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Investigation on the Dielectric, Physical and Chemical Properties of Palm Oil and Coconut Oil under Open Thermal Ageing Condition

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Abstract – In this paper, a study is carried out to investigate the dielectric, physical and chemical properties of Palm Oil (PO) and Coconut Oil (CO) under open thermal ageing condition. The type of PO used in this study is Refined Bleached and Deodorized Palm Oil (RBDPO) Olein. The ageing experiment was carried out at 85 °C and 115 °C for 1, 3, 5, 7 and 14 days. Several parameters were measured such as AC breakdown voltage, dielectric dissipation factor, relative permittivity, resistivity, viscosity, moisture and acidity throughout the ageing duration. Based on the study, it is found that there are no significant changes on the AC breakdown voltages and relative permittivities for both RBDPO and CO. At ageing temperature of 115°C, there are clear reduction trends of dielectric dissipation factor for CO and resistivities for most of RBDPO. On the other hand, no clear trends are observed for viscosities, moisture and acidities of RBDPO and CO throughout the ageing duration.

Keywords: Refined Bleach Deodorized Palm Oil, Coconut Oil, Open Thermal Ageing, Transformers

1. Introduction

Due to the increasing tight regulations on the environment and safety in recent years, alternative fluids such as vegetable oils are currently been considered for transformers application. Vegetable oils offer a suitable alternative for mineral oil since it is biodegradable, non-toxic, environment friendly and have high fire/flash points which ensure more in-service safety [1, 2].

Generally, vegetable oil also known as natural ester is made of triglyceride which consist of glycerol and fatty acids as shown in Fig. 1 [3, 4]. The fatty acids in triglycerides can determine the physical and chemical properties of vegetable oils such as viscosity, melting/pour points, oxidation stability and ageing characteristics [5]. For example, as the percentage of unsaturated fatty acids contents increase, the melting and pour points will decrease [6]. There were different types of vegetable oils that had been examined for application in transformers [1, 7-19].

Palm Oil (PO) and Coconut Oil (CO) are among the type of vegetable oils that are proposed as dielectric insulating fluids in transformers. Generally, there are 3 types of fluids that can be obtained from a palm nut which are Crude Palm Oil (CPO), Palm Kernel Oil (PKO) and Refined, Bleached, Deodorized Palm Oil (RBDPO) [12]. The most common PO considered for application in transformers is RBDPO [13-15]. RBDPO has an almost balance composition of saturated and unsaturated fatty acids while CO has a high percentage of saturated fatty acids.

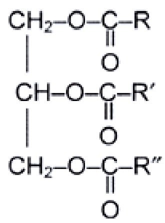

Fig. 1. Triglyceride structure [3, 4].

Previously, a number of researches had been carried out on RBDPO and CO which cover on various aspects including the AC breakdown voltage, dielectric properties, viscosity, moisture and acidity [13, 15, 16-19]. Most of these studies mainly focus on its basic properties and there is still less information that can be obtained on the performance of RBDPO and CO especially under thermal ageing at different conditions.

Among the common ageing mechanisms of dielectric insulating fluids in transformers under normal loading are oxidation and hydrolysis [1, 20-22]. For vegetable oils, oxidation mainly involved with the double C=C valence bonds within the triglyceride where the final by products of this mechanism includes aldehydes, ketones, alcohols and acids [23-25]. Hydrolysis of vegetable oils is initiated through interaction with water which will produce fatty acids as final by products [1, 25, 26].

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Since the in-service failure could be costly, it is important to examine the thermal ageing performances of RBDPO and CO before it can be used for future application in transformers. In this paper, an examination on the dielectric, physical and chemical properties of RBDPO and CO aged under open condition are presented. The aim of the study is to examine the effect of presence of air on the properties of these oils under thermal ageing. Different parameters such as AC breakdown voltage, dielectric dissipation factor, relative permittivity, resistivity, viscosity, moisture and acidity were measured on the RBDPO and CO throughout the ageing duration.

