

# Pre-Breakdown Streamer Propagation and Positive Lightning Breakdown Characteristics of Palm Oil Impregnated Aged Pressboard

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**ABSTRACT** This paper presents the investigation on the breakdown characteristics and pre-breakdown streamer propagation of Palm Oil (PO) impregnated aged pressboard under positive lightning impulse voltages. The experimental work was carried out under a non-uniform field with needle-plane electrodes configuration. The streamer stopping length and breakdown voltage of 2 types of refined, bleached, and deodorized palm oil were examined in the presence of new and aged pressboards. The pressboard was placed in parallel to the needle-plane electrode at a gap distance of 50 mm. The lightning breakdown voltage was applied to the samples based on 1 shot per step rising voltage method under positive polarity as per IEC 60897. The presence of impregnated pressboard in both PO slightly increases the 50% positive lightning breakdown voltages. PO impregnated pressboards have lower 50% positive lightning breakdown voltages than MO. After subjected to ageing, the positive lightning breakdown voltages for PO and MO impregnated pressboards decrease. In the presence of aged pressboard, the streamers in PO generally propagate further than MO at the same voltage level.

**INDEX TERMS** Lightning impulse breakdown voltage, non-uniform field, palm oil, aged pressboard, streamer characteristics, transformers.

## I. INTRODUCTION

In recent years, there are significant numbers of researches on Palm Oil (PO) as dielectric insulation fluid in transformers [1]–[10]. Various properties have been examined and the electrical properties are one of the important parameters for dielectric insulation fluid. It has been shown that the AC/lightning breakdown voltages and partial discharge performances of PO are quite promising [1], [6], [9], [11]. An investigation on the pre-breakdown streamers of PO revealed similar streamer length and velocity with other types of commercial vegetable oils used in the transformers [12]. However, this investigation was carried out for

the open oil gap only. There is a need to examine the streamer characteristics in the presence of new and aged pressboards which is essential for practical application in the transformers.

Pressboard is normally used as a spacer or barrier between windings to enhance the dielectric strength of the oil gap. Creepage discharge along the surface of solid insulation i.e. pressboard is considered as one of the failure modes for transformers [10], [13]. It is an electric discharge phenomenon that occurs once the streamer propagates along the solid insulation and leaves the “tree-like” carbonized conducting or semiconducting paths. This phenomenon could cause further degradation of the solid materials [10]. In the worst-case scenario, a flashover might be initiated and lead to a total breakdown of the insulation system [10].

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Previous study on Mineral Oil (MO) revealed that the introduction of pressboard in the parallel direction to electric field had no significant effect on the streamer propagation and positive lightning breakdown voltage [14]. The 50% positive lightning breakdown voltage increased by 30% once the pressboard was placed in the perpendicular direction to the electric field based on needle-plane electrodes configuration for gap distances between 10 mm and 100 mm [14]. Meanwhile, other study reported no significant change on the positive lightning breakdown voltage of MO impregnated pressboard parallel to the electric field as compared to open oil gap [15]. For natural ester, the introduction of a pressboard in the parallel direction to the electric field has a similar effect as MO. No significant effect on the streamer stopping length and lightning breakdown voltage of natural ester was observed as compared to the open oil gap under both positive and negative polarities at a gap distance up to 75 mm [16]. Other study had shown that the positive streamer length and lightning breakdown voltage for rapeseed and soybean impregnated pressboards are similar to those with MO [17].

It had been reported that based on MO study, the presence of aged pressboard with DP as low as 162 in the perpendicular direction to the electric field could increase the negative lightning breakdown voltage under the uniform field configuration [18]. Under the non-uniform field, the positive and negative lightning breakdown voltages decreased by 4% and 15% once an aged pressboard was placed in the parallel direction to the electric field based on needle-sphere electrodes configuration [19]. A similar decrement effect was observed for a 29 years in-service aged pressboard in the perpendicular direction to the electric field whereby 30% reduction of lightning breakdown voltage is found under non-uniform field [20].

This paper presents an investigation on the streamer propagation and lightning breakdown of PO under the non-uniform field with and without the pressboard. The lightning impulse tests are carried out on the PO impregnated pressboards to study the effects of the different ageing durations on the streamer stopping length, velocity and breakdown performances. The results are compared with MO as a benchmark.

