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Temporal Effects of Thermal Stresses on Solid Dielectric Materials under Diverse Voltage Conditions

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Abstract- **Dielectric materials are an essential part of the power system and their healthy condition is necessary for the stable system operation. Thermal stresses occurring due to faults have adverse effects on the life of insulating materials. To assess the effects of thermal stresses on the life of solid dielectric materials, this work attempts to investigate the effects of thermal stresses on their various parameters such as dielectric strength, thermal conductivity, breakdown time, etc. Effects on these parameters are assessed at different temperatures and times using constant and variable alternating current voltage sources. Simulations are performed in COMSOL Multiphysics 5.6. It was found that high temperature due to thermal stresses affects polymer structure, density, length, thermal conductivity, and breakdown strength of insulating materials. Results show that thermal conductivity increases by increasing time and temperature. Results of the study can be valuable for power system operators for the life assessment of field insulators.**

Index Terms-- **breakdown strength; thermal stress; thermal conductivity; solid insulator.**

I. INTRODUCTION

Insulating materials play a vital role in electrical networks for handling electricity without causing any risk. When electric current passes through the conductors then its insulation becomes weak after some time [1, 2]. This deterioration is due to heat generated by flowing currents. In [3] author studied about the pressure affecting the thermal conductivity of insulating material. Therefore, knowledge of the thermal properties of insulating materials is essential. Polyvinyl chloride (PVC) is the most commonly used insulation material. Its morphology, stable molecular structure, inflammability, easy manufacturing at low cost makes it viable in the electrical system and its production touches 16 million ton per annum in the global synthetic polymer consumption [4, 5]. Like PVC, other insulating materials having vast usage scope are rubber and oil-impregnated paper (OIP). One of the first insulation material used for high voltage systems is paper [6].

The natural rubber has good electrical and mechanical properties but it possesses low thermal conductivity which limits its adoption for power applications [7, 8]. Therefore, most of the work available in the literature was aimed to increase its thermal conductivity, which also helps understand the behavior of the material at different temperatures.

Likewise, the breakdown voltage is another important factor for high voltage insulating material. Authors of [9] studied the thermal, electrical and chemical properties of OIP. Moreover, the effects of thickness and immersion time on the breakdown strength were also studied. Authors of [10] calculated the thermal conductivity of PVC for the tropical zone. In [11] author studied about the thermal properties of scrap rubber-sand composite properties as it behaves as insulating material. In [12], A. Chepurnenko et al. studied the non-stationary thermal conductivity of PVC cable having a single core and applied finite element analysis for problem-solving. In [13], authors prepared a blend of natural rubber (NR) and aluminum oxide and attempted to modify its properties with dopamine.

The main contributions of this work are as follows:

- It studies the thermal conductivity of solid dielectric materials at diverse temperature conditions.
- A broad range of materials has been investigated such as PVC, rubber, and OIP.
- It assesses the breakdown voltage of the materials under the various temporal conditions with constant and variable AC voltage sources.

II. CASE STUDY

Thermal conductivity is defined as the rate of heat transfer when the temperature difference occurs at the ends of any material. This work is aimed to investigate the thermal conductivity after the breakdown of materials at constant and variable AC voltage sources [14, 15]. Thermal conductivity and breakdown of PVC, rubber, and OIP are found by simulation in COMSOL Multiphysics 5.6. For constant AC voltage, 22 kV is selected while breakdown for variable AC voltage is found by iterative method built-in in COMSOL. During simulation, the materials are baked in an oven at five different temperatures for three different time spans and then their breakdown strength and the breakdown time are noted for constant and variable voltage sources. The thermal conductivity K , and thickness X is given by (1).|

$$K=[(MCX*\frac{dT}{dt})/A(T_1-T_2)] \quad (1)$$

Here dT/dt= cooling rate of the steel disc at T_2 and A = Area of the sample in contact with the steel disc. $T_1 - T_2$ Is equal to the temperature difference across the sample, M is the mass of steel disc and C represents the specific heat capacity of the steel disc.

