

# Fatigue Behaviour of Basalt and Glass Fiber Reinforced Polymer Composite Filled with Granite Fly Ash

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## Abstract

The granite processing industry produces substantial amounts of residual granite waste daily. This waste is collected through a filtration process during the drying and heating stages of concrete mixture production. This study conducts an experimental investigation into the potential use of granite fly ash (GD) as a filler to enhance the fatigue properties of basalt/glass composites (BFRC/GFRC). The research focuses on evaluating the tensile and fatigue characteristics of the developed fiber-reinforced polymer (FRP) composites. Composite samples were fabricated by incorporating granite fly ash (GD) in varying proportions, namely 1wt%, 3wt%, and 5wt%. The FRP laminates were produced using a hand lay-up technique with silicon mold and were cut using a cutting machine. The study's findings indicate significant improvements in tensile and fatigue properties, especially for FRP with 3% weight loading, in both BFRC and GFRC. Notably, adding just 1wt% granite fly ash (GD) resulted in an 8.6% increase in tensile and a substantial 26.9% increase in modulus for the BFRC composite. Under fatigue loading, the fatigue properties of the BFRP specimens showed better fatigue properties compared to GFRC. Furthermore, enhanced fatigue life counts were noted for the composite labeled BG3, which includes 3.0 vol% granite fly ash. However, an increase to 5.0 vol% resulted in a reduction in fatigue life counts. In summary, the study highlights the beneficial impact of incorporating granite fly ash, particularly within the 1%, 3%, and 5% weight range, on the mechanical properties of both BFRC and GFRC composites.

## 1. Introduction

Nowadays, sustainability has become a captivating topic in many fields, including civil and environmental engineering worldwide. Fiber-reinforced composites (FRCs) are widely researched materials in engineering,

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featuring a variety of reinforcing fibers and matrix properties [1]. The selection of both the fiber and matrix in an FRC depends on the intended application and the desired mechanical strength of the composite [2].

In the quest for enhanced material performance in structural applications, the development of fiber-reinforced polymer (FRP) composites has garnered significant attention. Among these, basalt and glass fiber reinforced polymers have emerged as promising FRP due to their superior mechanical properties, such as high strength-to-weight ratio, corrosion resistance, and durability. In recent years, there has been significant interest in using basalt fibers to reinforce polymer matrices, primarily as a replacement for glass fibers, due to their environmental benefits and favorable chemical and mechanical properties [3-4].

However, the incorporation of industrial by-products, such as granite fly ash, into these composites offers an innovative approach to not only improve their performance but also promote environmental sustainability. Granite fly ash, a byproduct, offers significant potential for reinforcement applications due to its notable properties, including high elasticity modulus and strength. Additionally, granite fly ash is considered industrial waste, posing a significant environmental risk [5-7]. During granite processing, substantial amounts of granite waste are produced, which can form colloidal waste when mixed with water, resulting in further increasing environmental concerns.

In the global quest for sustainability and environmental protection, innovative solutions that utilize the untapped potential of industrial byproducts have become a focus of scientific research and industrial practices. A remarkable example of granite waste is micro scale, an exceptional material with the capability to revolutionize various sectors through its unique properties and eco-friendly nature.

The integration of fillers such as granite fly ash into FRP composites has been explored to enhance their mechanical properties and extend their service life. Granite fly ash, a by-product of granite processing, is composed of fine particles rich in silica and alumina, which can improve the composite's hardness, wear resistance, and thermal stability. The incorporation of such fillers can also reduce the overall material cost and mitigate environmental issues associated with industrial waste disposal.

The utilization of granite fly ash as a filler material in polymer composites presents a dual benefit: it enhances the mechanical properties of the composite and provides an eco-friendly solution for industrial waste management. Previous studies have demonstrated that the addition of mineral fillers can significantly influence the fatigue behavior of FRP composites, which is crucial for their application in load-bearing structures subject to cyclic loading conditions [8].

