

EFFECTS OF MODIFIED KAOLIN ON MECHANICAL PROPERTIES OF ALUMINIUM METAL MATRIX COMPOSITE

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ABSTRACT

This study investigated the effect of modified kaolin on the mechanical properties of aluminium metal matrix composites (MMCs). Aluminium alloys are widely used for their lightweight properties but can be limited by mechanical strength. Metal matrix composites offer a potential solution by combining the benefits of metal and reinforcing materials. However, traditional reinforcing materials can be expensive. This study explores the possibility of using kaolin, a more cost-effective alternative, as a reinforcing material. Kaolin was modified at different temperatures (550°C and 1100°C) and incorporated into the aluminium matrix at varying weight percentages. The resulting MMCs were then subjected to mechanical testing to assess their compressive strength, tensile strength, hardness, and fracture toughness. The results revealed that the modification temperature and kaolin content significantly impacted the mechanical properties of the MMCs. Samples modified at 550°C exhibited higher compressive strength compared to those modified at 1100°C. In contrast, higher modification temperatures led to improved fracture toughness. The addition of kaolin also influenced hardness, with a general trend of decreasing hardness with increasing kaolin content. This study suggests that modified kaolin can be a viable reinforcing material for aluminium MMCs. The mechanical properties can be tailored by adjusting the modification temperature and kaolin content. Further research is recommended to optimize these parameters for specific applications.

Keywords: kaolin, aluminium, mechanical properties, compressive strength, hardness

1 INTRODUCTION

In recent years, there has been a growing fascination with both continuously and discontinuously reinforced MMCs. These composites possess a remarkable combination of qualities, such as exceptional strength, high elastic modulus, impressive toughness, and impact resistance. Additionally, they exhibit low susceptibility to temperature changes or thermal shock, boast high surface durability, and are less affected by surface flaws [1]. Furthermore, they offer excellent electrical and thermal conductivity, minimal vulnerability to moisture absorption leading to environmental degradation, and improved ease of fabrication using conventional equipment [2, 3]. Composites are gaining grounds in industrial applications where metals were traditionally used due, mainly, to their favourable strength-to-weight ratio and comparable (or in most cases, better) mechanical properties [4]. Additional aims of metal composite materials encompass enhancing yield strength and tensile strength at both room temperature and elevated temperatures, all the while preserving adequate ductility and toughness. In the realm of materials science, the pursuit of high-performance materials is a perpetual quest driven by the diverse demands of modern technology and industry. Lightweight metals, often favoured for their ease of use and versatility,

have become integral components in numerous applications ranging from aerospace engineering to automotive manufacturing. However, these monolithic light metals, such as aluminium, inherently possess limitations in terms of their mechanical properties, particularly when confronted with the rigorous requirements of high-performance and structural applications. The dichotomy arises from the fact that the very attributes making light monoliths attractive—such as low density and ease of fabrication—often come at the expense of mechanical strength, hardness, and wear resistance. These limitations become particularly apparent when engineering materials for critical applications where structural integrity and reliability are paramount [5]. Consequently, there is a pressing need to explore innovative avenues that merge the favourable lightweight characteristics of monolithic light metals with the robust strength capabilities of reinforcing materials, thereby creating composite materials that surpass the limitations of their individual components. Furthermore, the economic considerations associated with the production of metal matrix composites (MMCs) add an additional layer of complexity to the material design process. Traditional reinforcing materials, such as silicon carbide or alumina, are effective but can be prohibitively expensive. The high cost of these reinforcements limits the widespread adoption of MMCs, especially in cost-sensitive industries. Hence, it becomes imperative to identify and employ reinforcing materials that not only enhance the mechanical properties of the base metal but also do so in a cost-effective manner [6, 7]. It is generally agreed that micro hardness and resistance to wear of MMCs is created by reinforcement and also wear properties are improved remarkable by introducing hard intermetallic compounds into aluminium matrix [5, 8]. The reinforcement materials are generally SiC, Al₂O₃, TiO₂, SiO₂ etc. These reinforcement materials are however, very costly [9, 10]. In light of these challenges, the present study seeks out to determine the mechanical properties of modified kaolin on mechanical properties of aluminium metal matrix composite.