2. Experimental Descriptions

2.1 Fluids under test

The type of PO used in this study was RBDPO Olein. In total, 5 samples of RBDPO and 1 sample of CO were investigated. Different RBDPO were used in this study due to the consideration on the fat and vitamin E/A contents. All samples were obtained from readily available cooking oil products in the market. Table 1 shows the composition of fats and vitamin E/A of these oils. The composition of saturated and unsaturated fats among the RBDPO are almost equal. There is a difference on the vitamin E contents where RBDPOE has the highest vitamin E followed by RBDPOD, RBDPOC, RDBPOB and RDBPOA. Only RBDPOA has vitamin A while CO mainly consists of saturated fat and has no either vitamin E or A.

Table 1. Fat, vitamin E/A contents of all samples

Samples	S. fat (g)	P-U.S. fat (g)	M-U.S. fat (g)	V. E (mg)	V. A (μg)
RBDPOA	45.4	11.6	43.0	4.4	264
RBDPOB	44.4	12.2	43.3	50.0	-
RBDPOC	44.3	12.1	43.6	56.0	-
RBDPOD	43.0	12.0	45.0	60.0	-
RBDPOE	43.0	14.0	43.0	75.0	-
CO	92.8	3.6	3.6	-	-

* S. fat= Saturated fat, P-U.S. fat= Polyunsaturated fat, M-U.S. fat = Monounsaturated fat, V. E= Vitamin E, V. A= Vitamin A

2.2 Thermal ageing procedure

All samples were first pre-processed by filtering through a membrane filter with a pore size of 0.2 μm and dried in an oven at 85 °C for 48 hours. The oven used for the thermal ageing has 2 sources of air intake. One of the valves is located at the bottom of the oven and remains open. The second valve at the back of the oven can be controlled and was kept closed in this study in order to reduce the intake of air from outside into the oven. The volume of each oil sample used for the ageing experiment was 500 ml. All samples were aged in glass bottles at 85 °C and 115 °C under open condition. The ageing durations of all samples for both temperatures were set to 1, 3, 5, 7 and 14 days respectively. All samples were rested further at ambient temperature for another 24 hours before tested for AC breakdown voltage, dielectric dissipation factor, relative permittivity, resistivity, viscosity, moisture and acidity.

2.3 Test Descriptions

2.3.1 AC Breakdown Voltage

The AC breakdown voltage measurement was conducted according to ASTM D 1816 by an automatic oil breakdown tester, BAUR DPA 75C at ambient temperature [27]. The test was carried out using VDE electrodes with a diameter of 36 mm facing each other where the gap distance between two electrodes was set to 1 mm. The volume of the oil used for measurement was 400 ml and the voltage ramping rate was set to 0.5 kV/s. The time between breakdowns was set to 5 minutes. It was set longer than the recommended time in ASTM D 1816 in order to give time for expulsion of breakdown by products since vegetable oils such as RBDPO and CO have higher viscosities as compare to mineral oil [28, 29]. In total, 50 measurements of AC breakdown voltages were obtained for each oil sample and average value was used in this study.

2.3.2 Dielectric Dissipation Factor, Relative Permittivity and Resistivity

Dielectric dissipation factor, relative permittivity and resistivity were measured according to IEC 60247 by a BAUR DTL C oil tester [30]. The test temperature was set to 90 °C and the volume of oil tested was 70 ml. Within the frequency range stated in IEC 60247, the dielectric dissipation factor, tan δ can be calculated at frequency under interest using (1) [30].

$$\tan \delta_{f1} = \tan \delta_{f2} (f_2/f_1) \tag{1}$$

The relative permittivity, ε_x can be expressed based on simplified formula in (2) [30].

$$\varepsilon_x = C_x/C_a \tag{2}$$

where C_x is the capacitance of the cell filled with the liquid under test in farad and C_a is the capacitance of the cell with air as the dielectric in farad. The resistivity, ρ can be determined according to (3) [30].

$$\rho = K\,(U/I) \tag{3}$$

where K is the cell constant in metre, U is the reading of the test voltage in volt and I is the reading of the current in ampere [30].

2.3.3 Viscosity

Viscosity was measured by an automatic SVM 3000

Stabinger viscometer according to ASTM D 445 [31]. All samples were tested at 40 °C and the volume of the oil used for the measurement was 5 ml.