The fatigue behavior of FRP composites is a critical factor in determining their suitability for various applications, especially in structures subjected to cyclic loading, such as bridges, aircraft, and automotive components. Fatigue loads are recognized as the cause of many, if not the majority, failures in engineering structures [9]. Fatigue refers to the deterioration in mechanical performance that results in the failure of a material or component under repeated loading [10]. Fatigue damage can occur even when a material is exposed to cyclic loading significantly below its ultimate tensile strength.

Fatigue failure in FRP composites typically occurs due to the progressive accumulation of damage under repeated loading, leading to matrix cracking, fiber-matrix debonding, and eventual fiber fracture. Studies have shown that the fatigue performance of FRP composites can be significantly influenced by the type and content of fibers, matrix materials, and fillers. Basalt fiber-reinforced composites, for instance, have demonstrated superior fatigue resistance compared to glass fiber-reinforced composites, primarily due to the higher fracture toughness and thermal stability of basalt fibers [8]. Additionally, the inclusion of mineral fillers like granite fly ash can alter the fatigue behavior by enhancing the matrix's stiffness and reducing the stress concentrations around the fibers.

This study aims to investigate the fatigue performance of basalt and glass fiber reinforced polymer composites filled with granite fly ash. The primary focus is to evaluate the synergistic effects of fiber reinforcement and mineral filler on the fatigue life and mechanical properties of the composites. By understanding these effects, we can contribute to the development of more resilient and sustainable composite materials for various engineering applications. Therefore, this study is novel as it introduces the use of granite fly ash as a filler in basalt and glass fiber-reinforced polymer composites, highlighting the potential for improved mechanical properties and enhanced environmental sustainability.

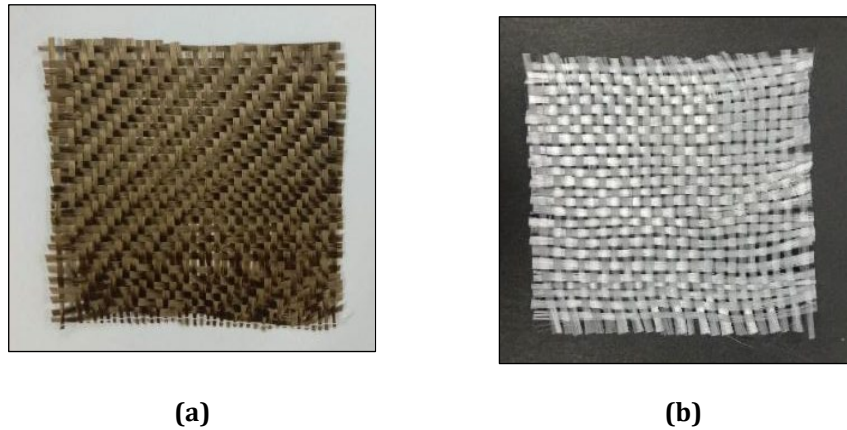
This research is particularly relevant in the context of advancing material science and engineering, where the balance between performance and sustainability is paramount. The findings from this study are expected to provide valuable insights into the design and application of FRP composites in industries such as construction, automotive, and aerospace.

## 2. Methodology

### 2.1 Preparation of Materials

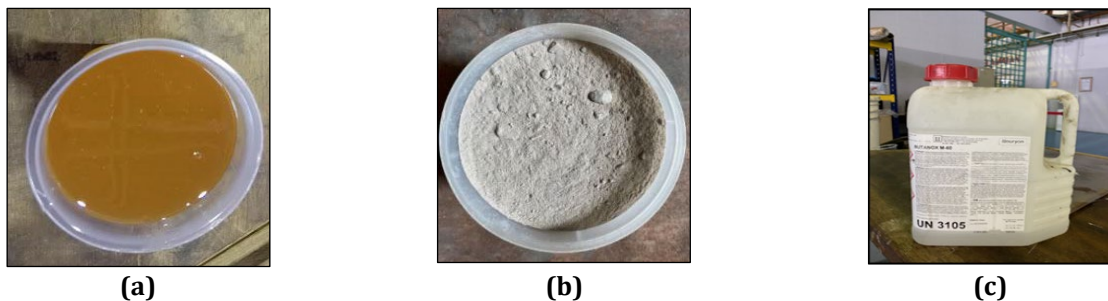
The experiment used mineral-based basalt fiber from Innovative Pultrusion Sdn. Bhd., based in Seremban, Negeri Sembilan. Woven roving glass fibers were supplied by Vistec Technology in Puchong, Malaysia. Both fibers were

