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Thermal Behavior of Bio-Fibers Reinforced Paving Bricks

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Abstract

Paved areas are among sources of ambient temperature rise due to heat radiation that has been absorbed by pavement materials and then released into the air. The materials that are widely used in paving grounds include concrete, asphalt concrete and cement sand bricks. The paved surfaces absorb the incoming solar radiation from the sun, which is converted into heat, resulting into higher surface temperature than the ambient air temperature, thus contributing to the global warming. In an attempt to solve this problem, a study on paving bricks reinforced with bio-fibers has been done aiming at establishing the thermal behavior of the bricks. Bio-fibers from grass and coconut coir were studied for their heat insulation, and then were included in the green mix of cement-sand (1:6 ratio) during manufacturing of bricks. On attaining the testing age, the bricks were tested for compressive strength and heat flow. The results showed that bio-fibers reinforced bricks meet the compressive strength specifications of ASTM C 902 and their heat flow rate was less when compared with traditional cement sand bricks. Also, during cooling, bio-fibers reinforced bricks cooled faster than traditional bricks, indicating that they are suitable for paving streets and grounds as they offer good thermal resistance that lowers the Urban Heat Island by 9 ° C below that of traditional bricks.

Keywords: Bio-fibers; Reinforced bricks; Compressive strength; Urban heat island.

Introduction

Nowadays, many cities worldwide are experiencing a problem of high-temperature air known as heat island effect. This is due to the presence of paved areas using normal paving bricks of gray to blackish color which absorb a lot of heat energy and later release it into the surrounding air. Figure 1 illustrates how heat rays from the sun strike the pavement, absorbed, and then emitted back into the surrounding air, resulting in the heat island effect. During the night, the warming continues because the short-wave radiation is not easily released by the pavement materials such as asphalt, bricks and concrete. At night, the heat energy absorbed during the daytime is slowly released as long-wave radiation (Osman et al. 2012, Shreya et al. 2021). The Urban Heat Island (UHI) effect is widely recognized as a heat accumulation phenomenon, which is the most obvious characteristic of urban climate caused by urban construction and human activities. In the early 19th century, scholar Yanga et al. (2016) firstly measured and discussed UHI effect when studying urban climate in London, England. Since then, many scholars around the world have conducted extensive research on the characteristics of UHI effect. In an effort to reduce or eliminate this problem, various attempts have been made by researchers in order to arrive at a feasible solution which would result into cooler streets, parking lots, and the general environment.

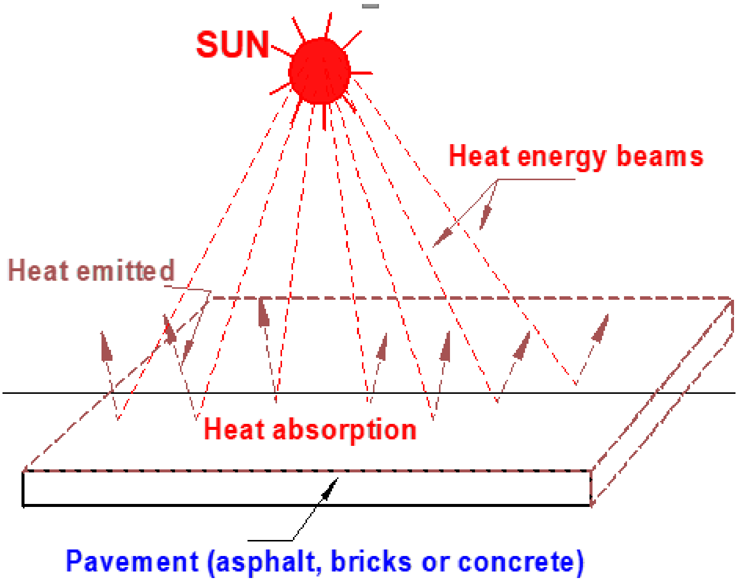

Figure 1: heat absorption and reflection

In a paper authored by Youssef et al. (2016), they provide an overview of the promising technique of cool pavements recently employed in research work. These are porous coverings that can decrease the air temperature in hot weather by evaporating water from their pores. Thus, these are pavements that promote the evaporation phenomenon. It has been shown that, in order to decrease the air temperature through cool pavements, it is necessary to decrease the surface temperature of the pavements by increasing their albedo, thermal conductivity and evaporation flux. In promoting the evaporation flux of the pavements, it is necessary to improve their porosity in order to retain more water and air inside them.