III. RESULTS AND DISCUSSION

A. PVC

PVC pertaining to three different timelines, and the noticeable difference shows us the change in the properties of the material as it is heated up further and further. The breakdown of the material happens faster with deteriorated properties. In Table I, the values are obtained interchangeably for 24, 48, 72 h spans. Hence the effects demonstrate the overall performance of the material when it is placed in the oven.

As temperature increases, both the number of free electrons and lattice vibrations increase. Thus, the thermal conductivity of the metal is expected to increase. From Table I it is clear that the coefficient of expansion (α) of PVC goes on increasing by increasing temperature. While its length increases but polymer chain becomes shorter. PVC is heated then the elasticity goes on increasing. Figure 1 shows that thermal conductivity increases from 0.16 $(Wm^{-1}k^{-1})$ to 0.2$(Wm^{-1}k^{-1})$. Figure 4 shows that its breakdown time decreases from 6 h to 4 h as material becomes weaker upon heating.

Similarly, as mentioned in Table I, When the time span of 48 h and baked at 45, 50, 60, 70 and 90C Its breakdown strength goes on decreasing from 4 h to 3 h. Figure 1 shows that thermal conductivity changes from 0.2 $(Wm^{-1}k^{-1})$ to 0.26 $(Wm^{-1}k^{-1})$. From Table I, it is clear that when the time span of 72 h at the above-mentioned temperatures and baked it. Figure 1 shows that its thermal conductivity changes from 0.27 $(Wm^{-1}k^{-1})$ to 0.28$(Wm^{-1}k^{-1})$.

If the voltage applied across a piece of the insulator is increased, at a certain electric field the number of charge carriers in the material suddenly increases enormously and its resistivity drops, causing a strong current to flow through it. This is called electrical breakdown. Let us study the behavior of insulator PVC samples under varying voltage to study the effect on breakdown strength, breakdown time. Figure 7 shows that in the case of a variable voltage source, all the above mentioned factors remain but its breakdown time changes from 2 min to 40 s, and its breakdown voltages change from 27.8 kV to 16.4 kV for 24h at above mentioned temperatures. For 48 h, breakdown time changes from 1 min to 40 s, and breakdown voltage changes from 16 kV to 10 kV. For 72 h, the breakdown time changes from 35 s to 25 s, and its breakdown voltage changes from 10 kV to 5 kV except at the beginning of a sentence.

B. Rubber

From Table II, Rubber does not behave like other substances when warm, it would not expand. However, because of the arrangement of the rubber molecules, unlike most materials, it shrinks when you heat it and expands when you cool it. When cold, rubber typically becomes brittle and less fragile, whereas heat causes it to become sticky. If the rubber is presented in a high-temperature environment, then the long chains of polymer shorten cause the rubber to contract. While in a low-temperature environment, rubber can expand. Rubber shows quite different behavior as compared to PVC when subjected to heat or baked in an oven. For 24 h by increasing temperature from 45 to 90C, the elasticity, density, and coefficient of expansion (ε) of rubber decreases. The length of rubber materials decreases and its polymer structure shortens. Figure 2 shows that the thermal conductivity of the material remains 0.5$(Wm^{-1}k^{-1})$, which shows there is no remarkable effect on it. Figure 5 shows that the breakdown time of rubber materials decreases from 6 h to 3 h at 22 kV. When rubber is subjected to heat for 48h at above mentioned temperatures. Breakdown time of material changes from 4 h to 3 h at 22 kV. Figure 2 shows that the thermal conductivity of rubber changes from 0.5$(Wm^{-1}k^{-1})$ to 0.52$(Wm^{-1}k^{-1})$. When rubber is subjected to heat environment for 72 h, Figure 2 shows that thermal conductivity remains the same 0.6 $(Wm^{-1}k^{-1})$, which shows that rubber is sustainable to heat. Figure 5 shows that its breakdown time changes from 3 h to 2 h at 22 kV.

From Figure 8, for the variable voltage source, all the factors remain the same only breakdown time and voltage changes. For 24 h, in above mentioned temperature ranges. Breakdown time changes from 2 min to 1.5 min while its breakdown voltage changes from 37.4 kV to 25.5 kV. For 48 h, the breakdown time changes from 1.5 min to 20 s while its breakdown voltage changes from 25.5 kV to 17.5 kV. For 72 h, the breakdown time changes from 1 min to 15 s while its breakdown voltage changes from 15 kV to 11.3 kV.

