Journal of Science and Engineering Applications Vol. 08, No. 01, pp. xx–xx, June 2026

Journal of Science and Engineering Applications

Contents are available at https://jsea.iujournals.com

Investigate the physical and mechanical properties of autoclaved aerated concrete reinforced with sisal fiber

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ARTICLE INFORMATION

Received date: 23-02-2026
Revised date: 4- 04-2026
Accepted date: 2-06-2026

Keywords

Autoclaved aerated concrete (AAC), sisal fiber, Aerated concrete, compressive strength, and density.

ABSTRACT

Autoclaved aerated concrete (AAC) is a lightweight, environmentally friendly concrete made from cement, sand, lime, water, and aluminium powder. Having a crucial interest for the last decade, due to their low density and thermal properties. This study shows the effect of sisal Fiber on the density and compressive strength of AAC blocks. Therefore, three groups of samples were produced, with fiber contents of 0.1%, 0.2%, and 0.3% of total volume. The study's results show that AAC reinforced with sisal fibers had a density between 652 and 731 kg/m3. However, 0.2% represents the optimal fiber content for achieving the highest density. Furthermore, the compressive strength recorded 3.23, 4.09, and 4.17 Map for fiber contents of 0.1%, 0.2%, and 0.3%, respectively. Based on the results, it can be concluded that the AAC reinforced with sisal fiber significantly improved the density and compressive strength of AAC specimens. This type of AAC is suitable for partition and non-load-bearing wall applications.

1. Introduction

Autoclaved Aerated Concrete (AAC) has a crucial interest due to its physical and mechanical properties, which offer excellent thermal insulation, fire-resistant, energy-efficient, environmentally friendly, and sustainable blocks. AAC was invented in early 1923 by Swedish architect Johan Axel Eriksson. He developed AAC as an alternative to timber due to a shortage of wood in Sweden at that time. The density of Autoclaved Aerated Concrete ranges from 460 to 750 kg/m³, nearly one-third of normal [1]. These attributes make it ideal for modern construction. Furthermore, as an entirely inorganic material, AAC is 100% resistant to termites and unaffected by decomposition or mold. These combined properties have led to its widespread adoption in modern construction for both residential and commercial use [2].[3]. AAC is produced by mixing sand (silica), cement, lime, water, and aluminum powder as an expansion agent, then pouring the mixture into molds, where the aluminum powder reacts with lime to produce millions of microscopic hydrogen bubbles. These bubbles are responsible for creating highly aerated concrete, which is then cut into blocks or panels and cured by steam and pressure in an autoclave [4]. AAC blocks are most commonly used as masonry units in construction. Undoubtedly, AAC blocks possess many positive physical properties that have attracted attention

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worldwide, but there are also some drawbacks, including low compressive strength. Researchers have attempted to enhance the mechanical properties of AAC blocks. Some efforts yielded no noticeable improvements, while others improved mechanical properties but altered other characteristics. In fact, adding glass fiber increases the compressive strength of Autoclaved Aerated Concrete blocks by 10%, 24%, and 13.8% at fiber contents of 0.1%, 0.2%, and 0.3%, respectively. While a slight increase in density (about 0.2%) between the normal and modified Autoclaved aerated concrete blocks was detected [3]. Another study showed that the best compressive strength (6.0 N/mm2) was observed with carbon fiber-reinforced AAC [5]. Additionally, [6] mentioned that the reinforcement of aerated concrete with coconut fiber (CF) with 0.6% of the total mass of cement, increased the Compressive Strength of 15%, corresponding to the reference specimens. AAC has low mechanical strength despite being lightweight. Most previous studies have focused on synthetic fibers in AAC, such as [3] used glass fibers in AAC, and [5] used adding polypropylene, carbon, basalt, and glass fibers into AAC, while the use of sisal fibers in AAC has not been studied. Sisal fibers are natural fibers taken from the leaves of the Agave sisalana plant. They are extracted after soaking, washing, and drying to remove the sticky substance, then the fibers are combed and cleaned to produce strong, shiny, yellowish-white threads, so this process is considered environmentally friendly because it does not require chemicals. And chemically, these fibers mainly consist of 40–60% cellulose, 20–40% hemicellulose, and 10–25% lignin, with small amounts of other substances, including sugars and waxes [7]. In this study, Sisal fiber can meet the requirements due to its physical, mechanical, and cost-effective properties. The tensile Strength of these fibers is 363–700 MPa [2]. Fiber affects various properties of AAC, such as density and compressive strength, when it is incorporated. Prompting on the influence of sisal fibers on AAC's density, thermal conductivity, flexural strength, and compressive strength when reinforced with it. The study aims to produce AAC with good mechanical and physical properties. Also, the sisal fibers achieve sustainability due to improves the environment by increasing oxygen and reducing carbon dioxide during the growth period, thus reducing global warming.

