Mechanical Stabilization of Red Soil with Cinder and Waste-Recycling-Plant Slag: Compaction and CBR Performance for Pavement Subbase

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Abstract

Industrial cinder, waste recycling plant (WRP) slag are granular residues that, in bulk disposal occupy land and generate mineral fractions that are not used as useful resources. The suitability of this type of material for use as mechanical modifiers in a red soil pavement subbase/improved subgrade application is evaluated. One part of the red soil had 1.30% gravel content, 64.60% sand content and 34.10% silt-clay fraction content. The soil, cinder and WRP slag had natural moisture contents of 2.80%, 4.70% and 3.29% respectively and specific gravities of 2.59, 2.26 and 2.79 respectively. The parent materials and red soil mixtures of 25%, 50% and 75% cinder or WRP slag were compacted using standard proctor compaction. Selected mixtures were tested using the California bearing ratio (CBR) test. The optimum moisture content (OMC) of the natural soil was found to be 12% while the maximum dry density (MDD) was 1.87 g/cm³. The highest MDD for 50:50 soil/cinder was 2.14 g/cm³ (a 14.4% increase), and for 25% WRP slag, the MDD was 2.08 g/cm³ (an 11.2% increase). CBR of the treated soils increased and 50% cinder soil had higher CBR (2.62%) compared to the untreated soil (2.54%) whereas 25% WRP slag soil had CBR of (2.58%). So, in this way, the particle packing condition was significantly improved, and the bearing resistance was slightly improved in the recorded test condition. The work determines the optimum contents for the different densities, and demonstrates that compaction gain does not necessarily equate to structural adequacy. Prior to field adoption, the tests related to replicated soaked-CBR, durability tests were performed.

Keywords: Red soil; Cinder; WRP slag; Industrial by-product; Mechanical stabilization; Standard Proctor compaction; California bearing ratio; Pavement subbase

1. Introduction

The use of granular soil and aggregate in pavement earth-work consumes large quantities and power and metallurgical industries produce coarse mineral residues which need to be stored, transported and managed in the long term in the environment. Residuals that are brought in to pavement layers can help minimize the amount of raw source materials required and the amounts of waste placed in the landfill, but they should be accepted with certification of gradation, compaction, bearing resistance and environmental compatibility, not for waste-diversion claims alone [1-5].

Red soils are common in tropical areas and can be iron-oxide coated, sand-sized grains and a variable fine fraction. Its engineering response is, for this reason, highly variable depending on the type of parent rock, weathering and the nature of the clays and their moisture content. In the case of pavement use, it is not the colour designation that is of concern, but the grading, plasticity, compaction characteristics and strength of the soil in the moist condition it will be subject to during service. The material examined in this paper is sand-dominated but contains 34.10% of the silt and clay fraction which can lead to moisture sensitivity and low CBR when the fine fraction is controlling the interparticle contact.

Cinder is a coarse, porous material that remains from burning coal. Lower particle density and lower particle content is its vesicular texture; these can cause higher water demands, however, the angularity may enhance grading and friction at an appropriate mix content. The results of earlier studies on coal bottom ash have demonstrated that they are mixture dependent, meaning that moderate amounts can enhance the particle packing and bearing resistance while maximum replacement causes some decrease in dry density or formation of a weak, porous skeleton [6-9]. Therefore, an optimum would need to be determined experimentally rather than taken from another source of ash.

In this study WRP slag refers to the non-metallic slag fraction of steel slag after metallic recovery in waste recycling plant. WRP slag will not be substituted for blast furnace slag, ground granulated blast furnace slag or ladle furnace slag. Published WRP slag has been reported as mostly granular, non-plastic material with relatively high specific gravity and good CBR and frictional resistance [5]. However, the properties of steelmaking slag are very sensitive to the furnace route, cooling and ageing and crushing process as well as to free lime and magnesia remaining in the slag [1-4,10]. The variability requires source-specific characterization and dimensional stability and leaching should be confirmed prior to permanent placement.

The following investigation is based on mechanical blending as opposed to an activated binder system. So, immediate performance will be primarily a result of the size distribution, particle arrangement, particle contact interlock, and attainable density changes. If the specific residue is found to contain reactive calcium- or aluminosilicate-bearing phases, and sufficient moisture and curing is provided, then there may be cementitious reactions.

