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Examination of Impulse Breakdown Voltage of a New EFB Insulation Paper

(Pemeriksaan Voltan Pecahan Impuls Penebat Kertas EFB yang Baru)

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ABSTRACT

Demand of softwood fiber has rapidly increased as a result from the variety of new softwood products. Therefore, non-wood fibers have been introduced as alternatives in pulp for presspaper making to supplement the limited wood fiber resources. Malaysia is the second largest producer of oil palm where the empty fruit bunch (EFB) has a potential to be developed as an insulating paper. This paper aims to determine the performance of EFB as non-wood fiber to evaluate its use as potential presspaper insulation in power transformer. The sample of EFB paper was produced through kraft pulping and laboratory handsheet process. The performance of EFB and kraft paper was evaluated by impulse breakdown test. The study is focused on the performance of insulating paper that were aged with the transformer oil at 90 °C for 30 days. In order to investigate the impulse breakdown voltage of the insulating paper, multistage impulse generator was used. As the aging temperature increases, the breakdown voltage will decrease. The thickness of insulating paper also has an effect to the breakdown strength as the thicker the insulating paper, the higher the breakdown voltage will be. For no aging sample, kraft fibres dominate the breakdown strength at 28.11 kV/mm, while for sample aged at 90 °C, EFB fibres dominate the breakdown strength at 3.62 kV/mm higher than the average of kraft fibres due to an effect of fibres arrangement between fibre-to-fibre bonding after the aging.

Keywords: Non-wood fibers, impulse breakdown, thermal aging, insulating paper, empty fruit bunch.

ABSTRAK

Permintaan serat kayu lembut meningkat dengan cepat hasil daripada pelbagai produk kayu lunak baru. Oleh itu, serat bukan kayu telah diperkenalkan sebagai alternatif dalam pulpa untuk pembuatan kertas tekan untuk menambah sumber serat kayu yang terhad. Malaysia adalah pengeluar kelapa sawit kedua terbesar di mana tandan buah kosong (EFB) berpotensi untuk dikembangkan sebagai kertas penebat. Kertas ini bertujuan untuk menentukan prestasi EFB sebagai gentian bukan kayu untuk menilai penggunaannya sebagai penebat kertas tekan berpotensi dalam pengubah kuasa. Sampel kertas EFB dihasilkan melalui proses kraft pulping dan handsheet makmal. Prestasi kertas EFB dan kraft dinilai oleh ujian kerosakan impuls. Kajian ini tertumpu pada prestasi kertas penebat yang berusia dengan minyak pengubah pada suhu 90 ° C selama 30 hari. Untuk menyiasat voltan kerosakan impuls kertas penebat, penjana impuls bertingkat digunakan. Apabila suhu penuaan meningkat, voltan kerosakan akan menurun. Ketebalan kertas penebat juga memberi kesan kepada kekuatan kerosakan kerana semakin tebal kertas penebat, semakin tinggi voltan kerosakan. Untuk sampel yang tidak dimakan, gentian kraft mendominasi kekuatan pemecahan pada 28.11 kV/mm, sementara untuk sampel berusia 90 °C, serat EFB mendominasi kekuatan pemecahan pada 3.62 kV/mm lebih tinggi daripada rata-rata gentian kraft kerana kesan susunan gentian antara serat yang terikat selepas penuaan.

Kata kunci: Serat bukan kayu, pemecah impuls, penuaan termal, kertas penebat, tandan buah kosong

INTRODUCTION

The rapid evolution of industry and technology around the world has led to a sharp increase in global energy supply. In order to meet these energy demand, the grid system needs to be upgraded which will definitely involve an increase in the number of transformers globally (Huang et al. 2016; Fernandez et al. 2016). Power transformers are subjected as the major equipment for all large and modern industries (Huang et al. 2016) and the main concern on power transformer is its breakdown voltage which the insulation system has become an important parameter (Chmura et al. 2012). There are many types of insulation that are being used in power transformers which is insulating oil, insulating paper, insulating tape, pressboard, and wood-based laminates. The most popular materials that are being used as the insulation for power transformers is insulating paper and insulating oil (Huang et al. 2016; El-Saied et al. 2012). The lifetime of power transformers depends on the performance of insulation system (Fofana et al. 2010). Typically, power transformers have 25 to 30 years lifespan except in North America which most of the power transformers can operate up until 60 to 80 years due to its performance and efficient insulation system.

