





# Thermal, tribological, and mechanical performance of nano- $\text{Al}_2\text{O}_3$ reinforced silicone rubber for high-temperature sealing applications

Zahraa Kadhum Rodhan<sup>1</sup>, Raed Salman Saeed<sup>1</sup>,  
Bashar Dheyaa Hussein Al-Kasob<sup>1</sup>, Alaa Shaker Obaida<sup>1\*</sup>

<sup>1</sup> Babylon Technical Institute, Al-Furat Al-Awsat Technical University, 54003 Najaf, Iraq

\* Corresponding author's e-mail: [alaa.obaida.iba12@atu.edu.iq](mailto:alaa.obaida.iba12@atu.edu.iq)

## ABSTRACT

When it comes to using silicone rubber for insulation and leakage applications in high-temperature environments, its chemical resistance and thermal stability are a major benefit, but unfortunately, its low thermal conductivity and wear resistance don't make it practical for engine applications. It's also susceptible to damage from oil, so the goal of this study was to find a way to strengthen silicone rubber for such uses. Silicone rubber composites were made by adding aluminum oxide nanoparticles ( $\text{Al}_2\text{O}_3$ ) to various loadings (0,1,3,5,7) parts per hundred rubber. The samples that were prepared were assessed on thermal conductivity, wear resistance amid dry and oil-greased circumstances, conduct of oil swelling, and compressibility. These findings revealed that the incorporation of  $\text{Al}_2\text{O}_3$  nanoparticles enhanced the thermal conductivity and wear resistance of silicone rubber to a large degree and oil swelling as well as compressibility was decreased. The composition with 5 pphr of the  $\text{Al}_2\text{O}_3$  was the most balanced in terms of thermal conductivity and wear resistance and resistance to oil. These results will show that  $\text{Al}_2\text{O}_3$  fortified silicone rubber reinforced materials have good prospects to be used in high temperature sealing application like automotive engine gaskets.

**Keywords:** silicone rubber, aluminum oxide nanoparticles, thermal conductivity, tribology, wear resistance, oil swelling resistance.

## INTRODUCTION

One of the common uses of silicone rubber (SR) is for insulating high-voltage power transmission lines due to its good mechanical and electrical properties [1,2]. Its high thermal stability also makes it an attractive insulation material for aircraft. Inorganic fillers, such as nano- $\text{BaTiO}_3$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{ZnO}$ , etc., are widely added to silicone rubber to improve its toughness, heat resistance, corrosion resistance, and electrical properties [3, 4]. However, because of the high surface energy of nanoparticles, the dispersion of nanoparticles in the polymer is poor, making it easy to generate agglomeration, reducing the overall insulating performance of the material [5,6]. A dielectric elastomer, silicone

rubber (SR) is frequently used as a matrix to create composite materials. SR may typically be employed in sealing applications because of its strong breakdown strength and low stiffness. The silicone rubber is combined with various micro- or nanoparticles (ceramic particles, conductive particles, or highly polarizable polymers) to be employed in various applications. [7,8]. This helps the silicon rubber-based composite's dielectric constant shift, which makes it suitable for devices like actuators or elastic and flexible charge storage. The majority of current research focuses on the thermal conductivity [9,10] or dielectric characteristics of silicone rubber composites reinforced with Al particles,  $\text{Al}_2\text{O}_3$ , particles [11], or  $\text{TiO}_2$  particles [12]. These investigations demonstrate that due

to their high dielectric permittivity or heat conductivity and strong elasticity, these composites may find usage in electromechanical actuators [13,14]. There are few studies in the literature that determine the electrical conductivity ( $\sigma$ ) or dielectric permittivity ( $\epsilon$ ) of composites composed of silicone rubber and Al particles, as well as experimental research on how both ( $\sigma$ ) and ( $\epsilon$ ) depend on the volume fraction of Al particles dispersed in silicone rubber [15,16].

Silicone rubber is widely used because of its exceptional flexibility, chemical stability, and durability to high temperatures, making it a good material of choice for automotive and electronic devices. Yet, because it has very low thermal conductivity and limited oil resistance, its potential effectiveness in high heat or lubricant-enriched applications (engine parts or thermal interface materials) is limited. Nanoscale aluminum oxide (nano- $\text{Al}_2\text{O}_3$ ), particulate materials have increasingly been applied to bypass these difficulties. Due to the excellent surface activity, chemical inertness, and good thermal conductivity of nano- $\text{Al}_2\text{O}_3$ , it can also improve the dimensional stability, wear resistance, and heat transfer of silicone rubber composites. To enable new silicone-based materials in mechanical sealing and thermal management, it is essential to investigate the influence of nano- $\text{Al}_2\text{O}_3$  concentration to improve the tribological characteristics, swelling behavior, and thermal interface resistance. Ouyang et al. [17] reported that adding  $\text{Al}_2\text{O}_3$  nanoparticles to silicone rubber increased the heat conductivity without much impact on electrical insulation. Increasing the concentration of  $\text{Al}_2\text{O}_3$  significantly improved Kim et al. [18] changed the surface of  $\text{Al}_2\text{O}_3$  particles using silane and glued them to a silicon matrix to decrease thermal interface resistance (RTH). Abdelsalam et al [19] the effect of  $\text{Al}_2\text{O}_3$  treatment with  $\gamma$ -APS on the mechanical properties and swelling behavior of rubber was investigated. The surface treatment reduced oil absorption (swelling) and improved bonding between the filler and the matrix. The resulting surface treatment improved dispersion within the rubber and significantly reduced RTH.

