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Experimental study on Geotechnical and Mechanical Performance of Reclaimed Asphalt Pavement (RAP) utilization in Cement-Treated Base (CTRB)

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Abstract
The increasing demand for sustainable pavement materials has prompted growing interest in Reclaimed Asphalt Pavement (RAP) as a substitute for virgin aggregates in Cement-Treated Recycled Base (CTRB) construction. Despite existing studies on RAP utilization, the integrated mechanisms governing density formation, cement bonding efficiency, and strength development in CTRB mixtures remain insufficiently understood. This study investigates the mechanical and compaction behavior of CTRB mixtures composed of six RAP–virgin aggregate (Base A) proportions, each stabilized with 5% Portland Composite Cement. Laboratory testing included Modified Proctor compaction, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) at 7, 14, and 28 days of curing. Finite Element Method (FEM) analysis using LUSAS software was also performed on the optimum composition to evaluate the stress, strain, and displacement responses under compressive loading. Results indicate that mixtures containing 50–70% RAP yield superior mechanical performance, with the BA50–R50 mixture achieving the highest 28-day UCS of 1.380 MPa and the BA70–R30 mixture recording the highest CBR of 275%. A key novel finding is the inverse CBR–UCS relationship observed across compositions: residual asphalt in RAP enhances cement matrix bonding and compressive strength, yet does not proportionally improve CBR, which is governed more strongly by aggregate density and gradation. FEM results confirmed linear-elastic behavior, with a maximum displacement of 0.0148 mm and microstrain levels, demonstrating the structural stiffness of the optimum mixture. These findings provide new mechanistic insight into RAP–cement synergy and offer practical guidance for designing sustainable, high-performance pavement base layers.

Keywords:
Cement Treated Recycled Base; Mechanical Properties; Reclaimed Asphalt Pavement;

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INTRODUCTION

Reclaimed Asphalt Pavement (RAP) is a recycled material consisting of a blend of asphalt binder and aggregate. It originates from the surface layer of flexible pavements, which is removed or milled during road reconstruction or rehabilitation activities. RAP is considered a cost-effective and environmentally friendly alternative to virgin pavement materials, primarily because it reduces the demand for new binder and aggregate. The use of RAP significantly reduces waste generated during pavement reconstruction while promoting circular economy principles through recycling. Moreover, the high content of recycled materials in RAP leads to reduced transportation requirements, lower environmental pollution, and shorter project durations [1][2].

Regulations regarding the use of RAP vary among countries, depending on environmental policies and the availability of processing technologies. In the United States, RAP is widely employed, with most states allowing approximately 15–30% RAP content in asphalt mixtures. In Europe, around 50% RAP is used in Hot Mix Asphalt (HMA) or Warm Mix Asphalt (WMA) mixtures. Japan maintains one of the most efficient recycling systems globally, with RAP utilization rates reaching up to 99%. In contrast, Australia and New Zealand exhibit diverse regulatory approaches; some states permit as little as 15% RAP, while others restrict its use in surface layers entirely [3]. India permits the use of up to 30% RAP in asphalt mixtures, supported by technological advancements in asphalt mixing plants (AMPs) and collaboration with local contractors [4]. In Indonesia, several technical specifications have been issued to guide the design and use of RAP in pavement construction. The "Special Interim Specification for Recycled Hot Mix Asphalt in Mixing Plants" governs the use of RAP in asphalt concrete (AC) and cold-mixed asphalt (LTBA) surface-layer mixtures. Additionally, the use of RAP in base and subbase layers is governed under Special Specifications for Cement Treated Recycling Base (CTRB) and Cement Treated Recycling Subbase (CTRSB) [5].

RAP can be used in both surface asphalt mixtures and cement-treated layers, such as CTRB and CTRSB. However, in both applications, RAP is rarely used in its entirety; it is typically blended with virgin aggregates in varying proportions to ensure optimal material quality and structural performance. According to international recommendations, RAP content in asphalt mixtures ranges between 15% and 50%, whereas in cement-treated applications such as CTRB or CTRSB, it can reach up to 80%. Therefore, from a sustainability perspective and in promoting material recycling practices, the optimized use of RAP in CTRB/CTRSB offers a more efficient strategy to reduce reliance on natural resources while maximizing the utilization of recycled materials.