2. Research gap and novelty

There are currently studies confirming that cinder/bottom ash as well as various steel slags can be applied in road earthworks, but three gaps are related to this dataset. First, the results from generic bottom ash or furnace slag cannot be directly applied to cinder or post-metal-recovery WRP slag due to differences in density, pore structure, chemistry and grading among the different sources. Secondly, most investigations have focused on a single residue, which makes it hard to compare two locally available wastes against a single parent soil in a similar compaction structure. Thirdly, compaction improvement is sometimes equated with strength improvement, but can differ.

The benefit of this work is the possibility of introducing both cinder and WRP slag at 25%, 50% and 75% by dry mass and make a comparison with the untreated red soil and residues. The design shows that different density optima have been found, which are an intermediate level of cinder content and a lower level of WRP-slag content. Selected CBRs are then subjected to tests to determine if the increased densities lead to improvement in bearings. The novelty is therefore comparative and diagnostic and not chemical, because it was not a packing that was fine-soil controlled and changed into granular residue skeleton, but rather this was the case of two types of packing that are only partially correlated for the data obtained.

2.1 Objectives

The study objectives are (i) to characterize the basic physical properties and grading of the red soil, cinder and WRP slag; (ii) to determine the OMC and MDD of the parent materials and binary mixtures; (iii) to compare CBR values of the untreated soil and selected density-favoured blends; and (iv) to identify technically defensible mixture ranges and additional evidence required for pavement use.

3. Materials and experimental investigation

3.1 Materials

Three dry samples were processed: red soil, cinder as one of the by-products of coal combustion and WRP slag produced in the process of processing iron/steelmaking slag for metallic recovery. The photographs from the source material have been shown in figure 1. The weathering and ageing of the slag materials are important for free-lime hydration and volumetric stability and it is important that such information is taken into account.

Fig. 1. Source materials: (a) red soil, (b) cinder and (c) waste-recycling-plant (WRP) slag. Photographs were recovered from the supplied experimental presentation.

3.2 Preliminary conditioning and characterization

Representative samples were air dried, disaggregated (but not crushed) and then reduced to test quantity. The natural water content was determined by the oven drying method at 105-110 °C following the principle laid down in IS 2720 (Part 2). Specific gravity was measured with the help of a density bottle/pycnometer method as per the IS 2720 (Part 3/Sec 1). The particle-size distribution of the soil was determined by dry sieving of soil as per IS 2720 (Part 4). The information from the available record was combined silt and clay.

3.3 Mixture proportions

Sample preparation was done on a dry mass basis with binary blends. The red soil was replaced by cinder at 25%, 50% and 75% and WRP slag was also tested at these replacements and shown in Table 1. Reference materials used were untreated red soil, 100% cinder and 100% WRP slag. Mixture codes are composed of RS, C or W, where RS is red soil, C is cinder and W is WRP slag, with the number indicating the percentage of the residue. Dry mixing was done for each constituent until uniform and water added in increments to obtain uniform compaction.

Table 1. Dry-mass mixture matrix used for compaction testing.

Mix ID	Red soil (%)	Cinder (%)	WRP slag (%)	Soil mixture
RS	100	0	0	Untreated control
C25	75	25	0	Cinder blend
C50	50	50	0	Cinder blend
C75	25	75	0	Cinder blend
C100	0	100	0	Cinder
W25	75	0	25	WRP-slag blend
W50	50	0	50	WRP-slag blend
W75	25	0	75	WRP-slag blend
W100	0	0	100	WRP-slag

3.4 Standard Proctor compaction

Light Compaction Tests were carried out as per IS 2720 (Part 7). Materials or blends were used for a number of specimens at a range of water contents. The volume of the mould was used to determine the dry density (γ_d) and its compacted mass was used to determine wet density (γ), then dry density was calculated as $\gamma_d = \gamma / (1 + w)$, where dry density ($\gamma_d$), wet density ($\gamma$) and water content (w) are expressed in decimal form. The data was plotted and a smooth compaction curve was plotted through the data. The maximum dry density (MDD) and optimum moisture content (OMC) were reported. One records from the source were used for each mixture – no replicate-series dispersion.

