Dielectric Properties of Natural Borneo Woods: *Keranji*, *Kayu Malam*, and *Kumpang*

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The dielectric behavior and properties of three types of Sarawak woods, under various conditions (untreated, alkaline treated, potassium carbonate treated, and heat treated), were investigated and discussed. The dielectric constant, loss, and dissipation factor tests were conducted *via* a dielectric impedance analyzer. The results revealed that the dielectric properties decreased in relation to an increase in frequency. With considerations to the treatment method, the highest dielectric constant values for the untreated samples were found in *Kumpang* wood, the highest dielectric constant values for the heat-treated samples and potassium carbonate treated samples were found in *Keranji* wood, and the highest dielectric constant values for sodium hydroxide treated samples were found in *Kayu Malam* wood. Therefore, it was evident that the physical properties, *e.g.*, internal structure, density, moisture, temperature, *etc.*, could affect the dielectric behavior and properties of the wood materials.

Keywords: Dielectric constant; Loss factor; Wood; Frequency; Treatment; Dissipation factor

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INTRODUCTION

Borneo is an island covered with a variety of plants, trees, and other woody materials. Sarawak is a Malaysian state, which is located in the equatorial tropical region of Borneo. Presently, it is known that there are over 25,000 species of plants and trees discovered in Sarawak (Hon and Shibata 2013). Most of these wood species are used in numerous applications; however, its usage depends on its species, structure (internal and external), and mechanical properties (Fan *et al.* 2009; Babu *et al.* 2010). Wood primarily consist of the following chemical constituents: hemicelluloses, lignin, and cellulose. The structures found in wood, *e.g.*, cell rays and tracheids, are used for the movement of water and nutrients (Ansell 2015). Therefore, many researchers have determined methods to utilize the unused waste obtained from wood, by exploiting and developing the byproducts of woods for various applications (Taghiyari 2014). Meanwhile, continuous discoveries and ongoing research on wood-based polymer composites provide an opportunity for new usages of wood wastes, especially in the area of electronics and nanotechnology (Taghiyari 2014). Therefore, a proper understanding of the dielectric properties of wood may help to ensure the materials are suitable for insulation or energy storage (Kakar *et al.* 2017; Jayamani *et al.* 2018; Bakri *et al.* 2019).

Babu *et al.* (2010) conducted an experiment examining the dielectric behavior of eight species of Myrtaceae and Mimosoideae trees, with frequencies ranging from 100 Hz to 10 MHz at 35 °C. They also observed that the dielectric constant of hardwood decreased to 1 MHz due to lower interfacial polarization. However, the softwood species that were tested tended to have a higher dielectric constant due to a higher content of dipolar groups, that binding to the rigid structures. Wood absorbing heat, due to high power storage (within the frequency range of 100 Hz to 1 MHz), caused a lower dielectric constant due to its high dielectric loss (Babu *et al.* 2010). Suslyaev *et al.* (2014) studied dielectric behavior of 4 types of woods, *i.e.* birch (*Betula pendula*), spruce (*Picea obovate*), cedar (*Pinus sibirica*), and pine (*Pinus sylvestris*) in terms of the frequency associated to the complex dielectric constants at a 2% and 4% moisture content in longitudinal and transverse fiber directions, respectively. Suslyaev *et al.* (2014) proposed that the most effective frequencies occurred between 0.1 THz to 0.5 THz, based on four wood species. At room temperature, the dried wood exhibited a decreased dielectric constant as the frequency increased, and anomalous dispersion was observed at 250 GHz at the maximum dielectric loss in the transverse direction (Suslyaev *et al.* 2014). Han *et al.* (2015) found firm evidence that the fundamental thickness, oven-dried thickness, twisting quality, and compressive quality parallel to the adjusted grain of wood demonstrated an undeniable increase in dielectric properties, in contrast with the natural characteristics of wood in terms of its dielectric properties. However, the water uptake of the altered wood was greatly diminished.