shown in Fig. 1. Unsaturated Isopolyester (CRYSTIC® 272E Isophthalic Polyester Resin) and Butanox M60 hardener were provided by Carbon Tech Global Sdn. Bhd., located in Rawang, Selangor, Malaysia.



**Fig. 1** Type of fiber (a) Basalt; (b) Glass

The granite fine powder used in the study was sourced from the Kelantan Branch of Jabatan Kerja Raya (JKR), Malaysia, as shown in Fig. 2. The polyester and hardener were mixed in a mass ratio of 100:2, according to the manufacturer's guidelines. The manufacturing process entailed creating composite materials by incorporating different weight proportions (1%, 3%, and 5%) of granite fly ash (GD) as the filler. The study centered on utilizing a blend of woven glass fiber, woven basalt fiber, and a particular polyester resin as the matrix.



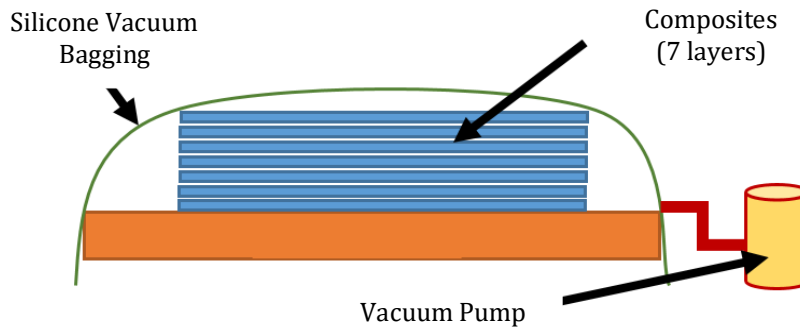
**Fig. 2** Matrix components (a) Polyester (PE); (b) Granite fly ash; (c) Hardener

The manufacturing process entailed creating composite materials by incorporating different weight proportions (1%, 3%, and 5%) of granite fly ash (GD) as the filler. The study centered on utilizing a blend of woven glass fiber, woven basalt fiber, and a particular polyester resin as the matrix.

The fabrication process for composite laminate begins with preparing the necessary materials and tools. It is essential to determine the accurate size and required thickness of the composite at the outset to ensure it meets the prerequisites for mechanical testing. Initially, basalt fiber, provided in roll form, is meticulously cut and shaped into 300mm x 300mm squares by carefully layering and interconnecting the sheets.

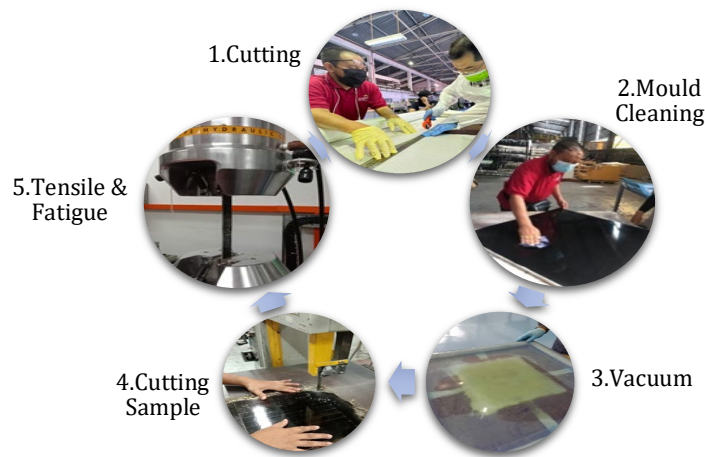
The composite matrix consists of polyester (PE) resin mixed with a hardener and granite fly ash, allowing effective curing at room temperature. To prevent premature resin hardening, a slow hardener was used, mixed in a weight ratio of 100 parts resin to 2 parts hardeners, ensuring precise control and optimal results. The equipment used includes a sturdy 10mm thick base plate, a reliable vacuum pump, vacuum tubing for seamless operation, a flexible silicon mold bag, and a dependable roller to ensure precision and uniformity throughout the process.