Numerous previous studies have investigated the application of RAP as an alternative material in CTRB mixtures. Chakravarthi et al. [6] explored the effect of varying cement contents on the mechanical properties of CTRB containing different proportions of RAP and conventional aggregates. His study concluded that increasing the cement content and decreasing the RAP proportion improved mechanical properties, including unconfined compressive strength (UCS) and elastic modulus. This improvement is attributed to stronger bonding from higher cement content, whereas higher RAP proportions tend to increase creep surfaces, weakening the mixture's internal cohesion. Furthermore, research by Mustafa et al. [7] showed that incorporating 4–6% cement not only enhances mechanical properties but also significantly affects the optimum moisture content (OMC) and maximum dry density (MDD). Pradhan & Biswal [8] reported similar findings. His study recommended an optimal composition of 80% RAP and 4% cement to improve key mechanical parameters, including UCS, California Bearing Ratio (CBR), compaction characteristics, and resilient modulus, based on repeated triaxial testing. Mariyappan et al. [1] focused on the use of RAP in base and subbase layers, concluding that using 100% RAP in these layers results in reduced strength and deformation resistance. Thus, blending RAP with conventional aggregates and admixtures, such as cement or fly ash, is necessary to achieve adequate mechanical strength and enhance resistance to fatigue cracking and rutting.

Although numerous studies have investigated the use of RAP in cement-treated base materials, most prior research focuses on individual performance indicators such as UCS, CBR, or compaction characteristics in isolation. A clear gap remains in explaining how RAP content simultaneously governs density formation, cement bonding efficiency, and strength development as an integrated mechanism. This study addresses that gap by demonstrating a previously underreported phenomenon: the presence of residual asphalt alters cement matrix bonding and pore structure, producing a non-linear relationship between density and mechanical strength. Unlike earlier studies that attribute performance changes primarily to cement content or RAP percentage, this research aims to reveal how an optimum RAP content creates a synergistic interaction between asphalt residue and cement hydration in CTRB, leading to enhanced strength efficiency rather than simply higher density. This specific mechanistic insight constitutes the core novelty of the present study.

MATERIAL AND METHOD

This study was conducted to evaluate the mechanical and physical characteristics of a Cement Treated Recycling Base (CTRB) mixture composed of various ratios of Reclaimed Asphalt Pavement (RAP) and virgin aggregates (Base A Aggregate), stabilized with Portland Composite Cement (PCC). The research was carried out at the Soil Mechanics Laboratory, STT Pekanbaru, Indonesia, using standardized procedures in accordance with ASTM and SNI (Indonesian National Standard) specifications to ensure the reliability and reproducibility of the results.

Material

The materials utilized in this research included three main components:

1. Reclaimed Asphalt Pavement (RAP)

This material was sourced from milled flexible pavement layers obtained during road rehabilitation works. The RAP, as seen in Figure 1, was crushed and screened to achieve a maximum particle size of 25 mm, ensuring compatibility with the gradation requirements for pavement base layers. RAP served as a recycled aggregate component with residual asphalt binder, contributing both aggregate and adhesive properties to the mixture.

2. Base A Aggregate

This virgin aggregate, as shown in Figure 2, met the SNI specifications for upper base layers. It served as a complementary granular material to balance the variability inherent in RAP and enhance the gradation and strength characteristics of the mix [9].

Figure 1. Reclaimed Asphalt Pavement

Figure 2. Base A Aggregate

3. Portland Composite Cement (PCC)

The cement was used as a hydraulic stabilizing agent at a dosage of 5% by weight of the dry mix. PCC enhances particle bonding and contributes significantly to the development of early and long-term strength in the treated base.
The blend ratio between RAP and Base A was varied. This ratio was selected based on prior research indicating an optimal balance between workability and mechanical performance.

Methods

A comprehensive series of laboratory tests was designed to evaluate both physical and mechanical properties of the CTRB mixtures. The experimental process consisted of several key stages:

1. Physical Property Evaluation

The physical characterization of the mixtures included determination of specific gravity, moisture content, and aggregate gradation. These tests were conducted in accordance with ASTM C127/C128 and ASTM C136. Aggregate gradation was assessed to confirm that the combined RAP and Base A materials fell within acceptable limits for base-layer applications. Moisture content was monitored to determine the water requirement for optimal compaction.