The pretreatments using sodium hydroxide (NaOH) cause fiber swelling, an expansion of the inner surface zone of cellulose, and reduced the level of polymerization and crystallinity of the wood polysaccharides (Lehto and Alén 2015). These structures improved the cleavage of the auxiliary linkages in the middle of the lignins and sugars, causing synchronous degradation of the lignin structure. Kol and Yalçın (2015) examined the relationship between mechanical strength and the dielectric loss factor for oak and fir woods. Lower R^2 was found in oak wood (0.76, 0.71, 0.59, and 0.68), when compared with to fir wood (0.45, 0.42, 0.29, and 0.33). Respectively, the mechanical properties of the modulus of rupture (MOR), modulus of elasticity (MOE), impact bending strength (IBS), and compression strength (CS) for oak wood is 0.63, 0.59, 0.55, and 0.55 and 0.40, 0.34, 0.24, and 0.22 for fir wood. The R^2 for the dielectric loss factor and density relationship for oak and fir wood were 0.78 and 0.56, respectively. Thus, these characteristics identified the important relationship between the mechanical properties and dielectric behavior of wood materials. Limited research has been conducted on the dielectric properties of Sarawak woods. Therefore, three native types of wood species were selected for this study, and their dielectric properties of the composites were analyzed to determine the effects of the wood species structure, chemical treatment, moisture level in the wood, and frequency. These preliminary dielectric wood properties will be used in an application, where the woods are mainly used as reinforcement materials for polymer matrix composites.

EXPERIMENTAL

Materials

Three wood species were used in the present study, *Dialium indum* (*Keranji*), *Diospyros blancoi* (Kayu Malam), and *Myristica cinnamomea* (Kumpang). *Keranji* is a heavy hardwood with an air-dried density of 755 kg/m^3 to 1250 kg/m^3 (Malaysia Timber Council). *Kayu Malam* is a medium hardwood heavy with an air-dried density of 595 kg/m^3 to 1,055 kg/m^3 (Malaysia Timber Council). *Kumpang* (also called as *Penarahan)* is a light hardwood with an air-dried density of 370 kg/m^3 to 770 kg/m^3 (Malaysia Timber Council). For treatment purposes, anhydrous potassium carbonate (K_2CO_3) was obtained from HmbG Chemicals (Hamburg, Germany) with product code C1040-22114903. A pellet of sodium hydroxide (NaOH) was obtained from UNI-CHEM (Jiangsu, China) with product code S41298-4I. Table 1 shows a summary of the properties of the selected wood species and their usage.

Table 1. Properties of the Selected Wood Species

Wood Types	Density (Air Dried)	Shrinkage
Dialium indum (*Keranji*)	755 kg/m^3 to 1250 kg/m^3	Radial shrinkage average: 2.3%
		Tangential shrinkage average: 3.7%
Myristica cinnamomea (Kumpang)	370 kg/m^3 to 770 kg/m^3	Radial shrinkage average: 2.2%
		Tangential shrinkage average: 3.2%.
Diospyros blancoi (Kayu Malam)	595 kg/m^3 to 1055 kg/m^3	Radial shrinkage average: 4.7%
		Tangential shrinkage average: 8.7%

Methods

Sample preparation and treatment

Five samples for each type of wood, *i.e.*, *Keranji*, *Kayu Malam*, and *Kumpang*, were prepared using a CNC milling machine (VMC 1300, Denford Ltd., Brighouse, United Kingdom). The wood was cut into disk shapes with a diameter of 50 mm and a thickness of 5 mm. The wood disk was cut directly proportional to the wood plank (tangentially), as shown in Fig. 1.

Fig. 1. The sample wood disk cutting direction (tangentially)

The wood sample disk was divided equally into four segments; untreated, potassium carbonate treated, sodium hydroxide treated, and heat-treated. For the no-treatment segments, the samples were conditioned at room temperature according to ASTM standard E41-92 (2010). For the potassium carbonate and sodium hydroxide treatments, the wood samples were soaked into a 5 wt% anhydrous potassium carbonate solution and a 5 wt% sodium hydroxide solution (from a pellet), respectively. The solutions were prepared by diluting the anhydrous potassium carbonate, and the sodium hydroxide pellets with distilled water. The samples were left in the solutions for 24 h at room temperature. They were then rinsed with distilled water to remove the excessive chemicals and to neutralize the samples. They were dried in an open ventilated oven (ECOCELL 55, MMM Medcenter Einrichtungen GmbH, Planegg, Germany) for 4 h. The samples were removed from the oven and conditioned at room temperature, and at pressure and humidity conditions according to ASTM standard E41-92 (2010). The heat-treated samples were heated for 4 h in open ventilated oven and were kept in a vacuum chamber before testing (at room temperature to maintain the wood moisture levels after the heat treatment).

