430%, 65.694%, and 54.075%. Decrease in tensile strength due to the addition of silica sand by 10-phr, 20-phr, 30-phr, and 40-phr on a rubber compound containing 50-phr waste rubber tire to the tensile strength value of rubber compound 50-phr waste rubber tire respectively were 14.265%, 35.633%, 58.485%, and 57.905%.

The modulus of elasticity value of rubber compound with the addition of waste rubber tire has also decreased as in Figure 5 (c). This is due to the small load, rubber is still able to increase in length up to 6 times the original length, so that the strain that occurs is large enough and makes the modulus of elasticity small. The elongation that occurred is still quite large, which is between 450% to 650%. The addition of 25-phr waste rubber tire to the rubber compound caused the modulus of elasticity to decrease by 43.188% of the modulus of elasticity without the addition of waste rubber tire and the addition of 50-phr waste rubber tire caused the modulus of elasticity to decrease by 54.239% from the modulus of elasticity without the addition of waste rubber tire.

The addition of silica sand to the rubber compound mixture also results a decrease in the modulus of elasticity. The decrease occurred in the addition of silica sand by 10-phr to 30-phr, but there was a slight increase when adding as much as 40-phr. The cause of the decrease is the elongation which is still quite high but the load applied is small, so the strain that occurs is still quite large. The smallest elongation due to the addition of the silica sand was 200% and the largest was 500%. The comparison graph with the addition of silica sand to rubber mixture with waste rubber tire as much as 25-phr and 50-phr can be seen at Figure 5 (d). Decrease in modulus of elasticity due to the addition of silica sand by 10-phr, 20-phr, 30-phr, and 40-phr on a rubber compound containing 25-phr waste rubber tires to the modulus of elasticity value of 25-phr waste rubber tire successively were 4.769%, 8.896%, 36.087% and 35.938%. Decrease in modulus of elasticity due to the addition of silica sand by 10-phr, 20-phr, 30-phr, and 40-phr on a rubber compound containing 50-phr waste rubber tire to the modulus of elasticity value of rubber compound 50-phr waste rubber tire respectively were 0.181%, 5.572%, 26.385%, and 25.877%.

4.2. Modulus of Rigidity
The addition of 25-phr waste rubber tire caused a decrease in the the shear modulus because the waste rubber tire soften the compound rubber then causes the rubber to be less rigid. However, the addition of 50-phr waste rubber tire caused the shear modulus increases due to friction arising between the waste rubber tire and compound rubber. The modulus of rigidity of rubber compound with the addition of waste rubber can be seen in Figure 6 (a). The addition of 25-phr waste rubber tire to the rubber compound caused the modulus of rigidity to decrease by 9.52%
Figure 5: (a) Tensile strength with waste crumb rubber tire mixture (b) Tensile strength with waste crumb rubber tire and silica sand mixture (c) Modulus of elasticity with waste crumb rubber tire mixture (d) Modulus of elasticity with waste crumb rubber tire and silica sand mixture

of the modulus of rigidity without the addition of waste rubber tire and the addition of 50-phr waste rubber tire caused the modulus of rigidity to decrease by 18.13% from the modulus of rigidity without the addition of waste rubber tire.

The addition of silica sand caused heat due to friction between the grains and friction of silica sand with rubber, so the shear modulus value tends to increase compared to rubber compounds without silica sand. The existence of permanent deformation also affects the shear modulus results because the initial deformation value obtained is based on that value. Comparison graph of the shear modulus due to the addition of silica sand to rubber compound with 25-phr and 50-phr waste rubber tire with 10 cm x 10 cm x 2.5 cm specimens shown in Figure 6 (b). The maximum shear modulus properties was achieved with the addition of 40-phr silica sand and 25-phr waste rubber tire, which is 1.14 MPa. Increase in modulus of rigidity due to the addition of silica sand by 10-phr, 20-phr, 30-phr, and 40-phr on a rubber compound containing 25-phr waste rubber tire to the modulus of rigidity of 25-phr waste rubber tire successively were 25.99%, 58.72%, 99.97% and 151.93%. Increase in modulus of rigidity due to the addition of silica sand by 10-phr, 20-phr, 30-phr, and 40-phr on a rubber compound containing 50-phr waste rubber tire to the modulus of rigidity of rubber compound 50-phr waste rubber tire respectively were 5.87%, 12.08%, 18.65%, and 23.61%.

