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Assessing the Structural properties of the Sandbag wall for alternative housing construction

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Abstracts: It is estimated that 1.6 billion people live in substandard housing, and more than 100 million people have no housing. In South Africa, about 12.7% of households lived in informal dwellings in 2019. This suggests that the existing conventional methods of construction and materials are incapable of solving the housing problems. The sandbag building material has been proposed as an affordable, sustainable, and recyclable alternative building material capable of accelerating housing provision in South Africa. However, previous studies show significant variations in filling materials used. There is also a lack of understanding of the sandbag wall based on the infill material. Therefore, this study examined the structural properties of the sandbag when filled with dune sand and crusher dust. Laboratory tests included compressive load on a three-bag stack, frictional shear strength between the interface of sandbags, and the structural stability of sandbag walls when subjected to vertical loading. A key finding was that although the displacement limits were reached before the bags failed, the bags of both fill materials could sustain compressive loads far beyond the ultimate design loads with large deflections in the bags. This suggests that the filled sandbags are not the determining factor in the design of sandbag structures.

Key Words: Building material, Compressive test, Crusher dust, Dune sand, Frictional shear, Housing, Sandbag wall, Stability

Introduction

According to United Nations (2019), about 1.6 billion people – more than 20% of the world's population lack adequate housing, and an estimated 100 million people are homeless. About 12.7% of households in South Africa lived in informal dwellings in 2019 (StatsSA, 2019). Slum-dwellers are described as a group of individuals living in a house that lacks structural quality or durability, among other conditions (United Nations, 2019). This suggests that the existing construction methods and materials are incapable of solving the problems of inadequate housing and a need to develop alternative building materials. Sandbags (typically known as earthbags or soil bags) are polypropylene bags or polymer materials filled with granular materials. The sandbag has been proposed as an affordable, sustainable, recyclable, and alternative building material capable of providing access to housing (Ecobuilders, 2019), because of the high and increasing cost of modern materials.

Sandbags have been widely used since the 17th century for military defence and flood protection. They have also been used in soil retaining walls and embankments to increase the bearing capacity of footings (Cataldo-Born et al., 2016). The use of sandbags as a structural material for housing has gained interest over the years because of the advantages of being versatile and manageable and can be filled with any suitable granular material. However, no standardized guidelines exist on which materials to use or that specify the structural properties (Santos and Beirão 2016). Also, current project designs are based only on the experience of the builders or trial and error construction. Furthermore, studies reviewed (see Dunbar and Wipplinger, 2006 and Daigle, 2008) show significant variations in both materials and test methods used to evaluate the sandbags.

Therefore, this study investigates the behaviour of sandbags under uniaxial compression when filled with dune sand or crusher dust. The paper presents the review of recent research on the structural performance of sandbags based on the types of tests done and their purposes and the results obtained. After that, it presents the experimental test methods, including commentary on the preparation of sandbags and testing, the results obtained from the testing, and conclusions.

Literature review

The subject of sandbags has not been adequately explored in terms of research in the construction industry. Although there are no guidelines for sandbag construction nor testing, research has been conducted over the past decade to investigate the use of sandbags in housing and other construction purposes. For example, in Dunbar and Wipplinger (2006), no details on the material composition were provided, neither were the average bag deformation values provided, and the bag sizes were not specified. The study by Daigle (2008) used testing procedures in ASME 447 (now ASTM C1314), which was inadequate as it only relies on 3-unit stacks when testing compressive strength. This section briefly presents a review of previous studies and their findings related to the research objective. The performance of sandbags is governed by both the material properties and structural properties. Material properties relate to the fill, bags, and type of reinforcement used to construct the sandbag structures. In contrast, structural properties are associated with the behaviour of the sandbag structure when subjected to compression, flexural, shear, or impacts

Material properties of sandbags

The material properties of sandbags vary with changes in the composition of the fill. Previous studies such as Dunbar and Wipplinger (2006) did not investigate fill properties. The only tests carried out were the shear box tests done by Vadgama and Heath (2010) and Ralph (2009) on the builders' sand, of which it proved to have shear strength and friction angle of 76.60 kN/m2 and 26.5^0, respectively. Though soil particles are typically divided into clay, silt, and sand, sand fills are usually preferred due to their cohesion; hence, they have been the most used fill material. However, filling made up of clay particles is particularly important since clay acts as a binding agent. Because clay has a disadvantage of expanding when exposed to high moisture levels, an acceptable optimal range between 5% and 30% is typically used. Daigle (2008) confirmed this by having 37% and 27% of clay and silt in the topsoil and sandy soil fill, respectively. In addition, sandbag structures are more commonly constructed using a fill material with at least 10% fines to aid compaction. While only one study (Daigle, 2008) considered large-sized particles such as crushed granite, it was found that this material resulted in early cracking or tearing of the bags.

