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Effects of Ground Coal Bottom Ash and Calcium Chloride on the Compaction Properties of Cement Stabilized Cold In-Place Recycling (CIPR) Pavement Base Course

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ABSTRACT

Flexible asphalt pavement relies on a strong road base layer for structural support throughout its service life. Deteriorated pavement conditions require continuous maintenance and rehabilitation, resulting in maintenance costs. Cold In-Place Recycling (CIPR) offers a sustainable and cost-effective solution compared to the conventional method of 'remove and replace.' CIPR involves recycling degraded existing pavement materials with a certain depth of aggregate base to form a new base layer, with the addition of stabilizing agents. Proper compaction before curing is crucial since inadequate compaction reduces base density, risking stability and causing rutting and deformation under traffic. This study investigated the compaction properties in CIPR-based pavement construction, integrating stabilizing agent comprising ordinary Portland cement (OPC), ground coal bottom ash (GCBA), and calcium chloride ($CaCl_2$) to achieve optimal moisture content (OMC), maximum dry density (MDD), and bulk density. Three different ratios of crushed aggregate (CA) and recycled asphalt pavement (RAP) were used, ranging from 25% to 75%, alongside 1% - 4% OPC, 0% - 3% GCBA, and 0% - 3% $CaCl_2$. It was discovered that the OMC and MDD values were 5.22% and 1.86 Mg/m³ for CA25RAP75, 5.60% and 1.93 Mg/m³ for CA50RAP50, and 5.87% and 1.94 Mg/m³ for CA75RAP25 using the modified Proctor test. Results also found that stabilizing agents minimally affect bulk density, but the percentages of CA and RAP significantly influence it, with design mixes with higher CA content providing higher bulk density. The findings from this study provide initial results on the OMC, MDD, and bulk density values but do not reliably indicate the strength acquired by the proposed design mix. Further strength tests should be considered.

Keywords: Cold in-place recycling (CIPR), stabilizing agent, Ordinary Portland Cement (OPC), ground coal bottom ash (GCBA), calcium chloride ($CaCl_2$), compaction properties

INTRODUCTION

A high-quality and well-performing road pavement is crucial as it serves as the backbone of transportation infrastructure. Pavements are not merely a means of facilitating the movement of vehicles but are integral to delivering a safe environment to road users. The quality and performance of road pavements directly influence safety, efficiency, and overall user satisfaction.

In the highway transportation system, asphalt pavement is the most common type. In addition to their advanced characteristics, asphalt pavements have drawbacks that might arise over their lifetime (Wang et al. 2021). Consequently, pavement rehabilitation becomes necessary. In cases of severe pavement damage, rehabilitation may extend down to the base course layer. Typically, the base course is made up of unbound materials that, if necessary, can be stabilized to improve the mechanical properties (Barbieri et al. 2022). This layer must be engineered to withstand the stresses and strains imposed by vehicular loads, environmental factors, and other external forces. A compromised pavement base course not only jeopardizes the overall safety of road users but also leads to increased maintenance costs and a shortened service life for the road infrastructure.

Rehabilitating an existing deteriorated pavement base course through the conventional 'remove and replace' method presents a series of challenges, primarily centred around the cost implications associated with the use of virgin materials and the logistics of transportation. This method involves the complete removal of the deteriorated pavement and its underlying base layer, followed by the transportation of new materials to the construction site. Due to the economic impracticality of the existing approach, the cold in-place recycling (CIPR) method is introduced. CIPR enables the utilization of existing pavement materials, fostering a sustainable construction approach. The procedure involves milling, screening, and crushing of the deteriorated pavement materials, facilitating their reuse in the construction process (Lee et al. 2014). Analysis of the life cycle of construction and maintenance practices disclosed that this method proves to be the most economical, leading to a reduction in the total expenses associated with sustaining the longevity of the road pavement (Santos et al. 2017). Moreover, the expenses related to construction can be diminished by 40% when contrasted with conventional methods, primarily because the process involves lesser utilization of new materials. (Sufian et al. 2009).