2. Compaction Testing

Modified Proctor tests were performed based on ASTM D1557 to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for each mix variant. These parameters are essential for assessing how moisture and compaction effort influence the density and stiffness of the treated base. Samples were compacted in a standard Proctor mold using a mechanical rammer, ensuring uniform energy application across replicates.

3. Unconfined Compressive Strength (UCS)

To assess the load-bearing capacity of the stabilized mixtures, UCS testing was conducted on cylindrical samples at curing ages of 7, 14, and 28 days. The procedure followed ASTM D1633, which specifies dimensions, compaction protocol, curing environment (typically a humidity-controlled room at 23 ± 2°C), and loading rate. This test measures the axial compressive resistance of the material without lateral confinement, serving as a primary index of mixture strength development over time. Each mixture variation was tested in duplicate to minimize variability and enhance statistical confidence.

4. California Bearing Ratio (CBR)

CBR testing was conducted to evaluate the subgrade support capacity of the CTRB mixtures, which is particularly relevant to structural pavement design. Samples were compacted and soaked in water for 4 days prior to testing to simulate field moisture conditions. The test adhered to ASTM D1883, measuring the force required to penetrate the specimen with a standard plunger under specified conditions. High CBR values indicate good load-distribution properties, essential for base layers under repeated traffic loading.

The experimental matrix comprised six mix designs corresponding to the variety of RAP and Base A aggregate mix ratio. The said variety is shown in Table 1.

Each design was tested across both UCS and CBR parameters. For each mix, two replicate specimens were prepared and tested. By employing a methodical and standardized approach, this research aimed to generate reliable, reproducible data on the performance of cement-stabilized recycled mixtures. Furthermore, the results are expected to contribute to ongoing efforts to optimize RAP utilization in pavement structures, balancing sustainability objectives with engineering performance.

To clarify the overall research process, a schematic flowchart (Figure 3) has been added to illustrate the sequence of activities, starting from material collection and preparation, laboratory testing (compaction, CBR, and UCS), data analysis, and interpretation of the results. The research framework links each experimental stage to its expected output, establishing how the RAP proportion affects physical and mechanical behavior through compaction and cementation mechanisms.

RESULTS AND DISCUSSION

This section presents the results of laboratory testing conducted to evaluate the physical and mechanical characteristics of the Cement Treated Recycling Base (CTRB) mixtures incorporating various ratios of Reclaimed Asphalt Pavement (RAP) and Base A aggregates.

Table 1. Mix Design Variety

Code	Ratio (%)		Cement (%)
	BA	RAP	
BA100-R0	100	0	5
BA70-R30	70	30	5
BA60-R40	60	40	5
BA50-R50	50	50	5
BA40-R60	40	60	5
BA30-R70	30	70	5

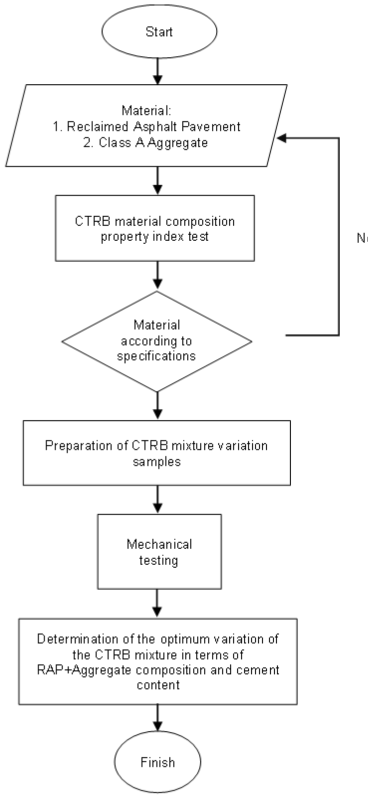

Figure 3. Research Flowchart

Laboratory Test Results

a. Optimum Moisture Content (OMC)

Figure 4 shows the compaction test results. The chart indicates that OMC increases with the higher proportion of new aggregate (Base A) in the mixture. For the 100% RAP mixture (BA100-R0), the optimum moisture content was only 5.70%, whereas in the mixture with 70% Base A (BA30-R70) the value rose to 7.55%.

