Study the possibility of using sisal fibres in building applications

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Abstract

In this study, the potential of utilizing natural fibres in construction substances is studied such as the compression strength and heat conductivity. Gypsum walls are reinforcement using sisal fibres for the industrial and construction applications. The sisal fibre has been washed by fresh water and treated with concentration of NaOH (6%), to achieve a real interfacial adhesion between the gypsum and sisal fibres. To survey the impact of different volume fractions of glass and sisal fibres on the conductivity of gypsum, a newly designed heat conductivity test setup was developed. Also, compressive test was carried out for the selected materials. The scanning electron microscopy (SEM) is using to figure out the failure mechanisms by examining the samples after compressive test. The test outcomes detected that the addition of fibres to the gypsum matrix enhances the compressive strength and led to minify brittleness. The optimum fibre content for sisal fibre-gypsum composite and glass fibre-gypsum composite are at 25 vol. and 30 vol. %, respectively. The pure gypsum samples have achieved the highest value of thermal conductivity among other composite samples in thermal conductivity test. The thermal conductivity of the composites reduces with the increase of fibre volume fraction for both glass and sisal addition of the fibres. Due to porous nature of sisal fibre-gypsum composites, as the presence of air voids work as traps and impeded the heat transfer, sisal fibre-gypsum composites performs better than glass fibre-gypsum composites as an insulation material. Copyright © 2019 VBRI Press.

Keywords: Gypsum walls, fibre-gypsum composite, sisal fibre, glass fibre, construction materials, compression strength, thermal conductivity.

Introduction

Recently, there is a growing attention in the evolution of natural fibres for industrial applications by engineers and researchers. Many efforts are focused on the possibility of replacing natural fibres with the more synthetic fibres, such as aramid, carbon and glass. Natural fibres possess good properties, suitable to be used as engineering materials. These properties include high strength-to-weight ratio, low cost, less health hazards, and obtained from renewable resources [**1-3**]. A particular interest for the use of natural fibres is in the form of reinforcing fibres in composite materials. This can be observed in the automotive industry, whereby in the last decades, many Western European automotive manufactures, such as Audi, BMW and Volkswagen are using these types of composites within various parts of a vehicle, mainly as interior linings, padding and paneling [**4**]. However, glass fibres are one of the most widely used interior construction material in the world. They are widely used to reinforce plastics as they are relatively cheaper than aramid and carbon but with fairly good mechanical properties [**5, 6**]. The production of glass fibres create lots of environmental issues associated with the significant increase of waste disposal sites. In addition, the lack of landfills in some areas and how to regulate them is one of the major challenges that current civil engineers are facing. In Australia, 8.5 million tons of construction and demolition waste was disposed to landfill in the year 2008-2009 [**7**]. Thus, it is urgent to promote sustainable building materials to reduce the negative impact on the environment brought by non-biodegradable materials.

The civil engineering industry had witnessed many changes and development in the use of building materials. Most recently is the application of fibres as reinforcement for cement, concrete and polymers. Another possible combination is with gypsum, to provide finishing interior work, paneling and partition walls in buildings. It is estimated that about 95% of total gypsum produced is consumed by the building sector [**8**]. The main contribution of this material is to provide comfort to people residing in buildings due to its thermal and acoustical properties.

The mechanical properties of a material are important benchmarks to evaluate its capability to be used in civil structures. The bending, compressive and tensile behaviour are the most studied properties in the research of composite materials. Antich, Vázquez [**9**] studied and evaluated the tensile and fracture properties of hybrid fibre composites– polystyrene (HIPS) reinforced by short sisal fibres. This study reported that for 25% sisal volume, the composite displayed an increment in Young's modulus, but a reduction in the tensile strength and elongation break rate. And, by morphological examination, the lower in mechanical characteristics is noted to be owing to poor interfacial adhesion between sisal fibre and HIPS matrix. On the other hand, Ramesh, Palanikumar [**10**] reported that the sisal fibres are able backing glass fibres as reinforcement in hybrid fibre composites – polyester reinforced by sisal fibre, jute fibre and glass fibre and improved its mechanical properties such as flexural and tensile strength. Also, the morphological results also detected that the breakage occurred in the sisal/jute fibres. Towo and Ansell [**11**] investigated the effect of alkali treatment (0.06 M NaOH) on mechanical behaviour of the thermoset-sisal fibre composites. The results displayed a betterment on both polyester and epoxy matrix composites after the alkali treatment. It was found that the fatigue strength of sisal fibre composites are high suitable for many industrial applications. Furthermore, a low thermal conductivity of the developed materials is desirable target especially in construction applications. Therefore, many researchers have studied the thermal conductivity of a variety of materials and composites in order to obtain optimum energy saving from the use of proper materials to serve their intended use. A study by Ramanaiah, Ratna Prasad [**12**] on typha angustifolia natural fibre reinforced polyester composites have found that the thermal conductivity lowers with increases in fibre content. The authors justified this behaviour of the composite owing to the lower thermal conductivity of the fibre being loaded in the matrix. It was concluded that these composites have good insulation behaviour and proper for many applications such as insulation purposes, automobile industry, building application. Korjenic, Petránek [**13**] studied the thermal conductivity for a new developed insulating material using jute, flax, and hemp for civil applications. The results of the composite samples detected that natural fibre composites are potential to turn into a convenient substitutional to commonly used boards. Panyakaew and Fotios [**14**] used coconut husk and bagasse to fabricate a low density thermal insulation board. It is found that the bagasse insulation board has a low density (350 Kg/m3) and a thermal conductivity values from 0.046 to 0.068 W/mK and are comparable to cellulose fibres and mineral wool.