Mineral oil is used as an insulation in power transformers in order to strengthen the dielectric properties of solid insulation and act as coolant. However, the mineral oil becomes contaminated as the power transformers ages in service (Fofana et al. 2010). In fact, press paper is the best electrical insulation known and has the cheapest price compared to other types of material (El-Saied 2012). Typically, kraft fibre or softwood fibre is the main source in order to develop insulating paper (Kwoon et al. 2016; Kim et al. 2013). Nevertheless, with the increasing demand of power transformers that leads to the high demand of insulation system caused the lack of sources of softwood fibres. Therefore, a study for a new insulation paper material from non-wood fiber has been conducted.

Malaysia is the second largest producer of palm oil that has about 4.9 million hectares of its plantation area (Sequino & Avenido 2015). The residue of the palm oil which is empty fruit bunch (EFB) has a potential to be developed as paper as it has a high cellulose content (Rafidah et al 2017). Insulating materials are the materials that permits only negligible current to flow in phase with the applied voltage (Chandrashekar et al. 2012). The ideal insulating paper may have all these characteristics which is high dielectric strength, high resistivity, good thermal conductivity, high tensile strength, high degree of thermal stability, ability to withstand moisture, and able to withstand chemical attack and heat. Insulator paper also should withstand operational stress without breaking down for the whole period of operation (Chmura et al. 2012). Normally, the best insulation system is the insulation which can operate for a period of 30-40 years. But, for the kraft paper, the average of its lifespan is about 15 years at 98 °C.

Abdelmalik et al. (2013) had studied about aging of kraft paper insulation in natural ester dielectric fluid. They proposed that the performance of insulation paper that were impregnated with oil shows the similar behavior before and after aging, but there is a reduction about 5% in tensile strength. They impregnated the kraft paper insulation in the oil with the ratio of 33 g paper to 400 ml Nynas oil. As a result, they suggest that the aging time will reduce the performance of insulating paper. The longer the time aging, the tensile strength becomes lower. For the breakdown strength, impregnation in oil could enhanced the breakdown strength of the paper.

Sari et al. (2018) had investigated about the effect of thermal aging on the mechanical characteristics of insulating paper impregnated with different insulating oils. They compared the result of three different insulating liquids. Before the experiment was conducted, the samples were aged together with the oil. The 160 g of paper were soaked in the 1 600 g of insulation oil with 66 g of copper as catalyst. As a result, tensile strength of the insulating paper decreased over time aging in all three different insulating liquid. For the degree of polymerisation value, it will also decrease over the time aging. From the result obtained, there is no direct relationship between DP value and tensile strength.

Munajad et al. (2017) studied about the effects of thermal aging on insulating paper for high voltage transformer composite with natural ester from palm oil using FTIR and EDS. They studied about the importanve of insulating liquid in transformers. They suggest that natural ester will replace the role of mineral oil as the transformer oil in future. This is because natural ester is more environmental compared to mineral oil. Furthermore, natural ester can enhance the lifespan of insulating paper in power transformers. Before the experiment was conducted, 10 g of insulating paper were soaked in 200 g of transformer oil with 8.75 g of copper as catalyst. Its purpose is to have the aging process before the testing was conducted. As a result, DP decreased against the high temperature of aging. At 150 °C, DP decreased faster as compared to 120 °C. The result for tensile strength also shows the same pattern. The tensile strength of insulating paper decreased due to thermal aging under accelerated temperature.

From some of the literature review, many researchers agree that aging of insulating material could decline the performance of insulation system. Aging at high temperature will damage the structure of the paper and the oil. Besides that, the purpose of this investigation is to overcome the lack of resources of softwood fibres. In order to have a new insulation material, the best way to investigate its electrical and mechanical properties is by aging at certain temperature [19]. Therefore, this study is conducted to investigate the impulse breakdown under thermal aging of 90 °C EFB fibres insulation paper.

EXPERIMENTAL PROCEDURE

In order to develop a new insulating material, we need to investigate the mechanical and electrical properties of the insulation paper (Fernandez et al. 2016). The best way to conduct an experiment for a new insulation material is by aging the paper and oil (Chmura et al. 2012). Kraft insulating paper with different thickness and the mixture of Kenaf and EFB fibre with different ratio were aged before testing.

