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Compatibility of transformer construction materials with mineral, natural ester, and synthetic ester insulating oils

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ABSTRACT

This paper presents the experimental findings on the compatibility of kraft paper strips and gasket materials (fluoroelastomer (FE) and nitrile butadiene rubber (NBR)) with mineral (MO), natural ester (NE), and synthetic ester (SE) insulating oils. First, three insulating oil samples were prepared, and kraft paper strips, pressboards, and FE and NBR gasket materials were immersed in the oils. Metal catalysts were added into the insulating oil samples to simulate the actual conditions of oil-immersed transformers. The samples were thermally aged at 130 °C for 400 h. The results show that the tensile strength of the kraft paper immersed in NE increased by 1.82%, while the tensile strength of the kraft paper immersed in MO and SE decreased by 6.23 and 0.80%, respectively. The Shore A hardness of FE thermally aged in MO and SE decreased by 2.64 and 11.16%, respectively. In contrast, the FE thermally aged in NE became slightly harder, with a percentage degradation of +1.62%. On the other hand, the NBR thermally aged in MO, NE, and SE drastically decreased by 94.30, 86.70, and 93.67%, respectively. Hence, it is concluded that NBR is incompatible with the insulating oils tested in this study. In contrast, FE is most compatible with NE, followed by MO and SE.

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1. INTRODUCTION

Transformers are the backbone of electrical energy distribution. To date, mineral oils (MOs) are the de facto standard for oil-immersed transformers. However, the use of insulating oils is shifting from MOs to vegetable-based oils, where much effort is being made to develop vegetable-based insulating oils. For example, insulating oils such as BIOTEMP®, VG-100®, MIDEL eN 1204, MIDEL eN 1215, Envirotemp™ FR3™, and palm fatty acid ester have been developed and are now commercially available. Other insulating oils are derived from coconut, rice bran, corn, *Jatropha curcas*, *Terminalia catappa*, palm kernel, palm olein, rapeseed, castor, sunflower, soybean, canola, peanut, and cottonseed oils, as well as used cooking oils [1].

Few studies have been carried out regarding the compatibility of vegetable-based insulating oils with transformer construction materials such as cellulose materials, gaskets, sealing materials, coating materials, polymeric materials, enameled copper windings, steel cores, and silver components of on-load tap changers that regulate the turns ratio of transformers [2], [3]. For instance, Qian *et al.* [4] performed an experimental study on the compatibility between hydrogenated and naphthenic insulating oils and transformer construction materials (rubber seals, paper insulation, and varnish). The results showed that the hydrogenated insulating oil had good compatibility with the transformer construction materials. Wilhelm *et al.* [5] evaluated the effect of kraft paper, varnish, steel core, and gasket materials (nitrile rubber and fluorosilicone rubber) on the physicochemical properties of natural esters (NEs) (soybean oil and corn oil) and MO heated at 100 °C for 716 h. The results revealed that nitrile rubber was more influenced by thermal ageing than fluorosilicone rubber. Mužík *et al.* [6] studied the compatibility of cable ties, rubber cork gasket, and part of transformer bushing with synthetic rapeseed oil and MO. The samples were thermally aged at 140 °C for 1,000 h. The results showed that the Shore A hardness of the rubber cork gasket immersed in synthetic rapeseed oil decreased whereas it increased for the rubber cork gasket immersed in MO. Pan *et al*. [7] studied the compatibility between transformer construction materials (four rubber-based gaskets, inner surface coating, steel sheet coating, and enamelled wire) with NE, synthetic ester (SE), and modified ester. The samples were thermally aged at 120 °C for 168 h. The results showed that NE had the least effect on the hardness of the rubber-based gaskets. Karambar and Tenbohlen [8] studied the compatibility of three different silicone rubbers with MO. The samples were thermally aged at 130 °C for 360, 720, and 1,080 h. The results revealed that the insulative silicone rubber exhibited good compatibility with MO compared with conductive silicone rubber and dual-layer (conductive and insulative) silicone rubber. Avila *et al.* [9] evaluated the compatibility of four different nitrile rubber seals with MO and NE. The samples were thermally aged at 100 ± 1 °C for 7 and 14 days. The nitrile rubber vulcanized with peroxide showed a lower increase in hardness compared with nitrile rubber vulcanized with sulphur.