2.3.4 Moisture

The moisture measurement was carried out by a Metrohm 831 Karl Fisher (KF) Coulometer according to ASTM D 6304 [32]. The volume of the oil used for the measurement was 1 ml.

2.3.5 Acidity

Acidity was measured by a Metrohm 877 oil Titrano plus according to ASTM D 974 [33]. The weight of the oil used for the measurement was 10 g.

3. Dielectric Characteristics under Thermal Ageing

3.1 AC breakdown voltage

There are no significant reductions of AC breakdown voltages for all samples at both ageing temperatures. At ageing temperature of 85 °C, all RBDPO show reduction of the AC breakdown voltages initially where the percentage of reduction is between 9.8% and 28.2% as shown in Fig. 2 a). The breakdown voltages of most of the RBDPO start to increase after 1 day of ageing. Meanwhile, CO shows an increment of 33.3% on the AC breakdown voltages immediately after the ageing is started. The AC breakdown voltages for most of all samples remain almost unchanged between 3 days and 7 days of ageing. Apart from RBDPOB, all samples show a reduction on the AC breakdown voltages after 7 days of ageing.

On the other hand, the patterns of AC breakdown voltages for all samples at ageing temperature of 115 °C are slightly different from 85°C as seen in Fig. 2 b). Almost all samples show increment of AC breakdown voltages from start until 3 days of ageing. After 3 days of ageing, the AC breakdown voltages of all RBDPO slightly decrease with the percentage of decrement ranging between 5.4% and 14.6%, while for CO, it continues to slightly increase. The AC breakdown voltages for all samples start to fluctuate at values between 44 kV and 53 kV at the later stage of the ageing.

3.2 Dielectric dissipation factor

The dielectric dissipation factors of all RBDPO remain low even after 14 days of ageing at both ageing temperatures.