One of the critical aspects demanding careful consideration in this foundational phase is the compaction properties. These properties hold exceptional significance as they directly influence the density, stability, and load-bearing capacity of the underlying layers, forming the basis for the entire pavement structure. Adequate compaction ensures that the materials in each layer are densely packed, reducing voids and enhancing load-bearing capacity. In addition, compaction significantly affects the load-bearing capacity of pavement. Proper compaction ensures a high level of road service (Zhu et al. 2018). According to Abu-Farsakh et al. (2004), compaction is a crucial step in the construction of road pavements since it has an immediate impact on the strength and durability of the pavement aggregate bases. Insufficient compaction leads to a lower density of the base material, reducing its stability. This can result in rutting, deformation, and overall pavement failure under traffic loads. Materials selection, aggregate gradation, stabilizing agent, and moisture content are also important factors that must be considered. Road base stabilization is a common engineering method

Hence, this study is undertaken to examine the compaction properties involved in constructing the pavement base course using CIPR technique, incorporating a chemical stabilizing agent. According to Tan & Chan (2021), the most common chemical stabilizing agent use in Malaysia is Ordinary Portland Cement (OPC). This is due to its effectiveness in providing structural strength and durability as well as being readily available. However, the extensive use of cement in construction has become a significant environmental concern due to its substantial contribution to global CO_2 emissions. Yadav et al. (2020) stated that the production of cement contributes approximately 4–8% to global CO_2 emissions. This makes it a major contributor to climate change. Considering the importance of sustainable construction materials, it is crucial to utilise industrial waste products as partial replacements for cement (Mangi et al. 2018).

One of the industrial wastes that can be considered is coal bottom ash. A study by Abdullah et al. (2019) has mentioned that the costs associated with opening new landfill areas, transporting to disposal sites, and maintaining reclamation facilities will increase significantly due to the growing accumulation of bottom ash. Plant operators have begun collaborating with researchers and industries to maximize the utilization of the substantial volume of accumulated bottom ash.

Therefore, coal bottom ash that has been ground to become ground coal bottom ash (GCBA), along with calcium chloride ($CaCl_2$), is being used in this study as chemical stabilizing agent to reduce the amount of OPC. Most researchers suggest that GCBA has the potential to function effectively as a secondary supplementary cementitious material when enhanced its fineness, making it a promising pozzolan (Basirun et al. 2017).

In understanding the compaction properties with the inclusion of this stabilizing agent, this study is conducted with the aim to achieve the optimum moisture content (OMC), maximum dry density (MDD), and bulk density of the proposed design mix. These parameters are essential for evaluating the effectiveness of the stabilization process in enhancing the structural integrity and performance of the pavement base. The findings obtained from this study will be utilized to strategize the upcoming tests aimed at examining the mechanical properties of the base course.

MATERIALS

The design mix for the main structure of the pavement base course involved the integration of two essential materials which are crushed aggregate (CA) and recycled asphalt pavement (RAP). This sustainable approach not only addresses environmental concerns by repurposing existing materials but also contributes significantly to the circular economy. These two key materials, CA and RAP, play pivotal roles as foundational elements, imparting essential characteristics to the mix. Together, they form a harmonious blend that not only enhances the overall composition but also ensures the structural integrity and longevity of the pavement.

Three different compositions of CA-RAP serving as the main structure are proposed in this study based on potential variations encountered at the construction site. In addition, a stabilizing agent made up of OPC, GCBA, and $CaCl_2$ is added to the mixture in order to assess its impact on the bulk density of the mix. The OPC used is CEM type I while raw coal bottom ash (CBA) used is obtained from Jana Manjung Power Plant in Perak. CBA has good potential to be used as pozzolanic material due to the presence of silica in high amounts (Khaskheli et al. 2020). However, raw CBA is inappropriately utilized as a pozzolanic material in its natural state due to its larger size and porosity as shown in Figure 1. Instead, it has to be ground to a particle size maintained on sieve no. 325 (44µm) is less than 5%, which exhibited good pozzolanic capabilities (Jaturapitakkul & Cheerarot 2003). Therefore, raw CBA this study is grounded to a passing 45µm sieve size to produce ground coal bottom ash (GCBA). In addition, $CaCl_2$ used is a 74% minimum flake industrial grade. Generally, $CaCl_2$ is used as an accelerator that can significantly increase the hardening rate of cementitious materials, reducing the time required by more than one-third compared to the normal duration (Williams et al. 2020)

Table 1 provides a summary of the percentage composition of the materials employed in the CIPR base course for this study. The proportions of CA to RAP mix vary from 25% CA to 75% RAP up to 75% CA to 25% RAP, reflecting a spectrum of ratios used in asphalt recycling and rehabilitation practices. All percentages of stabilizing agent are based on the total dry weight of the CA-RAP sample. The total percentage of stabilising agent, comprising both OPC and GCBA, is fixed at 4%. This percentage is determined to be the optimal amount required for effective stabilization during construction activities.