Dielectric test

The dielectric properties of the wood samples were tested using a E498A Precision LCR Meter and a 16451B Dielectric Test Fixture, both supplied by Keysight Technologies (Santa Rosa, US). The tests were performed according to ASTM standard D150-11 (2011). The tests were conducted and averaged over the 5 samples with frequencies ranging from 100 Hz to 2 MHz, for each of the sample segments. The values of the dielectric constant, loss factor, and dissipation factor against the change in frequency were obtained and plotted.

RESULTS AND DISCUSSION

Dielectric Constant of the Wood Samples

Figures 2, 3, 4, and 5 show the dielectric constant values observed for the three types of wood, which were exposed to no treatment, heat treatment, potassium carbonate treatment, or sodium hydroxide treatment, respectively. At a low log frequency, Fig. 2 shows that *Kumpang* had the highest dielectric constant (6.29), followed by *Kayu Malam* (5.80), and *Keranji* (5.1).

Thus, an increase in the overall wood density decreased the dielectric constant value. *Keranji* exhibited the highest density, followed by *Kayu Malam*, and *Kumpang* had the lowest density, as shown in Table 1. In addition, as the frequency increased, the dielectric constants dropped drastically, to 3.74, 3.25, and 2.95 for *Kumpang*, *Kayu Malam*, and *Keranji*, respectively.

According to Tripathi *et al.* (2015), the decrease in the dielectric constant value of wood, which was caused by the rise in the frequency, was due to a decrease in orientation polarization. However, according to Notingher *et al.* (2010), Jie *et al.* (2015), and Babu *et al.* (2010), a low dielectric constant at high frequencies was due to lower permanent dipoles.

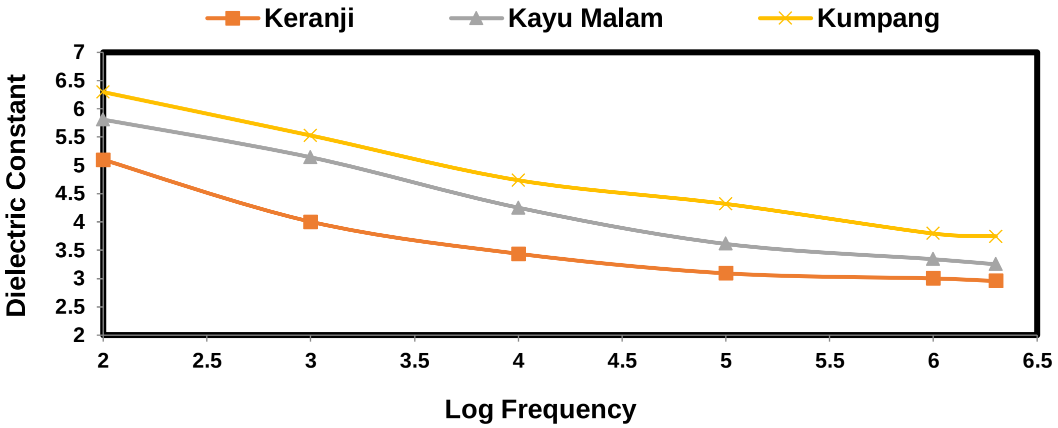

Fig. 2. Dielectric constants of the untreated wood samples

Figure 3 shows the variation of the dielectric constants of the heat-treated wood samples. These samples had a lower moisture content than the untreated wood samples. *Kumpang* had an average reduced moisture content of 11.5%, with a dielectric constant of 1.99 at the initial frequency, which was reduced to 1.78 at the final frequency. It was also observed that *Kayu Malam* had an average reduced moisture content of 9%, with a dielectric constant of 2.9 at the initial frequency, which was reduced to 2.14 at the final frequency. *Keranji* had an average reduced moisture content of 7%, with a dielectric constant of 3.08 at the initial frequency, which decreased to 2.56 the final frequency. The decreases in the dielectric constants were attributed to reduced water dipoles rotation and reduced hydrophilicity of the dry wood samples (Singha *et al.* 2013; Jie *et al.* 2015).

