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Free Swelling and Modulus of Elasticity of Compacted Black Cotton Soil Treated with Reclaimed Asphalt Pavement

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ABSTRACT

Black Cotton Soil (BCS), collected from Numan, in north-eastern region of Nigeria was stabilized with Reclaimed Asphalt Pavement (RAP), collected from failed road surface, along Minna-Bida road in Niger state Nigeria. The BCS was replaced with RAP at 0%, 10%, 20%, to 100% by weight of the soil. X-ray diffraction test on the BCS revealed predominantly, presence of quartz, microcline, albite and kaolinite, while that of RAP shows quartz, albite, orthoclase, phylogopite and actinolite. Maximum Dry Density (MDD) of the mixtures increased from 1890kg/m^3 at 0% RAP content to maximum value of 2036kg/m^3 at 30% RAP, after which the value reduced to 1925kg/m^3 at 100% RAP. Scanning Electron Microscopy showed fewer cracks in mixture with 20 and 30% RAP contents, rather an interlocking of particles of different sizes in a very dense state was revealed. Unconfined Compressive Strength (UCS) increased from 392kN/m^2 at 0% RAP to 947kN/m^2 at 30% RAP content, representing 58.6% increase. The values, thereafter, reduced to 17.5kN/m^2 at 100% RAP content. Modulus of Elasticity increased from 10.4Mpa at 0% RAP to 42.5MPa at 30% RAP, representing 75.5% increase. The values, thereafter, reduced to 2.9MPa at 100% RAP content. The swelling potential of the mixtures reduced from medium at 0% RAP content to low at 30% RAP content.

1. Introduction

Generally, expansive clay soils have been a major problem to foundation engineers. This problem emanated from the nature of the expansive clay minerals present in the soil [1-5]. These minerals which varies from kaolinite through illite to montmorillonite, causes adverse swelling with ingress of water and shrinkage with removal of water, a process which causes serious dynamic instability on light structures founded on such soils.

BCS is one of those problematic clay soils found in many parts of the world. Large deposits of BCS exist in the north-eastern part of Nigeria and also have the problem of causing serious damages to road pavement structures and light building structures founded on them. These soils cannot also be borrowed for use in any component of road pavement structure or fill of any sort because of their soft and swelling characteristics. A lot of researches have been carried out [6-9] to evaluate the swelling characteristics of clays including BCS. Other similar researches attempted to correlate swelling characteristics with consistency limits [10 and 11] to ease the process of evaluating swelling properties and reduce the time required to conduct the real swelling tests. The cost of damages that have been caused by BCS in various parts of the world as reported by various researchers was recorded by Gidigasu and Gawu [1].

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Table 1: Estimated cost of damages due to undesirable swelling/heave of expansive soils

Country	**Amount**
Britain	3 billion (2001)
China	100 million
France	3.3 billion (2002)
India	Several lakhs of rupees
Saudi Arabia	>US$300 million (1977 and 1987)
Sudan	>US$6 million (1983)
United State of America	US $2 billion (annually)

Sources: Gidigasu and Gawu [1]

In order to avert these damages, a lot of research has been conducted to modify or stabilize BCS using various additives to improve its swelling-shrinkage characteristics, physical, and geotechnical properties. Some researchers [3, 4 and 12] used lime to either modify or stabilized the soil. The authors recorded improvement in the physical and to some extent, geotechnical properties of BCS. Some other researchers [13-20] worked on admixture stabilization of BCS using mixtures of lime, fly ash, rice husk ash, sugarcane bagasse ash, electric arc furnace dust and stone dust. These materials were used individually and mostly in conjunction with lime to improve the physical and geotechnical properties of BCS. All these authors recorded measurable improvement in the properties of the soils. Efforts were also made by some authors to reduce the swelling-shrinkage characteristics of clay soils [21, 22 and 23].