Even though studies [4]-[9] have been carried out to investigate the compatibility of transformer construction materials with insulating oils, the materials were thermally aged in the absence of catalysts. The presence of metallic particles such as copper, aluminium, iron, and zinc from transformer components as well as moisture (which is present in the structure of kraft paper and pressboard) can act as catalysts, which will contribute to the ageing of the oil–paper insulation system. Hence, this study is conducted to investigate the compatibility between transformer construction materials (kraft paper strips and gasket materials) and three types of insulating oils (MO, NE, and SE) in the presence of four metal catalysts (copper, aluminium, iron, and zinc) subjected to accelerated thermal ageing test. It is believed that the findings of this study will be beneficial to scholars and industrial practitioners as they provide insight into the compatibility of transformer construction materials with MO, NE, and SE in the presence of metal catalysts, simulating the actual conditions of oil-immersed transformers.

2. MATERIALS AND METHODS

The insulating oils used in this study were MO, NE, and SE. Kraft paper strips and pressboards were used as the solid insulations. Viton® fluoroelastomer (FE) and nitrile butadiene rubber (NBR) sheets were selected as the gasket materials. Four metal catalysts were used in this study, namely, copper, aluminium, iron, and zinc. Nitrogen gas, which is a chemically inert gas with a purity of 99%, was used for the nitrogen bubbling treatment. The procedures of the accelerated thermal ageing test and measurements of the properties of the insulating oil samples (moisture content, acidity, AC breakdown voltage, polarisation index, relative content of dissolved decay products (relative DDP)) and measurements of the properties of the kraft paper strips (tensile strength) and gaskets materials (shore A hardness) are elaborated in detail in this section.

2.1. Preparation of the insulating oil and solid insulation samples

Three insulating oil samples were prepared in this study. Each sample consisted of insulating oil (MO, NE, or SE), kraft paper strips, pressboards, metal catalysts, and gasket materials (FE and NBR). The details of the samples are tabulated in Table 1.

Table 1. List of materials used to prepare the samples for the accelerated thermal ageing test

Sample	Insulating oil	Solid insulations	Metal catalysts	Gasket materials
1	MO	Kraft paper strips and pressboards	Copper, aluminum, iron, and zinc	FE
2	NE			and
3	SE			NBR

The volume of insulating oil for each sample was 500 mL. The insulating oils were first filtered and then subjected to nitrogen bubbling treatment to ensure that the moisture content of the insulating oils was below the permissible limits (≤35 mg/kg (MO) and ≤200 mg/kg (NE and SE)) [10]. The acidity and AC breakdown voltage of the transformer oils were measured to ensure that the acidity was ≤0.03 mg KOH/g (MO and SE) and ≤0.06 mg KOH/g (NE), and the AC breakdown voltage was ≥20 kV (permissible limit of the AC breakdown voltage for an electrode gap distance of 1 mm). These limits are specified in the ASTM D3487 [11], ASTM D6871 [12], and IEC 61099 [13] standards for MO, NE, and SE respectively.

The dimensions of the FE and NBR gasket materials were 8.5×25×0.3 cm. The kraft paper strips (dimensions: 28×2×0.075 cm) and pressboards (dimensions: 6×2.5×0.22 cm) were weighed to ensure that the solid insulations were 1:10 of the insulating oil mass. The weights of the copper, aluminium, iron, and zinc catalysts were fixed at 1.25, 0.25, 1.25, and 0.25 g respectively. After weighing, the kraft paper strips, pressboards, and metal catalysts were dried in a forced air ventilation oven at 105 °C for 12 h in accordance with the BS EN 60641 standard [14]. The drying process is essential to ensure that the weight of the kraft paper strips is 0.05 wt.% lower than their initial weight. Following this, the kraft paper strips, pressboards, metal catalysts, and gasket materials were immersed in the insulating oil samples for 24 h at room temperature prior to the accelerated thermal ageing test. The accelerated thermal ageing test was conducted using a laboratory oven set at 130 °C in the absence of air for 400 h [15]. After the thermal ageing process, the insulating oil samples were taken out from the oven and left at room temperature for 24 h before the properties of the insulating oils, kraft paper strips, and gasket materials were measured.

