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Characterization and Comparative Analysis of Natural, Sustainable Composite Material Properties Using Bio-Binder for Eco-Friendly Construction Applications

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Abstract: The utilization of waste materials like bio-binders and fine aggregates in construction is crucial for achieving environmentally sustainable building practices. By reusing these materials, we can significantly reduce waste production and preserve precious natural resources, making it a vital aspect of sustainable construction. This paper presents the experimental findings on the mechanical characteristics of using micro sand silica mixed with a bio-binder such as okra. The estimated mechanical properties that are discussed in this research include modulus, strength, and toughness. Okra with three different weight percentages (5, 10, and 15%) was mixed with four different micro-size particles (25, 250, 425, and 850 µm) and then compressed into a cylindrical sample. Okra demonstrated good adherence characteristics to sand silica particles, where the test results indicate that adding okra significantly affects the mechanical properties. Thermal analysis and SEM were employed to investigate the material degradation, surface morphology, and the internal structure of the composites. In general, it has been observed that at a particle size of 250 µm, the best mechanical properties have been achieved at a 15% weight ratio of the okra bio-binder.

Keywords: bio-binder; sustainable material; composite; construction; eco-friendly

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1. Introduction

Bio-binders can be mixed with aggregates to produce new construction materials; this is a promising approach to sustainable building practices. Traditional construction materials, such as cement, significantly contribute to carbon emissions. The production of construction materials requires a high amount of energy and releases carbon dioxide, a greenhouse gas contributing to global warming. Using bio-binders as a replacement for traditional construction materials can mitigate the carbon footprint of concrete. Bio-binders come from natural materials, such as agricultural waste, and do not require the same high-energy production process as cement. Additionally, the use of bio-binders can divert waste from landfills, which is a significant environmental concern.

For various renewable resources, biomass conversion is considered a favorable and accurate substitute energy option because of reduced greenhouse gas (GHG) emissions and the production of petroleum substitutes. Biomass is a plant-based material that can be used to generate fuel for electricity and heat in homes and industries. It is becoming particularly relevant as a renewable and sustainable energy source in recent times. In addition, it is an abundant and inexpensive energy resource [1]. The versatility of biomass consumption, which allows it to be utilized as a direct fuel source and be converted into various types of energy, is one of its key benefits. According to a report generated on global renewable energy by IRENA, by the year 2030, biomass will be the most substantial source of renewable energy. It will be able to deliver 60% of the total energy supply [2]. Considering that environmental sustainability is critical at the moment, but energy demand keeps growing, biomass provides an alternative fuel that can replace fossil fuels and thus enhance sustainability. Sources of biomass that can be turned into renewable energy include wood, industrial waste, energy crops, and farm and animal waste [3].

The use of agricultural waste in the production of environmentally friendly building materials offers a solution that not only includes reducing the consumption of energy but also the consumption of natural resources [4]. Moreover, employing plant wastes as a bio-binder could also contribute to the utilization of agricultural waste in an efficient way. It is predicted that the outcomes of this information will lead to greater acceptability of the usage of agricultural wastes in building applications [5]. Another study also stated that construction materials that are low in carbon emissions, sustainable, and multifunctional are called agricultural concrete [6]. Construction waste accounts for 35% of all solid waste produced of which building waste has a high concentration of heavy metals; hence, a rise in the concentration of heavy metals in the soil is detrimental to the quality of the soil due to the action of several biochemical processes [7,8]. In addition, the process of piling up waste from building projects causes the breakdown of certain organic materials, which results in the emission of toxic gases that contribute to environmental pollution. Additionally, the germs and particles in the waste carried by the wind might negatively impact the air quality [9,10]. Therefore, opting for agricultural materials such as okra can reduce the production of construction waste to an extent, which results in the controlling of various harmful emissions and deposition of toxic materials into the environment.

A recent study reported that the automotive industry has realized the benefits of biomass and is using biomass-derived products to improve engine efficiency and emission quality [6]. Further, biomass materials revealed excellent properties when used in the construction industry and for the synthesis of minerals [11,12]. Malico et al. noted that solid biomass is appropriate for use in the iron and steel, petrochemical, food, tobacco, and beverage industries because it will significantly reduce the process heat these industries consume [13]. However, Nunes et al. noted that although biomass is ideal for use in the textile industry, it poses logistic challenges that prevent its effective use in industrial units [14]. In contrast, when using biomass as binders, it was found that composites consisting of rice straw pulp combined with starch to regulate industrial noise exhibited superior sound absorption capabilities compared with those containing synthetic binders. It has been determined that biomass from bamboo particles is helpful in the construction industry in that it provides higher thermal insulation and significantly reduces the impact of humidity on construction [15,16]. Another study suggested that adding coal tar, bentonite, and polypropylene into rice straw-based binders would improve the quality of briquettes and make them waterproof [17].

Sand is predominantly composed of silica dioxide (SiO_2) and can be utilized as one of the notable filler additions used in numerous experiments. In particular, sand is commonly used as a filler in the development of composite materials, which are typically made up of a matrix material (such as a polymer or ceramic) and one or more filler materials. The addition of sand as a filler can help to enhance the mechanical and physical properties of the composite, including its strength, stiffness, toughness, and thermal stability. Sand can be a valuable filler material in many scientific experiments and industrial applications thanks to its abundance, cost-effectiveness, and compatibility with many different matrix materials. The use of sand as a filler material can help to improve the mechanical and physical properties of composite materials, making them more suitable for a wide range of applications. SiO_2 has been classified as a biologically safe material that may be consumed in the agriculture and pharmaceutical industries with no known health risks, despite being crystalline. In general, silica provides features that could be mixed with many polymeric materials to increase their ultimate characteristics and qualities. In addition, silica has been extensively used as a filler to improve the mechanical behavior of polymeric materials [18,19]. The preparation of SiO_2 nanoparticles is relatively easy and cost-effective. It is commonly applied to catalysts, chemical sensors, chromatography, and ceramics.

Bio-binders can be used in various industries, including agriculture, health, food, and automobiles. A few standard binders that are already in use in various industries include polylactic acid (PLA), polyhydorxyalkanoates (PHA), and polycaprolactone [20]. *Abelmoschus esculentus* (commercially known as okra) gum showed significant results when used as a tablet binder. It has been concluded that it might be a feasible alternative for compositions [21]. Okra is a plant commonly produced in some areas, such as Africa and Asia. Its extract is natural, low-cost, and non-toxic, making it a promising material for various industry sectors since different parts of this plant have long been applied in traditional medicine as antidiabetic, antibiotic, and cancer-fighting agents [22].

Flavonoids, polysaccharides, polyphenols, caffeine, and pectin are a few of the biologically active substances in okra. Recent research has indicated that incorporating okra waste as a binder in briquette production results in an increase in heating value, minimal production of ash and moisture content, and the potential for the briquettes to maintain their structural integrity for up to 7 days [23]. Another study by Ogaji et al. concluded that when okra gum is extracted from the pod and coated with the drug paracetamol, the drug does not easily chip when dropped, and the coating remains intact and durable [24]. Yank et al.'s study aimed to produce and test briquettes from rice husks by using okra stem gum, rice dust, and cassava wastewater as binders. According to their findings, the briquettes produced using okra stem gum had the lowest weight, those made with rice dust were the most durable and had the longest lifespan, and the ones made with cassava water were the most dense [25].