The intrinsic characteristics of the materials can explain this trend. RAP, due to the presence of a residual asphalt film on its surface, generally exhibits lower water absorption and reduced affinity for moisture, which consequently results in lower OMC values. Conversely, virgin aggregates typically have a rougher texture and higher porosity, thereby demanding more water to achieve optimum compaction [10]. This finding is consistent with a recent review of RAP geotechnical properties, which reported that OMC values for RAP commonly fall within the range of 4–9%, depending on gradation, surface condition, and fines content [11].

Thus, the observed increase in OMC with higher proportions of virgin aggregate in this study aligns well with previously reported trends, reinforcing the role of aggregate type and porosity in governing optimum moisture demand.

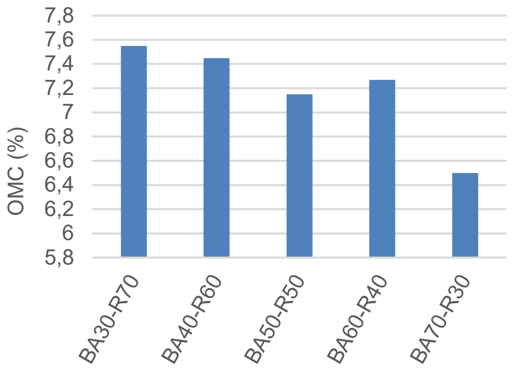

Figure 4. Optimum Moisture Content Result

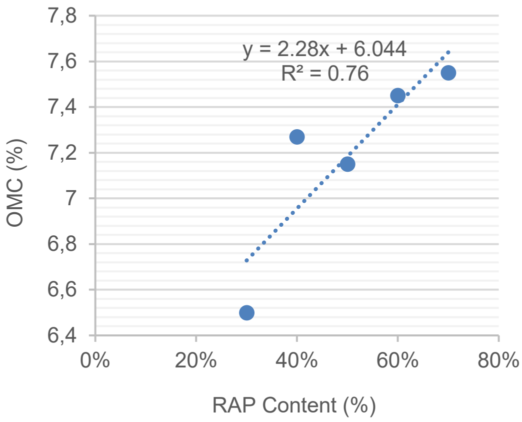

Figure 5. Correlation between percentages of RAP in the mixture of RAP and BA and the optimum moisture content.

The linear relationship between the percentage RAP in the mixture of RAP and BA and the OMC is depicted in Figure 5. The regression analysis produced a coefficient of determination (R^2) of 0.76, indicating a strong positive correlation between the two parameters.

b. Maximum Dry Density (MDD)

The results for maximum dry density (MDD) shown in Figure 6 display an inverse trend relative to OMC: mixtures with higher proportions of RAP yield higher MDD values, while those dominated by virgin aggregate (Base A) exhibit lower MDD values. For example, the 100% RAP mixture (R100-BA0) achieved the highest MDD of 2.246 g/cc, whereas the mixture containing 70% Base A (BA30-R70) dropped to 2.032 g/cc. This pattern aligns with findings from Ramadhan et al. [12], who reported that in FDR mixtures containing both RAP and virgin aggregate, the introduction of virgin aggregate lowered the MDD compared to mixtures with a higher RAP proportion, particularly when the virgin aggregate was coarser.

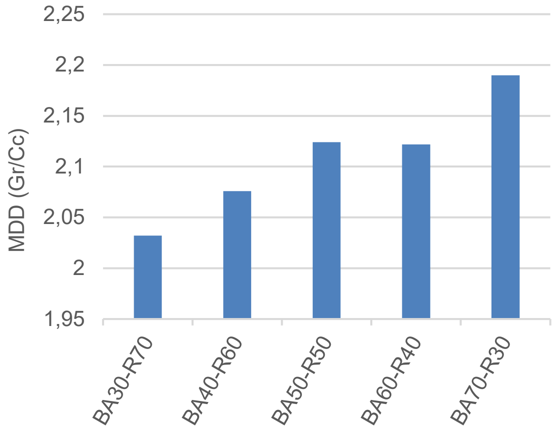

Figure 6. Maximum Dry Density Result

Additionally, Guerrero-Bustamante et al. [13] demonstrate that RAP sources with finer gradation and certain surface textures produce higher MDD when blended with virgin aggregate—but as virgin content increases, the effect of inter-particle voids grows, reducing maximum dry density. Therefore, the observations in the current study are consistent with recent literature, confirming that aggregate type, gradation, and the presence of residual asphalt binder are critical in determining MDD.