Experimental

Materials selection

As shown in **Fig. 1**, the gypsum used in this project is in a dry powder form manufactured by Gyprock Australia. The product is Gyprock Base Coat (45) which was packed in a 10 kg bag and comprises of calcium sulphate, calcium carbonate, mica, talk and calcium carbonate. The glass fibres used were manufactured by Diggers. The product comes as a 1.0 meter square chopped sheet fiberglass matting. And as for the raw sisal fibres, they were imported from Kuwait, but are originally from West Kenya. The length of the sisal fibres were 80 cm and the diameters range from 100~250 μm.

Fig. 1. Material selection.

Alkali treatment of sisal fibres

The raw sisal fibres were washed with fresh water and then dried at room temperature for 24 hours. Then, the dried fibres were cut into a desired length (100 ±2 mm). Thereafter, the fibres were submerged in the solution with concentration 6 wt. % Sodium Hydroxide (NaOH) for 24 hours and then washed with water. The NaOH liquid was produced by dissolving NaOH pallets manufactured by Scharlau. Finally, the fibres were washed with tap water and then left to dry at room temperature for 24 hrs.

Fabrication of composite samples

The composites based on gypsum with sisal fibre (SF) and glass fibre (GF) were fabricated with variable fibre compositions (± 20, 25, 30 and 35 vol %). The composites were moulded in PVC cylinder pipes (length = 100 cm and diameter = 4.5 cm) as shown in **Fig. 2**. Prior to fabrication works, the interior surfaces of the PVC moulds were applied with Nu-Ceara Wax, a mould release manufactured by Huntsman Composites.

Fig. 2. PVC moulds.

As per manufacturer's guidelines, the gypsum was mixed with water to form a viscous substance. Then, the PVC cylinders were filled with the gypsum mixed with sisal and glass fibres at various percentage of fibre volume fractions (20, 25, 30, and 35 vol %). The fibres were weighed prior to volume measurement, using 0.01 mg precision weighing scale (Sartorius CP225D). To ensure that the mixture is compacted well to produce composites with low air voids, tamping was performed on the fresh mixture at three layers using a small metal rod. For each layer, the mixture was tamped for 20 minutes. The PVC cylinders filled with the composite mixtures were left to harden at room temperature for 24 hours. These hardened samples were then placed in an oven at 70 ºC for 72 hours to ensure that they are completely dried. Finally, the PVC mould was cut open to release the cylindrical samples. These samples will be used for thermal conductivity test and compressive test. The samples used in this study are listed in **Table 1**.

Table 1. List of composite samples.

Sample	Type of Fibre	Fibre Volume Fraction
PG	None	0%
SF20-G	Sisal	20%
SF25-G	Sisal	25%
SF30-G	Sisal	30%
SF35-G	Sisal	35%
GF20-G	Glass	20%
GF25-G	Glass	25%
GF30-G	Glass	30%
GF35-G	Glass	35%

Compressive test and morphology of fracture surfaces

The study of the compressive behaviour of the developed materials was performed using MTS 647 Hydraulic Wedge Grip with a 100 kN maximum capacity and at a rate of 3 mm/min. The testing machine is shown in **Fig. 3a**. Four samples of sisal fibre-gypsum composites, four samples of glass fibre-gypsum composites and one pure gypsum (0% fibre) were tested. The length of all the samples is 6 cm with a diameter of 4.5 cm. The software used to record the data for this test was MTS Flex Test 40. From the data obtained, the stress-strain curves were plotted and the mechanical properties of the samples were evaluated. Scanning Electronic Microscope (SEM), Jeol JCM-6000, was utilized to examine the morphology of sisal fibres as shown in **Fig. 3b**.