The purpose of this study is to evaluate the effects of different weight percentages of okra on the mechanical properties of a composite made with sand silica particles of varying sizes. The goal is to determine whether this composite can be used as an environmentally sustainable material in the construction sector. In addition, the produced samples were characterized using TGA, XRD, and SEM.

2. Materials and Methods

2.1. Materials

Silica sand, a form of silicon dioxide (SiO_2) and is commonly known as quartz sand, was collected from the UAE desert at latitudes 24°00′ and 26°40′ N and longitudes 55°00′ and 56°00′ E. The relative humidity is around 30%. A chemical analysis was used to determine the mineral content composition, as shown in Table 1 [26].

Table 1. Chemical composition of Silica sand.

Chemical Composition	Mass Fraction of the Sample (%)
SiO_2	45.64
CaO	16.90
MgO	9.98
Fe_2O_3	2.98
$A1_2O_3$	2.34
K_2O	0.76
SO_3	0.35
Na_2O	0.31
Cl	0.22

Pure silica sand that was gathered was first dried in the oven at 100 °C for 24 h. Secondly, it was pressed and molded in stainless steel cylindrical molds of 12.5 mm × 25 mm to test its compressive strength. Finally, it was found that the compressive strength was 0.1 MPa. The sand particles were very fine, which resulted in a decrease in the mechanical properties [27–29]. The sand silica density was estimated to be around 2059 kg/cm^3 [30,31].

The bio-binder utilized in this experiment was *Abelmoschus esculentus* (known as okra), with a particle size of 80 µm. Nitrogen gas of ultra-high purity (99.999%) was used to conduct the thermogravimetric analyzer (TGA) experiments. Distilled water free from ions was used for mixing the samples.

2.2. Preparation of the Composite

Numerous samples were prepared using various concentrations (5%, 10%, and 15%) of *Abelmoschus esculentus* (okra) with silica sand. The primary purpose of performing size analysis on aggregates is to identify and get an understanding of their granulometric qualities as well as their textural features. The evaluation of the depositional environment, as well as the identification of certain petrophysical and geotechnical properties, demands that this information be collected initially. There are a few different methods available for determining the size of sediments. In this study, the sieve analysis is the one that has been applied in order to determine the distribution of the sand grains' particle sizes [26,32,33]. A heavy-duty grinder grain mill was used to produce smaller size particles, such as 25 µm. In addition, the samples of silica sand were passed through an automated sieve shaker for 10 min to remove contaminants from the surfaces of the silica sand particles. This shaker consisted of a range of sieves with square mesh apertures of 25 µm, 250 µm, 425 µm, and 850 µm. The composite material was prepared by mixing (0.35 g, 0.70 g, and 1.05 g) *Abelmoschus esculentus* (okra) and (6.65 g, 6.30 g, and 5.95 g) silica sand, adding deionized water up to 1.5 mL. The mixture was stirred for 5 min at room temperature, and the mixture was then poured into specially designed stainless steel cylindrical molds of 12.5 mm × 25 mm according to ASTM D695 [34]. Mold releaser was sprayed on the inside surfaces of the molds to prevent the mixture from adhering to the mold walls and to facilitate the process of removing the sample. The samples were cured by hot pressing in a Carver TM hydraulic hot press at 80 °C for 30 min under a load of 500 kg/cm^2. Finally, the samples were placed in an oven for 20 min at 80 °C to dry. The samples were kept in glass incubators to cool off at room temperature and to prevent moisture absorption. After 24 h, the samples were tested for compression.

2.3. Characterization of the Composite

The component elements in silica sand and okra composites were analyzed by Malvern Analytical's XPert3 powder XRD. The XRD scans the sample powder at an angle 2θ in the range of 10–60 degrees at a scan speed of 0.02 degrees per second, a voltage of 40 kV, an intensity of 20 A, and 1.5406 Cu K radiation. Analyses of the morphology and elemental content of pure and composite materials were conducted using a scanning electron microscope (SEM) equipped with energy-dispersive X-ray spectroscopy (EDX) from the JEOL-JSM 6010 at 10 kV. Tests using a thermogravimetric analyzer (TA instruments: Q500 V20.10) were carried out in an inert gas atmosphere characterized by a flow of nitrogen gas at 60 mL/min. The 0.015 g composite and pure samples were crushed and set on a platinum pan with a heating rate of 10 °C/min between 25 °C and 800 °C to determine the stability, activation energy, and degradation temperatures. The compressive mechanical properties of the samples were analyzed using the Universal testing machine (Shimadzu, Kyoto, Japan) at a load rate of 0.5 mm/min. Figure 1 illustrates the compression test on the different composite samples.

(**a**) (**b**) (**c**)

Figure 1. The compression test on the biomass composite; (**a**) 5% okra, (**b**) 10% okra, (**c**) 15% okra.

3. Results and Discussion

Conducting a comprehensive assessment of a composite's mechanical features is a crucial measure in comprehending its operational qualities and appropriateness for various purposes. Some key mechanical properties typically analyzed for particulate composites include compressive strength, elastic modulus, yield strength, ductility, and toughness. Analysis of the composite's mechanical properties are shown in Figures 2–6. The research indicates that both the amount of okra and the particle size of silica sand have a significant impact on the mechanical properties of the composite material. There is a strong and highly significant interaction between okra and the silica sand particle size. Based on these findings, it is observed that the impact of okra adhesive characteristics is dependent on the particle size of the silica sand.

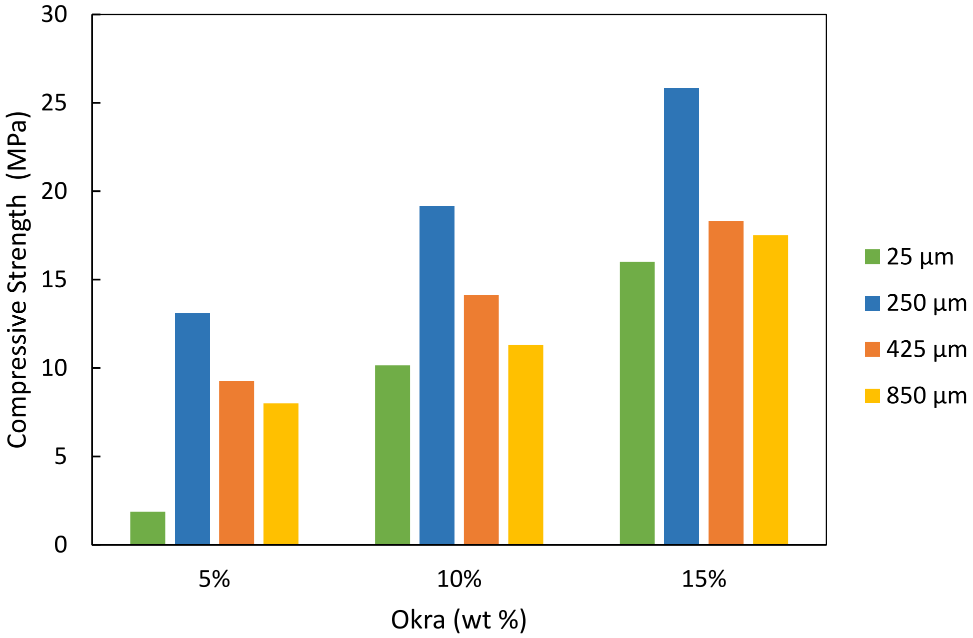


Figure 2. The compressive strength of the biomass composite.