3.5 California bearing ratio

CBR tests were conducted following the load-penetration principle of IS 2720 (Part 16). The reported percentage was calculated as the measured load divided by the standard load at the same penetration, multiplied by 100. Values were recorded at 2.5 and 5.0 mm. The source table adopts the 5.0-mm value because it exceeded the 2.5-mm value for all three selected materials. The record does not state whether the samples were soaked, whether the test was repeated to confirm selection of the 5.0-mm value, or what surcharge was used. For scientific accuracy, this paper therefore reports the measurements as 'recorded laboratory CBR' and does not claim soaked design CBR.

The load penetration principle of IS 2720 (Part 16) was used to perform the CBR tests. The percentage reported was the measured load divided by the standard load at the same penetration. Values were measured at depths of 2.5 and 5.0 mm.

3.6 Experimental variables and reporting status

The experimental investigation is reported in the Table 2 with the test condition.

Table 2. Experimental variables and limitations of the available source record.

Variable	Experiment condition	Reporting status
Natural water content	Over drying at 105°C	Usable; standard temperature range clarified
Specific gravity	Pycnometer method	Usable; test temperature not recorded
Grain-size analysis	Gravel, Sand, combined silt and clay	Mechanical grain size analysis
Compaction	Standard Proctor curves and OMC/ MDD	Standard laboratory light compaction method
CBR	2.5 mm and 5.0mm values	Laboratory compaction unsoaked condition

4. Results and discussion

4.1 Physical properties and grading

The natural moisture content of all three materials was low ranging from 2.80% to 4.70% (Table 3). The specific gravity for the cinder was the lowest at 2.26, which was consistent with a combustion residue with a porous structure, while WRP slag had the highest specific gravity value at 2.79, which was consistent with an iron bearing granular by-product. The soil value is 2.59, a reasonable value for a weathered mineral soil with an appreciable fine fraction. These differences suggest that the volume occupied by solids and the geometry of their packing are also affected by mass replacement, there is a distinction between mass percentage and volume percentage.

Table 3. Recorded physical properties of the constituent materials

Property	Red Soil	Cinder	WRP slag
Natural moisture content (%)	2.8	4.7	3.29
Specific gravity	2.59	2.26	2.79
Gravel (%)	1.30	-	-
Sand (%)	64.60	-	-
Silt and clay (%)	34.10	-	-