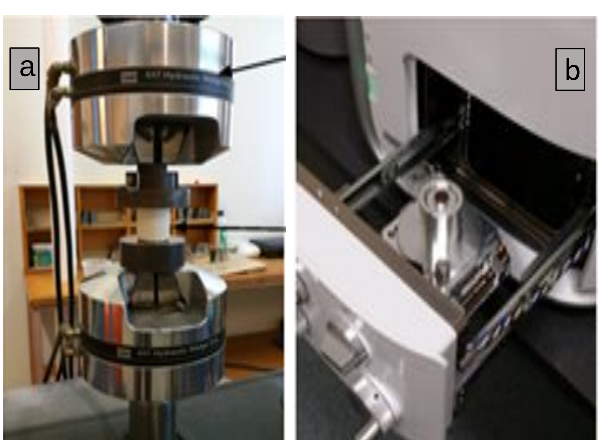

Fig. 3. Compression and SEM machines.

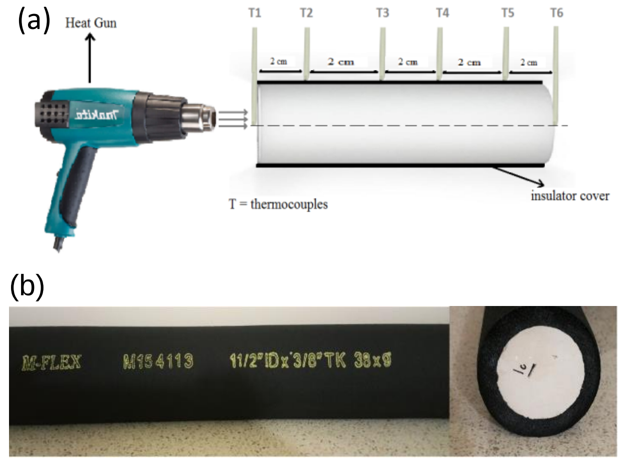

Fig. 4. Thermal Conductivity Measurement and M-Flex Pipe Insulation.

Thermal conductivity test

To test the thermal conductivity of gypsum with different content of sisal fibres and glass fibres, a test setup was developed as shown in **Fig. 4a**. This setup consists of a heat source placed on one side of the cylindrical samples. The heat flux is expected to pass through the composites towards the other end of the samples. Prior to testing, the samples were placed inside a pipe made of PVC covered completely with an isolator made up of m-flex pipe insulation as shown in **Fig. 4b**. Four thermocouples were inserted in the samples at every 2 cm with another two of these thermocouples attached at both ends of the composite samples. The temperatures of the composites were measured using these thermocouples at every 5-minute intervals for a total duration of 90 minutes. The temperature measurement is based on ASTM C518. The heat gun used in this experiment is Makita thermocouple heat gun model hg 1100 cs/662q. The heat gun is set at 120 ºC throughout the experiment.

Results and discussion

Compressive behaviour of composite samples

In this section, the results of the compression test on the samples i.e. pure gypsum, sisal fibre-gypsum composites and glass fibre-gypsum composites are discussed. The impact of different volume fraction on the compression strength of the composites is evaluated. The comparison between the two fibre reinforcement on the composite strength is also reported.

In **Fig. 5a**, pure gypsum shows brittle nature, since the strain value is much lesser than the composites. In term of strength, all the sisal composites shows higher strength compared to the pure gypsum sample. From strength and ductility point of views, the addition of the sisal significantly improves the compressive strength of the gypsum. This has been reviewed by John and Thomas [**15**] on various natural fire based composites whereby the addition of fibres reinforced the mechanical strength of the matrix material.

Similarly, to the behaviour of sisal fibre-gypsum composites, **Fig. 5b** shows the stress-strain diagram for different composites reinforced with glass fibres at different volume fractions. With respect to the influence of the fibre volume fractions on the strength of the composites, the 25 and 20 vol. % of the sisal fibres introduced the highest strength to the composites compared to the highest volume fraction of 35 %. While, the optimum volume fraction for glass fibre in gypsum composite was 30 vol. %. In other words, there is an optimum volume fraction that needs to be considered to obtain the highest composite strength as reported by many researchers [**16, 17**] . This indicates that the higher content of fibres leads to insufficient matrices to provide cohesion within the composite and to support the fibres and ensure the integrity of the composites[**17, 18**].

