Mechanical and dynamic properties of composite rubber (RSS and SBR) with waste rubber crumb and copper fiber

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Abstract. Waste rubber tire is difficult to decompose by nature, but it can be reused as a part of composite rubber materials. In this research, waste rubber crumb was mixed into Ribbed Smoked Sheets (RSS) and Styrene-Butadiene Rubber (SBR) compound to form a composite rubber. The aim of this research is to investigate the mechanical and dynamic properties of RSS and SBR compounds with waste rubber crumb and copper fiber. For this purpose, another composite material in the form of copper fiber is also added which is expected to increase the damping properties of the rubber even though the mechanical properties of the rubber will decrease. RSS and SBR rubber compounds consist of 25-phr and 50-phr waste rubber crumb. Waste rubber crumb is taken from used vehicle tires with the granular size passes through the mesh sieve number # 100. 5-phr, 10-phr, 20-phr, and 30-phr of copper fibers were added into 25-phr and 50-phr respectively. The copper fiber used is 0.3 ± 0.05 mm in diameter and length to diameter ratio is 40. The results of this study indicate that the addition of waste rubber 25-phr and 50-phr decreases the tensile strength, elastic modulus, and shear modulus but increases the damping properties. The addition of copper fiber 5-phr until 30-phr decreases the tensile strength and elastic modulus but increases the shear modulus and the damping properties.

1. Introduction

Indonesia is a country with a high number of motor vehicles. According to [1] there are 138 million vehicles in Indonesia in 2017. The large number of vehicles increases the amount of waste, one of which is waste rubber tire. The waste rubber is difficult to decompose by nature, so it must be recycled so as not to pollute the environment.

Waste rubber can be processed as a mixture for rubber products [2]. The waste rubber was mashed into a crumb. Waste rubber crumb can be mixed into new rubber as a filler or as a composite. According to [3] the addition of waste rubber crumb as a filler can increase mechanical properties of rubber but according to [4] the addition of waste rubber crumb as composite up to 30-phr with 80 mesh granules size to polyethylene and SIR-20 rubber causes a decrease in mechanical properties such as strong tensile, elastic modulus, and elongation at break. If the waste rubber crumb is added in mixing mortar, this can also improve the damping ratio of hardened mortar significantly [5].

Fiber can also be used as a rubber composite mixture. According to [6–8] the addition of fiber to rubber as a filler can increase the tensile strength, hardness and stiffness of Styrene-
butadiene rubbers (SBR) rubber. Meanwhile, according to [9–11] the addition of fiber to rubber as a composite (fiber length ± 10 mm) can reduce the tensile strength of rubber. According to [12] the addition of viscous elastic dampers can increase attenuation and reduce deviation due to earthquake loads by up to 40-55% in the 3-story structure that is burdened. The addition of HDR on the continuous beam bridge model gives a horizontal damping ratio of 16.77% [13].

Addition of waste rubber tire crumb can decrease mechanical properties and damping properties in rubber. The addition of composite materials to rubber can also increase its damping value, due to the internal friction forces arising from the composite material [14]. According to [15] at frequency 2 Hz – 8 Hz, rubber with sisal and banana fiber have smaller displacement than rubber with no fiber. It is expected that the addition of fiber to rubber, especially copper fiber, can increase the damping value of rubber.

Based on previous research, this study aims to determine the mechanical and dynamic properties of rubber composites. The difference between this research and previous research is the use of waste rubber crumb and copper fiber as composite materials. Waste rubber crumb and copper fiber added are expected to increase the dynamic properties of composite rubber.

2. Materials and Experimental Procedure

2.1. Material

First material in this study was rubber compound. Ribbed Smoked Sheets (RSS) rubber and Styrene-butadiene rubbers (SBR) used as the main components of rubber compound. RSS and SBR rubbers were mixed with other ingredients to make compound in the form of sheets as in Figure 1(a). This rubber compound was taken from Langgeng Jaya Rubber Agency located in Semarang, Indonesia.

Second material was waste rubber crumb. Waste rubber was taken from the tires of trucks. According to [2] there are 4 methods for making waste rubber crumb, namely by grinding or crumbing, cryogenic process, water process, and ambient processes. Waste rubber in this study was ground until it reaches crumb of granular size that passes through the mesh sieve number # 100 as shown in Figure 1(b).

Third material was copper fiber. The copper fiber used was of 0.3 ± 0.05 mm diameter as shown in Figure 1(c). According to [16] the optimum ratio of fiber length to diameter ratio (L / D) was between 40 to 250. So, in this study, copper's fiber lengths were 40 times the diameter or around 12 mm.