2 METHODOLOGY

2.1 Materials

Aluminium alloy which belongs to the 6000 series was used as the matrix in the synthesis of the composite. It was processed into smaller pieces in order to keep the alloy inside the crucible properly. Composition of the matrix alloy was analyzed and the complete composition reported. Kaolin was used as the reinforcing material. The reinforcing material was obtained from kaolin deposits in Bauchi state, Nigeria. The solid particles were also crushed into the required particle size of kaolin.

2.2 Thermal Modification of Kaolin

The kaolin was modified by heating it to specified temperatures for 30 minutes according to the methods specified by [11]. This process was conducted at the University of Maiduguri Faculty of Engineering Teaching Workshop. Part of the raw kaolin obtained was heated in a furnace to 550°C in order to dehydroxylate the kaolin (Al₂(Si₂O₅)(OH)₄) to metakaolin (Al₂O₃.2SiO₂). The other part was heated to 1100°C to transform to a metastable phase of spinel-type structure. Unmodified kaolin, kaolin modified at 550°C and kaolin modified at 1100°C were each used as reinforcement in aluminium metal composite.

2.3 Preparation of the Metal Matrix Composite

In order to achieve uniform dispersion of the dispersoid, a stir casting route was employed to synthesize the composite. Aluminium alloy was introduced into a furnace and melted to 750°C after which, kaolin and carbon pre-heated to 700°C (to remove moisture and gases from the surface of the particulates) was introduced into the molten metal. Simultaneously, the molten MMC was well agitated by means of a graphite stirrer, rotating at a specified speed, to create vortex motion. The melt will then be poured into a mould and allowed to solidify. After casting the samples were prepared for test.

2.4 Sample Formulation

Modified kaolin at 550°C and 1100°C are each mixed with aluminium using the weight percentage depicted in Table 1. The selected percentages are based on findings from previous research and pilot studies

indicating that these compositions offer a good compromise between different properties. The 100% aluminium sample (Sample A) serves as a control to compare the properties of the composite samples.

Table 1. Composition of the Metal Matrix Composite

Samples	Aluminium (% wt)	Kaolin (% wt)	Thermal modification temperature (°C)
A	100	0	-
B	97	3	550
C	94	6	550
D	91	9	550
E	97	3	1100
F	94	6	1100
G	91	9	1100

2.5 Testing Procedure

2.5.1 Tensile Tests

The tensile stress test was carried out using OKHARD Universal Testing Machine (UTM). The specimen was readied in accordance with ASTM E8/E8M standard (2021) and had dimensions of 25 x 25 x 200 millimeters. It was affixed to the UTM at both ends. The machine was programmed with information regarding the specimen's dimensions, material type, and the intended test type, followed by pressing the OK button. Upon pressing OK, the machine initiated the process of pulling the specimen until it fractured, and the resulting values, such as yield strength and ultimate strength, were displayed on the screen.

2.5.2 Hardness Tests

The ASTM E18 standard (2021) was followed to conduct Rockwell hardness tests on metallic materials. The sample surfaces were prepared according to specification of 100 mm by 200 mm, and the hardness testing machine was calibrated as per the manufacturer's instructions. A minor load was applied, followed by a major load, and a specified dwell time allowed for stabilization. Subsequently, the major load was released while maintaining the minor load. The resulting hardness value was then measured. The entire procedure adhered to the standard guidelines and manufacturer's instructions to ensure accurate and reliable hardness test results.

2.5.3 Compressive Stress Test

The tensile stress test was carried out using ELE Automatic Compression Machine (S/N 016615). In accordance with the ASTM E18 standard (2021), the specimen was fashioned in a cubic shape with dimensions of 400 × 400 millimetres. The initial step involved recording the dimensions to calculate the area of the cubic specimen. Subsequently, the specimen was placed into the machine, covered, and the loading process was initiated. During the loading process, readings were monitored using an analogue meter detector. The recording was halted promptly upon the specimen's fracture.