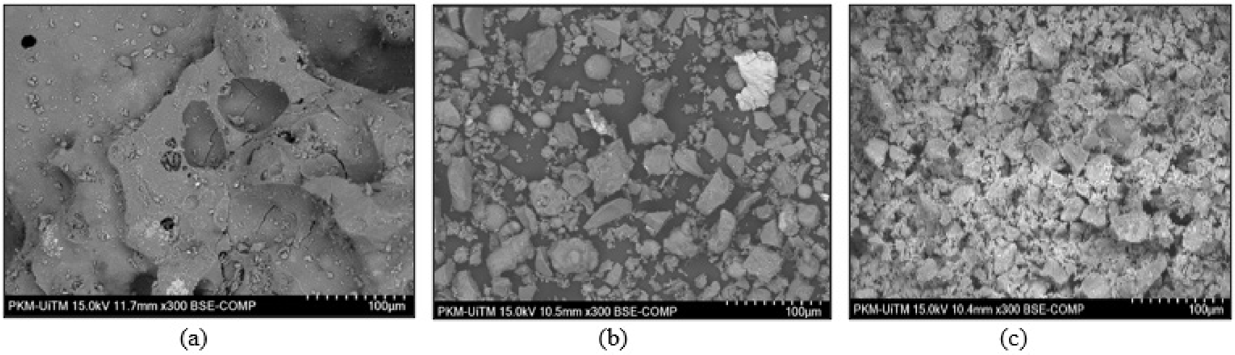


FIGURE 1. Scanning electron microscope at 300X magnifying power of a) raw coal bottom ash, b) ground coal bottom ash, c) ordinary Portland cement

TABLE 1. Materials composition used for the design mix

Aggregate ratio of CA:RAP (%)	Stabilizing Agent		
	OPC (%)	GCBA (%)	$CaCl_2$ (%)
CA25RAP75	1 - 4	0 - 3	0 - 3
CA50RAP50	1 - 4	0 - 3	0 - 3
CA75RAP25	1 - 4	0 - 3	0 - 3

In order to ensure the quality of CIPR aggregates in the design mix, it is essential to adhere to a gradation envelope defined by the upper and lower limits, incorporating both CA and RAP. This compliance follows the specifications outlined in the Malaysia Public Work Department (JKR) Standard Specifications for Road Works (JKR, 2008), facilitating uniform distribution during sample preparation. Figure 2 shows the particle size distribution curve of the CA-RAP used in this study.

