The International Journal of Engineering and Information Technology

journal homepage:www.ijeit.misuratau.edu.ly

Effect of Kaolin and Phonolite Particulates Addition on Hardness and Abrasive Wear Behavior of Glass−Fiber Composites

Mohamed Ali Ballem
Department of Materials Science and Engineering, Misurata University
mohamed.ballem@eng.misuratau.edu.ly

Salem Ali Garrab
Department of Materials Science and Engineering, Misurata University
sgarrab@eng.misuratau.edu.ly

Khalid Eldwaib
Department of Materials Science and Engineering, Misurata University
kedwaib@yahoo.com

Mustafa Aldarwish
Department of Materials Science and Engineering, Misurata University
mmosab@yahoo.com.au

Abstract— **The aim of this experimental investigation is to study the hardness properties and abrasive wear behavior of glass fiber reinforced polymer (GFRP) composites modified with kaolin and phonolite particles as natural fillers. Three composites were fabricated by hand lay-up method using chopped glass fibers as reinforcement agent and unsaturated polyester resin as a matrix material. The first composite was prepared without any particulate additions to serve as a reference; the other two composites were prepared by incorporating the kaolin and phonolite particles at weight percentage of 10% in the polyester resin, respectively. Brinell hardness test was conducted to determine the hardness values of the composites, and the abrasive wear performance was evaluated using two-body abrasive wear test. Experimental results revealed that the addition of kaolin and phonolite particles improved both the wear resistance and hardness of the studied composites; nevertheless, the significant improvements were observed with phonolite-filled composite, the hardness and wear resistance of this composite were increased by 69% and 24.3%, respectively. The findings of this study indicate that the lack of abrasive wear resistance and hardness properties of GFRP composite which limit their use as wear-resistant materials can be improved or overcome by selecting and using of proper particulate fillers.**

Index Terms— **Abrasive wear; Composites; Hardness; Glass fiber; Kaolin; Phonolite.**

I. Introduction

Over the last years, composite materials, ceramics, and plastics have been the dominant promising materials. The volume and number of their potential applications have grown steadily, and each year, composites keep on replacing traditional materials like aluminum and steel. The main advantages of composites over traditional types of materials that the unique combination of properties such as high toughness, high strength to weight ratio, good electrical and thermo-physical properties, which can not be achieved for "simple" materials; also, the ability to control their properties over a wide range by simply changing fabrication conditions and/or their composition [1-3]. The most common composites are fiber reinforced polymer (FRP) composites, they are a polymer-based composites reinforced with fibers that can be from glass, carbon, aramid or basalt; such composites gained a unique properties from the high strength and high stiffness of the fibers [2, 4]. Due to the bonding between the fibers and polymer matrix, and since both of them maintain their original mechanical, physical and chemical properties, the resulting composite will have superior properties that can not be realized if either of the constituents were acting alone [5].

Among the different types of FRP materials, glass fiber reinforced polymer (GFRP) composites are mostly suitable for designing parts that used in wide range of applications as substitution for metals in aerospace, automobile, marine, constructions, armor, medical, sporting goods, and oil and gas industries [6, 7]. However, still there are some areas where FRP composites are very rarely applied on it because of the lack of good wear resistant properties of these materials [8, 9].

Wear is defined as damage to a solid surface, usually involving progressive loss of material, because of relative motion between contacting surfaces. There are five main types of wear including, adhesive, abrasive, erosion, fretting and fatigue wear. The most important type among these forms of wear is the abrasive wear since it contributes almost 63% of the total cost of wear [10, 11]. Due to the importance of the tribological properties of FRP composites, several attempts have been made in order to improve their wear resistance; this enchantment can be achieved by proper selecting of the fiber and matrix materials, also, incorporation of particulate fillers in polymer matrix results in excellent wear properties [9, 12].

Generally, there are many reasons for the use of fillers into the polymeric composites, for instance it is utilized to improve the mechanical, physical and thermal properties of the composites; also the wear resistance and hardness improve significantly by incorporation of

Received 01 Feb, 2025; Revised 20 May, 2025; Accepted 27 May, 2025.
Available online 31 May, 2025.
DOI: https://doi.org/10.36602/ijeit.v13i2.537

suitable fillers in the polymer composites, furthermore, reduction in the cost of the final product can be achieved [9, 13-17]. Different types of fillers in micro and nano size such as TiO_2, SiO_2, SiC, Al_2O_3, graphite, etc. were used to improve the wear performance of the polymer based-composites [8, 9, 12, 18, 19]. Clays such as kaolinite (known as kaolin), chlorite, bentonite, and montmorrilonite have been used as fillers in polymer systems due to their low cost and their efficiency of improving the physical and mechanical properties of the resultant polymer [20-23].