2.2. Measurements of the properties of the insulating oils, kraft paper strips, and gasket materials

The moisture content of the insulating oil samples was measured according to the ASTM D1533 standard [16] using Metrohm 899 coulometer for coulometric Karl Fischer titrations. The acidity of the insulating oil samples was measured according to the ASTM D664 standard [17] using Metrohm 848 Titrino plus compact titrator. The AC breakdown voltage of the insulating oil samples was determined using Megger OTS60PB portable oil tester in accordance with the ASTM D1816 standard [18]. The polarisation index of the insulating oil samples was calculated in accordance with the IEEE Std 43 standard [19]. The relative DDP of the thermally aged insulating oil samples was determined using an ultraviolet–visible (UV–VIS) spectrophotometer (Model: UV-1800, Shimadzu Corporation, Japan) [20]. The tensile strength of the kraft paper strips was determined by placing a kraft paper strip between the upper and lower clamps of a benchtop EI-1007E computerised servo-controlled universal testing machine. The upper clamp was then moved upward until the kraft paper strip ruptured and the tensile force required to rupture the kraft paper strip was simultaneously measured and recorded in accordance with the BS 4415-1 standard [21]. The Shore A hardness of the gasket materials was measured according to the ASTM D2240 standard using a durometer [22].

3. RESULTS AND DISCUSSION

After the insulating oil samples (MO, NE, and SE) were treated (i.e., filtered and subjected to nitrogen bubbling treatment), the moisture content, acidity, and AC breakdown voltage of the insulating oil samples were measured. Following this, three samples (Table 1) were prepared by immersing the dried kraft paper strips, pressboards, FE and NBR gasket materials, and metal catalysts into the treated MO, NE, and SE. All of the samples were then thermally aged at 130 °C for 400 h. After thermal ageing, the properties of the insulating oils (acidity, polarisation index, and relative DDP), tensile strength of the kraft paper strips, and Shore A hardness of the gasket materials were measured, and the results are presented and discussed in this section.

3.1. Properties of the insulating oils prior to accelerated thermal ageing test

The moisture content, acidity, and AC breakdown voltage of the insulating oils (Table 2) prior to accelerated thermal ageing test were found to comply with the permissible limits prescribed in the ASTM D3487, ASTM D6871, and IEC 61099 standards: moisture content ≤35 mg/kg (MO) and ≤200 mg/kg (NE and SE), acidity ≤0.03 mg KOH/g (MO) and ≤0.06 mg KOH/g (NE and SE), and AC breakdown voltage ≥20 kV for an electrode gap distance of 1 mm (MO, NE, and SE). Other properties of the insulating oils (polarisation index and relative DDP) prior to thermal ageing are also presented in Table 2.

Table 2. Properties of the treated insulating oil samples prior to accelerated thermal ageing test

Property	Unit	Insulating oil sample		
		MO	NE	SE
Moisture content	mg/kg	21	135	140
Acidity	mg KOH/g	0.0252	0.0600	0.0221
AC breakdown voltage	kV	37	31	52
Polarisation index	—	1.59	1.16	1.27
Relative DDP	—	0	0	0

3.2. Effect of thermal ageing on the acidity, polarisation index, and relative dissolved decay products of the insulating oils

The percentage degradation in the acidity, polarisation index, and relative DDP of the thermally aged MO, NE, and SE after accelerated thermal ageing test are tabulated Table 3. Initially, SE showed the lowest acidity (0.0221 mg KOH/g), followed by MO (0.0252 mg KOH/g) and NE (0.0600 mg KOH/g). After the thermal ageing process, the acidity of the insulating oil samples increased to 0.0341 mg KOH/g (MO), 0.0830 mg KOH/g (NE), and 0.2098 mg KOH/g (SE). The percentage degradation in acidity of the thermally aged insulating oil samples were −35.3% (MO), −38.8% (NE), and −849.0% (SE). The significant increase in the acidity of the thermally aged SE can be attributed to the occurrence of hydrolysis and pyrolisis reactions in the SE, which form long-chain or medium-chain fatty acids [7].

Table 3. Percentage degradation in acidity, polarisation index, and relative DDP of the thermally aged MO, NE, and SE

Insulating oil sample	Acidity (mg KOH/g)	Percentage degradation in acidity (%)	Polarisation index	*Percentage degradation in polarisation index (%)	Relative DDP	*Percentage degradation in relative DDP (%)
Thermally aged MO	0.0341	−35.3	1.07	−32.7	165.1	−165.1
Thermally aged NE	0.0830	−38.3	0.85	−26.7	112.8	−112.8
Thermally aged SE	0.2098	−849.0	0.98	−22.8	78.7	−78.7

*Percentage degradation in acidity, polarisation index, and relative DDP were determined relative to the acidity, polarisation index, and relative DDP of the MO, NE, and SE prior to accelerated thermal ageing test. The negative sign indicates a decrease.