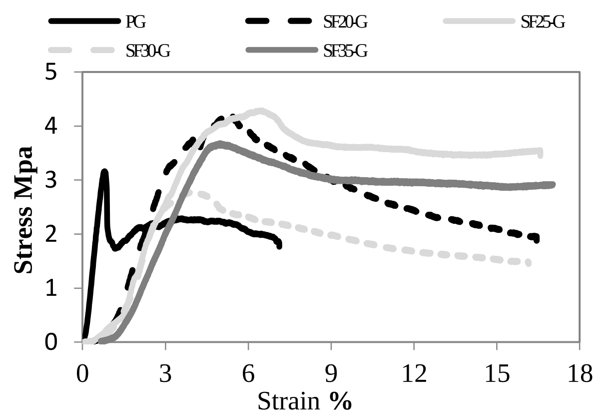

Fig. 5a. Stress-Strain Diagrams of Sisal Fibre-Gypsum Composites.

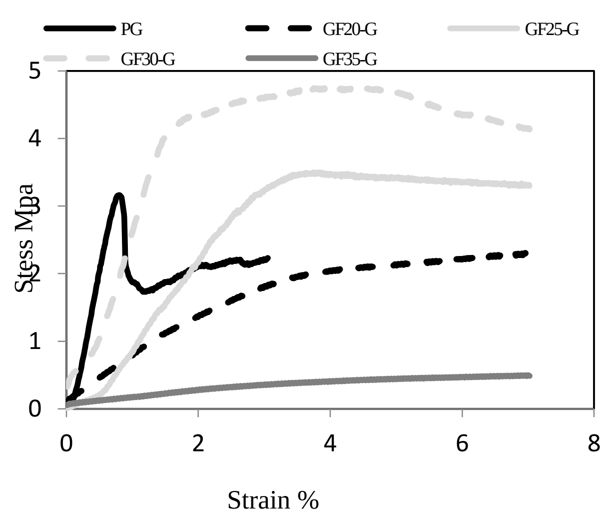

Fig. 5b. Stress-Strain Diagrams of Glass Fibre-Gypsum Composites.

Comparison between sisal and glass fibre-gypsum composites

The strengths of both composites with different fibre materials were compared and are presented in **Fig. 5c**. The highest compression strength achieved in both cases was at ± 4.75 MPa by GF30-G, the composite sample with 30 vol. % glass fibres. However, for the other fibre volume fractions, sisal fibre-gypsum composites have higher strength than glass fibre-gypsum composites for the same fibre content.

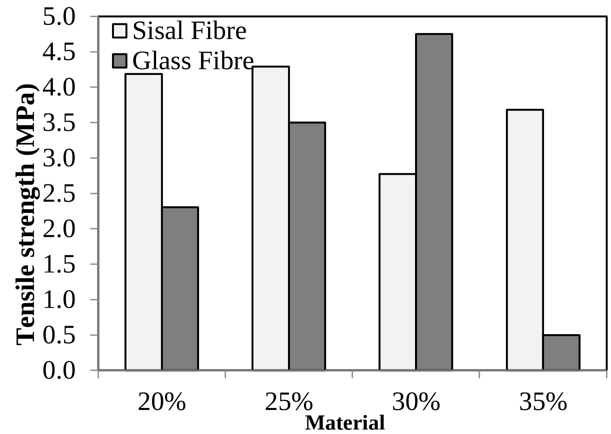

Fig. 5c. Tensile Strength of Sisal and Glass Fibre-Gypsum Composites.

It was reported by Baets, Wouters [**19**] that natural fibre composites performs less in compression compared to glass fibre composites. However, other researchers have reported that natural fibres perform comparably well in compression as glass fibres, and in some cases, slightly better. Gupta [**20**] has obtained a value of 32 MPa on the compressive strength of flax fibre-epoxy composite which was comparable to 31.2 MPa for glass fibre-epoxy composite. Therefore, apart from GF30-G, generally, it was noted that the sisal fibre-gypsum composites are superior in compression than the glass fibre-gypsum composites. This indicates that the sisal fibre-gypsum composite is a suitable candidate for wall panelling material in buildings.

Morphology of fractured samples

The micrographs of the fractured composite samples are shown in **Fig. 6A** and **Fig. 6B**. Firstly, from the micrographs of the sisal fibre-gypsum composites, it is apparent that the gypsum particles are firmly attached on the sisal fibres as shown in **Fig. 6A**. This is shown for 20% and 30% fibre volume fraction of sisal fibres. The rough fibre surface provides a good medium for interlocking with the gypsum matrix [**21**]. Rout, Misra [**22**] and Shanmugam and Thiruchitrambalam [**23**] suggested that the alkali treatment had increase the possibility of bonding of the fibre-matrix interface thus improving the strength of the composites.

