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Geotechnical characterisation of recycled biopolymer-stabilised earthen materials

Caractérisation géotechnique de matériaux de terre recyclés stabilisés au biopolymère

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ABSTRACT: Earthen structures (i.e. structural units manufactured from soil) are often regarded as sustainable forms of construction due to their characteristically low carbon footprint. Unstabilised earthen materials can easily be recycled or disposed, however, modern earthen structures rely on cement to obtain desirable strength and durability. This lowers both green credentials and recyclability potential of the material. With growing global interest in sustainability, it becomes imperative to explore alternatives to chemical stabilisers which can address these issues without compromising on the desired engineering properties of earthen construction materials. It has been reported that, earthen material treated with biopolymers, namely guar and xanthan gums have improved strength and durability properties. This study reports a preliminary assessment of the recyclability potential of these biopolymer treated earthen materials. Geotechnical properties of the recycled soil mixture such as particle size gradation, Atterberg limits and linear shrinkage were compared with the original unamended soil mixture to assess the changes due to recycling. Findings from this study provide an insight on the recyclability potential of biopolymer treated earthen materials and any associated environmental concerns relating to their disposal.

RÉSUMÉ: Les structures en terre (c'est-à-dire les unités structurelles fabriquées à partir de mélanges de sol) sont considérées comme des constructions durables en raison de leur faible empreinte carbone. De plus, les matériaux non stabilisés à base de sol peuvent être recyclés ou éliminés. Cependant, pour atteindre la résistance et la durabilité requises, ces structures terrestres modernes reposent sur le ciment, ce qui réduit le potentiel de recyclabilité du matériau. Avec l'intérêt croissant pour la construction durable, il devient impératif d'explorer des alternatives aux stabilisants chimiques qui garantissent la durabilité structurelle sans compromettre les propriétés durables des matériaux de construction à base de terre. Récemment, il a été observé que la résistance et la durabilités des matériaux en terre stabilisés sont améliorées par l'incorporation de biopolymères, à savoir le guar et le xanthane. Cette étude présente une évaluation préliminaire du potentiel de recyclage de ces matériaux à base de terre stabilisés par des biopolymères. Les propriétés géotechniques (distribution granulométrique, limites d'Atterberg et retrait linéaire) ont été comparées au mélange de sol d'origine non stabilisé.

Keywords: Earthen material, biopolymers, recyclability, rammed earth

1 INTRODUCTION

Construction and demolition waste are the largest contributor to the total waste generated across the world. However, only a small proportion gets recycled, the rest ending in landfill (Calkins, 2008). This situation motivates for sustainable building processes which not only fulfil social needs but also addresses environmental concerns. Earthen construction is considered to be a sustainable building form for its low carbon footprint and lower operating costs (e.g. heating/cooling). From an ecological perspective, an earthen material‘s ability (in its simplest form as compacted soil and water mixture) to replasticize offers recycling potential and reduced environmental impact on disposal (Schroeder, 2016; Gallipoli et al., 2017). However, in case of modern earthen structures, the unit elements (i.e, rammed earth or compressed earth blocks) are stabilised with cement to achieve strength and durability. Inclusion of cement has not only lowered the “green credentials“ of the stabilised earthen materials (Lax, 2010), but also has created problems in its recycling (Gallipoli et al., 2017). As a potential alternative to cement, the authors have explored the possibility of using two industrial biopolymers to stabilise earthen materials, showing that there is clear potential for biopolymers to improve strength and durability of treated earthen materials (Muguda et al., 2017; Muguda et al., 2018a; Muguda et al., 2018b). The current study focusses on understanding the recyclability potential of biopolymer treated earthen materials through geotechnical characterisation.

2 BACKGROUND STUDY

In this section we briefly summarise our research to date on the use of two industrial biopolymers(guar and xanthan gums) in stabilising earthen construction materials. These biopolymers were considered due to their good stability properties against pH and temperature (Mudgil et al., 2011) and to date their influence on strength and durability properties of the earthen material have been studied. Biopolymer stabilisation is achieved through hydrogels which bind soil particles through hydrogen bonding along with/without ionic bonding depending on the biopolymer used (Muguda et al., 2017). It has been found that for both biopolymers, there was significant improvement in compressive strength for the treated material, while only xanthan gum improved tensile strength (Muguda et al., 2017). It was also noted that, about 1.5-2.0% of biopolymer content was sufficient to achieve comparable air-dried compressive strength of 8.0% cement stabilised earthen material.