2.5.4 Fracture Toughness Tests

The tensile stress test was carried out using OKHARD Universal Testing Machine. The specimen was fashioned in adherence to ASTM standard E399 (2009), featuring dimensions of 100 × 100 × 10 millimeters. It underwent a cutting process at the centre, using a cutting machine, resulting in a cut extending up to 25 millimeters. Subsequently, the specimen was positioned inside a prepared container, which was then inserted into the machine. A sharp tool was introduced into the cut section, and compressive load was applied until the specimen fractured. Following the fracture, measurements of crack length and area were taken and recorded. The material's critical stress and toughness were then calculated based on the recorded data.

3 RESULTS AND DISCUSSION

3.1 Characterization of the Aluminium Alloy

Figure 1 shows the elemental composition of the aluminium alloy used in the study. Aluminium is the base metal of the alloy, and it makes up 55.21% of the weight. Silicon is the second-most common element, and it makes up 25.55% of the weight. Silicon is a hardener, and it helps to improve the strength of the alloy. Calcium, iron, silver, sodium, magnesium, chlorine, potassium, Sulphur, phosphorus, and titanium are all minor elements, and they make up less than 5% of the weight of the alloy. The specific composition of the aluminium alloy will affect its properties, such as its strength, hardness, ductility, and toughness. For example, the addition of silicon will increase the strength of the alloy, while the addition of iron will decrease the ductility of the alloy [12].