The composite laminates were fabricated using a combination of hand lay-up and silicon vacuum mold techniques (Fig. 3). The base plate is thoroughly cleaned and coated with mold release wax to eliminate impurities. Seven layers are then sequentially assembled, each placed carefully on top of the previous one. A symmetrical flow of resin mixture is poured onto each layer with precision, ensuring even distribution. This process results in a composite thickness of 2mm.



**Fig. 3** Schematic of vacuum bagging setup for composite fabrication

The silicone vacuum bag is gently secured around the assembled layers. After vacuum bagging, the samples were left to cure at ambient temperature for 24 hours, ensuring complete and thorough curing. Once cured, the composites are precisely cut to the desired dimensions according to ASTM standards. Fig. 4 illustrate the entire process and the resulting composites. Table 1 below shows a summary of the designated and composition of composites.



**Fig. 4** Composite laminates process

**Table 1** Designated and composition of composites

Composite designation	Electrode placement
UMG	Glass Fiber with Un-Modified Polyester Resin
G-1GD	Glass Fiber with 1% Granite Fly Ash Modified Polyester Resin
G-3GD	Glass Fiber with 3% Granite Fly Ash Modified Polyester Resin
G-5GD	Glass Fiber with 5% Granite Fly Ash Modified Polyester Resin
UMB	Basalt Fiber with Un-Modified Polyester Resin
B-1GD	Basalt Fiber with 1% Granite Fly Ash Modified Polyester Resin
B-3GD	Basalt Fiber with 3% Granite Fly Ash Modified Polyester Resin
B-5GD	Basalt Fiber with 5% Granite Fly Ash Modified Polyester Resin

## 2.2 Tensile Test

The experimentation was conducted under standard ASTM D3039 (ASTM 2014) conditions, ensuring room temperature consistency. Tensile properties of the composite laminates were evaluated using universal testing apparatus (UTM-SHIMADZU 3366), with a controlled cross head speed of 2 mm/min and specimens measuring 250 x 25 mm. Rigorous testing involved a minimum of five specimens per hybrid composite laminate

configuration. The SHIMADZU 3366 universal testing machine and visual representation of the specimens are depicted in Fig. 5.



**Fig. 5** Tensile and fatigue testing machine

## 2.3 Fatigue Test

The fatigue test was performed using universal testing equipment (SHIMADZU 3366). Fatigue experiments were in accordance to ASTM D3479 (Method 2000) and conducted under the following conditions:

- i. Loading mode: tension-tension fatigue
- ii. Stress Ratio,  $R$  (minimum stress to maximum stress ratio) = 0.5
- iii. Stress level: 90 %, 70 %, 50 % and 30% of ultimate tensile strength
- iv. Test frequency: 5 Hz

All fatigue specimens were tested using the same machine from the previous tensile test and same specimen size. The machine cycles the specimens to failure and the number of cycles-to-failure was recorded by computer data acquisition system. For BFRC and GFRC, all computations based on the values measured were performed in the same manner. Newton units (N) were used to present the applied load ( $F$ ).

## 3. Result and Discussions

The outcomes of this investigation are based on the mean values extracted from the meticulous analysis of five distinct samples within each classification of composite laminates. The observed divergence among these samples is linked to the varying weight percentages of granite fly ash that were integrated into the PE resin prior to the pouring stage in the manufacturing process. This study conducted a thorough exploration of multiple attributes of composite laminates, embracing pivotal variables like density and tensile properties.