For durability properties of biopolymer treated earthen materials, erosional resistance was determined as per the “Geelong“ drip tests (NZS 4298, 1998) and were performed for different sample configurations namely, block, cylinder and tile for the biopolymer treated material at 7 and 28 days from preparation. It was noted that the depth of erosion for all samples was within the permissible limit as prescribed by NZS 4298 (1998). The durability performance of the biopolymer treated specimens were compared with unamended and cement treated specimens and they performed better than the unamended specimens (Muguda et al., 2018a; Muguda et al., 2018b). Here we continue investigation of these interesting materials focussing on their recycling potential.

3 MATERIALS & METHODOLODY

3.1 MATERIALS

The durability test specimens used in a previous study (Muguda et al., 2018b) were used to recycle. Soil mixture (2-7-1) comprising 20% kaolin, 70% sand and 10% gravel by mass was used to make 150x150x20mm tiles to assess durability performance. The soil mixture conformed to standard earthen construction recommendations (MOPT, 1992; Houben and Guillard, 1994; AFNOR, 2001). The properties of the engineered soil mixture are given in Table 1.

3.2 RECYCLING PROCEDURE

True recycling of earthen materials means retrieval of the original desired soil properties i.e., soil gradation and plasticity, so that it can be re-used again for earthen construction (Schroeder, 2016). To achieve this, soil washing, a water-based process separating the coarse soil fraction from finer particles was considered in this study (Griffiths, 1995). The surface of the tiles was cleaned off using a wire brush. The tiles were then broken down gently into smaller pieces using a wooden mallet. A known mass of this disintegrated earthen material was soaked in distilled water. After 1 hour of soaking, any lumps of soil were disintegrated manually and slurry consistency of the mixture was achieved. The slurry was left to settle for 24 hours before being tested for particle size analysis, Atterberg limits and linear shrinkage tests. Additionally, chemical tests were performed on the water collected after soil washing.

3.3 METHODOLOGY

3.3.1 PARTICLE SIZE ANALYSIS

The prepared slurry was washed through a 63μm sieve to separate the coarse fraction of the soil mixture from the finer particles. Both soil fractions were then oven dried at 100 ± 5^0C for 24 hours, after which, the dried coarse fraction was weighed and particle size variation was obtained through dry sieve analysis as per BS 1377-2 (1990). Sedimentation analysis by the pipette method was performed for the fine fraction of the soil mixture as per BS 1377-2 (1990). Particle size distribution analyses were performed for both biopolymer treated soils and the unamended soil mixture. These results along with the recommended limits for earthen materials are plotted in Figure 1.

3.3.2 ATTERBERG LIMITS AND LINEAR SHRINKAGE TESTS

For the recycled soil mixtures, slurry as mentioned in Section 3.2 was placed on a 425 µm sieve and washed thoroughly using distilled water. Washing was continued until clear water and no visible soil fines were passing through the 425 µm sieve. The soil fraction passing was collected and oven dried for 24 hours at 100 ± 5^0C. After 24 hours, the dried soil fraction was broken down into smaller fractions and mixed thoroughly with distilled water until a stiff consistency was achieved. This mixture was left to equilibrate in air-tight polythene bags for 24 hours, after which Atterberg limits and linear shrinkage tests were performed as per BS 1377-2 (1990). The results of Atterberg limits and linear shrinkage are presented in Figures 2 and 3 respectively.

Table 1. Physical properties of the unstabilised soil mixture used in this study

Soil	**Clay (%)**	**Silt (%)**	**Sand (%)**	**Gravel (%)**	**Liquid Limit (%)**	**Plastic Limit (%)**	**OWC (%)**	$\gamma_{d,max}$ **(kN/m³)**
2-7-1	16	04	70	10	36.2	18.4	9.8	19.62

$\gamma_{d,max}$: maximum dry density

3.3.3 CHEMICAL TESTS ON WATER

In a real life scenario, the water used for washing a soil during recycling would need to be safely disposed of or treated. This requires an understanding of the effect of the presence of the biopolymers on the water used on soil washing to ensure its safe disposal. In order to understand this, the surplus surface water of the slurry which was left to settle for 24 hours (mentioned above) was collected in air-tight 250mL Duran bottles and stored in a dark environment at 21^0C. Chemical properties of these waters were then tested after 1 and 7 days respectively. Standard chemical tests such as pH, oxidation reduction potential (ORP), dissolved oxygen (DO), electric conductivity tests were performed using a HANNA digimeter with respective probes. The results were compared with the chemical properties of the tap water and World Health Organisation (WHO) recommendations (2011).