The linear relationship between the percentage RAP in the mixture of RAP and BA and the MDD is depicted in Figure 7. The regression analysis produced a coefficient of determination (R^2) of 0.85, indicating a strong positive correlation between the two parameters.

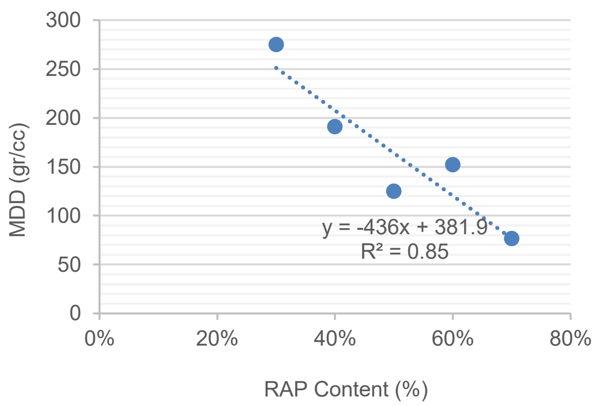

Figure 7. Correlation between percentages of RAP in the mixture of RAP and BA and the maximum dry density

c. California Bearing Ratio (CBR)

Figure 8 shows that the CBR values among the tested mixtures vary considerably, reflecting the critical influence of material proportions and the presence of stabilizer. The highest CBR was observed in the BA70-R30 blend (275%), whereas the lowest was in the mixture with a dominant virgin aggregate (BA30-R70), at 76.5%. The 100% RAP mixture still presented a relatively high CBR (137%), though lower than balanced RAP-virgin mixtures. These observations align with findings from Boaventura et al. [14], who demonstrated that soil-RAP mixtures lacking sufficient virgin aggregate or stabilizer exhibit declining CBR with increasing RAP content. In contrast, modest additions of cement restore substantial bearing capacity.

The interaction between asphalt residue and cementitious bonding can explain the observed variations in mechanical performance. The presence of residual asphalt on RAP particles reduces surface energy, partially hindering cement hydration at the interface. However, at moderate RAP proportions (50–70%), this effect is offset by improved packing density and interparticle contact, resulting in stronger matrix cohesion and reduced porosity.

d. Unconfined Compressive Strength (UCS)

The UCS tests at 7, 14, and 28 days demonstrated consistent strength gains with increasing curing period, reflecting ongoing cement hydration and matrix development. The BA50-R50 mixture achieved the highest UCS at 28 days (1.138 MPa), slightly exceeding that of BA70-R30 (1.128 MPa). Mixtures dominated by virgin aggregate (BA30-R70) yielded the lowest UCS (0.903 MPa at 28 days). These observations correspond to findings by Pradhan [15], who evaluated RAP-virgin aggregate mixtures with varying cement percentages (1-4%) for subbase layers and observed that UCS increases with cement content, and that mixtures with substantial RAP content still attain good compressive strength if virgin aggregate and cement are balanced.