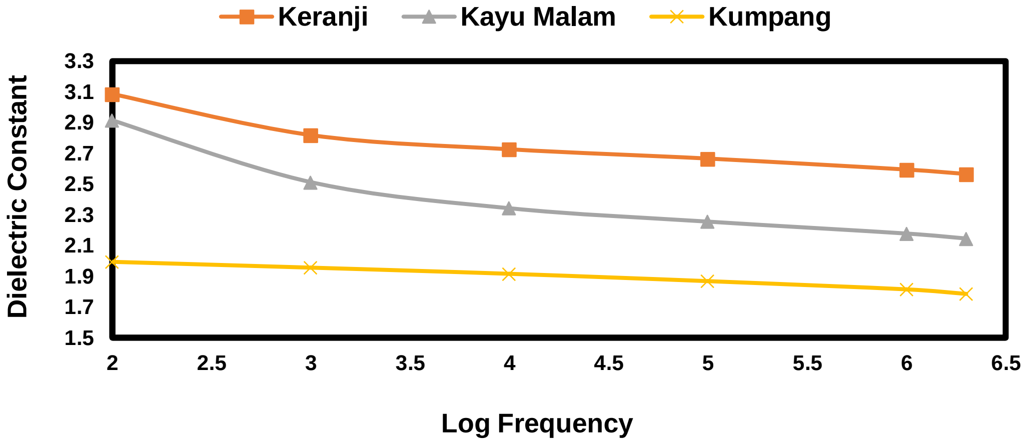

Fig. 3. Dielectric constants of the heat-treated wood samples

According to Han *et al.* (2015), the trend of the dielectric constant being lower at low moistures, from low to high frequency, were due to the lower dipoles and lower orientation polarization in comparison to moist wood at similar frequencies. The weight of the wood affects the density of the wood, which subsequently affects the moisture absorption and other structure content, depending on the wood types. With similar specimen dimensions, *Kumpang* had an average weight of 7 g, followed by *Kayu Malam* with an average weight of 9 g, and *Keranji* with an average weight of 11 g. In addition, *Kumpang* had a higher moisture content and higher dielectric constant than the other types of wood at similar frequencies, however, a large decrease in the dielectric constant occurred after drying. Rehn *et al.* (2003), Islam *et al.* (2015), and Ahire (2013) also had similar observations in terms of the relationship between the density, moisture content, and dielectric constant.

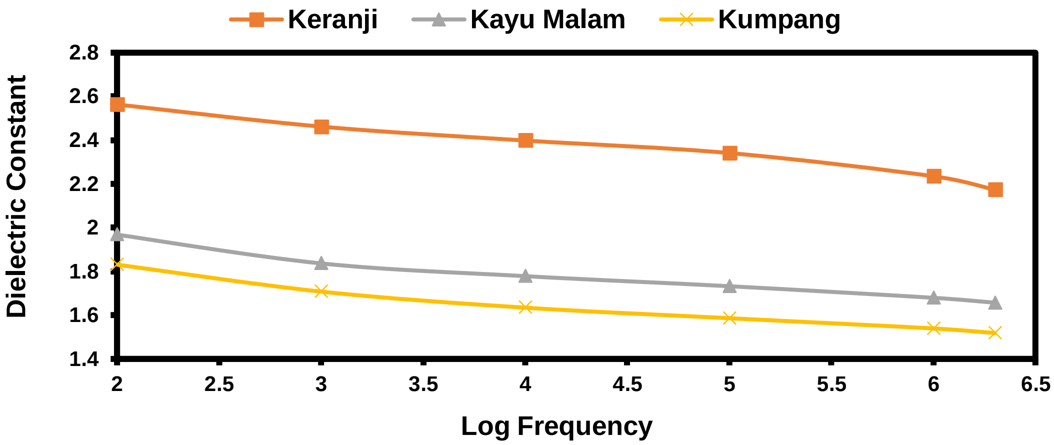

Fig. 4. Dielectric constants of the potassium carbonate treated wood samples

The potassium carbonate and sodium hydroxide treatments had different effects on the dielectric constants of the wood samples. For the potassium carbonate-treated wood, as shown in Fig. 4, the dielectric constant of *Kumpang* at a low frequency was 1.83, which decreased to 1.52 at a higher frequency. In comparison to the untreated wood samples, whose dielectric constant was 6.29 and decreased to 1.83 at a low frequency, this indicated that the potassium carbonate-treated wood had less moisture than the untreated wood. The dielectric constant of *Kayu Malam* at a low frequency was 1.97, and it decreased to 1.65 at a higher frequency. The dielectric constant of *Keranji* at a low frequency was 2.56, and it decreased to 2.17 at a higher frequency.