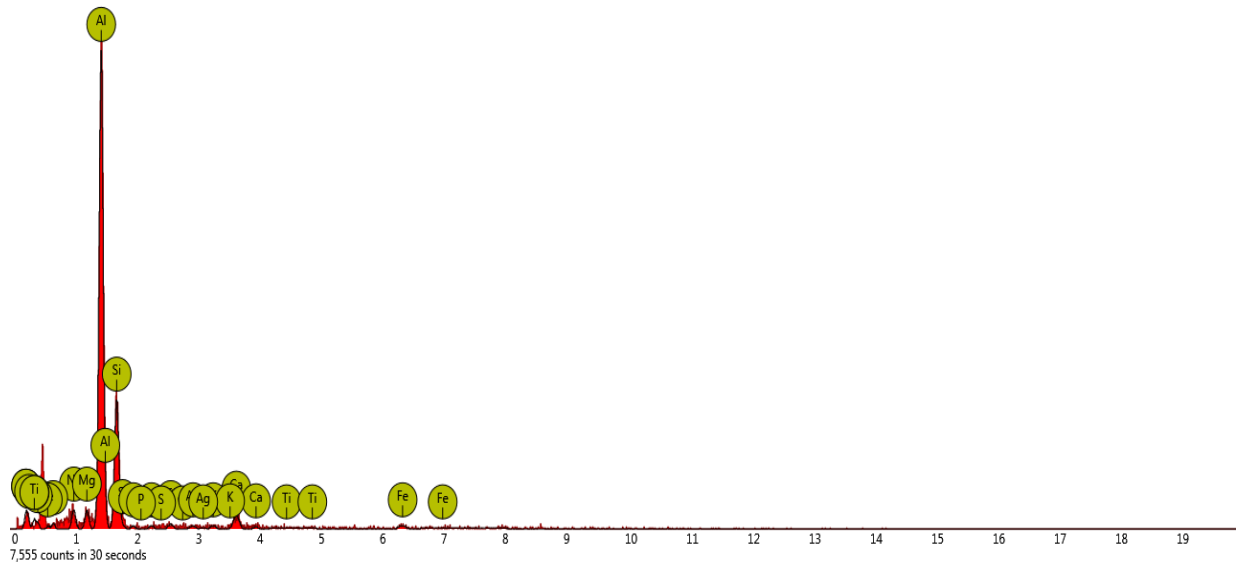


Figure 1. Elemental composition of aluminium alloy

3.2 Modification of Kaolin

Unmodified kaolin was heated to temperature of 550°C and 1100°C respectively and the change in the constituents of the kaolin is presented in Table 2. The increase in SiO₂ content at 550°C and its subsequent decrease at 1100°C may be attributed to the structural changes during modification. It has been reported by Malima *et al.* [13] that kaolin undergoes various transformations at elevated temperatures, and these changes can affect its silica content. The decrease in Al₂O₃ content at 550°C followed by an increase at 1100°C indicates the thermal transformation of kaolin. The decrease is associated with dihydroxylation and other structural changes, while the increase could be due to the formation of new alumina phases. The significant increase in Fe₂O₃ at 550°C suggests the oxidation of iron-containing impurities or the transformation of iron compounds in kaolin as similar result was reported by Khalfa *et al.* [14]. The subsequent decrease at 1100°C is due to the reduction or volatilization of certain iron species. The changes in K₂O and CaO content may be linked to the alteration of potassium and calcium-bearing phases in kaolin during modification as similar results were obtained by Kentsa *et al.* [15]. The variations are attributed to the release or incorporation of these elements under different temperature conditions.

Table 2. Oxides of kaolin

Oxides	% concentration (wt)		
	Unmodified kaolin	Modified at 550°C	Modified at 1100°C
SiO ₂	57.948	59.848	58.545
V ₂ O ₅	0.240	0.308	0.144
Cr ₂ O ₃	0.017	0.029	0.016
MnO	0.055	0.042	0.054
Fe ₂ O ₃	2.391	3.206	1.915
Co ₃ O ₄	0.006	0.011	0.003
NiO	0.009	0.013	0.006
CuO	0.055	0.086	0.036
Nb ₂ O ₃	0.025	0.043	0.015
MoO ₃	0.001	0.000	0.000
WO ₃	0.000	0.007	0.000
P ₂ O ₅	0.010	0.000	0.000
SO ₃	0.000	0.494	0.246
CaO	0.565	0.340	0.165
MgO	0.000	0.000	0.000
K ₂ O	0.858	0.829	0.464
BaO	0.015	0.000	0.062
Al ₂ O ₃	31.303	26.549	33.747
Ta ₂ O ₅	0.059	0.017	0.013
TiO ₂	4.839	6.298	3.460
ZnO	0.027	0.035	0.061
Ag ₂ O	0.000	0.000	0.000
Cl	0.814	1.266	0.742
ZrO ₂	0.763	0.581	0.307
SnO ₂	0.000	0.000	0.000

Figure 2 shows the change in the elemental composition of unmodified and modified kaolin. The elemental composition data for unmodified kaolin and kaolin modified at different temperatures reveals notable changes in the concentrations of various elements. At 550°C, a slight decrease in oxygen content is observed, indicating potential structural alterations in the kaolin matrix. The decrease in aluminium (Al) content is associated with dihydroxylation processes or structural configurations. Silicon (Si) content remains relatively stable, suggesting resistance to significant changes at this temperature. The increase in Sulphur (S) and chlorine (Cl) content at 550°C could be attributed to the incorporation or release of these elements during modification. Additionally, elements like titanium (Ti) and iron (Fe) show an increase at 550°C, suggesting potential modifications in their speciation. Figure 2. Elemental composition of kaolin at different modification temperature. At 1100°C, the oxygen content increases, possibly due to oxidation processes occurring at higher temperatures. Al and Si contents show variations, indicating continued structural changes. The decrease in Sulphur and chlorine contents at 1100°C suggests volatilization or transformation of these elements. Overall, these changes highlight the dynamic nature of kaolin under different modification temperatures, indicating structural adjustments and potential transformations of specific elements [16].

