Analysis of Sorghum Stalks and Fibres for Use in the Production of Low-Cost Housing Materials

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Abstract

Research into low-cost housing solutions, especially for low- and middle-income countries, has grown in recent years. Greater use of natural materials, both mineral and bio-based, offers opportunities for more affordable and sustainable materials and products. In the low- and middle-income countries, residential buildings are too expensive for most people due to the use of the concrete in buildings. Utilisation of agricultural wastes can serve a threefold purpose: (i) minimise the impact of construction products on the environment, (ii) reduce waste, and (iii) decrease the cost. The aim of this study was to investigate fibres and stalks from the sorghum plant as potential additives in low-cost brick production. Analysis of the sorghum fibres and stalks has included microstructural examination using a scanning electron microscope and mercury intrusion porosimetry, together with tensile strength testing of fibres. Fibres and stalks did not undergo chemical pre-treatment. Sorghum stalks and fibres were found to have comparable tensile strength to fibres currently used for brick production, and the methods used to prepare stalks were not found to adversely affect their strengths. Consequently, this research has shown that fibres produced from local agricultural wastes have potential for use in low-cost housing such as one-storey residential load-bearing structures and buildings.

Keywords Sorghum stalk fibres · Tensile strength · Scanning electron microscopy · Mercury intrusion porosimetry

Introduction

Synthetic and natural fibres are widely used in composite construction products to enhance their mechanical and other physical properties (Farhan et al., 2021; Q. Li et al., 2021). Natural fibres derived as co-products from food crops can offer low-cost solutions for a variety of applications (Kumar et al., 2019; Onuaguluchi & Banthia, 2016). Sorghum is one of the top five cereal crops cultivated worldwide, and especially in Africa (Surpam et al., 2019); fibres derived from the waste plant stalks offer potential for use in construction materials. Sorghum stalks contain fibres that can be readily extracted by peeling off the inner layer of the stalk, although these fibres

are relatively short, as they are interrupted by the internodes along the stalk; this is similar to other natural plants that grow longer than 2 m (Chen, 2020; Perrier et al., 2017).

From the top 20 countries in the world in crop production based on crop per capita, only seven are classified in 2021 as high-income countries, while the rest are upper-middle or lower-middle income countries (FAO, 2019; The World Bank, 2021). Furthermore, according to the 2015 report prepared by DESA, “more than half of global population growth between now and 2050 is expected to occur in Africa” (UN, 2015). More affordable and sustainable forms of construction, for example, utilising agricultural wastes, are required to meet the demand for housing. Using wastes in construction can serve to both minimise the cost of housing and decrease the depletion of natural resources. The performance of bricks can potentially be improved by the inclusion of agricultural waste fibres.

Using wastes to produce useful materials can be referred to as upcycling or industrial symbiosis. Although upcycling can also refer to the reprocessing of used materials while increasing their value or quality, it can also refer to waste materials, with upcycling being the enhancement of the value or quality of these waste materials in new products,

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which contributes to the circular economy concept as an alternative to the linear economy (Sung, 2015; Sung et al., 2019). Industrial symbiosis emerges from, and applies the principles of, industrial ecology, where it benefits from inter-industrial collaboration to minimise the material, energy, resources, and knowledge waste, hence, reducing waste and arising to a more sustainable approach in comparison to traditional individual sector industry (Mirata & Emtairah, 2005). To put this in action in the construction industry, some researchers have suggested implementing an industrial symbiosis between the construction and landscape industries due to their mutual interaction with the built environment (Shooshtarian & Hosseini, 2021). In this sense, wastes from both sectors can be utilised in the other, such as what this study is proposing.

The properties of natural fibres, straws, and stalks have been widely studied. The tensile strengths of these materials have been reported to vary significantly, from around 200 MPa in sugarcane bagasse, sorghum rind, and kenaf fibres (Bakeer et al., 2013; Kumar et al., 2019) up to 700, 800 to 1600 MPa in sisal, hemp and jute, and flax (Cigasova et al., 2013; Duval et al., 2011; Kumar et al., 2019; Stevulova et al., 2014; Stevulova & Junak, 2012), respectively. However, although the tensile strength of individual fibres is one of its most important properties, it is not the only important factor influencing their use within a construction material. Other important factors include fibre and stalk bond with the surrounding matrix, essential for stress transfer, which is affected by the surface texture and morphology of the fibre and stalk particles. Improved bond can increase the fracture energy of a matrix (Ali et al., 2013; Merta & Tschegg, 2013). The porosity of the natural fibres and stalks is another important factor, as it affects the water available for cement hydration in concrete blocks, and may affect the linear shrinkage in earth bricks, and hence, durability (Eliche-Quesada et al., 2011; Thomas, 2018). These factors, along with other social and economic considerations, can limit the wider use of natural fibres, which is often the case with construction and demolition wastes. A review by Shooshtarian et al. (2020) indicated that although the use of recycled products in construction can significantly reduce greenhouse gas emissions, they are still hindered due a number of reasons including lack of confidence and information; low expectations; cost concerns; unsupportive regulations; and limited technologies for waste recovery (Shooshtarian et al., 2020). All of these factors can apply to the case of using agricultural wastes in construction.

