State-of-the-art for Magnetorheological Elastomers Fabrication and Hydro-tribological Characterisation

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Abstract. Magnetorheological effect on mechanical properties of its specific applications has been studied. Mechanical properties such as hardness, tribology characteristic and salt water and water absorption with hygrothermal effect will be further studied on wear performance of MRE on marine equipment applications. Isotropic, anisotropic and anisotropic with added N330 carbon black filler of Ni Zn Ferrite Magnetorheological Elastomers (MREs) were prepared with Ni Zn Ferrite filler, Ni1 - x ZnxFe2O4 particles weight fraction of 70%. Images of Scanning Microscopy Electron (SEM) and Energy Dispersive X-Ray Analysis (EDX) are identified with the presence of the structure of Ni Zn Ferrite in the natural rubber matrix. Anisotropic Ni Zn Ferrite MREs with added carbon black filler given highest hardness value of 90.78; least effected on salt water and water absorption and hygrothermal effect; better wear performance with a low average specific coefficient of friction (COF), specific wear rate and least loss of wear volume. Therefore, it is most suitable use for future application in a wet environment for a long period.

Introduction

Magnetorheological elastomers (MREs) are classified as smart materials that have the capability to alter their mechanical, electrical, magnetic properties with external factors applied such as temperature, magnetic or electrical field, stress and moisture. Combination of rubber matrix (non-magnetic) with ferrite particles (magnetically permeable) in the scale of a micron or nano size with external magnetic field applied on the magnetic mold during curing process provide elastomers to enhance its rheological properties. The reasons of chosen ferrite particles as the main component of MREs as they have high permeability and low hysteresis loss compared to other magnetical particles [1].

There are two types of solid-state Magnetorheological elastomers (MREs) which are isotropic MREs and anisotropic MREs. With the discovery of phenomena structure of Isotropic MREs and anisotropic MREs by Khimi et al. shown in Fig. 1[2].Structure of isotropic MREs shows a noticeable structure of a uniform distribution of ferrite particles inside the rubber matrix. Anisotropic MREs give special chain-like structures of ferrite particles linked arrangement in rubber matrix from the process of curing matrix when applied the magnetic field.
The chosen of ferrite particles are Ni Zn Ferrite (NZF) Ni$_{1-x}$Zn$_{x}$Fe$_2$O$_4$, where $x>1$ with particle weight fraction is 70% inside a base natural rubber matrix and applied magnetic field with 230 mT. Particles size of NZF in between 10 to 30 μm with irregular shape form which added to rubber matrix during compounding stage. Advantages of input NZF particles used in rubber matrix as formed of MREs provide high saturation magnetization, high electrical resistivity, enhance mechanical hardness, tensile strength and cost-effectiveness [3, 4]. Magnetorheological elastomers (MREs) consists of liquid-state and solid-state material[5-6]. The advantages of providing MR fluid (MRF) are it can change its rheological properties frequently and provides better mechanical, electrical, damping properties compare to the conventional rubber products application. However, for liquid-state MREs has occurred a problem of particle sediment which can be solved by solid-state MREs. Solid-state MREs are formed with the rubber-matrix such as natural rubber as the major component to provide excellent mechanical performances without disturbing the performance of MRF effect [7]. Natural Rubber used was under the Standard Malaysia Rubber Grade L (SMRL). Natural rubber also is known as the ecological friendly natural product that provides less pollution and waste to the environment [8-15].

The aim of this research is to study the relationship between water and salt water absorption properties along with hygrothermal effecting tribological performance on isotropic, anisotropic and anisotropic with added Carbon black (CB) filler NZF MREs prepared. Additional of CB as a secondary fillers could increase viscosity, the rate of vulcanisation, hardness, tan δ, and the tensile strength of the finished MRE’s compound[16]. In this research, solid-state MRE is chosen with added NZF filler as the experimental specimen. Physical properties of Ni Zn Ferrite Magnetorheological Elastomers (NZF MREs) such as mechanical hardness and tribology studies on wear and friction characteristic will be studied with specially applied of the external factor such as water and salt water absorption at room temperature and a high temperature about 60°C.