C. OIP

In capacitors, many times paper is used as a dielectric. Being porous, it contains air and moisture which must be removed and replaced by a fluid with good dielectric properties. Air and moisture are removed under a high temperature of above 1000 C, and then an oil/jelly/ wax is introduced (depending upon the type of capacitor and requirements). This is the process of impregnation. It is also used in transformers and cables as an insulating material. The composite dielectric combines properties of the impregnation medium and paper to give an “impregnated paper capacitor “. As the paper is a different type of material from PVC and rubber, so it has different factors to explain its properties after heating.

From Table III, for 24 h when OIP is subjected to heat at above-mentioned temperatures, then surface resistivity and volume resistivity decreases. While its dielectric loss remains constant at 45C and decreases at 45, 50, 60, 70 and 90C. Figure 3 shows that thermal conductivity of OIP 0.46, .0.5($Wm^{-1}k^{-1}$). Figure 8 shows that breakdown time vary from 2h to 1.5h at 22kV.

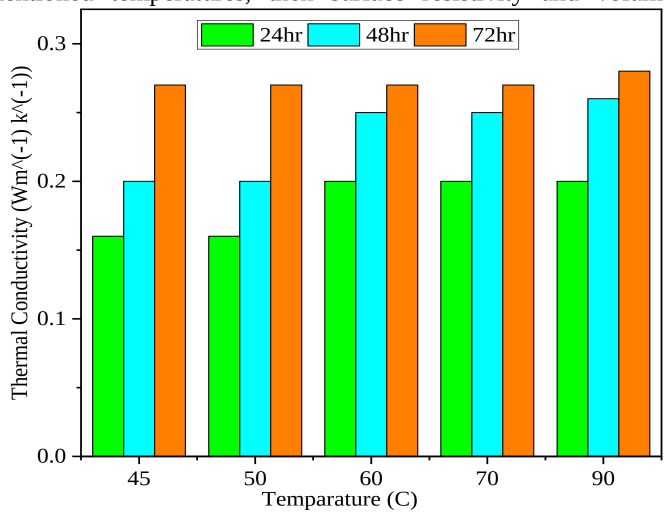

Figure 1. PVC Thermal Conductivity

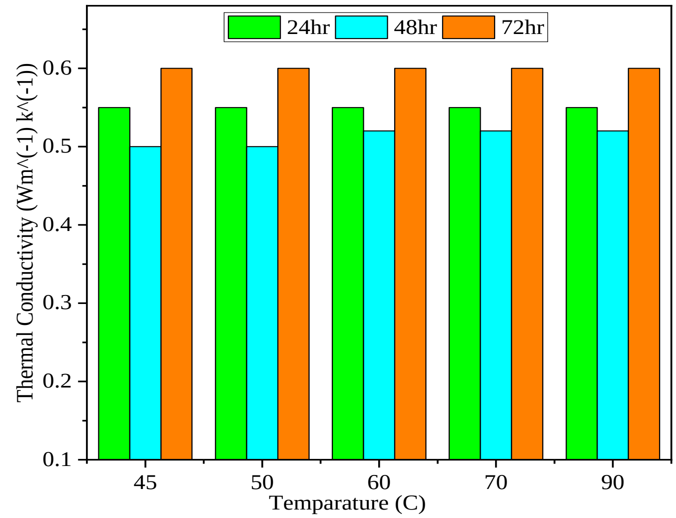

Figure 2. Rubber Thermal Conductivity

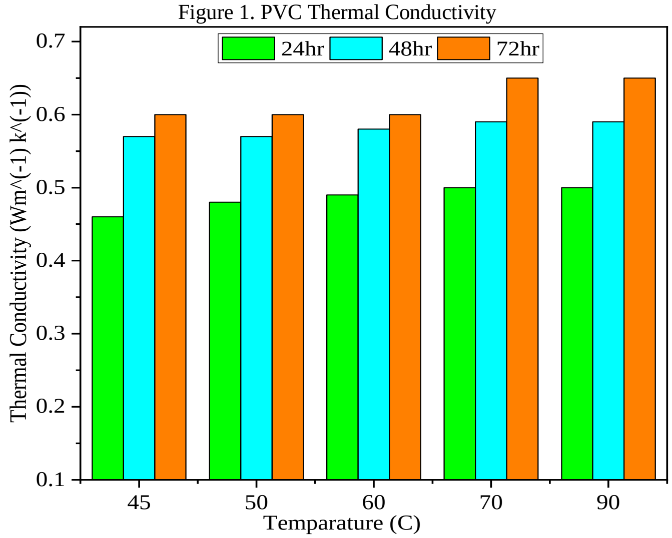

Figure 3. OIP Thermal Conductivity

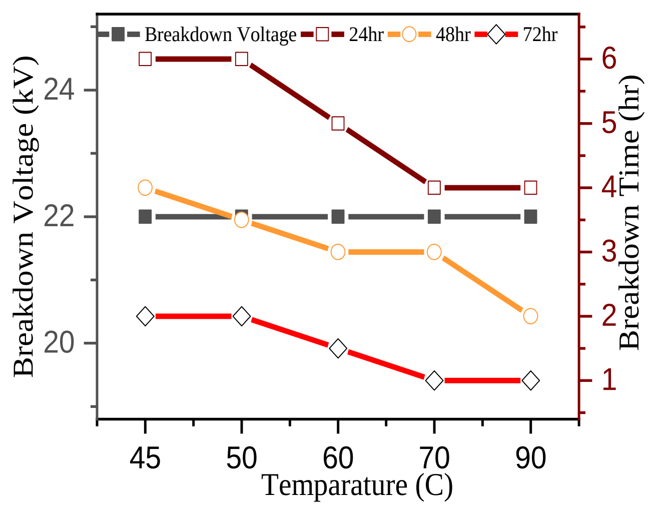

Figure 4. PVC Breakdown at constant voltage

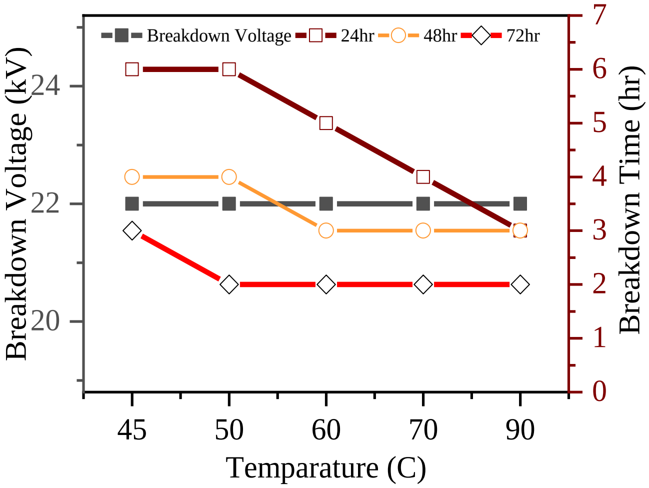

Figure 5. Rubber Breakdown at constant voltage

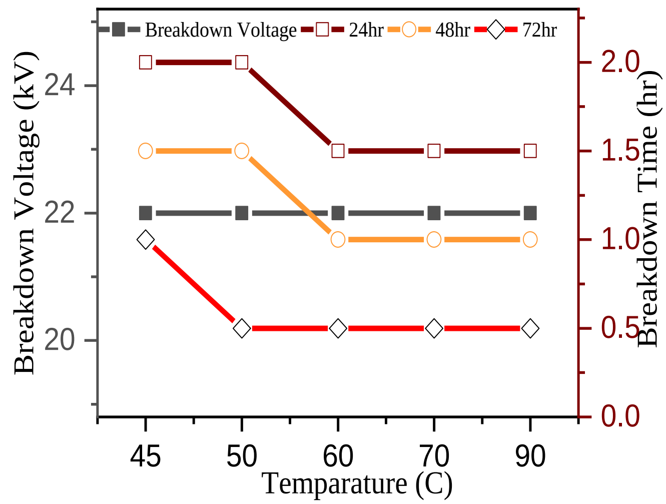

Figure 6. OIP Breakdown at constant voltage