During maintenance or reconstruction of asphaltic pavement surfaces, including roads and air fields, a lot of Reclaimed Asphalt Pavement (RAP) is removed from the failed surfaces. While the technology for reuse of this material is advanced in most developed countries, its reuse is very limited in most African countries including Nigeria, where the material is rather allowed to litter the environment. RAP contains aggregates which can improve the stability of deficient clay soils and bitumen which gives adhesive properties to soil and coat the surfaces of the particles. This contributes to the strength of the soil and delay in percolation of water in to the fine soil particles. The use of RAP to stabilize soils has double profit of protecting the environment and minimizing the cost of fill.

A lot of studies have been carried out on the possible use of RAP to improve the physical and geotechnical properties of deficient clay soils [24-29]. Some of these studies used Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) to confirm the microstructural processes that led to the results observed Garach *et al* [30], Wu and Zong [31] and Hoy *et al*, [32]. All these studies showed positive results, indicating the possibility of using RAP to enhance the performance of BCS. However, none of these studies focused on the effect of RAP on the free swelling of BCS.

The aim of this research is to study the microstructure of compacted mixtures of BCS and RAP towards evaluating the effect of RAP on the free swelling and modulus of elasticity of the BCS.

2. Methodology

The BCS used in this study was collected from Numan in Adamawa State of Nigeria. The soil sample was prepared according to the method highlighted in BS 1377 [33]. The RAP used was collected manually along Minna-Bida road in Niger State, Nigeria. It was dried and pulverized to pass through British Standard sieve 5.0 mm before being used.

Physical and some geotechnical properties tests were conducted on the disturbed and remoulded BCS at standard proctor compaction energy level. However, only grading and extraction tests were carried out on the RAP material. The BCS properties tested include grain size analysis, Atterberg limits, compaction test, triaxial compression test and consolidation tests.

The grain size analysis which are mechanical sieve analysis and hydrometer analysis were conducted in line with the method highlighted in BS 1377 [33] to obtain the composition of gravel, sand, silt and clay contained in BCS sample. The Atterberg limits were also carried out in conformity with the method contained in BS 1377 [33] to obtained the consistency limits so as to classify the clay under Unified soil classification (USCS) and AASHTO soil classification systems. In a similar manner, preliminary compaction test was carried out on the clay soil to obtain the compaction characteristics which were used to mould the soil for preliminary triaxial compression test and consolidation tests. The triaxial compression test gave the preliminary shear strength parameters and modulus of elasticity of the clay. The consolidation test however, gave the preliminary compression index of the BCS.

The grading test on the RAP is to obtain the grain size composition while the extraction test which was conducted using the method highlighted in BS 2343 1997, is to obtain the bitumen content of the RAP. X-ray Diffraction was also carried out in National Geosciences Research laboratory of the Nigeria Geological Survey Agency (NGSA), Kaduna, Nigeria (NGRL/OP/5334/2017/0049) on the natural BCS and RAP only. This will furnish the predominant minerals composed in these materials.

The method involves heating the RAP openly on a stove to 100˚c with continues stirring while using thermocouple to measure the temperature during the heating. This temperature is far above the melting temperature of asphalt which is 60^0C. The heating allowed some of the bitumen which had remained bound to the aggregates to melt away from it. The hot RAP was then removed from the stove and immediately mixed with a finely grounded BCS so as to allow the melted bitumen to coat some of the clay particles and lumps. It was then used to replace the BCS at ratios of 0:100, 10:90, 20:80, 30:70, 40:60, 50:50, 60:40, 70:30, 80:20, 90:10 and 100:0. Compaction test was carried out at modified energy level on all the mixtures using the method highlighted in BS 1377 [33]. For small scale construction or maintenance, this mixture can be made manually on site by heating the RAP in large drums to the required temperature after which it is mixed with BCS before placement and subsequent compaction.

Scanning Electron Microscopy (SEM) was also carried out in Chemical Engineering Department, Ahmadu Bello University, Zaria, Nigeria, on the compacted specimens of all the mixtures. This is to visualize the compacted state of all the mixtures.