Moreover, Tavares et al. [16] observed that UCS peaks occur at intermediate proportions of RAP and virgin aggregate; beyond this, the dominance of one component degrades strength due to diminished matrix bonding or increased voids. Supporting this, another study by Khoirunnisa et al. [17] also reported that RAP-Base A blends with cement ≥5% reached UCS values compliant with Indonesian CTRB specifications. The UCS test results are shown in Figure 9

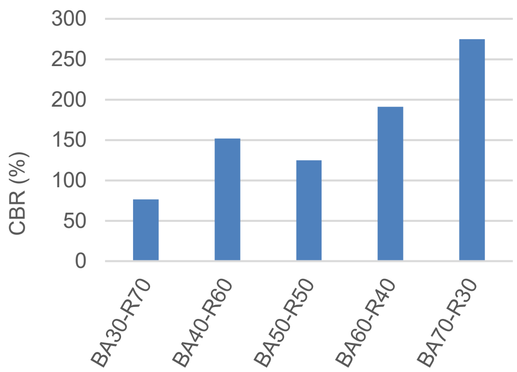

Figure 8. California Bearing Ratio Test Result

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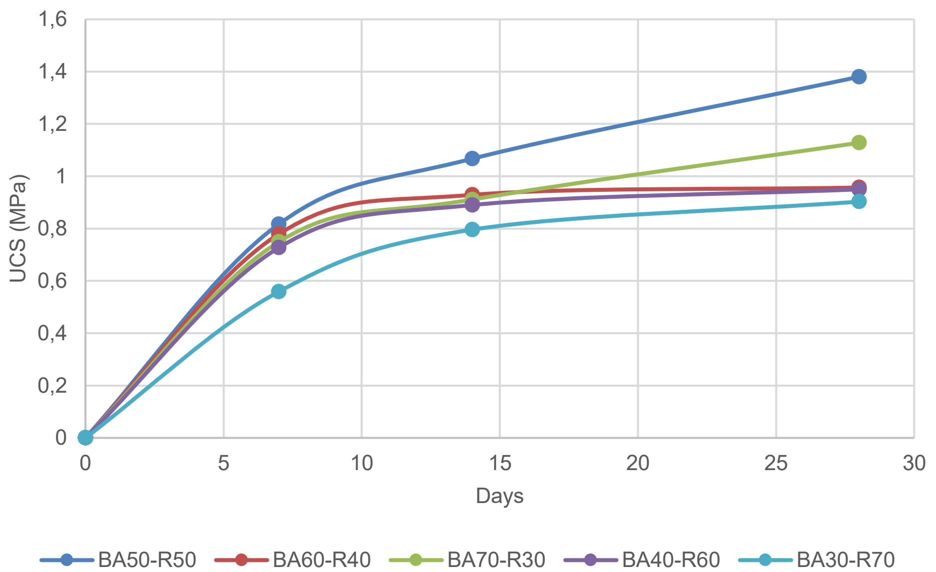


Figure 9. Unconfined Compressive Strength Test Result

Parameter Correlations

a. Correlation between Compaction Results and CBR

In general, mixtures with higher Maximum Dry Density (MDD) tend to yield higher CBR values, though not in all cases; the correlation is strongest in the interpolated range of mixture compositions where compaction, gradation, and moisture conditions align optimally. Pradhan & Biswal [8] demonstrated that in GSB mixtures with RAP + natural aggregate, as RAP content increases up to a moderate level, MDD increases correspondingly and soaked CBR also improves; beyond certain RAP proportions, however, CBR declines. Similarly, Plati [18] reported that RAP-BA blends with ~45-55% RAP that achieve high MDD deliver significantly greater CBR compared to extremes.

Additionally, Lillian et al. [19] observed that sub-base materials with recycled content (including RAP) that reached near-optimal densification exhibited superior CBR performance, illustrating that densification (i.e. achieving high MDD) is a key predictor of bearing capacity when other parameters are well managed.

b. Correlation between CBR and UCS

The relationship between CBR and UCS in mixtures reflects patterns observed in recent studies: while both parameters improve with stabilization and curing, their magnitudes and peak mixtures often diverge. BA70-R30 produced the highest CBR (275%) but did not achieve the highest UCS (1.128 MPa), whereas BA50-R50, with slightly lower CBR, attained the highest UCS (1.138 MPa). The relationship between CBR and UCS was further analyzed statistically and presented in Figure 10.

The highest CBR value was recorded for the BA70-R30 mixture (275%); however, the highest 28-day UCS was observed in the BA50-RA50 mixture (1,380 MPa).

