Laboratory Assessment of Metakaolin Effect on the Volumetric Shrinkage of Black Cotton Soil for Flexible Pavement Construction

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Abstract

A dark grey Black Cotton soil treated with up to 24% Metakaolin content was compacted using British standard light (BSL),West African standard (WAS) or "intermediate"and British standard heavy (BSH) compactive efforts at moulding water contents -2, 0, 2, 4 and 6% of optimum moisture content. Specimens where extruded from compaction moulds and allowed to air dry on the table in the Laboratory in order to assess the effect of Volumetric Shrinkage on the material for use in Flexible Pavement construction. Results recorded showed that Volumetric Shrinkage strain (VSS) values were large within the first 5 days of drying; VSS values increased with higher moulding water content,water content relative to optimum. Generally, the Metakaolin improves the Shrinkage properties of the expansive soil irrespective of the compactive effort. Volumetric Shrinkage potential reduced by about 76%, 61% and 42% at 24% Metakaolin for the WAS, BSL and BSH compactive efforts respectively, as compared to the Virgin soil. It can be concluded that the Metakaolin had shown promising influence on the Shrinkage properties of expansive soil, thereby giving an advantage in improvement of problematic expansive soils.

Keywords: Expansive soil, Volumetric Shrinkage Strain, Metakaolin, Compactive effort,Moulding Water content, Flexible Pavement.

Introduction

Expansive soils are a world wide problem, and they undergo considerable amounts of volume changes due to moisture content fluctuations either as a result of seasonal climatic variations (cyclic dry and wet periods) or artificial causes (Nelson and Miller,1992). Typically,these volume changes of expansive soils cause considerable distress to Civil infrastructures founded on them (Pedarla *et al.*;2011).Hence, it is important to appropriately estimate the total volume change potentials of these soils,from both swell and shrink related movements, thus enabling us to better characterize the nature of the subsoils, and explore appropriate treatment or modification methods to reduce the volume changes tendency of these soils. In Nigeria,one problematic soil which exhibit expansive behaviuors is the black Clay (Black Cotton Soils) occupying an estimated area of 104,000km^2 and are typically found in the North Easthern region of the country such as Borno, Gombe, Adamawa, Yobe and Taraba States. This volumetric problem is well pronounce at Deba in Yamaltu/Deba Local Government Area(LGA) of Gombe state,as evident in cracks on buildings and roads within the town. Ola(1983) reported 70% montmorillonite in the Nigerian black cotton soils. The soil therefore swells excessively when it absorbs water during the wet season, exerting many Kilo-Newton per square area of swelling pressure and shrinks extremely, developing cracks,because of evaporation of water during the dry season. Adeniji,(1991) reported that cracks,often measuring 70mm wide and 1.0m deep may develop when the soil shrinks and may extend up to 3.0m in case of high deposits. Similarly,when wet,the soil has high index properties,its bearing value and strength is low.

This dual characterstic of the expansive soil causes distress in the structures founded on them. An estimate of the damages caused by expansive soils on Civil engineering structures in the form of swelling and shrinkage that cost billions of dollars are reported in various parts of the world (Al-Rawas,1991;Erguler and Ulusay,2003;Gourlay *et al.*,1993;Nelson and Miller,1992;Ramana,1993;Shi *et al.*,2002). In the North Eastern part of Nigeria where these soils are found,construction of roads generally poses a great problem because of high volume change,low bearing value and severe cracking during dry and wet season.The lack of good drainages and construction materials couple with large volume of traffic most of which are overloaded further complicates the problem. To control the severity of distress caused on structures founded on these soils, many different modification and stabilization techniques with additives such as lime and fly ash have been applied.(Osinubi,1995; Basma *et al.*,1991;Chummar, 1987;Desai *et al.*,1977). The effectiveness of lime and cement in treatment of cohesive soils with expansive properties have been reported,(Chen,1988; Hausmann,1990; Osinubi,1995). These chemical additives have been found effective in improving expansive properties such as the control of volume change,increase strength,decrease plasticity index and swell shrinkage strain potential of expansive soils and fine-grained cohesive soils.(Hausmann,1990;Osinubi,1998a,b;1999a,b; Osinubi and Katte,1977;1999).

Pozzolan can improve a soils physical characteristics/index properties; it can provide an array of divalent and trivalent cations under ionized conditions; promoting flocculation of dispersed clay particles. It has the potential to reduce swelling and cracking of expansive soils.(Cocka,2001; Graber *et al*.,2006).Reducing plasticity and shrink-swell potential of fine grained soils is also a common objective.(Nicholson *et al*.,1993; Cocka,2001).The stabilized material typically is more stronger and more durable.(Pandian and Krishma,2003;Trzebiatowski *et al*.,2004).Like fly ash, rice husk ashes, Metakaolin etc. possess pozzolanic properties in measures and can be therefore applied in the field of Civil engineering.

Metakaoilin is a highly pozzolanic,reactive and supplementary cementatious material that conforms to ASTM C 618 and AASHTO M295 specification. It is unique in that it is neither the by product of an industrial process nor is it entirely natural. Metakaolin is derived from naturally occurring mineral and is manufactured specially for cementing applications; it is refined kaolin clay that is fired (calcined) under carefully controlled conditions to create an amorphous aluminosilicate that is reactive in concrete and is obtained by calcination of the kaolinitic clay at temperatures 600 – 800°C (Equ. 1). (Salvador,1995; Zampieri,1989). The chemical equations describing this process is

$$\underset{\text{Kaolin}}{AL_2Si_2O_5(OH)_4} \xrightarrow[\textbf{Heat}]{600-800\ ^0C} \underset{\text{Metakaolin}}{AL_2O_3.2SiO_2 + 2H_2O} \qquad (1).$$

2.0 Materials and Methods

2.1 Materials.

2.1.1 Soil : The soil sample used in this study (dark grey in colour) was obtained along the Gombe-Biu road in Yamaltu/Deba Local Government Area of Gombe State,Nigeria, using the method of disturbed sampling. The location falls between Latitude 10^o 12^I N and Longitude 11^o 23^I E.

2.1.2 Metakaolin : The Kaolin used for the production of the Metakaolin was obtained locally from Chikun Local Government Area of Kaduna State, Nigeria and heated to 600 – 800°C in a Kiln of the Kaduna Bricks and Clay products Limited,KM 15,Kachia road, Kaduna, Nigeria. According to ASTM C618 (2005),the minimum amount of SiO_2, AL_2O_3 and Fe_2O3 that needs to be present in a class N Pozzolan is 70%. From the Oxide composition of the Metakaolin used as shown in Table 2; and as determined by the method of Energy dispersive X-Ray Flourescence (XRF) of the Nigerian Geological Survey Agency, Kaduna, Nigeria. From the Oxide composition the amount of these compounds is approximately 95%, this is an indication that the material is highly reactive.