The widely used bags for the construction of sandbags are polypropylene bags. These bags come in different sizes, with 20 kg as the ideal bag weight to allow individual handling during construction. From the studies undertaken by Daigle (2008), Ralph (2009), and Vadgama and Heath (2010), the only parameter tested was the tensile strength of the bag material. The reasons for the variation in results between the different studies – about 19KN/m (Ralph, 2009; and Vadgama and Heath, 2010) and about 7KN/m (Daigle, 2008) is unknown but could be related to the bag thickness, size, and thread count, as well as differences in the test methods used to obtain results, all of which would need to be investigated further.

Compressive strength of sandbags

Compression tests on bag stacks, such as those carried out by Dunbar and Wipplinger (2006), Daigle (2008), Ralph (2009), and Vadgama and Heath (2010), allow the compressive strength of the sandbags to be determined. Dunbar and Wipplinger (2006) tested the soil dirt, sand, and rubble-filled sandbags in a 3-bag stack, while Daigle (2008) tested crushed granite, sandy soil, and topsoil-filled specimens on 3-bag, 6-bag, and 9-bag stacks, Ralph (2009), and Vadgama and Heath (2010) conducted tests on stack heights of 1, 3, 5 and 8, filled with builders' sand, in which the 8-bag stack fill material was also stabilized, and the three and 5-bag stacks were reinforced with 3-point barbwire.

The studies obtained different results for the 3-bag stacks, summarized in Table 1. The fine-soil fill type includes soil dirt and topsoil, medium-sand type includes sand, sandy soil, and builders' sand, and coarse-granular type includes rubble and crushed granite. It is to be noted that Ralph (2009) and Vadgama and Heath (2010) experienced initial bag tearing at 1.61 MPa; however, the ultimate strength of the stacks was considered invalid due to end-restraint effects. The soil dirt-filled bags in the study by Dunbar and Wipplinger (2006) were unable to be loaded to failure (i.e., bag tearing) due to the limited capacity of the testing equipment, meaning the bag strength at failure could not be obtained. This was also observed in the study by Daigle (2008), where the soil-filled (topsoil and sandy soil) bulged but did not fail by tearing. Failure by bag tearing was observed in both the studies by Dunbar and Wipplinger (2006) and Daigle (2008) of rubble and crushed granite-filled bags. This was attributed to the coarseness and angularity of the fill material that tore the bags at lower loads.

Authors	Ultimate strength of different fill material types (MPa)		
	Fine soil	Medium sand	Coarse granular
Dunbar and Wipplinger (2006)	2.14	0.30	0.40
Daigle (2008)	2.33 – 2.98	2.33 – 2.98	1.27 – 1.29
Ralph (2009) & Vadgama and Heath (2010)	-	1.61	-

Table 1: Compressive strength of 3-bag stacks, with different fill material types from various studies

The results by Daigle (2008) were also shown to be higher than those obtained by Dunbar and Wipplinger (2006), Ralph (2009), and Vadgama and Heath (2010). A possible reason for the higher strengths could be the different fill materials used, as they differed in composition. Also, for stacks greater than three bags, Daigle (2008) obtained lower loads than Ralph (2009) and Vadgama and Heath (2010) with close-related stack heights. Like the three bag findings, the difference in results could be attributed to the different fill materials used, as Daigle (2008) used crushed granite fill and Ralph (2009) and Vadgama and Heath (2010) used builders' sand. Daigle (2008) also observed that the increase in stack height decreased the compressive strength of the sandbag stack, which was owed to the confinement caused by the loading plates, which was shown to be less impactful as the overall height of the stack increased. Ralph (2009) and Vadgama and Heath (2010) saw the same trend and considered the 8-bag stacks most relevant to minimize end-restraint effects caused by the loading plates.

Bag failure was observed as one of the failure mechanisms by different authors. Considering the 3-bag stacks, Dunbar and Wipplinger (2006) and Daigle (2008) expected the sandbags to fail by bag tearing, leading to a sudden drop in strength and compromising the integrity of the sandbag. Vadgama and Heath (2010) expected the sandbags to fail by loss in confinement or to tear the bag at the top and bottom faces due to the bags' tensile capacity being reached. In Dunbar and Wipplinger (2006)'s study, this was observed in the rubble-filled specimen, where tearing occurred in two parallel lines on the top and bottom faces of the middle bag. Daigle (2008)'s crushed granite-filled sandbags failed by bulging, tearing the bag material.