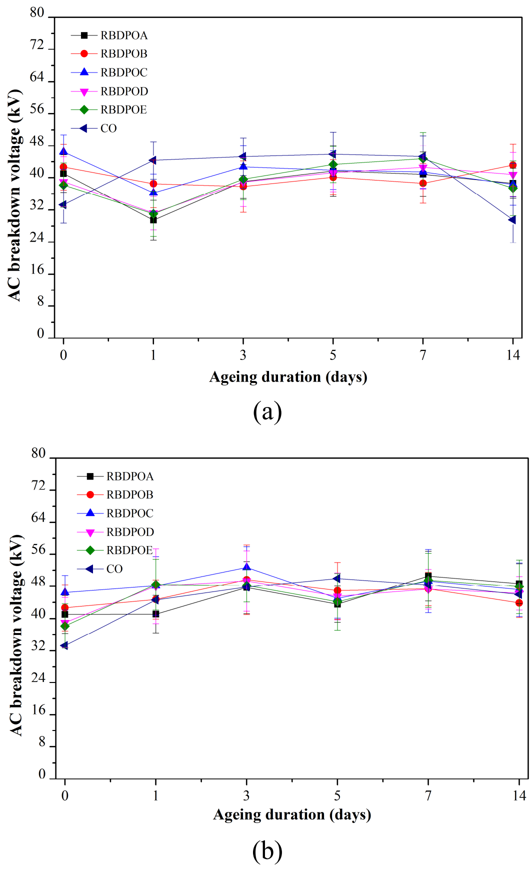


Fig. 2. Average AC breakdown voltages of all samples at (a) 85 °C, (b) 115 °C

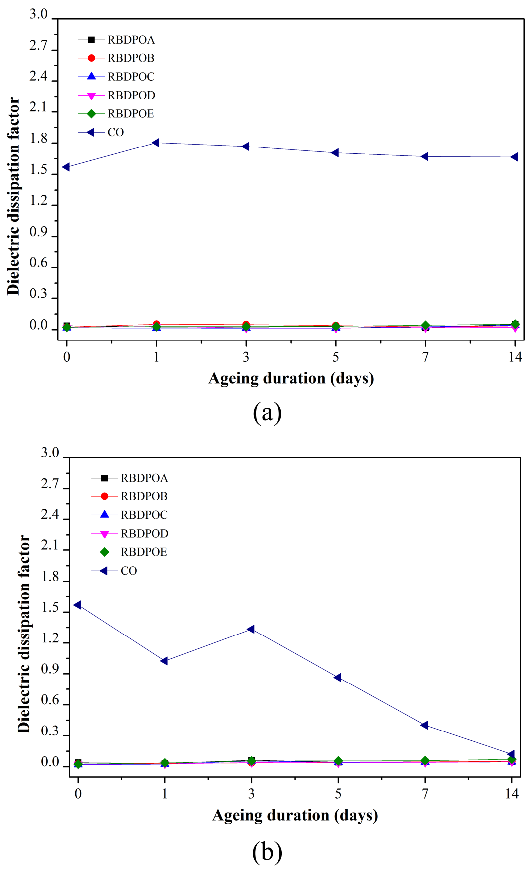


Fig. 3. Dielectric dissipation factors of all samples at (a) 85 °C, (b) 115 °C

At ageing temperature of 85 °C, the dielectric dissipation factors of all RBDPO are between 0.016 and 0.055 while at ageing temperature of 115 °C, the values are between 0.02 and 0.073. The dielectric dissipation factor of CO remains the highest throughout the ageing duration at both ageing temperatures. At ageing temperature of 85 °C, the dielectric dissipation factor of CO slightly increases initially and later slightly decreases to 1.67 at the end of the ageing duration as shown in Fig. 3 a).

There is a clear reduction trend of dielectric dissipation factor for CO at ageing temperature of 115 °C as shown in Fig. 3 b). The dielectric dissipation factor of CO decreases initially where the percentage of reduction is 34.5%. It slightly increases after 1 day of ageing and decreases almost linearly close to the RBDPO values at the later stage of the ageing.

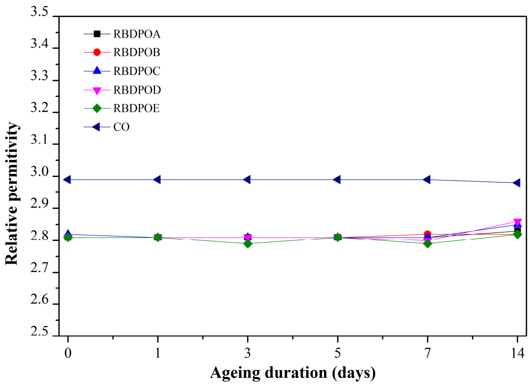
3.3 Relative permittivity

The relative permittivities of all samples remain almost unchanged throughout the ageing duration at both ageing temperatures as shown in Fig. 4. The range of relative permittivities of all RBDPO is between 2.79 and 2.86 at both ageing temperatures. The relative permittivity of CO remains the highest throughout the ageing duration at both ageing temperatures with values ranging between 2.93 and 2.99.

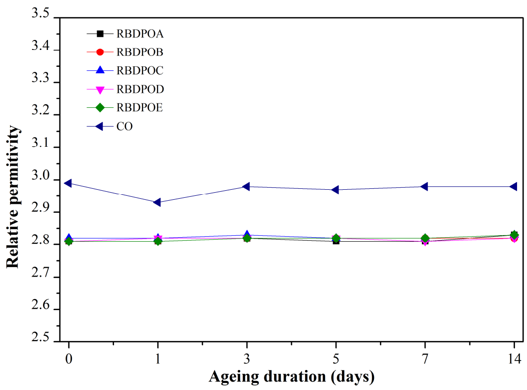
3.4 Resistivity

At ageing temperature of 85 °C, most of the RBDPO show fluctuation of resistivities throughout the ageing duration. Only RBDPOC and RBDPOE show slight reduction trend of resistivities as seen in Fig. 5 a). On the other hand, the resistivity of CO remains lower than RBDPO throughout the ageing duration at values between 7.79×10^7 Ωm and 8.7×10^7 Ωm.

The reduction trends of resistivities of all RBDPO are quite clear at ageing temperature of 115 °C as seen in Fig. 5 b). There are rapid reductions of resistivities for all RBDPO from start until 3 days of ageing and maintain at values ranging between 1.98×10^9 Ωm and 3.9×10^9 Ωm at the later stage of the ageing. The pattern of resistivity for CO is the same as at ageing temperature of 85 °C, where the value is much lower than all RBDPO. The resistivity of CO remains almost unchanged for the first 5 days of ageing. It starts to increase significantly after 5 days of ageing to a final value of 1.27×10^9 Ωm.