For the sisal fibre-gypsum composites, the fracture plane was observed to occur across the gypsum matrix due to enhance the interlock between the fibres and matrix. At 20% volume fraction, the micrograph shows a fracture plane across the end of a sisal fibre while at 25%, the side view of the composite shows obvious matrix cracking. At 35% volume fraction, the fracture plane cut across the matrix surface, with no visible fibre can be observed which may indicate that the failure occur without significant effect from the fibres.

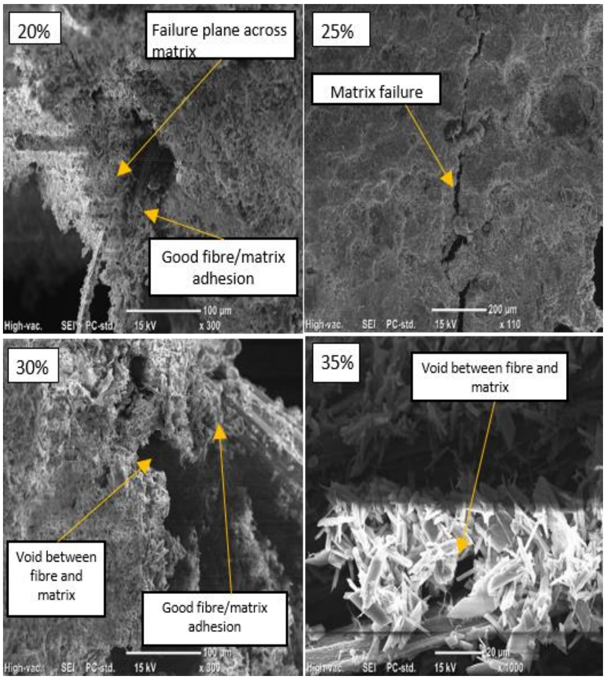

Fig. 6A. Micrographs of Fractured Sisal Fibre-Gypsum Composites.

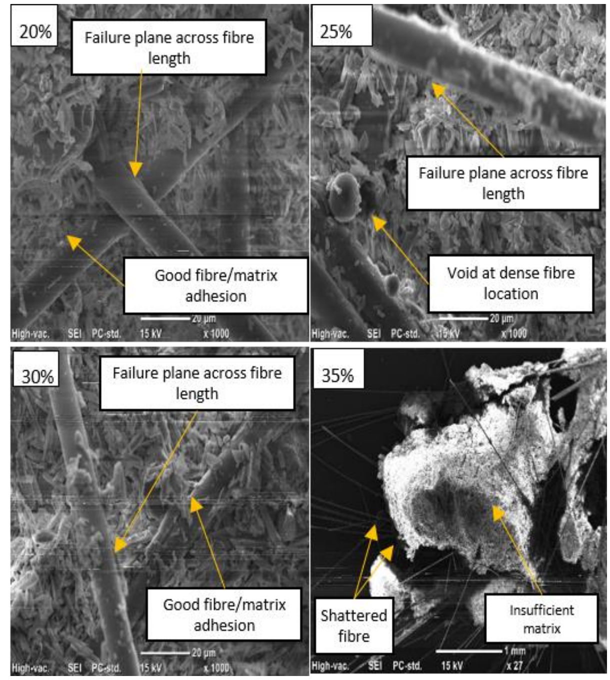

Fig. 6B. Micrographs of Fractured Glass Fibre-Gypsum Composites.

However, for the glass fibre-gypsum composites, at each volume fraction, we can see a similar pattern on the fractured surface, whereby glass fibres are visible, with the plane cutting across them longitudinally, meaning across the length of the fibres as shown in **Fig. 6B**. This is evident that the failure was dominated by delamination of the composites, with the interface of the separation is along the glass fibres.

The difference on the location of failure between these two composites may be attributed by the properties of the fibres. As the glass fibres are stiff and rigid compared to the sisal fibres, they are not able to deform easily as the compressive pressure are being applied. This causes the interlocking between the matrix and the fibres to weaken; resulting in slipping and breaking of the composites across the length of the fibres. Other fibres at different orientation in respect to the failure plane are broken or crushed during the failure process. This can be observed on micrographs for 20% and 35% volume fraction as shown in **Fig. 6B**. The glass fibres were shattered in order to release the stress build-up within the composite samples. On the other hand, the sisal fibre is easier to deform and to adjust itself as the composites are being compressed. Therefore, the matrix cracks with less influence by the flexible fibres.

