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Effects of polypropylene fiber on the compaction and strength characteristics of cement-bound lateritic soils

Effets de la fibre de polypropylène sur les caractéristiques de compactage et de résistance des sols latéritiques liés au ciment

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ABSTRACT: Cement bound lateritic soils (CBLS) have been used in pavement constructions for a long time. However, the brittleness and high cracking potential of CBLS have discouraged its use as pavement base material. Instead, crushed rock has since been exploited. The mining, crushing and transportation of these crushed rock has led to large increases in project cost. Reinforcing CBLS with fiber has been offered as a possible solution to the problem, but there is little or no experience of fiber reinforcement on local soils. This study is a laboratory investigation into the effects of polypropylene fiber (PPF) on the compaction and strength characteristics of CBLS. A lateritic soil was blended with 2%, 4%, 6% and 8% by mass of Portland cement and its properties in terms of Specific Gravity, Atterberg Limits, Grading, Compaction and 4days California Bearing Ratio (CBR) were determined. For each cement content the strength in terms of the Unconfined Compression Strength (UCS) and the Split Tensile Strength (STS) were determined after curing for 4, 11, 18 and 32 days. Another set of samples were prepared at the Optimum Cement Content (OCC) but with varying percentages of PPF from 0.2% to 0.8% by mass in increments of 0.2%, mixed and compacted. The reinforced samples were cured for 4, 11, 18 and 32 days after which UCS and STS tests were performed. The effects of cement content and PPF content on the strength properties of CBLS are analyzed and discussed.

RÉSUMÉ : Les sols latéritiques liés au ciment (SLLC) sont utilisés depuis longtemps dans les constructions de chaussées. Cependant, la fragilité et le potentiel de fissuration élevé du SLLC ont découragé son utilisation comme matériau de base de la chaussée. Au lieu de cela, la roche concassée a depuis été exploitée. Cependant, l'extraction, le concassage et le transport de la roche concassée ont entraîné de fortes augmentations du coût du projet. Le renforcement du SLLC avec de la fibre a été proposé comme solution possible au problème, mais il y a peu ou pas d'expérience de renforcement de fibre sur les sols locaux. Cette étude est une enquête en laboratoire sur les effets de la fibre de polypropylène (PPF) sur les caractéristiques de compactage et de résistance du SLLC. Un sol latéritique a été mélangé avec 2%, 4%, 6% et 8% en masse de ciment Portland et ses propriétés en termes de gravité spécifique, les limites d'Atterberg, le calibrage, le compactage et les essais de rapport de roulement californien (RRC) de 4 jours ont été déterminés. Pour chaque teneur en ciment, la résistance en termes de résistance à la compression non confinée (RCC) et de résistance à la traction fractionnée (RTF) a été déterminée après durcissement pendant 4, 11, 18 et 32 jours. Un autre ensemble d'échantillons a été préparé à la teneur optimale en ciment (TOC) mais avec des pourcentages variables de PPF de 0.2% à 0.8% en masse par incréments de 0.2% mélangés et compactés. Les échantillons renforcés ont été durcis pendant 4, 11, 18 et 32 jours, après quoi des tests RRC et RTF ont été effectués. Les effets de la teneur en ciment et de la teneur en PPF sur les propriétés de résistance du CBLS sont analysés et discutés.

KEYWORDS: Polypropylene Fiber, Soil Reinforcement, Cement-Bound-Lateritic Soil, Pavement, Material.

1 INTRODUCTION

Cement-bound lateritic soil (CBLS) is a hardened material made up of cement, soil, and water. CBLS usually show an increase in the strength and stiffness compared to natural lateritic soils. But it has been reported to be brittle and with high cracking potential under low strain (Kuhlaman 1994). Some performance issues reported on CBLS, as shown in Figure 1, include block cracking, dry-land cracking, and concrete pavement cracking.