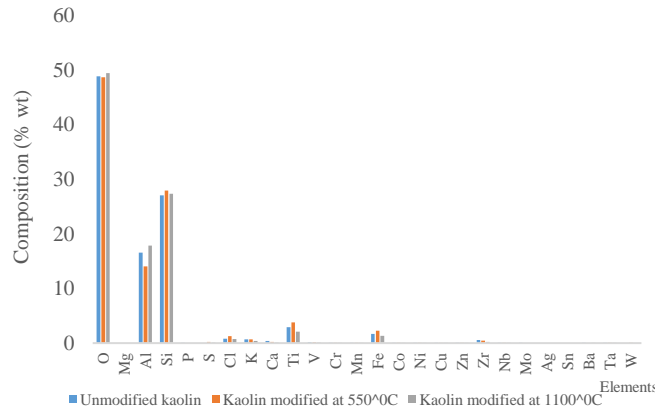


Figure 2. change in the elemental composition of unmodified and modified kaolin

3.3 Elemental Composition of the Aluminium-Kaolin Composite

The percentage concentration of the elements by weight of the different samples are shown in Table 3. The samples are as designated in Table 3.1. 500 g is taken as 100% aluminium (sample A) and the remaining samples are taken as 97% aluminium 3% kaolin, 94% aluminium 6% kaolin and 91% aluminium 9% kaolin. The elemental composition of samples A to G shows significant variations in the weight percentages of various elements. Notably, the oxygen content ranges from 42.707% (sample B) to 47.639% (sample G), indicating variations in oxide content. Al content varies from 12.101% (sample B) to 34.921% (sample G), reflecting a wide range of alloying concentrations. Si content shows a range from 13.388% (sample G) to 21.099% (sample B). Cl content varies significantly, with the highest concentration in sample B (13.328%). Cu and Zn also exhibit notable variations, with sample B having the highest Cu content (2.189%) and sample E having the highest Zn content (5.780%). These differences suggest diverse alloy compositions with potential implications for mechanical, thermal, and corrosion properties [5, 17].

Table 3. Elemental composition of samples

Element	% wt						
	A	B	C	D	E	F	G
O	44.948	42.707	45.705	46.552	43.962	46.961	47.639
Mg	2.433	6.316	0.000	0.000	0.000	0.000	0.000
Al	20.196	12.101	22.959	25.701	24.604	28.691	34.921
Si	18.497	21.099	18.470	18.811	15.772	17.212	13.388
S	1.413	1.831	0.622	0.000	0.000	0.000	0.173
Cl	5.820	13.328	1.511	1.466	1.956	0.730	0.368
K	0.000	0.000	0.130	0.144	0.464	0.000	0.147
Ca	1.813	0.695	1.070	0.336	0.994	0.298	0.449
Ti	0.142	0.216	0.447	0.378	0.306	0.080	0.048
V	0.000	0.000	0.016	0.013	0.042	0.026	0.006
Cr	0.038	0.022	0.022	0.029	0.045	0.014	0.028
Mn	0.236	0.107	0.304	0.155	0.415	0.205	0.117
Fe	1.007	0.780	1.594	0.995	2.247	0.816	0.568
Ni	0.029	0.015	0.057	0.074	0.082	0.029	0.019
Cu	1.048	0.156	2.189	1.834	2.707	1.168	0.654
Zn	2.160	0.349	4.425	3.095	5.780	3.472	1.311
Zr	0.012	0.048	0.023	0.022	0.023	0.012	0.002
Nb	0.019	0.036	0.022	0.007	0.052	0.004	0.003
Mo	0.018	0.060	0.004	0.015	0.027	0.002	0.003
Ta	0.124	0.031	0.378	0.249	0.406	0.219	0.118
W	0.046	0.049	0.054	0.119	0.115	0.055	0.037

3.3 Mechanical Properties of the MMC

3.3.1 Compressive strength

The compressive strength of the samples all of area 2500 mm² is depicted in Figure 3. Samples B, C, and D modified at 550°C show relatively higher compressive strengths compared to samples E, F, and G modified at 1100°C. High-temperature modifications might result in changes in the microstructure of the material, leading to altered compressive properties [18]. Comparing within the same temperature modification, samples with lower kaolin content (B, C, and D) generally exhibit higher compressive strengths. This indicates that kaolin is likely affecting the material’s structural integrity and strength, and higher percentages may lead to reduced strength. Samples B, C, and D with moderate compressive strengths could find applications in areas where a balance between strength and other properties is needed. Samples E, F, and G, despite having lower compressive strengths, might still be suitable for applications where high-temperature resistance is more critical than compressive strength.