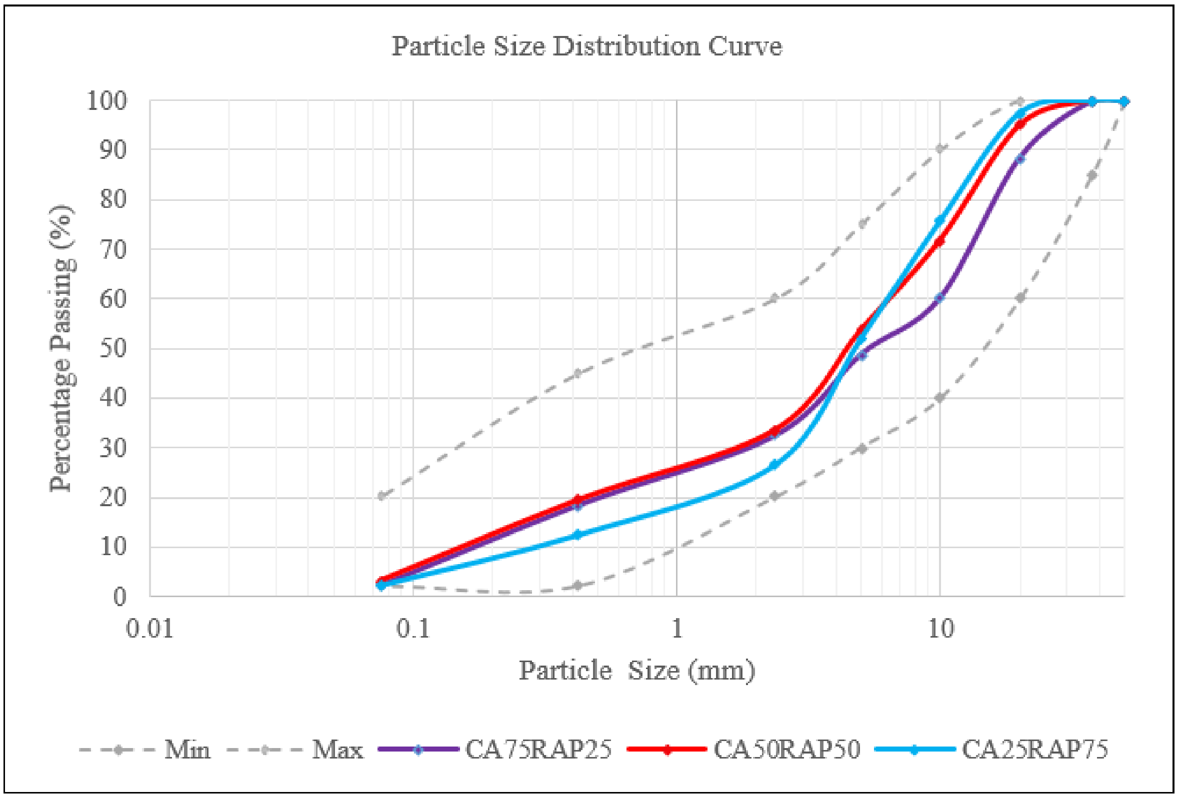


FIGURE 2. Particle size distribution curve for CA-RAP

METHODS

DETERMINATION OF OPTIMUM MOISTURE CONTENT (OMC) AND MAXIMUM DRY DENSITY (MDD) DATA ANALYSIS

The initial stage of the test involves establishing the OMC and MDD of the specimen. Notably, this test is carried out in the absence of any stabilizing agent. The purpose of this phase is to evaluate the fundamental properties of the specimen, providing essential baseline data on its moisture content and density characteristics without the influence of a stabilizing agent. The Modified Proctor Test, conducted in accordance with BS 1377: Part 4: 1990, serves to establish the correlation between moisture content and dry density for a specific compaction effort in the design mix. Prior to initiating the compaction test, aggregates of CA and RAP are first extracted after passing through a 20 mm sieve. These specimens are crafted within a cylindrical mould shown in Figure 3, featuring an internal diameter of 105 mm and a height of 115.4 mm, with the appropriate water content. The compaction process involves five layers, each subjected to 27 blows per layer using standard compaction. A 4.5 kg rammer is then dropped onto the specimen's surface from a height of 45 cm. Subsequently, the specimen is extruded and placed in the oven at the temperature around 100°C for 24 hours for moisture content analysis.

FIGURE 3. Modified proctor test specimen

DETERMINATION OF BULK DENSITY

A similar method shown in Figure 4 is used to determine the bulk density of the specimens. In this phase, the specimens are prepared with the addition of stabilizing agent using the OMC and MDD obtained in the first stage. The specimen is formed using the same cylindrical mold employed in determining the OMC and MDD, consisting of five layers. Each layer is compacted using a 4.5kg rammer with 27 blows. Subsequently, the specimen is weighed to ascertain the bulk density of the design mix. Technically, this particular test plays a crucial role in elucidating the volume characteristics of the road base material, providing valuable insights into the material's stability and performance within the base layer.