In place of CBLS, crushed rock has in recent times been exploited. The mining, processing, and transportation of crushed-rock for projects has led to large increases in project cost. The search and use of locally available alternate pavement base material is becoming futile hence the need to reintroduce CBLS while overcoming the problem of brittleness and high cracking potential. Reinforcing CBLS with polypropylene fiber (PPF) has been offered as a possible solution (Mcgrown et al., 1978; Morel et al., 1997). PPF is an organic synthetic polymer transformed from about 85% propylene gas in the presence of titanium chloride. It is the second most widely produced commodity plastic after polyethylene and the commonest geosynthetic material used to reinforce concrete and soil.

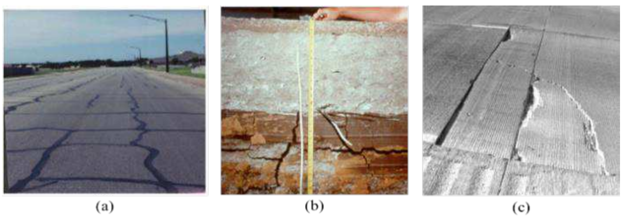

Figure 1. Some Performance issues with CBLS: (a) Block cracking (Scullion 2002), (b) Dry-land cracking (Scullion et al. 2003) and (c) Concrete pavement cracking (Jung et al. 2009).

Maher and Ho (1993) reported that the addition of fiber in cement treated sand significantly increased the peak compressive strength, tensile strength and energy absorption capacity. Mo et al. (1999) showed that reinforcing soil-cement with glass fiber increased the unconfined compressive strength (UCS) and split tensile strength (STS) properties of the composite mixture by

30% and 38%, respectively. Olgun (2013) revealed that PPF reinforcements in clay fly ash soil reduced stiffness and changed their brittle behaviour to a more ductile one as UCS and STS strengths increased. Chore et al. (2015) revealed that the addition of 1 % fiber to cement-fly ash-soil composites yields optimum UCS and STS performance in both unsoaked and soaked conditions.

The objective of this research is to investigate the effects of PPF on the compaction and strength characteristics of CBLS.

The Specific objectives include the following:

1. Characterization of the lateritic soil for use as stabilized base material.
2. Investigation into the effects of Rapid-Hardening Portland Cement (R-HPC) content on the compaction, unconfined compressive strength and the tensile strength characteristics of CBLS mixtures.
3. Investigation into the effects of PPF content on the compaction, unconfined compressive strength and the tensile strength characteristics of CBLS mixtures blended at the OCC.

2 MATERIALS AND METHODS

2.1 *Materials*

The study soil was obtained from the Danchira borrow pit in the Greater Accra region of Ghana. According to USCS and AASHTO classifications, it is classified as GW and A-2-4 respectively, implying the study soil is a granular material (Figure 2). The physical properties of the study soil are shown in Table 1. Results of X-RF analysis (Table 2) carried out to determine the major oxide composition of the study soil and the rapid hardening Portland cement (R-HPC) used in the investigation revealed the study soil is a lateritic soil (SiO_2 to Al_2O_3+ Fe_2O_3 ratio of 1.42) with SO_3 content of 0.31%. The standard special specification for roads and bridges (SSRB) 2006, recommend SO_3<0.50% for cement stabilization. CaO and SiO_2 content of approximately 84% in R-HPC indicate hydration processes will be efficiently improved in CBLS composites. The R-HPC (42.5R) used is Type 1 with specific gravity of 3.15. The Properties of PPF (Table 3) indicate it is a combined monofilament/fibrillated form with similar properties as the PPF used by Olgun (2013) to reinforce clay soil. Figure 3 shows combined PPF used in study.

