Resilient modulus and deviatoric stress of cemented soils treated with crushed waste ceramics (CWC) for pavement subgrade construction

Abstract

The behavior of resilient modulus of cemented lateritic soils treated with crushed waste ceramics and utilized as pavement underlain has been investigated under laboratory conditions. This is the measure of the rigidity of soils used as foundation materials. The rampant failures of pavements due to undesirable characteristics exhibited by the foundations have spurred this research work to enable a better understanding of the behavior of soils used as foundation materials and how best they can be handled or treated to ensure stability and durability of the structures. The soils were first characterized and found to belong to A-7, A-7-6, A-7 and A-7-5 group of soils according to the AASHTO classification method. Also, they were found, from basic experiments, to be highly plastic soils with high clay contents. The soils were treated with crushed waste ceramics in the proportion of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 110% and 120% by weight of solid with a constant addition of 2.5% by weight ordinary cement. The results of the examination showed that the resilient modulus increased substantially with increased rate of crushed waste ceramics. This showed that crushed ceramic waste is a good pozzolanic material for soils stabilization in the construction of pavement foundations. Keywords: resilient modulus, deviatoric stress, cemented soils, crushed waste ceramics, solid wastes, geomaterials, pavement foundation

1. Introduction

The unbounded aggregate layer and unsaturated state upon which pavement foundations are constructed play an important role in the performance of pavements more especially with the hydraulically bound conditions where rise and fall of moisture due to suction plays another role [1, 2, 3, 4, 5]. It is wrong to assume that pavement layers are under steady saturated conditions and this assumption affects the design and eventually the stiffness and stability of the pavement foundations [6, 7]. According to Ba et al. [8] it is noted that moisture migration and percolation into the pavement layers either through suction and surface water seepage affects the resilient modulus and stability of subgrade materials, which commonly are constructed with compacted lateritic soils. It has been proven through research that moisture affects the carrying capacity and strength of clayey soils due to the loss of strength on immersion [7, 9]. The behavior of soils under suction is
directly corresponding with the resilient modulus of such soils especially when subjected to the effect of moisture [10, 11]. This behavior brings about the failure of pavements when they are underlain with unsuitable and expansive soils, which behave in undesirable pattern under the influence of matric suction [2, 12]. Due to the fluctuations in the water conditions of the subgrade, the pavement foundations are designed for the most critical exposure conditions [13, 14, 15]. Soils stabilization has been adopted to improve on the inadequate properties of the soils utilized as subgrade materials [2-5, 10]. This is achieved through the use of chemical compounds like the ordinary Portland cement or biobased or lignocellulose materials, which are environmentally friendly geomaterials [10, 16, 17, 18]. The biobased or lignocellulose materials are derived through controlled direct combustion to have ash or through crushing to achieve powder with good gradation. In this work, crushed waste ceramics is derived by crushing waste ceramic materials collected from dumpsites. This material is used as a geomaterial in the stabilization of soils for use as subgrade materials because of its pozzolanic properties [18]. Due to the high content of aluminosilicates in the CWC, its blend with soft lateritic soils produce compacted stabilized subgrade soils with high rigidity, density and stability. This behavior gives rise to the improvement of the resilient modulus of the treated material at optimum molding moisture conditions [1]. The objectives of this work were to evaluate the effect of crushed ceramics wastes on the deviatoric stress and resilient modulus of the treated soils.

2. Materials

2.1 Soils

Four borrow pits in four different locations in Abia State, Nigeria were the source of the soil samples. These borrow pits are located on coordinates 5°29’16” North and 7°28’58” East (for Olokoro location soil), 5°27’0” North and 7°31’60” East (for Amaba location soil), 5°31’0” North and 7°26’0” East (for Ohiya location soil) and 4°53’14” North and 7°21’26” (for Akwete location soil). The samples were sundried for 7 days, 500 grams each was measured and prepared for use.

2.2 Crushed waste ceramics

The ceramics were collected from dumpsites within Umuahia urban area, sundried for two days and crushed by ball milling. The crushed ceramic waste was characterized and sieved to determine its gradation and particle distribution. Afterwards, it was stored for use in the stabilization exercise.

2.3 Ordinary Portland cement

Portland cement was used at a steady rate of 2.5%, that meets the requirements of ASTM C618 [18], as a binder as shown in the chemical oxide composition presented in Table 2. The preliminary characterization exercises were conducted on the test materials to determine their gradation and chemical oxide composition (aluminosilicates content). These test admixtures were utilized in the percentages of 10% to 120% in an incremental rate of 10% to treat the soils.