The UCS tests and modulus of elasticity (E) tests were also conducted on the BCS-RAP mixtures compacted at modified energy level using 50mm diameter and 100mm length of soil specimen.

Fig. 1: Unconfined compressive strength test

Free swelling test (Fig. 5) was also conducted on the compacted mixtures using the method highlighted in the United State Department of Housing and Urban Development code. This was to evaluate the effect of RAP on swelling potential of the BCS.

Fig. 2: Free swelling test

3. Results and Discussions

3.1 *Geotechnical Properties*

From table 2, the BCS classified under clay of high plasticity (CH), according to Unified Soil Classification System (USCS). This implies that the soil cannot be used for any component of road structure and will therefore require stabilization to improve its strength and durability properties.

Table 2: Geotechnical properties of natural BCS and RAP

Description	**Quantity**	
	BCS	RAP
Gravel (%)	0.0	7.6
Sand (%)	42.8	86.0
Silt (%)	34.9	6.4
Clay (%)	22.3	-
Liquid Limit	52.4	-
Plasticity Index	26.3	-
Specific gravity	2.49	2.01
MDD (kg/m^3)	1890	1925
OMC (%)	13.7	8.0
Classification (USCS)	CH	SP
Classification (AASHTTO)	A-7-6	A-1-a
Cohesion (C) kN/m^2	32.0	-
Angle of friction (Φ) deg.	3.0	-
Modulus of elasticity (E) MPa	5.714	-
Compression Index (C_c)	0.449	-

The grain size analysis of the RAP showed coefficient of uniformity of 6 and coefficient of curvature of 1.63. This shows that the RAP is uniformly graded. It classified under A-1-a according to AASHTTO soil classification system and SP according to USCS. The grading composition of the RAP can therefore enhance the stability of the BCS.

The 6.4% fine recorded in RAP is higher than the 0.83% recorded by Edeh *et al* (2012) [27] and is probably due to the method of RAP collection, which must have allowed fines from the road base to stick to the collected RAP. The specific gravity of BCS-RAP mixtures showed decrease with increase in RAP content down to 100% RAP content. The value of specific gravity recorded for 100% RAP is within the 1.94-2.30 specified by FHWA [34] for RAP materials.

From the analysis of the triaxial compression test, it was observed that the angle of internal friction Φ, the cohesion C and the modulus of elasticity E are 3^0, 32kN/m^2 and 5.714MPa respectively. These values agree with result of other clay soils in literatures.

The analysis of results of one-dimensional consolidation showed that the compression index is 0.449 which implies large magnitude of settlement on application of load.

3.2 *Extraction Test*

Result of the extraction test conducted on the RAP shows the bituminous content to be 5.99%, which is within the value of 5 – 6% reported by Mishra [28] for most RAP materials.

3.3 *X-Ray Diffraction Test*

Results of the X-ray diffraction for both the BCS and RAP are shown in Figs. 3 and 4 respectively.

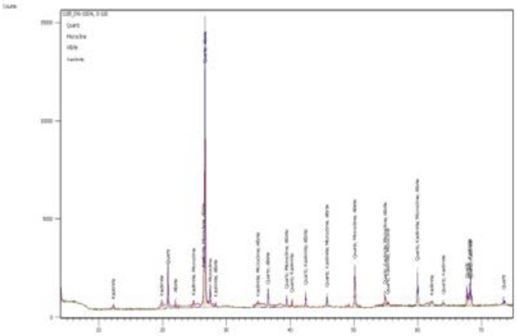


Fig. 3: X-ray Diffraction result for BCS

The BCS consists predominantly of quartz, microline, albite and kaolinite. This result is similar to XRD results obtained by Ogundalu and Oyekan [2] for black cotton soils in Nigeria. The RAP however, consists of quartz, albite, othorclase, phlogopite and actinolite. This is slightly different from XRD results of RAP obtained by Hoy *et al* [32] which include calcium–magnesium, dolomite, quartz, calcite, mullite, hematite and calcium sulphate. Some of these elements are contained in the complex actinolite, which contains Fe, Mn Mg, Ca, Na, Si, Al, K, H, O, F and Cl. The source of the RAP used in the study can also affect its mineralogical composition.