4.2 Compaction response of cinder-modified soil

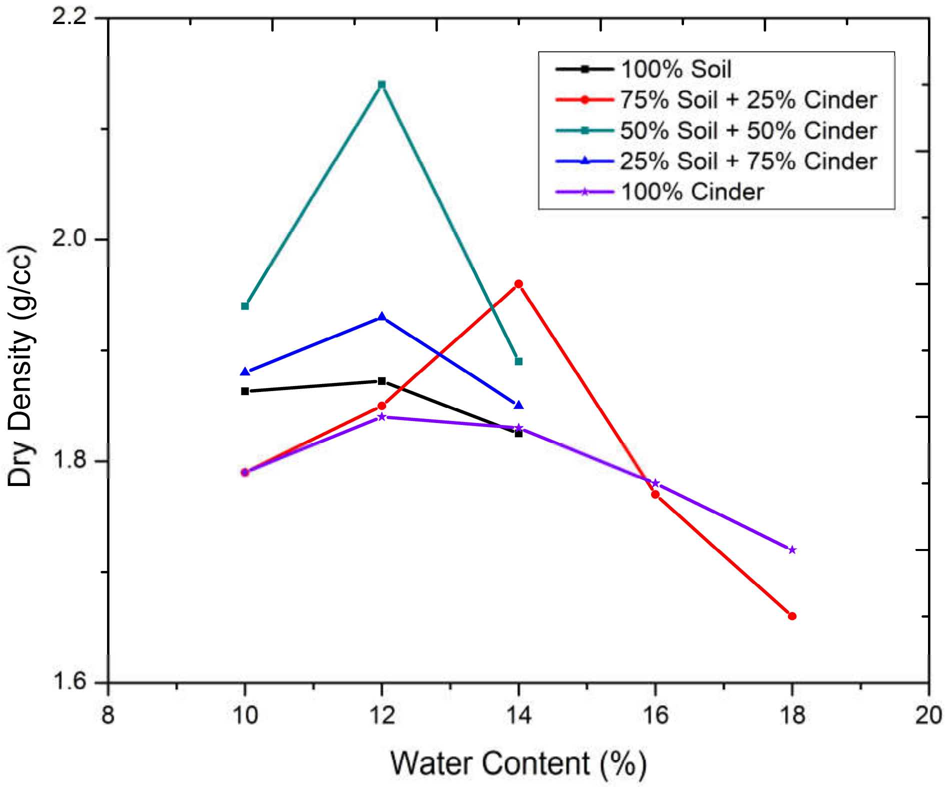

Fig. 2. Standard Proctor compaction curves for red soil and cinder mixtures. Curves reproduce the recorded single-series observations; error bars are unavailable.

At 12% water content, the untreated soil had a density of 1.87 g/cm³. When the cinder content was raised to 25% the MDD increased to 1.96 g/cm³, but the OMC decreased to 16%. This combination indicated that there was the need for more water lubrication and the added porous, angular fraction filled part of the grading gap. The 50% cinder mixture gave the highest MDD in the test the OMC of 12% which was 2.14 g/cm³. Relative to RS, the increase was 0.27 g/cm³ or 14.4%. The peak is narrow, the recorded density decreased to 1.89 g/cm³ at 14% moisture and to 1.94 g/cm³ at 10%. Water content in the field would be important.

With 75% cinder, MDD came down to 1.93 g/cm³ and cinder to 1.84 g/cm³. The non-monotonic trend suggests a packing optimum instead of just an additive-density effect. Cinder grains can get into a composite framework up to 50% in the form of cinder, occupying intergranular space and providing the stability of contacts in the red-soil. In turn, as the amount of the lower specific-gravity more porous cinder fraction increases beyond that level, the skeleton is increasingly dominated and the attainable dry mass per unit volume is decreased. Similar dose-response relationships have been observed in coal bottom ash, ranging from 11% to 18% depending on the porosity of the ash, the grading and compactive effort of soil [6-9].

4.3 Compaction response of WRP-slag-modified soil

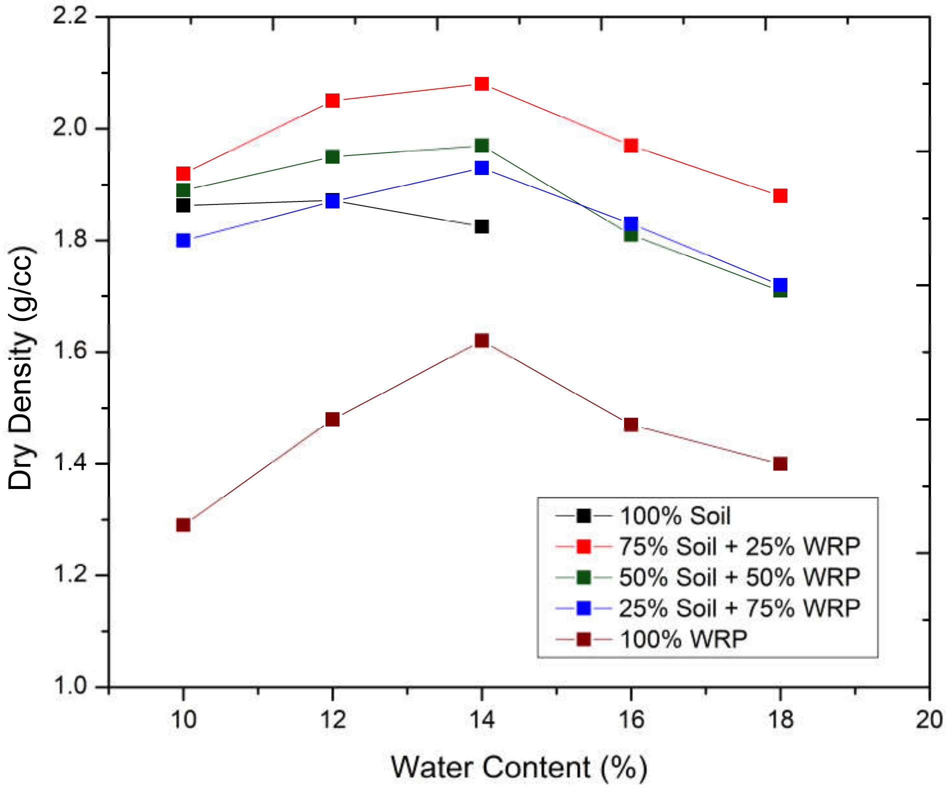

Fig. 3. Standard Proctor compaction curves for red soil and WRP-slag mixtures.