When discussing enhancing the performance of silicone rubber, researchers have been looking to add nano-aluminum oxide,  $\text{Al}_2\text{O}_3$ , as a supporting material and to determine its potential to create customized mechanical, thermal and abrasion resistance in the material.

## EXPERIMENTAL PART

### Materials and methods

A polymer matrix of VMQ-type silicone was used, which is a polydimethylsiloxane, or PDMS, coming straight from the German company Wacker Chemie, when developing silicone rubber compounds. PDMS is known for its thermal stability that goes up to 250 degrees Celsius, resistance to chemicals, flexibility and top-notch electrical insulation qualities making it basically the ideal choice for high-temperature sealing applications, Well-known for their thermal conductivity and stability, yet retaining their elasticity, aluminum oxide nanoparticles were added to the silicone rubber mixture. The 20-50 nanometer sized particles that are nearly 100% pure (supplied by Sigma-Aldrich in the USA) were included at anywhere from 0 to 7 parts per hundred rubbers, which is the ratio of nanoparticles to the rest of the compound. A silane coupling agent, 3-aminopropyl tert-ethoxysilane, was also used to ensure that the nanoparticles distribute well within the silicone matrix and stick firmly to it. chains, improving compatibility between filler and matrix. A mixture of 5% dimethyl silicone oil (Dow Corning, USA) with a viscosity of 100 cSt was used to act as a plasticizer, when creating the nanocomposites. This gave a nice balance between workability and compound stability, and also helped ensure the uniform distribution of the nanoparticles. Zinc oxide, with its ~99% purity, from Merck, Germany, was used as a vulcanization catalyst to improve the thermal stability of the curing process. Thermal cross-linking was achieved using dicumyl peroxide (DCP, AkzoNobel, Netherlands), which decomposes at elevated temperatures to generate free radicals that initiate crosslinking reactions within the silicone network. To limit thermal and oxidative degradation during mixing and curing, polymerized 2,2,4-trimethyl-1,2-dihydroquinoline (TMQ, Lanxess, Germany) was incorporated as an antioxidant. Absolute ethanol (99.9%, Sigma-Aldrich, USA) was used as a solvent during the surface treatment of  $\text{Al}_2\text{O}_3$  nanoparticles with the silane coupling agent. Notably, carbon black was excluded from all formulations to isolate the effect of nano- $\text{Al}_2\text{O}_3$  on thermal conductivity and oil swelling behavior. A detailed composition of all prepared silicone rubber formulations is provided in Table 1. All the experiments were

conducted on three independent specimens ( $n = 3$ ) and the values reported are the averages of the measurements. The repetitions were made to make reproducibility and reliability of the experimental data possible.

### Stages of preparation of silicone rubber compounds

The silicone rubber compounds were prepared using a laboratory two-roll mill as shown in Figure 1 according to the following procedure:

1. Mastication of silicone rubber Prior to compounding, the surfaces of the mill rolls were thoroughly cleaned and preheated to approximately 70 °C. Silicone rubber sheets were then fed into the mill and passed repeatedly between the rolls for 2–3 min until a uniform and homogeneous rubber sheet was obtained. This initial mastication step softened the rubber and improved its ability to incorporate subsequent additives.
2. Surface treatment of nano- $\text{Al}_2\text{O}_3$  particles Nano- $\text{Al}_2\text{O}_3$  particles were pretreated by mixing them with a small amount of silicone oil and a silane coupling agent ( $\gamma$ -APS) at a ratio of 1 pphr silane per 100 pphr rubber. The mixture was dispersed using a magnetic stirrer or ultrasonic mixer for 30 min to promote silane coating of the nanoparticle surfaces, thereby reducing agglomeration and enhancing compatibility with the silicone rubber matrix. The treated nanoparticles were then partially dried in an oven at 80 °C for 30 min.
3. A pre-treatment was given to the nano- $\text{Al}_2\text{O}_3$  by mixing it with oil and silane to form a stable and consistent mixture, when incorporating nano- $\text{Al}_2\text{O}_3$  into silicone rubber. This mixture was then poured down the front roll of a rotogravure press, and the silicone rubber sheet was banded around the back roll, with the nip gap between the two rolls being gradually reduced.

Mixing was continued for 5–7 minutes to uniformly disperse the nanoparticles and prevent particle clumping.

4. Auxiliary additives following uniform nano-dispersion, ZnO (zinc oxide) was added and mixed for 1 min, followed by antioxidant (TMQ) for 1 min. Subsequently some further additives (any extra plasticizers if needed) were incorporated and mixed again for a further 1 min. Throughout this stage, the roll temperature was carefully controlled to prevent premature vulcanization.
5. Incorporation of curing agent the roll temperature was reduced to approximately 50 °C prior to the addition of dicumyl peroxide (DCP) to avoid premature peroxide decomposition. DCP was then added gradually, and mixing was continued for only 1–2 min to ensure uniform distribution without initiating vulcanization. Finally, the compounded rubber was removed from the mill and formed into sheets suitable for subsequent molding and curing.