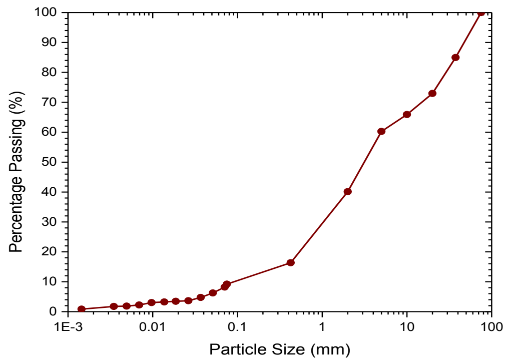

Figure 2. Particle Size Distribution of Study Soil


Figure 3. Combined PPF used in study

Table 1. Geotechnical characteristics of Study soil

Property	Value	Unit
NMC	12.84	%
S.G	2.53	*
Organic Matter	2.10	%
pH	7.52	*
Gravel	63.80	%
Sand	29.17	%
Silt	5.76	%
Clay	1.27	%
Liquid Limit	24.76	%
Plastic Limit	14.60	%
Plasticity Index	10.24	%
MDD	2.243	g/cm^3
OMC	6.43	%
CBR (4 days)	114.76	%
USCS	GW	*
AASHTO	A-2-4	*

Table 2. Elemental Composition of Natural lateritic soil and Rapid-Hardening Portland cement

Major Oxide	Study Soil	R-HPC	Unit
SiO_2	51.48	20.65	%
Al_2O_3	18.43	4.69	%
Fe_2O_3	17.82	3.48	%
Na_2O	0.0	0.42	%
MgO	1.20	2.55	%
K_2O	6.02	0.79	%
CaO	1.40	62.97	%
P_2O_5	0.0	0.14	%
MnO	0.05	0.07	%
TiO_2	2.16	0.00	%
SO_3	0.31	2.73	%

Table 3. Fiber Characteristics

Property	Value	Unit
Form	Monofilament/Fibrillated	*
Colour	Gray	*
Water Absorption	Nil	%
Fiber Length	38-54	mm
Acid/Alkaline Resistance	Excellent	*
Tensile Strength	570-660	MPa
Specific Gravity	0.91	*

2.2 *Sample preparation and testing*

A series of tests (S.G, Atterberg Limits, Grading, Compaction, and CBR) were performed on the natural lateritic soil after which R-HPC was used as a stabilizing agent in proportions of 2%, 4%, 6% and 8% by dry mass of soil to randomly mix the natural lateritic soil. The S.G, Atterberg Limits, Grading, Compaction, CBR, UCS and STS were performed on the CBLS specimen. The compaction, CBR and index properties were performed in accordance with BS 1924 and BS1377. The UCS and STS specimen were prepared and tested in accordance with BS1924 and ASTM C496 respectively after curing specimen for 4days (1hr moist curing + 4days wet soaking), 11days (7days moist curing + 4days wet soaking), 18days (14days moist curing + 4days wet soaking) and 32days (28days moist curing + 4days wet soaking). During moist curing periods, specimen were wrapped with air tight polyethene bags and placed in a temperature control rooms at 25ºC whiles during the wet curing period, the air tight polyethene bag is removed from the moist cured specimen after which the specimen is placed in water at a temperature of 25ºC for each curing period.

Figure 4 shows moist curing in process whiles Figure 5 shows wet curing in progress. A total of thirty two (32) CBLS specimen were prepared at the OMC and tested for UCS and STS properties. The optimum cement content (OCC) was then selected based on UCS requirements of the MRH (2007) developed in Ghana which states that, UCS of stabilized base material should be (2.0 - 3.0) N/mm² after 7days moist curing and 4days wet curing. CBLS prepared at the OCC was randomly reinforced with PPF in proportions of 0.20%, 0.40%, 0.60% and 0.80% by mass to find out its effects on compaction (MDD & OMC) and strength (UCS & STS) properties. The curing periods for the CBLS before testing for UCS and STS were similarly replicated for the reinforced CBLS before testing for UCS and STS properties. A total of thirty two (32) reinforced CBLS specimen were prepared at the OMC and with the OCC after which the optimum PPF content was determined.