Agricultural wastes, such as fibres and stalks from different plants, have been utilised in several construction materials, such as mud bricks, stabilised bricks, and concrete bricks. Due to their relatively low strength in comparison to their synthetic counterparts, such as steel and glass fibres, their use in their natural state is limited. Chemical

and mechanical treatment of natural plant-derived materials to improve their properties has been suggested by several researchers (Ismojo et al., 2019; Symington et al., 2009). However, even without treatment, many natural stalks and fibres satisfy the minimum requirements for low-cost construction materials, in particular earth and stabilised soil bricks, which require a compressive strength that ranges between 1.0 and 2.5 MPa (Adam, 2001; Millogo et al., 2014; Salih et al., 2020b).

To date, there has been little research into potential uses of sorghum stalk fibres. In an attempt to fill this gap, the research study presented in this paper considers the use of sorghum stalks and fibres in the production of construction materials for the purpose of low-cost housing in low- and middle-income countries. The specific aim of the study presented here has been to assess the viability of using sorghum stalk waste for use in the production of low-cost materials such as earth and cement-based matrices to be used in Sudan. Objectives of the study were to (1) identify the morphology and geometry of sorghum fibres and sorghum stalks, (2) determine the tensile strength of sorghum fibres and stalks, (3) determine the effect of change in test rate on the fibres and stalks strength, and (4) examine the effect of shredding and cutting the stalks on their strength.

Materials and Methods

For the purpose of the study, tests to identify geometry, morphology, and strength were applied on sorghum stalks and fibres. The tests conducted were mercury inclusion porosimetry, scanning electron microscopy, and tensile strength tests. As this research was focussed on low-cost housing in the country of Sudan, sorghum, one of the most cultivated crops in the country, was selected for investigation. Sorghum is the number one cereal consumed in Sudan and its waste currently has no added value. According to Sudan Trade Point (Alamin, 2007), about one-fifth of Sudan sorghum is cultivated in the eastern region. The sorghum stalks used in this study were imported from Al-Gadarif state in east Sudan. To extract the fibres, the stalks were initially submerged in water for 2 weeks. The procedure often referred to in literature as water retting (Akubueze et al., 2019; Wolela, 2019) which facilitates extraction of the fibres from the inside of the stalks when their outer parts decomposes. As can be seen from Fig. 1a, the sorghum stalks consisted of three key parts: the rind; the internal vascular bundles; and the pith. The fibres extracted for this study were targeted mainly from the inside wall of the rind, as shown in Fig. 1b. The fibres in the internal vascular bundles were also used in the study when it was possible to extract them from the pith without breakage.

Fig. 1 *Sorghum* stalks' (a) cross-sectional view and (b) fibres in the rind's inside wall

Fig. 2 Materials used: cut sorghum stalks to the top left, shredded stalks to the top right, sorghum fibres to the bottom

In addition to the fibres, the remaining sorghum stalks were also examined, for comparison, following two separate processes: (i) manually cut stalk after fibre extraction; (ii) after shredding with a blender. These are shown in Fig. 2.

Water absorbency was determined following submersion of the stalks in water for 24 h. Specimen mass was recorded before (m_1) and after (m_2) immersion. The latter value was measured in a saturated dry surface condition, which was achieved by removing excess water with a paper towel. Water absorption capacity (w) was measured as follows:

$$w = \frac{m_2 - m_1}{m_1} \times 100\% \quad (1)$$

Pre-treatment of the fibres comprised submerging in water for 1 day after extraction, followed by surface cleaning of natural contaminants, such as wax as shown in Figs. 3 and 4, by gentle brushing. The influence of these contaminants on the fibre tensile strength was evaluated by comparing the tensile strength of fibres both with and without contaminants.