Nicola and Eugenio (2019) studied modeling the impact of green solutions upon the urban heat island using satellite data from green roofs as a case study. Their results showed that a massive implementation of green infrastructure in cities can decrease temperatures about one degree at the local level during heat waves. The study concluded that tree planting or replacing urban materials, changing the colors of paving materials (albedo) and morphological features (i.e., urban sky roughness, porosity, street canyon geometry, etc.).

Vajreshwari et al. (2021) studied the cooling potential of trees and green facades to reduce UHIs in summer conditions. Using ENVI-met model simulations, they investigated the influence of green facades and trees on surface and ambient air temperature and their role on air fluctuations in the hot, humid climate of Austin, USA, with a primary focus on pedestrian height (1.40 meters) temperature variations. The simulation results showed that a combination of trees and green facades has a greater cooling effect, and the results were congruent with previous studies which also indicated that the added greenery slightly increases relative humidity. Alexander et al. (2022) compared conventional urban materials and noted that high-albedo materials reduce surface and air temperatures during the day by reflecting incoming solar radiation. Typical urban materials, such as asphalt and concrete, have albedos in the range of 0.05–0.1 and 0.3–0.4, respectively, whereas the albedo of reflective surfaces tends to be greater than 0.5. The use of roofing materials that reflect short-wave radiation back to the atmosphere results in decrease of energy budget for roof surface and the underlying structure.

A study with the objective of analyzing the most important properties of concrete paving blocks (CPB's) made from crushed polyethylene terephthalate (PET) particles derived from soda bottles was conducted by Wilhem et al. (2022). The PET content ratios to aggregates were taken as 15%, 25%, and 35%, by volume. Standardized water absorption and compressive strength tests after 21 and 28 days of curing were selected. A replacement of 15% of conventional aggregates by PET yielded a maximum increase of 25% in the characteristic compressive strength (f_{cu}). It reached a value of 32.12 N/mm^2, which is close to the minimum requirement value for standard traffic strength of 35.00 N/mm^2. This may be attributed by higher interlocking of the plastic particles within the concrete matrix, as well as the proper amounts of plastics, natural aggregates, and Portland cement in the sample and the high elastic modulus of PET. However, the f_{cu} values decreased to 26% and 66% for plastic contents of 25% and 35%, respectively, but they can still be used on non-traffic areas such as landscapes, walkways and pedestrian areas.

Osman et al. (2012**)** conducted a study on the use of waste marble in making blocks so as to utilize the said waste material and save the environment. In the study, aggregates were replaced by waste marble in making the blocks utilizing cement as binder. Test results for physical and mechanical tests revealed that the mechanical strength decreased with increasing marble content, while freeze-thaw, durability and abrasive wear resistance increased. It was concluded that waste marble is well-usable for replacing the usual aggregates in the concrete paving blocks production.

Nowadays, awareness of use of recycled aggregate as a construction material is gaining importance around the world, as discussed by Shantanu and Amit (2018). Hence, a study on use of recycled aggregate as a material replacing coarse aggregates in paver blocks was conducted. The properties of recycled aggregates namely specific gravity, particle size distribution, water absorption, moisture content, impact value, crushing value, flakiness, and elongation index were studied. According to IS 15658 (2006) code, the required samples of paver blocks were cast, and after maturing for 28 days, they were tested for compressive, tensile, flexure, and abrasion values. Changes in the properties of paver blocks with increasing recycled coarse aggregates (RCA) percentage, with partial replacement of cement by fly ash at 10% by weight of cement, were analyzed extensively. It was concluded that the optimum use of RCA has economic benefits when replacing conventional coarse aggregates in making paver blocks.

With regard to the above studies, it has been shown that various materials used to pave the areas which experience heat island effect include concrete, asphalt concrete and cement sand bricks/blocks. However, the issue of incorporating bio-fibers into the making of bricks/blocks to reduce the heat island effect in urban areas has not been extensively addressed. This paper attempts to address the use of bio-fibers reinforced bricks that can have sufficiently insulation thermal properties. The paper reports on; firstly, determination of insulation properties of bio-fibers, and secondly it discusses on bricks preparations and establishment of their thermal insulation properties which can help to reduce the urban heat island problem.