The present study selected kaolin and phonolite (from Libyan origin) as fillers for modification of the matrix of GFRP composites. This selection was based on their unique chemical and physical properties, as well as their natural abundance, local availability, and cost-effectiveness compared to synthetic fillers such as SiC and Al_2O_3, making them attractive alternatives for composite reinforcement. Kaolin is a natural clay mineral formed over many millions of years, and it has the chemical composition $Si_2Al_2O_5(OH)_4$, and 1:1 layer structure consisting of tetrahedral and octahedral layers [24, 25]. Kaolin is widely used in various applications, such as ceramics, paper coating and filling, paints, and rubber industries [26, 27]. Another particulates addition that used in this work to modify the polymer matrix is phonolite; phonolite is grey to dark green volcanic rock, it belongs to a group of extrusive igneous rocks (lavas) that essentially composed of nepheline and alkali feldspar; usually it contains 12% or more of alkaline oxides (both Na_2O and K_2O) which makes it widely used in the production of tiles and dark phonolite glass [28-30].

Although there are several studies regarding the use of kaolin particles as fillers to improve the hardness and wear properties of the polymer composites, however, to our knowledge, the use of phonolite particles as fillers for this purpose has so far not been studied. Thus, this work aims to investigate the effect of the incorporation of phonolite particles into polyester resin on the hardness and abrasive wear behavior of GFRP composites, and compared with un-filled and kaolin-filled composites. Additionally, the paper shows the possible utilization of igneous rocks such as phonolite to improve the hardness and wear properties of GFRP composites.

II. MATERIALS AND METHODS

A. Materials

Chopped strand mat made from E-glass fiber MAT8–450 (450 g/m^2) was used as reinforcement material, and unsaturated polyester resin EK–300 Tix (1.23 g/cm^3) was used as polymer matrix; methyl ethyl ketone peroxide M–60 was used as a hardener. These materials were purchased from (Libya Glass Company/Misurata-Libya). Kaolin and phonolite that used as fillers were obtained from (The Investment Complex for Building Materials (INCOMA)/Misurata-Libya). To facilitate removal of the fabricated composite from the mold, wax paper was used as a releasing agent. The chemical compositions of Kaolin and phonolite are presented in Table 1.

Table 1 Chemical composition (wt%) of the used kaolin and phonolite.

Component	Kaolin	Phonolite
SiO_2	64.60	57.17
Al_2O_3	30.33	21.30
Na_2O	0.23	8.12
K_2O	0.81	7.25
Fe_2O_3	1.82	2.17
CaO	0.38	2.17
MgO	0.26	0.46
TiO_2	1.46	0.32
ZrO_2	–	0.18
MnO	–	0.17
Cl	0.07	0.26

B. Preparation of kaolin and phonolite filler particles

Raw kaolin clay and phonolite rocks were milled into powder using a ball mill (FAST-MILL modular, Gabbrielli Technology), and then passed through a stack of sieves (Linker Test Sieve) that placed on a sieve shaker (Endecotts Octagon Sieve Shaker) as shown in Figure 1. Kaolin and phonolite particles with size of (75 to 125 μm) were collected to be used for preparation of matrix modified composite specimens.

Fig. 1. Sieves and Shaker used for fillers preparation.

C. Preparation of the composites

Three plates of glass fiber reinforced polymer composites were fabricated by using hand lay-up technique; each specimen contains seven layers of chopped fibers mat with a dimension of (300×300 mm). Resin and hardener were mixed in ratio of 100:2, and then a layer of the resin was applied on the release paper which covers the mold plate, after that the first layer of the reinforced chopped mat was placed and entirely wetted by the resin. Consequently, the other layers were assembled by repeating theses steps. Finally, the prepared composite was allowed to cure at room temperature for 24 h. For the preparation of matrix modified composites, the same procedure was followed except that the pre-prepared filler particles (without any surface treatment) were added to the resin at 10 wt % and stirred gently for 10 min to obtain homogeneous mixture, and then the hardener was added. More details regarding the fabrication of the composites have been reported elsewhere [31, 32]. The prepared laminated plates are shown in Figure 2; the composite that reinforced with only chopped glass fiber and without any filler particles was denoted (GFRP), the composite laminates contain kaolin and phonolite particles were denoted (K-GFRP) and (Ph-GFRP), respectively.

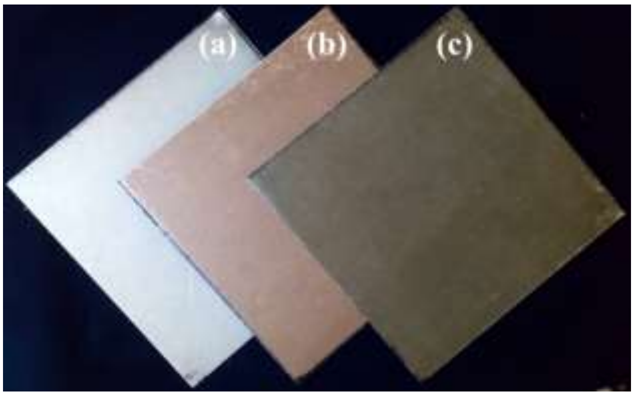

Fig. 2. The fabricated composites, (a) GFRP, (b) K-GFRP, and (c) Ph-GFRP.