**Experiment**

Three types of magnetorheological elastomer (MRE) compounds which natural rubber filled with NZF particles sized between 10 to 30 μm and comprising with particles weight fraction 70%. Compound 1 is an isotropic compound without applied magnetic field. Compound 2 and 3 are an anisotropic compounds with the applied magnetic field 230mT whereby Compound 2 without added filler of N330 carbon black and Compound 3 with an added filler of N330 carbon black with particles sized around 300μm. These three compounds are formulated using a conventional two roll mill machine (model XK 160). Cure times were determined using rheometer MDR 2000. The three compounded MREs are cured using hot press under temperature of 150 °C. N330 Carbon Black filler is chosen as another anisotropic compound of MRE with particle weight fraction of 50 wt.% for better wear performance. Basic formulation is shown in Table 1.

| Materials       | Isotropic MRE (phr) | Anisotropic MRE (phr) | Anisotropic MRE CB (phr) |
|-----------------|---------------------|-----------------------|-------------------------|
| SMRL grade NR   | 100                 | 100                   | 100                     |
| ZnO             | 5                   | 5                     | 5                       |
| Stearic acid    | 1                   | 1                     | 1                       |

Table 1 Formulation of Ni Zn Ferrite MREs
The fabrication of Isotropic NZF MREs consists of two major steps which are mixing and curing without the applied magnetic field. While fabrication of anisotropic NZF MREs consists of three major steps which are mixing, pre-alignment and curing. The mixing process for both isotropic and anisotropic are using a conventional laboratory two roll mill with model XK 160 according to ASTM D3184-80. The total cycle time of mixing is tabulated in Table 2 [16].

![Table 2 Total cycle time of mixing process](image)

The cure time of three MREs compounds were determined by using MDR Rheometer with model 2000 according to ASTM D 2084. The optimum cure time ($t_{90}$) is the time required for the torque to reach 90% of the maximum achievable torque. The curing characteristic was determined at 150°C and a vulcanization curve was plotted from the graph of torque versus time to obtain $t_{90}$ [16]. The value of $t_{90}$ in units of m.m represented as required minutes of cure per millimeter of wall thickness. Therefore, the appropriate cure time of MRE compounds should multiply with the thickness of the MREs fabricated using equation (1).

\[
\text{Appropriate Cure Time} = t_{90}(m.m) \times \text{thickness of the frame} \quad (1)
\]

![Fig. 2 (a) Compounded rubber sample weighted in frame mould (b) Fabricated Anisotropic NZF (c) and (d) manual punching with 12 mm puncher (e) punched sample 12 mm diameter with 3 mm thickness](image)
Compounded rubber samples were weighted 35 g to 40 g and then placed in a frame mould with dimension 288 x 240 mm and covered by as shown in Fig. 2 (a). For compounded rubber to fabricate as isotropic NZF MRE were cured in compression frame mould at 150 °C under pressure 10 MPa by using hot press machine with model 120T. For anisotropic NZF MREs were fabricated with external magnetic mould 230 mT. The external magnetic mould needs to preheat at 80 °C before compounded rubber sample was put between the external magnetic mould to undergo pre-alignment of NZF particles using manual hot press machine at 80 °C for 30 minutes under pressure 12 MPa. Laser thermometer was used to check the temperature frequently. After the pre-alignment process, the compounded rubber samples undergoes post cure at 150 °C under pressure 10 MPa using hot press machine with model 120T. The fabricated NZF MRE sample was taken out and removed the excessive rubber compound as shown in Fig.2(b). Treatment of cooling fabricated NZF at room temperature to re-orientate the magnetic dipoles after post cure [5]. After 24 hours of cooling treatment, NZF MRE can be punched out using manual puncher with the 12mm diameter puncher to a sample with dimension 12 mm diameter x 3 mm thickness as shown in Fig.2(c)-(e).