![Figure 1: (a) Rubber Compound, (b) waste rubber crumb, (c) copper fiber](image)

2.2. Mixing Waste Rubber and Copper Fiber

Researcher [17] mixed waste rubber with granular size passing sieve number 60 and with a total mixing of 30-phr, 40-phr, and 50-phr to rubber compound. Based on previous research, in this study 25-phr and 50-phr of waste rubber crumb were used as composite material. Refers to [7]
which adds 10-phr, 20-phr, and 30-phr fibers to the rubber, in this study, elaborated 5-phr, 10-phr, 20-phr, and 30-phr copper fibers to the rubber compound. The amount of addition waste rubber crumb and copper fiber can be shown in Table 1.

**Table 1: Rubber Compounds, Waste Rubber, and Copper Fiber Compositions**

| Test Specimen | Rubber Compound (-phr) | Waste Rubber Crumb (-phr) | Copper Fiber (-phr) |
|---------------|------------------------|---------------------------|---------------------|
| R1            | 100                    | 0                         | 0                   |
| R2            | 100                    | 25                        | 0                   |
| R3            | 100                    | 50                        | 0                   |
| R4            | 100                    | 25                        | 5                   |
| R5            | 100                    | 25                        | 10                  |
| R6            | 100                    | 25                        | 20                  |
| R7            | 100                    | 25                        | 30                  |
| R8            | 100                    | 50                        | 5                   |
| R9            | 100                    | 50                        | 10                  |
| R10           | 100                    | 50                        | 20                  |
| R11           | 100                    | 50                        | 30                  |

2.3. Making of Test Specimen

Preparation and making of sample were carried out at the Rubber Workshop of Politeknik ATK Yogyakarta. Preparation of test specimens was carried out by measuring rubber compounds, waste rubber crumbs and copper fibers. Manufacturing process of test specimens was carried out by mixing waste rubber and copper fiber and was formed into cube shape using a mold. Waste rubber crumb that has been weighed according to the composition in table 1 was mixed into a rubber compound using a two roll mills machine as shown in Figure 2(a). The rubber compound that rotates inside the machine is sprinkled with waste rubber crumb until it is spread evenly. Rubber that has been mixed with waste rubber is removed from the mill machine in a sheet form.

Composite rubber that has been shaped sheet cut into pieces according to the desired test object size. In this study, 2 different cube size of composite rubber. Each size of cube was coded as shown in Table 2.

**Table 2: Cube size code**

| Code | Dimension            | Function       |
|------|----------------------|----------------|
| A    | 17.5 cm x 22 cm x 2 mm | Tensile Test  |
| B    | 10 cm x 10 cm x 2.5 cm | Shear Test    |

Cube specimen was consist of 2 layers for the size A and 3 layers for the test specimen with size B. Copper fiber was added in the inter-layer section of cube specimen. Cube specimen was inserted into the mold as shown in Figure 2(b), then it was pressed with press machine at 160°C and a pressure of 90-100 kg / cm² for 6 minutes as shown in Figure 2(c) refers to rheological test result as shown in Figure 5.

2.4. Testing

The test was carried out at the Physical Laboratory of Center for Leather, Rubber and Plastics Special Region of Yogyakarta for tensile testing. Shear testing was carried out at the Structural
Figure 2: (a) Two roll mills, (b) Rubber Mold, and (c) Press Machine

Laboratory of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada.

Tensile testing according to [18] was done by making dumb-bells that are cut from cube specimens size A for 5 samples. The size of specimen depends on the speed of the machine. For machine speed of 500 mm/min the size of specimen as shown in Figure 3.

Figure 3: Dumb-bells

Shear testing refers to [19]. The test was done by placing the 2 equal samples between 3 sliding plates made of aluminum with a slope of 1:20. The test specimen used was size A. The cube specimen and sliding plate were placed inside a press machine that has been given a load cell and LVDT in the horizontal directions. The plate and rubber were pressed until they shift by 65% from the height of the rubber sample for 4 to 6 minutes. After that the engine was released and pressed again up to 4 cycles. The slide test sketch can be seen in Figure 4.

Figure 4: (a) Shear test detail (b) Section A-A

3. Discussion

3.1. Rheology Test

Rheology test was carried out to determine the optimum temperature for the vulcanization process of the rubber. In addition it can also be determine the minimum time required for the
process. Based on the results of rheology tests on compound samples such as in Figure 5 (a), the optimum temperature was 160°C and the minimum time required for the vulcanization process is 3 minutes 19 seconds.