4 RESULTS AND DISCUSSION

4.1 PARTICLE SIZE ANALYSIS

Figure 1 shows the particle size distribution curves for unamended and recycled soil mixtures within the recommended limits for earthen construction. On observing the Figure 1, it can be noted that the recycled soil mixtures have higher coarser fraction and lesser finer fraction in comparison to the unamended soil mixtures. These higher coarser fractions of the recycled soil mixtures can be attributed to the formations of soil agglomerations due to biopolymer stabilisation (Latifi et al., 2017).

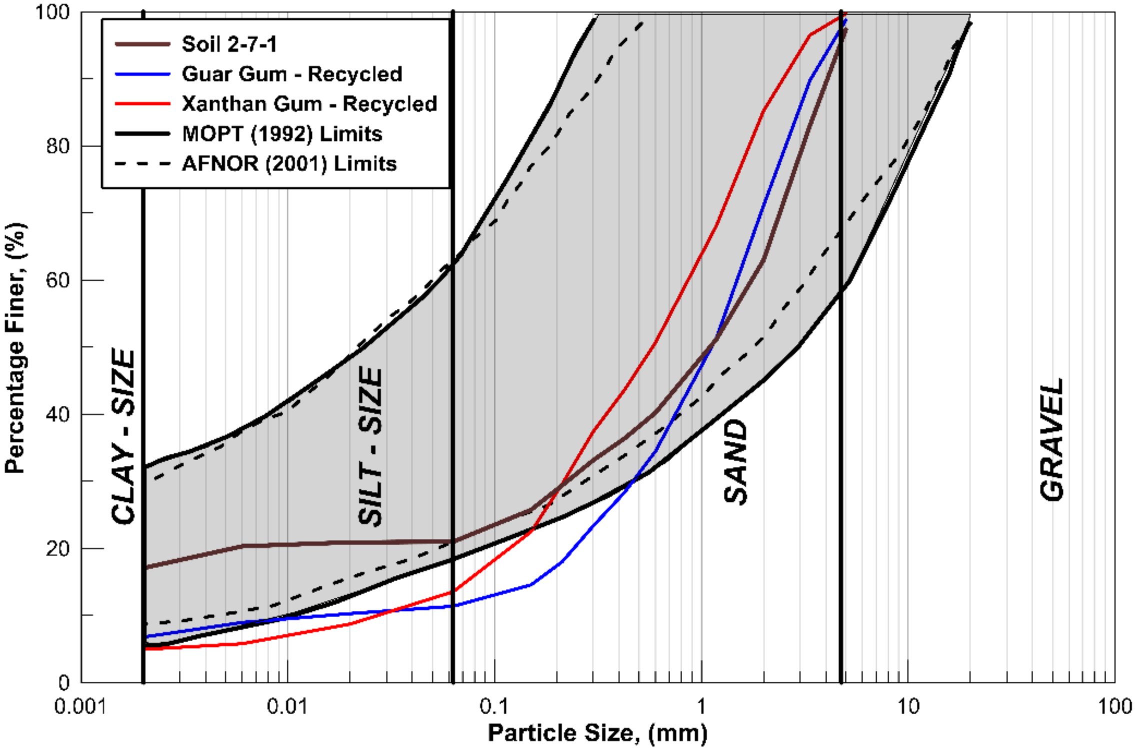

Figure 1. Comparison of particle size distribution curves

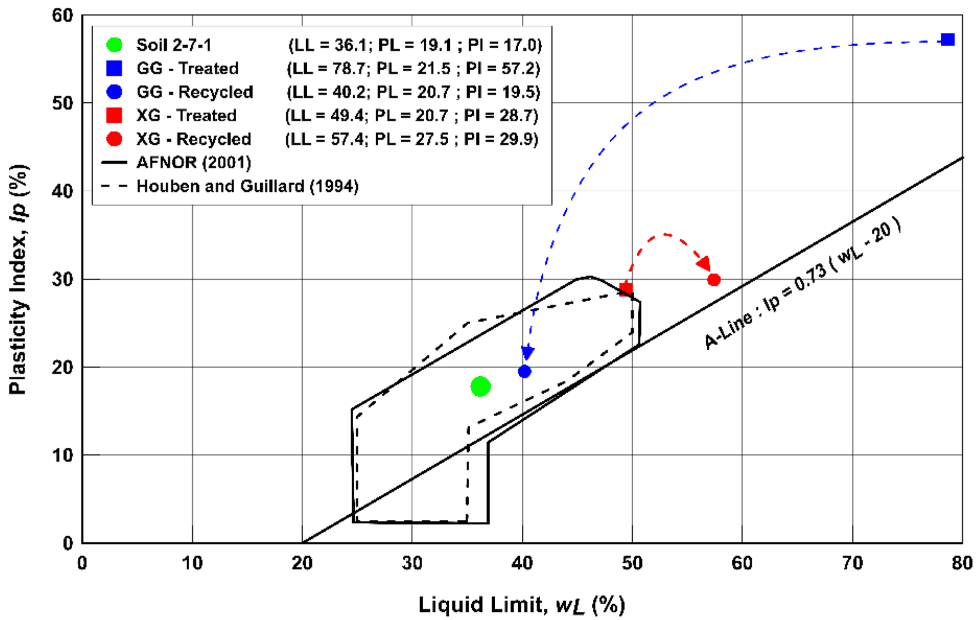

Figure 2. Plasticity properties of the unamended, treated and recycled material

On recycling much of these agglomerations have disintegrated for the guar gum treated soil mixture, while many agglomerations have remained intact for xanthan gum treated soil mixture. Compared to guar gum, xanthan gum has ionic bonds with clay particles in addition to hydrogen bonds which are chemically stronger (Chen et al., 2013; Chang et al., 2015; Muguda et al., 2017). Due to these additional stronger bonds, it can be expected that xanthan treated soil mixture to have many agglomerations which resist washing, certainly in these test conditions. In terms of soil gradation, both the recycled soil mixtures need slight modification through addition of fines fraction in order to be re-used for the original application in earthen construction.

4.2 ATTERBERG LIMITS AND LINEAR SHRINKAGE TESTS