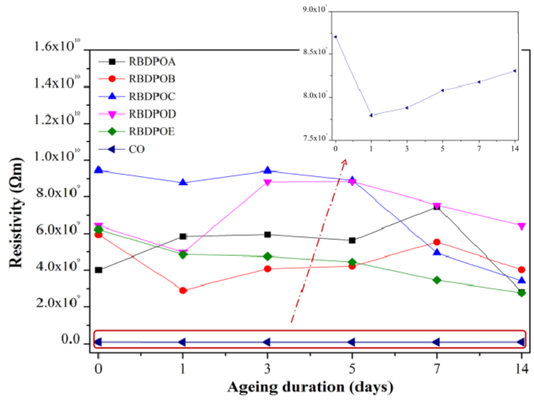


(a)

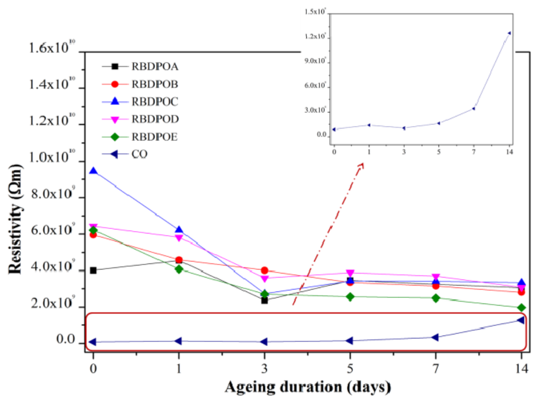


(b)

Fig. 4. Relative permittivities of all samples at (a) 85 °C, (b) 115 °C



(a)



(b)

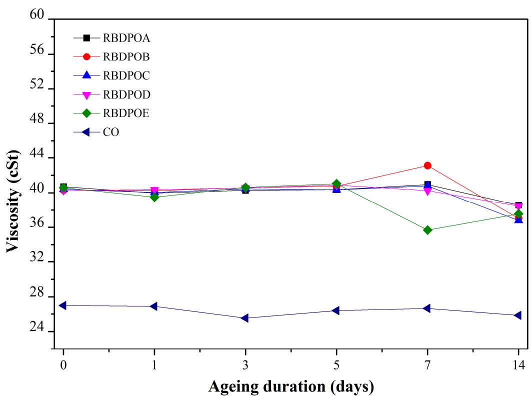
Fig. 5. Resistivities of all samples at (a) 85 °C, (b) 115 °C

4. Physical and Chemical Characteristics under Thermal Ageing

4.1 Viscosity

There is only a minor effect of ageing on the viscosities of all samples. The viscosity of CO remains almost unchanged and lower than all RBDPO throughout the ageing duration at both ageing temperatures at values ranging between 25.5 cSt and 27 cSt. At ageing temperature of 85 °C, the viscosities of all RBDPO remain almost unchanged close to 40 cSt from start until 5 days of ageing as shown in Fig. 6 a). After 5 days of ageing, the viscosities of all RBDPO start to fluctuate at values between 35.7 cSt and 43.1 cSt.

The viscosities of RBDPOA, RBDPOD and RBDPOE samples remain stable throughout the ageing duration at ageing temperature of 115 °C as seen in Fig. 6 b). On the other hand, the viscosities of RBDPOB and RBDPOC remain almost unchanged initially and start to slightly decrease after 3 days of ageing. After 5 days of ageing, the viscosities of RBDPOB and RBDPOC increase to final values of 41.1 cSt and 42.8 cSt respectively.–