The degree of hardness of isotropic, anisotropic and anisotropic with added of carbon black NZF MREs samples were measured using TECLOCK GS-706G Type A Durometer according to ASTM D2240. A base of durometer was in contact with NZF MREs samples by applied pressure force manually. These tests were repeated on three times for each compound.

The density of isotropic, anisotropic and anisotropic with added of carbon black MREs sample were determined by using indirectly method from Archimedes’ Principle. Initial mass of dry and clean volumetric cylinder was measured using a digital analytic balance with precision 0.0001 g and recorded as M_{o}. The NZF MRE sample in air was weighed as M_{b}. Distilled water was filled in the volumetric cylinder and a sinker was put into water and read from the scale level from volumetric cylinder and recorded as V_{s}. The NZF MRE sample with a sinker was submerged in the volumetric cylinder with containing distilled water. The volume of water displaced from submerged NZF MRE sample was read on the scale of volumetric cylinder and recorded as V_{b}. The density of NZF MRE sample was calculated using equation (2).

\[ Density, \frac{g}{cm^3} = \frac{M_{b}}{(V_{b} - V_{s})} \quad (2) \]

Morphology of microstructures of isotropic, anisotropic and anisotropic with added of carbon black NZF MREs were observed using Hitachi S-3400 Scanning Electron Microscope (SEM). The samples were coated with a thin layer of Au using Quorum SC7620 Sputter Coater with applied pressure 2 MPa and time 90 seconds. Elemental composition of NZF MREs samples were analyzed using Energy Dispersive X-Ray Analysis (EDX). Source of X-Ray has interacted with points of samples surface that selected and each element has a unique atomic structure with the presence of peak on its electromagnetic emission spectrum.

Wear and friction characteristic of isotropic, anisotropic and anisotropic with added of carbon black NZF MREs were studied by DUCOM Pin On Disc tester with model TR-20 according to ASTM G99. For the preparation of the testing sample, a MRE sample with diameter 12 mm and thickness 3 mm was attached to the bottom end of a metal pin by using super glue and dried using air dryer around 10 minutes. The MRE sample pin was weighted using a digital analytical balance with precision 0.0001 g and recorded as initial mass before wear test, M_{t}. Sandpaper with grade 1000 was stick on top the steel rotating disc and wear track diameter was adjusted to 50 mm and screwed tightly. The MRE sample pin was held against the counterface of the rotating steel disc and ensure the surface of the MRE sample pin has an effective contact of the flat surface with the sandpaper on rotating disc. The MRE sample pin was loaded 5 N against the disc through a dead weight loading system. Tribology testing for all MRE samples were conducted under sliding speed of 30 rpm, 50 rpm and 70 rpm and normal loads of 5 N and 10 N. By setting up of WINDUCOM 2010 software in desktop, filename, sample id and remarks were entered and rotary mode was selected before beginning the test. Sliding speed (RPM), load applied (in kg), wear track diameter (mm) and test time for 30 minutes on each sample testing were acquired. The reference point needs to be set zeroing before the test started.
After reaches elapsed time, MRE sample pin was ejected and measured mass after wear test, M₂. Wear volume loss was calculated by using equation (3) and specific wear rate, k was calculated by using equations (4) and (5) [17].

\[ \text{Volume loss, mm}^3 = \frac{\text{Mass loss (M}_1 - \text{M}_2)}{\text{Density} \times 1000} \]  
(3)

\[ \text{Specific Wear rate, k (mm}^3/\text{Nm)} = \frac{\text{Volume loss}}{\text{Load} \times \text{Sliding distance}} \]  
(4)

\[ \text{Sliding distance, } m = \pi \times D(m) \times \text{Sliding Speed(}m/s) \times \text{Time(s)} \]  
(5)