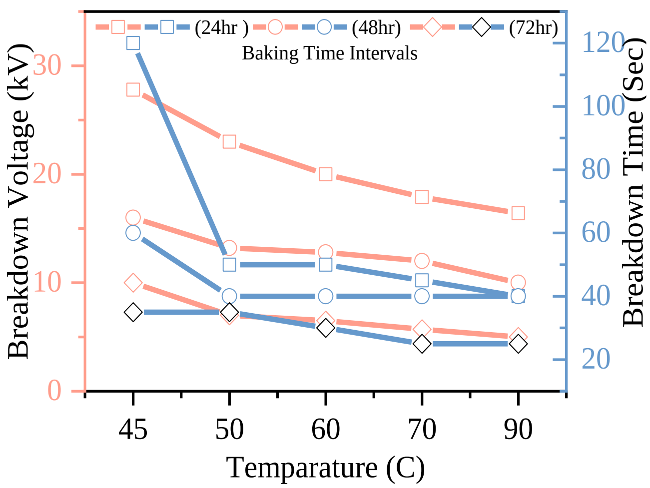

Figure 7. PVC Breakdown at variable voltage

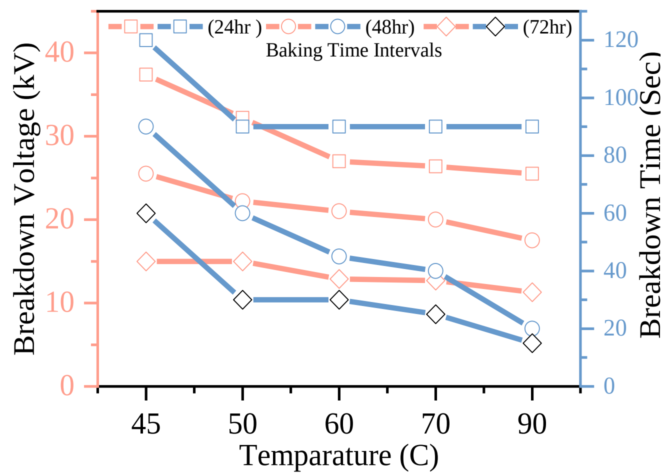

Figure 8. Rubber Breakdown at variable voltage

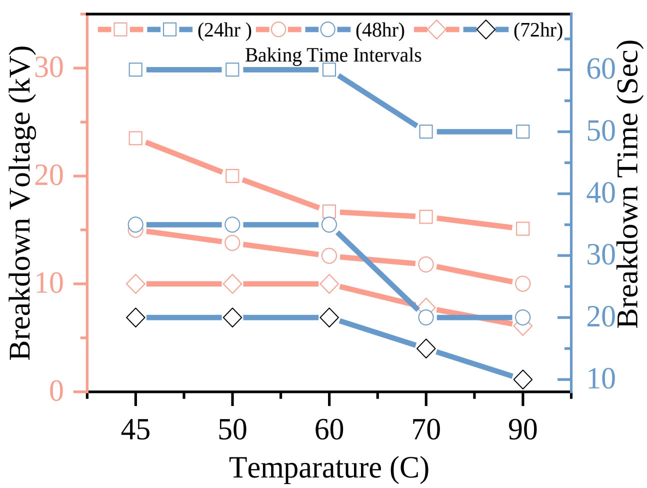

Figure 9. OIP Breakdown at variable voltage

Table I. Results of different parameters for PVC

Parameter	45C	50C	60C	70C	90C

	24	48	72	24	48	72	24	48	72	24	48	72	24	48	72
α	0.25	0.44	0.77	0.32	0.48	0.8	0.33	0.48	1	0.36	0.59	1.3	0.39	0.63	1.32
ΔL	Inc.	Inc.	Inc.	Inc.	Inc.	Inc.	Inc.	Inc.	Inc.	Inc.	Inc.	Inc.	`Inc.	Inc.	Inc.
Polymer Chain	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.
ε (M Pa)	800	1200	2000	950	1400	2050	1100	1400	2050	1200	1800	2100	1300	1820	2300
ρ	Les.	Les.	Les.	Les.	Les.	Les.	Les.	Les.	Les.	Les.	Les.	Les.	Les.	Les.	Les.