Fig. 3 Optical microscope imaging for contaminants on fibres' surface (a) wax and (b) black spots

Fig. 4 SEM image of a single sorghum fibre showing wax on its surface

Geometry and Morphology of Sorghum Stalks and Fibres

For the purpose of this study, cut and shredded sorghum stalks were assumed to have a rectangular cross-section, while the sorghum fibres were assumed to be of circular cross-section. The dimensions of cut and shredded stalks were measured using a calliper, and assuming their cross-section were approximately rectangular. The fibre diameters along with the length of the internodes were measured using an optical microscope; a minimum of ten measurements were taken and the average calculated. Fibre cross-sectional areas were assumed to be solid for the purpose of calculating the tensile strength.

The pore size distribution of both the fibres and stalks was determined using mercury inclusion porosimetry (MIP). Three specimens of each were tested; the results presented here are the mean values. Samples were stored under 50°C for a minimum of 2 days, then were tested at a surface tension of 0.48 N/m, mercury contact angle of 140°, and a maximum pressure of 400 MPa. Furthermore, fibre and stalk morphology was examined under a scanning electron microscope (JEOL JSM-6480LV SEM).

Tensile Strength

Tensile stress testing was performed on a fibre gauge length of 20 mm, at room temperature. Fibres and stalks were initially glued by their ends to a piece of paper to facilitate preparation for testing; the sides of the paper were cut once the specimen had been mounted in the universal testing

Fig. 5 Tensile test specimen

machine (Instron 3369 test frame), but prior to force application, as shown in Fig. 5. A total of 66 individual sorghum fibres were tested at a rate of 0.5 mm/min (strain rate 2.5 min^{-1}). Another 24 individual fibres were tested with change in the tensile rate to 0.25 mm/min (strain rate 1.25 min^{-1}) to examine the effect of loading rate on performance, as it was indicated in literature that might have an effect (Mukhopadhyay et al., 2008). A total of 60 stalk specimens were tested in a rate of 0.5 mm/min (33 of shredded stalks and 27 cut ones); 19 specimens of shredded stems were tested at 0.2 mm/min. The modulus of elasticity was calculated as the slope of the linear part of the stress/strain graph for each individual specimen from its own elastic phase, which was ranging between 0.04–0.33 of maximum strength in some specimens and 0.0–0.9 in others.

Outline of Data Analysis

The effect of different contaminants, test rates, and preparation procedure of stalks was evaluated using the means and coefficients of variance. All the results were included in the calculations.

Results

Stalk and Fibre Geometry Studied Under SEM and Optical Microscope

Straight stalk and fibre internode lengths were measured to be between 300 and 500 mm long. The cross-sectional area of the tested stalks samples ranged between 0.09 and 1.87 mm², which is a massive variability mainly resulting from shredding processing. Fibre diameters varied from 190 to 350 µm, which is similar to the mean diameters of other natural fibres (Ali et al., 2013; Y. Li et al., 2000; Wolela, 2019). The connection node between fibres (Fig. 6) was found to have lengths between 5 and 6 mm. This connection was noted as the weakest point of the fibre's length, and hence, it was removed before further testing.

Morphology Studied Under SEM

A cross-sectional view of a single sorghum fibre is shown in Fig. 7a. It consists of multiple microtubes, of diameters varying between 5 and 15 µm, that form a honeycomb-like frame around three larger sized cells. The diameter of the larger cells ranged between 90 and 100 µm, while the smaller tubes were around 35 µm. Smaller pores (Fig. 7b) were observed on the side of the fibre and ranged between

0.7 and 2 µm. This porous structure can be contributing to the high level of water absorbency of the fibres.

Tensile Strength

Fibres

The tensile stress–strain response of a typical sorghum fibre is shown in Fig. 8. Tensile curves were found to be initially linear, propagating to a nonlinear phase after stress levels exceeded 30–50% of the maximum tensile strength. Failure at maximum stress was brittle. These results are consistent with literature (Kim & Netravali, 2010), while the elongation in sorghum fibres was lower than other recorded natural fibres; this may suggest that these fibres are more brittle. Modulus of elasticity ranged from 0.9 to 33.6 GPa, and from 1.0 to 24.5 GPa for fibres tested with 2.5 and 1.25 min⁻¹, respectively. These values are lower than values reported for other natural fibres such as hemp which ranges between 14 and 70 MPa (Kumar et al., 2019; Stevulova et al., 2014); this reflects them as being less stiff than other natural fibres.

The individual fibre tensile strengths varied from 24 to 167 MPa, with the mean strength and the coefficient of variance (CV) given in Table 1. The average values for both test rates were close, and both their CV were less than 100%. The CV for the higher strain application rate was 20% higher

Fig. 6 SEM image for connection node between fibres

Fig. 7 SEM image of a single sorghum fibre. **a** Cross-section. **b** Side

Fig. 8 Tensile test result of a single fibre

than for the lower strain application rate, but could be related to the larger sample size.