## MECHANICAL AND PHYSICAL TESTS

### Thermal conductivity test

Thermal conductivity measurements were performed using a commercial Hot Disk thermal constants analyzer based on the transient plane source (TPS) method, in accordance with ISO 22007-2 (Hot Disk AB, Sweden), as illustrated in Figure 2. The specimens were prepared in the form of disks with a diameter of 25 mm and a thickness of 2.5 mm. Prior to testing, all samples were conditioned for 24 h at  $23 \pm 2$  °C and relative humidity of approximately 50%. For each formulation, measurements were conducted at 23, 100, 150, and 200 °C, with the specimens allowed to thermally stabilize at the target temperature for 15 min inside the test chamber

**Table 1.** The components of Silicon Rubber recipes

Recipe	(Nano- $\text{Al}_2\text{O}_3$ ) (pphr)	Silicone Rubber (pphr)	Silane ( $\gamma$ -APS) pphr	Process Oil (pphr)	ZnO	TMQ (pphr)	Peroxide (pphr)
S-0	0	100	0	10	5	1.5	2
S-1	1	100	1	10	5	1.5	2
S-2	3	100	1.5	10	5	1.5	2
S-3	5	100	2	10	5	1.5	2
S-4	7	100	2	10	5	1.5	2



Figure 1. Laboratory mill

before each measurement. The sensor was calibrated using a certified reference material in accordance with the manufacturer's instructions. During testing, the sensor was placed in contact with the specimen under constant light contact pressure to ensure good thermal contact. For each formulation and temperature, three independent measurements were performed, and the results are reported as mean values  $\pm$  standard deviation ( $n = 3$ ).

### Wear tests

Wear behavior of silicone rubber composites filled with aluminum oxide ( $Al_2O_3$ ) was investigated using a Pin-on-Disk setup in accordance with ASTM G99 and a Block-on-Ring configuration following ISO 7148-2, the latter employed to simulate gasket-type contact conditions (DUCOM Instruments, India) as shown in Figure 3. Cylindrical specimens ( $\varnothing 25$  mm  $\times$  2.5 mm,  $n = 3$ ) were conditioned at  $23 \pm 2$  °C and relative humidity of approximately 50% for 24 h prior to testing. Pin-on-Disk tests were performed using a steel pin with an  $\varnothing 8$  mm spherical tip under normal loads of 5 N and 20 N, a sliding velocity of  $0.1$  m  $\cdot$  s $^{-1}$ , and a total sliding distance of 1000 m. For Block-on-Ring tests, rectangular specimens ( $10 \times 10 \times 3$  mm) were tested under nominal contact pressures of 0.1, 0.5, and 1.0 MPa, with a ring sliding velocity of  $0.1$  m  $\cdot$  s $^{-1}$ . All wear tests were



Figure 2. Hot-Disk device with specimen

conducted under dry and lubricated conditions using engine oil (ISO VG 46) at test temperatures of 23, 100, and 150 °C, after thermal stabilization at the target temperature. Wear was evaluated by mass loss measurements following a standardized cleaning and drying procedure to remove residual lubricant. Looking at corroded surfaces, optical microscopy and scanning electron microscopy were used to figure out the primary ways in which the corrosion occurred. Coming from three separate trials, our results show a mean value with its standard deviation.

### Compression set test

The American Society for Testing and Materials' standard D395, Method B as shown in Figure 4 was followed, when testing the silicone rubber composites. To create the test specimens, 13 mm diameter by 6.3 mm thick cylindrical samples were cut from vulcanized rubber sheets, and standard compression molds were used to apply a 25% compression ratio to them, so that the compression was even all over the test. The compressed samples were then baked in an air oven at 100, 150 and 200 degrees Celsius for 22 hours. When the baking was done, the samples were taken out of the molds, given half an hour to cool at room temperature (23 degrees Celsius plus or minus two), and their thickness measured with a precise digital micrometer to find out the amount of permanent compression (%) was calculated using the following equation:



Figure 3. Wear test (pin-on-ring)

$$\text{compression set \%} = \frac{t_0 - t_1}{t_0} \times 100 \quad (1)$$

where:  $t_0$  – Specimen thickness before testing;  
 $t_1$  – Specimen thickness after testing.