3. Methods

The particle size distribution, compaction, Atterberg limits, shrinkage limits, free swell index, and specific gravity were generally conducted on the test soils in accordance with BS 1377 [19]. This was carried out to determine the characterization and basic properties of the test soils. Similarly, chemical oxide composition and particle size distribution tests were conducted to determine the aluminosilicate content and gradation respectively in accordance with ASTM C618 [18] and BS 1377 [19] respectively. Of particular interest to this work was the stiffness of the treated soils as subgrade or pavement materials, which was determined with the resilient modulus test carried out on the CWC treated soils in accordance with AASHTO [10], AASHTO T 22-03 [1], and BS 1924 [20]. Specifically, the resilient modulus of both the control specimen and treated test soils was determined under the laboratory conditions. This represented the simulated physical and stress conditions of geomaterials treated soils A, B, C and D overlain by flexible pavements subjected to dynamic traffic loads. A cyclic axial stress of fixed magnitude under deviatoric stress, load duration of 0.1s, and cyclic duration of 3s is applied to prepared cylindrical test specimens in a modified triaxial compression set up. The final recoverable axial deformation response (recoverable strain) and the deviatoric stress of the test specimens were measure and the resilient moduli at different proportions of the additives were determined with Eq. 1.

$$M_R = \frac{\Delta \rho_d}{\varepsilon_r}$$

where: $M_R$ = resilient modulus, $\Delta \rho_d$ = deviatoric stress, $\varepsilon_r$ = strain

4. Results and analytical remarks

4.1 Classification Characteristics of Test Materials

The basic properties of the test soils are presented in Table 1, Fig. 1 and Table 2. The test soil were observed to possess 2.85%, 10%, 4.6% and 7.6% passing sieve No. 200, and classified as A-7, A-7-6, A-7 and A-7-5 respectively according to AASHTO classification method. Test soils A, B, C and D were classified as poorly graded according to unified soil classification system. The results of the consistency protocol show that the test soils are highly plastic soils (> 17%) with high free swell index. The basic results of the resilient modulus show that the soils fall under clayey subgrade (0.345E+05 to 1.034E+05 kN/m²) [16]. The chemical oxides composition test results presented in Table 2 show that the test materials possess high aluminosilicates responsible for the pozzolanic, calcination and hydration reactions that take place in a stabilization process.
Property description of test soils and units

<table>
<thead>
<tr>
<th></th>
<th>Test soil (A)</th>
<th>Test soil (B)</th>
<th>Test soil (C)</th>
<th>Test soil (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing Sieve, No 200</td>
<td>2.85</td>
<td>10</td>
<td>4.6</td>
<td>7.6</td>
</tr>
<tr>
<td>NMC (%)</td>
<td>12.1</td>
<td>13.49</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>LL (%)</td>
<td>40</td>
<td>46</td>
<td>64</td>
<td>65</td>
</tr>
<tr>
<td>PL (%)</td>
<td>18</td>
<td>21</td>
<td>36</td>
<td>33</td>
</tr>
<tr>
<td>PI (%)</td>
<td>22</td>
<td>25</td>
<td>28</td>
<td>32</td>
</tr>
<tr>
<td>SL (%)</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>FSI (%)</td>
<td>250</td>
<td>234</td>
<td>275</td>
<td>296</td>
</tr>
<tr>
<td>$G_s$</td>
<td>2.6</td>
<td>2.43</td>
<td>2.12</td>
<td>2.08</td>
</tr>
<tr>
<td>AASHTO Classification</td>
<td>A-7</td>
<td>A-7-6</td>
<td>A-7</td>
<td>A-7-5</td>
</tr>
<tr>
<td>USCS</td>
<td>GP, CH</td>
<td>GP</td>
<td>GP, CH</td>
<td>GP, CH</td>
</tr>
<tr>
<td>MDD (g/cm3)</td>
<td>1.76</td>
<td>1.85</td>
<td>1.80</td>
<td>1.56</td>
</tr>
<tr>
<td>OMC (%)</td>
<td>13.1</td>
<td>16.2</td>
<td>13.13</td>
<td>15.4</td>
</tr>
<tr>
<td>CBR (%)</td>
<td>12</td>
<td>13</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>R-Value</td>
<td>11.74</td>
<td>11.70</td>
<td>11.70</td>
<td>11.50</td>
</tr>
<tr>
<td>MR (kN/m2)</td>
<td>0.42E+05</td>
<td>0.42E+05</td>
<td>0.42E+05</td>
<td>0.72E+05</td>
</tr>
<tr>
<td>Color</td>
<td>Reddish Brown</td>
<td>Reddish Gray</td>
<td>Reddish Ash</td>
<td>Ash</td>
</tr>
</tbody>
</table>

Table 1 Basic properties of test soils
1. táblázat A vizsgált talajok alapvető tulajdonságai

Materials Oxides Composition (content wt %)