![Figure 5: (a) Rheology test result (b) Force Stress – Elongation Diagram](image)

### 3.2. Tensile Strength

The tensile strength test that was carried out produces a load against extension graph for each variation as in Figure 5 (b). The maximum load obtained based on the graph is calculated to get the rubber tensile strength using Eq. (1).

\[
\sigma = \frac{P}{A_0}
\]

where: \(\sigma\) : tensile strength (MPa), \(P\) : load (N), \(A_0\) : rubber area (mm²). Based on Figure 6 (a) it is shown that the addition of waste rubber crumb can reduce the tensile strength of rubber composites. This may be caused by the weak bond between the rubber compound and the waste rubber tire crumb in the composite. The tensile strength of rubber composites consist of 25-phr waste rubber crumb has decreased by 38%. The tensile strength of rubber composites consist of 30-phr waste rubber crumb has decreased by 61%.

The addition of copper fiber can reduce the chemical bond in the rubber. Composite rubber with the addition of 25-phr waste rubber crumb and copper fiber makes tensile strength decreases in line with the more addition of the copper fiber as shown in Figure 6 (b). Composite rubber with the addition of 25-phr waste rubber crumb and 5-phr copper fiber makes tensile strength decrease 10%. Composite rubber with the addition of 25-phr waste rubber crumb and 10-phr copper fiber makes tensile strength decrease 19%. Composite rubber with the addition of 25-phr waste rubber crumb and 20-phr copper fiber makes tensile strength decrease 34%. Composite rubber with the addition of 25-phr waste rubber crumb and 30-phr copper fiber makes tensile strength decrease 47%.

Composite rubber with the addition of 50-phr waste rubber crumb and copper fiber makes tensile strength decreases in line with the more addition of the copper fiber as shown in Figure 8. Composite rubber with the addition of 50-phr waste rubber crumb and 5-phr copper fiber makes tensile strength decrease 11%. Composite rubber with the addition of 50-phr waste rubber crumb and 10-phr copper fiber makes tensile strength decrease 21%. Composite rubber with the addition of 50-phr waste rubber crumb and 20-phr copper fiber makes tensile strength decrease 38%. Composite rubber with the addition of 50-phr waste rubber crumb and 30-phr copper fiber makes tensile strength decrease 51%.
3.3. Elastic Modulus

Elongation rubber due to tensile load was also be observed in the tensile test carried out at the Physical Laboratory of Center for Leather, Rubber and Plastics Special Region of Yogyakarta. The elongation was observed at 2 points at a distance of 20 mm apart in the middle of the dumb-bells just before the rubber breaks (\(\Delta L\)). The increase length at those 2 points can be used to calculate the maximum strain that occurs in rubber specimen using Eq. 2.

\[
\varepsilon = \frac{\Delta L}{L_0}
\]

where: \(\varepsilon\): strain, \(\Delta L\): elongation (mm), \(L_0\): initial Length (mm).

In addition to strain, the maximum stress (\(\sigma\)) that occurs in the rubber can be calculated. Stress on composite rubber was calculated using Eq. 1. Based on data of maximum stress and maximum strain that occurs in composite rubber can calculated the elastic modulus of rubber. The rubber remains elastic until it approaches breaking point. The elastic modulus was calculated at the point where the rubber breaks. The rubber elastic modulus is calculated using Eq. 3.

\[
E = \frac{\sigma}{\varepsilon}
\]

where: \(E\): elastic Modulus of Rubber (MPa), \(\sigma\): tensile strength of Rubber (MPa), \(\varepsilon\): strain of Rubber.

Test specimens with the addition of waste rubber have decreased along with more waste rubber crumb added as in Figure 7 (a). Natural rubber without any additives (R1) has the highest elastic modulus. Composite rubber with 25-\text{phr} waste rubber crumb was decreased
elastic modulus 33%. Composite rubber with 25-\textit{phr} waste rubber crumb was decreased elastic modulus 55%. This can be caused by waste rubber crumb added to the rubber causing cavities in the rubber and reducing the elastic modulus.

Test specimens with the addition of 25-\textit{phr} waste rubber and copper fiber have the tendency to change the value of the elastic modulus as shown in Figure 7 (b). The value of elastic modulus decreases with the addition of the amount of copper fiber. Elastic modulus of composite rubber with 25-\textit{phr} waste rubber crumb and 5-\textit{phr} copper fiber (R4) was decreased 4%. Elastic modulus of composite rubber with 25-\textit{phr} waste rubber crumb and 10-\textit{phr} copper fiber (R5) was decreased 8%. Elastic modulus of composite rubber with 25-\textit{phr} waste rubber crumb and 20-\textit{phr} copper fiber (R6) was decreased 15%. Elastic modulus of composite rubber with 25-\textit{phr} waste rubber crumb and 30-\textit{phr} copper fiber (R7) was decreased 21%.