Figure 2 presents plasticity characteristics of unamended, treated and recycled earthen materials. The liquid and plastic limits of the unamended soil mixture were 36.1% and 18.7% respectively. The plasticity properties of the unamended soil mixture fall within the recommended plasticity criteria (Houben et al., 1994; AFNOR, 2001). When the soil mixture was treated with 2.0% biopolymer content, the Atterberg limits for both biopolymer treated soils increased and this increase was more significant for guar gum treated soils. The fines fraction of the soil mixture was initially classified as CI i.e., clay of intermediate plasticity. In the biopolymer treated soils, for guar gum, the fines fraction of the soil mixture was classified as CH i.e., clay of high plasticity, while for xanthan gum it was classified as CI. These differences in Atterberg limits for guar and xanthan treated soils are mainly due to the different stabilizing mechanisms of the biopolymers (Nugent et al., 2009; Chen et al., 2013).

Compared to xanthan gum, guar gum has higher affinity towards water (Nugent et al., 2009) and this may have led to the higher water contents at Atterberg limits for guar gum treated soil mixture. After recycling, the plasticity properties of the guar gum treated specimens were similar to that of the unamended soil mixture which fall within the recommended plasticity criteria. As indicated by (Nugent et al., 2009; Chen et al., 2013; Muguda et al., 2017), the primary bonding for guar gum treated soils is achieved only through hydrogen bonds and on recycling these bonds are easily broken. Thus, the treated material can be recycled easily ensuring the original plasticity characteristics of the soil mixture are retrieved.