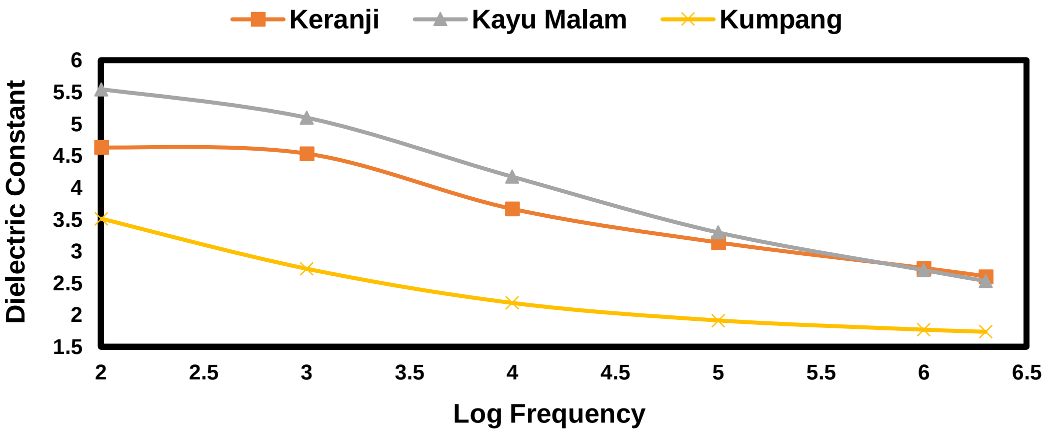

Fig. 5. Dielectric constants of the sodium hydroxide treated wood samples

For the sodium hydroxide-treated wood, as shown in Fig. 5, the dielectric constant of *Kumpang* at a low frequency was 3.51, and it decreased to 1.73 at a higher frequency. In comparison to the untreated wood, whose dielectric constant was 6.29 and decreased to 3.51 at a low frequency, this indicated that the sodium hydroxide treated wood had less moisture than the untreated wood. The dielectric constant of *Kayu Malam* at a low frequency was 5.54, and it decreased to 2.53 at a higher frequency, whereas the dielectric constant of *Keranji* at a low frequency was 4.63, and it decreased to 2.60 at higher frequency.

For the potassium carbonate treatment method, depending on the chemicals used, there was a huge reduction in the dielectric constant value in comparison to the corresponding reductions observed in the sodium hydroxide and heat treatments. This showed that potassium carbonate greatly decreased the hydrophilicity of wood, as it reacted with the –OH groups and decreased the orientation polarization (George *et al.* 2013; Singha *et al.* 2013). The treatment of wood specimens with potassium carbonate also degraded the hemicelluloses (Severo *et al.* 2016). When compared with the sodium hydroxide treatment results, lowering the total moisture absorption *via* the potassium carbonate treatment was more effective. The reason behind this may be due to the compatibility of wood to absorb nutrients that are similar to its own diet or needs; potassium is needed to sustain plant growth while sodium is viewed as a waste ion that plants do not need.

Loss Factor of the Wood Samples

The loss factor over a given time is an average power factor. As shown in Fig. 6, it was observed that untreated *Kayu Malam* samples had a loss factor of 1.02 at a lower frequency and a loss factor of 0.20 at a higher frequency, untreated *Kumpang* samples had a loss factor of 0.92 at a lower frequency and a loss factor of 0.22 at a higher frequency, while untreated *Keranji* samples had a loss factor of 0.57 at a lower frequency and a loss factor of 0.08 at the final frequency. Generally, the results of the heat treatment (as addressed in Fig. 7) and potassium carbonate treatment (as presented in Fig. 8), indicated a decreased loss factor at all frequencies when compared to the untreated wood samples, except for a few values for the sodium hydroxide treated samples (as shown in Fig. 9). The loss factor of the heat treated *Kumpang* decreased from 0.07 to 0.03, and then they increased to 0.15. The loss factor of the potassium carbonate treated *Kumpang* decreased from 0.19 to 0.041, then increased to 0.15. The loss factor of the sodium hydroxide treated *Kumpang* decreased from 0.58 to 0.092. Whereas, the loss factor of the heat treated *Kayu Malam* decreased from 0.39 to 0.05, and then they increased to 0.15, while the loss factor of the potassium carbonate treated *Kayu Malam* decreased from 0.14 to 0.033, and then increased to 0.06. The loss factor of the sodium hydroxide treated *Kayu Malam* decreased from 1.26 to 0.024. The loss factor of the heat treated *Keranji* decreased from 0.32 to 0.05, and then increased to 0.13. Whereas, the loss factor of potassium carbonate treated *Keranji* decreased from 0.25 to 0.043, and then increased to 0.15, while the loss factor of the sodium hydroxide treated *Keranji* decreased from 0.74 to 0.092. A useful observation was that the rate that the loss factor increased at was less steep than the rate that the dielectric constant increased at (Jie *et al.* 2015). The lower loss factor of the samples after undergoing the treatments and drying was a result of the lower polarization, as observed from studies conducted by Ahire (2013), Singha *et al.* (2013), and Islam *et al.* (2015).