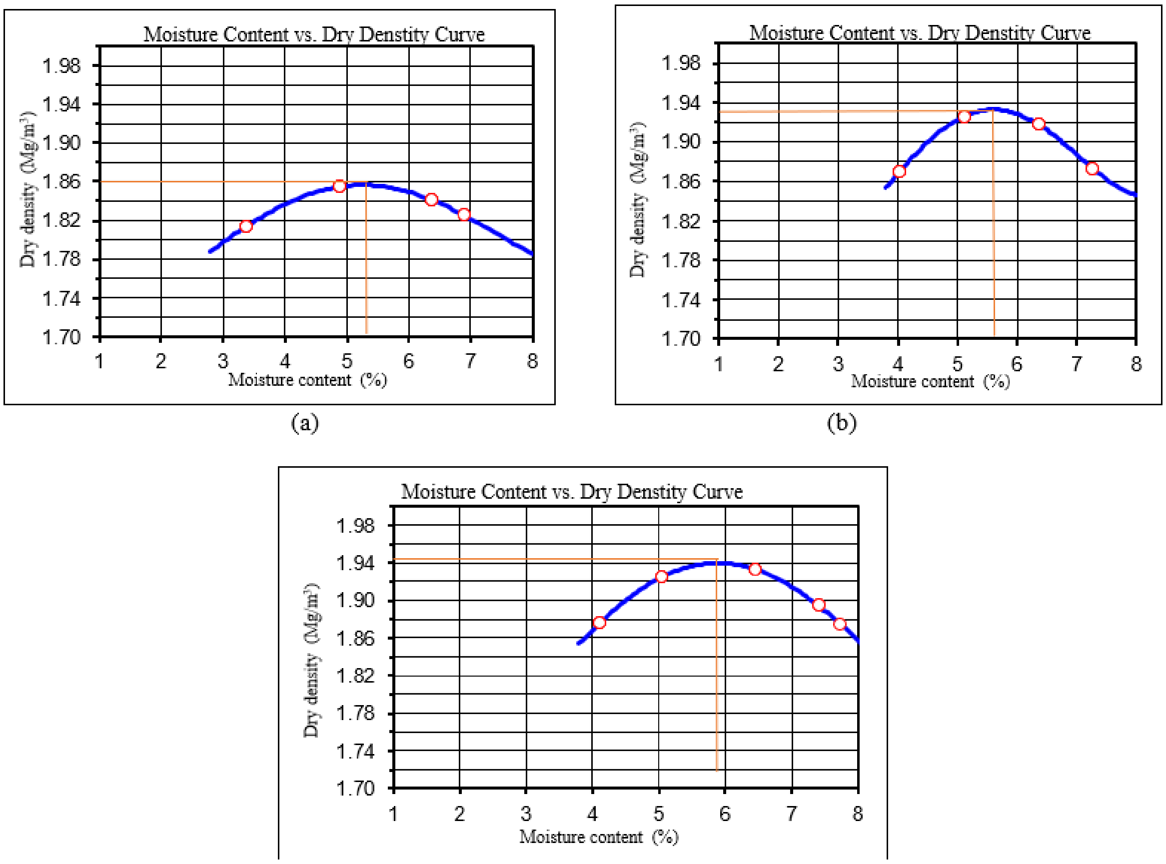
FIGURE 4. Bulk density specimen

RESULTS AND DISCUSSIONS

OPTIMUM MOISTURE CONTENT (OMC) AND MAXIMUM DRY DENSITY

Figures 5 (a) – (c) and Table 2 collectively illustrate the relationship between OMC and MDD, revealing a discernible pattern of escalating moisture content corresponding to an increase in the percentage of CA in the design mix. Specifically, in the CA25RAP75 mix, the recorded OMC and MDD values stood at 5.22% and 1.86 Mg/m³, respectively. Transitioning to the CA50RAP50 mix, the OMC increased to 5.6%, while the MDD remained constant at 1.93 Mg/m³. Furthermore, in the CA75RAP25 mix, the OMC reached 5.87%, and the MDD was measured at 1.94 Mg/m³. These findings highlight the influence of varying CA-RAP compositions on the moisture content and density characteristics of the specimens.

The increase in OMC with the progressive inclusion of CA in the design mix is explained by the irregular shapes and varied sizes of CA particles. These attributes lead to less effective packing compared to RAP which comprises finer particles. The irregular shapes of CA particles and the larger gaps between them create a demand for increased water to fill these voids and aid in compaction, resulting in an increase in moisture content. Conversely, RAP particles exhibit a more efficient interlocking behavior, facilitating effective moisture retention within the mix. The contrast in particle characteristics between CA and RAP significantly influences the moisture requirements for achieving proper compaction in the base course mixture.