Furthermore, Vadgama and Heath (2010)'s sandbags failed by tearing longitudinally on the upper and lower faces of the sandbags. It is to be noted that Dunbar and Wipplinger's and, Vadgama and Heath's bags were tied the same way by twisting the open end and folding the tied end underneath the bag when stacking. Hence the same failure pattern was obtained. On the other hand, Daigle's bags were tied by folding the end and spiral screw with pins at the edges and centre of the fold.

Stability of sandbag walls under lateral load

The stability of sandbag walls was tested under lateral loads by Thiart (2008) and Croft and Heath (2011), who conducted flexural testing on constructed sandbag walls. Both walls were rendered with chicken wire mesh and cement plaster. Thiart's wall withstood a lateral load of 15.78 kN at failure, while Croft and Heath's wall withstood 7.32 kN. The difference between the two walls could be related to the wall size tested as Croft and Heath's wall was smaller (0.23 x 1.07 m) than Thiart's (4 x 2.5 m), which was also supported by return walls. The study by Croft and Heath (2011) also illustrated the benefit that plaster has on the wall's strength and stiffness, which were shown to be superior to those not plastered. However, the strength of the plaster might also have been contributed by the chicken wire mesh used, which would need to be explored further.

Locally in South Africa, the sandbag construction method was developed to solve the housing shortage experienced in the country due to its advantages of low energy consumption and affordability. However, there is limited research in South Africa on the structural performance of sandbags as a construction material. The studies done by Thiart (2008), Dlambulo (2009), and Herman (2009) were done to satisfy the Agrément standards in South Africa. The only similarity between these local studies and the studies reviewed is the performance of sandbag walls under lateral loads, which was done by Thiart (2008) and discussed earlier. As mentioned before, structural performances of sandbags walls were influenced by material and structural properties. However, in these studies, the material properties of the sandbags and fill material used were not reported on, which might impact the performance of the wall. Another aspect to consider is the chicken wire mesh and plaster, whose effects on the sandbag wall were not investigated.

There is still a need for more research as the current knowledge and understanding of sandbags as a construction material is still lacking. The tests carried out in the reviewed studies showed that sandbag walls do not behave the same as brick walls. Hence, guidelines for masonry wall construction do not apply to sandbag construction, and there is a need to develop standardized guidelines and test methods for sandbag wall construction.

Methods

This research conducted three tests: compressive loading (prism test), frictional shear strength at bags interface, and the stability of sandbag wall under vertical loading. The compressive load test looked further to understand the behaviour of sandbags under vertical load and attempt to quantify the compressive strength of sandbags, with variations in material content (fill). The sandbag shear strength test aimed to determine the shear strength between two sandbags, while the stability test was intended to assess the wall's stability when subjected to vertical loads. Dune sand and crusher dust were used as fill material for the experiment, as no preference was given to the material to be used. However, only the compressive strength test used both fill materials. Only dune sand was used for the wall stability and shear strength test. The dune sand particles are between 0.5 and 1 mm in size, while the crusher dust, on the other hand, shows that more than 55% of its particles are larger than 1mm. Figure 1 shows images of the bag empty and filled. The bags also have a foldable collar of 100mm used to retain material once filled.

Figure 1. The polypropylene sandbags; empty (left) and filled (right)

The sandbags used measured 300 x 300 mm in size. These bags were made of double-stitched non-woven polypropylene fabric from recycled plastic. When filled, these bags measure approximately 290 x 290 x 60 - 75 mm.

Design loads

The design loads were used to compare what the bags would be expected to withstand in service and inform the vertical loads applied in the frictional shear strength and wall stability tests. In design, two limit states are considered. The first is the serviceability limit state (SLS), which looks to restrict deformations, displacements, and local damage of the structure during service. At the same time, the second is the ultimate limit state (ULS), which focuses on safety and corresponds to the maximum load-carrying capacity a structure is expected to take. The service and ultimate loads computed were based on a 75 m^2 single-storey house and determined as per SANS 10160-2, the South African National Standard used to determine the load imposed on a structure. For simplicity, the following assumptions were made in determining the weight and imposed loads: the roof was a free-draining 120 mm thick reinforced concrete slab, and only the longitudinal walls were load-bearing.