2. Materials and Methods

2.1. Materials

The materials used in this study were sisal fibers, fine aggregates, Ordinary Portland Cement, lime, water, and aluminium powder.

2.1.1. Sisal Fiber

Sisal fibers, as shown in figure (1) are natural fibers extracted from the leaves of the sisal plant, scientifically known as Agave sisalana. These fibers are characterized by their strength, durability, and lightweight nature. They are also an environmentally friendly and biodegradable material. Sisal fibers are used in many industrial applications, such as the manufacture of ropes, carpets, and textiles. They are also increasingly used in engineering to strengthen concrete and composite materials, contributing to improved tensile strength, reduced cracking, and increased durability.

Figure (1): Sisal fibers

Table (1): feature of sisal fibers

Material property	Result
Length (mm)	5mm
Color	creamy white
Density (g/cm^3)	1.5
Tensile strength (MPa)	385 to 728 [8]
Elongation of cut (%)	2.7 [8]
Moisture	6.5 [8]

2.1.2. Cement

The properties of the cement are shown in **Table ((2).** The cement was tested in accordance with the Iraqi Standard Specification (I.Q.S. No. 5, 2019) [9].

Table (2) properties of cement

properties	Test result	Iraq specification (No.5 of 2019)
Fineness (Blaine Method) m^2/kg	306 m^2/kg	Not less than 300 m^2 /kg
Time of setting (Vicat's apparatus)		
Time of initial setting, minutes	175 min	> 45 min
Time of final setting, hours	4.0 hours	<10 hours
Compressive strength		
2 days, MPa	22.8	> 20MPa
28 days, MPa	45.05	> 42.5MPa

2.1.3. Fine Aggregate

Sand greatly affects the mechanical characteristics of the finished product. The characteristics of the sand were assessed, as shown in **Table (2)** and complied with the Iraqi specification (I.Q.S No.45-1984) [9].

Table (3) Properties of Fine Aggregate

properties	Test results	Limits of Iraqi specification (IQS No.45/1984)
Absorption	1.7%	2.5% Max
Sulfate content SO3	0.4%	≤0.5%
Fineness modules	3.1	2.3-3.1
Fine materials passing through the 75 µm sieve	3%	5%

2.1.4. Lime

Lime is one of the oldest binding materials that has been used in construction. Lime is used as a powder (14 % by total volume) in the manufacture of autoclaved aerated concrete (AAC) blocks.

2.1.5. Aluminium

Aluminium is used as an expansion agent; aluminium powder is used at a rate (0.04%) by volume.

2.1.6. Water

Water used in this study was potable and also suitable for mixing, as it was devoid of acids, contaminants, and suspended particulates that could threaten the integrity of the resultant AAC.