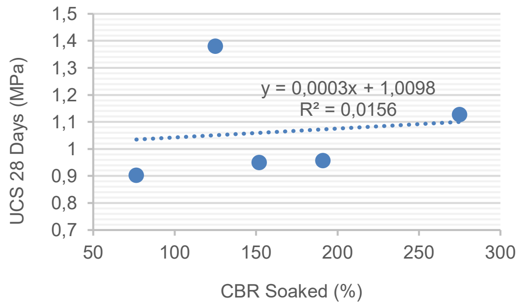


Figure 10. Correlation between CBR and UCS

This indicates that the CBR–UCS correlation in this dataset is inversely proportional: as CBR increases, UCS tends to decrease. This notable phenomenon can be attributed to the residual bitumen present in the Reclaimed Asphalt Pavement (RAP), which provides chemical bonding that enhances UCS.

Nevertheless, this bonding does not proportionally improve CBR, as CBR is more sensitive to aggregate density and gradation than to cementitious or bituminous binding characteristics [20]. Ghimire & Bheemasetti [21] showed that appropriately stabilized RAP-based base mixes can achieve good UCS values, but that peak CBR often occurs at different blend ratios. Khan et al. [22] found that UCS and CBR for cement-treated recycled aggregates increase together. However, the ratio of increase is not identical—CBR often responds more sharply under soaked conditions. Similarly, Jibon et al. [23] reported that as UCS increases with higher cement content and improved compaction, CBR also increases, though not always proportionally, since CBR depends more on penetration resistance and saturation. In contrast, UCS reflects cement matrix cohesion [24].

Potential Use of RAP in Sustainability Issues

The use of Reclaimed Asphalt Pavement (RAP) in cement-treated recycled base (CTRB) mixtures not only delivers competitive technical performance but also offers significant sustainability benefits. RAP is a recycled material obtained from old pavement, and its utilization directly reduces the demand for natural aggregates, the extraction of which has adverse environmental impacts [25]. Furthermore, using RAP helps reduce the accumulation of road construction waste at disposal sites, thereby mitigating environmental pollution and landfill use [26][27]. From an economic perspective, RAP utilization can lower the production costs of pavement layers—life-cycle cost analysis in road asphalt applications has demonstrated cost savings in the double-digit range when RAP is included relative to conventional asphalt mixes [28]. Therefore, integrating RAP into CTRB can be considered a strategic step toward environmentally friendly and cost-efficient sustainable infrastructure.

CTRB Behavior Study When Given A Compressive Force Using a FEM Software Approach

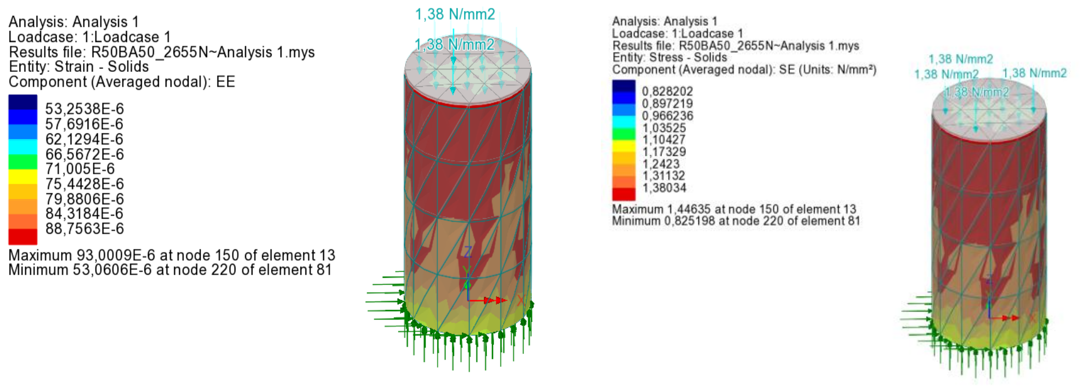
The data employed in this study were derived from experimental results of Cement-Treated Recycled Base (CTRB) specimens with the R50–BA50 composition, which yielded the highest Unconfined Compressive Strength (UCS). The input parameters used in the numerical program comprised density, maximum applied load, elastic modulus, and Poisson's ratio, while the output variables included stress, strain, and displacement (settlement deformation) of the specimens. The results are shown in Figure 11.