2.2 Methods.

2.2.1 Index Properties : Laboratory tests were conducted to determined the index properties of the natural Soil and Soil-Metakaolin mixtures in accordance with BS 1377,1990a;BS 1924;1990b, respectively.

Compaction : Three compactive energies namely British standard light (BSL),West African standard (WAS) or "intermediate" and British standard heavy (BSH) were performed on the natural Soil and the Metakaolin treated Soils. Air dried Soil Samples passing through British Standard Sieve with 4.75mm aperture mixed with 0%, 4%, 8%, 12%, 16%, 20% and 24% Metakaolin by weight of dry Soil were used. British Standard light and British Standard heavy compactive efforts were carried out in accordance with BS 1377(1990).The BSL Compactive effort was derived from a Hammer weighing 2.5kg falling through 30cm onto 3 layers each receiving 27 blows. In the case of WAS compaction (Nigerian General Specification for Bridges and Road Works,(1997) the energy exerted was derived from a 4.5kg Hammer falling through 45cm onto 5 layers, each receiving 10 blows, while for the BSH compaction, the energy applied was obtained from a 4.5kg Hammer falling through 45cm onto 5 layers each receiving 27 blows.

2.2.2 Volumetric Shrinkage : The Volumetric Shrinkage upon drying was measured by extruding cylindrical specimens compacted using the three compactive efforts above on well mixed Soil-Metakaolin mixtures 0% (natural Soil), 4%, 8%, 12%, 16%, 20% and 24% (Metakaolin contents) at five different moulding water content ie; 2% dry of optimum (-2), optimum moisture content (0), 2% wet of optimum (+2), 4% wet of optimum (+4) and 6% wet of optimum (+6), from the compaction moulds. The extruded cylindrical specimens were air dried on a Laboratory table at a uniform temperature of 24± 2°C for a period of 30 days.Three measurements of diameter and height,for each specimen were taken and recorded every 5 days with the aid of an electronic digital Vernier Calliper accurate to 0.01mm. At each reading a minimum of three height and three diameter measurements for each height at 120^0 intervals were recorded. The average diameters and heights were used to compute the Volumetric Shrinkage Strain using the following expression :

$$VSS = \frac{(V_O - V_f)\times 100}{V_0} \qquad (2)$$

Where;
VSS = Volumetric shrinkage strain.
V_o = Original volume of moist compacted cylindrical specimen.
V_f = Final volume of dry compacted cylindrical specimen.

3.0 Results and Discussion

3.1 Properties of materials.

The index Properties of the natural Soil show that it is an A-7-6 Soil according to AASHTO classification system (AASHTO,1986),Clay with high plasticity(CH), using the Unified Soil classification system,USCS (ASTM,1992) and High swell potential,Nigerian Building and Road Research Institute (NBRRI,1983). The Soil has a Liquid Limit value of 79.00%,Plastic Limit of 21.00%,Plasticity index of 58.00%,Linear Shrinkage of 21.00% and a Specific gravity of 2.30 with 86.00% of the Soil particles passing the BS NO. 200 Sieve (0.075mm aperture). The predominant clay Mineral is Montmorillonite. The properties of the natural soil are summarized in Table 1, while its Particle size distribution curve is shown in Figure 1. The Specific gravity; G_S of the Metakaolin used in this study is 2.70 and its Oxide composition is given in Table 2.;with its physical properties shown in Table 3.

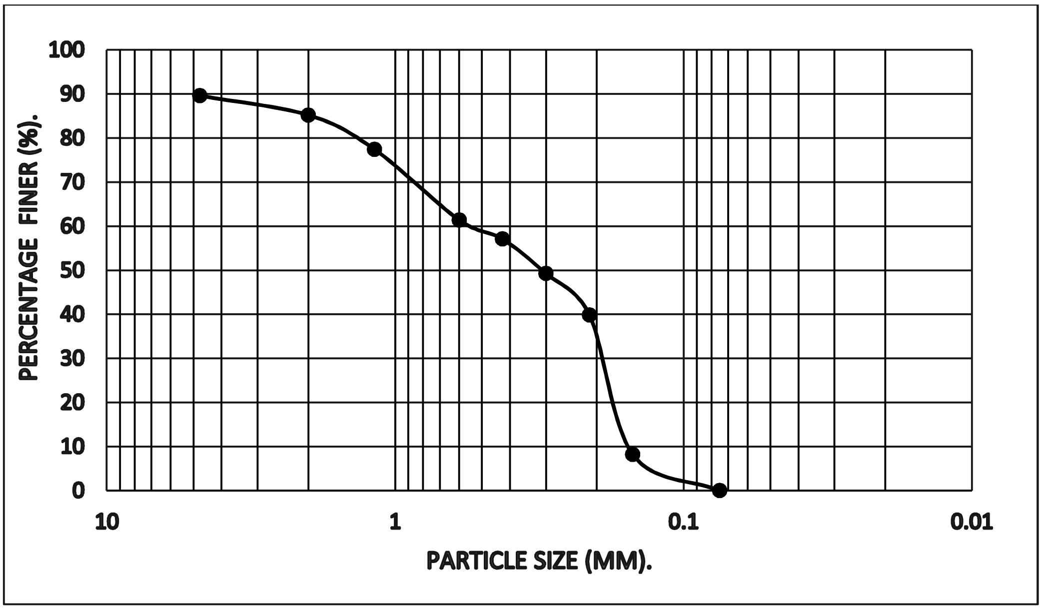

FIGURE 1 : Particle size distribution curve for the natural Black cotton soil.

Table 1 : Properties of the natural black cotton Soil.

Property	Quantity.
Percentage passing BS No 200 Sieve (%)	86.00
Natural moisture content (%)	15.00
Liquid Limit (%)	79.00
Plastic Limit (%)	21.00
Plasticity index (%)	58.00
Linear Shrinkage (%)	21.00
Free Swell (%)	90.00
Specific gravity	2.30
AASHTO Classification	A-7-6
USCS	CH
NBRRI Classification	High swell potential.
Group index	16
Maximum Dry Density (mg/m^3)	-
British standard light (BSL)	1.41
West African standard (WAS)	1.52
British standard heavy (BSH)	1.65
Optimum Moisture Content (%)	-
British standard light (BSL)	30.60
West African standard (WAS)	25.20
British standard heavy (BSH)	20.00
Ph	7.2
Colour	Dark grey
Dominant Clay Mineral	Montmorillonite.

Table 2: Oxide Composition of Metakaolin used.