After manufacturing of the laminates, the specimens were cut from each composite slab in a proper geometry as shown in Figure 3 to carry out hardness and abrasive wear tests according to the ASTM standards. Furthermore, physical properties including the theoretical and actual densities, as well as the void content were measured. The actual density (relative density) was measured by using the Archimedes principle (buoyancy method) and according to ASTM D792 standard [33]; the theoretical density and the volume fraction of voids were measured as per ASTM D2734 standard [34]. Details of these measurements were reported in a previous study [32].

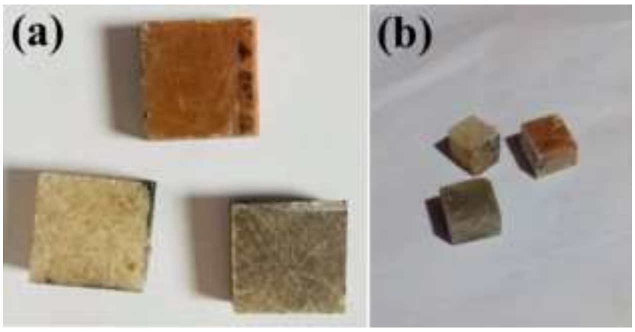

Fig. 3. Extracted specimens for: (a) Hardness and (b) abrasive wear tests

D. Testing of the composites

D.1. Hardness test

Brinell hardness test was conducted on the composite specimens using a GUNT WP 300 Universal Materials Testing Machine that shown in Figure 4.

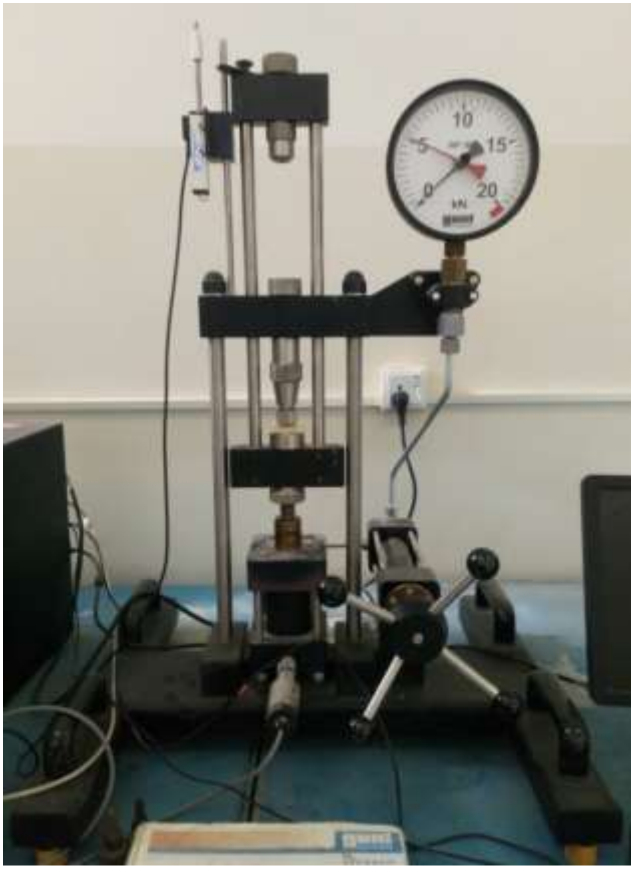

Fig.4. GUNT WP 300 Universal Materials Testing Machine used for Brinell hardness measurements

The test was carried out at lab conditions and the measurements were performed at five specimens extracted from different locations of the studied composite and then the average value was considered. A load of 4900 N was applied on the specimen for 15 sec using a hardened steel ball indenter with diameter of 10 mm; two perpendicular diameters of the test indentation were measured on the specimen surface using a measuring magnifier (SCHWEIZER Tech-Line, Magnification 8 X) with an accuracy of 0.1 mm, and then the mean diameter of the indentation is obtained. Brinell hardness was calculated as per the equation given below [35]:

$$\mathrm{HBS} = 0.102 \times \frac{2F}{\pi D\left(D - \sqrt{D^2 - d^2}\right)} \ \ldots\ldots\ldots\ldots (1)$$

Where: F is the test force in (N), D is the diameter of the indenter ball in (mm), and d is the mean diameter of the indentation in (mm).