## II. MATERIALS AND METHODS

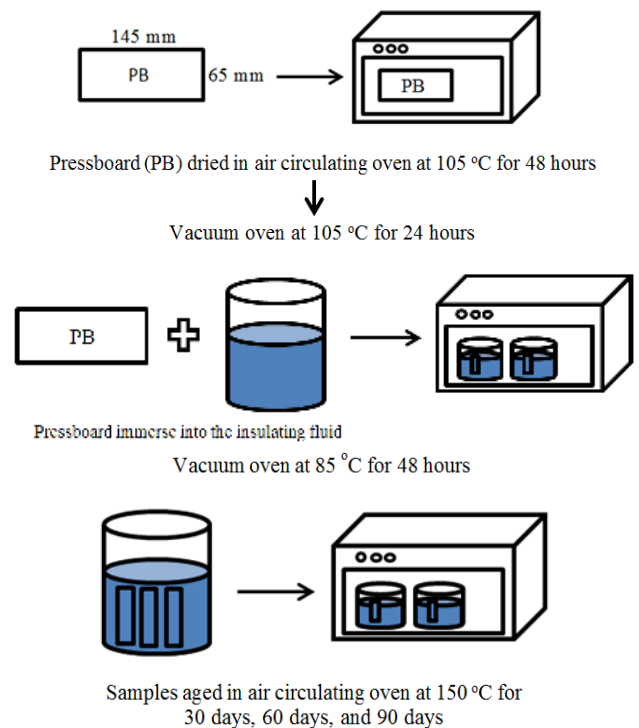
### A. SAMPLES

Two types of refined, bleached and deodorized palm oil olein from readily available products in the market were used as the testing samples in this experiment while MO was used as the benchmark. The fatty acids and vitamin contents for each of the POs are shown in Table 1. Gas Chromatography (GC) analysis was used to determine the fatty acids composition while the vitamins contents were obtained from the manufacturer's datasheet.

The dimension of the oil-impregnated pressboard used was 145 mm long  $\times$  65 mm high  $\times$  3 mm thickness. Figure 1 shows the pre-processing procedure for the pressboards. The pressboards were firstly dried in an air circulating oven at 105 °C for 48 hours and further dried in a vacuum condition

**TABLE 1.** Fatty acids and, vitamin E/A contents of PO.

Contents		Samples	
		POA	POB
Saturated fatty acid (%)	C12:Lauric	0.10	0.30
	C14:Myristic	0.90	0.90
	C16:Palmitic	39.3	39.0
	C18:Stearic	4.20	4.20
Monounsaturated fatty acid (%)	C18:Oleic	41.1	43.0
Polyunsaturated fatty acid (%)	C18:Linoleic	12.2	10.4
	C18:Linolenic	0.30	0.20
Others fatty acid (%)		0.10	0.10
Vitamin E (mg)		75.0	4.40
Vitamin A ( $\mu$ g)		-	264



**FIGURE 1.** Pre-processing procedures of the pressboard.

(less than 500 Pa) at 105 °C for 24 hours. Next, the pressboards were immersed into the respective oils under vacuum (less than 500 Pa) at 85 °C for 48 hours. The final moisture content of the pressboard was less than 0.5% as per IEC 60814 and it was measured by a Metrohm 774 oven method [21]. Finally, the pressboards were thermally aged under open condition at 150 °C for 30, 60 and 90 days.

### B. EXPERIMENTAL SETUP

The lightning impulse test was carried out based on the experimental setup as shown in Figure 2. A needle-plane electrode system was used to investigate the breakdown voltage and streamer propagation. The copper needle with tip radius curvature of  $50 \pm 5 \mu\text{m}$  was placed perpendicular to the grounded plane electrode. The needle tip radius was measured by a BA310Met-T metallurgical microscope. The

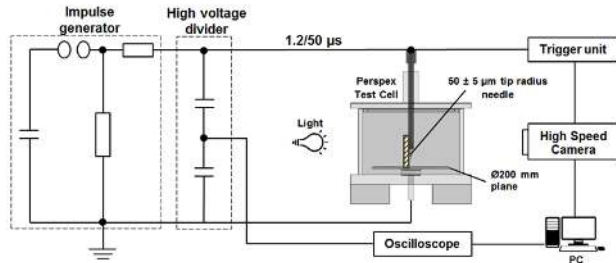


FIGURE 2. Test setup for lightning impulse voltage.