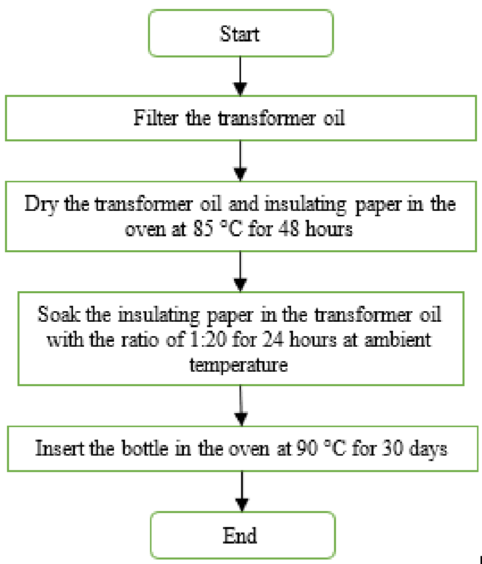

FIGURE 1. Flow chart of sample preparation

This investigation will use two different types of sample which is kraft insulating paper and mix of Kenaf and EFB fibres insulation paper. For kraft insulation paper, the thickness was varied which is 0.06mm, 0.08mm and 0.12mm. While, for mix of Kenaf and EFB fibres insulation paper, the ratio between two fibres being varied as shown in Table 1.

TABLE 1. Percentage of Kenaf and EFB fibres

Kenaf fibres concentration, %	EFB fibres concentration, %
0	100
25	75
50	50
75	25
100	0

Figure 1 shows the flow chart of sample preparation. Before the experiment was conducted, 450 ml of transformer oil was filtered by using FB70155 Vacuum Pump to remove suspended particle as shown in Figure 2. Then, the oil is dried in the oven at 85 °C for 48 hours with unsealed bottle in order to remove the moisture in the oil (Abdelmalik et al. 2013; Ran et al. 2016). After 48 hours, the bottle was taken out from the oven, sealed, and left at ambient temperature in order to remove the vapor. After that, 18 g of insulation papers for every ratio and thickness were dried in the oven at 85 °C for not less than 24 hours (Munajad et al. 2017; Rapp et al. 2015). The insulating papers were then rolled and tied with thread before being dried as shown in Figure 3. The ratio of paper to oil is 1:20 which is 1 g of paper is equivalent to 20 g (25ml) of oil (Munajad et al. 2017). Before the aging process starts, the insulating papers were untied and soaked in the transformer oil for 24 hours in order to impregnate the paper in the oil (Rapp et al. 2015). Then, the bottle was sealed with aluminum foil and tied with copper wire as shown in Figure 4. This is to replace the bottle cap as to ensure that the cap is not broken when enduring high temperature. Finally, the bottles that contain the oil were placed in the oven at 90 °C for 30 days for aging purpose. After 30 days, the samples were taken out from the oven and subjected to the testing.

Repeat the procedure for sample preparation that are not aged. For this sample, the insulating papers were soaked in the transformer oil and left at ambient temperature for 24 hours. There is no ratio for the insulating paper to soak in the transformer oil.

FIGURE 2. Transformer oil filtration

FIGURE 3. The insulating paper being tied before dried

FIGURE 4. The bottles being sealed with aluminum foil

IMPULSE BREAKDOWN TESTING

Figure 5 shows the flow chart of steps to conduct impulse breakdown testing. After 30 days of aging, bottles that contain insulating papers and transformer oil was taken out from the oven. Then, the bottles were left at ambient temperature in order to decrease the temperature of the bottle for about 30 minutes. Before conducting an impulse breakdown testing, the test cell must be dried at ambient temperature for 24 hours (Chmura et al. 2012). Then, place the insulating paper between two metal cylindrical electrodes (IEC 2013). Insert new transformer oil in the test cell in order to impregnate the insulating paper when conducting the impulse breakdown testing. Make sure that the gap between two metal cylindrical electrodes is not less than 3 mm. The diameter and the thickness for both metal cylindrical electrodes is 25 mm, respectively, as shown in Figure 7. Connect the impulse voltage cable at the top electrode while ground cable at the bottom electrode as shown in Figure 6. In order to generate the impulse voltage, the multistage impulse generator was used as shown in Figure 8. The multistage impulse generator has 8 steps where one step has the maximum charging voltage of 100 kV. For the first testing, start with the charging voltage of 0 V with the constant increment of 1 kV until breakdown happens (IEC 2013; Chmura et al. 2012). After that, proceed to the second test that starts with 50% of breakdown voltage with the constant increment of 2 kV until breakdown happens. The wavefront and wavetail is constant during testing which is 1.2/50 µs. Observe the breakdown voltage and waveform for every testing by using Lianapac Measure (V15.5.1e) and CCK-2712 controller (100).

In order to conduct a new test on another sample, make sure that the multistage impulse generator is fully discharge. Then, make the grounding to the electrode that is attached at the test cell. Finally, change the new sample between two metal cylindrical electrodes.