Materials and Methods

The materials for this study were locally available materials which include grass, coir fibers, cement and sand. The insulation properties of the grass were assessed by testing the them in a laboratory (Figure 5) before its use in bricks manufacturing, because there was no available literature on the insulation properties other than the general use of grass such as for roofing purposes as indicated in Figure 2. For example, many African tribes have lived in homes made completely of grasses (Figure 2) and soil/clay for many years **(**Makunza 2015**)**.

Figure 2: Full suit grass (L) Mud bricks house (R) grass.

Coir fibers shown in Figure 3 were studied by Majid (2011) and Anthony et al. (2012) on the mechanical properties of coconut fibers reinforced concrete and it was found that they have potential to be used as reinforcement in low cost structures as they increased the strength and workability of concrete. The influence of 1%, 2%, 3%, and 5% fiber contents by mass of cement and lengths of fibers of 25, 50, and 75 mm was investigated. The study concluded that by adding 5% fiber content by mass of cement and fiber length of 50 mm, the properties of concrete improved.

Figure 3a: Coconut fibers

Collection of raw materials and production of bio-fibers reinforced bricks

Grasses for the study were collected from Iringa, Tanzania and were then transported to BAM Germany where tests on the grasses were conducted. The test specimens were prepared by first casting cement sand blocks of size 300 x 500 x 100 mm from a mix of ratio 1:8 and w/c of 0.4 (Figure 5). After curing for 7 days, the blocks were left in air to dry, and after reaching an age of 28 days, they were ready for testing. Four insulator material pieces of size 300 x 500 x 60 mm thick were prepared, thus; one was left intact solid, and the other three were each hollowed leaving a 50 mm thick boundary web wall to allow for parking the grass as indicated in Figure 5(b). One hollowed piece was left without packing any grass for comparison of air and grass heat flows. Other materials were collected from around Dar es Salaam which included sand from Mbagala, Portland Cement (42.5 N) from Twiga Cement Factory, and coir fibers were produced from coconuts taken from Msasani area. Figures 3a and 3b show the coconut husks and fibers. The coir as well as the grass were cut to size of not more than 180 mm long pieces to allow for 10 mm cover at brick ends.

Figure 3b: Coconut fibrous husks

Production of bio-fibers reinforced bricks

Most of the paving bricks used in Dar es Salaam are manufactured locally where automated processes are not used. There are very few companies which produce paving bricks by using machines. The bricks (Fig. 4) are expensive and are used in roads and in petroleum filling stations where heavy trucks can pass. The bricks manufactured for this study are specifically designed for paving areas intended for pedestrian and light vehicle uses. The size of bricks produced was 200 × 100 × 70 mm, from a mix ratio of 1:6 (cement to sand) with water cement ratio of 0.45. Three sample types of paving bricks were prepared. The first sample was solid paving bricks made from mixing sand and cement plus water only as control sample. The second sample group was made from cement and sand plus grass laid in two layers in the mortar. The two layers of grasses were inserted such as to allow 20 mm covers at top and bottom, while the layers were separated by approximately 10 mm thick mortar. The materials were then compacted, removed from the mold and on the next day curing started up to 14 days. The third sample type were bricks made from cement–sand mixture with coconut fibers in percentages weight of coir to the weight of cement in three ratios namely 0.5%, 1% and 1.5%, then cured in the same manner as the previous two types.

Figure 4: Paving bricks

Grasses preparation

Grasses of two types; 1- 4 mm and 3 - 8 mm thick, were cut to size that fits to park in the hollowed insulator frame like elements. The weights of the grasses were 740 g for thick grass and 888.2 g for thin grass, but the volumes were almost equal.

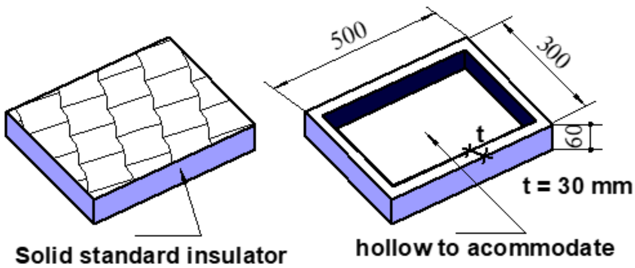

Figure 5: (a) Insulator elements **(b)** Grass parked in the hollow

The test setup started by arranging four block elements at bottom, followed by the insulator elements, then parking the grasses in the hollows for two sets as shown in Figures 5b and 6. One set was left without any grass, while the final set had a solid insulator. Temperature gauge sensors were fixed as indicated in Figure 7. The heating was controlled by setting the switch at a maximum temperature of 70 °C to assimilate the highest temperature possible that can be radiated by the sun to paved grounds and open to sky slabs. The temperature at the established gauges was automatically recorded at specified set intervals of not less than one hour.