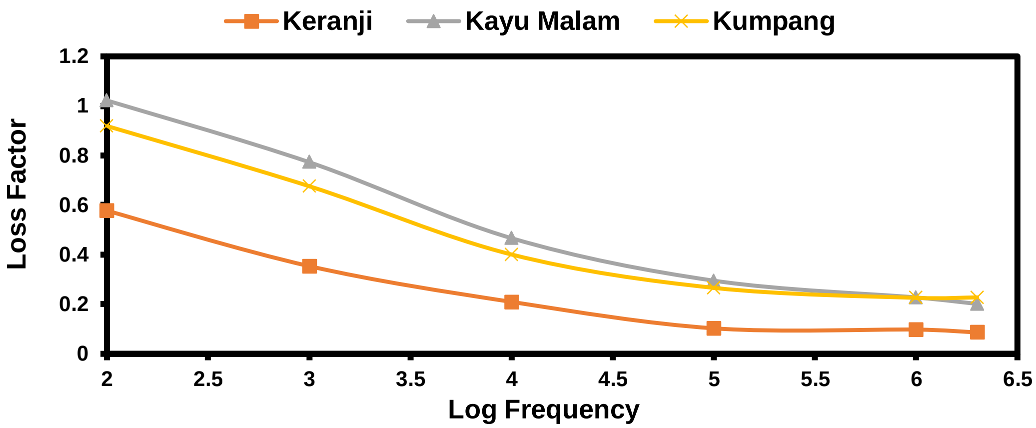

Fig. 6. Loss factors of the untreated wood samples

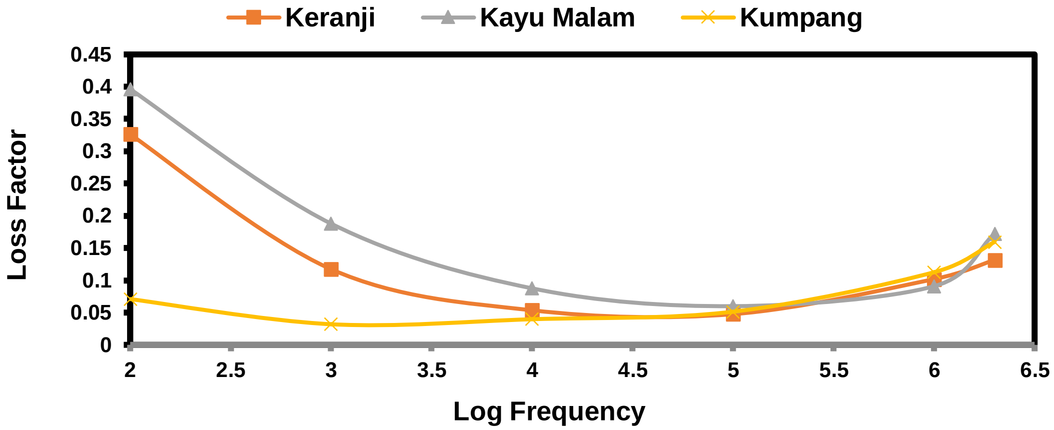

Fig. 7. Loss factors of the heat-treated wood samples

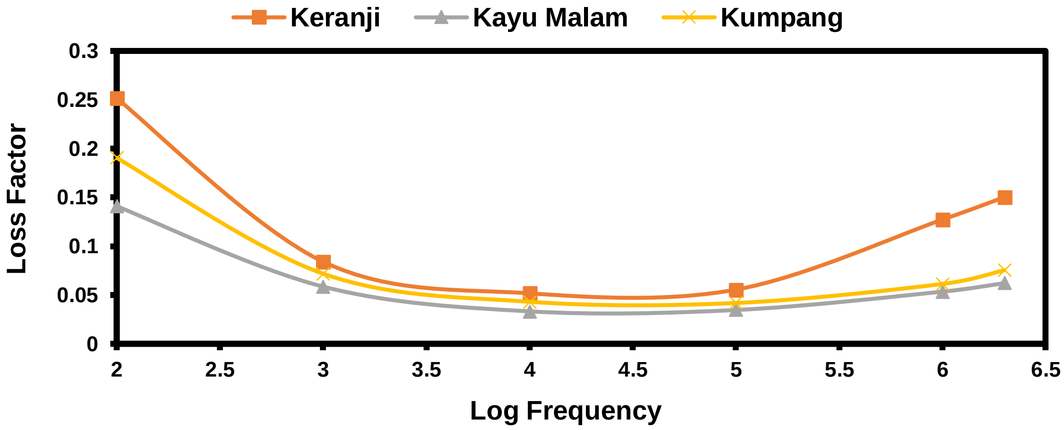

Fig. 8. Loss factors of the potassium carbonate treated wood samples

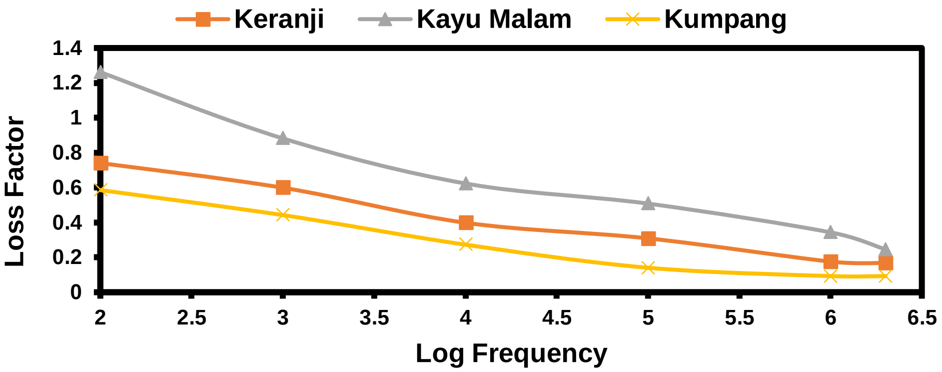

Fig. 9. Loss factors of the sodium hydroxide treated wood samples

Dissipation Factor of the Wood Samples

The multiplication of the dissipation factor and the dielectric constant equals the loss factor, which caused both figures to have similar data trends with different values. This meant that the frequency, moisture, treatment, and polarization properties could cause the same influences for both the dissipation factor and the loss factor. The dissipation factors (as shown in Fig. 10, Fig. 11, Fig. 12, and Fig. 13) depicted similar trends to the loss factor figures.