At higher volume fractions, the presence of voids is identifiable from the micrographs of both composites. For the sisal fibre-gypsum composites, voids are presence in between fibres at 30 and 35% volume fraction, while at 35% glass fibre content, the fractured sample show insufficient matrix. The increase amount of fibres may have restricted the flow of matrix to encapsulate the fibres during fabrication. This may result in reduced strength of the composites.

Thermal conductivity of composite samples

In this section, the results of the heat conductivity study are presented. The test was conducted on pure gypsum, sisal fibre-gypsum composites and glass fibre-gypsum composites with prolong heat exposure of 120 ºC at T1. The reading for temperature increment up until 90 minutes were taken at points T1, T2, T3, T4, T5 and T6 as per
Fig. 6C. The difference in the temperature between adjacent points was calculated as ΔT1, ΔT2, ΔT3, ΔT4 and ΔT5. The impact of different volume fraction on the thermal conductivity of the composites is evaluated. The comparison between the two fibre reinforcement on the composites' conductivity is also reported.

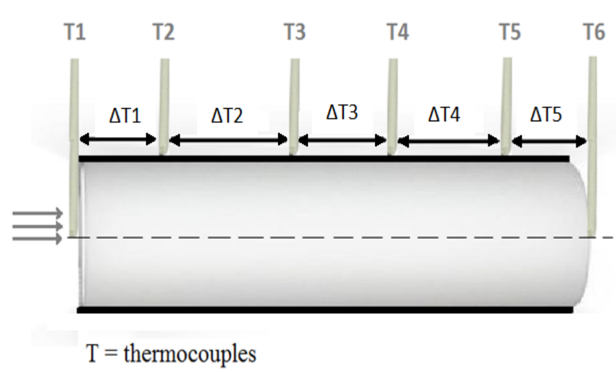

Fig. 6C. Temperature Reading Across Samples.

Sisal fibre-gypsum composites

The final temperature differences between adjacent points across the sisal fibre-gypsum samples are calculated and tabulated in **Table 2**.

Table 2. Temperature difference across sisal fibre-gypsum composites.

Materials	ΔT1	ΔT2	ΔT3	ΔT4	ΔT5
PG	62.7	15.5	12.4	4.0	0.3
SF20-G	67.4	17.5	7.1	3.3	2.3
SF25-G	68.5	15.7	6.8	3.3	0.6
SF30-G	71.0	18.8	8.9	4.6	0.6
SF35-G	73.0	15.8	7.8	3.9	2.2

From **Fig. 7**, it can be observed that ΔT1 shows consistent reading for all samples. ΔT1 increases with the addition of sisal fibres, with the maximum achieved by SF35-G. The higher temperature difference between point T1 and point T2 indicates that less heat had been transferred across the two points, resulting in higher temperature gap. This shows that with the addition of sisal fibres, the heat conductivity of the composite reduces, making it a preferable heat insulation. The increase in heat insulation properties is 7.50, 9.25, 13.24 and 16.43% for 20, 25, 30 and 35 vol. % of sisal fibres, respectively.

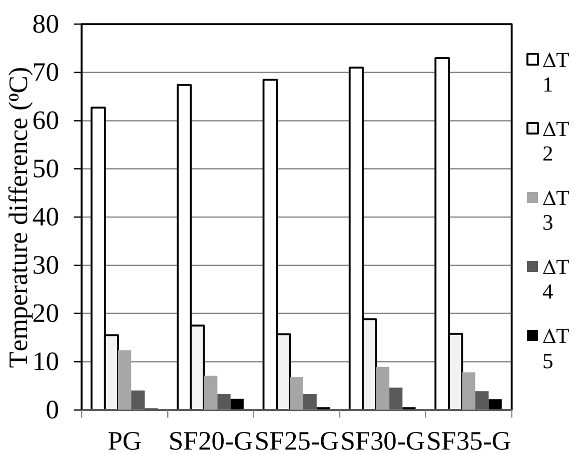

Fig. 7. Temperature difference at 90 Minutes for Sisal Fibre-Gypsum Composites.

However, the data collected at ΔT2, 3, 4 and 5 do not present good correlation. This could be due to the distant from the heat source. As the location of measurement becomes further from the heat source, the effect of heat becomes less sensitive. Therefore, the accuracy of the data collected by the thermocouples may have been reduced. Also, randomness of the particles inside the samples could be reason for the variance the data collected at ΔT2, 3, 4 and 5. The heat conductivity may be affected by air entrapments and the fibre distributions. It is difficult to standardize the fibre distribution within the samples as they are randomly oriented during sample fabrication. The transfer of heat may be affected by locations with high void contents or dense fibre volume which are not homogenous across each sample.