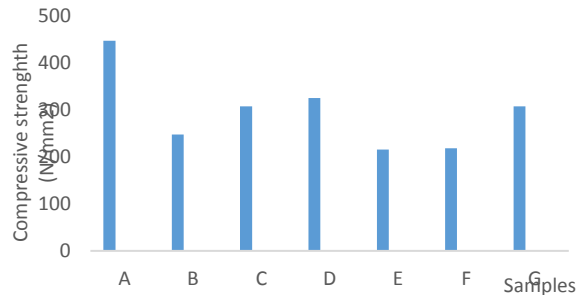


Figure 3. Compressive strength of the composites

3.3.2 Tensile Strength

The tensile strength of the samples all of area 625 mm² is shown in Figure 4. The tensile strength test results reveal distinct characteristics for each sample, with variations in yield strength, limited strength, and ultimate strength. Sample A exhibits the highest values across all categories, signifying its superior ability to withstand deformation before plastic deformation occurs. In terms of limited strength, samples B, C, D, and E show slightly lower values compared to A, representing the point at which limited plastic deformation occurs. Similarly, the ultimate strength of Sample A is the highest, indicating its capacity to endure maximum stress before failure. Comparing these tensile strength values to other materials is contingent on specific application requirements. Generally, the values fall within the typical range for aluminium alloys, suggesting that these samples possess characteristics consistent with common expectations for such materials [19].

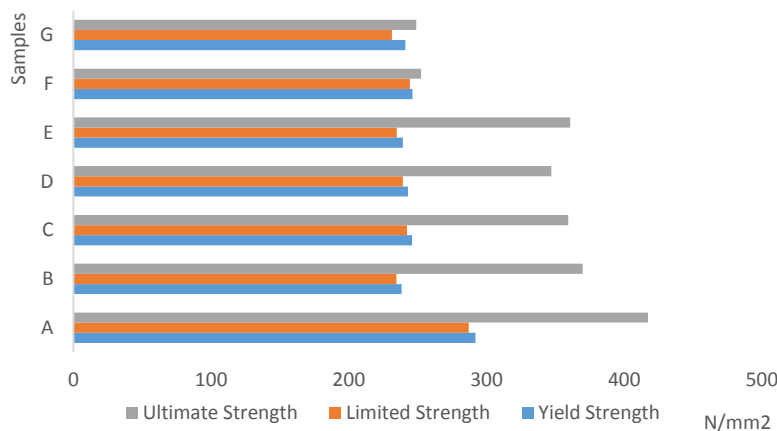


Figure 4. Tensile strength tests of the composites

3.3.3 Hardness

The results of the test after 3 impact trials and impact time (IT) of 1.0s is shown in Table 4. Samples modified at 550°C (B, C, D) show variations in hardness and impact trials. Sample A (pure aluminium) has the highest hardness, while modified samples (B, C, D) exhibit lower values. Samples modified at 1100°C (E, F, G) also demonstrate variations. Sample E, with 97% aluminium and 3% kaolin, has lower hardness compared to Samples F and G, which have 94% aluminium and 6% kaolin. Within each temperature group, there is a trend of decreasing hardness with an increasing percentage of kaolin. For example, in the 550°C group, Sample D with 9% kaolin has the lowest hardness, while in the 1100°C group, Sample E with 3% kaolin has the lowest hardness. This suggests that the addition of kaolin contributes to a reduction in hardness, due to changes in the material’s microstructure or the formation of softer phases as similarly reported by Melia et al. [20]. Comparing samples at the same modification temperature, the likelihood is that a higher percentage of aluminium relative to kaolin correlates with higher hardness values. For example, in the 550°C group, Sample B (97% aluminium) has higher hardness than Sample D (91% aluminium). However, the effect of the aluminium-to-kaolin ratio is also influenced by the modification temperature. At 1100°C, Sample E (97% aluminium) has lower hardness than Samples F and G (94% and 91% aluminium, respectively).