WRP slag generated a different optimum. The 25% blend achieved 2.08 g/cm³ at 14% OMC, an increase of 11.2% over RS. Increasing slag to 50% reduced MDD to 1.97 g/cm³; 75% produced 1.93 g/cm³; and neat WRP slag produced 1.63 g/cm³. The recorded OMC for all four slag blend was 14%. The density reduction at high values (above 25%) may be due to the progressive removal of the soil fines necessary to fill the interstices between the slag grains and the particle grading and shape of the specific type of slag treated. The outcome should not be extended to all steel slags, as it has been reported that the specific gravity and density of other steel slags, for example WRP slag, varied due to the difference in the metallic-oxide content and size distribution and compaction effort [5].

The pure WRP-slag result seems to be low compared with some of the studies related to steel slags [2-5,10-12]. This does not necessarily constitute distress, as the present material can be a more open graded material, weathered porous particles or have a higher percentage of low-density non-metallic fractions post metal recovery. However, it allows reinforcement of the necessity to report the WRP processing route, gradation curve, absorption, bulk density and mineralogy. These variables mean that the reason for the low slag MDD is not yet a proven conclusion, but a hypothesis.

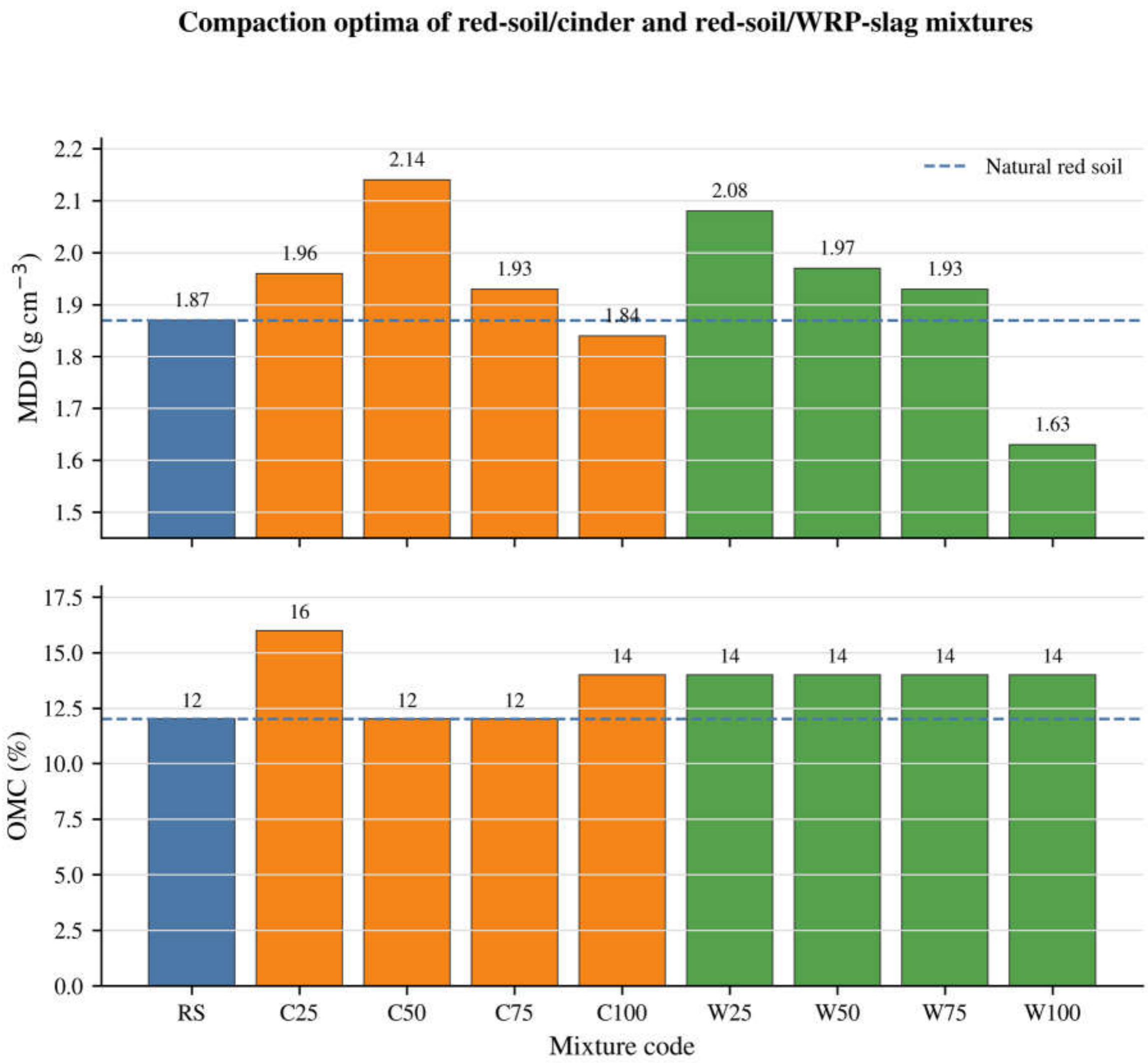

Fig. 4. Summary of maximum dry density (MDD) and optimum moisture content (OMC). RS = red soil; C and W = cinder and WRP slag; numerals are residue percentages.