needle-plane electrodes were placed in a cubic test cell with 10 liters volume. The gap distance between the needle-plane electrodes was set to 50 mm. In total, 60 oil impregnated pressboard samples were tested for lightning breakdown voltages; unaged POA, 30 days aged POA, 60 days aged POA, 90 days aged POA, unaged POB, 30 days aged POB, 60 days aged POB, 90 days aged POB, unaged MO, 30 days aged MO, 60 days aged MO and 90 days aged MO. All POA, POB and MO impregnated pressboards were tested for lightning breakdown voltages with new as-received oils. An oscilloscope was used to obtain the breakdown waveform and the time to breakdown.

The streamer images were captured by a high-speed camera Phantom version 7.3 with 14-bit image depth and a maximum resolution of  $800 \times 600$  pixels CMOS sensors. Each image exposure time was set to  $2 \mu\text{s}$ . The inter-frame setting was set to 90,000 frames per second. Due to the fast streamers and hardware limitations, the resolution of the high-speed camera has been reduced to  $254 \times 254$  pixels to obtain the required images. Shadowgraph technique was used to obtain the streamer images with the help of a back flashlight. This technique can provide similar information in terms of streamer stopping length as compared to various photographing techniques including shadowgraph, reflective image and integral light image [22].

Degree of Polymerization (DP) of the pressboard impregnated in PO and MO was measured based on IEC 60450 using Rheotek RPV-1 polymer viscometer equipment [23]. The measurements of the lightning breakdown voltages were carried out based on 1 shot per step rising voltage method under positive polarity according to IEC 60897 [24]. The increment voltage was set to 10 kV with the initial voltages of 60 kV. These initial voltages were determined based on the recommendation in IEC 60897 whereby the breakdown voltage of PO was taken as the reference [24]. The test was repeated after 3 and 5 minutes time interval. A total of 5 breakdown readings were recorded for each of the samples. For each of the voltage levels, the average value of the streamer length was determined based on 5 measurements. The needle electrode and oil samples were changed after every 5 breakdowns. In addition, the needle tip radius was also monitored after each of the breakdowns and re-sharpened to  $50 \pm 5 \mu\text{m}$  once a significant change was observed on the tip radius.

The streamer length was analysed and obtained by public domain software, "ImageJ". Once the impulse voltage

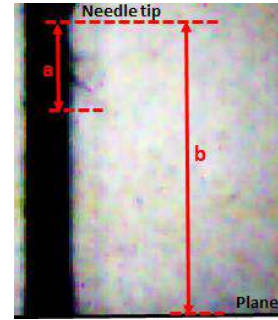


FIGURE 3. Measurement of a streamer length for POB at 80 kV.

was applied, the streamer started to initiate, propagate and stop at a certain distance from the needle tip if there is no breakdown. The streamer propagation process was recorded by a high-speed camera of which the time interval between each frame was set to  $11 \mu\text{s}$ . The distance from the needle-point electrode to the farthest tip point of the streamer was defined as the streamer stopping length. The actual streamer stopping length,  $l$  can be calculated using Equation (1) where  $a$  is the image streamer stopping length and  $b$  is the image gap distance measured from the needle tip to plane electrode as shown in Figure 3. The average streamer velocity,  $v_a$  before breakdown can be calculated based on streamer stopping length,  $l_a$  and propagation time,  $t_a$  according to Equation (2). The propagation time in this study was set to  $22 \mu\text{s}$  and it was defined as the streamer stopping length in this study. The average streamer velocity,  $v_b$  after breakdown can also be calculated based on Equation (3) where  $d$  is the gap distance and  $t_b$  is the time to breakdown.

$$l = (a/b) \times 50 \quad (1)$$

$$v_a = l_a / t_a \quad (2)$$

$$v_b = d / t_b \quad (3)$$

The 50% lightning breakdown voltage, streamer length and streamer velocity for all samples were analysed with and without the pressboard. The lightning impulse tests for unaged and aged pressboard durations were investigated with new as-received oils. After each of the breakdowns, the surface morphology of the pressboard was analysed via LEO 1455VP Scanning Electron Microscope (SEM).