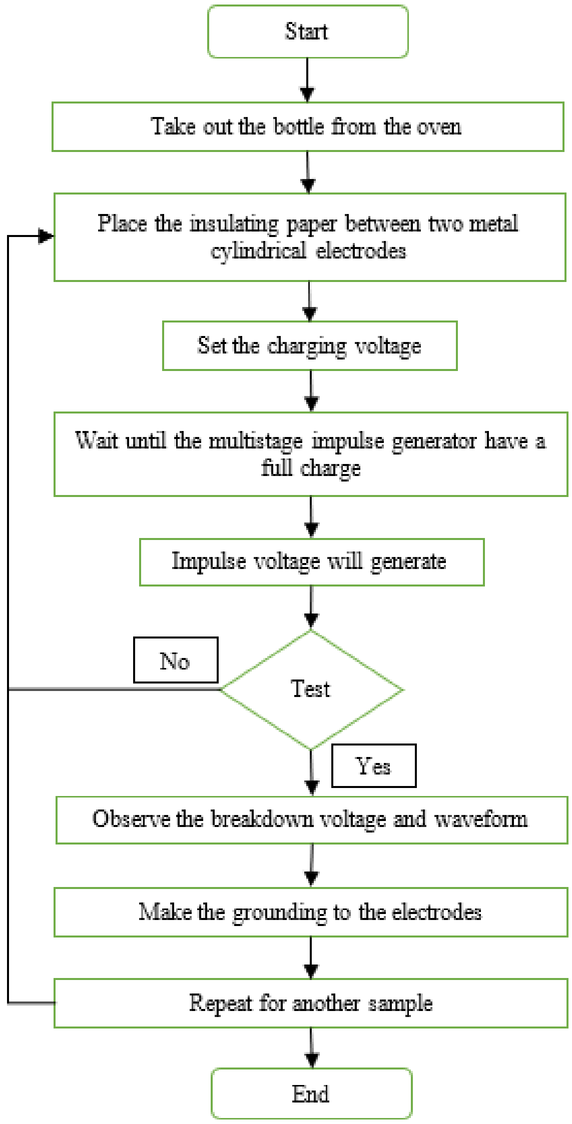

FIGURE 5. Flow chart to conduct impulse breakdown test

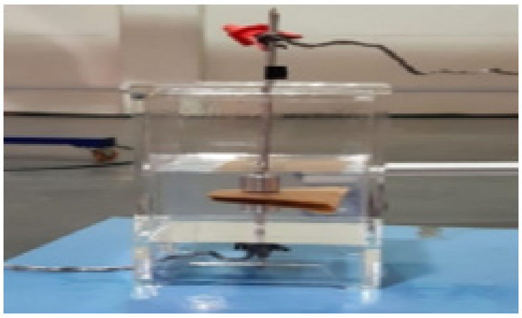

FIGURE 6. Test cell setup and electrode connection

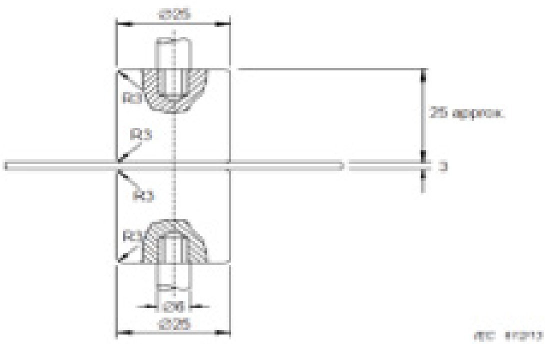

FIGURE 7. Electrodes and specimen dimension [5]

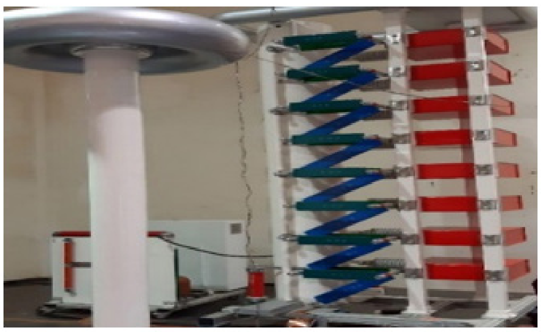

FIGURE 8. Multistage impulse generator

RESULTS AND DISCUSSIONS

PARTICIPANTS

For the breakdown voltage, 8 samples being used in order to differentiate the result which is kraft insulating paper with different thickness and five mixed ratios of kenaf and EFB fibres insulating paper. The test was conducted in the test cell where electrodes were impregnated in the transformer oil. The gap between two metal cylindrical electrodes are 4 mm and the insulating paper is placed between the electrodes. The average of 10 results for each samples were considered as the breakdown voltage (IEC 2013). To obtain the actual breakdown voltage, the average result is divided by four as the electrode gap is 4 mm. This is to follow the standard of other researchers as they use different value of gap when conducting the testing.