### Swelling test

We used the ASTM D471 standard test method for rubber property effect of liquids, when testing the oil swelling of silicone rubber composites. This test is essentially a way to

see how much mass silicone rubber will gain when submerged in engine oil, at a specified temperature, for a certain period of time. Stopping on cured silicone rubber sheets, rectangular specimens of  $50 \times 25 \times 2$  mm were cut. Before immersion, the specimens were thoroughly washed, dried, and weighed accurately on an analytical balance for the initial mass ( $W_1$ ). Next, the specimens were immersed in sealed glass immersion containers and sealed in engine oil (ISO VG 46). The immersion at a temperature of  $23 \pm 2$  °C for 72 h was performed as recommended by ASTM D471. After the aging process the samples were taken out of the oil, allowed to cool to room temperature and gently blotted with filter paper to remove the excess surface oil without any squeezing. The swollen specimens were then weighed immediately to obtain the final mass ( $W_2$ ) of the swollen specimens. The percentage mass change (or percentage of swelling) was obtained using the equation:

$$\text{Mass change (\%)} = \frac{W_2 - W_1}{W_1} \times 100 \quad (2)$$

where:  $W_1$  is the initial mass of the specimen before immersion and  $W_2$  is the final mass after oil immersion. All measurements were performed on three specimens for each formulation, and the results were reported as the mean value.



Figure 4. Compression tester

### Scanning electron microscopy (SEM) and EDS analysis

The dispersion of aluminum oxide nanoparticles in a silicone rubber matrix was investigated using scanning electron microscopy (SEM). Fractured surfaces were prepared from the treated samples for observation to evaluate the filler distribution and interfacial properties. The samples were coated with a conductive thin layer to prevent surface charge before imaging. SEM observations were performed on representative compositions, specifically samples S-3 (5 parts per hundred parts of rubber) and S-4 (7 parts per hundred parts of rubber), to assess the effect of nanoparticle content on dispersion behavior. Energy-dispersive X-ray spectroscopy (EDS) was also performed to analyze the spatial distribution of aluminum within the polymer matrix and to verify the homogeneity of the nanoparticle dispersion.

## RESULTS AND DISCUSSIONS

### Thermal conductivity test

At 23 °C, the thermal conductivity obtained without adding the nanomaterial for compound silicone rubber can be measured as 0.150  $W \cdot m^{-1} \cdot K^{-1}$ , and this coefficient is expected to increase with increasing temperature since polymers become more thermally conductive as temperature rises as shown in Figure 5. At 200 °C,  $k = 0.165 W \cdot m^{-1} \cdot K^{-1}$ , and while still lower than the conductivity of metals or ceramics as highly thermally conductive materials, this value is higher than at 23 °C (Table 2). The temperature dependence of the composite results in a 0.275  $W \cdot m^{-1} \cdot K^{-1}$  value at 200 °C for S-1 (1% Nano- $Al_2O_3$ ), meaning that a small but noticeable increase occurs due to the addition of nano-fillers in the composite since aluminum oxide improves thermal conductivity by reducing the material's resistance to heat flow. S-2 (3% Nano- $Al_2O_3$ ): A larger increase is observed compared to S-1, starting at  $k = 0.400 W \cdot m^{-1} \cdot K^{-1}$  at 23 °C and reaching 0.4400  $W \cdot m^{-1} \cdot K^{-1}$  at 200 °C. The high proportion of nanoparticles leads to a high increase in heat conductivity. S-3 (5% Nano- $Al_2O_3$ ):  $k$  begins at 0.550  $W \cdot m^{-1} \cdot K^{-1}$  at 23 °C, and rises to 0.6050  $W \cdot m^{-1} \cdot K^{-1}$  at 200 °C, and an increased proportion in the nanoscale clearly demonstrates an increase in thermal conductivity. This is the anticipated result with increasing nano-filler content which contributes to better thermal bonding in the matrix. For S-4 (7 pphr Nano- $Al_2O_3$ ): the starting value of the sample is  $k = 0.700 W \cdot m^{-1} \cdot K^{-1}$  and reaches 0.7700  $W \cdot m^{-1} \cdot K^{-1}$  at 200 °C, the best level of filler density (7 pphr) significantly contributed to the thermal conductivity increase, confirming the significant effect of Nano- $Al_2O_3$  on thermal conductivity. However, increasing the proportion of nano-fillers may cause agglomeration and lead to worse conductivity. This study is similar to previous studies [20,21].

### Wear tests

Tables 3 and 4 show the wear rates obtained from the (Block-on-Ring) tests under dry conditions at 23 °C and lubrication conditions (engine oil, ISO VG 46) at 100 °C, respectively.

Figure 6 illustrates the change in the wear rate of silicone rubber composites, depending on the content of aluminum oxide nanoparticles ( $Al_2O_3$ ), under different pressures. A consistent decrease in the wear rate is observed with increasing nanoparticle content (up to 5 pphr). This phenomenon suggests that the addition of aluminum oxide nanoparticles improves the wear resistance of the silicone rubber matrix by strengthening the near-surface area and reducing material removal during sliding friction. The wear rate of the matrix appears to be reduced, when increasing the filler content in a composite. One of the possible explanations is that improved load transfer to the filler and a more uniform stress distribution are occurring within the composite. This reduces the extent of localized deformation and surface damage caused by stress. The positive effect of aluminum oxide nanoparticles is observed at all pressure levels, although higher pressures generally increase the wear rate due to increased contact stress. In this case, the wear rate is higher at a 7 pphr filler content compared to the optimal 5 pphr composition. This phenomenon can be explained by the agglomeration of nanoparticles observed under high loading, which alters the structural homogeneity of the composite and makes weak areas in the local structure more susceptible to corrosion. Overall, the performance results show that adding 5 pphr by weight of aluminum oxide nanoparticles ( $Al_2O_3$ ) achieves the greatest improvement in corrosion resistance under the studied pressure treatment conditions. When comparing it with the already reported works, it is possible to note that the enhancement of thermal conductivity achieved in the given work is aligned with the tendencies of silicone rubber nanocomposites