The numerical analysis conducted using the Finite Element Method (FEM) with the LUSAS software on the CTRB specimen with BA50–R50 composition revealed that the strain ranged from 0.000053 to 0.000093 (Figure 11a). These values indicate negligible deformation at the microstrain level, consistent with linear-elastic material behavior within the applied load range. The stress distribution ranged from 0.825 to 1.380 N/mm², with a maximum stress of 1.446 N/mm² and a minimum stress of 0.825 N/mm². The stress contour plot (Figure 11.b) exhibits a predominance of orange-to-red zones concentrated in the mid-section to the upper surface of the cylindrical specimen, indicating the primary load transfer zone resulting from the compressive loading of 1.38 N/mm² applied at the top surface. Conversely, the lower region near the support exhibits comparatively lower stress values, attributable to deformation restraint imposed by the boundary conditions.

The strain value (ε) obtained under an applied load of 2,655 N using the LUSAS software was 0.000093, corresponding to a stress value of 1.446 MPa. The resulting failure pattern indicates that settlement occurred uniformly across each layer, consistent with the application of a uniformly distributed load. Each segment of the specimen exhibited a distinct displacement value, represented by different colors (Figure 12). In the displacement contour plot, dark blue represents the minimum displacement value, while red denotes the maximum. The highest displacement value of 0.0147 mm was observed at the upper surface of the specimen. Displacement decreased progressively with depth, reaching 0 mm at the base, consistent with the fixed-boundary condition applied at the bottom support.

The modeling results indicate that the greatest displacement occurred at the upper surface of the cylindrical specimen, while the lower region, serving as the support point, experienced minimal displacement approaching zero at Node 1. The displacement distribution exhibited a uniform color gradient from the base to the top of the specimen, indicating linear axial deformation consistent with the compressive loading applied to a symmetric geometry.

The maximum displacement was recorded at 0.014778 mm at the upper surface of the cylinder, corresponding to the point of load application. The minimum displacement of 0.0 mm was recorded at Node 1, which represents the reference point or fixed boundary condition. The relatively narrow displacement range indicates that the CTRB BA50–R50 mixture exhibits favorable structural stiffness and can sustain applied loads elastically without excessive deformation. These characteristics are of considerable significance in the design of road base layers, as low vertical deformation directly contributes to the pavement structure's resistance to repeated traffic loading.



(a) (b)

Figure 11. Correlation between percentages of RAP in the mixture of RAP and BA and the maximum dry density

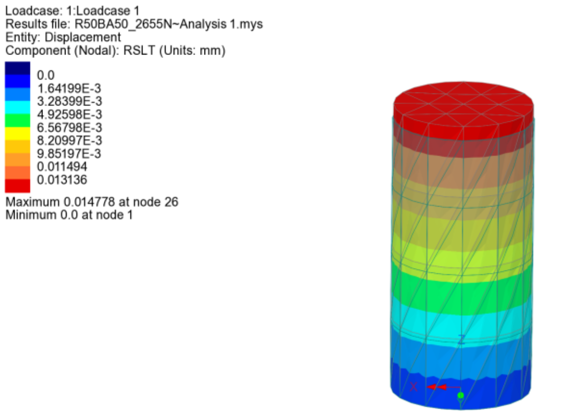


Figure 12. Displacement contour of the sample surface with a load of 2,655 N

CONCLUSION

This study demonstrates that RAP can be effectively utilized in cement-treated recycled base mixtures without compromising mechanical performance when properly proportioned. The experimental results show that RAP contents between 50% and 70%, combined with 5% cement, provide an optimal balance between compaction behavior, bearing capacity, and compressive strength. Beyond confirming performance, the key contribution of this study lies in identifying a density–strength interaction mechanism in CTRB mixtures, in which residual asphalt modifies cement bonding and pore structure, resulting in non-linear relationships among MDD, CBR, and UCS. This finding extends existing knowledge by explaining why maximum density does not always correspond to maximum strength in RAP-based mixtures. From a practical perspective, the results support the use of RAP-rich CTRB as a sustainable pavement base solution that reduces natural aggregate consumption while maintaining structural integrity. The study thus contributes both mechanistic insight and practical guidance for sustainable pavement engineering.

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