Where Inc. =Increase, Shrt. =Shorten, and Les. =Lessen, Expansion Coefficient=α, Change in Length=ΔL, Elasticity= ε

Table II. Results of different parameters for Rubber

Parameter	45C			50C			60C			70C			90C		
	24	48	72	24	48	72	24	48	72	24	48	72	24	48	72
α	5.7	4.4	3.7	5.4	4.3	3.4	5.3	4.2	3.3	4.7	4.0	2.7	4.5	3.6	2.5
ΔL	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.
Polymer Chain	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.	Shrt.
ε (M Pa)	10	5	6.2	8.2	4.8	6.1	8.0	4.6	5.7	7	4.7	5.65	6	4.4	5.4
ρ	70	61	40	65	55	33.4	63	47	33.2	63	44	30	60	42	28

Where Inc.=Increase, Shrt.=Shorten, and Les.=Lessen, Expansion Coefficient=α, Change in Length=ΔL, Elasticity= ε

Table III. Results of different parameters for OIP

Parameter	45C			50C			60C			70C			90C		
	24	48	72	24	48	72	24	48	72	24	48	72	24	48	72
Surface Resistivity	1.7	1.1	.5	1.5	1.0	.5	1.4	.8	.4	1.23	.8	0.4	1.1	.7	.4
Volume Resistivity	4.3	3.75	3.6	4.2	3.74	3.6	4.2	3.74	3.5	4.0	3.74	3.2	3.5	3.54	2.8
Dielectric Loss	Con.	Con.	Con.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.	Dec.

Where Con. =Constant, and Dec. =Decrease

For 48 h, Fig. 6 shows that thermal conductivity changes from 0.57 to 0.59$(Wm^{-1}k^{-1})$ and Fig. 6 show that its breakdown Time changes from 1.5 h to 1 h at 22 kV. For 72 h, Fig. 3 shows that thermal conductivity changes from 0.6$(Wm^{-1}k^{-1})$ to 0.65$(Wm^{-1}k^{-1})$. Figure 6 shows that breakdown time changes from 1 h to 0.5 h at 22 kV.

From Fig. 9, for the variable voltage source, all factors remain the same only breakdown time and voltage changes. For 24 h, the breakdown time changes from 1 min to 50 s, and its breakdown voltage changes from 23.5 kV to 15.1 kV. For 48 h, the breakdown time changes from 35 s to 20 s, and breakdown voltages change from 15 kV to 10 kV. For 72 h, the breakdown time changes from 20 s to 10 s while its breakdown voltage changes from 10 kV to 6.1 kV.

For 48 h, the breakdown time changes from 35 s to 20 s, and breakdown voltages change from 15 kV to 10 kV. For 72 h, the breakdown time changes from 20 s to 10 s while its breakdown voltage changes from 10 kV to 6.1 kV.

IV. CONCLUSION

The proposed work focused on electrical and physical properties of dielectric materials like PVC, Rubber, and OIP under thermal stresses for various temporal and voltage conditions. The obtained results shows that for 24h at 45^{0}C, 50^{0}C, 60^{0}C, 70^{0}C and 90^{0}C, thermal conductivity changes to 25% for PVC and 8.6% for OIP. The results for 48h at45^{0}C, 50^{0}C, 60^{0}C, 70^{0}C and 90^{0}C, thermal conductivity changes 30% for PVC, 4% for rubber and 3.5% for OIP. Furthermore, for 72h it also have increasing trend. The Thermal conductivity of PVC, Rubber, and OIP increases by increasing temperatures and time, thereby increasing leakage currents in the dielectric materials due to thermal stresses. The thermal conductivity of rubber is less affected as compared to PVC and OIP. The breakdown time of insulating materials at constant voltage source (22KV) decreases as their life is effected by temperature. The breakdown time for 24h changes 33.33% for PVC, 50% for rubber and 25% for OIP. The breakdown time for 48h changes 50% for PVC, 25% for rubber and 33.33% for OIP. The breakdown time at 72h changes 50% for PVC, 33.33% for rubber and 50% for OIP. The breakdown time of the dielectric materials for constant voltage application is more than in case of variable voltage source while in case of variable voltage source, the breakdown voltage and breakdown time have decreasing trend. In the case of PVC and rubber, polymer structures are weakened which deteriorates the physical properties of the materials.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