### 3.1 Effect of Granite Fly Ash on Tensile Strength and Modulus of BFRC and GFRC

The impact of granite fly ash on tensile properties is detailed in Table 2, with tensile strength and its effect on modulus. The study revealed a notable pattern in the tensile strength of BFRC. Without any incorporation of granite fly ash (0wt%), the tensile strength measured 255.89 MPa. Adding just 1wt% of granite fly ash increased it to 270.25 MPa, a 5.3% rise, consistent with previous research [11–12].

**Table 2** Tensile properties of BFRC and GFRC

Composite	Properties	0%GD	1%GD	3%GD	5%GD
BFRC	Tensile Strength (MPa)	255.894	270.258	278.020	231.245
	Tensile Strain (%)	2.453	2.700	2.889	2.611
	Tensile Modulus (GPa)	11.742	12.266	14.911	11.035
GFRC	Tensile Strength (MPa)	196.122	215.024	233.726	194.151
	Tensile Strain (%)	2.366	2.503	2.600	2.425
	Tensile Modulus (GPa)	11.415	11.964	13.058	11.074

As the granite fly ash content increased up to 3wt%, the tensile strength continued to climb, reaching 278.02 MPa, a 2.9% increase from the 1wt% level. This indicates a positive relationship between the amount of granite fly ash and tensile strength. However, at 5wt% granite fly ash, the tensile strength dropped by 20%. This decrease was observed in both GFRC and BFRC materials, with the 5wt% concentration resulting in a 10.7% reduction in tensile strength compared to the composite without granite fly ash.

Previous studies by Sapiai et al. [13] found similar results. High filler levels can cause the modified matrix resin to form clumps, leading to stress concentration and composite failure. Additionally, higher filler amounts can increase the resin's viscosity, causing poor bonding and reduced wettability, which negatively impacts the adhesion between fibers, fillers, and resin.

This effect comes from the natural properties of granite fly ash, which tends to clump together up to a certain [13–14]. In this study, the best amount to improve tensile properties was found to be 3wt% [13]. This is the point where the benefits of adding granite fly ash are at their highest before it starts clumping too much.

There is a clear link between the tensile modulus and tensile strength of the samples. Higher tensile modulus values mean the material is stiffer, not more elastic. The results showed that both BFRC and GFRC had their highest tensile strengths at 3wt% granite fly ash, with average values of 14.911 GPa and 13.058 GPa, respectively. Samples with 1wt% had the next highest strengths, while the 5wt% samples had the lowest tensile modulus.

In summary, adding granite fly ash to composite materials significantly improves their tensile properties, peaking at 3wt%. This improvement is due to the balance between the large surface area of granite fly ash and its tendency to clump. More than 3wt% causes the granite fly ash to clump, reducing the tensile properties of the FRP. This property of granite fly ash was also explained by [14–15].

### 3.2 Effect of Granite Fly Ash on Fatigue Behavior of BFRC and GFRC

Fig. 6 and Fig. 7 shows the linear fitting S–N relationships calculated from the test data using the least-square method according to Equation (1).

$$\sigma_{max} = A \log(N_f) + B \quad (1)$$

where  $\sigma_{max}$  represents the maximum fatigue stresses,  $N_f$  represents the corresponding number of cycles to failure, and A and B are model parameters that will be determined by the available fatigue data.

Table 3 illustrates the fatigue life counts for different composite designations at varying stress levels, specifically 50%, 70%, 90% and 100% (UTS). From the graph (Fig. 6), it can be observed four different datasets, possibly representing basalt fiber composites with different treatments or conditions labeled as UMB, B B-1GD, B-3GD & B-5GD.

As expected, higher initial stress levels lead to fewer cycles to failure. All the curves show a decreasing trend, indicating the typical behavior of materials under cyclic loading where the material can withstand a high number of cycles at low stress but fails more quickly at high stress.

It is observed that the addition of granite fly ash particle further improves the fatigue life counts [16-17]. This improvement is because the presence of silica reduces the void content and improves the adhesion between particle and matrix. This adhesion improved particle-matrix interface effectively transfers the load and lowering the stress intensity factor.