In comparison with other research works, it was highlighted by Chikhi, Agoudjil [**24**] that the relation between the thermal conductivity of gypsum based materials and the concentration of date palm is an Inverse relation. The authors noted that the reduction in heat conductivity was caused by increased fibre loading, whereby the fibres are less conductive than the gypsum. In terms of presence of air voids in the samples, a case study was conducted by Pia and Sanna [**25**] regarding the influence of microstructure voids on thermal conductivity in fractal porous media. The results proved that thermal conductivity is extremely affected by size of pore, geometric organization and intricacy of the porous media. Importantly, "pore walls" and a great number of small pores found in materials play considerably role in decrease the value of thermal conductivity. Therefore, this supports the hypothesis of inconsistency of the results for ΔT2, 3, 4 and 5.

Glass fibre-gypsum composites

The final temperature differences between adjacent points across the glass fibre-gypsum samples are calculated and tabulated in **Table 3**.

Table 3. Temperature difference across glass fibre-gypsum composites.

Materials	ΔT1	ΔT2	ΔT3	ΔT4	ΔT5
PG	62.7	15.5	12.4	4.0	0.3
GF20-G	63.5	17.2	9.8	4.6	1.4
GF25-G	65.6	16.4	8.1	3.3	1.2
GF30-G	67.2	16.8	7.1	3.0	0.4
GF35-G	68.2	19.7	7.8	4.7	1.2

As observed in **Fig. 8**, similar results were obtained for glass fibre-gypsum composites as compared to sisal fibre-gypsum composite which was previously discussed. Steady increment for ΔT1 occurred as the volume of glass fibres is increased. Pure gypsum showed relatively high heat transfer than the samples with glass fibres. The increment in heat insulation properties is 1.28, 4.63, 7.18 and 8.77% for 20, 25, 30 and 35 vol. % of glass fibres, respectively. This again shows that the presence of fibres have slowed down the transfer of heat across the sample making gypsum less conductive to heat.

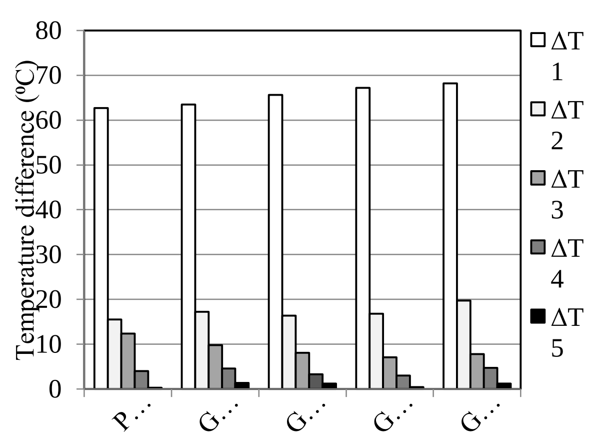

Fig. 8. Temperature difference at 90 minutes for Glass Fibre-Gypsum Composites.

Again, it was hard to find a correlation for ΔT2, 3, 4 and 5 as the data collected had insignificant differences between all the samples. The same hypothesis as previously discussed may have also contributed to this occurrence. Cao, Liu [**26**] have been studied the thermal insulation properties of the glass fibre board used for indoor building applications. The author agreed that it is hard to straight characterize the internal structure of a porous medium due to its complicated nature. Only statistic-based structural information could be obtained and this includes porosity, fibre diameter distributions and fractal dimension. It was also highlighted that the effective thermal conductivity decreases with the increasing porosity at a near-linear rate.

Comparison between sisal and glass fibre-gypsum composites

The data obtained for ΔT1 at the end of the test for both sisal fibre-gypsum composites and glass-fibre gypsum composites were compared and presented in **Fig. 9.**

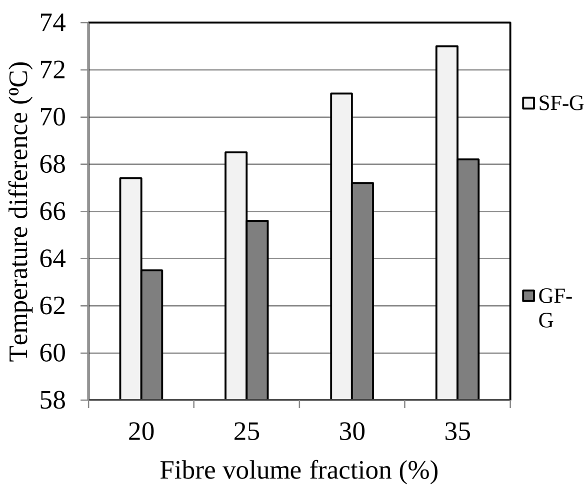

Fig. 9. Temperature difference at 90 minutes for ΔT1 of Both Composite Samples.