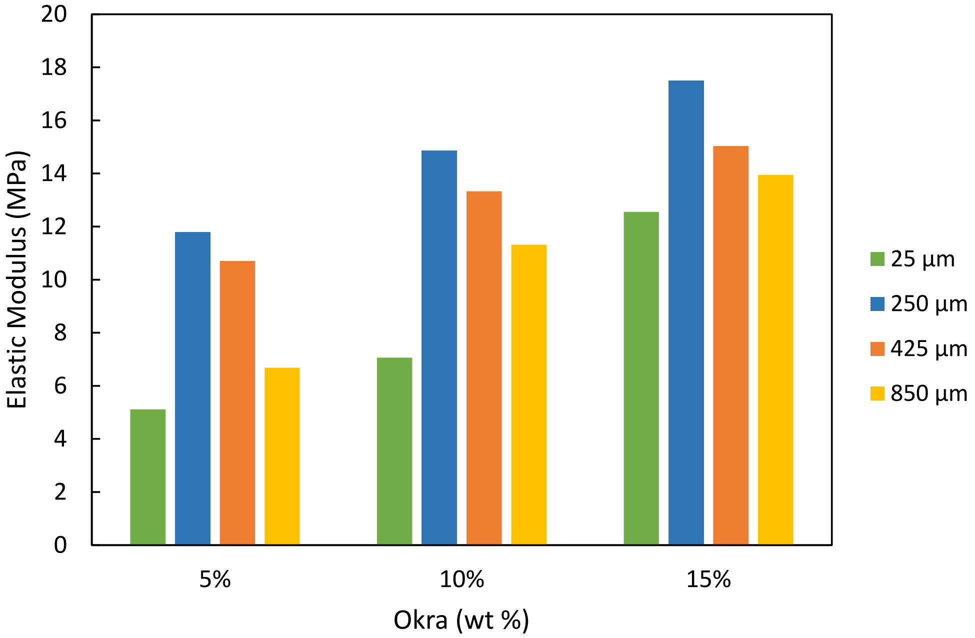


Figure 3. The elastic modulus of the biomass composite.

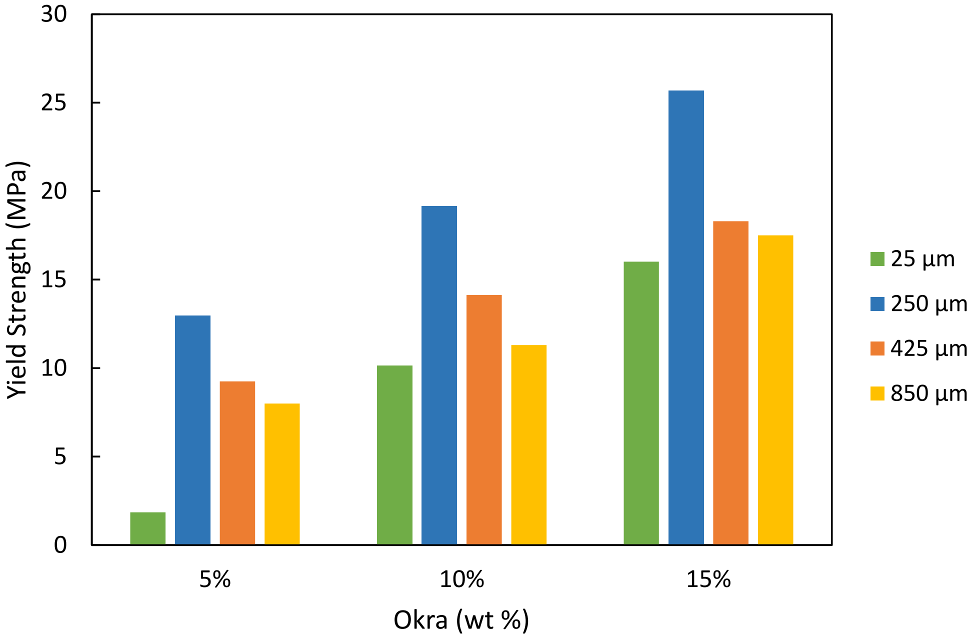


Figure 4. The yield strength of the biomass composite.

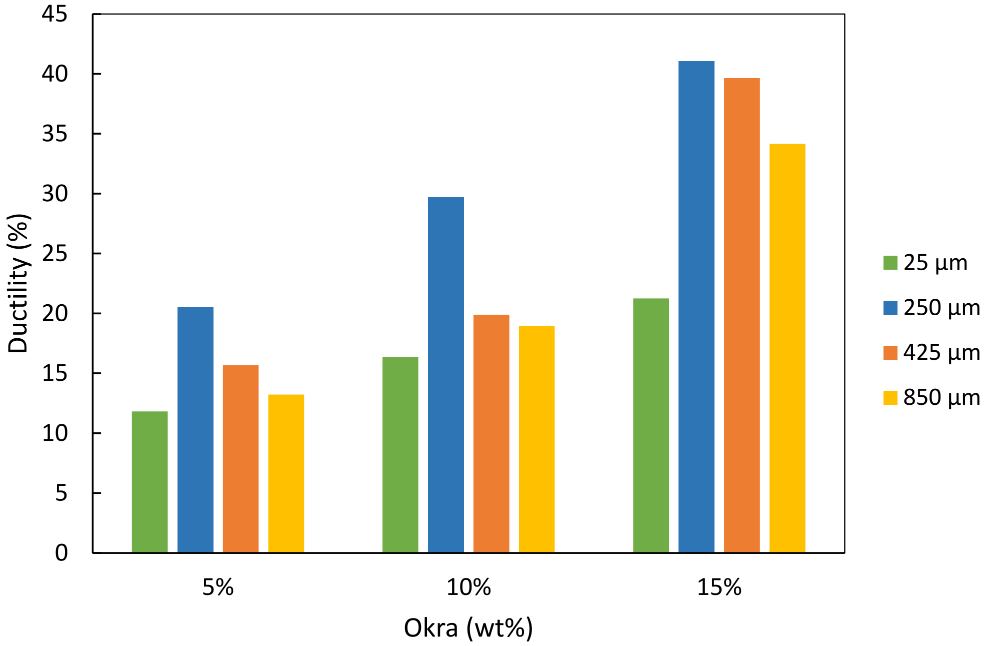


Figure 5. The ductility of the biomass composite.

Studying the effects of adding different percentages of okra to silica sand with varying particle sizes is an important step in understanding the behavior of the resulting composite material. In this case, the effect of adding okra to silica sand with particle sizes of 25, 250, 425, and 850 µm is being investigated, with a fixed particle size of 80 µm for the okra. The addition of okra to silica sand is expected to have a number of effects on the properties of the resulting composite material. For example, adding okra to silica sand can help to improve the material's mechanical properties, such as its strength, toughness, and ductility. Okra is recognized for its polysaccharides and other natural substances, which have the potential to increase the adhesion between particles in the composite, thus improving its mechanical properties. The effects of adding different percentages of okra to the silica sand can be analyzed by conducting a series of tests on the resulting composite material. Okra was added to the mixture in weight proportions of 5%, 10%, and 15%, respectively. The effect of different particle sizes of silica sand on the overall compressive strength was studied. The compressive strength of each mixture was measured and meticulously analyzed.