B-3GD seems to have the longest fatigue life at lower stress levels, maintaining higher stress for more cycles than the other composites. Material with a high tensile strength would result in excellent fatigue strength [18]. However, further addition of granite fly ash particles at stress level decreased the life. B-5GD has the shortest fatigue life across all stress levels, indicating that whatever treatment or characteristic it represents may be detrimental to the material's fatigue resistance. This decrease is due to the aggregation of particles and the buildup of stress in areas of the matrix highly saturated with granite fly dust. Consequently, cracks initiate in these stress-concentrated regions and propagate, leading to plastic deformation.

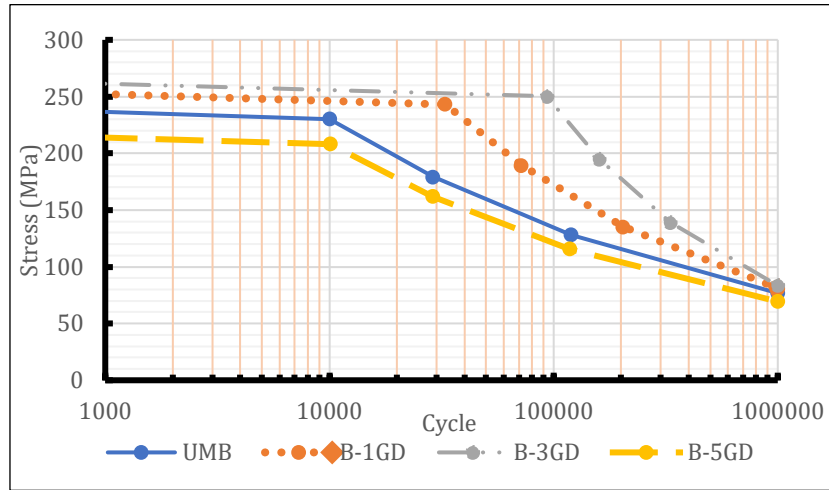


Fig. 6 Stress–N data of the BFRP specimens

Table 3 Fatigue properties of BFRPC

UMB		B-3GD	
Stress (MPa)	N <sub>f</sub> (Cycle)	Stress (MPa)	N <sub>f</sub> (Cycle)
255.894	1	278.020	1
230.305	10044	250.218	93124
179.126	29002	194.614	160250
127.947	119954	139.010	331443
76.76	1000000	83.406	1000000

B-1GD		B-5GD	
Stress (MPa)	N <sub>f</sub> (Cycle)	Stress (MPa)	N <sub>f</sub> (Cycle)
270.258	1	231.245	1
243.232	32936	208.120	10096
189.180	71885	161.871	28896
135.129	204387	115.623	118101
81.077	1000000	69.373	1000000

Composite glass also shows a similar trend to composite basalt. G-3GD showed better fatigue life compared to others as shown in Fig. 7 and Table 4. However, glass experiences lower stress than basalt for low fatigue life [18].

The results of the fatigue tests revealed significant differences in the fatigue performance of the basalt and glass fiber reinforced polymer composites filled with granite fly ash. Basalt fiber composites exhibited higher fatigue strength and longer fatigue life compared to glass fiber composites, which can be attributed to the superior mechanical properties of basalt fibers and their better interfacial bonding with the matrix [8].

The addition of granite fly ash as a filler further enhanced the fatigue performance of both types of composites [16–17]. The filler particles improved the load transfer between the fibers and the matrix, reducing the stress concentrations and delaying the initiation and propagation of fatigue cracks. SEM analysis showed that the presence of granite fly ash particles in the matrix helped to prevent crack growth and increase the overall toughness of the composite [8].

The study also highlighted the influence of filler content on the fatigue behavior of the composites. An optimal filler content was identified, beyond which the fatigue performance began to decline due to agglomeration of filler particles and reduced fiber-matrix bonding. This finding underscores the importance of optimizing the filler content to achieve the best balance between mechanical properties and material cost.