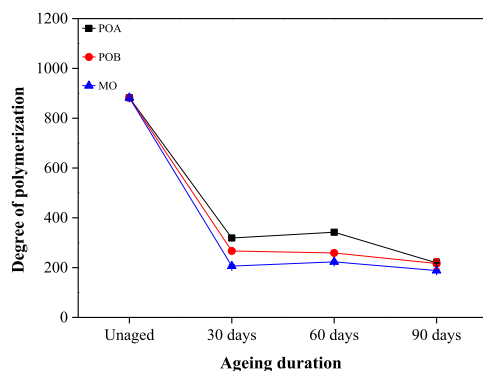
### III. RESULTS

#### A. PHYSICAL APPEARANCE AND DEGREE OF POLYMERIZATION OF NEW AND AGED PRESSBOARD

The physical appearance of the unaged and aged pressboard at different ageing duration are illustrated in Figure 4. Overall, the color of the PO impregnated pressboard changes from light to dark brown as the ageing duration increases to 90 days. Meanwhile, the color of MO impregnated pressboard changes to black as early as 30 days and becomes darker as the ageing duration reaches to 90 days. Furthermore, significant discoloration of the MO impregnated pressboard occurs as early as 30 days of ageing.



**FIGURE 4.** Physical appearance of unaged and aged pressboards for POA, POB, and MO.

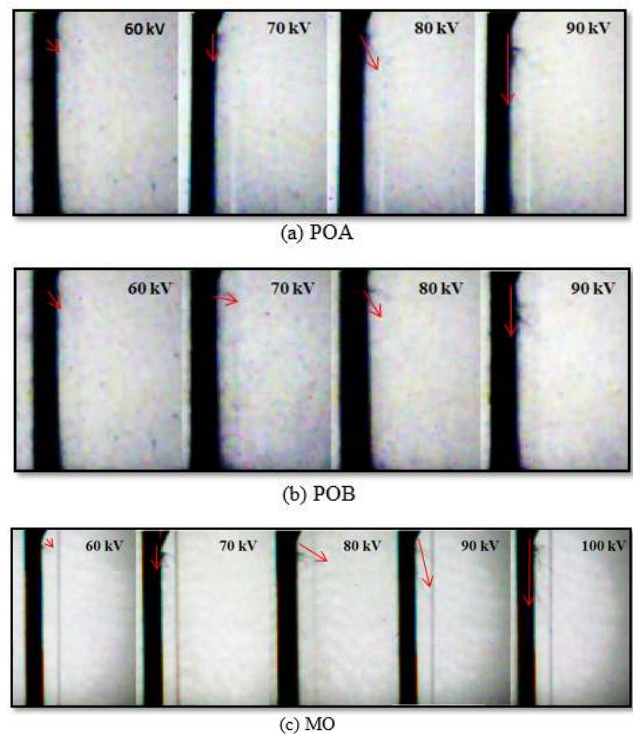


**FIGURE 5.** Relationship between degree of polymerization and ageing duration for POA, POB and MO impregnated pressboards.

All samples experience a significant reduction of DP up to 30 days of the ageing as shown in Figure 5. Table 2 displays the dispersion of the DP data for all samples. The DP of pressboards impregnated in POA, POB and MO maintain almost unchanged as the ageing duration increases higher than 30 days. Notably, the DP of pressboard impregnated in POA and POB remain higher than MO between 30 and 90 days of ageing. The percentage of the difference on DP between MO and POA impregnated pressboards is between

**TABLE 2.** DP of PO and MO impregnated aged pressboard.

Samples	Aged pressboard duration	DP Measurement 1	DP Measurement 2
POA	30 days	307	323
	60 days	324	348
	90 days	218	220
POB	30 days	269	265
	60 days	255	263
	90 days	231	202
MO	30 days	210	202
	60 days	220	226
	90 days	186	190



**FIGURE 6.** Positive streamer propagation in the presence of pressboard,  $d = 50$  mm.

16% and 53% while for POB impregnated pressboard, it is between 16% and 30% throughout the ageing duration. The average initial DP value of the unaged pressboard is around 882 with 884 and 880 as 1<sup>st</sup> and 2<sup>nd</sup> measurements. POB impregnated pressboard exhibits the highest difference between 1<sup>st</sup> and 2<sup>nd</sup> DP measurements with a value of 29. The differences between 1<sup>st</sup> and 2<sup>nd</sup> DP measurements for each of the samples show no clear relationship with the pressboard ageing duration.