3. Mix proportion and Mixing

The proportions of the ingredients used for the manufacturing of the Autoclaved aerated concrete (AAC) in this study are as follows

Table (4) mix proportions

Samples	A	B	C
Slurry 64%	9 Kg	9 Kg	9 Kg
Water 17%	2.5L	2.5L	2.5L
Cement 13%	2Kg	2Kg	2Kg
Lime 6%	1Kg	1Kg	1kg
Aluminum 0.04	6 g	6 g	6 g
Sisal 0.1%,0.2%,0.3%	40.2 g	80.4 g	120.6g

Initially, the slurry is poured into the mixer in the specified proportion, followed by the cement and lime. Then, water is added. The mixing is performed using an agitator rotating at 30-40 RPM. The ingredients are mixed for about 3-5 minutes. During mixing, the temperature is maintained at approximately 40-45°C to accelerate chemical reactions. Temperature is monitored either by an automatic batching machine or a laser thermometer. Subsequently, the sisal fibers are added to the mixture and thoroughly mixed to ensure uniform distribution within the AAC. Finally, the aluminum is added and mixed for a very restricted period, approximately 30 to 35 seconds. This short mixing time ensures the expansion of the AAC mixture in the mixer.

Figure (2): mix of AAC

4. Casting

After the mix of the raw materials is ready, it is poured into the molds. The molds used for this study were 20 cm long, 20 cm wide, and 67 cm high. Before casting, the molds are coated with a thin layer of oil. The aim of applying the oil is to avoid the sticking of the AAC to the mold. After the application of the oil, the concrete is poured into the molds up to 50 cm of the mold. After the pouring, the molds are placed in a drying chamber with a temperature ranging between 45-65 °C. The aluminum begins reacting with the calcium hydroxide, and the AAC starts rising in the mold like a cake. This takes about 2-4 hours to rise to the top of the mold, and a green cake is formed.

Figure (3): (a) the molds, (b) the drying room, and (c) the green cake of AAC

5. Autoclaving

The green cakes are placed into a closed vessel called an autoclave for steam curing. They are then cured with steam in the autoclave for 10-12 hours at a temperature of about 180°C to 200°C and a pressure of approximately 12 bar (1200 KPa). The curing process passes in three stages. In the first stage, the pressure is gradually increased to 4 bar (400 KPa) over four hours. In the second stage, the pressure is raised to 12 bar (1200 KPa) and maintained for about six hours. In the final stage, the pressure is gradually decreased to prevent cracks caused by the sudden cooling of the AAC. The pressure and temperature inside the autoclave are controlled through steam generated by the steam generation chamber or boiler.

Figure (4): The Autoclave of AAC

6. Cutting

When demolding is finished, the autoclaved aerated concrete (AAC) is moved for cutting. The cutting process occurs in two stages. First, a cubic sample measuring 10 cm length is made, and second, a prism measuring 4mm x 4mm x 16mm is created. The samples then moved to the laboratory for testing.

7. Results and Discussion

7.1. Density

This test is performed to determine the bulk density of Autoclaved Aerated concrete using three cubes. The average of their values is taken as the final result. Density is measured by dividing the mass (M) by the volume (V), as shown in **Equation (1)**, according to the Limits of Iraqi specification IQS No.810 [10].

$\boldsymbol{D}=\boldsymbol{M}/\mathbf{V}$ …. (1) Where: M= mass (Kg) ,V=volume (m^3) , D= density (Kg/ m^3)

Figure (6) shows the effect of sisal fibers on the density of autoclaved aerated concrete (AAC).

Figure (5): Weighing the samples for density testing.

Figure (6) shows the effect of sisal fibers on the density of autoclaved aerated concrete