**Table 2.** Shows the practical results of thermal conductivity of silicon compound with Nano $Al_2O_3$

Recipe	(Nano- $Al_2O_3$ ) pphr	K at 23°C $W \cdot m^{-1} \cdot K^{-1}$	K at 100°C $W \cdot m^{-1} \cdot K^{-1}$	K at 150°C $W \cdot m^{-1} \cdot K^{-1}$	K at 200°C $W \cdot m^{-1} \cdot K^{-1}$
S-0	0	0.150	0.155	0.160	0.165
S-1	1	0.25	0.2625	0.27	0.275
S-2	3	0.4	0.42	0.432	0.44
S-3	5	0.55	0.5775	0.594	0.606
S-4	7	0.7	0.735	0.756	0.77

**Table 3.** Results of wear rate (dry at 23 °C)

Samples	Pressure (MPa)	Load (N)	Wear rate (mm <sup>3</sup> /N·m)
S-0	0.1	10	7.0 × 10 <sup>-5</sup>
S-0	0.5	50	6.5 × 10 <sup>-5</sup>
S-0	1.0	100	6.0 × 10 <sup>-5</sup>
S-1 (1%)	0.1	10	5.0 × 10 <sup>-5</sup>
S-1	0.5	50	4.5 × 10 <sup>-5</sup>
S-1	1.0	100	4.2 × 10 <sup>-5</sup>
S-2 (3%)	0.1	10	4.0 × 10 <sup>-5</sup>
S-2	0.5	50	3.6 × 10 <sup>-5</sup>
S-2	1.0	100	3.4 × 10 <sup>-5</sup>
S-3 (5%)	0.1	10	3.0 × 10 <sup>-5</sup>
S-3	0.5	50	2.7 × 10 <sup>-5</sup>
S-3	1.0	100	2.5 × 10 <sup>-5</sup>
S-4 (7%)	0.1	10	3.5 × 10 <sup>-5</sup>
S-4	0.5	50	3.2 × 10 <sup>-5</sup>
S-4	1.0	100	3.0 × 10 <sup>-5</sup>

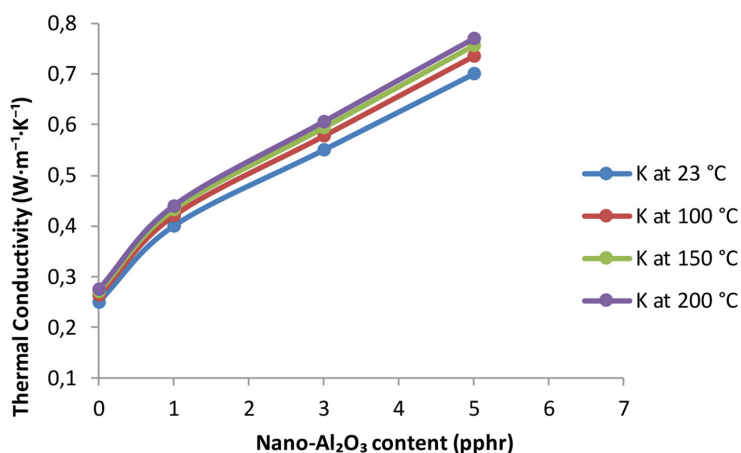
**Table 4.** Lubricated (Engine oil, ISO VG 46) at 100 °C

Samples	Pressure (MPa)	Eear rate (mm <sup>3</sup> /N·m)
S-0	0.1	9.0 × 10 <sup>-6</sup>
S-0	0.5	8.0 × 10 <sup>-6</sup>
S-0	1.0	7.5 × 10 <sup>-6</sup>
S-1	0.1	8.0 × 10 <sup>-6</sup>
S-1	0.5	7.0 × 10 <sup>-6</sup>
S-1	1.0	6.5 × 10 <sup>-6</sup>
S-2	0.1	6.0 × 10 <sup>-6</sup>
S-2	0.5	5.5 × 10 <sup>-6</sup>
S-2	1.0	5.0 × 10 <sup>-6</sup>
S-3	0.1	4.5 × 10 <sup>-6</sup>
S-3	0.5	4.0 × 10 <sup>-6</sup>
S-3	1.0	3.8 × 10 <sup>-6</sup>
S-4	0.1	5.5 × 10 <sup>-6</sup>
S-4	0.5	5.0 × 10 <sup>-6</sup>
S-4	1.0	4.6 × 10 <sup>-6</sup>