(a)

(b)

(c)

FIGURE 5. OMC and MDD for a specimen of a) CA25RAP55, b) CA50RAP50, c) CA75RAP25

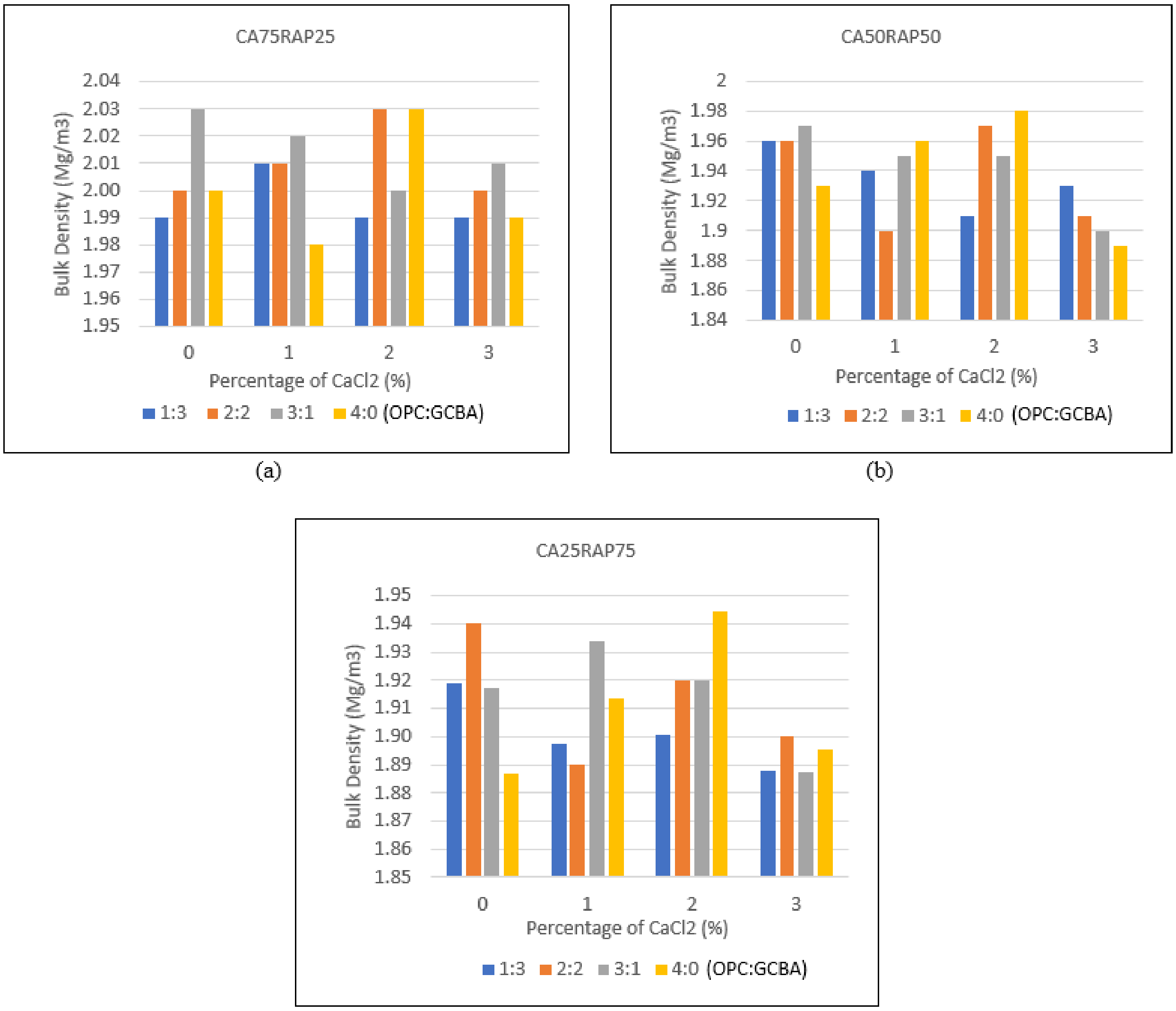
TABLE 2. Summary of OMC and MDD of the specimen

Grading Sieve Size (mm)	Aggregate Proportion (% Passing)		
	CA25 RAP75	CA50 RAP50	CA75 RAP25
50	100.0	100.0	100.0
37.5	100.0	100.0	100.0
20	97.4	95.0	88.5
10	75.7	71.9	60.2
5	51.9	53.7	48.8
2.36	26.6	33.6	32.4
0.425	12.5	19.6	18.3
0.075	2.3	3.2	2.0
OMC (%)	5.22	5.60	5.87
MDD (Mg/m³)	1.86	1.93	1.94

BULK DENSITY

Figure 6 (a) – (c) illustrates the results obtained on the bulk density of the mixture incorporating various proportions of CA-RAP and a stabilizing agent. Analysing the impact of the stabilising agent on bulk density, the CA75RAP25 design mixture demonstrated a bulk density ranging from 1.98 to 2.03 Mg/m³, while the CA50RAP mixture exhibited a range of 1.90 to 1.98 Mg/m³. For the CA25RAP75 design mixture, the bulk density fell within the range of 1.89 to 1.94 Mg/m³. Notably, examining the trend across different percentages of the stabilising agent reveals inconsistent values, suggesting a minimal impact on the overall bulk density of the design mixture.