In case of the xanthan gum treated soil mixture, the bonding of the soil particles occurs via a different mechanism (as discussed above) and with these bonds, the xanthan gum treated soil mixture may form a complex network of soil agglomerations, thus stabilising soil and trapping free water (Chen et al., 2013). Interestingly, Atterberg limits of the recycled soil mixture was more than the treated soil mixture, changing the fines fraction classification to CH. As noted in the previous section, even after soil washing, many soil agglomerations remained stable. At liquid limit, these agglomerations needed more water for it be remolded and achieve the liquid limit consistency. Hence, the observed liquid limit for recycled soil mixture is higher than that of treated soil mixture. However, the plastic limits for both the treated and recycled soil mixtures were similar. With high plasticity, the recycled xanthan gum soil mixture fails to achieve the original soil plasticity and in this condition the soil mixture cannot be considered for re-use in earthen construction.

With reference to the shrinkage tests, it can be seen that the linear shrinkage of the unamended soil mixture was 5.0% (see Fig 3) while the linear shrinkage of the guar gum treated samples was higher. This increased value of linear shrinkage may be linked to the high affinity of guar gum towards water (Nugent et al., 2009) leading to formation of hydrogels through hydrogen bonding. However, on recycling, these bonds are removed and thus the recycled material has similar linear shrinkage value as that of the unamended soil mixture at 6.2%.

In case of xanthan gum, the additonal stronger ionic bonds with weaker hydrogen bonds has led to much stabler soil agglomerations and hence the lower shrinkage value. On recycling, the agglomerations formed due to ionic bonds may have been disturbed, while the hydrogen bonds maybe removed. This may have led to disorientation of hydrogels in the recycled material leading to a higher linear shrinkage value of 8.7%.

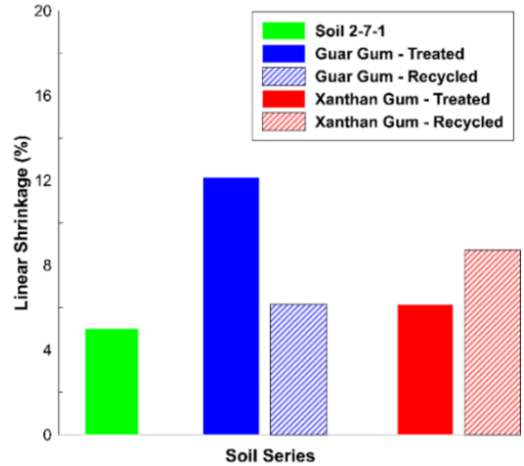

Figure 3. Variation of Linear Shrinkage

4.3 CHEMICAL TESTS ON WATER

Table 2 presents the chemical properties for the water collected on 1st and 7th day after recycling. The chemical properties suggest that compared to tap water, pH for water collected for washing guar and xanthan gum treated soils is slightly more alkaline. Lower ORP and DO values on 7th day indicate the water used for recycling for both biopolymer may be prone to microbial activity which has caused the consumption of the dissolved oxygen in the water. Electric conductivity results, which are an indirect measurement of total dissolved solids, indicate that there is slight increase of dissolved solids for xanthan gum treated water, while the increase in guar gum treated water is negligible. However, it can be concluded that no special disposal treatment may be necessary if the water is disposed immediately after washing.

Table 2. Results for the chemical tests of water

Test Conducted	**Tap water**		**Guar gum**		**Xanthan gum**		**WHO recommendations**
	1d	**7d**	**1d**	**7d**	**1d**	**7d**	
pH	6.9	6.7	7.7	7.0	7.9	6.5	6.5-9.5
ORP (mV)	291	96.7	278	12.4	302	55	-
DO (mg/L)	6.6	6.4	6.1	1.1	6.7	1.7	10-12
Temperature (C)	19.8	19.9	20.4	20	20.5	19.9	15
Electric Conductivity(μs/cm)	181	199	135	153	127	239	<1500

5 CONCLUSIONS

Based on the test results, it can be concluded that the soil washing technique used was sufficient to recycle and retrieve back much of the original soil gradation and plasticity properties for guar gum treated earthen material. In case of xanthan gum treated material, soil washing technique was not so successful in recycling it completely. The recycled material resisted washing, leading to higher coarser fraction. Further, the recycled material had higher plasticity characteristics. In both cases, the water collected after washing showed increased demand for oxygen with time indicating potential microbial activity. Thus, it would be appropriate to dispose the water immediately after washing to ensure safe disposal. Clearly, the results here relate to a single reuse of these materials and to a particular washing procedure however, as an alternative to cement, biopolymers may have potential not only in improving the strength and durability of earthen construction material, but also has potential for recycling.

6 ACKNOWLEDGEMENTS

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