D. 2. Abrasive wear test

Two-body abrasive wear test was conducted by using a custom-built pin-on-disc wear test apparatus as per ASTM G99 - 17 standard [36]. Figure 5 shows a schematic drawing of the designed pin-on-disc wear test system, as illustrated in this figure, the setup consists of a grinding and polishing machine (BUEHLER METASERV Grinder-Polisher, model type 95-C2268-250) placed on a steel table, a pin specimen holder attached to a pivoted loading lever-arm, the loading arm is supported in bearing arrangements to allow the pin specimen to be forced against the revolving disc of the grinding machine. A counter balance weight is attached to one end of the lever to keep the specimen un-loaded before adding the weights at the other end of the lever-arm.

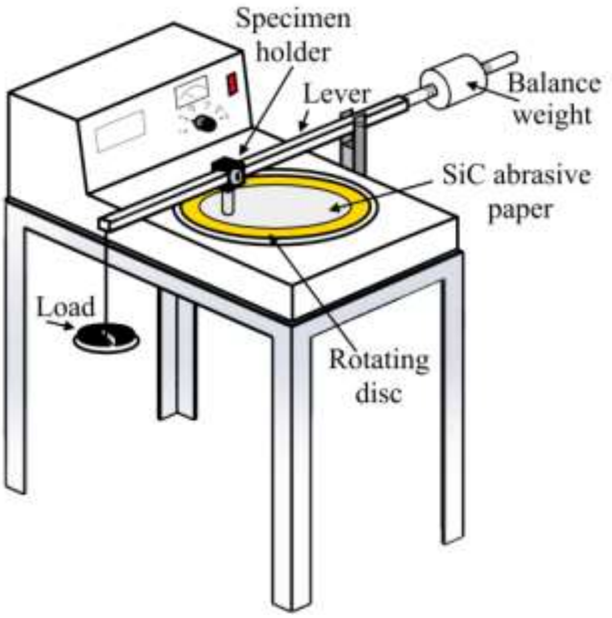

Fig.5. Schematic illustration of pin-on-disc wear test apparatus

To carry out the test, a specimen with dimensions of (10 mm×10 mm×the thickness of the composite in mm) was mounted at the pin so that its fibers layers and surface in parallel to the disc surface when in contact, and then abraded against a 400 grit water proof silicon carbide (SiC) abrasive paper at a constant running speed. Prior to testing, the specimens were polished against a 600 grit SiC paper in order to have a uniform contact with the disc surface. All composite specimens were tested dry under laboratory conditions (23°C, 50% humidity). The applied load and rotational speed were 25 N and 50 rpm, respectively. After a sliding distance of 100 m, the weight loss measurements were carried out using a digital analytical balance (METTLER TOLEDO Jewelry Carat Balance, model JB1603-L-C) with an accuracy of 0.1 mg; For each composite, the test was conducted for five times and the average of weight loss was taken, and then was converted into volume loss using the measured density, as stated by the equation:

$$\Delta V = \frac{\Delta W}{\rho} \times 1000 \ \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where: ΔV is the volume loss (wear volume) in (mm^3), and ΔW is the average of weight loss in (g), and ρ is the measured density (actual density) in (g/cm^3).

Consequently, wear rate (K), specific wear rate (K_s), and wear resistance (R) can be calculated as per the following equations:

$$K = \frac{\Delta V}{S} \ \ldots\ldots\ldots\ldots (3)$$

$$K_s = \frac{\Delta V}{P \times S} \ \ldots\ldots\ldots\ldots (4)$$

$$R = \frac{1}{K} \ \ldots\ldots\ldots\ldots (5)$$

Where: S is the sliding distance in (m), and P is the applied normal load in (N).

III. RESULTS AND DISCUSSION

A. Hardness

Hardness test is one of the tests that are conducted on the materials to evaluate their resistance to indentation, and it can be performed by various techniques depending on the materials properties. Brinell hardness values for the fabricated composites are shown in Figure 6; it is obvious that the lowest Brinell hardness of 16 BHS was obtained with GFRP composite that only consisting of chopped glass fibers as reinforcement agent and polyester resin as a matrix. The other two composites that their matrix was modified with kaolin and phonolite particles observed hardness values of 20 BHS, and 27 BHS, respectively. The enhancement in hardness has reached to 25% in the K-GFRP composite, and approximately 69% in the Ph-GFRP composite when compared with GFRP composite. The relatively small error bars shown in Figure 6 across all three composites reflect good fabrication quality and uniform filler dispersion. Minor variations may arise from slight differences in manual mixing intensity, subtle fluctuations in resin viscosity during casting, small misalignments during indentation, or the finite resolution of the measurement magnifier.