Elastic modulus of composite rubber with 50-\textit{phr} waste rubber crumb and 5-\textit{phr} copper fiber (R8) decrease 8%. Elastic modulus of composite rubber with 50-\textit{phr} waste rubber crumb and 10-\textit{phr} copper fiber (R9) was decreased 15%. Elastic modulus of composite rubber with 50-\textit{phr} waste rubber crumb and 20-\textit{phr} copper fiber (R10) was decreased 27%. Elastic modulus of composite rubber with 50-\textit{phr} waste rubber crumb and 30-\textit{phr} copper fiber (R11) was decreased 38%. This can be caused by the part of rubber filled with copper being hollow and easily torn when pulled.

3.4. Shear Modulus

Previous tests of shear modulus have shown that shear modulus has decreased from cycle 1 to cycle 4 [20]. Based on [19], shear modulus used is the value in the 4th cycle. Shear modulus can be obtained the value of shear modulus from rubber (G) using Eq. 4.

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

where: G: shear modulus of rubber (MPa), F1: the force that occurs when the rubber deviates in x1 (N), F2: the force that occurs when the rubber deviates in x2 (N), A: rubber Area (mm²), n: plate slope ratio.

Shear modulus of rubber decrease in the addition of waste rubber tire as shown in Figure 8 (a). The addition of the waste rubber tire crumb damaged chemical bonds in the composite rubber. It makes the rubber becomes more flexible and easily deformed. Shear modulus of composite rubber with 25-\textit{phr} waste rubber crumb (R2) was decreased 5%. Shear modulus of composite rubber with 50-\textit{phr} waste rubber crumb (R3) was decreased 18%.

Shear modulus of rubber increases in line with the more addition of the copper fiber as shown in Figure 8 (b). This increase may be caused by internal friction that occurs on copper fibers. The internal friction of the copper fiber makes the composite rubber more rigid, so to make a composite rubber deformation 65% of its height requires a greater force.

Composite rubber with the addition of 25-\textit{phr} waste rubber crumb and copper fiber makes shear modulus was increased in line with the more addition of the copper fiber as shown in Figure 8 (b). Shear modulus of composite rubber with 25-\textit{phr} waste rubber and 5-\textit{phr} copper fiber (R4) crumb was increased 9%. Shear modulus of composite rubber with 25-\textit{phr} waste rubber and 10-\textit{phr} copper fiber (R5) crumb was increased 18%. Shear modulus of composite rubber with 25-\textit{phr} waste rubber and 20-\textit{phr} copper fiber (R6) crumb was increased 40%. Shear modulus of composite rubber with 25-\textit{phr} waste rubber and 30-\textit{phr} copper fiber (R7) crumb was increased 65%.

Composite rubber with the addition of 50-\textit{phr} waste rubber crumb and copper fiber makes shear modulus was increased in line with the more addition of the copper fiber as shown in Figure 8 (b). Shear modulus of composite rubber with 50-\textit{phr} waste rubber and 5-\textit{phr} copper fiber (R8) crumb was increased 2% . Shear modulus of composite rubber with 50-\textit{phr} waste rubber
rubber and 10-\textit{phr} copper fiber (R9) crumb was increased 5\%. Shear modulus of composite rubber with 50-\textit{phr} waste rubber and 20-\textit{phr} copper fiber (R10) crumb was increased 9\%. Shear modulus of composite rubber with 50-\textit{phr} waste rubber and 30-\textit{phr} copper fiber (R11) crumb was increased 14\%.

![Graph](image)

**Figure 8:** (a) Relationship between rubber’s shear modulus and amount of waste rubber added (b) Relationship between rubber’s shear modulus and amount of waste rubber and copper fiber added

### 3.5. Damping Ratio

The damping ratio was the ability of a material to reducing oscillations caused by force. According to [21] the damping ratio can be calculated using a ratio of the load-deformation graph area divided by the triangle (potential energy) area as in Eq. 4 and Figure 9.

![Graph](image)

**Figure 9:** Area of the hysterical curve and potential energy

$$\zeta = \frac{1}{2\pi} \times \frac{A_{hyst}}{F_0 \times u_0}$$  \hspace{1cm} (5)

where: $\zeta$: damping ratio, \%, $A_{hyst}$: area of the hysterical curve, kNmm, $F_0$: maximum load displacement, kNmm, and $u_0$: maximum displacement, mm.