![Fig. 3 MRE samples immersed in water at room temperature](image)

The behavior of isotropic, anisotropic and anisotropic with added carbon black filler NZF MREs were studied by immersing the samples with the dimension of 12 mm diameter and thickness 3 mm in salt and distilled water separately according to ASTM D570. At first, the samples were dried in an oven at 70 °C about 16 hours and weighed of the conditioned samples were taken before immersion in salt water and water. The water absorption experiments were carried out for 14 days at room temperature as shown in Fig. 3. During the period of 14 days immersion, the weight of wet samples were taken daily to calculate the percentage increase in weight during immersion by using equation (6). The samples need to be wiped with absorbent paper before weighing using a digital analytical balance with precision 0.0001 g. After weighing process, the samples need to immerse back into the water immediately. At the end of 14 days of water absorption test, tribology characteristic testing was being studied on the NZF MREs samples to investigate the effect of water absorption on these three compounds.

\[ \text{Increase of weight, } M = \frac{\text{M}_w - \text{M}_c}{\text{M}_c} \times 100 \]  
(6)

where \( \text{M}_w \) the weight of is wet sample after immersion to a certain period and \( \text{M}_c \) is the weight of conditioned dried sample before immersion in water and in salt water.

**RESULTS AND DISCUSSION**

In Fig. 4 (a), the graph of torque against time, a vulcanization curve was shown to determine \( T_{90} \) value. The curves consist of two parts which are maximum torque and minimum torque. Maximum torque represented as the shear modulus of a fully vulcanized compound at the 150 °C while minimum torque is used to measure the viscosity of NZF MRE compound as shown in Fig. 4 [17-19].

![Fig. 4 (a) Vulcanization curve [20] (b) stages of vulcanization curve[21]](image)

There are 3 stages of curing conditions as represented by a vulcanization curve shown in Fig. 4(b). As the first stage, a slow chemical reaction between rubber and the additives when compound was heated under pressure. The second stage is when curing of rubber compound started which lead to torque increases with time. Scorch time (\( t_{1/2} \)) was determined as induction time where the time crosslinking
starts. The slope will continue to increase until it reaches the steady peak value of torque and plateaus out as the third stage (overcuring) [19-20]. \( T_{90} \) value is determined when the torque reaches 90% from the maximum torque. This is also represented as the time required for optimum vulcanization of NZF MRE. Comparative table of determine cure time and scorch time for three compounds was tabulated as shown in Table 3 which can be referred to Figs. 5(a) –(b) and (c).

| Compounds                      | Isotropic | Anisotropic | Anisotropic with added carbon black |
|--------------------------------|-----------|-------------|------------------------------------|
| \( T_{90} \) (m.m)             | 3.12      | 3.58        | 2.80                               |
| \( t_{s2} \) (m.m)             | 1.30      | 1.64        | 1.12                               |

Table 3 Cure time and scorch time determined for three compounds

Each compound of NZF MREs has its own unique cure time and scorch time due to different mixing time when under fabrication of rubber compounding. Lower cure time and scorch time for anisotropic with added carbon black are because of the cross-linking happened between natural rubber and others additives with carbon black [21].

![Fig.5](image1) (a) Isotropic compound cure time determined (b) Anisotropic compound cure time determined (c) Anisotropic with added carbon black compound cure time determined

Average hardness value against all type of MRE and density was plotted as shown in Fig. 6(a) and (b) respectively.

![Fig. 6](image2) (a) Average Hardness Value (b) Density specification for all types of NZF MRE

Isotropic NZF MRE shows the lowest hardness compare to anisotropic and anisotropic with added carbon black. Isotropic NZF MRE does not undergo special treatment on applying the magnetic field during curing. For anisotropic and anisotropic with added carbon black with applied magnetic field have higher hardness value which are 83.87 and 90.78 respectively than the isotropic non-applied magnetic field which is 76. The applied magnetic field during curing of NZF will change the stiffness and strength of NZF MRE due to the formation of the chain-like structure of magnetic particle within the rubber matrix. Moreover, additional N330 carbon black filler reinforced NZF MRE by enhancing the mechanical properties of NZF MRE and modify the stiffness, hardness, thermal stability and shrinkage of anisotropic NZF MRE [22].