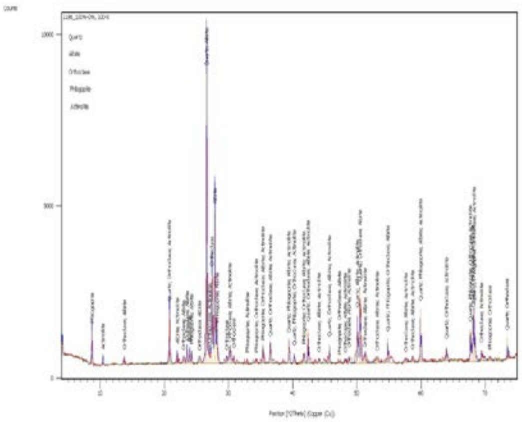


Fig. 4: X-ray Diffraction result for RAP

3.4 *Compaction Characteristics*

The MDD and optimum moisture content (OMC) of BCS-RAP mixtures is shown on Fig. 5. The MDD increased from 1890kg/m^3 at 0% RAP content to 2036kg/m^3 at 30% RAP content, after which the values reduced down to 1925kg/m^3 at 100% RAP. This trend is common for most mechanical stabilization of clay soils [34].

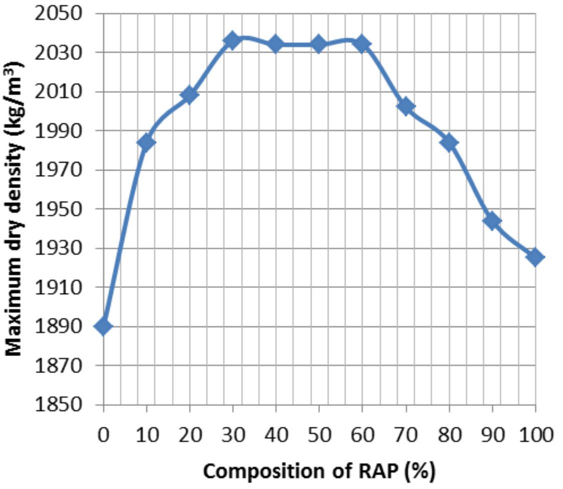


Fig. 5: Variation of MDD with varied amount of RAP

Addition of RAP to the BCS is the same as adding aggregate and bitumen to the mixture which has high and low specific gravities respectively. The aggregate will increase the MDD, while the bitumen will tend to reduce it. Reduction of the MDD observed at RAP content beyond 30% showed that the low specific gravity bitumen becomes substantial and tend to overcome the presence of aggregate contained in the RAP. The bitumen content of the mixture containing 30% RAP is 3.07% and is termed the fixation point for RAP-BCS mixtures [32]. This value is lower than the 3.5% recorded by Hoy *et al* [33] at 50% RAP-50% soil.

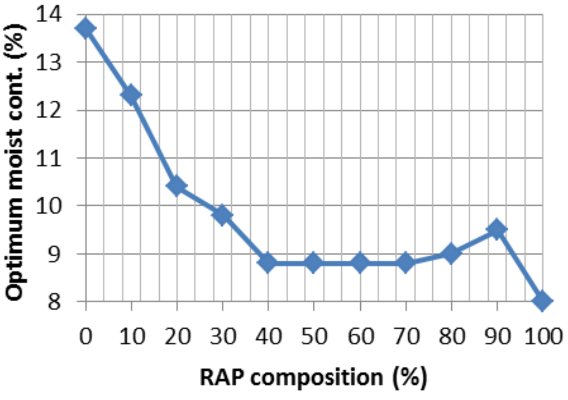


Fig. 5: Variation of OMC with varied amount of RAP

The OMC undergoes reduction from 13.7% at 0% RAP content to 8.8% at 40% RAP content. This continued at 8.8% to 70% RAP content after which it increased slightly to 9.5% at 90% RAP content. The value reduced to 8.0% at 100% RAP content. The initial reduction must have resulted from the increased BCS coating by bitumen. Beyond 40% RAP content replacement, all BCS has been coated with bitumen which makes the OMC to be constant. The slight increase in OMC observed beyond 70% RAP content can be attributed to the poor gradation of the mixture, which must have created extra pore spaces that is filled by the moisture.