## B. STREAMER PROPAGATION, STOPPING LENGTH AND VELOCITY WITH AND WITHOUT THE AGED PRESSBOARD

The positive streamer propagation images for all samples with the pressboard at a gap distance of 50 mm can be seen in Figure 6. Sharp images of the streamers are difficult to



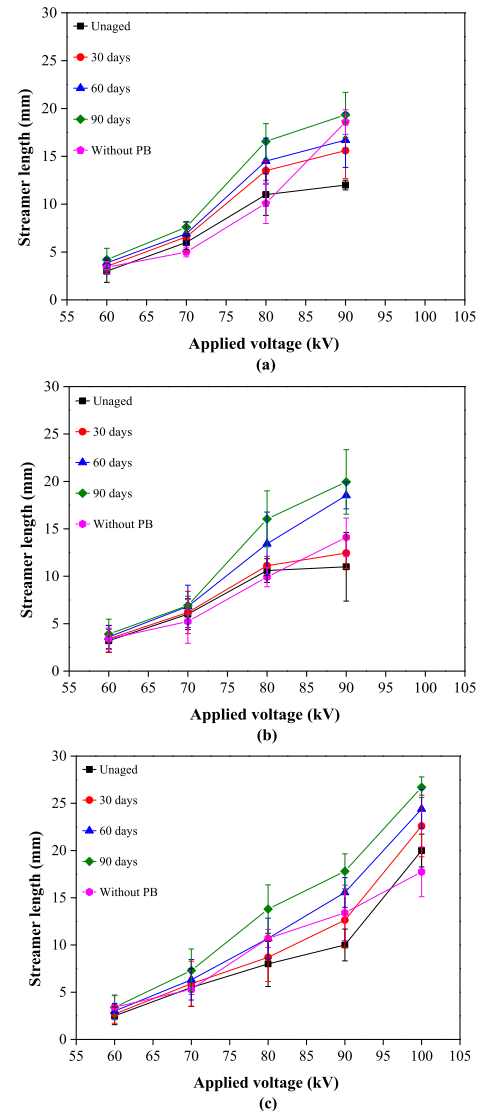
be obtained especially on thin branches with small diameter. The streamers for all samples propagate along the surface of pressboard and appear in tree-like structures.

Streamer stopping length is one of the important parameters in the streamer propagation studies. It is defined as the farthest tip point of a stopped streamer to the needle tip electrode. The stopping lengths of streamers for POA, POB and MO with and without the aged pressboard at 50 mm gap distance can be seen in Figures 7 (a), (b) and (c). For all the cases, the streamer lengths exhibit a gradually increasing trend as the voltage and ageing duration increases. Under the open oil gap, both POs have slightly shorter streamer stopping lengths at voltage level less than 80 kV as compared to the samples with the pressboard. There are significant increases in the streamer lengths for both POs and MO impregnated pressboards as the voltage increases higher than 70 kV for all ageing duration. For POA impregnated aged pressboard, the streamer length increases from an initial value of 0.07 mm/kV to 0.22 mm/kV and from 0.07 mm/kV to 0.21 mm/kV for POB impregnated aged pressboard as shown in Figures 7 (a) and (b). The streamer length increases steadily from 0.08 mm/kV to 0.27 mm/kV for MO impregnated aged pressboard as shown in Figure 7 (c). Generally, at the same voltage level, the streamers for both POs impregnated aged pressboards propagate further than MO aged impregnated pressboard. The differences on the streamer length between POs and MO at 90 kV are between 0.2 mm and 3.0 mm for all ageing duration.