Initially, MO showed the highest polarisation index (1.59), followed by SE (1.27) and NE (1.16). After the thermal ageing process, the polarisation index of the insulating oils decreased to 1.07 (MO), 0.98 (SE), and 0.85 (NE). A higher polarisation index indicates a better insulation state, whereas a lower polarisation index may indicate the presence of moisture, which can deteriorate the insulation system. It can be observed that after thermal ageing, MO still had the highest polarisation index, followed by SE and NE. However, the percentage degradation in polarisation index of the thermally aged insulating oil samples was 32.7% (MO), 22.8% (SE), and 26.7% (NE). The percentage degradation in polarisation index was most pronounced for MO, followed by NE and least of all, SE.

The relative DDP can be estimated from the numerical integration of the area below the absorbance curve measured using a UV–VIS spectrophotometer [23]. An insulating oil with a darkened colour contains more decay products (i.e., contaminants and suspended particles) as a result of thermal ageing [24]. New insulating oils essentially have a pale yellow, transparent appearance, resulting in a relative DDP of 0 for MO, NE, and SE [25]. After the thermal ageing process, the relative DDP of the thermally aged transformer insulating oil samples increased to 165.1 (MO), 112.8 (NE), and 78.7 (SE).

3.3. Effect of thermal ageing on the tensile strength of the kraft paper strips

Table 4 shows the percentage degradation in the tensile strength of the kraft paper strips immersed in MO (KP-MO), NE (KP-NE), and SE (KP-SE) after the accelerated thermal ageing test. Figure 1 shows the tensile strength of the kraft paper strips. The tensile strength of the original kraft paper strip (KP) was 91.00 MPa. After 400 h of thermal ageing, the tensile strength of the KP-MO and KP-SE decreased to 85.33 MPa (−6.23%) and 90.27 MPa (−0.80%). In contrast, the tensile strength of the KP-NE increased to 92.66 MPa (1.82%). The kraft paper strip impregnated with insulating oil will be drier if the insulating oil absorbs more moisture. In other words, the condition of the kraft paper strip is dependent on the moisture saturation point of the insulating oil. An insulating oil with a higher moisture saturation point is capable of absorbing more moisture, which prevents the kraft paper strip from hydrolytic degradation, thus preserving its tensile strength. The results indicate that NE had the highest moisture saturation point, followed by SE and MO.

Table 4. Percentage degradation in tensile strength of the thermally aged kraft paper strips

Kraft paper strip	Tensile strength of the kraft paper strip (MPa)	* Percentage degradation in tensile strength of the kraft paper strip (%)
KP	91.00	—
KP-MO	85.33	−6.23
KP-NE	92.66	+1.82
KP-SE	90.27	−0.80

*Percentage degradation in tensile strength was determined relative to the tensile strength of the original kraft paper strip. A positive sign indicates an increase whereas a negative sign indicates a decrease.