Figure 6: Testing of specimens

Results and Discussion

Heat flow in grass

Test results on grasses are presented in Figures 8a and 8b. With regard to Figure 8a, at top of the top blocks, the temperature values are close (Figure 8) to each other for all four sets, i.e. gauges 1- 4 (T1 to T4 in Figures 7 and 8a). At bottom of top blocks with gauges 5 to 8 (T5 to T8), the set without any insulator material; gauge 7, (T7) had the lowest temperatures throughout the test by a difference of about 6 °C during heat application, and around 4 °C at cooling. At bottom of top blocks, which is above the grass and the standard insulator material, the temperatures are close to one another, after passing through the cement sand blocks of 100 mm thick. The non-insulated set of blocks with gauges 11 and 15 in Figures 7 and 8 had lower temperatures of around 7 to 9 °C below that of grass as well as the standard insulator material (gauges 8 and 12 in figure 7) due to the presence of air which is a bad conductor of heat.

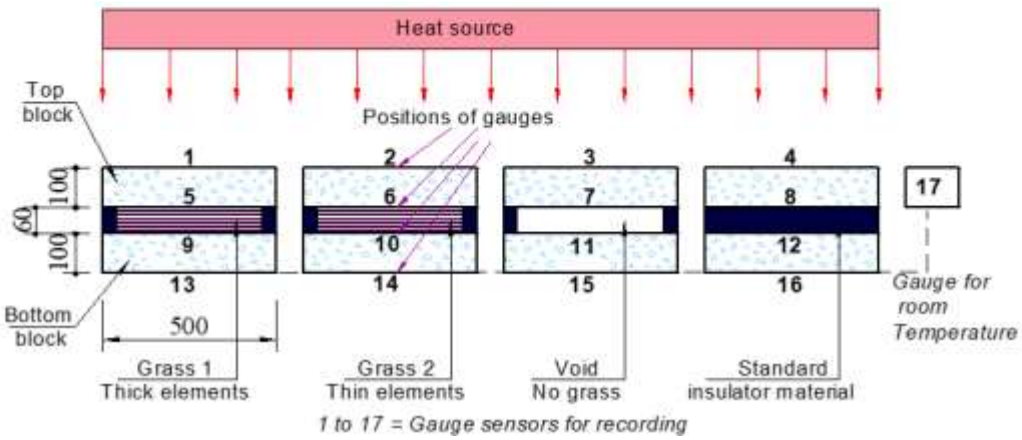

Figure 7: Heat flow in grass test set up and positions of temperature gauges

At top of bottom blocks, below the grass as well as the standard insulator, the temperatures were slightly lower than 65 °C as seen in Figure 8b. However, the set without any insulation material had lower temperatures of 4 ºC to 9 °C below others.

Under the bottom blocks, the temperatures reached not more than 30°C for the grass and standard insulator material sets. However, the set without any insulation material had the highest temperatures of 4 °C to 5 °C above others. The recorded room temperature remained below 25 °C throughout the test as seen in Figure 7. Grass and coir fibers test results shown in Figures 7 and 8 have shown that they are both good heat insulator materials. The heat allowed to flow by these bio-fibers was almost the same as the standard industrial insulation material.

Paving bricks tests specifications

This section outlines the properties of paving bricks from Standards for suitable engineering properties. The required properties include density, compressive strength, water absorption, durability and abrasion resistance. The adopted standard was ASTM C 902 (2006); Standard for Pedestrian and Light Traffic Paving Bricks. The standard requires an average compressive strength of at least 13.8 N/mm^2 up to 55.2 N/mm^2, average cold water absorption of not more than 8.0%, and an abrasion index ranging from 0.11 to 0.50.

Compressive strength

The compressive strength test was done to determine the resistance strength of paving bricks against vertical loads. The bricks were tested flatwise as laid in Figure 4. The graphs in Figure 9 and Bar Chart in Figure 10 show the test results of 25 bricks. With reference to Figures 9 and 10, bricks without fibers and those with grass attained the compressive strength specified by ASTM 902 (2006) of 13.80 N/mm² at minimum margin.