Stalks

The tensile stress–strain curve of a one cut stalk is shown in Fig. 9. Similar to fibre tests, the tensile curves were found to be initially linear then propagating to a nonlinear phase. In contrast, the stress–strain curves of the shredded samples, shown in Fig. 10, were found to be linear through to failure. Failure at maximum load was brittle. The response of six specimens is shown in Fig. 10, each couple of colours, light and dark (yellow, blue and green), represent samples with close tensile strength but with different tension rates. The modulus of elasticity for the cut specimen ranged from 2.5 to 19.8 GPa, while shredded specimens varied from as low as 1.3 and 5.8 GPa to a maximum of 32 and 18 GPa, for the strain rates

Fig. 9 Tensile test result of a single cut stalk

1.0 and 2.5 min^{-1} , respectively. These values reflect a more consistent performance of cut samples compared to shredded ones.

The individual stalk tensile strength varied from a minimum of 10 and 28 MPa up to 247 and 342 MPa in cut and shredded samples, respectively. The averages and CVs are shown in Table 1. Figure 14 shows the dispersion of data collected from both cut and shredded samples. The averaged tensile strength for specimens tested with slower strain rate (1.00 min^{-1}) was lower than the average for those tested with higher rate (2.5 min^{-1}); nonetheless, the CV was higher for the former than the latter, reflecting more scattered data.

Discussions

Morphology

As was seen in Fig. 7, the fibre's cross-section was porous with more than 90% of the cross-sectional area being voids. This undoubtedly contributed to the high water absorbency of the fibres.

Table 1 Tensile strength parameters and results

Type	Strain application rate (min^{-1})	No. of specimens	Average f_t (MPa)	CV- f_t (%)	Average E (GPa)	CV-E (%)
Fibres	2.50	66	57.3	66.4	3.4	4.3
	1.25	24	49.0	47.3	3.5	4.6
Cut stalks	2.50	27	159.5	44.3	6.7	3.1
Shredded stalks	2.50	15	145.2	40.3	10.2	3.0
	1.00	19	91.5	74.1	7.0	6.9

f_t tensile strength, CV coefficient of variation, E modulus of elasticity.

Fig. 10 Tensile test result of six samples of shredded stalk

The microstructure of the fibres and stalks were studied with the use of MIP. The pore diameter that connects the larger pores is defined as the critical pore diameter, and indicates the connectivity of the specimen's pores and, consequently, how far liquid water will travel after intruding the specimen (Zhu et al., 2019). In MIP, testing a “critical pore diameter” is defined as the pore size corresponding to the highest peak in the $dV/d\log D$ graph, indicating that the critical size of pores governing the specimen. A “threshold diameter” is defined as the size beyond which the intruded volume increases significantly (Siddique, 2008); the threshold diameter provides a measure of how difficult it will be for water to penetrate in the specimen and consequently the specimen's permeability (Diamond et al., 2007). To minimise the effect of change in test parameters on test results (Beaudoin & Marchand, 2001), all specimens of fibres and stalks were subjected to the same pre-treatment comprising storage in a 50 °C oven for a minimum of 48 h before testing. MIP testing on the sorghum fibre samples (Fig. 11a) showed that both the threshold diameter and the critical pore size are close to 40 μm . For the shredded stalks (Fig. 11b), pore sizes were distributed across 0.003 to 100 μm , with a critical pore size of an average 19 μm . Shredded samples did not show a specific threshold diameter.

One of the cut stalks indicated a rather different behaviour under mercury intrusion, as presented in Fig. 11c. This specimen was discarded from the average calculations. Cut specimens presented three main peaks

in the $dV/d\log D$ log, corresponding to three critical diameters, namely 0.065 μm , 0.7 μm , and 30 μm . These pore values correlate to the very high level of water absorption (180%) of the sorghum stalks. During MIP tests, most of the pores were filled with relatively low pressures (< 20 MPa, where stabilised soil bricks are pressed with less than 4 MPa (Adam, 2001)) as depicted in Fig. 12. Fibres showed more volume intrusion than stalks as can be seen in Fig. 12, while shredding and cutting the stalks did not have a constant effect on their debility to intrude mercury. The higher volume intruded in fibres can be due to their extremely porous structure shown in Fig. 7, while the stalks retain the dermal tissue which minimise its porosity.