Figure 4. Moist curing of CBLS specimen in progress

Figure 5. Wet curing of CBLS specimen in progress

3 EXPERIMENTAL RESULTS

3.1 *Cement-bound Lateritic Soil Composites*

3.1.1 *Specific Gravity*

The results of specific gravity (S.G) test showed the CBLS composites increased progressively with increasing cement content (Figure 6). The S.G increased from 2.61 to 2.63, 2.66, 2.71 and 2.76 at 0%, 2%, 4%, 6% and 8% cement contents respectively. The increments in the S.G of the CBLS composites with increasing R-HPC contents could be attributed to the higher S.G of the R-HPC material used in the study. The S.G of the R-HPC used was determined as 3.15 compared to the low S.G value of the natural lateritic material which was determined as 2.61. In effect the R-HPC contents is responsible for the progressive increase in the S.G of the CBLS composites.

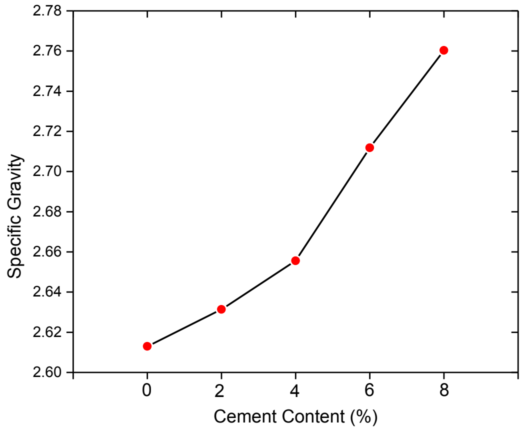

Figure 6. Variation of S.G with cement content

3.1.2 *Particle Size Distribution Characteristics*

The proportion of fines content (silt and clay particles) decreased with increasing R-HPC contents. The Silt and clay particle proportions within the CBLS composites decreased from 7.03% to 5.76%, 4.45%, 3.81% and 1.86% at R- HPC contents of 0%, 2%, 4%, 6% and 8% respectively (Figure 7). The reduction in silt and clay contents may be attributed to the pozzolanic reaction processes of R-HPC with study soil which might have flocculated the CBLS composites thereby binding the fine particles into solid lumps.

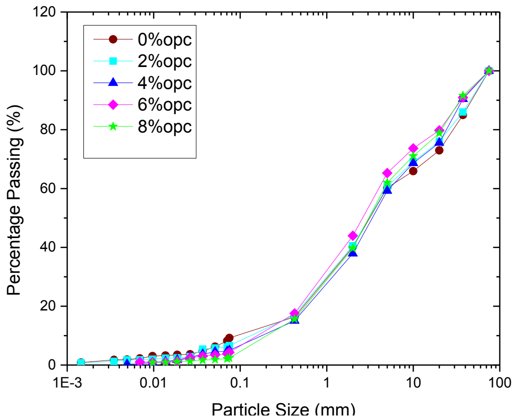

Figure 7. Variation of PSD with cement content

3.1.3 *Plasticity Characteristics*

LL and PL generally increased with increasing R-HPC content whiles the PI decreased with increasing R-HPC content (Figure 8). LL increased from 24.76% to 26.80% for 0% and 8% R-HPC contents respectively. PL increased from 14.60% to 19.20% for 0% and 8% R-HPC contents respectively. PI decreased from 10.24% to 7.60% respectively for 0% and 8% R-HPC contents.

The general increase in LL may be related to the presence of entrapped water within the intra-aggregate pores after the processes of flocculation and agglomeration has taken place. Cation exchange, flocculation and agglomeration reactions may have been responsible for the suppression of PI. Similar trends were reported by Afolayan (2017).