These findings imply that the chemical stabilising agent utilised in this investigation may not significantly alter the particle arrangement within the road base material. Instead, its influence seems to be directed more towards enhancing binding properties that significantly enhance the overall strength and durability of the stabilized material rather than directly affecting bulk density. Therefore, it is worth noting that chemical stabilizing agents primarily prioritize improvements in bonding and material properties, with less significant effects on the physical packing of the material.



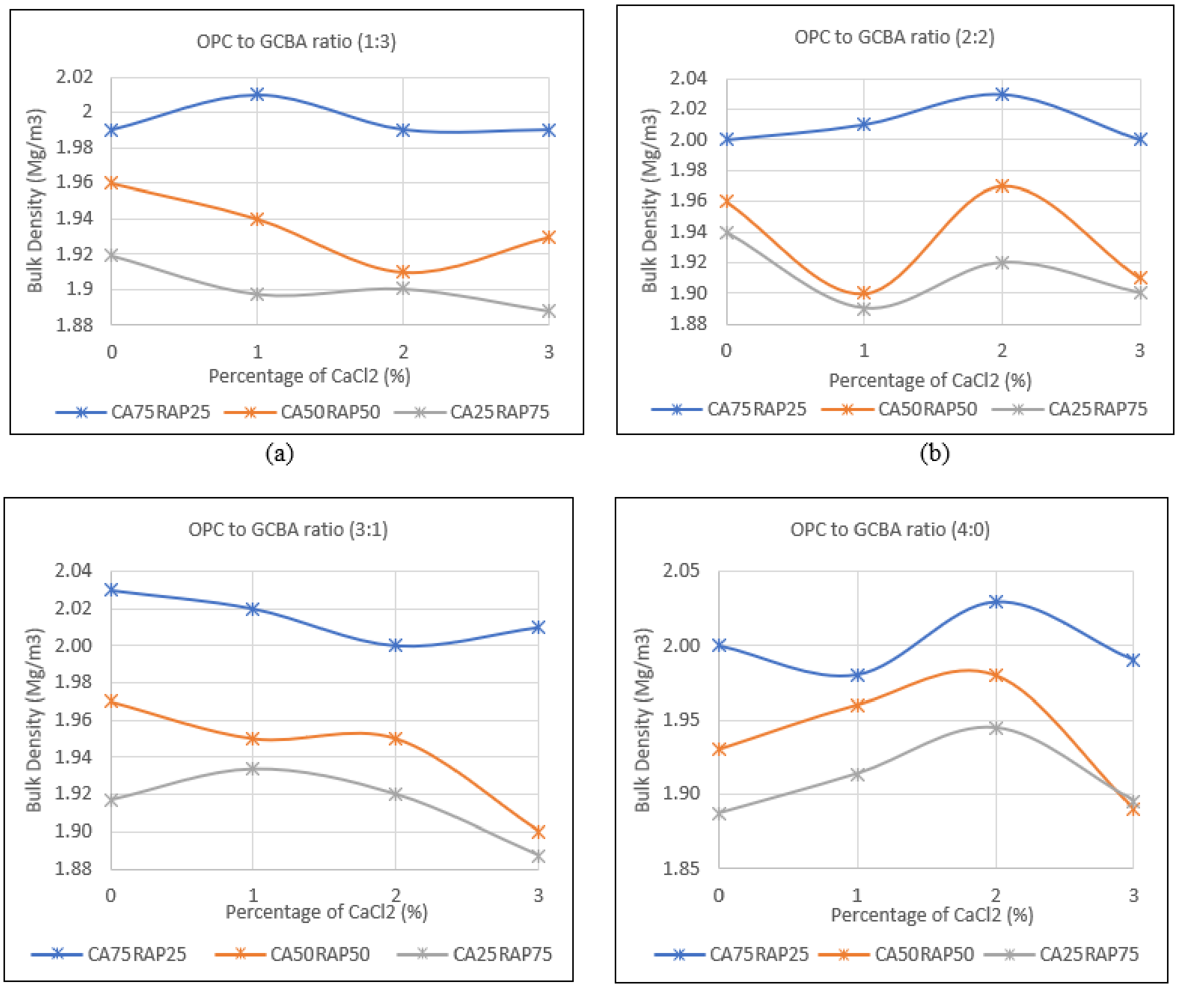
(a)