Oxide	Concentration (%).
Sio_2	57.32
Al_2o_3	23.70
Fe_2o_3	14.03
CaO	0.38
MgO	0.94
SO_3	ND
L.O.I.$^{\Delta}$	1.18
Na_2O	0.38
K_2O	0.65
TiO_2	1.30
P_2O_5	ND
MnO	0.03

***ND = Not detected.** **Δ= Loss on ignition.**

Table 3: Physical Properties of Metakaolin.

Property	Value
Specific gravity	2.70
Fineness	75µm passing
Bulk density (g/cm^3)	1.22
Colour	Reddish brown.
Specific surface area (m^2/g)	850
Physical form	Powder

3.2 COMPACTION CHARACTERISTICS.

Maximum Dry Density.

The variation of the maximum dry density (MDD) of the black Cotton Soil with MKL content is shown in Fig.2.There was a general increase in MDD for the BSL compactive effort, while a decrease in MDD was recorded for the WAS and BSH compactive effort respectively with increase in MKL content. The increase in MDD could be due to the MKL With a higher specific gravity (2.70) compared to that of the natural black Cotton Soil (2.30) occupying the voids within the Soil matrix as well as the flocculation and agglomeration of the Clay particles due to exchange of ions (Yoder and Witczak,1975; Osinubu,2000).The decrease in MDD for the WAS and BSH compactive efforts may be probably due to the fact that for any Soil-additive reaction, there is always a water content required to produce maximum strength (Osinubi,1999a). This trend is in agreement with the findings reported by Lees *et al* (1982); Ola (1991) and Lorliam *et al.*(2012).

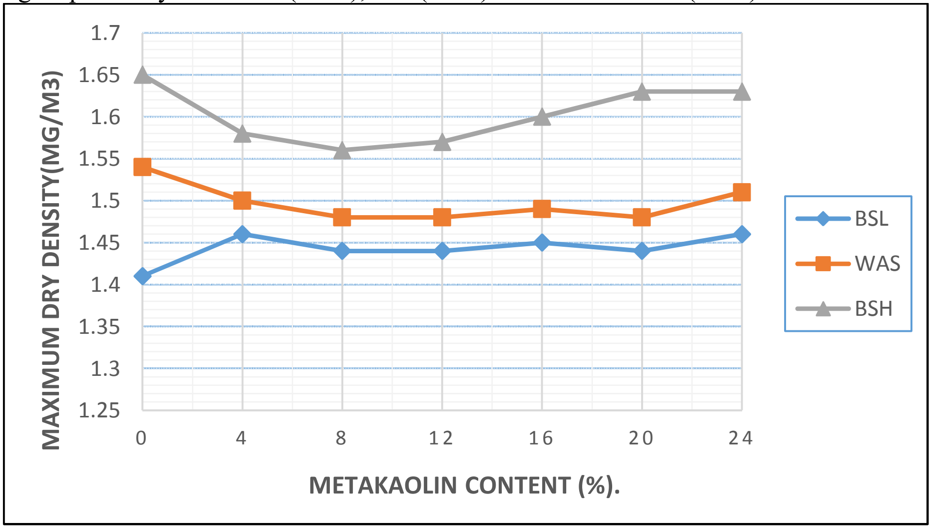

FIGURE 2. Variation of Maximum Dry Density with Metakaolin content.

OPTIMUM MOISTURE CONTENT.

The variation of Optimum moisture content (OMC) of the black Cotton Soil with MKL content is shown in Fig.3. There was a general decrease in OMC for the BSL compactive effort, while an increase was recorded for the WAS and BSH compactive efforts respectively with increase in MKL content. The decrease in OMC could be accounted to the fact that the replacement of soil with MKL content reduces the attraction to water particles. An explanation for this trend was the decrease in OMC with increase in MKL content might be due to Cation exchange reaction that caused the flocculation of Clay particles. The subsequent increase for the WAS and BSH compactive efforts with increase in MKL content could be attributed to the increase in fines content resulting from the inclusion of MKL With a larger surface area which lead to demand for water commensurate with the higher amount of MKL required for its hydration reaction and dissociation needed for cation exchange reaction. These results are in agreement with the findings reported by Ola (1978); Osinubi (1999a); Osinubi and Ijimdiya (2008).

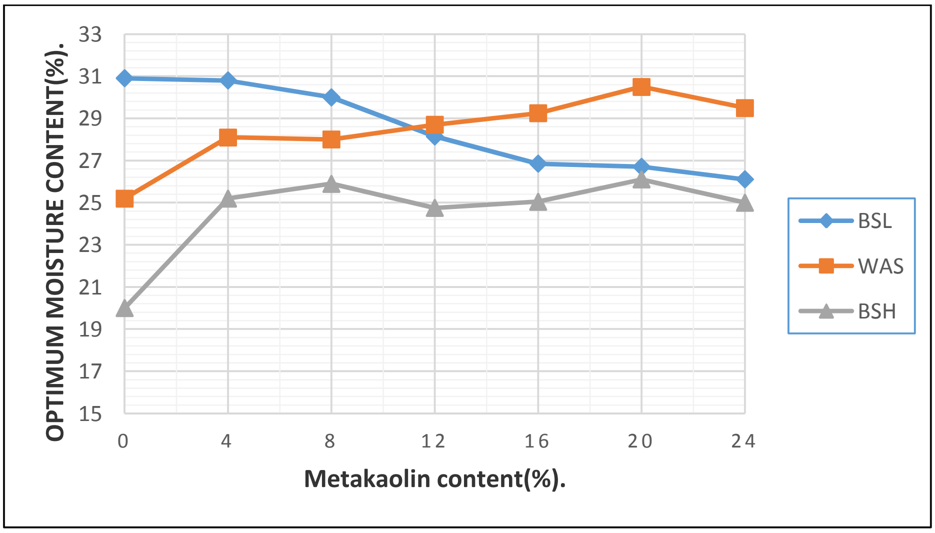

FIGURE 3: Variation of Optimum Moisture content with Metakaolin content.

Changes during drying

The changes in mass that occurred during drying of the compacted cylindrical specimens prepared at various compactive efforts for up to 24% MKL treatment are shown in Fig.4. Generally,in all cases the loss in mass was sharp within the first five days of drying as depicted from the slope of the graphs after which changes in mass were relatively constant until samples were fully dried. Similar results were reported by (Osinubi and Eberemu, 2010, Albrecht and Benson, 2001 and Osinubi and Eberemu,2009.). The changes in mass during drying were unaffected by the Metakaolin treatment and compactive effort although specimens with higher compactive effort plotted above those with lower effort from the plots of changes in mass during drying which is due to the higher dry density generated by higher compactive effort. These results are consistent with those reported by Osinubi and Eberemu, 2010, Albrecht and Benson, 2001 and Osinubi and Eberemu, 2009. The results of volumetric shrinkage strain (VSS) with time at the omc for the various compactive efforts with Metakaolin treatment up to 24% is shown in Fig.5. Results recorded show that the rates of change in volumetric shrinkage strain were generally sharp within the first five days of drying after which the compacted samples reduced gradually and became relatively constant by the tenth-fifteenth day when the samples were fully dried for all the efforts used.These changes were affected by the compactive efforts ie volumetric shrinkage values where higher at lower compactive efforts which is due to the higher moulding water content contained at lower compactive effort since volumetric shrinkage strain is proportional to the moulding water content.This result is also consistent with that reported by Albrecht and Benson, 2001, Das,1998.