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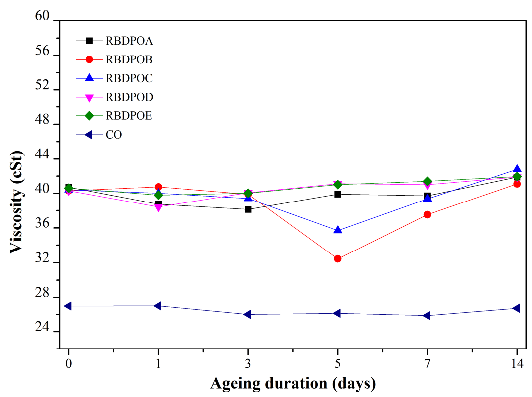
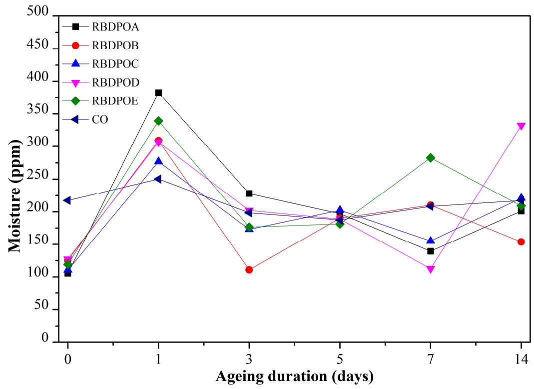
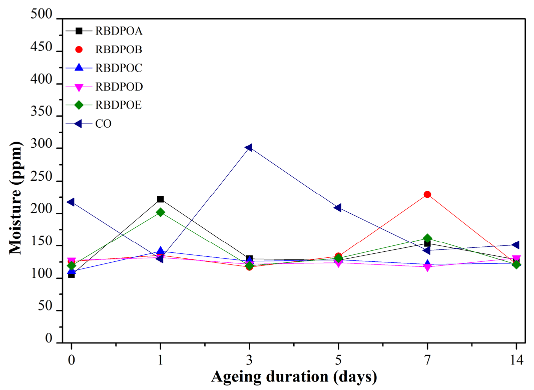


(b)

Fig. 6. Viscosities of all samples at (a) 85 °C, (b) 115 °C



(a)



(b)

Fig. 7. Moisture of all samples at (a) 85 °C, (b) 115 °C

4.2 Moisture

There are no clear trends of moisture can be observed at both ageing temperatures. At ageing temperature of 85 °C, the moisture of all samples fluctuates at values between 106 ppm and 383 ppm as shown in Fig. 7 a).

While at ageing temperature of 115 °C, the moisture of RBDPOC and RBDPOD remain almost unchanged throughout the ageing duration at values between 111 ppm and 142 ppm while for other samples, the moisture fluctuate at values between 106 ppm and 301 ppm as seen in Fig. 7 b).

4.3 Acidity

At ageing temperature of 85 °C, the acidities of all RBDPO remain at low values between 0.001 mg KOH/g and 0.004 mg KOH/g. CO has the highest acidity throughout the ageing duration ranging between 0.005 mg KOH/g and 0.013 mg KOH/g as seen in Fig. 8 a).

At ageing temperature of 115 °C, the acidities of RBDPOA, RBDPOD and RBDPOE remain low initially and start to slightly increase after 5 days and 7 days of ageing respectively. For other samples, the acidities fluctuate throughout the ageing duration at values less than 0.01 mg KOH/g as shown in Fig. 8 b).