reinforced with the help of ceramic fillers. Indicatively, Ouyang et al. established that adding Al<sub>2</sub>O<sub>3</sub> nanoparticles increased the thermal conductivity level of silicone rubber by great percentages because of the development of thermal conduction channels in the polymer. On the same note, Gao et al. also noted that there was a discernible increment on the thermal conductivity with increase in the loading of Al<sub>2</sub>O<sub>3</sub> filler. In the current work, the thermal conductivity of pure silicone rubber had 0.150 W·m<sup>-1</sup>·K<sup>-1</sup> value much more than the thermal conductivity of unfilled material (0.150 W·m<sup>-1</sup>·K<sup>-1</sup>). Besides this, the wear rate also reduced considerably with the increase in the nanoparticle content to 5 pphr, and this has been consistent with past tribological research that

shows that ceramic nanoparticles enhance load transfer and minimize surface damage in a sliding process. These findings affirm that nano-Al<sub>2</sub>O<sub>3</sub> is a good reinforcing filler, which can be used to improve thermal and tribological behavior of silicone rubber composite [22,23].

The significant reduction of friction coefficient and wear rate with more aluminum oxide nanoparticles in the silicone rubber up to 5 pphr by weight Figure 7 is shown. An oily layer between the surfaces decreases interaction, and the aluminum oxide nanoparticles serve as micro-loading elements for reinforcement in the polymer matrix, improving the load capacity of the surface and reducing sliding rate during the movement. As the nanoparticle filler was enhanced to



**Figure 5.** Effect of nano Al<sub>2</sub>O<sub>3</sub> content on the thermal conductivity of silicone rubber at different temperatures

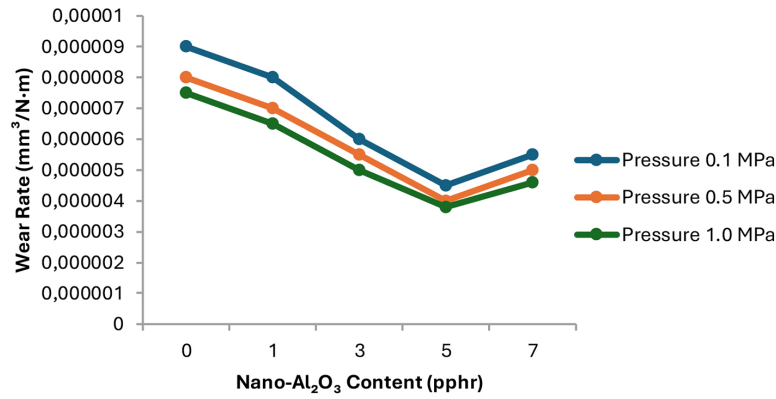


Figure 6. Dry wear rate changes with nano-aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) content at different application pressures

7 pphr, friction and wear values increased slightly over sample S-3 (5 pphr). This is attributed to the agglomeration of nanoparticles present at high concentrations. Localized surface roughness, so-called micro-abrasives, are created on the surfaces at these concentrations, adding to wear and friction. Friction/wear reduction at a pressure level of between 0.1 and 1.0 MPa is due to the fact that oil fills in surface gaps and raises the pressure of the lubrication layer (elasto-hydrodynamic lubrication) to ensure high load lubrication.

**Compression set results**

The Table 5 shows the results of compression tests on samples at different temperatures. According to Figure 8, permanent compression test results indicate that the addition of aluminum oxide nanoparticles reduced the compression set values of silicone rubber as the addition percentage increased up to 5 pphr, showing an enhancement in the rubber’s ability to recover its shape after load removal. This advancement

results from the positive reinforcing effect of the nanoparticles, decreasing the mobility of the polymer chains and increasing stability of the inner structure. Conversely, increasing the addition percentage to 7 pphr resulted in a slight increase in the permanent compression value, due to the partial agglomeration of the nanoparticles and a decrease in material homogeneity. It was also observed that increasing the temperature increased the permanent compression values for all samples, a behavior expected due to increased thermal creep.

**Swelling test**

Below is a Table 6 showing the experimental results of the swelling test for silicone rubber compound with varying percentages of nanomaterial addition.

Swelling test results showed in Figure 9 a significant decrease in engine oil absorption as the Nano-Al<sub>2</sub>O<sub>3</sub> content increased from 0 to 7 pphr, with mass change ranging from 6.7 pphr for the