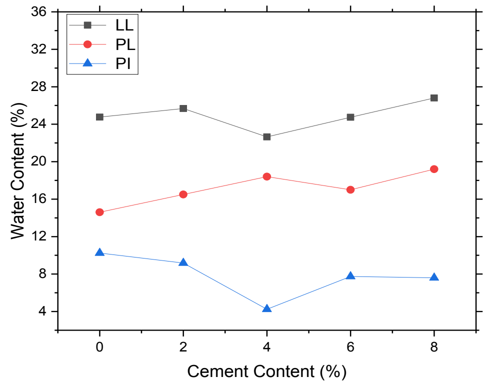

Figure 8. Variation of cement content with Atterberg limits of CBLS composites

3.1.4 *Compaction Characteristics*

The MDD increases whiles the OMC decreases with increasing R-HPC content (Figure 9). The MDD of the CBLS increased from 2.243g/cm3 to 2.256g/cm3, 2.261 g/cm3, 2.265g/cm3 and 2.271g/cm3 at R-HPC contents of 0%, 2%, 4%, 6% and 8% respectively. The OMC decreased from 6.43% to 6.20%, 6.13%, 5.94% and 5.73% at R-HPC contents of 0%, 2%, 4%, 6% and 8% R-HPC respectively. The increase in MDD of CBLS composites maybe attributed to the higher S.G value (thus 3.15) of the R-HPC material. The reduction in OMC with increasing R-HPC content imply that small amounts of water is needed for hydration and strength development processes of CBLS composite materials. Similar trends were reported by Oyederan (2011).

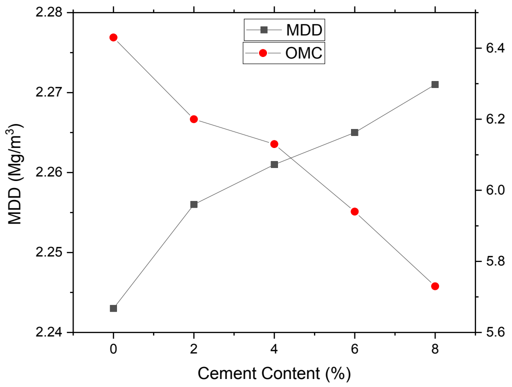

Figure 9. Variation of cement content with MDD and OMC of CBLS composites

3.1.5 *Strength Characteristics*

3.1.5.1 *Unconfined Compression Strength and Split Tensile Strength*

The UCS and STS properties of CBLS increases with increasing R-HPC contents and increasing curing age (Figure 10 and Figure 11 respectively). The CBLS composites mixed with R-HPC content of 2% recorded the lowest UCS values in the order of 1.39N/mm², 2.11N/mm², 2.70N/mm² and 2.97N/mm² for 4days, 11days, 18days and 32days of curing respectively. The CBLS mixed with 8% R-HPC content on the other hand recorded the highest UCS values in the order of 4.66N/mm², 5.78N/mm², 6.47N/mm² and 7.14N/mm² for 4days, 11days, 18days and 32days of curing respectively. Analysis of CBLS mixed with the lowest (2%) and highest (8%) R-HPC contents revealed that a percentage increase in UCS of approximately 235%, 174%, 140% and 140% were recorded respectively for 4days, 11days, 18days and 32days curing periods. Similar trends were observed by Jaritngam et al., (2014). Similar to the UCS behaviour, the lowest STS values in the order of 0.04N/mm², 0.13N/mm², 0.18N/mm² and 0.23N/mm² were recorded for 4days, 11days, 18days and 32days curing respectively when R-HPC content was lowest (thus 2%). Peak STS values in the order of 0.20N/mm², 0.35N/mm², 0.45N/mm² and 0.68N/mm² were recorded for 4days, 11days, 18days and 32days curing respectively when R-HPC content was highest (thus 8%). Analysis of 4days, 11days, 18days and 32days curing periods for the lowest (2%) and highest (8%) R-HPC contents revealed that a percentage increase in STS of approximately 400%, 169%, 150% and 196% were recorded.