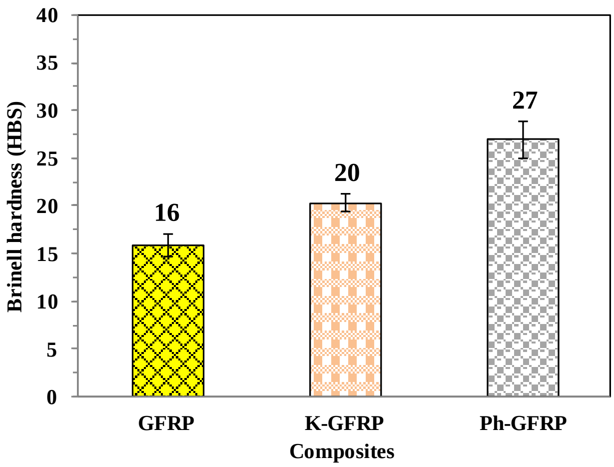

Fig. 6. Effect of particulates addition on hardness values of the prepared composites (standard deviations are shown as error bars).

Higher hardness means less penetration of test ball to the surface of fabricated composite due to the greater resistance of the material to local deformation and also indicates a stronger bonding between the substances of the composites [37]. The deformation mode under an indenter is a mix of compression, tension, and shear [38]; the tensile, compressive, and interlaminar shear strength of the studied composites were reported elsewhere [31], and represented in Table 2. As it is clear from Table 2, the existence of solid kaolin and phonolite particles in the polymer matrix has improved the mechanical properties of the modified composites, since they restrict polymer chain mobility; and consequently, the hardness is increased. Building on the detailed discussion presented in our previous study [31], we elucidate how differences in the chemical composition of these fillers influence their performance. Kaolin and phonolite essentially possess layered silicate structures whose mechanical behavior is governed by their aluminosilicate framework and cation content; this makes them effective crack-arresters within the polymer matrix. In particular, phonolite's roughly 15 wt % of alkali metal oxides (Na_2O and K_2O, Table 1) likely can interact more strongly with the unsaturated polyester chains, enhancing interfacial adhesion and stress transfer. As a result, Ph-GFRP shows superior strength compared to K-GFRP. Although we did not perform SEM or FTIR analyses in this work, future studies employing these techniques may validate the proposed mechanisms.

Table 2. Tensile, compressive, and shear properties of the fabricated composites.

Composite	Tensile strength (MPa)	Compressive strength (MPa)	Interlaminar shear strength (ILSS) (MPa)
GFRP	72.88	124.4	9.27
K-GFRP	89.59	158.6	11.04
Ph-GFRP	104.73	207	14.41

B. Abrasive wear

Abrasive wear is one of the most economically important types of wear due to the cost related to the damaged of equipment, down time, and materials loss. According to the ASM International, abrasive wear is defined as damage to a solid surface that usually involves loss of material due to relative motion between that surface and a contacting substance or substances, and it is categorized based on the types of contact between the surfaces into: two-body and three-body abrasive wear [11]. Figure 7 shows the average of weight loss for the studied composites using two-body abrasive wear test; it is clear from the figure that the highest weight loss of 0.0866 g was observed for the un-filled composite (GFRP), and the lowest value of 0.0711 g was for phonolite-filled composite (Ph-GFRP), where the K-GFRP composite shows a weight loss of 0.0813 g. Again, the small error bars reflect consistent sample preparation and high repeatability. Minor variations likely arise from slight misalignments in pin–disc contact, uneven abrasive grit distribution, or manual loading and positioning of the specimens.

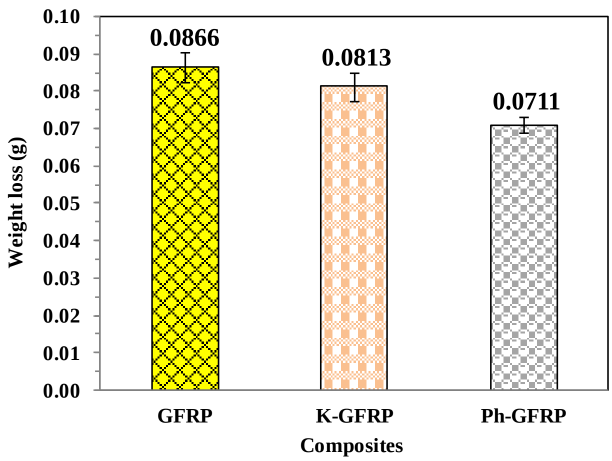

Fig. 7. Effect of particulates addition on weight loss of the prepared composites (standard deviations are shown as error bars).

To estimate the wear volume for the fabricated composites, the densities of the specimens were measured. Table 3 lists the theoretical and actual densities of all composites along with the corresponding volume fraction of void content. By using of equation 2, the volume loss was calculated and the obtained values are shown in Figure 8. It is obvious from the Figure 8 that the incorporation of the filler particles into the polymer matrix caused a decrease in the volume loss with about 8.5% in the K-GFRP composite, and approximately 19.7% in the Ph-GFRP composite when compared with GFRP composite.

Table 3. Theoretical and actual densities along with void content fractions in composites.