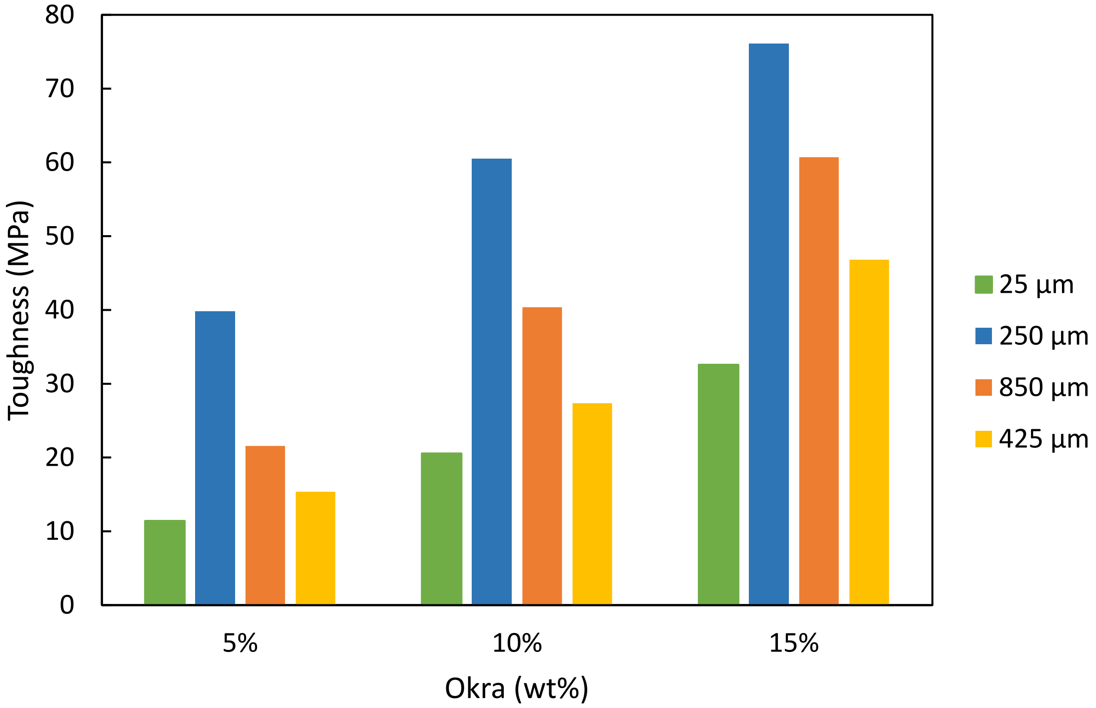


Figure 6. The toughness of the biomass composite.

3.1. Compressive Strength

The compressive strength was calculated according to ASTM D695-15 [34]. The observation that the highest compressive strength was attained by the mixture containing silica sand with a particle size of 250 µm is noteworthy, as it indicates that particle size is a crucial factor in determining the mechanical characteristics of the composite material. This result may be because silica sand particles of this size can fill the voids between the larger particles, creating a denser and more compact material. It underscores the need for careful selection and testing of particle sizes to achieve desired performance characteristics. As shown in Figure 2, adding 5%, 10%, and 15% okra by weight increased the compressive strength by approximately 35%, which can be attributed to the increased amount of medium-sized silica sand particles. Observations reveal that incorporating okra into the silica sand mixture enhances the adhesion between the sand particles, which leads to greater compressive strength. This is attributed to the high amounts of galactose, rhamnose, and galacturonic acid present in okra, which possess crosslinking properties that increase the adhesive potential. Furthermore, the strength was found to diminish by 40% between 250 µm and 425 µm in all the weight percentages of okra added. The adhesion between particles can be affected by particle size and the constant load applied. Smaller particles of silica sand of 25 µm produced the lowest compressive strength regardless of all amounts of okra added. This clearly indicated that the particle size of silica sand affected the overall strength of the composite.

It is observed that a 21% increase in compressive strength in the 850 µm silica sand at 10% okra by weight is a significant result. The results indicate that the addition of okra to silica sand can significantly enhance the mechanical properties of the composite material, especially for larger particle sizes. This increase in compressive strength may be because the okra can fill the voids between the larger silica sand particles, leading to improved particle/matrix adhesion and a higher degree of inter-particle contact. This can result in a more densely packed material that is better able to resist compressive stresses. This finding provides evidence that okra can increase the compressive strength of silica sand.

Sand particles that are too fine or too coarse may not have the optimal particle size distribution for producing strong and durable construction materials. Furthermore, it will result in a lack of strength and durability as the particles tend to pack together, reducing the amount of air voids in the composite material, and potentially leading to cracking and other forms of damage. Silica sand passing through 250 µm falls within the ideal range of particle size for producing construction material, such as concrete, with a high compressive strength. Utilizing silica sand that passes through a 250 µm sieve in construction work can be advantageous for producing greater compressive strength. The exact size of sand particles used in construction work may depend on the specific application and the desired properties of the construction material. It is important to bear in mind that various factors, including the properties and quality of the binder, the water-binder ratio, and the curing conditions, can significantly impact the resulting construction material's compressive strength. The use of okra in manufacturing concrete should be encouraged since it is eco-friendly and sustainable [35].

3.2. Elastic Modulus

The elastic modulus measures a material's stiffness or ability to resist deformation under stress. The elastic modulus is calculated based on ASTM D695-15, the proportion of nominal stress to corresponding strain below a material's proportional limit. It is represented in force per unit area based on the mean initial cross-sectional area [34]. Incorporating okra into a silica sand mixture has the potential to influence its elastic modulus by modifying the transmission and distribution of stress within the material. The specific effects of adding okra to a silica sand mixture on the elastic modulus would depend on various factors, including the amount and quality of the okra added, the particle size distribution of the silica sand mixture, and the specific testing conditions used to measure the elastic modulus. However, adding a fibrous material like okra to a composite material such as silica sand can increase its elastic modulus by providing additional stiffness and resistance to deformation. However, the degree to which the elastic modulus is affected would depend on the specific properties of the okra and the silica sand mixture and the specific testing conditions used to measure the elastic modulus. Moreover, introducing okra into a silica sand mixture might have additional implications for its conduct and effectiveness, such as modifications in density, porosity, or permeability, which could impact the elastic modulus and other mechanical characteristics. Therefore, the specific effects of the okra addition on the elastic modulus should be evaluated in the context of the specific application or use case for the material. As illustrated in Figure 3, an investigation of how okra affects the elastic modulus of silica sand was undertaken in this study. Okra was added to the silica sand mix in percentages of 5%, 10%, and 15%, with varying sizes of sand particles used. The elastic modulus was found to increase by 99% between the 25 µm and 250 µm sand in all the percentages of okra added to the silica sand mix. It appears that there is a correlation between the particle size of the silica sand mix and the amount of okra added, where an increase in particle size from 425 µm to 850 µm is associated with a decrease in the percentage of okra added to the mix by an average of 27%. The increase in the elastic modulus of silica sand upon the addition of okra is due to the strengthening of the bonds between the particles in the composite. Notably, the particle size does not influence a composite's Young's modulus, especially when the particles are micron-sized as is the case [36]. At a nano-scale, decreasing particle sizes could enhance the Young's modulus of the composite [37]. The elastic modulus of the 25 µm silica sand was the least among all particle sizes due to the substantial presence of dust particles that impaired its mechanical characteristics. Conversely, the 250 µm sand particle size had the highest elastic modulus, regardless of the amount of okra added to the mixture.