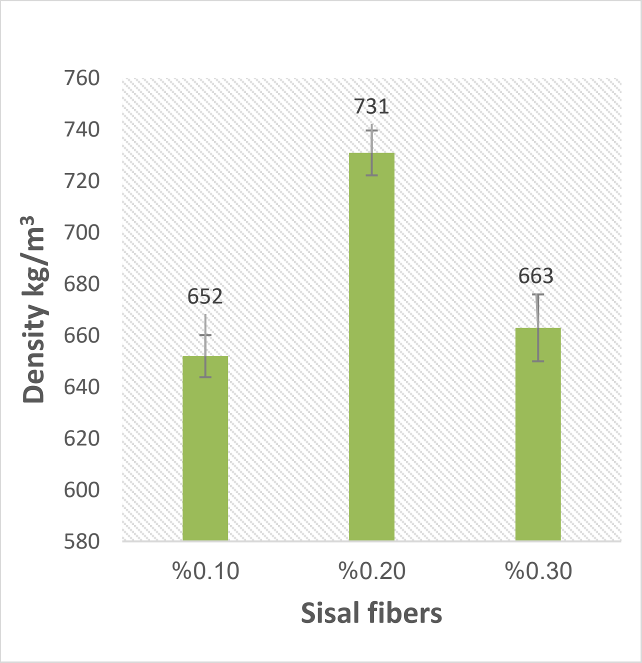

Figure (6): The relationship between density and sisal fibers in AAC

The density reached 652 kg/m³ at a fiber content of 0.1% due to the limited effect of the fibers on the porous structure. Increasing the fiber content to 0.2% resulted in a higher density of 731 kg/m³ due to an increase in the air bubble collapse, leading to a more compact structure. However, the density decreased to 663 kg/m³ at 0.3% due to fiber agglomeration (balling) and increased porosity, as shown in the figure (7).

Figure (7): The fiber clumping within the AAC sample.

7.2. Compressive strength

The compressive strength test is one of the most important mechanical tests for Autoclaved Aerated Concrete, demonstrating the ability of AAC to withstand applied loads. This test determines whether the AAC is accepted or rejected. In this study, the (Limits of Iraqi specification IQS No.810) [11] procedure was followed, and average of three samples were calculated for this test. The test specimens used measured (10*10*10) cm. The testing apparatus had a loading rate of 0.05 N/mm².min, and the compressive strength of each cube was calculated by dividing the force exerted on its cross-sectional area, as shown in figure (8). The main source of reactive silica in the mixture is sand. The crystalline phase of tobermorite is formed when it is finely ground and reacts with calcium that is available from lime during the autoclaving process.

Figure (8): Device of compressive test

Compressive strength was found to rise from 3.23 MPa at 0.1% to 4.09 MPa at 0.2%, then increase to 4.17 MPa at 03% sisal fiber, as shown in figure (9).

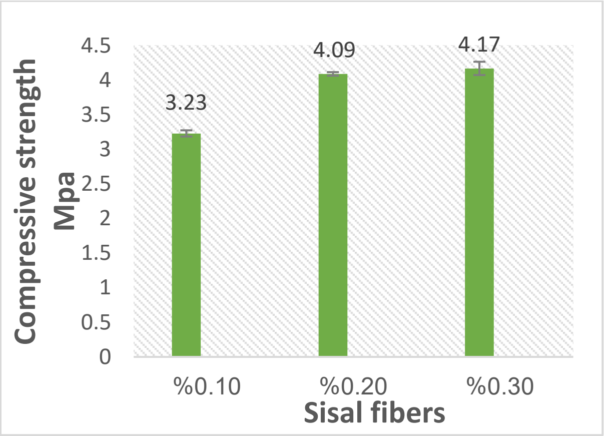

Figure (9): The relationship between compressive strength and sisal fibers in AAC

This improvement is attributed to the role of sisal fibers in reducing microcrack propagation and enhancing interfacial bonding (ITZ), thereby improving stress distribution and reducing brittleness. The fibers also contribute to strengthening the AAC microstructure, which positively impacts compressive strength.

7.3. Flexural Strength

Flexural strength measures the bending ability of prepared samples using specific mixing ratios. A prismatic sample measuring (40 x 40 x 160) mm is used, along with a digital testing device capable of at least 10 kN. The samples are supported on two steel supports, with a load applied at the center. The test is conducted on three samples. According to the specification (EN 1961-1997) [12], the flexural strength is calculated with equation (2).