Effect of moulding Water content : The variation of volumetric shrinkage with moulding water content is shown in fig. 6. for all the three compactive efforts used and at the various Metakaolin(MKL) treatments. Generally, volumetric shrinkage strain (VSS) increased with higher moulding water content. Specimens compacted at these mouding water contents shrank more during drying in agreement with the results of other reserchers (Osinubi and Eberemu,2010, Albrecht and Benson, 2001,Osinubi and Eberemu, 2009, and Daniel and Wu, 1993). This was so because drying shrinkage in fine-grained soils according to Mitchell, 1976, depends on particle movement as a result of pore water tension developed by capillary menisci, that if two samples of given clay are at the same initial water content but different fabrics, the one that is the more deflocculated and dispersed shrinks most; which is due to average smaller pore sizes,allowing greater capillary stresses and easier relative movement of particles and particle groups. Furthermore,samples compacted at higher moulding water content, had more water in their void spaces that resulted in higher shrinkage on drying since volumetric shrinkage is proportional to the quantity or volume of water leaving the pore spaces. This was explained by Haines. describing the drying process of saturated soils. For the natural soil ie 0% Metakaolin (MKL) compacted between -2 to +6 of the OMC and in all cases of Metakaolin treatment and compactive efforts the volumetric shrinkage increased with higher moulding water content as shown in Fig.6. For the natural soil between 28.60% - 36.60% moulding water content; volumetric shrinkage strain ranged from 22% - 31.79%, at BSL compactive effort, moulding water content between 23.20% - 31.20%, 18.00% - 26.00% has volumetric shrinkage strain of between 24.0% - 27.58%, 19.00% - 22.97% WAS,BSH compactive effort respectively. Treatment of soil with 4% Metakaolin and moulding water content of between 28.80% - 36.80%, 26.10% - 34.10%,23.20% - 31.20% yielded volumetric shrinkage strain of 23.49% - 29.63%, 24.57% - 32.50%, 20.83% - 24.50% for BSL,WAS and BSH respectively. At 8% additive treatment the values ranged from 23.57% - 31.49%, 23.34% - 28.83% and 22.0% - 25.17% for compacted moulding water content at 30.20% - 38.20%, 25.10% - 33.10%, 23.90% - 31.90% for BSL,WAS and BSH respectively. For 12%,16% and 20% MKL content with moulding water content of 26.15% - 34.15%, 24.85% - 32.85% and 23.00% - 31.00% for BSL, 24.00% - 32.00%, 21.30% - 29.30% and 20.00% - 28 00% for WAS, 22.75% - 30.75%, 23.05% - 31.05% and 19.10% - 27.10% for BSH has volumetric shrinkage ranging between 21.40% - 27.69%, 18.96% -28.61% and 13.65% - 24.80% for BSL, 19.34% - 26.41%, 15.55% - 19.76%, 11.30% - 21.57% for WAS and 19.19% -25.86%, 16.41% - 25.31% and 12.52% -19.91% for BSH. Finally, on treatment with 24% MKL and compaction moulding water content of betwwen 25.10% - 33.10%, 18.20% - 26.20% and 17.60% -25.60% yielded volumetric shrinkage strain of 9.70% -25.39%, 6.00% - 17.95% and 11.00% - 18.72% for BSL, WAS and BSH compactive efforts respectively. These results are in consistent with those of Haines, (1923), who described the drying process of saturated soil as having two stages; the first stage occurring as water leaves the soil without the entry of air,since air is not entering the soil,the volume change is equal to the volume of water leaving the soil. The main volume change occurs during the first stage when water surrounding the individual soil particles to move closer as the water retreats. At some point, the particles contact each other, and the drying process slows as the soil structure begins to resist additional volume change. In the second stage, air enters the soil and replaces the water being removed because the particles are in contact. Little changes in soil structure or total volume occur during this stage.

Effect of water content relative to optimum : The variation of volumetric shrinkage strain (VSS) with water content relative to the optimum upon addition of stepped percentages of MKL are shown in Fig.7. Generally, VSS increased with higher moulding water content relative to optimum.For the natural soil compacted at moulding water content in the range of -2 to +6 (dry to wet) of the OMC,maximum value of volumetric shrinkage strain value was recorded at 22%,24% and19% at the dry side of optimum for the BSL,WAS and BSH compactive efforts respectively, (see Fig. 7a). At 4% Metakaolin treatment,VSS values were obtained at 23.49%,21.45% and 20.83% at the dry side of optimum for BSL,WAS and BSH compactive efforts respectively (see Fig.7b). For 8% Metakaolin treatment,shrinkage values were recorded at 23.57%,23.34% and 22.00% at the dry side of optimum for BSL,WAS and BSH compactive efforts, respectively (see Fig.7c). At 12% Metakaolin introduction, volumetric shrinkage strain values were obtained at the dry side of optimum to be 21.40%,19.34% and 19.19% for BSL,WAS and BSH compactive efforts, respectively (see Fig.7d).With 16% Metakaolin at the three compactive efforts ,BSL,WAS and BSH volumetric shrinkage strain was obtained at 18.96%,15,55% and 16.41% respectively. At 20% Metakaolin treatment the values of VSS further decreased to 13.65%, 11.30% and 12.52% for BSL,WAS and BSH compactive efforts, respectively. Finally, at 24% Metakaolin replacement level the volumetric shrinkage strain value was obtained to be 9.70%,6% and 11% at the dry side of optimum for BSL,WAS and BSH compactive efforts,respectively. Generally, specimens compacted at higher moulding water contents relative to optimum irrespective of the MKL treatment shrank more during drying but with higher compactive energy, the relative effect of volumetric shrinkage strain reduced.This result is consistent with those reported earlier by other researchers (Albrecht and Benson,2001; Daniel and Wu,1993). Haines had earlier described the drying process of saturated soils the specimens compacted at higher moulding water contents, have more water in their void spaces which will lead to higher shrinkage on drying since volumetric shrinkage is proportional to the volume of water leaving the pore spaces.