4.3. Damping Properties
If the data is presented in graphical form as stated in Figure 7 (a) the damping ratio with addition of waste rubber tire can be observed. Apart from that, Figure 7 (b) shows the average damping ratio with each addition of silica to the compound rubber 25-phr waste rubber tire and compound rubber 50-phr waste rubber tire. The addition of 25-phr waste rubber tire to the rubber compound caused the damping properties to decrease by 8% of the damping properties
without the addition of waste rubber tire and the addition of 50-phr waste rubber tire caused the modulus of elasticity to increase by 29\% from the damping properties without the addition of waste rubber tire.

The damping ratio increased with increasing silica sand. However, there is a slight difference that the compound rubber 50-phr waste rubber tire reaches the optimal damping value when adding silica sand by 30-phr, while the compound rubber 25-phr waste rubber tire reaches the optimal damping value when adding silica sand by 40-phr. This is caused by the addition of silica sand which is done mechanically so that there can be a less uniform buildup and cause the specimen to be more rigid. The increase in damping properties due to the addition of silica sand at maximum observed damping ratio on rubber compound containing 25-phr waste rubber tire and rubber compound 50-phr waste rubber tire respectively were 235.48\% and 158.71\% from rubber compound damping properties without silica sand and waste rubber tire. Increase in damping properties due to the addition of silica sand by 10-phr, 20-phr, 30-phr, and 40-phr on a rubber compound containing 25-phr waste rubber tires to the damping properties of 25-phr waste rubber tire successively were 217\% , 243\% , 246\% and 263\% . Increase in damping properties due to the addition of silica sand by 10-phr, 20-phr, 30-phr, and 40-phr on a rubber compound containing 50-phr waste rubber tire to the damping properties of rubber compound 50-phr waste rubber tire respectively were 33\% , 64\% , 100\% , and 80\%.

![Figure 6](image1.png)

**Figure 6:** (a) Modulus of rigidity with waste crumb rubber tire mixture (b) Modulus of rigidity with waste crumb rubber tire and silica sand mixture

![Figure 7](image2.png)

**Figure 7:** (a) Damping properties of waste crumb rubber tire mixture (b) Damping properties of waste crumb rubber tire and silica sand mixture
4.4. Scanning Electron Microscopy (SEM) Energy Dispersive X-Ray (EDX)

SEM analysis with 300 magnification showed that the more waste rubber tires added, the surface topography will be more wavy and more white spots detected as seen in Figure 8 (a). Comparison of the elements due to the addition of waste rubber tires can be seen in Figure 8 (b). The addition of waste rubber tire results in the reduction of the carbon element, but increasing the oxygen element. This is because the waste rubber tire material contained many other elements such as silica, calcium, and sulfur which are high enough so that the percentage of carbon elements was reduced by the presence of these additional elements. The carbon and nitrogen elements are the most abundant element because the main filler of compound rubber was carbon black and natural rubber generally contain nitrogen element.

![Figure 8: (a) SEM analysis on rubber compound 0-phr waste rubber tire, 25-phr waste rubber tire, and 50-phr waste rubber tire (b) EDX analysis for rubber with waste rubber tire](image)

5. Conclusion

This research has discussed how to obtain the mechanical properties experimentally in laboratories with various types of tests. Based on the results and discussion of mechanical and damping properties of waste rubber tire composite with silica sand, it can be concluded as follows. The tensile strength and elastic modulus of composites waste rubber tire and silica sand showed a decrease along with the addition of waste rubber tire and silica sand. Shear modulus of rubber composite decreases when adding 25-phr waste rubber tire then rises when adding 50-phr waste rubber tire. The addition of silica sand results with an increase in shear modulus due to the addition of friction interactions and reaches optimum when adding 40-phr. The damping ratio decreases when adding 25-phr waste rubber tire then rises when adding 50-phr waste rubber tire in accordance with the shear modulus properties. The optimum damping ratio of composite rubber on the addition of 50-phr waste rubber tire was achieved with the addition of 30-phr silica sand, which is 8.02%, while optimum damping ratio on composite rubber with the addition of 25-phr waste rubber tire was achieved with the addition of silica sand by 40-phr, which is 10.40%. Bonding that occurs between compound rubber and waste rubber tire occurs mechanically in accordance with the results of EDX analysis and the addition of waste rubber tire interferes with the curing and vulcanization of the rubber compound thereby reducing inter-carbon bonds but increasing bonds with oxygen due to oxidation processes.

Acknowledgments

The authors express their gratitude and highest appreciation to Rekognisi Tugas Akhir (RTA) programme Directorate of Research and Development of Universitas Gadjah Mada Yogyakarta for funding this research. The authors also express their gratitude to Structure Laboratory Universitas Gadjah Mada, Rubber Workshop Polytechnic ATK Yogyakarta, and Physics
Laboratory of Center for Leather, Rubber, and Plastics Special Region of Yogyakarta for giving test facilities on this research.