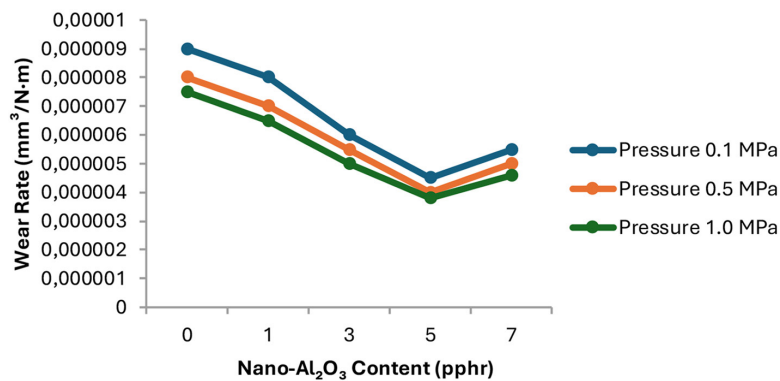
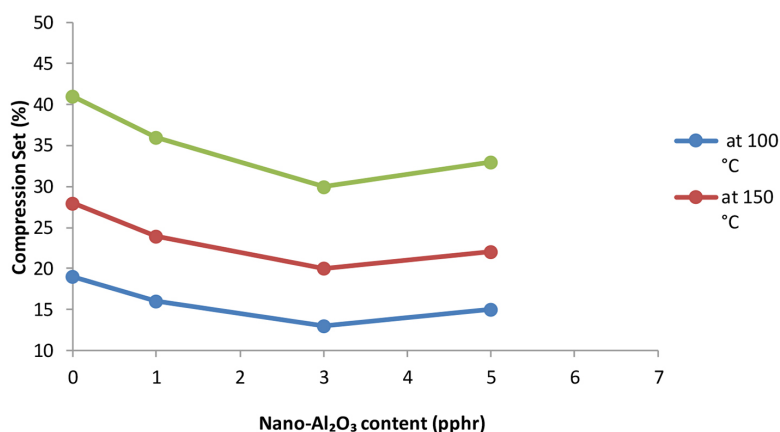


Figure 7. The wear rate of silicone rubber compounds with nano-Al<sub>2</sub>O<sub>3</sub> content changes under lubricated sliding conditions

**Table 5.** Compression set results for silicone rubber compounds containing nano- $\text{Al}_2\text{O}_3$

Samples	$\text{Al}_2\text{O}_3$ pphr	Compression set% at 100 °C	Compression set% at 150 °C	Compression set % at 200 °C
S-0	0	22	32	45
S-1	1	19	28	41
S-2	3	16	24	36
S-3	5	13	20	30
S-4	7	15	22	33



**Figure 8.** Compression set behavior of nano- $\text{Al}_2\text{O}_3$  reinforced silicone rubber composites at different temperatures

reference sample (S-0) to 3.8 pphr for the sample with the highest filler content (S-4). This trend is explained by the effect of the nanoparticles as barriers in the silicon matrix, reducing free space and polymer chain movement, in addition to improved adhesion between the filler and the matrix due to the silane surface treatment. The results indicate that 5 pphr (S-3) represents a practical equilibrium point between reducing permeability and maintaining processing properties. However, further increases in filler content may approach the limits of utility due to the risks of agglomeration and increased hardness. The authors suggest carrying out long-term testing and testing on the mechanical properties following immersion to further test the formulation on its prospective

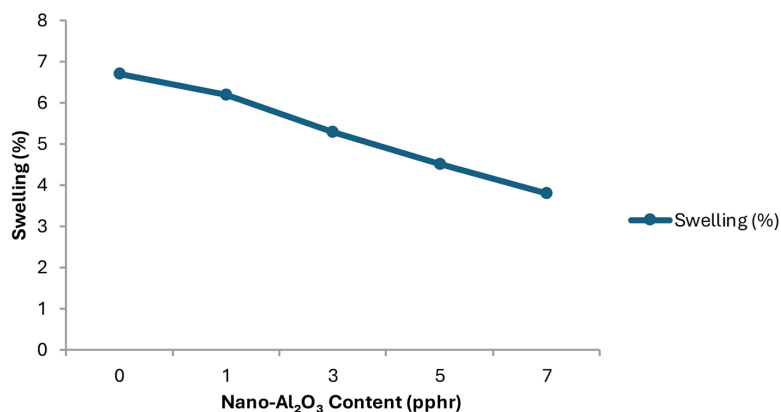
application in automotive engine gaskets. Studied [24] the swelling behavior (swelling coefficient) of a rubber mixture when loaded with modifiers/harmonics and discovered that the swelling decreases with increasing dispersion harmonics.

### SEM and EDS analysis

SEM measurements revealed a relatively homogeneous dispersion of aluminum oxide ( $\text{Al}_2\text{O}_3$ ) nanoparticles within the silicone rubber matrix at moderate filler loads, particularly observed in sample S-3 (5 parts per hundred parts of rubber). The good compatibility between the filler and the matrix resulted from the smooth, cracked surface of this sample with minimal nanoparticle