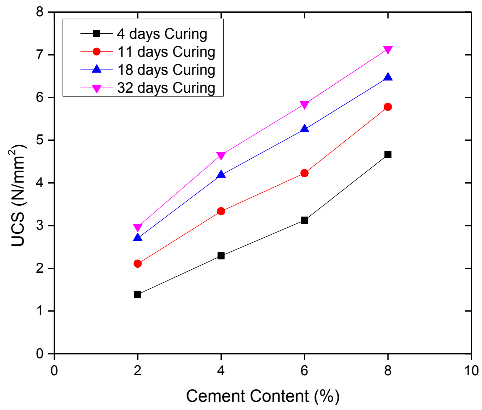

Figure 10. Variation of cement content with UCS of CBLS composites

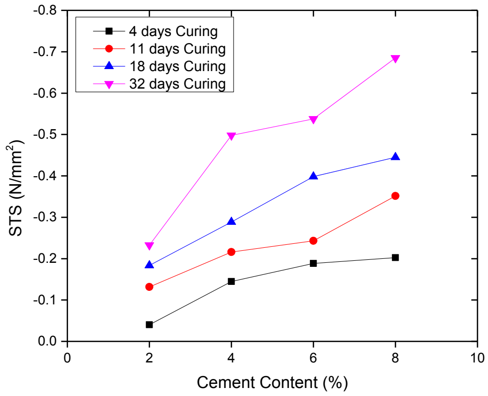

Figure 11. Variation of cement content with STS of CBLS composites

The significant gain in UCS and STS values with increasing R-HPC content and curing age is attributed to pozzolanic reaction processes. As R-HPC is added to lateritic soil, a soil-cement mixture known as calcium aluminate silicate hydrate (CASH) is formed. Continues pozzolanic reaction, gradually converts CASH into a well crystalline phase to form calcium silicate hydrate (CSH) and calcium aluminium hydrate (CAH) which hardens with age to form a permanent compound that binds the CBLS composites and increases their strengths.

UCS values in the order of 2.11N/mm², 3.33N/mm², 4.23N/mm² and 5.78N/mm² were recorded for 2%, 4%, 6% and 8% R-HPC contents respectively after 11days curing (which involved 7days moist curing and 4days wet soaking). However, the specifications of the MRH (2007) recommends that the optimum cement content (OCC) for a CBLS base material must achieve minimum UCS values between 2.0N/mm² and 3.0N/mm² after 7 days moist curing and 4 days wet soaking, hence the CBLS composite mixed with 2% R-HPC content which achieved UCS value of 2.11N/mm² was adequate and therefore selected as the OCC for the study soil.

3.1.5.2 *California Bearing Ratio Test*

The CBR (%) values for CBLS composites in soaked condition increases with increasing R-HPC content. After four (4) days soaking, the CBLS composites recorded CBR% values of 114.75% and 245.09% for 0% and 2% R-HPC contents respectively. The CBR (%) values for 4%, 6% and 8% R-HPC contents could not be determined due to the CBLS composite materials strength higher than the CBR equipment's maximum capacity of 50kN. Similar trends were observed by Jaritngam et al., (2014).

3.2 Reinforced Cement-bound lateritic soils

3.2.1. Compaction Characteristics

The results of compaction tests revealed that the MDD of reinforced CBLS composites decreases as the OMC increases with increasing PPF content (Figure 12). The MDD decreased from 2.256g/cm3 for the unreinforced soil to 2.187 g/cm3, 2.175 g/cm3, 2.161 g/cm3 and 2.158 g/cm3 at 0.2%, 0.4%, 0.6% and 0.8% PPF contents respectively. The OMC increase from 6.20% for the unreinforced soil to 6.50%, 6.64%, 6.86% and 7.02% at PPF contents of 0.2%, 0.4%, 0.6% and 0.8% respectively. The reduction in the MDD of the reinforced CBLS composite mixtures with increasing PPF contents can be attributed to the addition of PPF of a lesser specific gravity (0.90) than the unreinforced CBLS (2.61), hence a reduction of the average unit weight of solids in the reinforced CBLS. The OMC, on the other hand, increases with increasing PPF content. The addition of PPF in CBLS composite mixtures increases the surface area hence more water is required for effective compaction. Similar trends were observed by Qadir (2017).