For all volume fractions, the temperature differences for sisal-based samples are higher than glass fibre composites by 6.14, 4.42, 5.65 and 7.04% at 20, 25, 30, and 35 vol%, respectively. Similar results were obtained by a few researchers [**27, 28**]. A study conducted by Mounika, Ramaniah [**27**] have shown that the increased in volume fraction of bamboo fibre (from 0.15-0.30%) in polyester resin have decreased the thermal conductivity of the composites from 0.211 W/mK to 0.185 W/mK. This is lower than the thermal conductivity of glass fibre-polyester composite which was measured as 2.23 W/mK. The author attributed this to the porosity of the core of the fibres where air is entrapped, as higher voids reduce thermal conduction. Another study on borassus seed shoot fibre reinforced polyester composite had also shown a reduce in thermal conductivity from 0.193 to 0.176 Wm/K as the fibre volume fraction increase from 0 to 0.31% [**28**]. This is also considerably lower than polyester composites with glass fibres.

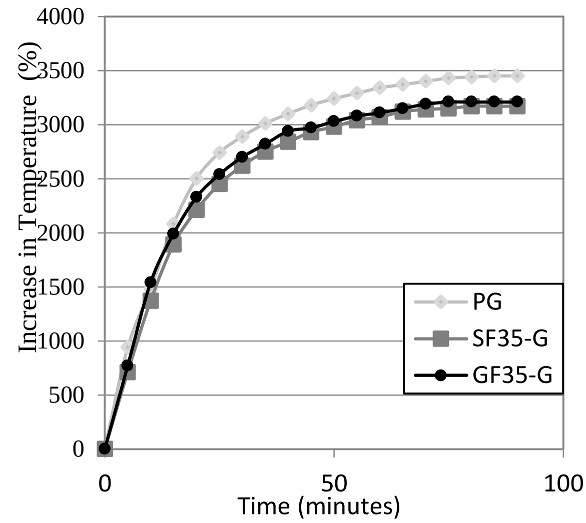

Fig. 10. Temperature Increase at T2 from 0 to 90 Minutes.

Fig. 10 presents the percentage of temperature increment at T2 for pure gypsum and the composites with both fibres at 35% volume fraction. T2 experienced the most consistent increment as compared to the other thermocouples. From the **Fig. 10**, it can be observed that both types of fibres have effectively reduced the thermal conductivity of gypsum, with sisal showing a slightly better result than glass throughout the test duration. Both have shown reduction in heat transfer rate at 15 minutes while the reduction in heat for pure gypsum starts at approximately 20 minutes. Individually, the thermal conductivity of the sisal fibres and glass fibres are 0.042 and 0.038 W/mK, respectively as reported by Neira and Marinho [**29**]. This shows that both types of fibres will have contributed similar degree of insulating property to the gypsum composite. Therefore, it can be concluded that the contribution of sisal fibres in insulating heat is comparable to glass fibres, and with proper composite fabrication, sisal fibres can be utilized to assist in reinforcing and insulating gypsum for wall panels in buildings.

Conclusion

From the compressive test, it was noted that the addition of fibres to the gypsum matrix have enhanced its strength of compressive and led to reduce brittleness. For sisal fibre-gypsum composite, the optimum fibre content is at 25 vol. % while for glass fibre-gypsum composite, the optimum fibre content is at 30 vol. %. At higher fibre contents, both composites suffer a decrease in strength indicating that the fibres are no longer effective in reinforcing the gypsum. Generally, the sisal fibre-gypsum composites perform better in compression compared with the glass fibre-gypsum composites. However, the maximum strength was achieved by the composites with 30 vol. % of glass fibres.

From the thermal conductivity study, pure gypsum was shown the highest thermal conductivity. Moreover, the thermal conductivity of the composites reduces with the increase of fibre volume fraction. Due to porous nature of sisal fibre-gypsum composites, as the presence of air voids work as traps and impeded the heat transfer, sisal fibre-gypsum composites performs better than glass fibre-gypsum composites as an insulation material. From this result, in terms of mechanical and thermal insulating properties, it can be inferred from this study that utilizing sisal fibres as reinforcement on gypsum produces composites convenient for wall panelling in building application.

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