The result of density specification of NZF MRE was plotted as shown in Fig.6(b). Anisotropic with carbon black NZF MRE shows the highest density (1.6927 g/cm\(^3\)). Additional of material 50 phr N330 carbon black in rubber matrix causes more material particles concentrated to the NZF MRE volume given. Next, anisotropic NZF MRE has advantages of alignment of ferrite particles with the applied magnetic field during curing. Therefore, the NZF particles will packed together tightly that lead to increase the density of the material (1.5991 g/cm\(^3\)). For isotropic NZF, NZF particles are not packed.
together and distributed uniformly through the volume space of NZF which causes it has lesser dense (1.5474 g/cm³) compared to the others. SEM images of isotropic, anisotropic and anisotropic with added carbon black of NZF MREs are captured and shown in Fig. 7 respectively. It can be clearly seen that isotropic NZF MRE had uniform NZF particles distribution in rubber matrix without any particles packed together in Fig.7(a). Both anisotropic NZF MREs in Fig. 7(b) and 7(c) shows that the NZF particles are aligned and formed chain-like columnar structure due to the cured under applied magnetic field during fabrication. In Fig.7(c), N330 carbon black particles will be distributed evenly in the rubber matrix. The carbon black particles have restricted the movement of NZF particles during curing under the applied magnetic field. Therefore, alignment of NZF particles are shorter in anisotropic NZF with added carbon black as agreed by [23].

Fig. 7 SEM images of (a) isotropic NZF MRE (b) anisotropic NZF MRE (c) anisotropic NZF MRE with added carbon black at 500 X magnification

From the EDX analysis, it can be clearly shown that presence of peaks NZF particles in all type of MREs as shown in Figs. 8(a)-(c) accordingly. The percentage weight of Nickel (Ni) shows between 0.68 % - 1.45 %. The percentage weight of Zinc (Zn) element shows between 5.09 % - 10.96 %. The percentage weight of ferrite (Fe) element shows between 4.93 % - 9.26 % while the percentage weight of carbon content for isotropic and anisotropic NZF MRE shows almost the same which are 67.01 % and 68.8 %. Yet, for anisotropic NZF MRE with added carbon black has the highest percentage weight amount of carbon content which is 78.33 % (Fig. 8c). These have confirmed the presence of added carbon black filler has contributed to the percentage weight of carbon content in the rubber matrix. After immersion of salt water and water in 14 days (336 hours) for all type of NZF MREs at room temperature, a graph of percentage of moisture absorption against immersion for 14 days was plotted as shown in Fig. 9(a) and (b).
From the result, it can be clearly shown that low moisture absorbed at weight fraction in salt water and water for all type of NZF MREs at room temperature. For isotropic NZF MRE, moisture absorbed at weight fraction up to 0.9301 % (salt water) and 1.2850 % (water); for anisotropic NZF MRE only 0.9124 % (salt water) and 1.2465 % (water); anisotropic with added carbon black NZF MRE only 0.7545 % (salt water) and 0.8333 % (water). This can be explained by free volume approach which defined as the available volume of the material being unoccupied by the molecules [24]. With the proper curing, uniform dispersion of NZF nanoparticles filler and N330 carbon black filler can reduce the segmental movement of the polymer chain and improve cross-linking in a rubber compound that highly reduces free volume inside a material.