This study examined the effect of introducing okra to silica sand production on the resulting material's elastic modulus. The research indicated that okra is a beneficial component in this regard, as it elevated the material's elastic modulus. The elastic modulus is a measure of a material's stiffness or its ability to resist deformation when stress is applied. If the elastic modulus increases, it implies that the silica sand material has become more rigid and less susceptible to deformation. Therefore, a sand particle size of 250 µm is recommended to be used in silica sand in all the amounts of okra added to the mix.

3.3. Yield Strength

Yield strength is measured according to ASTM D695-15, which is the first point on the stress-strain diagram where strain increases without stress increasing [34]. The addition of okra to a silica sand mixture could potentially affect its yield strength by altering the way stress is distributed within the material. The precise impact of incorporating okra into a silica sand mixture on yield strength would be influenced by several factors. These include the quantity and caliber of the added okra, the particle size distribution of the silica sand mixture, and the particular testing conditions used to assess yield strength. In general, fibrous material like okra, when added to a composite material, can increase its yield strength by improving its ability to distribute stress and resist deformation. However, the degree to which yield strength is improved would depend on the specific properties of the okra and the silica sand mixture and the specific testing conditions used to measure yield strength. Adding okra to a silica sand mixture could also have other implications for its behavior and performance, such as changes in density, porosity, or permeability. Hence, it is crucial to assess the influence of the okra incorporation on the yield strength in relation to the intended application or purpose of the composite material.

The effects of adding okra in different amounts to silica sand on yield strength are shown in Figure 4. With the exception of sand particle size and the quantity of okra added, all other variables remained constant. The yield strength of the material was observed to decrease by an average of 35% when transitioning from 250 µm to 425 µm sand particle sizes, irrespective of the amount of okra incorporated into the mixture. A 14% decrease in yield strength was recorded between the 425 µm and 850 µm sand in all the amounts of okra added. The outcomes demonstrated that the size of the sand particles had a significant impact on the yield strength of the silica sand. As a result, it was determined that there exists a connection between the proportion of okra added to a sand blend containing 250 µm particles and the composite's yield strength. To be more precise, augmenting the okra proportion from 5 wt% to 15 wt% resulted in a 43% growth in the composite's yield strength. Meanwhile, introducing okra from 5 wt% to 10 wt% led to a 50% surge in yield strength for the 425 µm silica sand. A light increase of 20% yield strength was pointed out at the 25 µm sand upon adding 15 wt% okra. Generally, yield strength was found to increase with an increase in the amount of okra added. This is because okra acted as a binder between the materials [38].

3.4. Ductility

The ductility was measured in this study based on ASTM D695-15 [34]. The addition of okra to the silica sand mixture could improve ductility by providing additional flexibility and resistance to cracking or fracturing. However, the specific effects of the okra addition on the ductility of the silica sand mixture would depend on a variety of factors, including the amount and quality of the okra added, the particle size distribution of the silica sand mixture, and the specific testing conditions used to measure ductility. The particle size of the silica sand mixture may affect its ductility because smaller particles tend to have more surface area and increased contact with each other, leading to greater inter-particle friction and making the material more resistant to deformation. Accordingly, it is possible that the effects of the okra addition on ductility could vary depending on the particle size of the silica sand mixture used in this study. Figure 5 shows the effects of adding okra to silica sand mix on ductility using sand passing through different mesh sizes. The study established an average increase in ductility by 92% between the 25 µm and 250 µm silica sand in all the percentage weights of okra used by weight. The results demonstrated that there was an average drop of 28% in ductility between the two larger sizes of silica sand (250 µm and 425 µm), regardless of the proportion of okra added. In other words, the smaller sand silica particles (250 µm) exhibited greater ductility than the larger sand silica particles (425 µm) in all samples, despite the varying proportions of okra. Ductility was reduced slightly by an average of 9% between the 425 µm and 850 µm silica sand used in all the amounts of okra used. This clearly indicates that the size of silica sand particles had a significant effect on the ductility.

It was observed that using a higher proportion of okra by weight resulted in a rise in ductility for all sand particle sizes used. This indicates that the flexibility and pliability of the material were enhanced by the inclusion of okra, reducing the likelihood of it cracking or breaking when subjected to stress. This is simply because an increase in okra increased the bond between particles in the silica sand leading to an increase in ductility and other mechanical properties of silica sand. In effect, the particles undergo the chemical van der Waal bonding, weak chemical bonds that cause the composite to have higher ductility since the bonds increase their flexibility [39]. In all of the tested proportions of okra, ductility was observed to be low for the 25 µm sand particle size. This can primarily be attributed to the abundance of extremely small sand and dust particles present in the mixture. The addition of 15 wt% okra by weight to the silica sand in combination with the 250 µm sand particles produced the highest percentage and, therefore, the best ductility.

3.5. Toughness

Toughness is defined as the area under the stress-strain curve [40]. The degree to which toughness is improved would depend on a variety of factors, such as the type and quality of the okra, the particle size and distribution of the silica sand mixture, and the specific testing conditions used to measure toughness. The potential advantages or disadvantages of adding okra to the silica sand mixture may also depend on the intended application or use of the resulting material. The effects of adding okra in percentages of 5 wt%, 10 wt%, and 15 wt% by weight to silica sand mixture on toughness were investigated as shown in Figure 6. The study investigated the effect of adding different proportions of okra to silica sand samples of two different sizes (25 µm and 250 µm) on their toughness. The results showed that there was an average increase of 65% in toughness between the two sizes of silica sand. In other words, the larger silica sand particles (250 µm) exhibited greater toughness than the smaller silica sand particles (25 µm) in all samples, despite the fact that the proportions of okra varied. On average, the toughness was observed to decrease by 50% when comparing the 250 µm sand to the 425 µm sand, regardless of the weight percentage of okra added. The changes in the degrees of toughness could be attributed to the changing size of the particles, where medium-sized particles produce the most toughness. Toughness increased with the amount of okra added to the mix in all the sizes of sand particles used in this study. To evaluate the toughness of the material, the experiment involved testing it under different conditions, including different weight percentages (10 wt% and 15 wt%) and sizes (25 µm, 250 µm, 425 µm, and 850 µm) of sand particles. The study results showed that the material's toughness increased by different ratios depending on the size of the sand particles. Specifically, the toughness increased by 78% in 25 µm sand, 40% in 250 µm sand, 70% in 425 µm sand, and 81% in 850 µm sand when the weight percentage was increased from 10 wt% to 15 wt%. The increase in toughness may be due to the sand particles filling in the spaces between the other components of the material, providing additional support and reducing the risk of cracks or fractures. The specific reasons for the increase in toughness may depend on the specific properties of the material being tested and the conditions under which the tests were conducted. The increase in toughness with an increase in the amount of okra added is because okra increases the interfacial bond strength between particles in silica sand [38]. The 250 µm sand produced the highest toughness in all the percentages of okra added. This was mainly due to the high amount of medium-sized particles of sand used, which increases toughness. A high amount of very fine particles in silica sand can increase the water-silica sand ratio, reducing the toughness of the material. Moreover, the excessive presence of fine particles can enlarge the surface area of the composite, which can elevate the possibility of chemical reactions and modifications in the material's characteristics. Overall, the presence of very fine particles and dust can have a significant impact on the toughness of silica sand. To improve the toughness of the material, it may be necessary to reduce the amount of very fine particles and impurities present, or to use a different type of silica sand with a more suitable particle size distribution and lower impurity content [41]. This study established that the toughness reached its peak with the addition of okra to 250 µm silica sand particles.