3.5 *Scanning Electron Microscopy (SEM) of Compacted Mixtures*

The SEM of the compacted mixtures of RAP and BCS are shown in Figs. 6 to 11.These pictures are similar to the SEM pictures of clay presented by Patricio *et al* [35], Mohanty *et al* [36], Muhmed and Wanatowski [37], and SEM pictures of RAP presented by Hoy *et al* [32], Wu and Zong [31], Du [38] and Paige-Green [39].

The microstructure of the compacted specimen of BCS showed fine crystals of particles with visible cracks as observed by Paige-Green [39]. These cracks were more pronounced in 10% RAP–90% BCS. The SEM pictures of 20% RAP–80% BCS and 30% RAP–70% BCS do not show these cracks but rather an interlocking of particles of varied sizes in a very dense state. This is probably responsible for the maximum MDD that was observed at 30% RAP–70% BCS. The cracks reappeared in 40% RA–60% BCS down to 70% RAP–30% BCS. Beyond 70% RAP, interlocking arrangement of particles reoccurred but with substantial amount of bitumen.

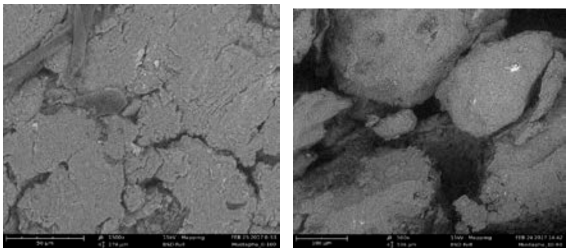

(a) (b)

Fig. 6: SEM pictures of compacted mixtures at
(a) 0% RAP-100% BCS, (b) 10% RAP-90% BCS

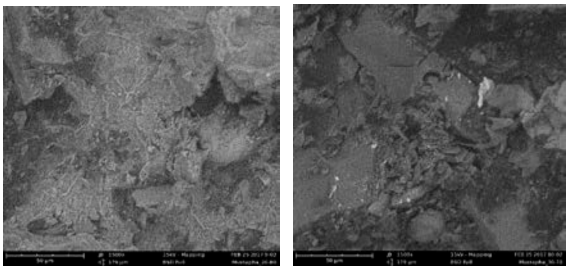

(a) (b)

Fig. 7: SEM pictures of compacted mixtures at
(b) 20% RAP-80% BCS, (b) 30% RAP-70% BCS

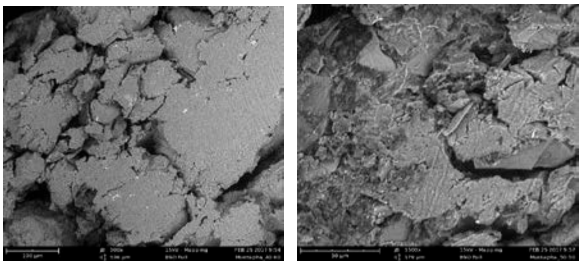
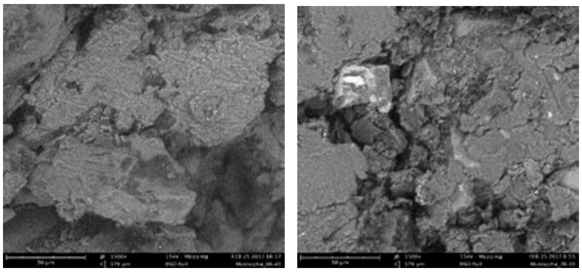
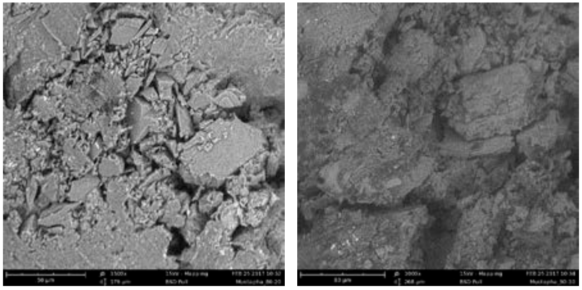