All bricks with coir fiber contents from 0.5% to 1.5% had their compressive strength higher than the minimum value given in the above code. Generally, the compressive strength of bricks decreases with the increase in porosity, hence strength is also influenced by good compaction and curing, since it reduces voids and makes dense concrete.

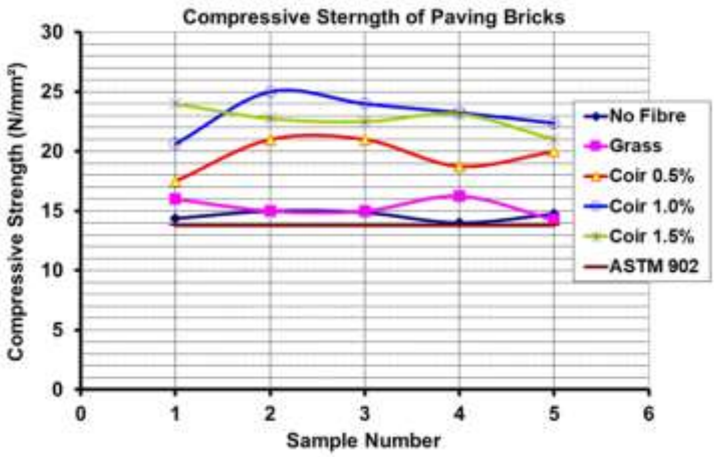

Figure 9: Compressive strength of concrete

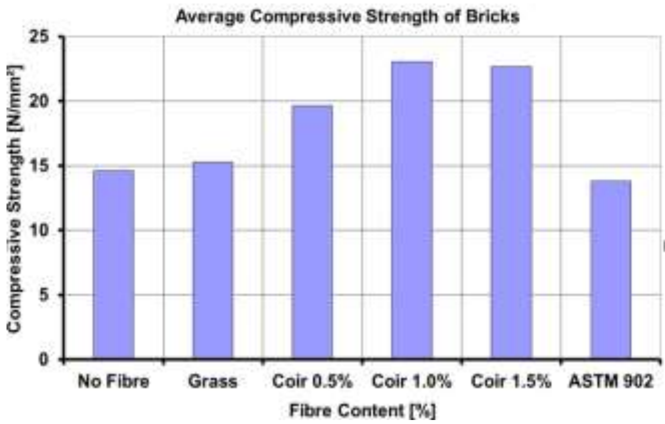

Figure 10: Average compressive strengths of bricks

The compressive strength of the bio-fibers reinforced bricks ranged from 14.0 N/mm^2 to 25.0 N/mm^2, complying to pavers of MX Class according to ASTM C 902 (2006). Bricks with coir fibers of 1.0% yielded the highest strength, followed by bricks with coir content of 1.5% (refer Figures 10 and 14). The variation of the strength values is mainly due to the compaction effort which was not absolute uniform. The increase of strength in comparison to the bricks without any fiber was due to the effective bond between sand particles and cement, and the interaction of the fibers among themselves. The fibers in the bricks increased the flexibility, making them behave as structural mesh and hold the sand and cement particles together to give higher strength. The fibers retained moisture during the curing process which was used in the hydration reaction of cement.

Water absorption

The test was carried out in order to assess the water absorption of the paving bricks. Twenty specimen bricks were tested, the results of which are ranging between 3.8%

and 5.8% as shown by bar chart in Figure 11. In this figure, it is evident that all bricks had their water absorption results less than the maximum vale given by ASTM 902 (2006) of 8%. With regard to coir fiber reinforced bricks, the water absorption value increased with the increase of coir content. Bricks reinforced with grass fiber had a water absorption value very close to that of bricks with 1.0% coir content. The test results imply that the fibers reinforced bricks are suitable for paving works. The porosity of bricks is assessed by the water absorption test.