$Rf = (3F l) / (2b^{2} d)$ …..(2)

The findings indicate that flexural strength gradually increases as fiber content rises, as shown in figure (10)

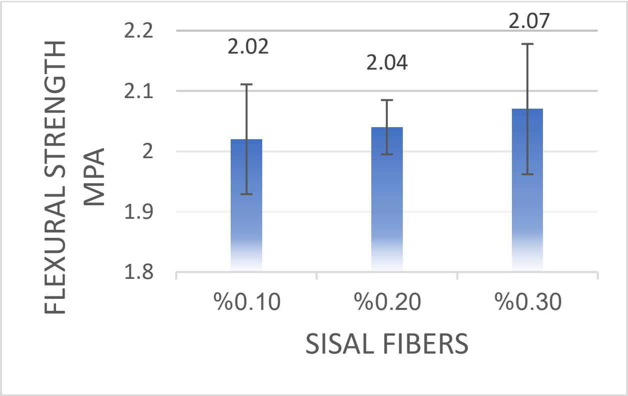

Figure (10): The relationship between flexural strength and sisal fibers in AAC

The primary reason for this improvement the sisal fibers act as "bridges" within the cementitious matrix, connecting the microscopic cracks when the AAC is loaded. In ordinary AAC (without fibers), when a crack starts to appear, it propagates rapidly, leading to brittle failure. However, with the presence of fibers, this propagation is inhibited because the fibers transfer stress from one side of the crack to the other, thus requiring more energy for the crack to continue spreading. As the fiber content increases from 0.10% to 0.20% and then to 0.30%, the number of these bridges within the AAC increases, thereby improving the material's flexural strength and energy absorption. The values increase from approximately 2.02 to 2.07 MPa. This improvement indicates increased ductility and reduced brittle behavior, meaning the material does not break suddenly but can withstand greater deformation before failure. Furthermore, the fibers contribute to better stress distribution within the AAC, reducing stress concentration zones, which directly translates to increased flexural strength.

Figure (11): The sisal fibers act as bridges within AAC

7.4 Thermal Conductivity

The capacity of AAC to conduct heat was assessed using a thermal conductivity test. The KD2 PRO [13], a battery-operated device that measures thermal conductivity, utilizes a prism measuring 4 cm × 4 cm × 16 cm for this test. A hole measuring 2.4 mm in diameter and extending to a depth of 10 cm from the center of the prism was drilled to perform the thermal conductivity test. The size of the sensor rod in the test apparatus is adequate to this. When the needle is inserted into the hole, the sensor heats it for at least 3-5 minutes and monitors the temperature as stated in the device's user handbook, in accordance with (ASTM D5334 2022)[14]. The result shows that at 0.3% sisal fibers, the thermal conductivity coefficient decreased significantly to 0.072 W/(m · K), as shown in Figure 12.

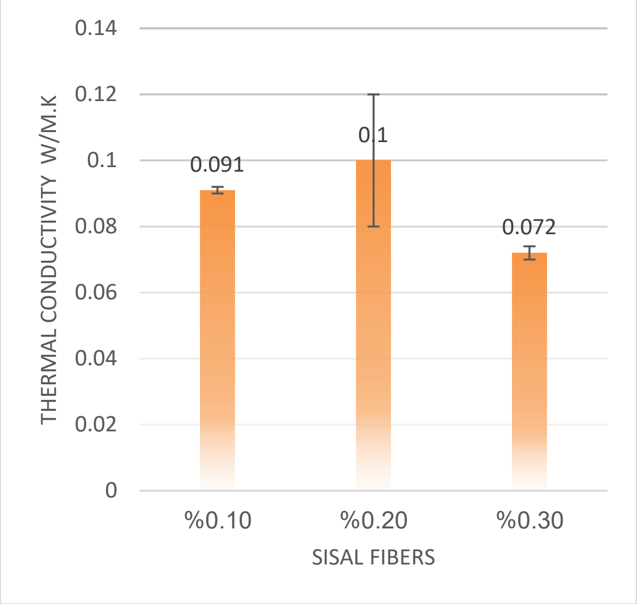

Figure (12): The relationship between thermal conductivity and sisal fibers in AAC

This is explained by the low conductivity of sisal fiber and the higher fiber content's increased porosity and air voids, where trapped air serves as an efficient heat insulator and enhances AAC's insulating qualities.