(a) (b)

Fig. 8: SEM pictures of compacted mixtures at
(a) 40% RAP-60% BCS, (b) 50% RAP-50% BCS



(a) (b)

Fig. 9: SEM pictures of compacted mixtures at (a) 60% RAP-40% BCS, (b) 70% RAP-30% BCS



(a) (b)

Fig. 10: SEM pictures of compacted mixtures at 80% RAP-20% BCS, (b) 90% RAP-10% BCS

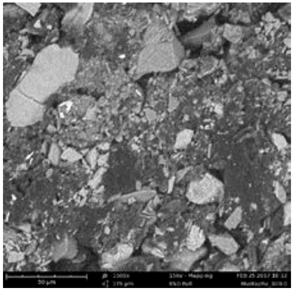


Fig. 11: SEM pictures of compacted mixture at 100% RAP-0% BCS

3.6 *Unconfined Compressive Strength (UCS) of the Compacted Mixtures*

The peak of the stress-strain curves shown in Fig.15 represents the UCS of the compacted specimens. The values increased from 392kN/m^2 at 0% RAP content to 947kN/m^2 at 30% RAP–70% BCS. Beyond 30% RAP-70% BCS mixture, the values reduced to 17.5kN/m^2 at 100% RAP content. The initial increase is attributed to the introduction of aggregates into the clay which improved the grading of the mixture. This kept improving up to 30% RAP–70% BCS, where appropriate aggregate void spaces Were available to be filled by the fine BCS.

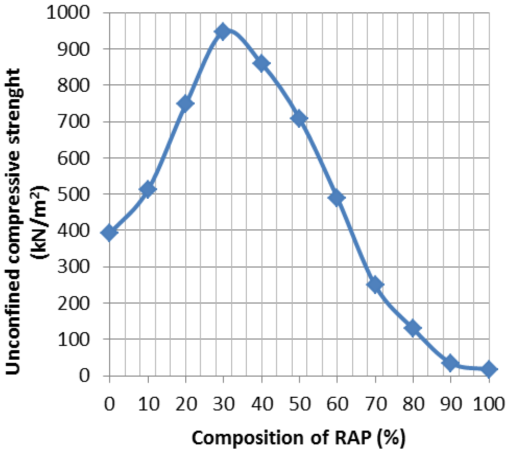


Fig. 12: Variation of UCS with varied composition of RAP

The amount of adhesion mobilized by the plastic BCS in the mixture at this proportion was optimal, hence the maximum UCS recorded. This represents 58.6% increase in UCS of compacted mixtures at optimal RAP content of 30%.

The UCS value is related with percentage RAP by the relationship:

$$UCS = 0.0051(RAP\%)^2 - 0.9791(RAP\%)^2 + 43.5(RAP\%) + 301.5 \quad (1)$$

The coefficient of determination R^2 is 0.956.