Carbon black filler able to control a large extent of water soluble residues and known as low absorption group [22]. Presence of sodium chloride (NaCl) in salt water solution has prevented the growth of microcavities therefore the percentage of moisture absorption for all NZF MREs are lesser than water absorption [10]. 35% of high concentration salt particles NaCl inside the NZF MREs will create an osmotic pressure which prevents the elastomer to absorb further water ingression [24]. For hygrothermal effect at temperature 60 °C, amount of salt water and water absorption of all NZF MREs had been increased as shown in Fig.9(b). For isotropic NZF MRE, moisture absorbed at weight fraction up to 1.7771 % (salt water) and 4.2162 % (water); for anisotropic NZF MRE only 1.7697 % (salt water) and 3.2172 % (water); anisotropic with added carbon black NZF MRE only 1.4769 % (salt water) and 2.3432 % (water). This has proven that NZF MREs have a weak resistance to temperature effect that soften the elastomer surface leads to higher moisture absorbed inside material when temperature increases [11].

A combination of sliding speed and load applied increases during wear test, wear loss volume will increases as shown in Fig.10. More wear particles are dispersed out from the elastomer surface causes high loss of mass during high sliding speed and high load applied. Isotropic NZF MREs has the highest wear loss volume in all states of sliding speeds and loads applied followed by anisotropic and anisotropic

![Fig.9](image1.png)

![Fig.10](image2.png)
with added carbon black. This shows that contribution of carbon black filler and applied the magnetic field during curing have significantly changed hardness, stiffness and strength of the elastomer cause anisotropic NZF MREs shows lower wear loss volume. The high hardness of anisotropic with added carbon black shows the lowest wear loss volume and fewer wear particles generated[18].

Anisotropic with added carbon black NZF MRE shows the lowest specific wear rate compared to the other two compounds at the initial dry condition as in Fig.11a. The reinforced carbon black filler contributed to the hardness of anisotropic NZF MRE which led to better mechanical properties and less deformation of elastomer composites [17]. In Figs. 11b-c, isotropic NZF MREs always shows the highest specific wear rate in all states of environmental conditions applied and different sliding speeds and loads applied on wear tests. This is because the low hardness of isotropic NZF MREs compound has contributed to the low shear strength and high wear loss volume without treatment of alignment of NZF particles through the applied magnetic field. For anisotropic and anisotropic with added carbon black, with the treatment of water and salt water absorption has enhanced wear performance on these two compounds which shows the reduction of specific wear rate compared to the initial dry condition shown in Fig. 12 except on the high sliding speed 70 rpm. Less NZF particles have been washed away by water and salt water absorption because of the NZF particles has been properly aligned by applied magnetic field[14].

Friction caused by shearing elastomer due to adhesion and defined as resistance to sliding. Friction caused by adhesion when actual contact area, the molecular interaction will form adhesion bonds between the elastomer and smooth surface of sandpaper [13]. Fig. 13(a) shows the result of average specific friction coefficient for all types of NZF MREs with applied of different sliding speed and load applied during wear and friction test. The average specific COF was calculated from the graph of friction coefficient range generated on pin-on-disc machine. For all states of sliding speeds with 10 load applied have shown the reduction of the COF. This result opposed the law of friction where load increases the average specific COF will also increase. This is because the wear debris on the surface causing surface roughness of NZF MRE formed a thin layer of lubricant effect which lead to the decrease of average specific COF when increase of load applied [13]. With the moisture absorption of water and salt water at room temperature, the results was shown in Figs. 19-20.
With the absorption of water and salt water can cause a decrease in the average specific coefficient for all types of NZF MREs compared to the initial dry condition as referred to Figs. 14b-c. The decrease of coefficient depends on the thickness of water film, nature of elastomer formed and smoothness of surface material and presence of foreign particles such as NaCl in salt solution. Increase water and salt water temperature at 60°C in water bath are shown in Fig. 14(a). In the case when there is absent of stick-slip phenomena, the average specific COF with the effect of water absorption at 60 °C for isotropic and anisotropic compounds are slightly increased compared to with room temperature as referred to Fig.14(b). This is because of increase in temperature leading to reduce the hardness of MREs due to the surface soften [12]. At salt water absorption at 60 °C, overall average specific COF for all types of NZF MREs compound are slightly reduced compared to the salt water at room temperature as in Fig. 15(b). The soften surface has been enhanced by penetrated salt particles on the surface leads to reduction of average specific COF.