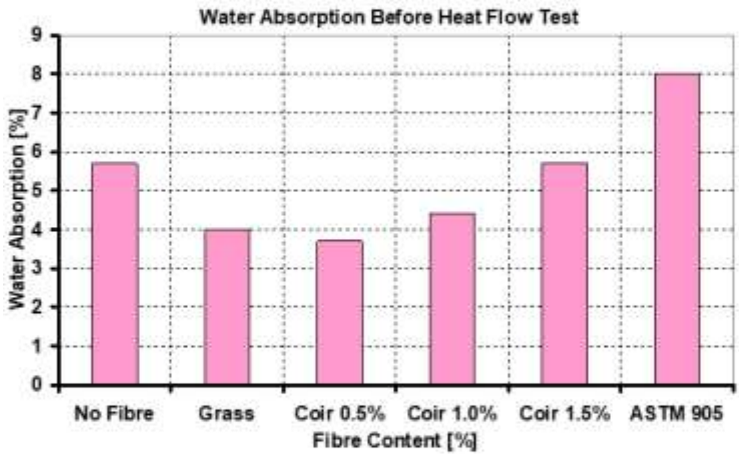

Figure 11: Water absorption test results for brick samples

Heat flow

The machine used to test heat flow had a capacity of emitting temperatures up to 300 ^{o} C. The heating chamber consisted of two heating lamps that emit electromagnetic radiation that reflects heat energy to the paving bricks, thus increasing their temperature in Centigrade units. A thermostat in the machine was used to control the temperature by switching heating or cooling knob on or off, in order to maintain the correct temperature. This test was done in order to measure the rate of heat flow in Centigrade degrees in the paving bricks.

NOTE: In regard to Figures 12 and 13, the notions of samples shall be as illustrated here:
Samples A1 and A2 represent samples which contain 1.5% of coir
Samples B1 and B2 represent samples which contain 0.5% of coir
Samples C1 and C2 represent samples which contain grass
Samples D1 and D2 represent samples which contain 1.0% of coir
Samples N_i represent control normal bricks without any fiber.

Figure 12 shows the temperatures which were measured at every 30 minutes for a duration of 2 hours. There were 12 samples put in sets of 3 samples in which the one at middle was without any fibre, while the two adjacent samples were reinforced with bio-fibres as indicated above in the NOTE.

After testing for heat flow in the sample bricks, they were removed from the machine and left to cool for two hours. The temperature during cooling process was recorded at intervals of 30 minutes again in order to study their behavior on loosing heat. The results in Figure 13 show that during cooling, the bricks with bio-fibers cooled faster in comparison to the bricks without any fiber. This implies that pavement made of bio-fiber reinforced bricks can reduce the amount of heat emitted into the air, hence reducing the rate of global warming as also recommended by Sweeney et al. (2020) and Neha C and Nisha A (2018**)** whose results also indicated good thermal absorption of slabs made of fiber reinforced concrete.