(b)

(c)

FIGURE 6. Effect of stabilizing agent on bulk density for specimen a) CA75RAP25, b) CA50RAP50 and c) CA25RAP75

However, a clear pattern emerges when comparing different percentages of CA-RAP content as shown in Figure 7 (a) – (d), indicating that the mixture with higher CA content tends to exhibit a higher bulk density.



(a) (b)

(c) (d)

FIGURE 7. Bulk density for different CA-RAP with various OPC-GCBA ratio; a) 1:3, b) 2:2, c) 3:1, d) 4:0

The results reveal a notable trend where the design mix containing 75% of crushed aggregate (CA75RAP25) content demonstrates the highest bulk density value, followed by the CA50RAP50 mix, and then the CA25RAP75 mix. This trend shows a consistent increase in bulk density corresponding to higher percentages of CA-RAP content. Specifically, the mix with CA75RAP25 exhibits the highest bulk density, suggesting that a higher proportion of CA significantly enhances the compaction and stability of the mixture.

This highlights the critical role of the CA-RAP composition in influencing bulk density outcomes within the design mix. Higher CA content contributes to a denser and more robust base layer, which is essential for the pavement's structural integrity and load-bearing capacity. The increased bulk density associated with higher CA proportions suggests improved interlocking of particles and reduced void spaces, leading to a more compact and stable pavement structure. This finding aligns with the general principle that coarser particles can be compacted to achieve a higher bulk density compared to finer particles (Worku & Shiferaw, 2004). Therefore, balancing the composition of CA and RAP in the mix is one of the key factors in determining the performance characteristics of the base course, emphasizing the need for careful consideration of these ratios in the design and construction of CIPR-based pavements. In addition, it also provides optimal compaction characteristics of the base course.

CONCLUSION

The aim of this study to evaluate the compaction properties of the CIPR base course stabilized with OPC, GCBA and CaCl2 using modified proctor compaction test has been accomplished. The following are the conclusions drawn from the study:

1. As the quantity of CA in the mix increases, there is also a corresponding elevation in the OMC level. It was observed that CA25RAP50 exhibited OMC of 5.22%. Subsequently, the OMC increased to 5.60% with CA50RAP50 and further rose to 5.87% with CA75RAP25.

2. This sequential trend highlights a progressive elevation in the OMC as the proportion of CA increased in the mix. Such findings indicate the influence of varying aggregate compositions on moisture sensitivity, emphasizing the need for careful consideration and optimization of mix designs to attain desired performance characteristics in pavement materials.

3. There were inconsistent trends observed on the effect of stabilizing agent of all the design mixes on the bulk density, indicating minimal impact on overall bulk density. It can be said that their primary function is to enhance the binding properties instead of bulk density.

4. In term of aggregate gradation, CA75RAP25 mix exhibited a bulk density range of 1.98 to 2.03 Mg/m³, CA50RAP mix ranged from 1.90 to 1.98 Mg/m³, and CA25RAP75 mix fell within 1.89 to 1.94 Mg/m³. This trend indicates a clear correlation between increased CA content and elevated bulk density. The observation highlights the significant influence of CA-RAP composition on bulk density outcomes within the design mix.

While the compaction test gave initial results on the OMC, MDD and bulk density values, they do not provide a reliable indication of the strength acquired by the proposed design mix. Additional laboratory tests specifically targeting the mechanical properties of the mix, such as compressive strength, indirect tensile strength, resilient modulus, etc. are essential to comprehensively evaluate its structural integrity and performance under varying loading conditions. Only through such comprehensive testing can a thorough understanding of the design mix strength characteristics be obtained, ensuring its suitability for real-world applications in construction and infrastructure projects.

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DECLARATION OF COMPETING INTEREST

None.

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