For the kraft insulating paper, the result as shown in Figure 9. All the insulating papers were impregnated in the oil before conducting the test. Every thickness of insulating paper were aged at 0 °C, 90 °C, and 140 °C. From the result, the kraft insulating papers that were not aged has higher value of breakdown voltage compared to the insulating papers that were aged at temperature of 90 °C and 140 °C. The value of breakdown voltage decreased as the aging temperature increased. For the thickness of 0.06 mm, the breakdown voltage of the insulating paper that was not aged is 22.18 kV/mm which is higher than the insulating papers that were aged at 90 °C and 140 °C for the same thickness. The breakdown voltage for the insulating papers that were aged at the temperature of 90 °C is 19.97 kV/mm which is higher than the insulating paper that were aged at 140 °C which result in 18.45 kV/mm for the thickness of 0.06 mm. The trend is the same for the insulating papers that have a thickness of 0.08 mm and 0.12 mm. For the thickness of 0.08 mm, the breakdown voltage for the insulating papers that were not aged is higher than the insulating papers that were aged at 90 °C and 140 °C which result in 24.09 kV/mm, 22.54 kV/mm, and 20.17 kV/mm, respectively. For the thickness of 0.12 mm, the result shows the same pattern too. The breakdown voltage for the insulating papers that were not aged has higher value compared to the insulating papers that were aged at 90 °C and 140 °C which result in 28.11 kV/mm, 24.39 kV/mm, and 22.87 kV/mm, respectively.

The trend shows that the higher the temperature of aging, the lower the breakdown voltage will be. This is because, when the papers undergo the aging process at high temperature for a long time, the fibres of insulating papers are damaged which causes the gap and the hole to increase greatly (Ran et al. 2016). From several literature reviews, many researchers agreed that the higher the temperature of aging, the lower the breakdown voltage will be (Ran et al. 2016; Chmura et al. 2012).

From the result as shown in Figure 9, the thickness also has an effect to the value of breakdown voltage too. The value of breakdown voltage is higher when the thickness of the insulating paper is higher. As shown in Figure 9, for the insulating papers that were not aged, the breakdown voltage for the thickness of 0.12 mm is higher than 0.08 mm and 0.06 mm. The result is the same for the papers that were aged at 90 °C and 140 °C. The breakdown voltage is increases as the thickness of the insulating paper increases. This is because, the activation energy decreases as the thickness of insulating paper increases (Chmura et al. 2012).

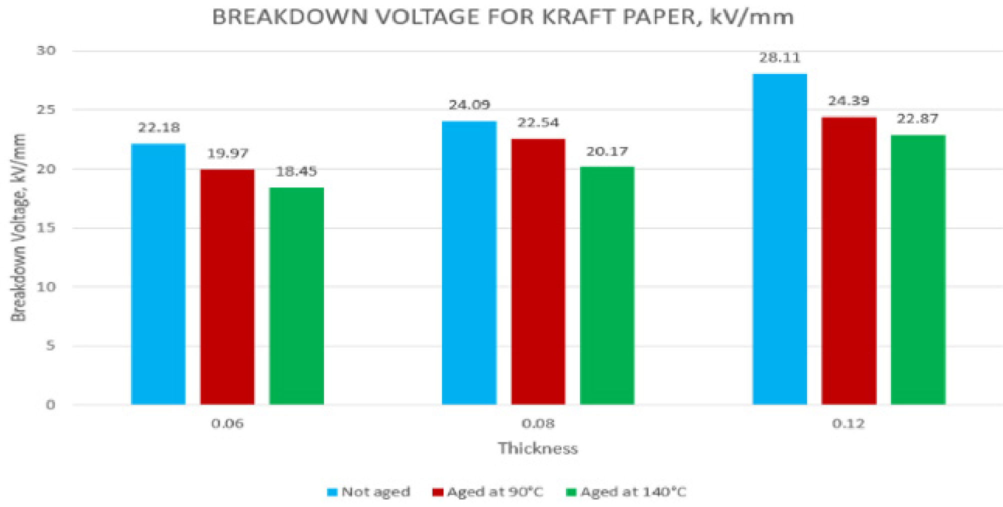

FIGURE 9. Breakdown voltage Kraft insulating paper

For the second type of insulating paper, which is the mix of Kenaf fibres and EFB fibres were also aged at temperature of 90 °C for 30 days. The insulating papers that were not aged was also tested as to investigate its breakdown strength performance. The result is shown in Figure 10 and Figure 12. Insulating papers that are made from mixture of Kenaf and EFB fibres are not used in any power transformers and electrical appliances as of now. So, in order to determine the performance of its breakdown strength, we would compare its breakdown voltage with the result of Kraft insulating papers that were not aged and also the ones that were aged at 90 °C for 30 days which have breakdown voltage of 22.18 kV/mm and 19.97 kV/mm. The thickness of the insulating paper that was made from mixed of Kenaf fibres and EFB fibres is 0.06 mm which is comparable with the Kraft insulating paper that have thickness of 0.06 mm as well.

Figure 10 shows the result of breakdown voltage for the mixed of Kenaf fibres and EFB fibres insulating papers that were not aged. From the result, it is shown that the insulating papers that were made by 100% Kenaf fibres has the highest value of breakdown voltage which result in 31.47 kV/mm compared to other ratios. For the insulating paper that was made by 75% Kenaf and 25% EFB has the breakdown voltage of 28.01 kV/mm which is lower that the breakdown voltage of 100% Kenaf insulating paper. While, for the insulating paper that was made from 50% Kenaf and 50% EFB has the breakdown voltage of 27.31 kV/mm which is much lower than the insulating paper that was made from 100% Kenaf. For the insulating paper that was made from 25% Kenaf and 75% EFB, it has the breakdown voltage of 27.12 kV/mm which is lower that insulating paper that was made from 50% Kenaf and 50% EFB. Lastly, for the insulating paper that was made by 100% EFB has the lowest breakdown strength which is 26.93 kV/mm.

From the result, it is shown that the Kenaf fibres has dominated the breakdown strength. As the ratio of Kenaf

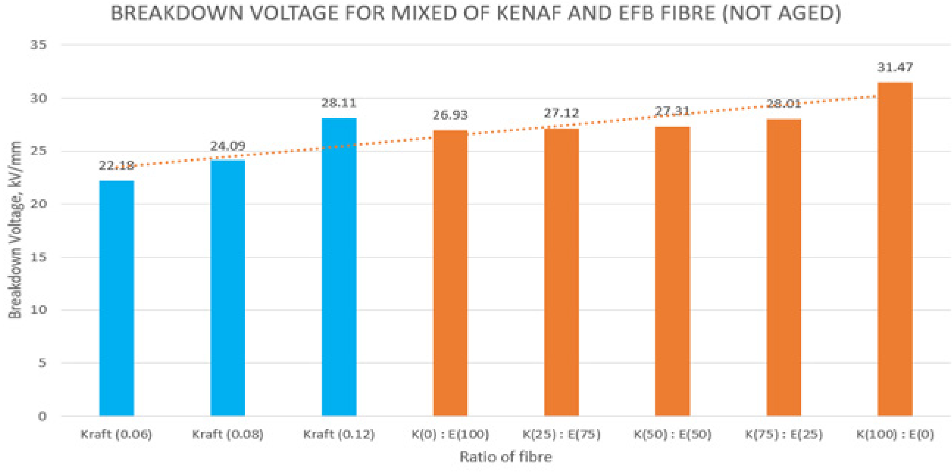

FIGURE 10. Breakdown voltage for mixed of Kenaf fibres and EFB fibres insulating paper that not being aged

fibres decrease, the breakdown voltage also decreases. Kenaf has long fibre arrangements that cause better fibre-to-fibre bonding (Rafidah et al. 2017). The better fibre-to-fibre bonding may slow down the breakdown to occur. So, the performance of insulating papers that were made from mixed of Kenaf fibres and EFB fibres has higher breakdown strength compared to Kraft insulating paper which both has the thickness of 0.06 mm.

Figure 11 shows the Weibull distribution for breakdown voltage of mixed of Kenaf fibres and EFB fibres insulating papers that were not aged. The distribution data of breakdown voltage for different fibres ratio is disperse in both sides of straight lines. So, it can be concluded that the breakdown voltage obeys Weibull distribution. Table 2 shows the Weibull distribution characteristic parameter of break-down voltage for different ratio of fibres.