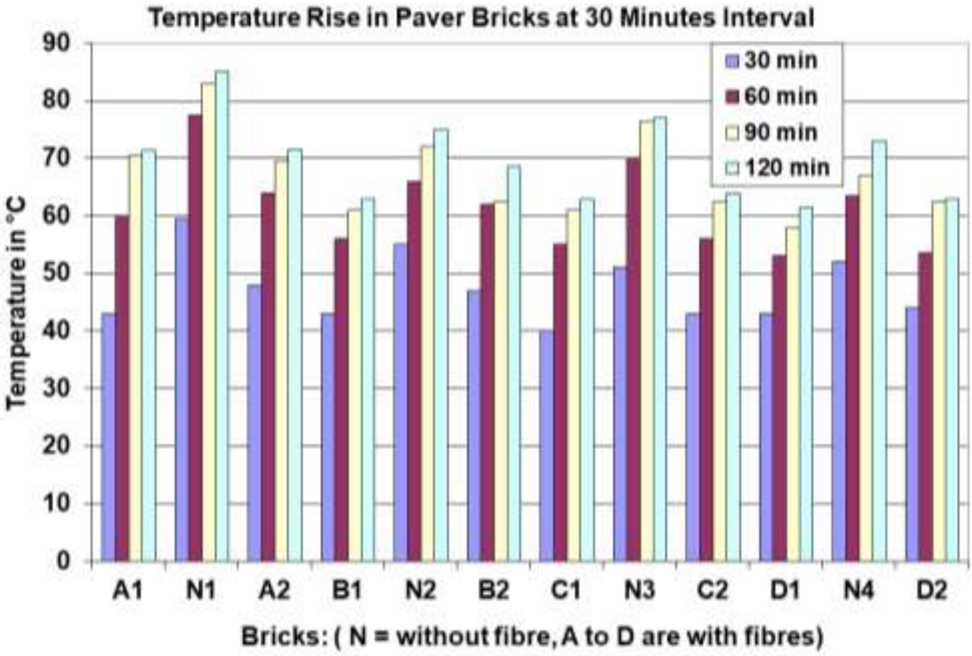

Figure 12: Heat flow comparison in bio-fiber reinforced and normal bricks

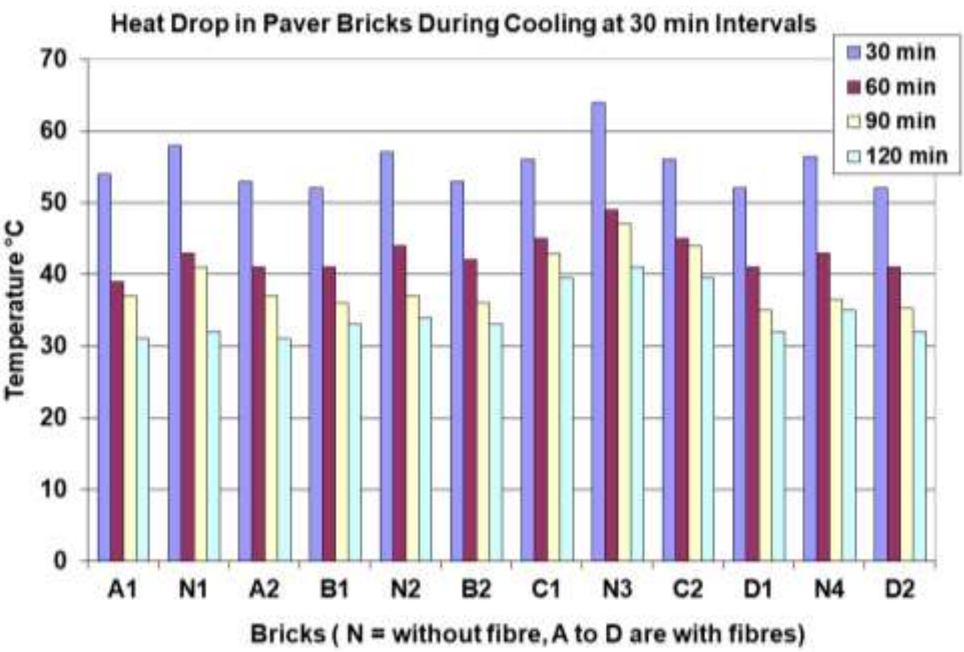

Figure 13: Temperature of paver bricks Cooling

Compressive strength and water absorption test results after heat flow test

After the bricks had cooled from heat flow test, the samples were taken for dry compressive and water absorption tests in order to assess their suitability as paving bricks during their service life of exposure to day-temperatures.

With regard to the compressive strength (Figure 14), it was noted that all samples with bio-fibers had their strengths above the minimum requirement of 13.8 N/mm² as stipulated in ASTM 902 (2006). Also all water absorption values (Fig.15) were below the maximum requirement of 8%. The obtained test results in both cases show that bio-fibers reinforced bricks are suitable for use in paving walkways and light traffic streets and grounds.