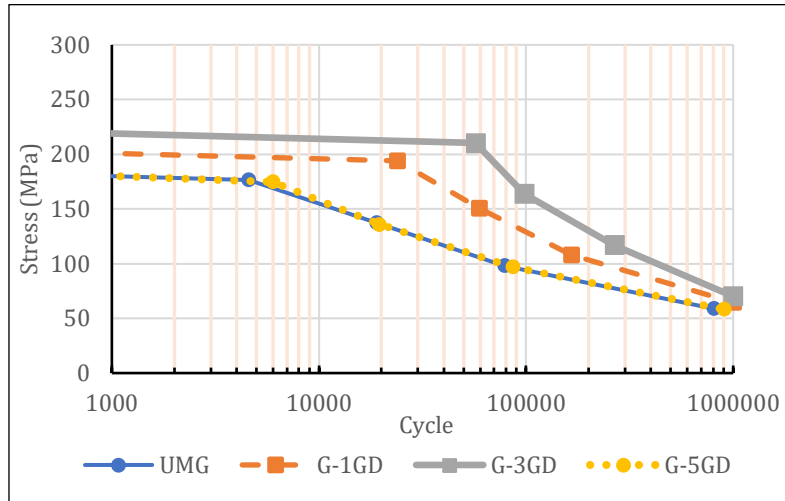


Fig. 7 Stress–N data of the GFRP specimens

Table 4 Fatigue properties of GFRC

UMG		G-3GD	
Stress (MPa)	N <sub>f</sub> (Cycle)	Stress (MPa)	N <sub>f</sub> (Cycle)
196.122	1	233.726	1
176.509	4575	210.353	56890
137.285	18965	163.608	98340
98.061	78400	116.863	267008
58.836	807056	70.118	1000000

G-1GD		G-5GD	
Stress (MPa)	N <sub>f</sub> (Cycle)	Stress (MPa)	N <sub>f</sub> (Cycle)
215.024	1	194.151	1
194.828	23804	174.736	5966
151.533	59430	135.906	19504
108.238	165606	97.076	86003
64.943	1000000	58.245	901239

#### 4. Conclusion

The fatigue analysis of basalt and glass fiber reinforced polymer composites filled with granite fly ash has demonstrated the potential of these materials for high-performance and sustainable engineering applications. The incorporation of granite fly ash not only enhances the mechanical properties and fatigue resistance of the composites but also contributes to environmental sustainability by utilizing industrial by-products. Future research should focus on further optimizing the filler content and exploring other types of mineral fillers to enhance the performance of FRP composites. Additionally, long-term durability studies under various environmental conditions are necessary to fully understand the behavior of these composites in real-world applications. In conclusion, the inclusion and integration of granite fly ash into glass/basalt fiber-reinforced composites significantly enhances their tensile and fatigue properties, thereby fortifying their mechanical properties to a considerable degree. This improvement is especially notable at a concentration of 3wt% granite fly ash. The highest tensile and fatigue results were exhibited by BFRC, specifically at a 3wt% inclusion of granite fly ash (GD) filler. It surpassed all the other composite designations. Clearly, the introduction of GD filler within BFRC significantly outperformed its counterpart, GFRC, leading to superior outcomes in mechanical properties. From the research work, the authors found that BFRC perform better than GFRC under fatigue loading.

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### Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

### Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Mohd Azrul Jaafar, Shahrul Azam Abdullah, Raja Mazuir Raja Ahsan Shah, Raymond Siew Teng Loy; **data collection:** Mohd Azrul Jaafar, Mohamad Asrofi Muslim; **analysis and interpretation of results:** Mohd Azrul Jaafar, Mohamad Asrofi Muslim, Zaidahtulakmal Mohd Zahib; **draft manuscript preparation:** Zaidahtulakmal Mohd Zahib, Raja Mazuir Raja Ahsan Shah, Aidah Jumahat. All authors reviewed the results and approved the final version of the manuscript.

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