Figure 12 shows the breakdown voltage of mixed of Kenaf fibres and EFB fibres insulating papers that were aged at 90 °C. From Figure 12, the breakdown voltage of insulating paper that was made from 100% of EFB is 25.92 kV/mm which is greater than the breakdown voltage of other ratios of Kraft insulating papers. For 25% Kenaf and 75% EFB insulating paper, its breakdown voltage is 25.87 kV/mm which is lower than the 100% EFB insulating paper. Next, for the 50% Kenaf and 50% EFB insulating paper, the breakdown voltage is 24.32 kV/mm which is much lower than 25% Kenaf and 75% EFB insulating paper. For the 75% Kenaf and 25% EFB insulating paper, its breakdown is slightly higher than the 50% Kenaf and 50% EFB insulating paper which is 24.91 kV/mm. Finally, the last ratio which is 100% Kenaf insulating paper, has the lowest breakdown voltage compare to other ratio which is 24.07 kV/mm.

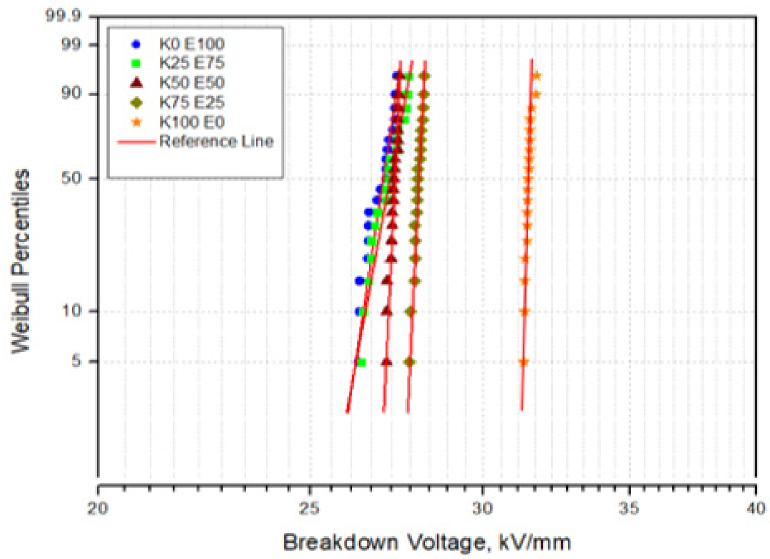

FIGURE 11. Weibull plot of breakdown voltage for mixed of Kenaf fibres and EFB fibres insulating paper that were not aged

TABLE 2. Weibull parameters of breakdown voltage for mixed of Kenaf fibres and EFB fibres insulating paper that were not aged

Paper	5% Conf. (kV/mm)	50% Conf. (kV/mm)	95% Conf. (kV/mm)
K0 E100	26	27	27.2
K25 E75	26	27	27.3
K50 E50	27	27.5	27.7
K75 E25	27.5	27.7	28
K100 E0	31	31.3	31.5

From the result, we can conclude that the EFB fibres has dominated the breakdown strength. As the ratio of EFB fibres decreases, the breakdown voltage also decreases. EFB fibres have a better opacity as the arrangement of short fibres causes the least leaving voids between the fibre-to-fibre bonding when in high temperature (Rafidah et al. 2017). The breakdown voltage gap between each ratio is small as the presence of Kenaf core fibres in the blended samples would expand the amount of short fibres. Kenaf fibres may damage when in high temperature. So, the performance of insulating papers that were made by mix of Kenaf fibres and EFB fibres has higher breakdown strength when being aged at 90 °C compared to Kraft insulating paper at same thickness which is 0.06 mm.

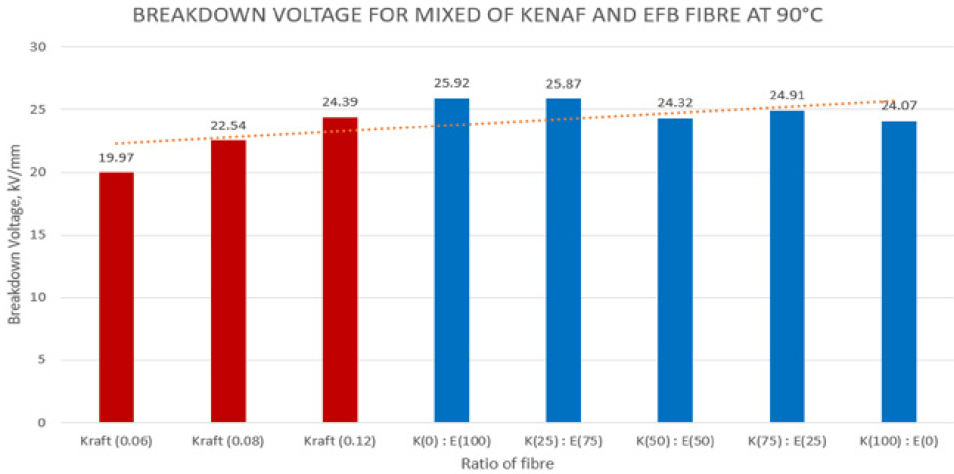

FIGURE 12. Breakdown voltage for mixed of Kenaf fibres and EFB fibres insulating paper that being aged at 90°C