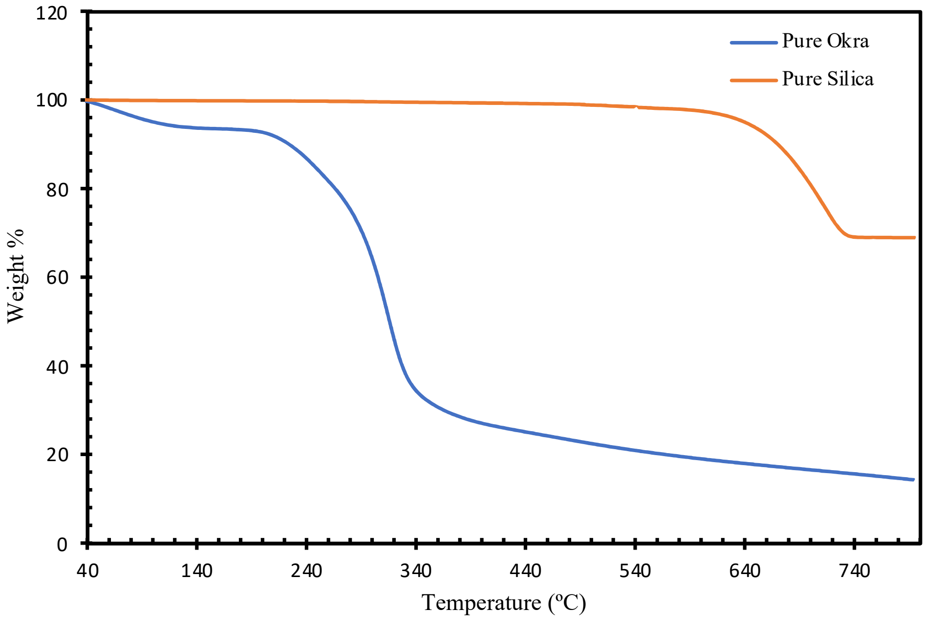
The addition of a bio-binder such as okra has enhanced the compressive mechanical properties of silica sand. However, as shown in Figure 7, it is noticeable that when increasing the weight percentage of okra to 20%, the sample starts to depreciate due to an okra bio-adhesive substance that negatively affected the sample and resulted in a noncohesive composite. Therefore, it was difficult to perform a compression test [42–44].

Figure 7. The sample of 20% okra and 80% silica sand.

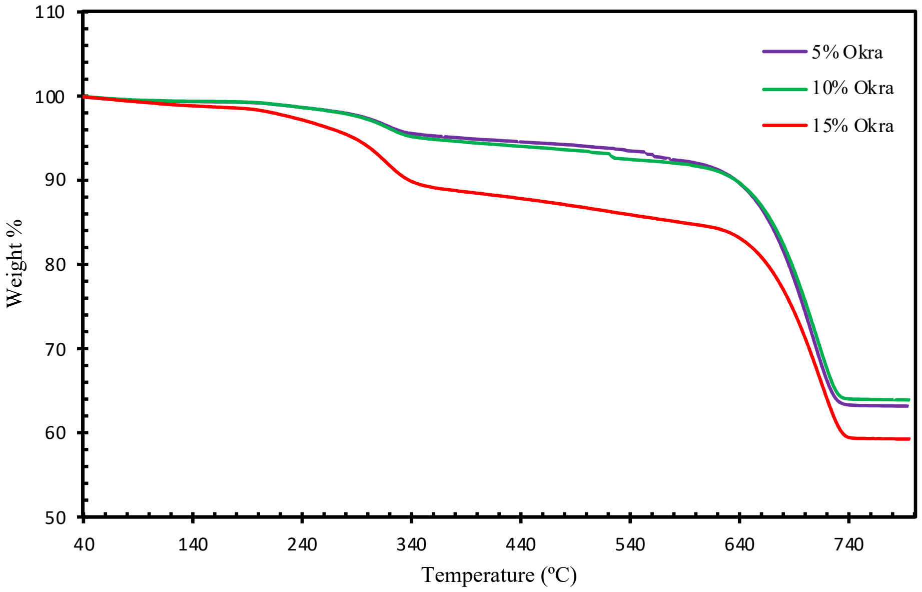
3.5.1. Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) monitors a material's thermal stability through changes in the mass of a substance against temperature changes. TGA also monitors the material's volatile components fraction by monitoring the changes in its weight when heated at a continual rate [45].

The given temperature range was selected to obtain an understanding of the material's stability and the effect of the bio-binder when it is exposed to higher temperatures [46,47]. As pure silica and pure okra have different properties, they degrade differently under temperature, as indicated in Figure 8a. Notably, there is a difference between the thermal behavior in the TGA analysis with 5 wt%, 10 wt%, and 15 wt% okra. The degradation process of pure okra involves the loss of adsorbed moisture and the degradation of cellulose macromolecules, resulting in a notable loss of weight. With this knowledge, it is evident that okra has comparatively high adsorption levels. When combined with another material, the thermal characteristics of the added okra will be affected. The behavior is indicated in Figure 8b. In the case of silica sand, there was no weight loss with an increase in temperature up to 600 °C, where there was a weight loss of up to approximately 65% before the weight stabilized at 740 °C, as illustrated in Figure 8a.



(**a**)



(**b**)

Figure 8. TGA analysis: (**a**) pure samples (okra, silica sand), (**b**) composite samples.

In pure silica sand, the linear stage with no significant change in slope indicates silica's stability with increasing temperature, which was maintained up to around 600 °C [48]. Pure okra, on the other hand, show gradual weight loss when heating started to about 200 °C when there was a sharp decline in weight followed by a moment of near stabilization in weight as the heating increased from 340 °C onwards. According to Rahman et al. [49], the first phase of the degradation is due to the loss of moisture in the substance, thereby leading to a slight weight loss. The second stage of degradation in pure okra involves the breakdown of hemicellulose and the cleavage of glucoside linkages, resulting in a substantial weight loss. The last stage is when char and a volatile material are formed, which is marked by a reduced rate of weight loss and, thus, the almost linear curve. Therefore, the two curves indicate that pure silica sand is more thermally stable than pure okra, as pure silica sand can withstand persistent heating over a higher temperature range than pure okra.

However, a comparative analysis with more addition of okra seems to insinuate an effect on the degradation process. Essentially, when increased to 10 wt%, the first phase of degradation, which entails moisture loss, is not much affected, although there is a more significant difference in the weight loss percentage at 15 wt% okra. The phase thereby indicates that the addition of more okra weakens the product's thermal stability. The thermal stability of a product containing 15 wt% of okra was analyzed. The analysis showed that the product experienced a loss of weight at a temperature of 340 °C, after which there was a period of linear change during the charring phase. The weight loss observed at 340 °C may be due to the thermal decomposition of the okra and/or other organic components in the product. This decomposition could release gases or vapors that lead to weight loss. The linear period at the charring phase may indicate that the remaining material in the product is undergoing a slower thermal degradation process. The specific implications of these results will depend on the nature of the product being analyzed and the intended application. In general, understanding the thermal stability of a product can be important for ensuring its safe and effective use and predicting its behavior under different conditions. The behavior recurs at 700 °C, where there is a subsequent high percentage reduction in weight and another stabilization when the volatile material forms.