A breakdown of the serviceability and ultimate limit states are presented in Table 2, which are given as a line load and load per single sandbag. A bag length of 300 mm was assumed in determining the load on a single sandbag. It should be noted that the assumptions listed above were only made to get an indication of the loading magnitudes that can be expected in the field. As such, the design loads presented here only serve as an approximation and may not accurately reflect those obtained from a detailed structural design.

Load limit state	Line load (kN/m)	Load per single bag (kN)
Serviceability Limit State	20.6	6
Ultimate Limit State	26.9	8

Table 2: Serviceability and ultimate limit states, as per SAMS 10160-2

Bag filling preparation

The moisten dune sand was placed in the sandbags using a cylindrical PVC container for the wall construction, as illustrated in Figure 2. Before filling, the fill materials were brought to their optimum moisture content to aid in compaction. This moisture content was determined for each material during testing. Dune sand and crusher dust had a water content of ±10% and ±3%, respectively. The bags were filled to mass between 7 and 8 kg for both materials. Once filled, the bags were closed by flipping the foldable collar on the bag over the opposite side and flattened using a wooden paddle.

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Figure 2. Bag filling preparation; moisten the sand; fill the PVC cylindrical container, and fill the bag

Compressive loading (prism test)

Two different materials were considered for this test: dune sand and crusher dust. The test involved stacking three bags filled with the same material on top of one another and applying a vertical compressive load. The test was carried out using an Amsler compression testing machine. The bags were stacked, with the folded collar facing the same direction. A steel block of 2.5 kg was then used to flatten and compact the bags, and the width and height of each bag were recorded. A constant displacement of 12 ±2 mm/min was applied when loading the bag stack, and compressive loads were measured every 30 ±2 seconds. The load was applied until the bags could not take any more load or when the piston head had reached its displacement limit. The failure criterion was assumed to be the bag tearing. After testing, the load was removed, the bags were inspected for damage and its dimensions were recorded.

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Stability of sandbag wall under vertical loading

Two 12 bag high wall variations were considered in the test for the stability of a sandbag wall when vertically loaded. The first sandbag wall was encased in a frame that measured 1000 mm high and 750 mm long and stacked in a stack bond arrangement, where bags were laid directly on top of one another. The second wall type was a standalone sandbag wall measuring approximately 930 mm high and 675 mm long and stacked in a masonry bond arrangement. The sandbags filled with dune sand were stacked in the frame to form the sandbag wall. This frame was constructed using braced timber battens held in place using 4 x 75 mm chipboard smooth shank screws. The braced timber battens are typically referred to in the South African sandbag building industry as “EcoBeams". They comprise two 38 x 38mm timber battens braced together with a steel lattice, at 150 mm apart. Four EcoBeams were assembled to form the frame for the sandbags.

The wall was constructed below the loading plate, and a plumb bob was used to centralize the wall’s vertical alignment with the actuator. A wooden paddle was utilized to flatten and shape the individual bags during wall construction, a common approach used in sandbag wall construction in South Africa. To ensure the standalone wall remained straight during its construction, a frame was used in encasing the sandbag wall. Once constructed, a steel spreader beam was placed on the wall and vertically loaded. The steel spreader beam measured 350 (H) x 200 (W) x 750 (L) mm and weighed 87 kg. The vertical loads were applied incrementally using a 250 kN loading capacity actuator. The framed wall was first subjected to 20 kN, followed by increments of 5 kN, while the standalone wall was subjected to 5 kN first, followed by increments of 5 kN. The initial load of 20 kN on the framed wall was based on the ultimate design load discussed earlier. The initial load of 5 kN was selected for the standalone wall, as it was anticipated that the wall would not be capable of withstanding this magnitude of loading. A load rate of 0.2 kN/s was applied between each load increment where the vertical load was kept constant, and the wall's stability was assessed visually.

Result and Discussion

Effect of different fill material

The study found a significant difference in the structural performance of sandbags depending on the fill material. The sandbags filled with dune sand reached a peak load of 42 kN (0.5 MPa), while the crusher dust bags reached 65 kN (0.77 MPa). Similar findings were reported in Dunbar, and Wipplinger (2006), who found the sand-filled bags have lower compressive strengths of 0.30 MPa than rubble and soil-filled bags with 0.40 MPa and 2.14 MPa, respectively. Daigle (2008), however, found the opposite, with the granite bags only able to bear loads between 1.27 and 1.92 MPa before tearing, while the sandy and topsoil filled bags were able to withstand loads of 2.33 and 2.98 MPa, without any tearing.