All of these results are evidence of the high porosity of the fibres and stalks, and hence, to their high water absorption. This should be considered when adding sorghum fibres and stalks to the soil bricks or cement blocks.

Tensile Strength

Fibres

Despite the low and variable tensile strength of the sorghum fibres under study, in comparison to other fibres (Akubueze et al., 2019; Kumar et al., 2019), they have potential as reinforcement in bricks in low-cost housing. Fibres with much lower tensile strength (< 16 MPa) have been used successfully in unfired clay bricks (Salih et al., 2020a). Furthermore, the

Fig. 11 MIP results for fibre (top), shredded stalks (middle), and cut stalks (bottom)

cross-sectional area of the fibres is overvalued for simplicity purposes and lack of equipment to determine the actual net area. This reflects a much higher strength than recorded here.

Treating the fibres with sodium hydroxide has previously been used to improve properties of natural fibres (Kim & Netravali, 2010; Meon et al., 2012). As part of on-going research, further tests are planned to understand the sorghum fibre behaviour in a soil clay matrix.

When observed under both optical microscope and SEM, some of the sorghum fibres were found to be partially or completely covered with wax or black spots, the later indicative of mould growth. The effect of these contaminants on the tensile

strength of fibres was explored further; fibre tensile strength results were found to be similar to the clean fibres (Fig. 13a).

The effect of strain rate in testing, varying between 1.25 and 2.5 min^{-1} , on fibre tensile strength was also investigated (Fig. 13b). There was little direct correlation between strain rate and tensile strengths, although the samples tested with 1.25 min^{-1} were less scattered compared to the higher rate.

Stalks

From Figs. 9 and 10, while both kinds of stalks failed in a brittle manner, shredded samples showed linear behaviour while cut samples demonstrated nonlinear behaviour in certain stages as explained earlier. This can be rationalised by the shredder breaking down the fibres constructing the stalk, while the manually cut stalks maintained their fibre integrity, hence underwent individual fibre failure at a time.

The effect of the test rate was found to not highly affect the behaviour of the shredded stalks undergoing tensile strength (Fig. 10), although a less scattered data can be argued with the lower CV value of the samples tested with higher test rate. While all the samples' behaviour was highly variable, the modulus of elasticity results indicated a more consistent behaviour in comparison to the shredded ones.

From Fig. 14 and Table 1, most of the specimen's results are clustering around an average strength of 130 MPa, which is lower than those recorded by Bakeer et al. (2013) for sorghum stalks; this difference can be attributed to the variation in number of specimens between both studies, as well as the difference in specimen's preparation.

Conclusions

In this study, sorghum stalks and fibres were tested to understand their morphology and to assess their viability in earth bricks and cement-based construction blocks for low-cost housing. The use of sorghum stalks waste can enhance the quality of housing in low-income countries in line with the vernacular structures in the region in which stalks are used to stabilise mud structures. This study is a step forward into increasing the durability of those structures with the least possible cost and impact on the environment. This study is a part of ongoing research to evaluate the possibility of using agricultural waste from Sudan in construction materials. The limited

Fig. 12 Pore size vs pressure for fibre samples **Fig. 13** Fibre diameter vs Tensile strength a) effect of contaminants on fibre surface, b) effect of test rate

time of the study did not help in applying more tests such as pull-out test and chemical characterisation, and the nature of importing crops from a different country limited the sample size giving indicative, but not conclusive, results on the viability of sorghum fibres and stalks; also, it resulted in working with one type of sorghum from Sudan. From conducted tests, the following specific conclusions and recommendations can be drawn:

- 1- Sorghum stalks and fibres demonstrate variable mechanical properties, complicating their characterisation as individual fibres or within a matrix.
- 2- For low-cost housing construction materials, the tested stalks and fibres showed sufficient strength for use in unfired clay bricks.
- 3- The high porosity of fibres and stalks needs to be managed before further use in soil or a concrete matrix.
- 4- Further research to investigate performance of the fibres and stalks within a soil or concrete matrix is needed, and the effect of natural contaminants, such as wax, on the bond should be noted.
- 5- Further research to investigate the effect of various species of sorghum and differences in their strength among other properties is needed.

Fig. 14 Tensile stress vs area for stalks

Author Contribution T.A. carried out the experiments, data analysis, and led drafting of the paper. P.W., K.P., and S.A. supervised the experimental work and data analysis. All authors contributed to the final manuscript drafting.

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Data Availability The datasets generated and analysed during the current study are not publicly available due to it being a part of an ongoing PhD research, but are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare no competing interests.

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