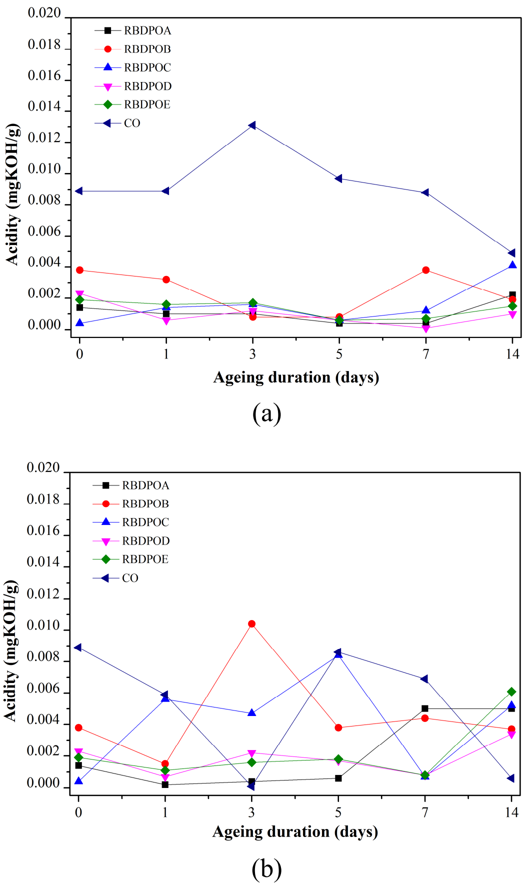


Fig. 8. Acidities of all samples at (a) 85 °C, (b) 115 °C

5. Ageing Performance of RBDPO and CO under Open Condition

Based on this study, it is found that the AC breakdown voltages of RBDPO and CO can still comply with the recommended limit for new, as-received vegetable oil suggested by ASTM D 6871 even after subjected to ageing [34]. The lowest AC breakdown voltages at both ageing temperatures for RBDPO and CO are 29.5 kV and 29.6 kV which are higher than the limit which is ≥ 20 kV at 1 mm gap distance [34]. For dielectric dissipation factors, only RBDPOC and RBDPOD are within the recommended limit suggested by IEC 62770 which is ≤ 0.05 at 90 °C. Most of other RBDPO samples exceed this value especially toward the end of the ageing duration. The dielectric dissipation factor of CO is much higher than the recommended limit of IEC 62770 throughout the ageing duration [35].

More importantly, it was found that under thermal ageing, the viscosities for RBDPO and CO under both ageing temperatures remain lower than the recommended limit suggested by ASTM D 6871 and IEC 62770, which is ≤ 50 mm^2/s at 40 °C [34, 35]. Acidities remain low where the highest values at both ageing temperatures for both RBDPO and CO are 0.0084 mg KOH/g and 0.0131 mg KOH/g respectively, which are well below the recommended limit of ≤ 0.06 mg KOH/g suggested by ASTM D 6871 and IEC 62770 [34, 35]. On the other hand, the highest moisture for RBDPO and CO throughout the ageing duration are 383 ppm and 301 ppm respectively which are slightly higher than the recommended limit suggested by ASTM D 6871 and IEC 62770 which is ≤ 200 ppm [34, 35].

It is also found that there are no significant differences on some of the dielectric, chemical and physical properties among the RBDPO. Only resistivity at ageing temperature of 85°C shows clear deviations among the RBDPO throughout the ageing duration. On the other hand, there are clear differences on the dielectric dissipation factor, relative permittivity, resistivity and viscosity between RBDPO and CO during the ageing duration. The difference of moisture for CO and RBDPO exist at 3 days and 5 days of ageing at temperature of 115 °C.

Oxygen is one of the main accelerators for oxidation of oil. Under current arrangement of accelerated thermal ageing, it is observed that the effect of oxidation is not significant on RBDPO and CO possibly due to the limited supply of oxygen resulted from the closure of the air valve at the back of the oven. This could be one of the reasons why there are no significant changes on some of the dielectric, physical and chemical properties of RBDPO and CO throughout the ageing duration. Further study will be carried out in the future to investigate the rate of oxidation of RBDPO and CO under different concentrations of oxygen and with the presence of copper and steel.

6. Conclusion

There is no significant effect of open ageing condition on the AC breakdown voltages of RBDPO and CO based on current arrangement of study. The dielectric dissipation factors of all RBDPO remain lower than CO throughout the ageing duration. There is a reduction trend of dielectric dissipation factor of CO especially at ageing temperature of 115 °C. The relative permittivities of both RBDPO and CO remain almost unchanged throughout the ageing duration. There are clear reduction trends of resistivities for all RBDPO especially at ageing temperature of 115 °C while the resistivity of CO remains lower than all RBDPO during the ageing duration.

In terms of physical and chemical properties, the viscosities of most of the RBDPO start to show slight changes after 3 and 5 days of ageing while the viscosity of CO remain almost unchanged throughout the ageing duration. There are no clear trends of moisture can be observed for both RBDPO and CO after subjected to ageing. In term of acidity, both of RBDPO and CO maintain at low values throughout the ageing duration and well below the suggested limit recommended in standards.

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