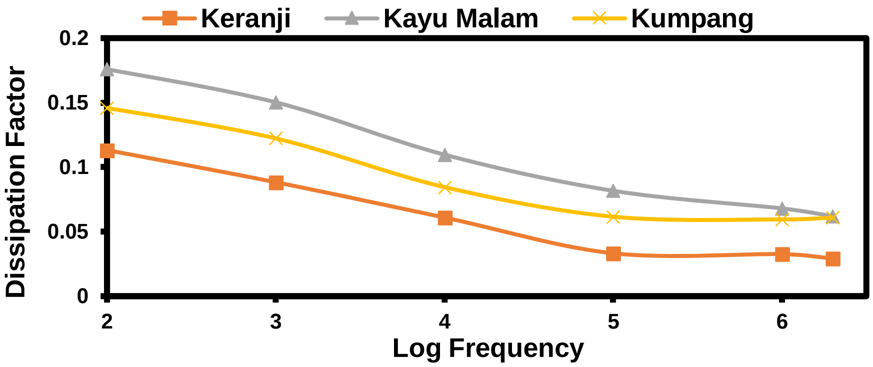

Fig. 10. Dissipation factors of the untreated wood samples

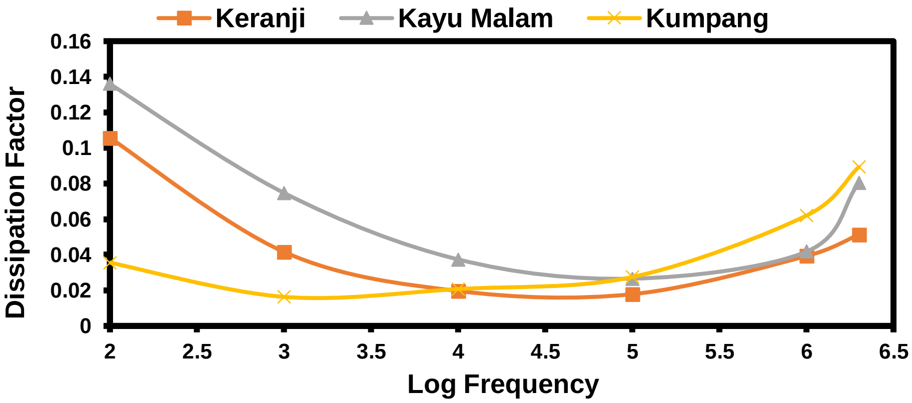

Fig. 11. Dissipation factors of the heat-treated wood samples

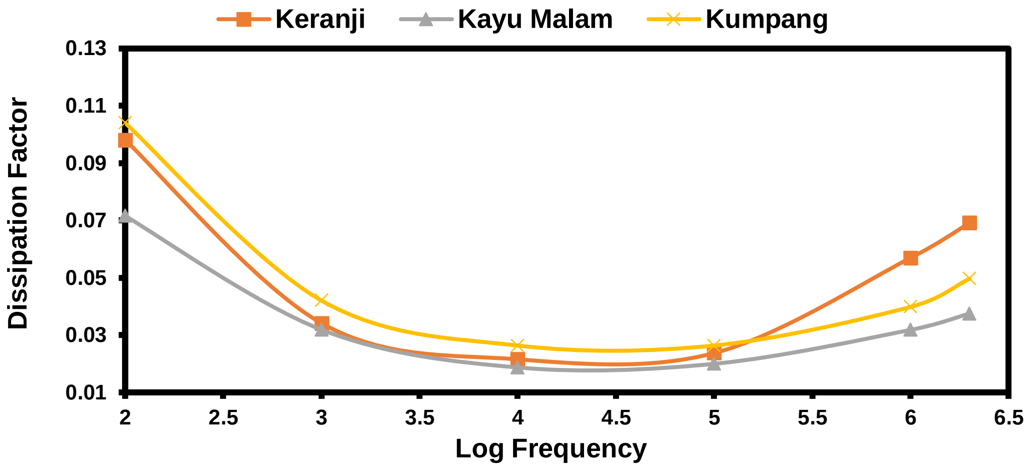

Fig. 12. Dissipation factors of the potassium carbonate treated wood samples

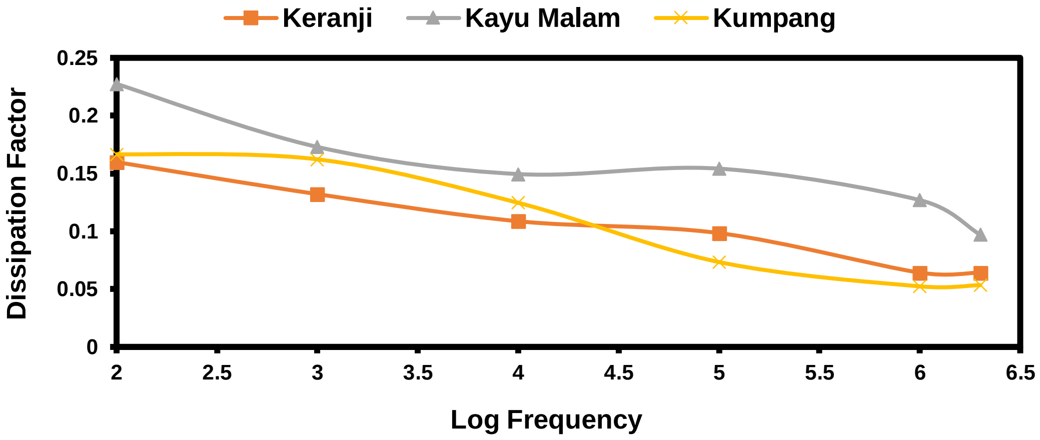

Fig. 13. Dissipation factors of the sodium hydroxide treated wood samples

CONCLUSIONS

1. The dielectric constant decreased as the frequency increased for the untreated, heat treated, potassium hydroxide treated, and sodium hydroxide treated wood samples.
2. The loss factor and dissipation factor of *Kayu Malam* were found to be higher for all sample except potassium carbonate-treated wood samples.
3. The maximum values of the dielectric constant at lower frequencies for each wood were attributed to the interfacial polarization.
4. With consideration to the treatment method, the highest dielectric constant values for untreated wood were found in *Kumpang* wood, the highest dielectric constant values for heat-treated wood and potassium carbonate treated wood were found in *Keranji* wood, and the highest dielectric constant values for sodium hydroxide treated wood were found in *Kayu Malam* wood.

5. As moisture was removed and the wood composition altered, the dielectric constant decreased, due the decrease in the number of polar groups, which caused lower polarization orientation.

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