Composite	Theoretical Density (g/cm^3)	Actual Density (g/cm^3)	Void Content, volume (%)
GFRP	1.511	1.498	0.86
K-GFRP	1.559	1.537	1.44
Ph-GFRP	1.543	1.531	0.82

From Table 3, it can be noted that the actual density of the modified composites was slightly increased with about 2.6% for K-GFRP composite, and 2.2% for Ph-

GFRP composite. Also, the volume fraction of voids was almost 1% for all the fabricated composites. According to ASTM 2734 standard, the void content is desirable for estimation the quality of composites, since a good composite may have 1% voids, whereas a poorly made composite can have a much higher void content. Furthermore, some of the mechanical properties of the composite may significantly affected by the void content [34].

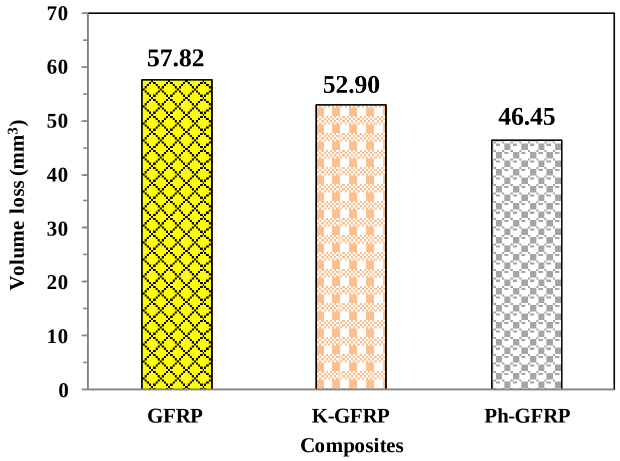

Fig. 8. Effect of particulates addition on volume loss of the prepared composites

To calculate the wear rate (K), and the specific wear rate (K_s) equations 3, and 4, were used, respectively. The results are shown in Figure 9; the obtained values follow a similar trend to that observed previously in weight loss and volume loss plots.

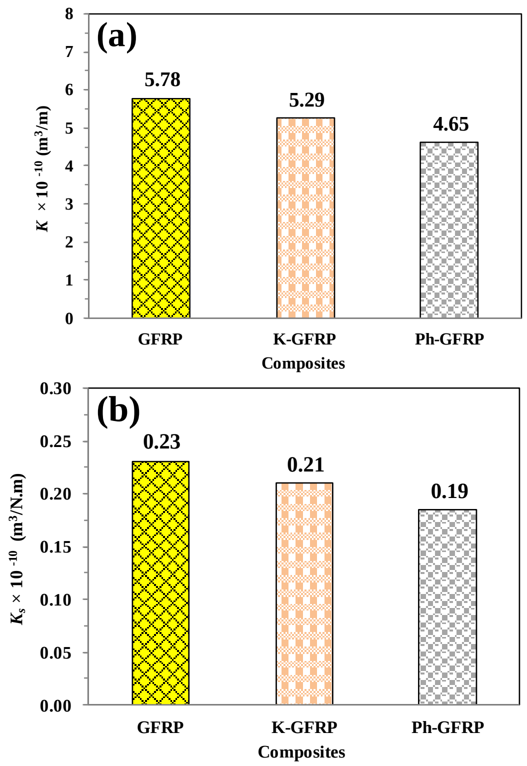

Fig. 9. Effect of particulates addition on: (a) wear rate, and (b) specific wear rate values.

Wear resistance (R) is an important mechanical property, and commonly, materials are described as having good or bad wear resistance; R is simply defined as the reciprocal of wear rate [11]. Figure 10 shows the obtained wear resistance values by using of equation 5; as it is shown in the figure, the incorporation of kaolin and phonolite particles into polymer matrix is considerably improved the wear resistance for the prepared composites. The enhancement in wear resistance has reached to 9.2% in the K-GFRP composite, and approximately 24.3% in the Ph-GFRP composite.

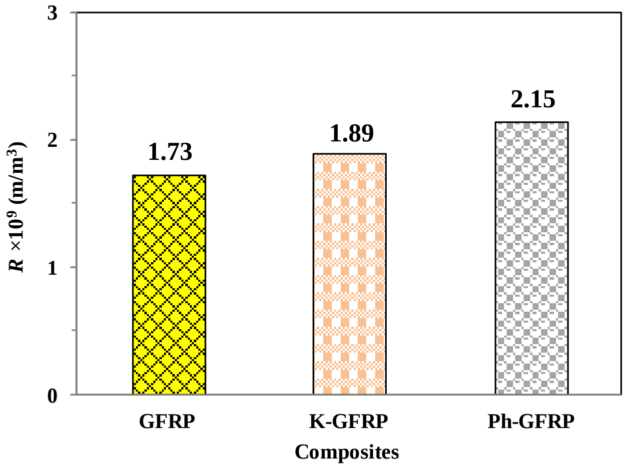

Fig. 10. Wear resistance values for the fabricated composites.