Relationship between rubber’s damping ratio and amount of waste rubber crumb added can be shown in Figure 10 (a). The damping properties both in the addition of 25-\textit{phr} waste rubber and 50-\textit{phr} waste were increased. So it can be concluded, the addition of waste tire rubber crumb up to 50-\textit{phr} can increase the ability of rubber to reduce the force applied to it.
The addition of copper fiber to rubber composites increases the rubber damping ratio as shown in Figure 10 (b). Maximum damping ratio of composite rubber with 25-phr waste rubber crumb and copper fiber was 8%. Maximum damping ratio of composite rubber with 50-phi waste rubber crumb and copper fiber was 6%.

![Figure 10](image)

**Figure 10:** (a) Relationship between rubber's damping ratio and amount of waste rubber crumb added (b) Relationship between rubber's damping ratio and amount of waste rubber tire crumb and copper fiber added

### 3.6. Rubber Morphology & Composition

Rubber morphology was seen using SEM with a magnification 1000 times as shown in Figure 16. According to [22] scanning electron microscopy (SEM) is a tool to see the surface or morphology of an object that cannot be seen with ordinary optical microscopy. The result is that the surface of the rubber which had given an additional waste rubber tire crumb looked rougher. The more addition of waste rubber tire crumb makes the surface of the rubber rougher.

![Figure 11](image)

**Figure 11:** Compound rubber morphology, with 25-phi waste rubber crumb added, and with 50-phi waste rubber crumb added in 1000x zoom

| Specimen | Elemental Composition (%) |
|----------|--------------------------|
|          | C  | N  | O  | Al | Si  | S  | Ca | Zn  |
| R1       | 66.08 | 21.96 | 7.06 | 0.9 | 0.94 | 1.81 | 0.22 | 1.03 |
| R2       | 64.41 | 20.38 | 8.95 | 1.01 | 1.80 | 2.05 | 0.45 | 0.96 |
| R3       | 63.35 | 20.44 | 9.92 | 0.74 | 2.32 | 1.84 | 0.81 | 0.60 |

SEM-EDX testing can also see elements contained in rubber with atomic number above 5. So that the constituent rubber elements such as hydrogen (H) cannot be read in this SEM-EDX test. As can be seen in Table 3, the main constituent elements of rubber such as carbon (C)
and nitrogen (N) decreased with the addition of the amount of waste rubber crumb. Carbon (C) and nitrogen (N) decrease because waste rubber carries other elements such as silica (Si) and calcium (Ca). Carbon (C) is the main element of rubber because rubber is a hydrocarbon. Hydrocarbon is composed from carbon (C) and hydrogen (H) chains. Nitrogen (N) is an element that is contained in natural rubber or in this case in RSS rubber.

Other elements like Silica (Si) and Calcium (Ca) increase can be caused by waste rubber composition. Based on the data in table 4, silica (Si) and calcium (Ca) are mostly contained in waste rubber. Silica (Si) and Calcium (Ca) are thought to be used as rubber tire fillers. So when added to the rubber compound, these elements come into the rubber. The entry of these elements can affect the bond held by the rubber, so that mechanical properties such as tensile strength, elastic modulus, and modulus in rubber decreases.

Table 4: Element composition of waste rubber based on SEM-EDX test result

| Specimen      | Elemental Composition (%) |
|---------------|---------------------------|
| Waste Rubber  | C  | N   | O   | Si  | S   | Ca  | Zn  |
|               | 56.31 | 15.85 | 16.22 | 6.05 | 2.41 | 2.46 | 0.7 |

4. Conclusion

Based on testing on the mechanical properties and damping of rubber composites mentioned in this study, the following conclusions can be drawn. The tensile strength of rubber has decreased with the addition of waste rubber or the addition of copper fiber to rubber. The elastic modulus of rubber also decreases with the addition of waste rubber tire crumb and copper fiber. The addition of waste rubber crumb makes the rubber softer so that the rubber shear modulus decreases, whereas the addition of copper fiber makes the rubber stiffer so that the rubber shear modulus becomes higher. The addition of copper fiber increases the damping ratio in rubber by up to 11% in rubber with 25-phr waste rubber and 7.85% in rubber with 50-phr waste rubber. The addition of waste rubber crumb increases the impurities in the composites rubber and reduces the pure constituent elements of rubber such as carbon (C) and nitrogen (N).

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