Table 4. Hardness test results

Sample	impact trials (J)			H (HL)	Sample	impact trials (J)			H (HL)	IT (s)
	550°C					1100°C				
	1	2	3		1	2	3			
A	227	255	274	256.00	E	217	214	220	217.00	1.0
B	222	224	258	234.00	F	220	228	224	224.00	1.0
C	220	221	175	205.00	G	224	220	231	225.00	1.0
D	218	175	215	202.00						

3.3.4 Fracture Toughness

The fracture toughness of the samples measured in MPa.m^{1/2} is depicted in Figure 5. MPa.m^{1/2} (megapascals per square root meter) is the SI unit of fracture toughness, which is a measure of a material’s resistance to cracking. It represents the stress intensity factor required to cause rapid crack propagation in a material under plane strain conditions. The stress intensity factor is a measure of the stress concentration around a crack tip, and it increases as the crack grows. Within the same temperature modification group, the impact of kaolin content on fracture toughness is not as clear-cut. Samples B, C, D, and E exhibit variations in fracture toughness despite being modified at 550°C. Sample D, with the highest kaolin content at 9%, does not have the lowest fracture toughness, indicating that the relationship between kaolin content and fracture toughness is nuanced. Comparing Samples B, C, D (modified at 550°C) with Samples E, F, G (modified at 1100°C), it is evident that the temperature of modification also plays a role in fracture toughness. Samples modified at 1100°C generally show higher fracture toughness, suggesting that the modification temperature affects the material’s structural properties and fracture resistance [18].

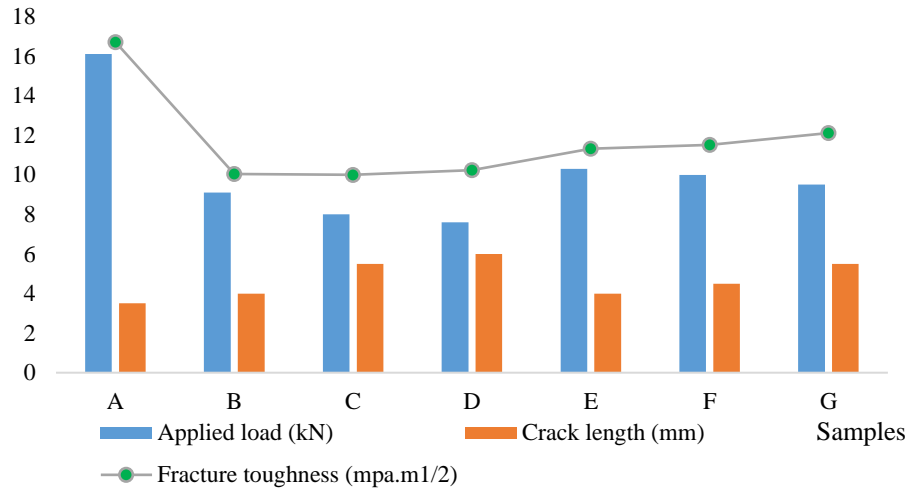


Figure 5. Fracture toughness tests of the composites

4 CONCLUSIONS

The elemental analysis of unmodified kaolin revealed a baseline composition, with SiO₂ being the predominant component. Other minor elements included Al₂O₃, Fe₂O₃, K₂O, and CaO, among others. The specific composition of unmodified kaolin forms a crucial foundation for understanding its role as a potential reinforcing material in aluminium matrix composites. The modification of kaolin at temperatures of 550°C and 1100°C resulted in distinct changes in its elemental composition. Structural transformations during modification were evident, as seen in alterations in SiO₂, Al₂O₃, Fe₂O₃, and other oxide content. These changes underscore the dynamic nature of kaolin under varying temperature conditions, providing insights into the thermal behaviour and potential applications of the modified material. Mechanical properties, including compressive and tensile strengths, hardness, and fracture toughness, reflected the influence of kaolin content and modification temperature. Notably, the addition of kaolin impacted structural integrity and deformation characteristics.

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