The streamer propagation velocities of all samples increase with the increment of the voltage as shown in Figure 8. At the same voltage level, the velocity of MO impregnated pressboard is almost close to both of PO impregnated pressboards. Both MO and PO impregnated pressboards exhibit propagation mode 1 of which the velocities are less than 1 km/s. It is also found that the streamer velocities for all samples with the pressboards are higher than the open oil gap. At 90 kV, the percentages of differences between POA, POB and MO impregnated pressboards and open oil gap are 41%, 15% and 25%, respectively. From 60 kV to 90 kV, the velocities for POA and POB impregnated aged pressboards increase from 0.1 km/s to 0.9 km/s as shown in Figures 8 (a) and (b). On the other hand, an increment of velocity from 0.1 km/s to 0.8 km/s is found for MO impregnated aged pressboard at the same voltage level as shown in Figure 8 (c).

### C. BREAKDOWN VOLTAGE WITH AND WITHOUT THE PRESENCE OF AGED PRESSBOARD

The 50% positive breakdown voltages of PO and MO with and without the presence of pressboard can be seen in Figure 9. For both PO, the 50% positive breakdown voltages increase with the introduction of pressboard. With the pressboard, the 50% positive breakdown voltages of POA and POB increase by 11% and 12% as compared to the sample without the pressboard. The 50% positive breakdown voltage of MO remains almost unchanged with the introduction of the pressboard. It is also found the differences of 50% positive

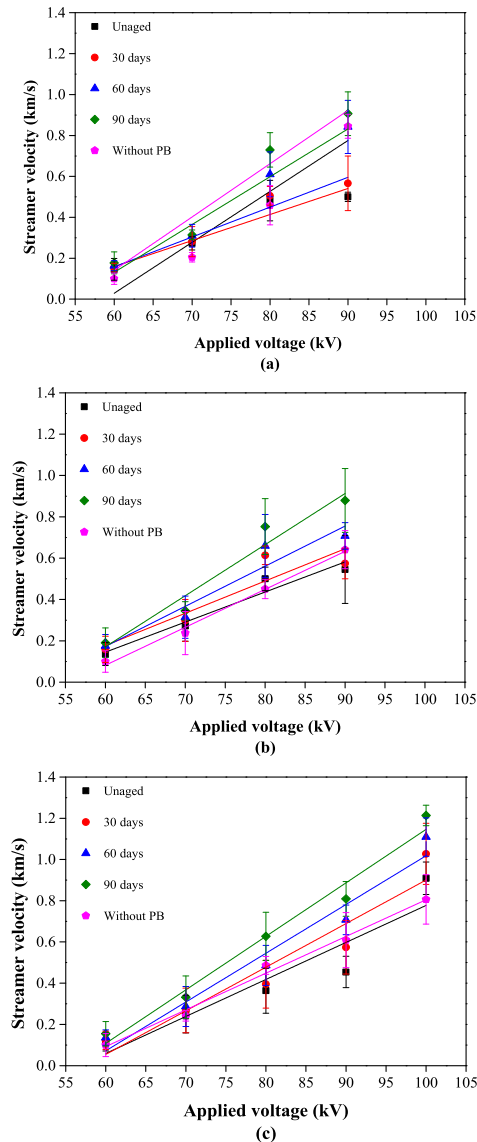


**FIGURE 7.** Streamer stopping length with and without the presence of Unaged, 30 days, 60 days and 90 days aged pressboard for (a) POA, (b) POB, and (c) MO.

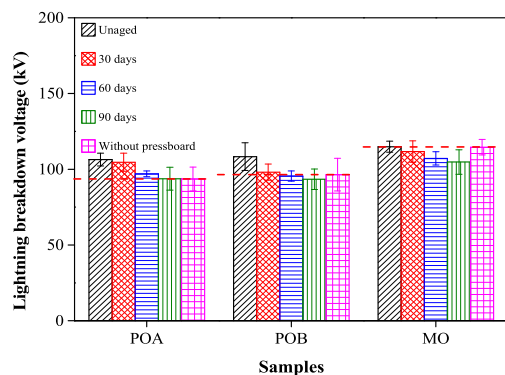
breakdown voltages for both PO and MO are lower in the presence of a pressboard. The highest percentages of differences between PO and MO for without and with pressboard are 18% and 9% respectively. The 50% positive breakdown voltages of all samples decrease as the ageing pressboard duration increases with the highest percentages of decrements can be 9% and 12% for POA and POB and 14% for MO.