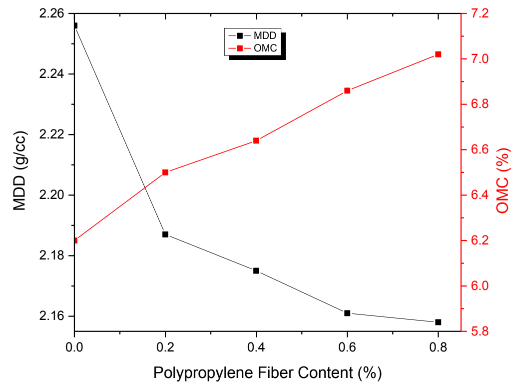

Figure 12. Variation of PPF content with MDD and OMC of reinforced CBLS composites

3.2.2 *Strength Characteristics*

3.2.2.1 *Unconfined Compression Strength and Split Tensile Strength*

The UCS of the reinforced CBLS increases with increasing PPF content until it reaches a peak at 0.60% PPF content beyond which it slightly reduces (Figure 13). The UCS values recorded for the unreinforced CBLS at the optimum R-HPC content were 1.39N/mm², 2.11N/mm², 2.70N/mm² and 2.97N/mm² respectively for 4days, 11days, 18days and 32days curing periods. The Peak UCS values recorded for the reinforced CBLS composites at PPF content of 0.60% after 4days, 11days, 18days and 32days curing were 3.77N/mm², 4.56N/mm², 4.99N/mm² and 5.98N/mm² respectively and were approximately 171%, 116%, 85% and 101% higher than the UCS values recorded for the unreinforced soil. This is an indication that reinforcing CBLS composites with PPF can efficiently improve the UCS.

The STS of the reinforced CBLS increases with increasing PPF content until it reaches a peak at 0.40% PPF content beyond which it reduces (Figure 14). The progressive increase in STS behaviour to a peak is similar to that of the UCS. The STS values recorded for the unreinforced CBLS at the optimum R-HPC content were 0.040N/mm², 0.13N/mm², 0.18N/mm² and 0.23N/mm² respectively for 4days, 11days, 18days and 32days.

The Peak STS values recorded for the CBLS composites reinforced with PPF content of 0.40% after 4days, 11days, 18days and 32days curing were 0.224N/mm², 0.340N/mm², 0.440N/mm² and 0.522N/mm² respectively and were approximately 460%, 158%, 140% and 124% higher than the STS values recorded for the unreinforced soil. This is an indication that the high tensile strength of PPF material makes it a better reinforcing material to improve upon the tensile strength of CBLS composites. Similar trends were observed by Chore et al., (2015) and Mei and Xu (2016) suggesting that the optimum PPF content which yields the maximum strengths varies with soil type, PPF type and cement content.