The higher loads sustained by the crusher dust were due to differences in particle shape and size distribution, with a higher proportion of fine and coarse particles than the dune sand. This, combined with the sharpness and angularity of the courser particles, could have provided enough binder to hold the particles together within the bag, thus improving the bag's resistance to loading. Despite this benefit, the angularity and sharpness of the crusher dust particles also resulted in the bags fraying, unlike the dune sand-filled bags that showed no damage. Such cases were also reported in Daigle (2008) and Dunbar and Wipplinger (2006), who attributed the tearing of the dirt and rubble-filled bags to the coarseness and angularity of the material.

Compressive loading

The results obtained from the testing showed both the dune sand and crusher dust bags to remain intact throughout testing and that the displacement limits of the piston head had been reached. Similar findings were also reported in Dunbar and Wipplinger (2006) and Daigle (2008) for the bags filled with sand, both of whom commented that the compressive strength of the bag is not the determining factor when working with sandbag construction. The compressive loads resisted by the bags were well above those required by the ultimate and serviceable design loads. However, the large deflections observed in the bags are of significant concern from a serviceability point of view. If the ultimate limit state of 8 kN is considered, the dune sand and crusher dust had compressed by approximately 8 and 14 mm, respectively. Similarly, in the case of the standalone wall, displacements were observed immediately after the loads were applied, which continued until failure. It could be said then that while the compressive strength of the bags is not the determining factor in design structures made from sandbags, the serviceability limit state is, which is also what Ralph (2009) and Vadgama and Heath (2010) concluded from their study.

Wall stability under vertical load

The framed and standalone sandbag walls tested withstood a maximum load of 31 kN (41.3 kN/m) and 15 kN (20 kN/m), respectively. Although the standalone sandbag wall failed below the ultimate design load of 20 kN, the framed wall surpassed this value by 55% (26.9 kN). Furthermore, signs of damage in the framed wall were only detected once the applied load went past 25 kN (125% of the ultimate design load). A concern, though, is the sudden torsional failure the framed wall experienced at 31 kN, as such sudden failure types (such as shear failure) are avoided when it comes to structural design.

Displacements in the thickness of the bag were seen for the standalone sandbag wall throughout testing, which failed below the serviceability limit state of 15.5 kN. Approximately 15% of the wall's height had compressed before being deemed to have failed. Gaps between adjacent sandbags were also observed, and these gaps were highest in the upper middle section of the wall, with the bottom and top layers showing no gaps. Similar to the end restraint effects observed for the compressive loading test, this behaviour can be attributed to the limited frictional resistance between the bags, enabling the bags to slide horizontally and form gaps. The results suggest that the EcoBeams play a significant role in the wall's stability and load-bearing resistance. The EcoBeams provide most of the wall's load-bearing resistance and confine the sandbags to the frame, limiting horizontal displacements between the bags. As for the sandbags, their structural contribution is only complementary when used with the EcoBeams.

Conclusion

This study investigates the behaviour of sandbags under uniaxial compression when filled with dune sand or crusher dust. Emphasis was placed on the material and structural properties of the sandbag walls. Three experimental tests were conducted: the compressive testing of a 3-bag stack, frictional strength testing between bags, and wall stability when subject to vertical loading. Dune sand and crusher dust were the fill materials for the compressive load test, while only dune sand was considered for the frictional shear strength and wall stability tests. It emerged that the crusher dust exhibited a higher load-bearing resistance than the dune sand due to its particle shape and size, which enable better interlocking between particles. It was found that the bags of both fill materials could sustain compressive loads far beyond the ultimate design loads. However, the large deflections observed in the bags are of significant concern from a serviceability point of view.

End restraint effects were also seen during this test, suggesting that this test does not yield representative results in the field and that a new test method be developed to evaluate bag stacks. The results of the wall stability under vertical loading suggest that the frame (EcoBeam) plays a significant role in the stability and load-bearing resistance of the wall and that the contribution of the sandbags was only complementary. Significant improvement on the shear friction between the sandbags is required if the frame is not considered, as the frame was shown to confine the sandbags and prevent lateral displacements. Based on these findings, the study concludes that the compressive strength of sandbags is not the determining factor in the design of sandbag structures. Instead, more focus should lie on the serviceability aspects, which include the sandbags' deformations and displacements and the sandbag structure's stability. Further studies are recommended into the influence of the render on the stability of sandbag walls.

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