3.7 *Modulus of Elasticity of Compacted Mixtures*

The Modulus of elasticity of the compacted

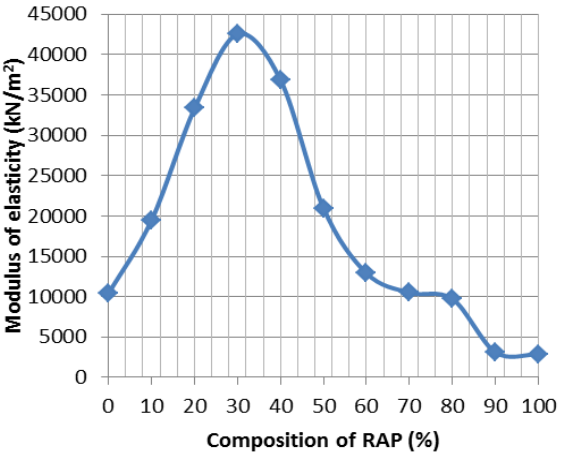


Fig. 12: Variation of modulus of elasticity with varied composition of RAP

mixture increased from 10.4Mpa at 0% RAP content to 42.5MPa at 30% RAP-70% BCS, representing 75.5% increase. Thereafter, it is reduced to 2.9MPa at 100% RAP content. The modulus of elasticity values are related with percentage RAP by the relationship:

$$E = 0.2841(RAP\%)^2 - 50.6(RAP\%)^2 + 2183.5(RAP\%) + 8162 \qquad (2)$$

The relationship has coefficient of determination, $R^2$of 0.956.

3.7 *Swelling Characteristics*

Results of the free swelling test of the compacted BCS–RAP mixtures are shown in Fig. 16. The expansion potential reduced from 16.08% at 0% RAP to 0% at 80% RAP content. Beyond 80% RAP content, the compacted mixtures, instead of swelling, began to undergo compression from 0.9% at 90% RAP to 1.25% at 100% RAP. This is because the little BCS contained in the mixtures have been coated with bitumen and could not absorb water, resulting to the mixture behaving more like saturated cohesion less soil.

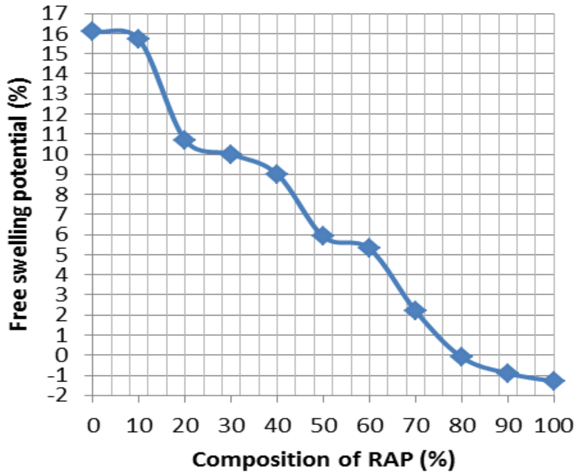


Fig. 13: Variation of swell potential with varied composition of RAP

The potential swelling value of 9.99% at optimal mixture of 30% RAP-70% BCS translates to 37.9% reduction. These values signifies swelling potential moving from medium at 0% RAP-100% BCS to low at 30% RAP-70% BCS. This action will contribute to the stability and durability of BCS-RAP mixture

4. Conclusions

1. Based on USCS and AASHTTO soil classification systems, the BCS classified under CH and A-7-6 respectively, while the RAP falls under SP and A-1-a respectively.
2. Maximum MDD of 2036kg/m^3 was recorded at 30% RAP–70% BCS. The microstructural view of the compacted specimens of this mix ratio, through SEM showed the best compact interlocking arrangement of the mixture.
3. The optimal UCS value of 947kNm^2 was recorded at optimal mixture of 30% RAP-70% BCS, which represents 54.5% increase. These values were found to correlate with percentage RAP with

$$UCS = 0.0051(RAP\%)^2 - 0.9791(RAP\%)^2 + 43.5(RAP\%) + 301.5$$

with correlation factor of 0.956.

4. A maximum modulus of elasticity (E) of 42.52MPa was also recorded at 30% RAP – 70% BCS representing 75.5% increase in E. These values also correlate with RAP with

$$E = 0.2841(RAP\%)^2 - 50.6(RAP\%)^2 + 2183.5(RAP\%) + 8162$$

and having R^2 to be 0.897.

The free swelling of the compacted mixtures reduced from 16.08% at 0% RAP to 0% at 80%, with 9.99% at optimal mixture of 30% RAP content, translating to 37.9% reduction in free swelling.

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