Generally, the wear behavior of the materials that slide over one another is affected by the hardness of the materials and the sliding conditions such as velocity, loading parameters, and environment [39]. In the presented study, all specimens were tested under dry conditions at the same load and velocity; therefore, the variations in the wear performance of the fabricated composites are attributed to the differences in their hardness. In fact, the abrasive wear is mainly dependent on the hardness of the materials, hardness plays a major role in improving the wear resistance of the composite [9]. As mentioned above, the hardness of modified composites was increased by the use of kaolin and phonolite particles as fillers, therefore wear properties of these composites were improved compared with un-filled one. Also, Chelliah [9] in his study of the mechanical properties and abrasive wear of basalt fabric reinforced epoxy composites, indicated that the presence of TiC filler in resin protects the fiber from further damage, and thus the abrasion wear resistance of filled composites was improved. A similar role can be expected by using of rigid kaolin and phonolite particles, and that is in agreement with the experimentally achieved improvements in wear performances of the modified composites.

IV. CONCLUSION

The effect of matrix modification on the hardness and abrasive wear performance of glass fiber reinforced polymer composites was investigated. Natural fillers of Kaolin and phonolite particles were used to modify the unsaturated polyester. Composites of modified and un-modified polyester were fabricated and compared in terms of their hardness and wear behavior. Incorporating of Kaolin and phonolite fillers into the polyester resin was improved the studied characteristics of the modified composites with negligible increases in their density. The enhancements may be an indication of better interfacial adhesion between the substances of the modified composites. Furthermore, the addition of rigid kaolin and phonolite particles in polymer matrix directly enhances the mechanical properties of the composites, which leads to improve their hardness and wear performance. The significant improvements were observed for the composite modified with phonolite particles, this enhancement was attributed to its superior properties as a feldspar rock, and to its chemical composition. Finally, the absence of SEM and FTIR analysis, and the fixed filler loadings and testing conditions represent limitations; therefore, future work may optimize filler ratios and employ microstructural analysis to deepen mechanistic insights.

Data Availability: All data that support the findings of this study are included within the article.

Declarations:

Funding Statement: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest: The authors declare that there is no conflict of interest regarding the publication of this article.

REFERENCES

[1] E. J. Barbero, *Introduction to composite materials design*: CRC press, 2010.

[2] P. K. Bajpai and I. Singh, *Reinforced Polymer Composites: Processing, Characterization and Post Life Cycle Assessment*: John Wiley & Sons, 2019.

[3] V. V. Tcherdyntsev, "Reinforced Polymer Composites III," vol. 15, ed: MDPI, 2023, p. 2069.

[4] F. Teklal, *et al.*, "A review of analytical models to describe pull-out behavior–Fiber/matrix adhesion," *Composite Structures,* vol. 201, pp. 791-815, 2018.

[5] Q. Wu, *et al.*, "Nano-analysis on the structure and chemical composition of the interphase region in carbon fiber composite," *Composites Part A: Applied Science and Manufacturing,* vol. 56, pp. 143-149, 2014.

[6] S.-O. An, *et al.*, "A study on the cutting characteristics of glass fiber reinforced plastics with respect to tool materials and geometries," *Journal of Materials Processing Technology,* vol. 68, pp. 60-67, 1997.

[7] V. Chaudhary, *et al.*, "An investigation on wear and dynamic mechanical behavior of jute/hemp/flax reinforced composites and its hybrids for tribological applications," *Fibers and polymers,* vol. 19, pp. 403-415, 2018.

[8] C. A. Chairman, *et al.*, "Mechanical and Abrasive Wear Performance of Titanium Di-Oxide Filled Woven Glass Fibre Reinforced Polymer Composites by Using Taguchi and EDAS Approach," *Materials,* vol. 14, p. 5257, 2021.

[9] A. Chelliah, "Mechanical properties and abrasive wear of different weight percentage of TiC filled basalt fabric reinforced epoxy composites," *Materials Research,* vol. 22, p. e20180431, 2019.

[10] M. Neale and M. Gee, *A guide to wear problems and testing for industry*: William Andrew, 2001.

[11] P. J. Blau, *Friction, lubrication, and wear technology* vol. 18: ASM Materials Park, USA, 1992.

[12] B. Suresha, *et al.*, "Investigations on the influence of graphite filler on dry sliding wear and abrasive wear behaviour of carbon fabric reinforced epoxy composites," *Wear,* vol. 267, pp. 1405-1414, 2009.

[13] K. Rahmani, *et al.*, "The experimental investigation of hardness and wear behaviors of inner surface of the resin tubes reinforced by fibers," *Results in Engineering,* vol. 11, p. 100273, 2021/09/01/ 2021.

[14] H. Pıhtılı and N. Tosun, "Investigation of the wear behaviour of a glass-fibre-reinforced composite and plain polyester resin," *Composites Science and Technology,* vol. 62, pp. 367-370, 2002.