4.4 Comparative interpretation of OMC and MDD

As can be seen in figure 4, the two residues reacted differently. At the same replacement level (50%), the higher MDD values were achieved with Cinder while the optimum MDD values were achieved with WRP slag for the replacement level of 25%. The OMC variation was also higher in the cinder series, in the range of 16% at C25, 12% at C50 & C75 and 14% at C100. The WRP series continued to stay at 14% OMC. These observations back up the practice of setting moisture-density control values specific to the mixture, instead of a single project-wide value. If all the mixes were to be made with the untreated-soil OMC, they would be subject to compaction below their recorded peak for C25.

Practically density improvement can be achieved by reducing void ratio and hence enhance particle rearrangement. It is not a full pavement acceptance criterion though. In a dense mixture, there can be weak contact between particles, moisture-sensitive fines, and/or cinder grains or slag constituents that are not resistant to degradation. All the above requirements must be tested separately for strength, resilient response, durability and drainage.

4.5 California bearing ratio

Table 4. Recorded laboratory CBR results. The source does not identify soaking, surcharge or replicate confirmation

Material	CBR at 2.5 mm (%)	CBR at 5.0 mm (%)	Adopted CBR (%)	Difference
Red soil	1.94	2.01	2.01	Reference
50% red soil + 50% cinder	2.66	2.69	2.69	+33.38%