Effect of Metakaolin Content.: The variation of volumetric shrinkage strain (VSS) with MKL content for the three compactive efforts considered and as shown in Fig.8. Generally, there was an initial increase in volumetric shrinkage strain with MKL content at 4% treatment and thereafter it decreases slightly till 24% replacement level for all the compactive efforts. This initial increase at 4% MKL is an indication showing tendancy to expand**.** The reason for this might be that the Soil particles were highly flocculated and capillary stresses were reduced while the average pore sizes were large which was more difficult for the particles to come together. Also,there was a general decrease in volumetric shrinkage strain (VSS) with increasing MKL content beyond 4% at OMC and at all energy levels.This is largely attributed to the pozzolanic input of MKL (increased physico-chemical reaction or ion exchange) (Osinubi and Eberemu,2009b,2010b). As observed from the graphs with increase in MKL content,the volumetric shrinkage strain (VSS) decreased for all the compactive efforts.

Conclusion

Laboratory tests were carried out on black Cotton soil treated with up to 24% MKL content (a class N Pozzolana as well as calcined Clay) to assess its suitability in reducing volumetric shrinkage potential for use in Flexible

Pavement construction. Specimens were prepared at moulding water content -2, 0, +2, +4 and +6 of the Optimum moisture content, OMC, and were compacted at the three energy levels (British standard light, West African standard or "intermediate" and British standard heavy. The soil was classified as A-7-6(16),CH and High swell potential Soil according to AASHTO,USCS and NBBRI classification respectively. There was a general increase in MDD for the BSL compactive effort, while a decrease was recorded for the WAS and BSH compactive efforts with stepped increase in MKL content. While on the other hand there was a general decrease in the OMC for the BSL compactive effort and an increase was recorded for the WAS and BSH compactive efforts respectively. Generally,the recorded VSS values for the black Cotton Soil-MKL mixtures resulted to decrease values up to 24% MKL treatment for all the energy levels considered with decrease in volumetric shrinkage strain (VSS) of 6.0%, 9.70% and 11.00% for WAS, BSL, and BSH respectively, compared to the VSS of the Virgin black Cotton Soil. The findings indicated a decreasing trend volumetric shrinkage with increase in MKL, suggesting its potential applications in the modification of problematic expansive Soils for construction work.

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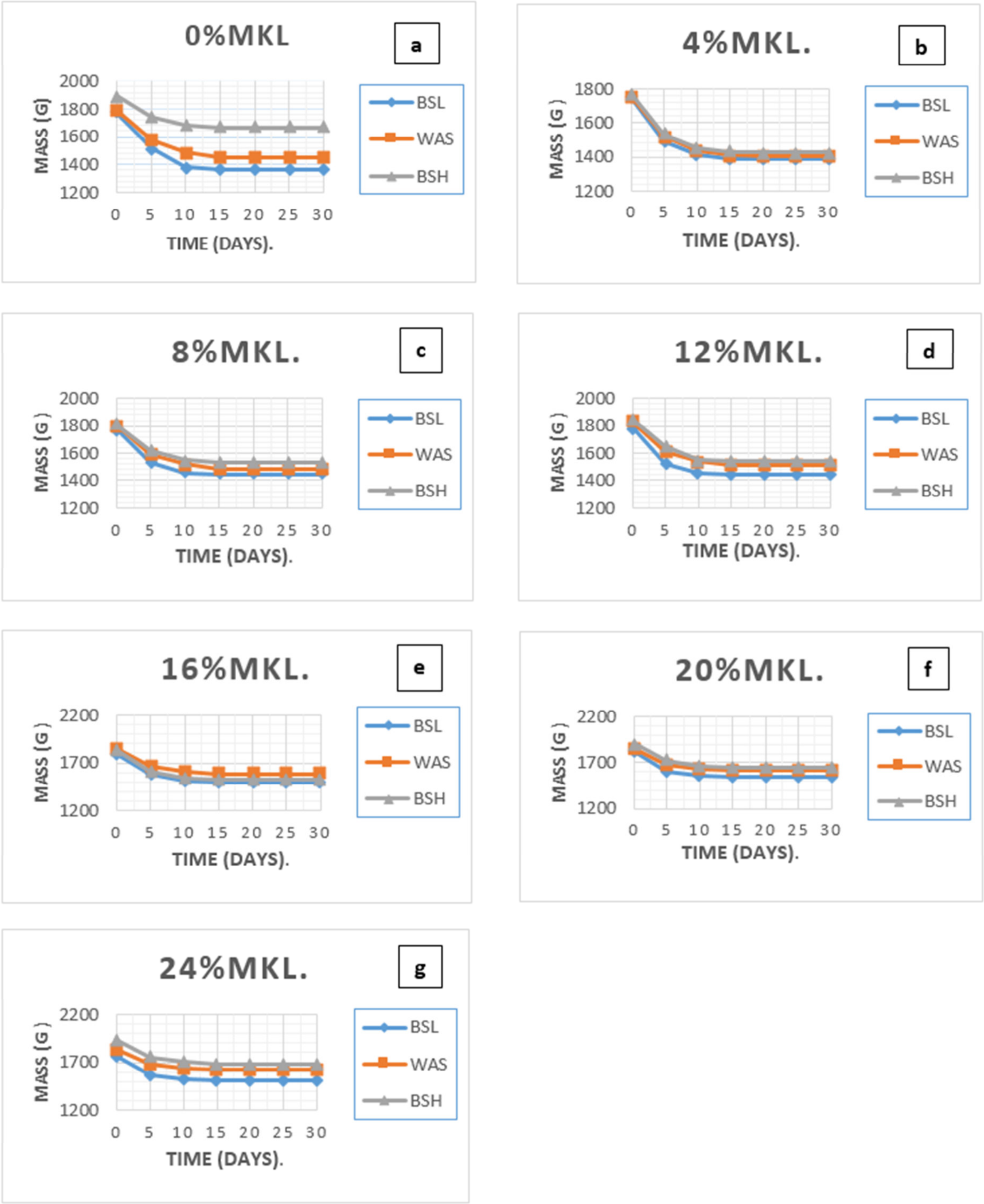


FIGURE 4.: Variation of mass(g) with time(days) at OMC for (a) 0% Metakaolin (b) 4% Metakaolin (c) 8% Metakaolin (d) 12% Metakaolin (e) 16% Metakaolin (f) 20% Metakaolin (g) 24% Metakaolin.