### D. SURFACE MORPHOLOGY OF PRESSBOARD

The surface morphology by SEM is used to examine any damages on the surface of the pressboard after subjected to a lightning breakdown test. Figure 10 shows a few detected damage images of pressboards in the samples after subjected to positive lightning impulse voltages. It is worth noting that under the similar test voltage or ageing duration, the fibre structures and surface morphologies for other pressboards could be different from what is shown in Figure 10. With no

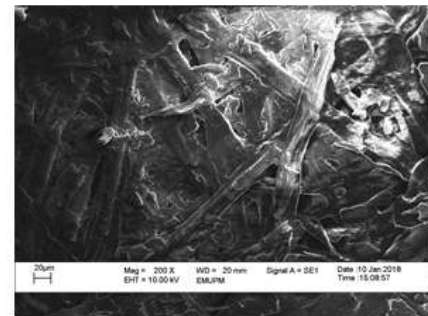


**FIGURE 8.** Streamer velocity with and without the presence of unaged, 30 days, 60 days and 90 days aged pressboard for (a) POA, (b) POB, and (c) MO.

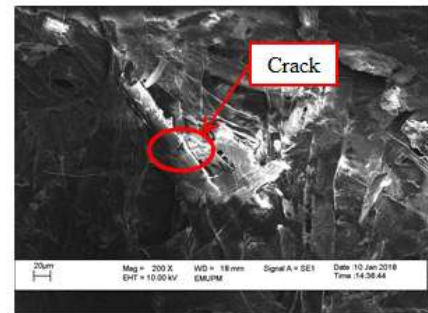


**FIGURE 9.** The 50% breakdown voltage for all samples with and without the presence of unaged, 30 days, 60 days and 90 days aged pressboards.

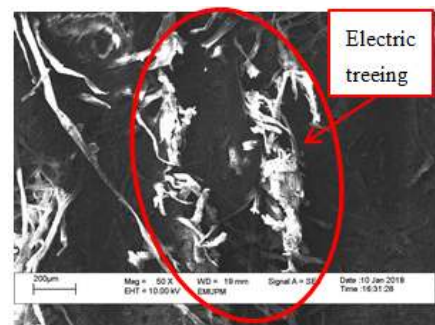
voltage applied, the fibres of the pressboard remain smooth and tightly bonded as shown by one the samples of unaged



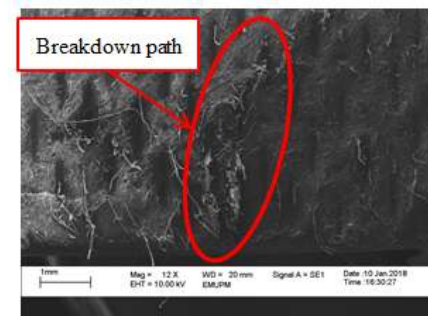
(a) New pressboard (no applied voltage)



(b) POB impregnated unaged pressboard  
(applied voltage = 97 kV)



(c) MO impregnated unaged pressboard  
(applied voltage = 121 kV)



(d) POA impregnated 60 days aged pressboard  
(applied voltage = 104 kV)

**FIGURE 10.** SEM images for the surface damage of pressboard: (a) new pressboard, (b) crack for POB impregnated unaged pressboard, and (c) electric tree for MO impregnated unaged pressboard and (d) breakdown path for POA impregnated aged pressboard.

POA impregnated pressboard in Figure 10 (a). After subjected to positive lightning impulse voltage, micro gaps and

cracks are detected in the fibres of the unaged impregnated pressboard as demonstrated by one of the POB impregnated pressboard shown in Figure 10 (b). The unaged impregnated pressboard can also be subjected to electric treeing after subjected to positive lightning impulse voltage as shown by MO impregnated pressboard in Figure 10 (c). The damages on the aged samples by the positive lightning impulse voltages are quite minimal whereby only a small treeing is observed on the surface of POA impregnated pressboard as shown in Figure 10 (d). Other aged pressboards show no apparent damages on its surfaces after subjected to positive lightning impulse voltages.