Figure 13 shows the Weibull distribution for breakdown voltage of mix of Kenaf fibres and EFB fibres insulating papers that were aged at 90 °C. The distribution data of breakdown voltage for different fibres ratio is disperse in both sides of straight lines. So, it can be concluded that the breakdown voltage obeys Weibull distribution. Table 3 shows the Weibull distribution characteristic parameter of breakdown voltage for different ratio of fibres.

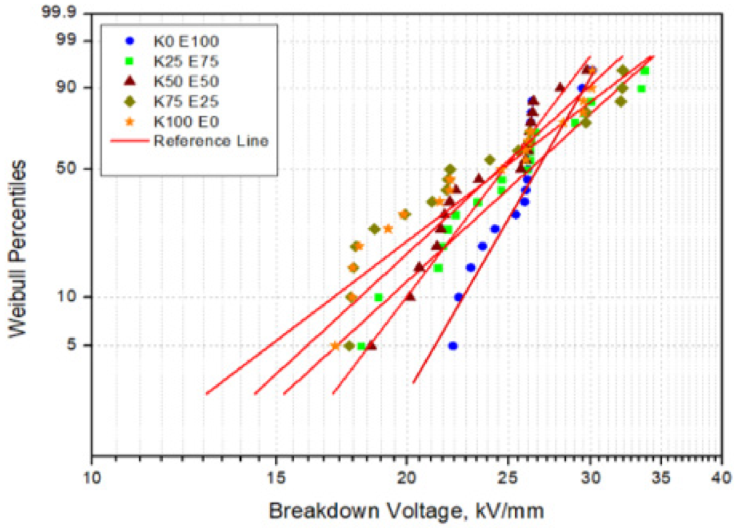

FIGURE 13. Weibull plot of breakdown voltage for mixed of Kenaf fibres and EFB fibres insulating paper that being aged at 90 °C

TABLE 3. Weibull parameters of breakdown voltage for mixed of Kenaf fibres and EFB fibres insulating paper that were not aged

Paper	5% Conf. (kV/mm)	50% Conf. (kV/mm)	95% Conf. (kV/mm)
K0 E100	22	26.2	29.5
K25 E75	17.8	26	33.5
K50 E50	18.2	25.6	27.7
K75 E25	17.4	22.3	32.7
K100 E0	16.9	24.2	30

CONCLUSION

In order to have the new insulating material, the investigation about electrical properties and mechanical properties is compulsory. From the testing that was conducted, we can conclude that the higher the aging temperature, the lower the breakdown voltage will be. This is because when the paper undergoes the aging process at temperature of 90 °C for a long time, the fibres of insulating paper are damaged which causes the gap and the hole to increase greatly. Secondly, the thicker the insulating paper, the higher the breakdown voltage will be. This is because, the activation energy decreases as the thickness of insulating paper increase.

From Figure 10, Kenaf fibres has dominated the breakdown strength. As the Kenaf fibres ratio decreases, the breakdown voltage also decreases. This is because Kenaf has long fibre arrangement which have better fibre-to-fibre bonding that may slow down for the breakdown to occur. But, after being aged at 90 °C for 30 days, EFB fibres has dominated in breakdown strength as shown in Figure 12. As the EFB fibres ratio decreases, the breakdown voltage also decreases. This is because, EFB fibres has short fibre arrangement that causes the least leaving of voids between fibre-to-fibre bonding when in high temperature. Kenaf fibres may damage due to high temperature.

From the result, we compared the mix of Kenaf fibres and EFB fibres insulating paper performance with the Kraft insulating paper. The thickness of both insulating paper is the same which is 0.06 mm. We noticed that the breakdown voltage of insulating papers that were made from mix of Kenaf fibres and EFB fibres is higher than the Kraft insulating paper. Therefore, the mix of Kenaf fibres and EFB fibres insulating papers has a potential to be used in power transformers as its breakdown strength is better than Kraft insulating paper. But, there are still many investigations on its electrical properties and mechanical properties that needs to be conducted before the insulating paper can be used widely in power transformers and electrical appliances.

DECLARATION OF COMPETING INTEREST

None

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