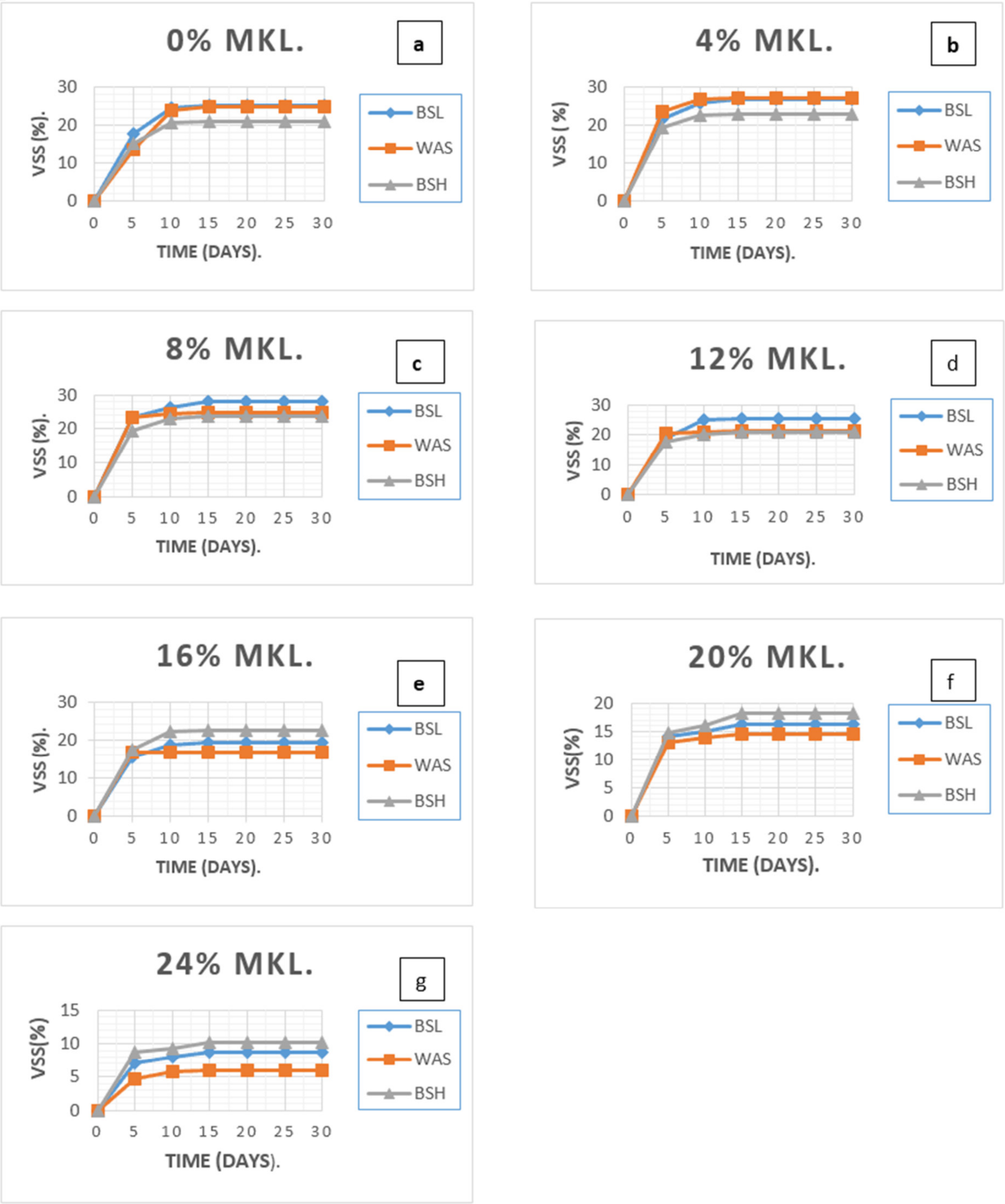
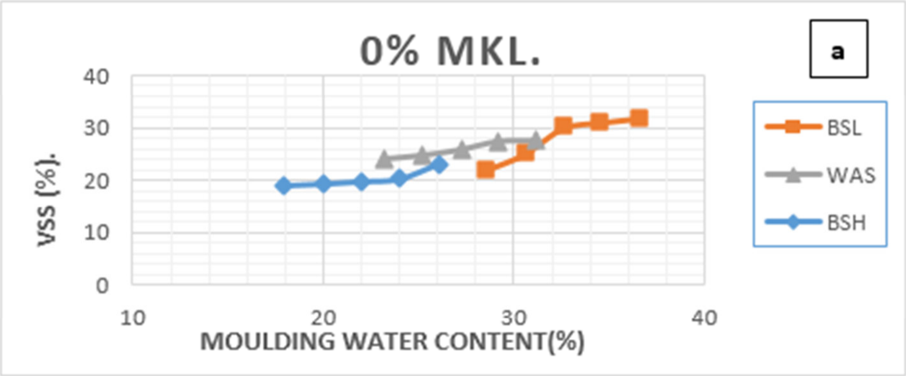
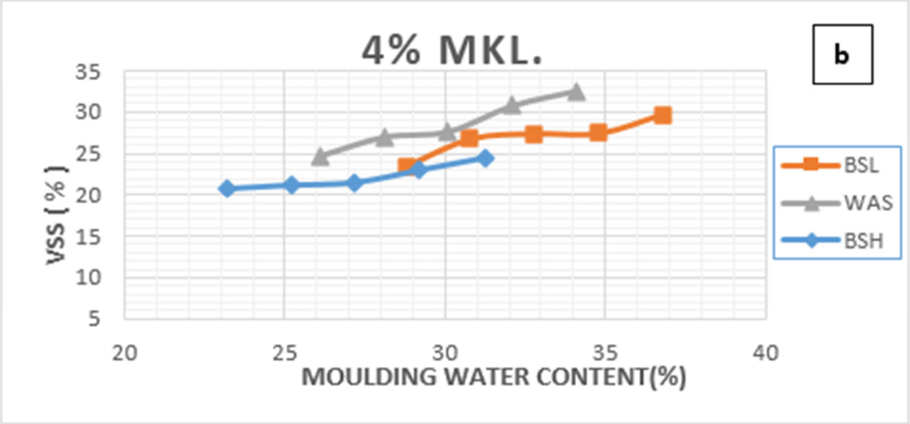
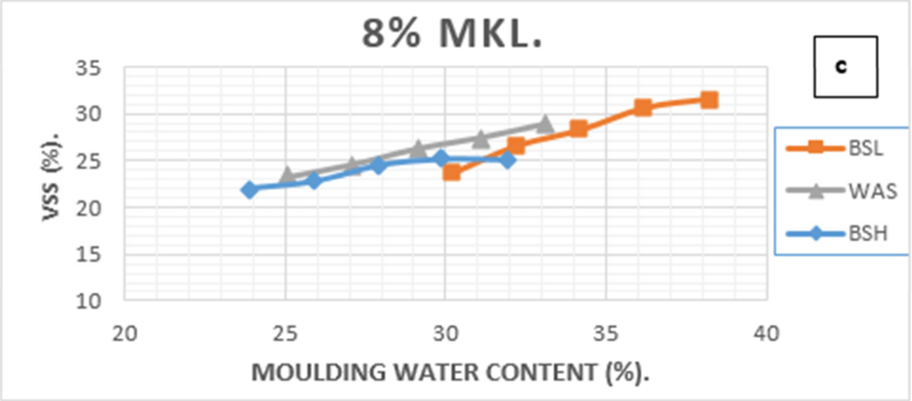
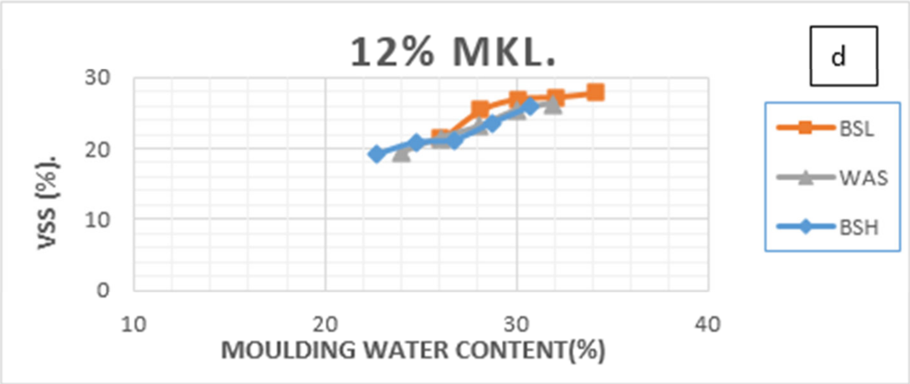


FIGURE 5.: Variation of volumetric shrinkage strain with time (days) at OMC for (a) 0% Metakaolin (b) 4% Metakaolin (c) 8% Metakaolin (d) 12% Metakaolin (e) 16% Metakaolin (f) 20% Metakaolin (g) 24% Metakaolin.


0% MKL.
a
VSS (%).
0
10
20
30
40
10
20
30
40
MOULDING WATER CONTENT(%)
BSL
WAS
BSH


4% MKL.
b
VSS (%)
5
10
15
20
25
30
35
20
25
30
35
40
MOULDING WATER CONTENT(%)
BSL
WAS
BSH


8% MKL.
c
VSS (%).
10
15
20
25
30
35
20
25
30
35
40
MOULDING WATER CONTENT (%).
BSL
WAS
BSH


12% MKL.
d
VSS (%).
0
10
20
30
10
20
30
40
MOULDING WATER CONTENT(%)
BSL
WAS
BSH

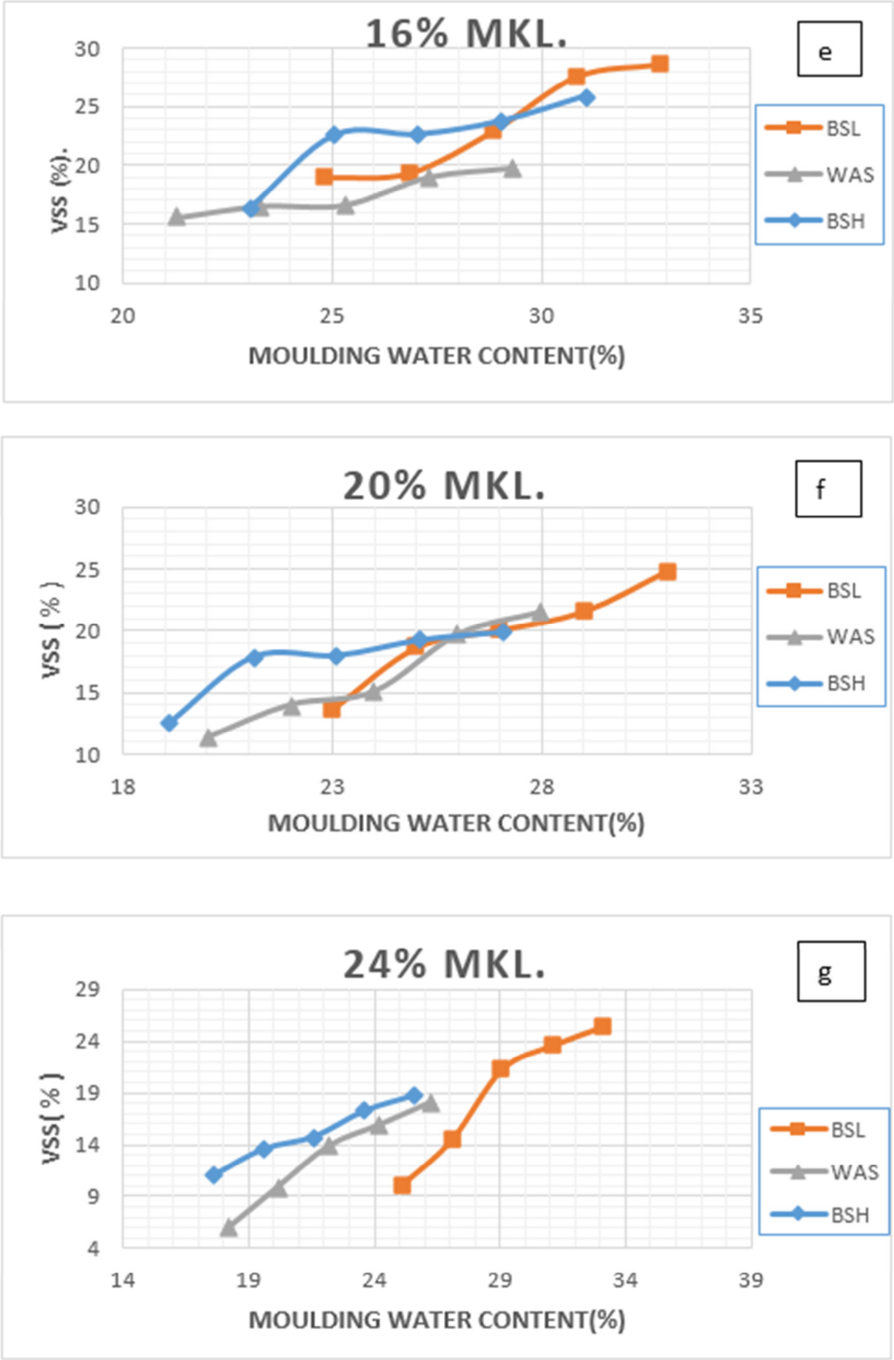


FIGURE 6.: Variation of Volumetric shrinkage strain with moulding water content at (a) 0% Metakaolin (b) 4% Metakaolin (c) 8% Metakaolin (d) 12% Metakaolin (e) 16% Metakaolin (f) 20% Metakaolin (g) 24% Metakaolin

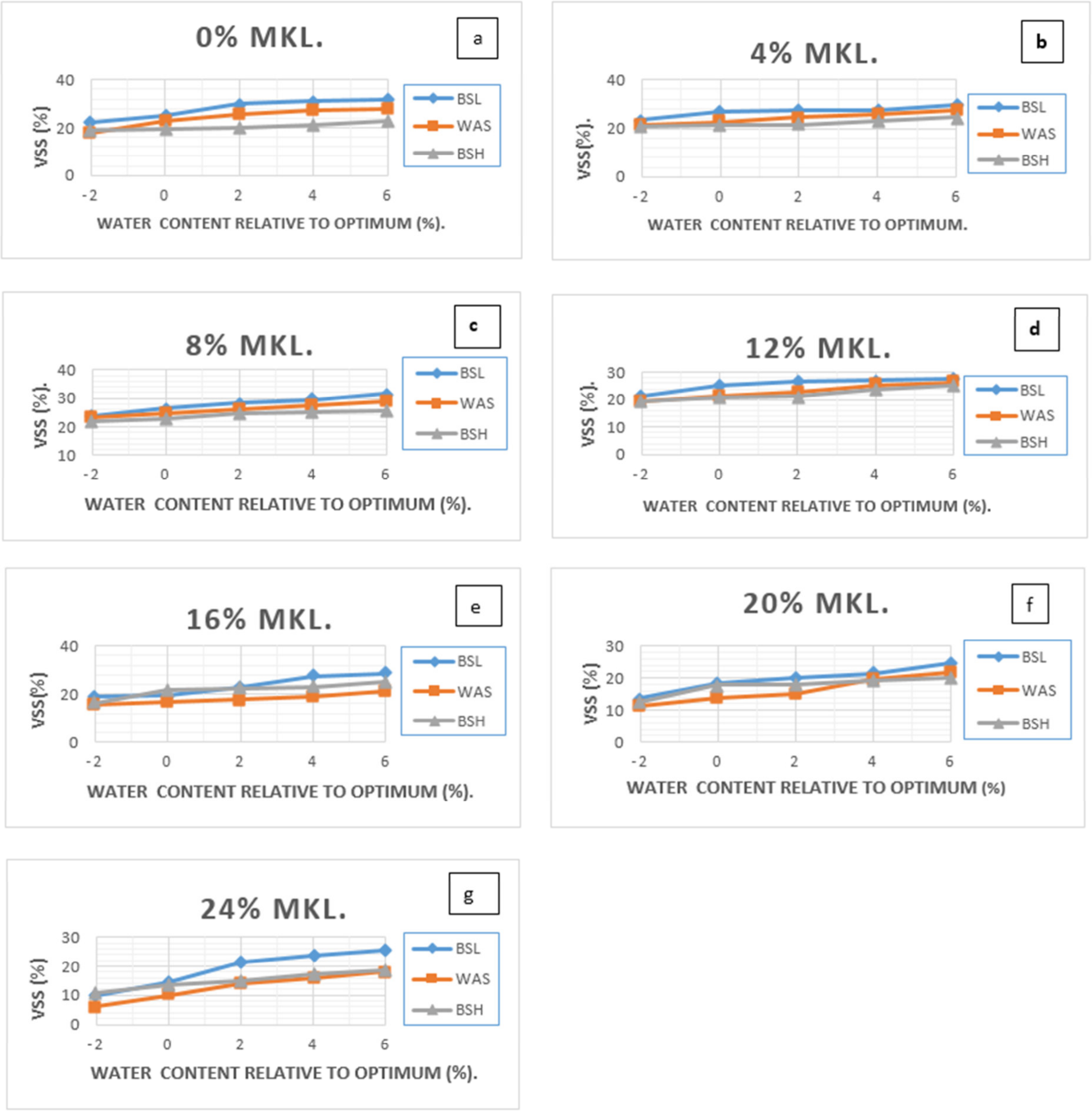


FIGURE 7.: Variation of Volumetric shrinkage strain with water content relative to optimum (wro) at (a) 0% Metakaolin (b) 4% Metakaolin (c) 8% Metakaolin (d) 12% Metakaolin (e) 16% Metakaolin (f) 20% Metakaolin (g) 24% Metakaolin.

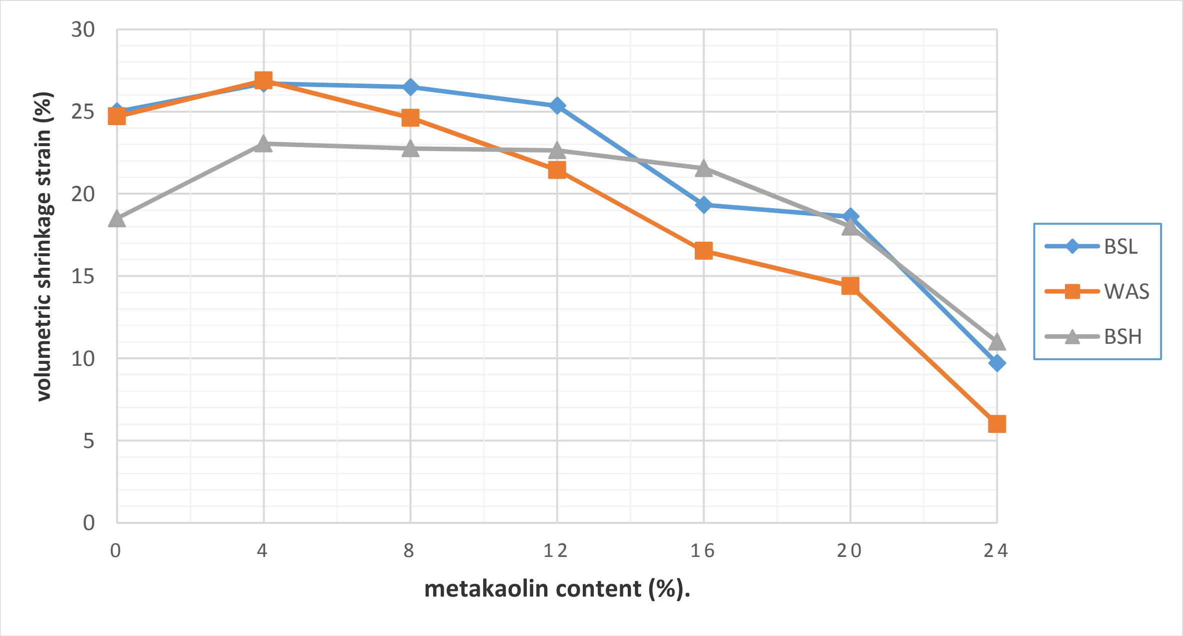


FIGURE 8.: Variation of Volumetric shrinkage strain with Metakaolin content at BSL, WAS, BSH compactive efforts.