[15] G. Agarwal, *et al.*, "Thermo-mechanical properties of silicon carbide filled chopped glass fiber reinforced epoxy composites," *International journal of Advanced structural Engineering,* vol. 5, pp. 1-8, 2013.

[16] G. Raghavendra, *et al.*, "A comparative analysis of woven jute/glass hybrid polymer composite with and without reinforcing of fly ash particles," *Polymer composites,* vol. 37, pp. 658-665, 2016.

[17] B. Yousif and N. El-Tayeb, "Wear characteristics of thermoset composite under high stress three-body abrasive," *Tribology International,* vol. 43, pp. 2365-2371, 2010.

[18] G. Shi, *et al.*, "Sliding wear behavior of epoxy containing nano-Al2O3 particles with different pretreatments," *Wear,* vol. 256, pp. 1072-1081, 2004.

[19] W. Alhazmi, *et al.*, "Tribological and mechanical properties of epoxy reinforced by hybrid nanoparticles," *Latin American Journal of Solids and Structures,* vol. 18, p. e361, 2021.

[20] M. George, *et al.*, "Mechanical and thermal properties of modified kaolin clay/unsaturated polyester nanocomposites," *Journal of Applied Polymer Science,* vol. 133, 2016.

[21] X. Kornmann, *et al.*, "Synthesis of epoxy–clay nanocomposites. Influence of the nature of the curing agent on structure," *Polymer,* vol. 42, pp. 4493-4499, 2001.

[22] Z. Arifin Mohd Ishak, "Effect of clay addition on mechanical properties of unsaturated polyester/glass fiber composites," *International Journal of Polymer Science,* vol. 2013, 2013.

[23] [23] M. Kotal and A. K. Bhowmick, "Polymer nanocomposites from modified clays: Recent advances and challenges," *Progress in Polymer Science,* vol. 51, pp. 127-187, 2015.

[24] L. Benco, *et al.*, "Upper Limit of the O− H - - - O Hydrogen Bond. Ab Initio Study of the Kaolinite Structure," *The Journal of Physical Chemistry B,* vol. 105, pp. 10812-10817, 2001.

[25] N. Kumari and C. Mohan, "Basics of clay minerals and their characteristic properties," *Clay and Clay Miner,* vol. 24, 2021.

[26] A. Anam, *et al.*, "An overview of kaolin and its potential application in thermosetting polymers," *Materials Today Communications,* vol. 36, p. 106827, 2023.

[27] N. M. Ahmed, *et al.*, "Characterization of a polymer composite from treated kaolin and unsaturated polyester based on PET waste," *Polymer composites,* vol. 34, pp. 1223-1234, 2013.

[28] R. W. Le Maitre, *et al.*, *Igneous rocks: a classification and glossary of terms: recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks*: Cambridge University Press, 2005.

[29] J. M. Hidalgo-Herrador, *et al.*, "Cold Plasma and Acid Treatment Modification Effects on Phonolite," *Acta Chimica Slovenica,* vol. 64, 2017.

[30] P. Andrade, *et al.*, "Effect of phonolite addition on sintering kaolinitic clay," *Cerâmica,* vol. 51, pp. 362-371, 2005.

[31] M. A. Ballem and R. R. Khalifa, "Effect of Kaolin and Phonolite Particulates Addition on the Mechanical Properties of Glass−Fiber Composites," *Submitted Manuscript,* 2024.

[32] M. A. Ballem, *et al.*, "Effect of Kaolin and Phonolite Particulates Addition on Some Physical Properties of Glass−Fiber Composites," *Submitted manuscript,* 2024.

[33] ASTM D792 Standard Test Method for Density and Specific Gravity (Relative Density) of Plastics by Displacement," *ASTM International: West Conshohocken, PA, USA,* 2007.

[34] ASTM D2734 Standard Test Method for Void Content of Reinforced Plastics," *ASTM International: West Conshohocken, PA, USA,* 1994 (Reapproved 2003)

[35] ASTM E10 - 00 Standard Test Method for Brinell Hardness of Metallic Materials," *ASTM International: West Conshohocken, PA, USA*, 2000.
[36] ASTM G99 - 17 Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus," in *ASTM International: West Conshohocken, PA, USA*, ed, 2017.
[37] M. K. Lila, *et al.*, "Characterization techniques of reinforced polymer composites," *Reinforced polymer composites: processing, characterization and post life cycle assessment,* pp. 119-145, 2019.
[38] R. Brown, *Handbook of Polymer Testing: Short-term Mechanical Tests*: Rapra Technology, 2002.
[39] L. Chen, *et al.*, "Fabrication of polymer matrix composites reinforced with controllably oriented whiskers," *Journal of materials science,* vol. 35, pp. 5309-5312, 2000.