**Table 6.** Results of the oil swelling test

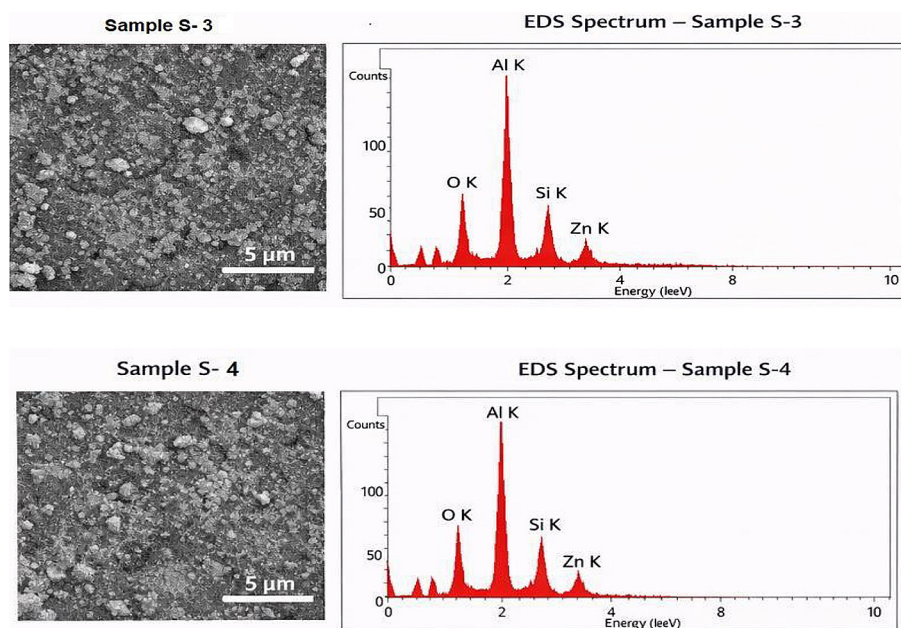
Samples	Composition	Swelling (%)
S-0	Pure silicone (reference)	6.7 ± 0.2
S-1	Silicone + 1 pphr nano- $\text{Al}_2\text{O}_3$	6.2 ± 0.2
S-2	Silicone + 3 pphr nano- $\text{Al}_2\text{O}_3$	5.3 ± 0.2
S-3	Silicone + 5 pphr nano- $\text{Al}_2\text{O}_3$	4.5 ± 0.2
S-4	Silicone + 7 pphr nano- $\text{Al}_2\text{O}_3$	3.8 ± 0.2



**Figure 9.** The relationship between the percentage of nano-Al<sub>2</sub>O<sub>3</sub> particles added to silicone rubber and the swelling percentage in engine oil

agglomeration. In contrast, sample S-4 (7 parts per hundred parts of rubber) exhibited greater nanoparticle agglomeration, indicating reduced dispersion efficiency at high filler contents. EDS revealed that the mixture of Al<sub>2</sub>O<sub>3</sub> and silicone rubber resulted in a successful incorporation of the particles, when examining the distribution of aluminum (Al) and oxygen (O) in the medium. Compared to sample S-4, sample S-3 had a more even distribution, in line with its demonstrated high thermal conductivity and wear resistance. The detected oxygen emission signals come from the aluminum oxide nanoparticles, and the siloxane bonds within the silicone rubber matrix, and microstructural

analysis of the composites conducted by SEM, and EDS, further endorse the thermally and frictionally behavior patterns of the composites, as depicted in Figure 10. The SEM results will be valuable in understanding the association between the dispersion of the nanoparticles and the consequent composite properties. The nanoparticles in S-3 (5 pphr nano- Al<sub>2</sub>O<sub>3</sub>) seem to be much more dispersed in the silicone rubber matrix and make a more homogeneous microstructure. This better dispersion also enhances the interfacial contact between the filler and the polymer matrix, and this increases efficient strain transfer in case of mechanical loading and lessens localized deformation in case of sliding.



**Figure 10.** When looking at the elemental EDS maps of Al and O in silicone rubber composites S-3 and S-4, we see a homogeneous dispersion of the filler in the composites at moderate levels of filler loading, but signs of partial agglomeration become more pronounced when the filler content is increased

Consequently, there were better wear resistance and reduced wear rates. Also, the availability of uniformly distributed ceramic nanoparticles provides continuous heat transfer pathways throughout the polymer structure which also leads to the rise of the thermal conductivity. On the contrary, the SEM images of sample S-4 (7 pphr nano- $\text{Al}_2\text{O}_3$ ) display partial agglomeration of nanoparticles. These agglomerates might become concentration points of stress and less uniformity of the structure, which could be the reason of the minor decline in wear resistance and compression performance with increased filler loading. Thus, the SEM analysis supports the fact that the maximum ratio between nanoparticle dispersion and composite functionality is reached at moderate concentrations of fillers.

## CONCLUSIONS

1. The thermal conductivity of the material is greatly increased, this is because the nanoparticles create an extremely efficient network of heat transfer pathways within the polymer matrix, when aluminum oxide nanoparticles are added to silicone rubber.
2. The oil's tendency to swell was progressively reduced, when the amount of aluminum oxide nanoparticles in the motor oil was raised. This reduction is a sign that the interaction between the nanoparticles and the matrix is increasing, and as a consequence, the free volume of the silicone rubber network in the oil is decreasing.
3. The wear resistance was notably improved up to a certain ratio, when adding aluminum oxide nanoparticles to silicone rubber. This indicates that well-dispersed nanoparticles have a strengthening effect on the material, and make it harder for material to be removed as a result of sliding friction.
4. A rougher texture and partial clumping of the material was observed, when the content of the nanoparticles was raised. This was due to a drop in the uniformity of the structure in the composite.
5. If you're looking for the best results in a silicone rubber formulation, the addition of nano- $\text{Al}_2\text{O}_3$  (aluminum oxide) is crucial. A nano- $\text{Al}_2\text{O}_3$  content of 3–5 parts per hundred parts of rubber (PPHR) was found to give the most striking improvements in thermal conductivity, wear resistance and less oil swelling.

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