References
[1] CNBC Indonesia, "BMKG: Terjadi 673 Gempa di Agustus 2019, 3 Gempa Merusak," 2019. Online. Available: https://www.cnbcindonesia.com/news/20190905161554-4-97403/bmkg-terjadi-673-gempa-di-agustus-2019-3-gempa-merusak. Accessed 2 Oktober 2019.
[2] M. E. Badoux and J. James, "Steel Bracing of RC Frames for Seismic Retrofitting," Journal of Structural Engineering-asce - J STRUCT ENG-ASCE, 1990.
[3] G. Oliveto and M. Marletta, "Seismic Retrofitting of Reinforced Concrete Buildings Using Traditional and Innovative Techniques," TSET Journal of Earthquake Technology, pp. 21-46, 2005.
[4] Z. D. Xu, "Earthquake Mitigation Study on Viscoelastic Dampers for Reinforced Concrete Structures," Journal of Vibration and Control, pp. 29-43, 2007.
[5] A. Lucia, M. Gratton, S. Seghar and N. A. Hocine, "Recycling of rubber wastes by devulcanization," J. Resource, Conservation & Recycling, pp. 250-262, 2018.
[6] M. Forrest, Recycling and Re-Use of Waste Rubber, Shropshire: Smithers Rapra Technology Ltd, 2014.
[7] I. S. Jallham and I. J. Maia, "Testing and Evaluation of Rubber-base Composites Reinforced with Silica Sand," Journal of COMPOSITE MATERIALS, vol. 40, no. 23, pp. 2099-2112, 2006.
[8] P. E. Imoisili, K. O. Ukoba, I. T. Adejuge, D. Adgidzi and S. O. O. Olusunle. "Mechanical Properties of Rice Husk /Carbon Black Hybrid Natural Rubber Composite," Journal of Chemistry and Materials Research, pp. 12-16, 2013.
[9] R. Suntako, "The rubber damper reinforced by modified silica fume (mSF) as an alternative reinforcing filler in rubber industry," Journal of Polymer Research, no. 24, 2017.
[10] M. Shen, F. Zhao, S. Wang and S. Zhao, "Effect of Type and Load of Silica on Dynamic Properties of Solution Styrene-Butadiene Rubber / Butadiene Rubber," Journal of Macromolecular Science, Part B: Physics, pp. 398-406, 2013.
[11] N. Rattanasom, T. Saowapark and C. Deepprasertkul, "Reinforcement of natural rubber with silica/carbon black hybrid filler," Journal of Polymer Testing, no. 26, p. 369–377, 2007.
[12] R. Zafarmehrabian, S. T. Gangali, M. H. R. Ghoreishy and M. Davallu, "The Effects of Silica/Carbon Black Ratio on the Dynamic Properties of the Tread compounds in Truck Tires," Journal of Chemistry, pp. 1102-1112, 2012.
[13] D. Christianto, Y. Lase and Yoespitta, "Pengaruh Pasir terhadap Rasio Redaman pada Perangkat Kontrol Pasif," Surakarta, 2013.
[14] A. N. Gent, Engineering with Rubber : How to Design Rubber Components, 3rd ed., M¨unchen: Carl Hanser Verlag, 2012.
[15] D. K. Setua, R. Awasthi, S. Kumar, M. Prasad and K. Agarwal, "Scanning electron microscopy of natural rubber surfaces: quantitative statistical and spectral texture analysis using digital image processing," FORMATEX, pp. 1642-1652, 2010.
[16] A. M. Idris and A. A. El-Zahhar, "Indicative properties measurements by SEM, SEM-EDX and XRD for initial homogeneity tests of new certified reference materials." Microchemical Journal, 2019.
[17] ASTM, Standard Specification for Concrete Aggregates, Pennsylvania: ASTM, 2003.
[18] J. F. Stanton and C. W. Roeder, "Elastomeric Bearing Design, Construction, and Materials," Transportation Research Board, National Research Council, Seattle, 1982.
[19] Badan Standardisasi Nasional, Spesifikasi dan metode uji bantalan karet (elastomer) untuk perletakan jembatan, Jakarta: BSN, 2013.
[20] P. F. Picauly, "Perbaikan Kinerja Tuned Mass Damper (TMD) Menggunakan Bahan Peredam Viscoelastic Polymer," UGM, Yogyakarta, 2018.