3.5.2. X-ray Diffraction (XRD)

The mineral composition of the composite was investigated from the XRD analysis, as shown in Figure 9a,b and Figure 10. All the samples showed the existence of four major minerals: quartz, kaolinite, olivine, and calcite. The difference in the samples was mainly in terms of the number of different compositions of the minerals; additionally, the crystalline silica sand particles dispersed within higher weight percentages of the bio-binder matrix, such as at 15 wt%, will generate new sharp peaks [50,51]. Quartz, composed of silicon dioxide, is a common mineral found in many rocks. Kaolinite is a clay mineral that is composed of aluminum and silicon and is commonly found in soils. Olivine is a mineral found in igneous rocks made of magnesium, iron, and silica. Calcite is a type of carbonate mineral that can be found in limestone, chalk, and marble [52]. In the case of pure okra, the absence of sharp peaks in the XRD pattern, as shown in Figure 9a, represents the amorphous nature of the material [53]. Pure silica is a mineral composed of silicon and oxygen and it is found in many forms such as quartz, kaolinite, olivine, and calcite as illustrated in Figure 9b. The intensity of the quartz peak is high, and as the degree increases, the intensity decreases but remains at its peak, unlike the other minerals. However, between the 2θ range of 25–35 degrees, the intensity is higher around 1500–2000. Kaolinite is a combination of silicon dioxide and aluminum oxide, and its intensity increases in the 2θ range between 25–35 degrees. In contrast, olivine, composed of a combination of iron and magnesium silicates, is found between the 2θ range of 20 to 36 degrees. Calcite or calcium carbonate is the most common carbonate mineral found in sedimentary rocks, and it was determined that the lowest intensity is between the 2θ range of 55–70 degrees [54].

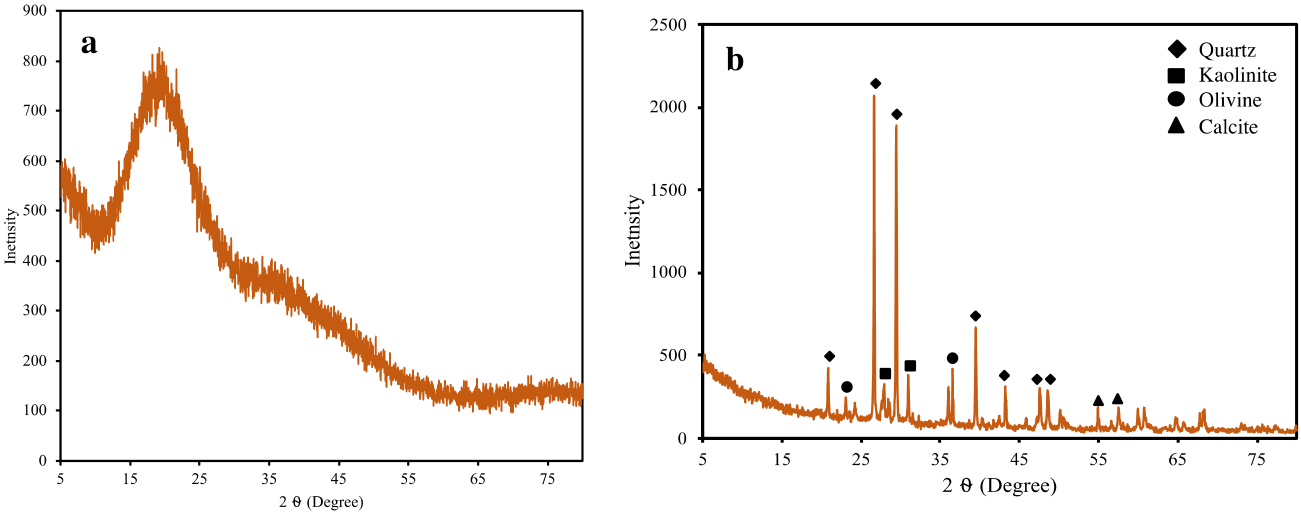


Figure 9. XRD analysis of the pure samples: (**a**) pure okra, (**b**) pure silica sand.

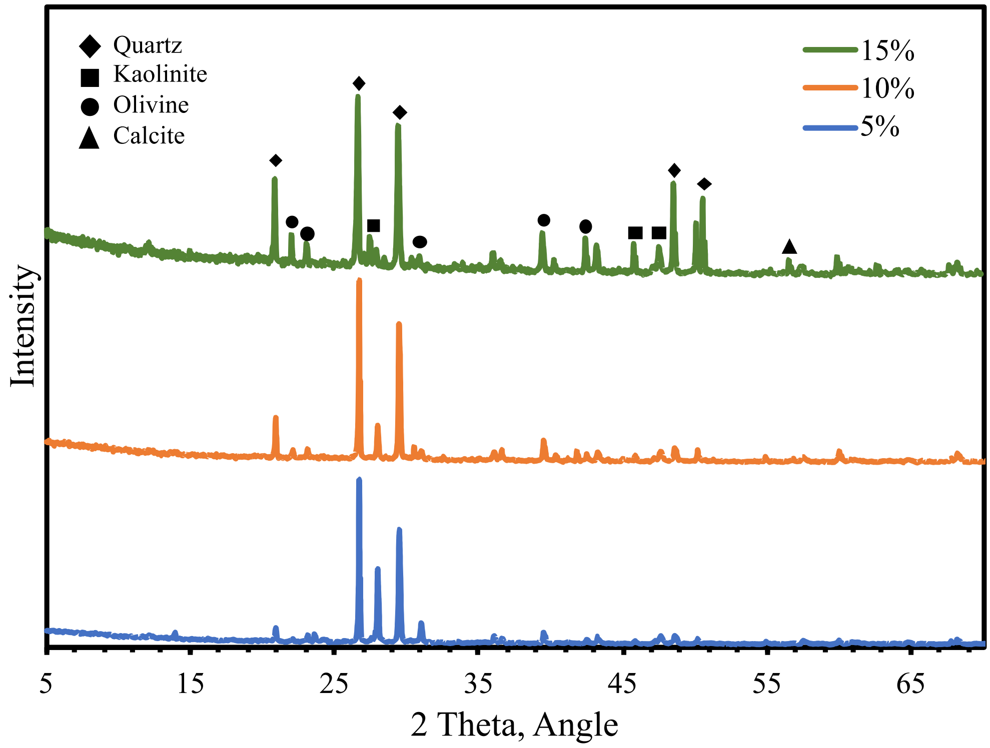


Figure 10. XRD analysis of the biomass.

The 5 wt% okra depicts the sample's relative intensity of quartz, kaolinite, olivine, and calcite. The highest peak in Figure 10 represents quartz, indicating its high concentration. In contrast, the intensity of the peaks in a sample containing both kaolinite and olivine minerals is related to the concentration of certain elements in the sample. Specifically, a lower intensity peak would indicate a lower concentration of the elements being measured. A minimal peak of calcite was also determined in the 5 wt% okra samples. The most abundant mineral in the 10 wt% okra concentration is quartz, along with kaolinite, olivine, and calcite with much lower intensities. The 10 wt% okra samples indicate a decrease in intensity as the degree of mineral compound increases. This decrease in intensity is likely due to the presence of other minerals. In the above samples of different okra concentrations, the concentration also rises as the intensity of peak increases. The different samples with varying amounts of okra can be used to establish a connection between the mineral composition in okra and the relative abundance of quartz, kaolinite, olivine, and calcite in the samples. However, a new phase begins for all compositions at 2θ of 25 degrees since the concentration decreases and the mineral compound in the okra is lost.