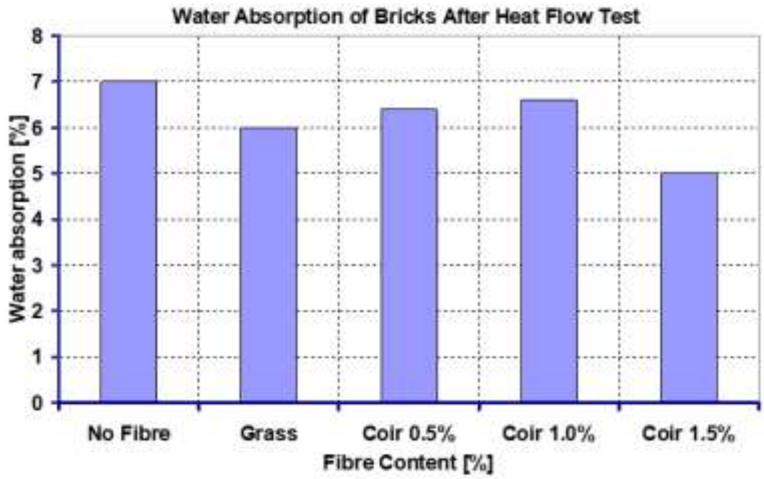

Figure 14: Absortion test results after heat flow test

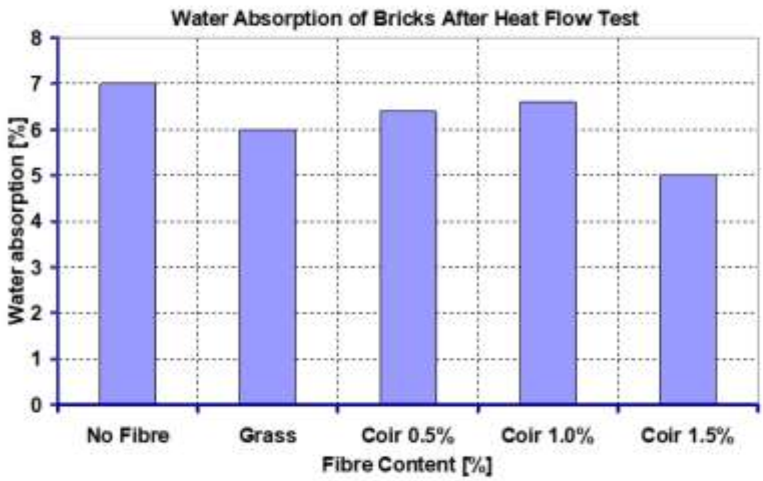

Figure 15: Compressive strength after heat flow test

Abrasion resistance

Paving areas are always exposed to the continual abrasive effect of pedestrian and vehicular traffic. Abrasion resistance of paving bricks is a measure of the resistance of the bricks to wearing action due to traffic.

ASTM C 902 (2006) lists two ways of abrasion resistance determination. The popular method is that of using an abrasion index calculated by dividing the 24-hour cold-water absorption by the compressive strength in psi (pound per square inch) and then multiplying by 100. Using this method, from the sample bricks as indicated in Table 1, the abrasion indexes output results are presented in the last column. The results indicate that all the bricks have sufficient abrasion resistance as their values are within the allowable range of 0.11 to 0.55 as specified in ASTM C 902 (2006).

Table 1: Abrasion Index Results

Brick samples	Compressive Strength (N/mm^2)	Compressive Strength (psi)	24hr Cold-Water Absorption (%)	Abrasion Index
Coir 1.5%	22.7	3293	5.8	0.18
Coir 1.0%	23.0	3336	4.4	0.13
Coir 0.5%	19.7	2858	3.8	0.13
Grass	15.3	2219	3.9	0.18
No Fiber	14.6	2118	5.1	0.24

Durability

The durability of a material is referred to its ability to withstand a particular recurrent weathering effect without any failure, which depends on the quality of the unit materials and the drainage efficiency of the pavement. For paving bricks, the durability is a function of the compressive strength, 24-hrs cold water absorption, and saturation coefficient. According to Table 1 in ASTM C 902 (2006), Classes MX and NX have no limit for the abrasion index, hence all the brick specimens meet the standard specifications.

Conclusion

With respect to the test results and discussions made above it has been established that studied roofing grass available in Tanzania is a good thermo insulator material as it competed with the normal industrial insulation material in reducing the temperature flow through it. Also, the studied bio-reinforced paving bricks have indicated that they offer sufficient resistance against heat flow when compared to bricks without any fiber reinforcement. The bio-reinforced bricks have proven that they conform to standard specifications given by ASTM C 902 (2006). The specifications include compressive strength, water absorption, abrasion index, and durability.

It is therefore recommended that roofing grass and coir bio-fibers can be included as reinforcement in paving bricks production to improve the strength and enhance heat insulation properties of the paving bricks. Also, bio-reinforced bricks from mix ratio of 1:6 (cement: sand) and 0.45 water–cement ratio and fiber ratios of 1.0% -1.5% by weight as described above have to be used to pave various grounds and streets which may be subject to light traffic in order to reduce the ambient temperature of the environment. Use of bio-fibers reinforced bricks in paving works will be an act of reducing global warming.

It is also recommended that further study be done using other locally available materials depending on the location, say where suitable soil for stabilization and other fiber types, like banana, grass, rice husks, and others that can be found.

Conflict of Interest

The author declares no conflict of interest.

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