Figure (13): The sample of AAC under the thermal Conductivity test

7.5. Microstructure test

7.5.1. Scanning Electron Microscope (SEM)

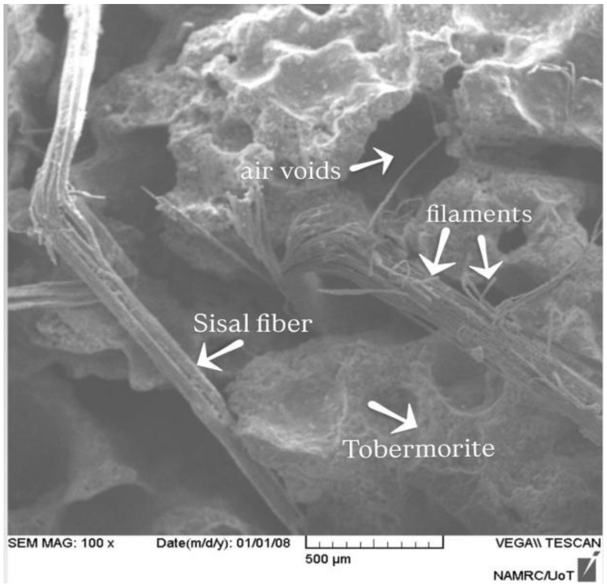

Figure (14): The SEM test for AAC reinforced with sisal fiber

Figure (14) shows a well-distributed fiber structure within the AAC, the fibers appearing interwoven with the cement paste matrix. Tobermorite formation around the fibers is also observed, indicating strong bonding between the fibers and the matrix. This bonding facilitates stress transfer between the matrix and the fibers, thus reducing crack propagation within the material. Furthermore, these sisal fiber filaments act as bridges, connecting pores and air voids, thereby mitigating their adverse effects on the material's strength. Consequently, the fibers contribute to improved compressive, tensile, and flexural strength through a bridging effect that prevents or delays crack growth. Therefore, the microscopic observations are consistent with the mechanical properties analysis, which demonstrated improved strength. The presence of the fibers and their strong bonding with the AAC matrix contribute to increased stress resistance and reduced brittle failure.

8. Conclusions

1. The results showed a direct relationship between increasing the percentage of sisal fibers and the strength of the AAC. Compressive strength increased from 3.23 MPa at 0.1% to 4.17 MPa at 0.3%.
2. The AAC exhibited a gradual improvement in flexural strength with increasing fiber content, indicating the role of sisal fibers in enhancing the internal cohesion of autoclaved aerated concrete. The flexural strength was

recorded (2.02, 2.04, and 2.07 MPa) with (0.1%, 0.2%, and 0.3%), respectively.

3. The results showed a significant advantage for sample (C) with 0.3% fibers in thermal insulation properties. Thermal conductivity decreased sharply to 0.072 W/m·K, making it an ideal material for use in structural insulation applications.
4. Sample (C) with 0.3% sisal is considered the best in terms of combining the highest compressive strength with the best thermal insulation efficiency.

5- This type of autoclaved aerated concrete is used in partitions and non-load-bearing walls.

Recommendation for future work

1-Assessment of Durability Characteristics: Conducting additional tests on physical properties, such as studies on permeability and porosity of concrete, and resistance of concrete to corrosion and chemicals.

2-Advanced mechanical properties: Conduct creep, tensile, and shrinkage tests for autoclaved aerated concrete modified with sisal fibers, especially if the goal is to use it in the future in structural or semi-structural elements.

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