3.5.3. Morphology

Adhesion and bonding between the articles are evident with the change of the composition, as apparent from SEM images shown in Figure 11a,b of a 250 µm set microscope exhibiting different behavioral bonds. Notably, the images show silica sand when combined with okra.

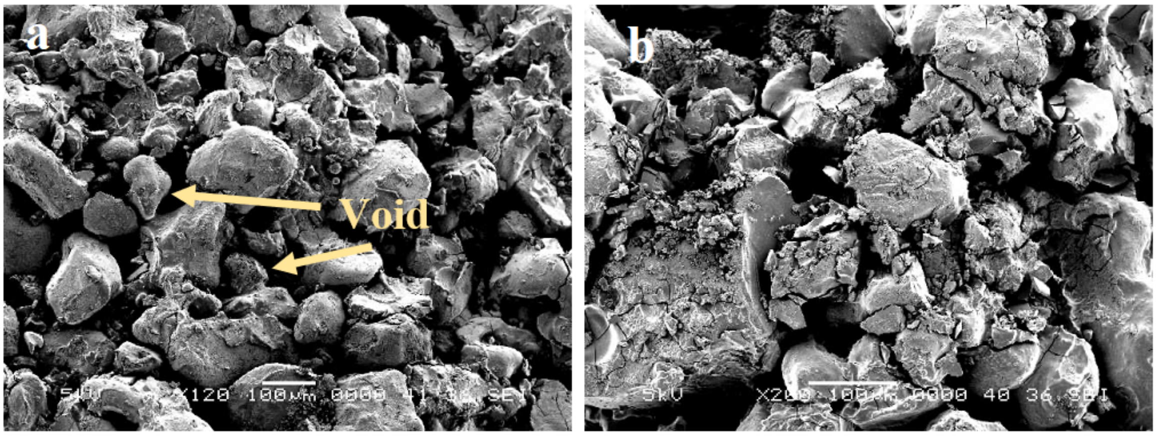


Figure 11. SEM images of the composite: (**a**) 5% okra, (**b**) 15% okra.

In Figure 11a, the fine particle distribution and the voids were clear, indicating less amount of bio-binder was added that resulted in weaker bonds [55,56]. This is due to the increase in okra adhesion levels and the eventual cohesiveness of the molecules as shown in Figure 11b. Normally, smaller particles in particulate composites can result in stronger adhesion between the particles and the matrix due to the increased surface area of the particles. This increased surface area allows more intimate contact between the particles and the matrix, resulting in stronger interfacial bonding. A robust composite with increased strength and toughness can be achieved by efficient load transfer, which is facilitated by a strong interfacial adhesion between the particles and the matrix. In addition, the increased surface area of the particles can also promote better dispersion of the particles in the matrix, reducing the likelihood of particle agglomeration and clustering. However, it is essential to note that the relationship between particle size and adhesion is not always straightforward. A variety of factors, including the chemical composition of the particles and the matrix, the processing conditions, and the loading conditions, can influence the adhesion between the particles and the matrix. In some cases, larger particles may result in stronger interfacial bonding due to their higher inherent surface roughness, which can promote mechanical interlocking with the matrix. The correlation between particle size and bonding in particulate composites can be intricate and reliant on multiple factors, even though smaller particles usually lead to stronger adhesion. Careful consideration of these factors is essential when designing particulate composites for specific applications. In this case, the differences in the diagrams indicate the action of okra on silica sand that resulted in a size increase in the microsphere size. Higher concentrations in the okra led to the formation of a more adhesive composite and eventual improvement in particle bonding. Overall, the addition of okra to a compound containing sand and silica particles leads to an improvement in its strength. Okra is a natural polymer that contains high levels of soluble fiber, which can act as a binding agent when mixed with other materials. The incorporation of okra into a silica particle mixture may lead to an enhancement in particle cohesion and the development of a stronger composite, possibly due to the binding of the particles by okra fiber. Okra improves pure silica sand's hardness by affecting its strength modulus.

Constructing buildings using sustainable materials can decrease the carbon footprint of the built environment with little environmental damage and aid in the creation of more sustainable and environmentally friendly buildings [57]. In addition, recycled materials are essential to sustainable construction, as they reduce waste and minimize the need for extracting raw materials from the environment; for example, recycled biowaste material can be used in construction as a replacement for different traditional building materials since it is lightweight and resistant to corrosion [58].

4. Conclusions

The biomass composite (silica sand/okra) can be used in buildings, such as limestone, clay, plastering, and construction materials for the production of concrete and other civil engineering work. It will minimize the disposal of waste and amount of harmful gases that are released into the atmosphere, preventing the destruction of the environment and leading to sustainable growth [59,60].

A comprehensive analysis of the experimental findings for the mechanical characteristics of micro silica sand and okra, including their modulus, strength, and toughness, is provided. The impact of particle size on the strength, ductility, and toughness of the particulate composites has been extensively studied. In general, the size and shape of the particles, the interaction between the particles and the matrix, and the volume fraction of the particles influence the mechanical properties of the particulate composites. Particle size plays a critical role in determining the strength and toughness of particulate composites. This increased surface area can enhance the adhesion between the particles and the matrix, resulting in a stronger and tougher composite. However, microscopic particles can also increase the tendency for clustering and agglomeration, reducing the composite's mechanical properties. The particle/matrix adhesion is another essential factor that affects the strength and toughness of particulate composites. A strong interfacial bond between the particles and the matrix can lead to an efficient load transfer, resulting in a more robust composite. Particle loading, or the volume fraction of particles in the composite, also has a significant impact on the mechanical properties of the material. Increasing the volume fraction of particles leads to a stiffer and heavier composite due to the presence of more load-bearing particles. However, excessive particle loading can also result in particle agglomeration and reduced matrix adhesion, leading to a decrease in toughness. In order to design and optimize the mechanical properties of particulate composites, it is crucial to take into account factors such as particle size, particle/matrix adhesion, and particle loading. So, it is important to conduct extensive investigations on these factors to better understand their impact on composite materials; the findings can inform the development of new and improved composite materials for a wide range of applications. The ideal micron size of silica sand that was enhanced with the addition of okra was 250 µm. It has been shown that there are some factors, such as particle/matrix adhesion, that have a significant impact on the composite materials' strength and toughness. This outcome is expected since toughness is controlled by adhesion, while strength depends on the effective transmission of stress between the binder and matrix. The composite strength is much lower than other sizes below a critical particle size, often in the range of 25 µm, because of the major impact of the particle size, due to the dust silica sand that caused agglomeration. However, for 425 µm and 850 µm, the larger particles were unequal in size, which caused voids that led to a decrease in the compressive strength. However, for 250 µm at 15 wt% of okra, the highest compressive mechanical properties were recorded. The maximum compressive strength was 25.8 MPa, whereas the peak of the elastic modulus was 17.5 MPa. On the other hand, the best yield strength of the developed composite was estimated at 25.6 MPa. Meanwhile, the maximum ductility measured was 41%. The material's capability to absorb energy was evaluated by evaluating the toughness of the composite, which was found to equal 76.5 MPa.

This study demonstrates the potential of silica sand and okra composites in producing sustainable construction materials. This work also presents future insights for prospective uses of high-performance bio-concrete based on aggregates with binders in other fields.

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