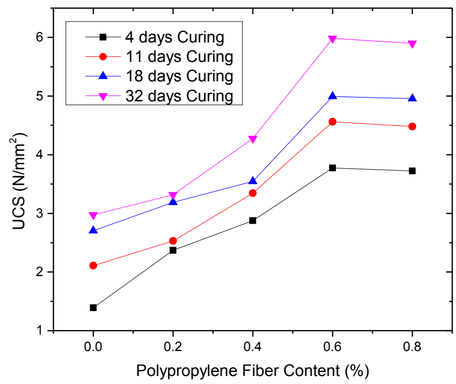

Figure 13. Variation of PPF content with UCS of reinforced CBLS composites

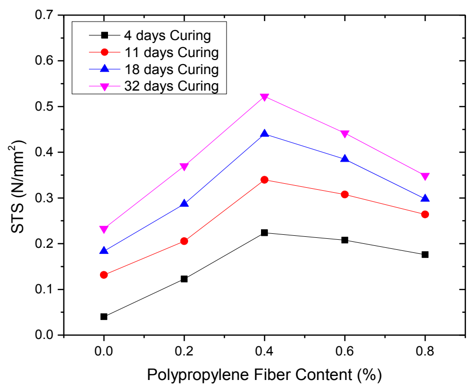

Figure 14. Variation of PPF content with STS of reinforced CBLS composites

The significant gain in UCS and STS values with increasing PPF content and curing age is as a result of the high tensile strength of PPF material. Under compressive and tensile stress, PPF in reinforced CBLS act like tree roots and spread tensile stress to a wider area whiles the shear strength at contact area within PPF-CBLS matrix prevent the relative movement (slide) and restricts the PPF from being pulled out. This results into the sustenance of higher stresses compared to unreinforced CBLS.

3.3 *Failure Characteristics*

Based on visual observations in the laboratory, two main failure modes were observed after the compression and tensile tests (Figure 15).

The unreinforced CBLS specimen failed by shearing with wide-spaced cracking appearing throughout the entire height and diameter of the compressed and tensioned specimen respectively and suggested a brittle failure. Whereas, the reinforced CBLS failed by bulging with narrower and shorter cracks spread across the entire height and diameter of the compressed and tensioned specimen. Plastic failure mode was observed with reinforced CBLS composites. The reduced crack width in the reinforced CBLS, could be attributed to the bridging effect phenomenon of the PPF material. Under compression and tension loading, the PPF in the reinforced CBLS acted as bridges between crack openings, and restricted the expansion of the cracks. As a result, narrower, shorter cracks occurred in reinforced CBLS.

Unreinforced CBLS composites recorded largest crack width of approximately 1.50cm and 0.90cm under compression and tensile failures respectively. Whiles reinforced CBLS at optimum PPF contents under compression and tension failures recorded the least crack widths of approximately 0.20cm (0.60%PPF) and 0.10cm (0.40%PPF) respectively. Cracks in reinforced CBLS were mostly on the surface and does not penetrate through the entire length and diameter of the reinforced CBLS composites.

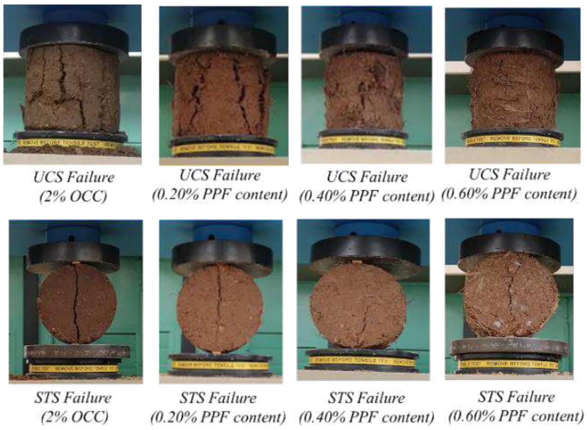

Figure 15. Failure Modes observed in testing UCS and STS of unreinforced and reinforced CBLS composites

4 CONCLUSIONS

Some of the conclusions deduced from the present study are as follows:

1. The study soil is a competent natural lateritic material that can be used for the construction of cement stabilized base pavements (As per MRH, 2007).
2. MDD of CBLS composites increases but OMC decreases with increasing R-HPC content. The MDD of reinforced CBLS, however, decreases whiles the OMC increases with increasing PPF content.
3. UCS and STS of unreinforced CBLS increases with increasing cement content, however, the UCS of reinforced CBLS increased to an optimum PPF content of 0.60% beyond which it slightly reduces. Whereas STS increased to an optimum PPF content of 0.40% beyond which it reduced.
4. UCS and STS of unreinforced and reinforced CBLS increases with increasing curing age. The UCS and STS values after 32 days curing were all higher than the UCS and STS values after 4days curing.
5. PPF can be effectively used to reduce cracking in CBLS base pavements. Reinforced CBLS recorded least crack widths under compression and tensile failures.

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