Surface morphology analysis for all types of NZF MREs were captured using SEM and width of abrasive wear debris formed were measured after wear and friction test with sliding speed 70 rpm and 10 N load applied as shown in Fig. 15. At the high sliding speed and load applied, the abrasive wear debris formed obviously. Anisotropic with added carbon black NZF MRE have less wear debris formed and width of wear debris around 0.082 mm to 0.172 mm. This is can be proven with its good mechanical properties such as high hardness, low wear rate and small and stable friction coefficient. Therefore, anisotropic with added carbon black compound shows relatively slight wear on the surface and highest wear resistance compared to the two compounds. For isotropic compound, long and large size of wear debris formed and width of wear debris around 0.362 mm to 0.558 mm. For anisotropic compound, wear debris formed shorter and smaller size than isotropic compound. Width of wear particles is between 0.181 mm to 0.204 mm. From the SEM observation on surface morphology on water and salt water absorption of NZF MREs, there is no any worn holes or obviously differences on wear surfaces which shows that moisture absorption treatment have reduced wear rate and better wear performance as shown in Figs. 16. With the water and salt water absorption at 60 °C for all types of NZF MREs still showing the similar pattern of wear debris formed as water absorption at room temperature as shown in Fig. 16. However, for high temperature effect at 60 °C on water absorption, isotropic compound started produces worn holes as shown in Fig. 17. This is because small size of sample isotopic NZF MRE started being wear
off at the end of the sample with high sliding speed and high load applied. The isotropic NZF MRE has weak resistance to temperature effect, high specific wear rate, low wear performance and low hardness.

Fig. 15 SEM of worn surface for (a) Isotropic (b) Anisotropic and (c) Anisotropic with C-black

Fig. 16 SEM of surface state after immersion in water and salt water at room temperature) (a) Isotropic (b) Anisotropic (c) Anisotropic with C-black

Fig. 17 SEM of surface state in Water and salt water absorption at 60°C) (a) Isotropic (b) Anisotropic (c) Anisotropic with C-black

**Conclusion**

Wear and friction properties inversely proportional to the hardness of NZF MREs. The high hardness of anisotropic with added carbon black leads to low wear loss volume, low specific wear rate, low average specific COF. Low hardness of isotropic NZF MREs has shown an increase of wear rate, wear loss volume and COF. With the effect of different environmental conditions such as water and salt water absorption at room temperature and at 60 °C, wear and friction characteristic have changed for all types of NZF MREs. Isotropic compound shows slight increase on specific wear rate and average specific COF because of the low hardness nature of isotropic NZF MREs on weak resistance to temperature effect and corrosion of NZF particles in both solutions due to improper alignment of particles during curing without applied magnetic field. It also shows the highest intake of moisture absorption compared to the other compounds. For anisotropic compounds, specific wear rate and average specific COF have slightly decreased when applied to the lubricating effect on water and salt water absorption and does not have significantly increase when effect of high temperature. With the advantages of added carbon black in anisotropic compound has the lowest specific wear rate, average specific COF and least moisture absorption when immersed in solutions. It shows the high resistance to any external factors on applied different environmental conditions. In a nutshell, based on all states of testing conditions such as low or high sliding speed and load applied; temperature effect at room temperature and at 60 °C; different testing solution such as water and salt water, anisotropic with added carbon black compound is the best durability, better wear resistance and always shows steady and stable COF without effect of tested environment conditions.
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Acknowledgement:
Special thanks to the Bridging Grant 304.PMEKANIK.6316322 USM