#### IV. DISCUSSION

The positive streamer mechanism in fluid begins with the ionization process of which the electrons are liberated under critical ionization potential [12]. Electron avalanches can be initiated which lead to the streamer propagation. These electrons accelerate toward the positive electrode and collide with other molecules of the fluids to cause further ionization and liberate more electrons in the system [12], [27]. The energy that is required for ionization could affect the speed and the length of the streamer propagation [12].

Based on this study, the 50% positive lightning breakdown voltages for both PO impregnated pressboards slightly improve with the introduction of the pressboard. The 50% lightning breakdown voltage of the MO impregnated pressboard is almost the same as the open oil gap shown in Figure 9. It is well reported that the introduction of the pressboard does not decrease the 50% lightning breakdown voltages of oil impregnated pressboard [14], [16], [25], [26]. In oil impregnated pressboard, both materials have components with different dielectric constants where oil has a lower dielectric constant and dielectric strength compared to the pressboard [27]. However, the breakdown phenomena are still not well understood since various factors can be involved such as the interaction between solid/fluid insulation materials and the presence of voids and impurities [27], [28]. However, it is known that for two parallel insulating materials, the weakest component will fail first and the permittivity should be matched in order to increase its electrical strength [28]. Failures of the solid insulating materials could result in thermal breakdown and treeing that is caused by tracking and it is shown by a few examples of SEM imaging in Figure 10 [27].

Thermal ageing is one of the common phenomena that could occur in insulation systems. Several laboratory experimental works have shown that ageing could affect the electrical performances of oil impregnated pressboard [19]. A similar finding is observed in this study whereby the 50% positive lightning breakdown voltages of both POA and POB impregnated pressboards decrease as the ageing duration increases as shown in Figure 9. MO impregnated pressboard shows a similar decrement trend until ageing duration of 60 days. It is known that ageing will weaken the inter-fibre bonding of the cellulose insulation [27]. Multiple

unintentional voids could be introduced which could promote electrical treeing which leads to tracking and breakdown path [27]. A study in [18] has shown that the fibre structures and surface morphology of oil impregnated pressboards could change significantly after subjected to thermal ageing. The gaps between fibres could be bigger whereby micro globules could be formed due to the breakage of hydrogen bonds between cellulose molecules [18]. This effect could be the contributing factor that causes the introduction of the unintentional voids that leads to a reduction trend of the 50% positive lightning breakdown voltages of PO and MO, longer streamer stopping lengths and faster streamer propagation velocities. In this study, only 1<sup>st</sup> propagation mode of the lightning streamers is observed of which the streamer velocities are less than 1km/s. The 3<sup>rd</sup> and 4<sup>th</sup> propagation modes are normally observed under overvoltage lightning impulse applied voltage that is not examined in the current study [22].

The applied positive lightning impulse voltage is not necessarily can cause physical damages on the aged pressboards whereby only POA impregnated pressboard at 104 kV is affected based on SEM analysis as shown in Figure 10. Both POA and POB impregnated pressboards exhibit similar positive lightning breakdown and pre-breakdown streamer propagation characteristics despite the presence of vitamin E and A. Further study will be carried out to examine breakdown characteristics and pre-breakdown streamer propagation under negative lightning impulse in the future.

#### V. CONCLUSION

The 50% positive lightning breakdown voltages for both PO impregnated pressboards are slightly higher than open oil gaps. For MO, the 50% lightning breakdown voltage maintains almost the same with the introduction of the pressboard. At the same voltage level, streamers on PO impregnated pressboards propagate further than MO impregnated pressboard. The 50% breakdown voltages for both PO impregnated pressboards are always lower than MO impregnated pressboard. The lightning breakdown voltages for POA, POB and MO impregnated pressboards decrease after subjected to ageing. The highest percentages of lightning breakdown voltages decrement for POA, POB and MO impregnated pressboards are 12%, 16% and 9%. Concurrently, the streamer lengths and velocities for POA, POB and MO impregnated pressboards increase as the ageing duration increases whereby the highest percentages of increments for both parameters are 45%, 38% and 44% as well as 45%, 38% and 44% respectively. In term of practical application, the lightning breakdown performances for both PO is still slightly lower than MO. The introduction of additives could improve the PO performances for in-service applications in the future.

#### ACKNOWLEDGMENT

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