[1] C. Leung, J. Staggs, J. Brindley, A. C. McIntosh, and R. Whiteley, "The effects of an inert central core on the thermal pyrolysis of an electrical cable," *Fire safety journal*, vol. 34, no. 2, pp. 143-168, 2000.

[2] G. L. Moses, "The purpose of electrical insulation," in *1960 EI National Conference on the Application of Electrical Insulation*, 1960: IEEE, pp. 112-114.

[3] Y. Zhou, Z.-Y. Dong, W.-P. Hsieh, A. F. Goncharov, and X.-J. Chen, "Thermal conductivity of materials under pressure," *Nature Reviews Physics*, pp. 1-17, 2022.

[4] K. Aouachria and N. Belhaneche-Bensemra, "Thermo-oxidative dehydrochlorination of rigid and plasticised poly (vinyl chloride)/poly (methyl methacrylate) blends," *Polymer degradation and stability*, vol. 91, no. 3, pp. 504-511, 2006.

[5] A. Hassan and B. Haworth, "Impact properties of acrylate rubber-modified PVC: Influence of temperature," *Journal of Materials Processing Technology,* vol. 172, no. 3, pp. 341-345, 2006.
[6] T. A. Prevost and T. Oommen, "Cellulose insulation in oil-filled power transformers: Part I-history and development," *IEEE electrical insulation magazine,* vol. 22, no. 1, pp. 28-35, 2006.
[7] S. Cheng, X. Duan, Z. Zhang, D. An, G. Zhao, and Y. Liu, "Preparation of a natural rubber with high thermal conductivity, low heat generation and strong interfacial interaction by using NS-modified graphene oxide," *Journal of Materials Science,* vol. 56, no. 5, pp. 4034-4050, 2021.
[8] J. Li *et al.*, "Advanced flexible rGO-BN natural rubber films with high thermal conductivity for improved thermal management capability," *Carbon,* vol. 162, pp. 46-55, 2020.
[9] L. S. Nasrat, N. Kassem, and N. Shukry, "Aging effect on characteristics of oil impregnated insulation paper for power transformers," 2013.
[10] E. B. Ettah, J. G. Egbe, S. A. Takim, U. P. Akpan, and E. B. Oyom, "Investigation of the thermal conductivity of polyvinyl chloride (pvc) ceiling material produced in Epz Calabar, for application tropical climate zones," *J. Polym. Text. Eng,* vol. 3, no. 2, pp. 34-38, 2016.
[11] Y.-L. Yang, T. Zhang, K. R. Reddy, J.-S. Li, and S.-y. Liu, "Thermal conductivity of scrap tire rubber-sand composite as insulating material: Experimental investigation and predictive modeling," *Construction and Building Materials,* vol. 332, p. 127387, 2022.
[12] A. Chepurnenko, S. Yazyev, and A. Evtushenko, "Non-Stationary temperature field modeling in electric cable with PVC insulatio," in *2017 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*, 2017: IEEE, pp. 1-4.
[13] C. Zhuang *et al.*, "Enhanced thermal conductivity and mechanical properties of natural rubber-based composites co-incorporated with surface treated alumina and reduced graphene oxide," *Diamond and Related Materials,* vol. 116, p. 108438, 2021.
[14] D. E. Njeumen Nkayem, A. Alegria, S. Arrese-Igor, and N. J. Nkengafac, "Rheological and thermal properties of purified raw natural rubber," *Journal of Rubber Research,* pp. 1-9, 2021.
[15] F. N. Gesa, R. Atser, and S. Aondoakaa, "Investigation of the thermal insulation properties of selected ceiling materials used in Makurdi Metropolis (Benue State-Nigeria)," *Am. J. Eng. Res,* vol. 3, no. 11, pp. 245-250, 2014.