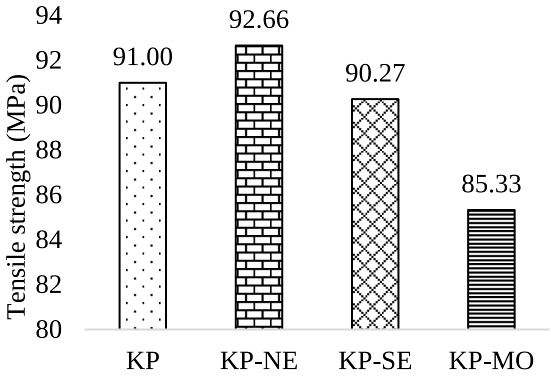

Figure 1. Tensile strength of the kraft paper strips

3.4. Effect of thermal ageing on the Shore A hardness of the gasket materials

Table 5 shows the percentage degradation in the Shore A hardness of the FE and NBR gasket materials immersed in MO, NE, and SE after accelerated thermal aging test. Figures 2 and 3 show the Shore A hardness of the gasket materials (FE and NBR) investigated in this study. The Shore A hardness of the FE and NBR were initially 82.17 and 79.00, respectively. After 400 h of thermal ageing, the Shore A hardness of the FE immersed in MO (FE-MO) slightly decreased to 80.00 (−2.64%) whereas the FE immersed in NE (FE-NE) slightly increased to 83.50 (+1.62%). The FE immersed in SE (FE-SE) decreased to 73.00 (−11.16%). Based on the results, the FE-NE became slightly harder compared with its initial condition. This is favourable because a harder gasket material helps in preventing oil leakage in transformers [6], [7]. In contrast, the Shore A hardness of the NBR significantly decreased after 400 h of thermal ageing, regardless of the insulating oil sample. The Shore A hardness of the NBR immersed in MO (NBR-MO) drastically decreased to 4.50 (−94.3%) and likewise, the NBR immersed in SE (NBR-SE) significantly decreased to 5.00 (−93.67%). The Shore A hardness of the NBR immersed in NE (NBR-NE) decreased to 10.50 (−86.7%), indicating that the reduction in Shore A hardness of this sample is not as marked as those of NBR-MO and NBR-SE. Nevertheless, NBR was incompatible with all of the insulating oils investigated in this study. On the other hand, NE was most compatible with FE, followed by MO and SE.

Table 5. Percentage degradation of the thermally aged FE and NBR gasket materials

Insulating oil sample	Shore A hardness of FE	* Percentage degradation in Shore A hardness of FE (%)	Shore A hardness of NBR	* Percentage degradation in Shore A hardness of NBR (%)
—	82.17	—	79.00	—
Thermally aged MO	80.00	−2.64	4.50	−94.3
Thermally aged NE	83.50	+1.62	10.50	−86.7
Thermally aged SE	73.00	−11.16	5.00	−93.67

* Percentage degradation in the Shore A hardness of FE and NBR gasket materials were determined relative to the Shore A hardness of the gasket materials prior to accelerated thermal ageing test. A positive sign indicates an increase whereas a negative sign indicates a decrease.

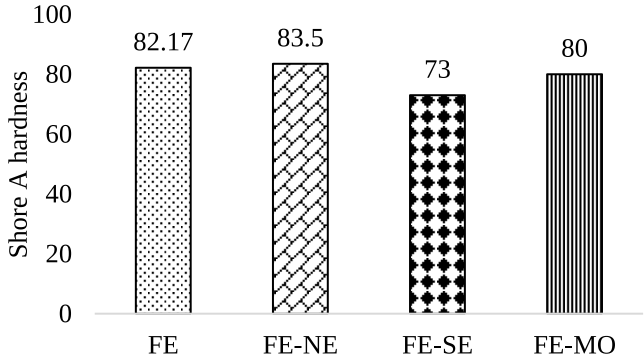

Figure 2. Shore A hardness of the FE gasket materials

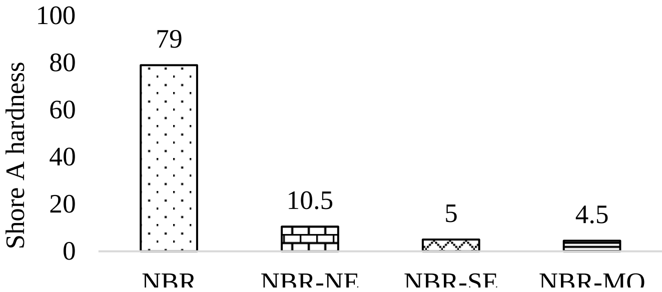

Figure 3. Shore A hardness of the NBR gasket materials

4. CONCLUSION

In this study, the compatibility of transformer construction materials (kraft paper strips and FE and NBR gasket materials) with MO, NE, and SE was investigated. Three insulating oil samples were prepared, where the kraft paper strips, pressboards, and FE and NBR gasket materials were immersed in MO, NE, and SE. Copper, aluminium, iron, and zinc metal catalysts were also added into the insulating oil samples to simulate the actual conditions of oil-immersed transformers. The samples were then subjected to accelerated thermal ageing test at 130 °C for 400 h. After the accelerated thermal ageing test, the acidity, polarisation index, and relative DDP of the insulating oil samples, tensile strength of the kraft paper strips, and shore A hardness of the FE and NBR gasket materials were measured. Based on the experimental results, it is concluded that NE is superior in preserving the tensile strength of the kraft paper strip, followed by MO and SE. In addition, NE is most compatible with FE, followed by MO and SE. NBR is found to be incompatible with all of the insulating oil samples investigated in this study, where the oils result in a significant decrease in Shore A hardness of the NBR.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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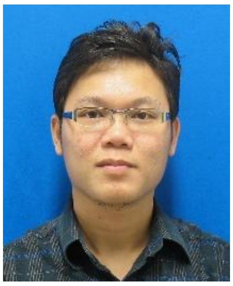

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