75% red soil + 25% WRP slag	2.05	2.58	2.58	+28.36%

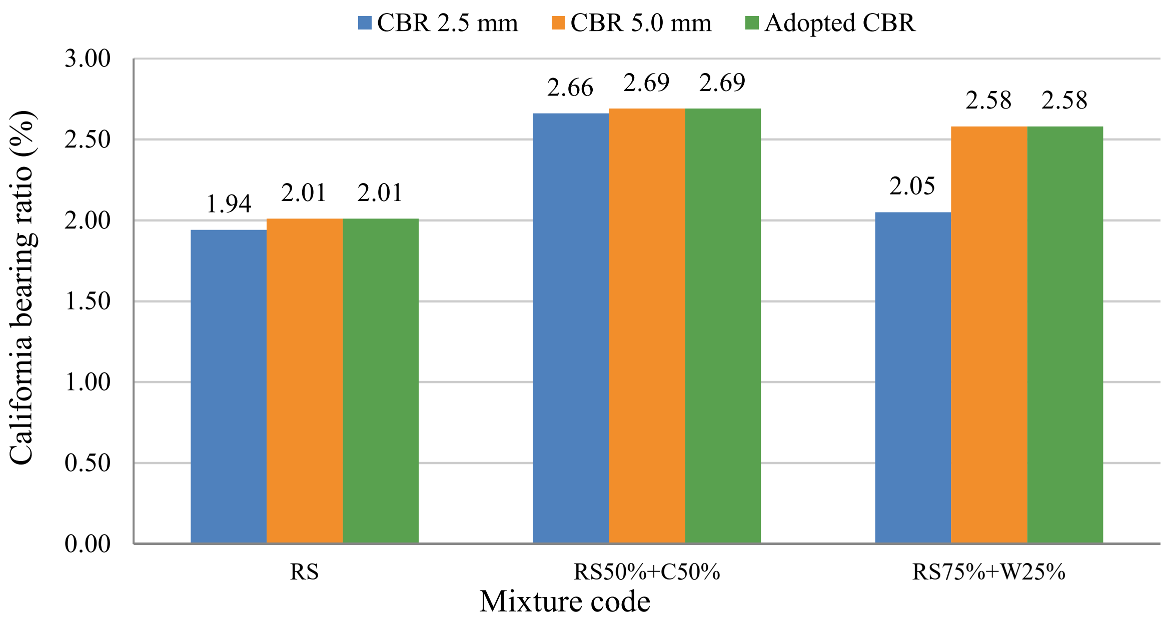

Fig. 5. CBR comparison for the untreated soil and selected mixtures. Values are single reported observations.

The adopted CBR of the untreated soil was 2.54%. RS50%+C50% increased this value to 2.69%, while RS75%+W25% produced 2.58%. These are the gains of 33.38% and 28.36% respectively. The changes are far less significant than the gains of 14.4% and 11.2% achieved by MDD. However, even at 2.5 mm penetration, where the relative differences are bigger, RS50%+C50% and RS75%+W25% performed better by around 37.11% and 5.67% respectively than RS.

This is the main result, the divergence between density and CBR. Compaction is the mass per moisture condition and the CBR is a measure of penetration resistance under a particular confinement and surcharge and moisture. Favourable packing may thus occur in the presence of low penetration resistance either because the bondage is low or because the fine fraction softens. The adopted values continue to be at a relatively low level and are not intended to represent suitability to be used for a structural subbase. At best, they indicate that RS50%+C50% and RS75%+W25% are potential options for a more full-scale verification program.

In all of the reported trials, the 5.0 mm CBR was greater than the 2.5 mm CBR. When it does happen, it is usually required to be confirmed. The supplied record does not include a repeat-test statement, so the values adopted of 5.0 mm are kept in the supplied record for traceability, but should be checked in a new repeat test series. Soaked testing is of particular importance because of the possibility of losing suction derived apparent strength in red-soil fines and the possibility of changing the drainage and water retaining properties of the red-soil fines in the case of slag or cinder.

5. Conclusions

The following conclusions are drawn from the recorded laboratory results:

1. The red soil parent material contained 1.30% gravel, 64.60% sand and 34.10% silt and clay and had a specific gravity of 2.59. The specific gravities of cinder and WRP slag were 2.26 and 2.79, respectively.
2. The OMC and MDD values of the untreated red soil were 12% and 1.87 g/cm³, respectively. The highest values of the cinder series were obtained at C50 with 2.14 g/cm³ at 12% OMC corresponding to a density increase of 14.4%.
3. The WRP-slag series was maximum for W25 with 2.08 g/cm³ at 14% OMC, which was an 11.2% increase in density. As the slag content increased, MDD decreased, and neat WRP slag had 1.63 g/cm³.
4. The adopted CBR increased only from 2.01% for red soil to 2.69% for C50 and 2.58% for W25. As a consequence, there was not a corresponding increase in bearing capacity when the substantial MDD improvement was achieved.

Declarations

Data availability: No external dataset was used. All numerical results were derived from the formulas, tabulated observations and finite compaction with the experimental investigation. The values supporting the findings are included in this article.

Conflict of interest: The authors declare no conflict of interest.

Funding: No specific funding information was supplied for this study.

Author contributions: Saravanan R: Conceptualization, Investigation, writing – original draft & review editing, analysis, methodology, project administration; Poongodi K: Supervision and methodology, project administration, validation and final approval; Preetha J: review and numerical analysis; Vembu T: grammatical review and formal analysis.

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