<table>
<thead>
<tr>
<th>Materials</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>TiO₂</th>
<th>LOI</th>
<th>P₂O₅</th>
<th>SO₃</th>
<th>IR</th>
<th>Free CaO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil A</td>
<td>76.56</td>
<td>15.09</td>
<td>2.30</td>
<td>2.66</td>
<td>0.89</td>
<td>2.10</td>
<td>0.33</td>
<td>0.07</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Soil B</td>
<td>77.57</td>
<td>14.99</td>
<td>3.11</td>
<td>1.78</td>
<td>0.86</td>
<td>1.45</td>
<td>0.23</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Soil C</td>
<td>77.73</td>
<td>16.65</td>
<td>1.42</td>
<td>3.22</td>
<td>0.07</td>
<td>0.89</td>
<td>0.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Soil D</td>
<td>72.34</td>
<td>17.30</td>
<td>5.40</td>
<td>2.32</td>
<td>0.34</td>
<td>2.13</td>
<td>0.17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CWC</td>
<td>64.45</td>
<td>24.14</td>
<td>0.25</td>
<td>1.3</td>
<td>0.28</td>
<td>3.69</td>
<td>2.51</td>
<td>0.18</td>
<td>1.09</td>
<td>2.11</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>DOPC</td>
<td>21.45</td>
<td>4.45</td>
<td>63.81</td>
<td>3.07</td>
<td>2.42</td>
<td>0.83</td>
<td>0.20</td>
<td>0.22</td>
<td>0.81</td>
<td>0.11</td>
<td>2.46</td>
<td>0.16</td>
<td>0.64</td>
</tr>
</tbody>
</table>

*IR is Insoluble Residue, LOI is Loss on Ignition, CWC: Crushed Waste Ceramics
DOPC: Dangote Ordinary Portland cement

Table 2 Chemical oxides composition of the materials used in this paper
2. táblázat A felhasznált anyagok kémiai oxidos összetétele

4.2 Deviatoric stress and resilient modulus (Mₙ) of the treated cemented soils

The results of the resilient modulus of the CWC treated soils used to characterize the treated matrix as a subgrade material is presented in Figs. 2 and 3. The applied deviator stress and the recoverable strain of the modified triaxial test on the treated specimens were used. The four test soils behaved in almost the same pattern with similar reactions with increased crushed waste ceramics (CWC). The deviatoric stress consistently increased with increase in the proportion of the admixture for test soils A, B, C and D. It is important to note at this point that the additive CWC is a highly aluminosilicate compound according to the requirements of American Standard for Testing and Materials [18], with a crystal texture prior to its utilization in the stabilization procedure. These compounds are responsible for pozzolanic reaction, and strengthening by forming silicates of calcium hydrates and aluminates. These further forms floc, which condense to the strength buildup of the treated materials. Test soils A, B and C had an improvement index of about 21%, while test soil D had an improvement index of 25%. The higher improvement index recorded with test soil D is in line with its natural soil high resilient modulus of 0.72E+05, which was improved upon. The hydration reaction between compounds of strengthening from the additive and the dissociated soil ions.

Fig 1 Grain size distribution of studied materials
1. ábra A vizsgált anyagok szemcseméret eloszlása
in contact with moisture caused the improvement on both deviatoric stress and resilient modulus of the treated soils. In addition, the cation exchange reaction between the dipole ions of the additive when in contact with molding moisture and those of soils caused the improved properties of the test soils \[21, 22\]. These results were recorded under cyclic loading on specimens subjected to testing sequences. The physical conditions that affect the resilient modulus (moisture and unit weight) were influenced by the introduction of the highly aluminosilicate CWC hence improving the strength behavior of the treated soils.

5. Conclusions

The experimental results of the treatment of soils with crushed waste ceramics have been observed and tabulated. The following remarks can be made; (i) the crushed waste ceramics was characterized and sampled as a silicate-based geomaterial with similarly particle gradation with the test soils and results show that the prepared materials contains binding properties that make it useful as a supplementary cementitious material. (ii) the soils were also tested for their basic properties which showed that they belong to A-2-7, A-2-6, A-7 and A-7-5 groups according to the American Association of State Highway and Transportation Officials classification method. Further characterization exercise on the soils shows that the soils are highly plastic soils, which implies that they are problematic and need modification to meet the requirements for use as construction materials. (iii) the soils were treated with the crushed waste ceramics at the rate of 10% to 120% by weight of solid in a steady increment of 10% by mixing and compacting to maximum dry density at an optimum moisture. (iv) the resilient modulus of the soils

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Fig. 2  Effects of CWC on deviatoric stress of the treated cemented soils

2. ábra  CWC hatása a cementált talajok deviátoros feszültségére

Fig. 3  Effects of CWC on resilient modulus, $M_r$, of the treated cemented soils

3. ábra  CWC hatása a cementált talajok rugalmassági modulusára ($M_r$)
was tested and results show that it improved consistently and substantially with increased rate of crushed waste ceramics. (v) the crushed waste ceramics showed that it can be utilized as a supplementary cementing construction material with its high content of aluminosilicates to improve the properties of soils used as pavement subgrade materials.

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References


Ref: