Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 05, May, 2025

Mechanical and Physical Evaluations of Fine Sand-RAP Blends for Subgrade and Subbase Applications

Mohamed H. Zakaria [1*], Mostafa El-Fewy [1], Sabry Fayed [1], Ali Basha [1]

[1] *Department of Civil Engineering, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh, 33511, Egypt.*

Received 21 December 2024; Revised 09 April 2025; Accepted 15 April 2025; Published 01 May 2025

Abstract

Fine sand has a low load-bearing capacity and tends to deform easily, limiting its use in road construction. Recycled asphalt pavement (RAP) may offer a sustainable solution to improve these properties. Accordingly, the primary objective is to assess how varying RAP content affects the gradation, compaction, bearing capacity, and California Bearing Ratio (CBR) of sand-RAP blends. RAP contents ranged from 0% to 100% by weight. The results show that integrating RAP improves sand gradation, making it suitable for subgrade layers, with mixtures containing 40%-60% RAP meeting subbase requirements. CBR increases significantly with RAP, from 8.78% in fine sand to 41.67% at 100% RAP. Dry density also improves by 12%-16% with 40%-60% RAP, while optimum moisture content (OMC) decreases by over 30%. Bearing capacity increases significantly with RAP content. At 40%-60% RAP, increases range from 299.53% to 411.83% (D_r = 60%) and 243.69% to 318.43% (D_r = 90%). RAP inclusion enhances stiffness, peaking at 530% (Dr = 60%) and 326% (D_r = 90%) between 40%-60% RAP. Initial gains are steady at 10%-30% RAP, but diminishing returns occur beyond 50% RAP. Generally, notable performance is achieved at 40% RAP, while 50% RAP ensures optimal stiffness and structural integrity, with diminishing returns afterward.

Keywords: Recycled Asphalt Pavement (RAP); Fine Sand-RAP Blends; California Bearing Ratio (CBR); Plate Bearing Tests; Sustainable Road Materials; Relative Density (Dr); Subbase; Subgrade.

1. Introduction

Road construction typically relies on high-quality soil for subgrade and subbase filler material. However, this technique encounters difficulties in ecologically sensitive environments, including riverbanks, coastlines, and deserts, which are characterized by fine sandy soils [1]. Sustainable alternatives for employing off-site fine sand in road construction have emerged to tackle this problem [2, 3]. Although fine sand is often used as a filler, its geotechnical characteristics pose certain challenges [1]. It is distinguished by particles that vary in size from around 0.10 mm to 0.25 mm [4]. The USCS defines fine sand as soil with a particle size between 0.075 mm and 0.425 mm, typically exhibiting a poorly graded distribution [5].

Several constraints exist when using fine sand as subbase or subgrade in road construction. A major concern is its low load-bearing capacity, making it prone to deformation under heavy loads [1, 6-8]. The lack of cohesiveness in fine sand causes instability, raising the risk of rutting, settling, and erosion, particularly when moist, which weakens the pavement's structural integrity [9, 10]. An additional risk pertains to drainage and susceptibility to frost [11, 12]. Fine sand holds less moisture than clay; nonetheless, it is more prone to frost heave and diminished bearing capacity when saturated, which could threaten infrastructure in colder areas. The previous features emphasize the necessity of stabilizing or replacing fine sand in road construction to ensure the durability of the pavement.

* Corresponding author: mohammed_hamed@eng.kfs.edu.eg

http://dx.doi.org/10.28991/CEJ-2025-011-05-017

A variety of strategies are used to improve the performance of sandy soil. Mechanical stabilization (20% to 50%) entails amalgamating sandy soil with coarser aggregates such as gravel or crushed stone, enhancing compaction, load-bearing capacity, and drainage characteristics [13, 14]. Chemical stabilization, ranging from 2% to 5%, involves using polymers or calcium chloride to bind sand particles together. This process improves cohesion and erosion resistance by reducing the susceptibility of the sand to moisture [15, 16]. Lime stabilization (3% to 8%) diminishes the deformation of sand by incorporating lime, enhancing the soil's stability and reducing its susceptibility to swelling or shrinking [17]. Cement stabilization, including 5 to 7%, entails the amalgamation of Portland cement with sand to create a material that exhibits enhanced resistance to subsidence and frost heave [18]. By adding one or two layers of geosynthetics and geogrids, the tensile strength of the sand is increased and the load distribution is balanced, resulting in a reduction in the need for additional stabilizers [19]. In addition, Sand may be made more water-resistant and cohesive by stabilizing it with bitumen or asphalt at a concentration of 4 to 6 percent [20]. Polymer stabilization, obtained by combining sand with synthetic polymers, adds a further 1% to 3% by weight, gives the material durability, and reduces erosion [21]. These solutions alleviate specific issues with sandy soil, allowing for the construction of pavements on a stable and durable basis. Recycled Asphalt Pavement (RAP) has emerged as a promising alternative. It offers a more sustainable solution by improving the mechanical properties of fine sand without the need for additional expensive or environmentally harmful additives. Despite its potential, the use of RAP in road construction, particularly in subgrade and subbase applications, has not been extensively studied.

This study aims to bridge this gap by investigating the mechanical and physical properties of fine sand when blended with RAP. It explores how varying RAP content influences the gradation, compaction, bearing capacity, and California Bearing Ratio (CBR) of sand-RAP blends for road construction. By evaluating these properties, the research seeks to identify optimal RAP content that improves fine sand's performance and meets engineering standards for subgrade and subbase materials. The paper is structured to comprehensively investigate the mechanical and physical properties of fine sand-RAP blends for subgrade and subbase applications. The literature review section sets the stage by reviewing existing literature on stabilization methods for fine sand, highlighting the limitations of current approaches, and identifying the gap in utilizing recycled asphalt pavement (RAP) as a potential solution. The testing program and measured variables section outlines the experimental setup, detailing the preparation of sand-RAP blends with varying RAP content (0%-100% by weight), along with the testing procedures for key properties such as gradation, compaction, California Bearing Ratio (CBR), and bearing capacity. The results section presents the findings from the experimental program, including how RAP content affects the mechanical performance of the blends, with a particular focus on the improvements in CBR, dry density, and bearing capacity. This is followed by a detailed discussion, where the results are analyzed in relation to existing literature, providing insights into the optimal RAP content for achieving improved subgrade and subbase materials. The paper concludes with a summary of the key findings, practical implications for road construction, and recommendations for future research on the use of RAP in sustainable infrastructure development.

2. Literature Review

Evidence from studies shows that using RAP in road pavement significantly reduces the adverse impact on the environment. In addition to enhancing pavement performance, this strategy recycles existing materials, which safeguards resources, minimizes waste, and decreases greenhouse gas emissions. RAP reduces the need for raw materials and has the potential to lessen environmental impact by 15–30% [22-25]. Research suggests that RAP might reduce GHG emissions by about 17% if used as a substitute for up to 50% of virgin aggregates [26]. A twenty percent reduction in environmental impacts, compared to natural aggregates, may be possible using RAP in unbound layers. This involves lessening the impact on the environment and human health by decreasing energy and water use as well as eutrophication and acidification [14]. The United States and Europe together generated more than 100 million tons of RAP in 2020. Reuse rates for this material exceeded 95% [27, 28]. Several Asian nations have successfully integrated RAP recycling procedures into their infrastructure and individual operations. These include Thailand, Indonesia, Japan, Korea, Malaysia, the Philippines, Singapore, and the Philippines [29]. As for Oceania, ARRB [30] reports that RAP is widely used in various pavement applications in Australia and New Zealand. In Africa, SABITA [31] and Mousa et al. [32] highlight that RAP is primarily produced in Egypt and South Africa.

Recycled Asphalt Pavement (RAP) is widely used in asphalt mixtures due to its sustainability benefits, such as conserving resources and reducing waste [33-35]. For example, in their study, Cubas et al. [33] explored the use of both pulverized recycled rubber (PRR) and RAP in hot mix asphalt (HMA) to enhance its properties and eco-friendliness. The researchers found that a combination of 3% PRR and 10% RAP significantly improved the physical and mechanical properties of asphalt. Thermogravimetric analysis revealed that the asphalt mixture degraded at 350°C, while infrared spectroscopy and scanning electron microscopy confirmed that PRR effectively adhered to the aggregates, thereby improving the texture and morphology of the HMA. This study highlights the potential of incorporating recycled materials like PRR and RAP for more sustainable and durable asphalt mixtures. Although RAP is extensively used, it poses significant challenges when mixed with asphalt [36-38]. The issues may include inconsistencies in the quality of RAP, specifically regarding binder content and particle size, which might influence the durability and efficacy of the resultant asphalt mixtures. Moreover, excessive RAP content may diminish the workability and rigidity of the combination, resulting in long-term performance problems. Considering these issues, using RAP in conjunction with soil may improve the characteristics of unbound layers, such as subbases or roadbeds [39-42]. RAP may serve as a material for base and sub-base layers in road construction, offering structural support due to its high-quality aggregates and residual binder. Reclaimed Asphalt Pavement (RAP) has diverse applications beyond its common use in asphalt mixtures, particularly in concrete production. Buhari et al. [43] explored the use of RAP as a fine aggregate in concrete, combined with Quarry By-Product (QBP) as a coarse aggregate, to promote sustainability in construction. The study aimed to optimize concrete performance by varying RAP and QBP percentages, developing eco-friendly concrete for paving blocks and tiles. Similarly, Tiza et al. [44] applied RAP in concrete optimization, utilizing the Box-Behnken model to enhance compressive strength. They analyzed the impact of water, cement, sand, RAP, and coarse aggregates, finding optimal proportions that achieved a compressive strength of 30 N/mm². Both studies highlight the potential of RAP as a sustainable material for improving the properties and performance of concrete, contributing to more efficient and environmentally friendly construction practices.

Studies show that using RAP can improve the strength and performance of problematic soils, making it highly valuable for soil stabilization, especially in pavement applications [45-50]. A study by Suddeepong et al. [45] explored the stabilization of crushed stones with cement and RAP. The results showed that mixtures with RAP had lower California Bearing Ratio (CBR) values. The highest CBR of 85.10% was achieved with a mixture of 80% crushed stone and 20% RAP. Miao et al. [46] examined the effects of finely milled material on pavement rutting at different temperatures. Their findings indicated that adding RAP reduces rutting potential due to the cohesiveness of the asphalt in the fine particles. Adhikari et al. [47] studied the effects of adding 15% RAP to geopolymer and soil in base and sub-base layers. They found that unconfined compressive strength (UCS) significantly increased, with values rising from 2.57 MPa to 4.68 MPa for soil A-7-5 and from 0.68 MPa to 1.62 MPa for soil A-7-6. Hasan et al. [48] found that the resilient modulus of subgrade soil increased with RAP content, reaching 300 MPa at 75% RAP. Suebsuk et al. [49] found that a 50% RAP mixture achieved the highest dry density of 21.90 kN/m³ and the lowest optimum moisture content in lateritic soil compaction. Lima et al. [50] found that adding RAP to sedimentary soil from the Guabirotuba Formation in Brazil improved unconfined compressive strength and splitting tensile strength. Using 80% RAP resulted in an 18.62% increase in CBR values and reduced expansion from 1.19% to 0.88%. A mixture of 40% RAP and 3% cement met sub-base layer criteria, with expansion <1% and CBR > 20%. Notably, a 50% RAP mixture achieved the highest dry density of 21.90 kN/m³ and the lowest optimum moisture content.

This study seeks to examine the novel incorporation of RAP with fine sand to improve its functionality as a subgrade or subbase layer in road construction. RAP's environmental and financial benefits make it an attractive material for recycling in asphalt pavement; nevertheless, there are certain drawbacks to consider, such as the material's increased brittleness and decreased flexibility. To produce a subgrade/subbase layer that satisfies the engineering standards, this research experimentally blends RAP with fine sand, which is an innovative approach that mitigates the negative aspects of each material while harnessing their potential. This study contributes by assessing the mechanical characteristics of the fine sand-RAP mixtures with experimental testing, such as California Bearing Ratio (CBR), Proctor compaction, and sieve analysis. Furthermore, plate-bearing tests will be performed at two relative densities (60% and 90%) to evaluate the material's bearing capacity and stiffness under varying loading conditions. This study will contribute to the existing body of knowledge by providing new insights into the effective reuse of RAP in combination with otherwise challenging subgrade materials like fine sand. Moreover, it will propose a sustainable construction solution that reduces dependence on virgin aggregates and improves the performance of fine sand as a viable subgrade component.

3. Research Methodology

This section details the comprehensive methodology employed to evaluate the performance of sand and Recycled Asphalt Pavement (RAP) mixtures in road construction, particularly for use in subgrade and subbase layers. The experimental process is organized into several stages, focusing on evaluating key physical properties of the mixtures, including grain size distribution, specific gravity, compaction properties, and California Bearing Ratio (CBR) values. A series of carefully designed tests were conducted, such as the Modified Proctor Compaction Test, California Bearing Ratio (CBR) test, and Plate Bearing Test, to examine the mechanical properties of the sand-RAP mixtures at varying RAP content levels (ranging from 0% to 100% RAP). The objective was to assess the suitability of these mixtures for different road construction applications and to identify the optimal RAP content that balances strength, stability, and cost-effectiveness. The results of these tests are analyzed to determine the impact of RAP addition on key parameters such as gradation, compaction, and load-bearing capacity, ultimately contributing to the optimization of material choices in road construction. The laboratory experiments were designed with specific parameters in mind, ensuring that the behavior of the sand-RAP mixtures could be effectively modeled under real-world conditions. These tests aim to provide insights into how varying RAP proportions influence the mixtures' gradation, compaction characteristics, and bearing capacity, all of which are essential considerations in road construction material selection. Figure 1 illustrates the step-by-step methodology employed in the study, providing a clear overview of the research process.

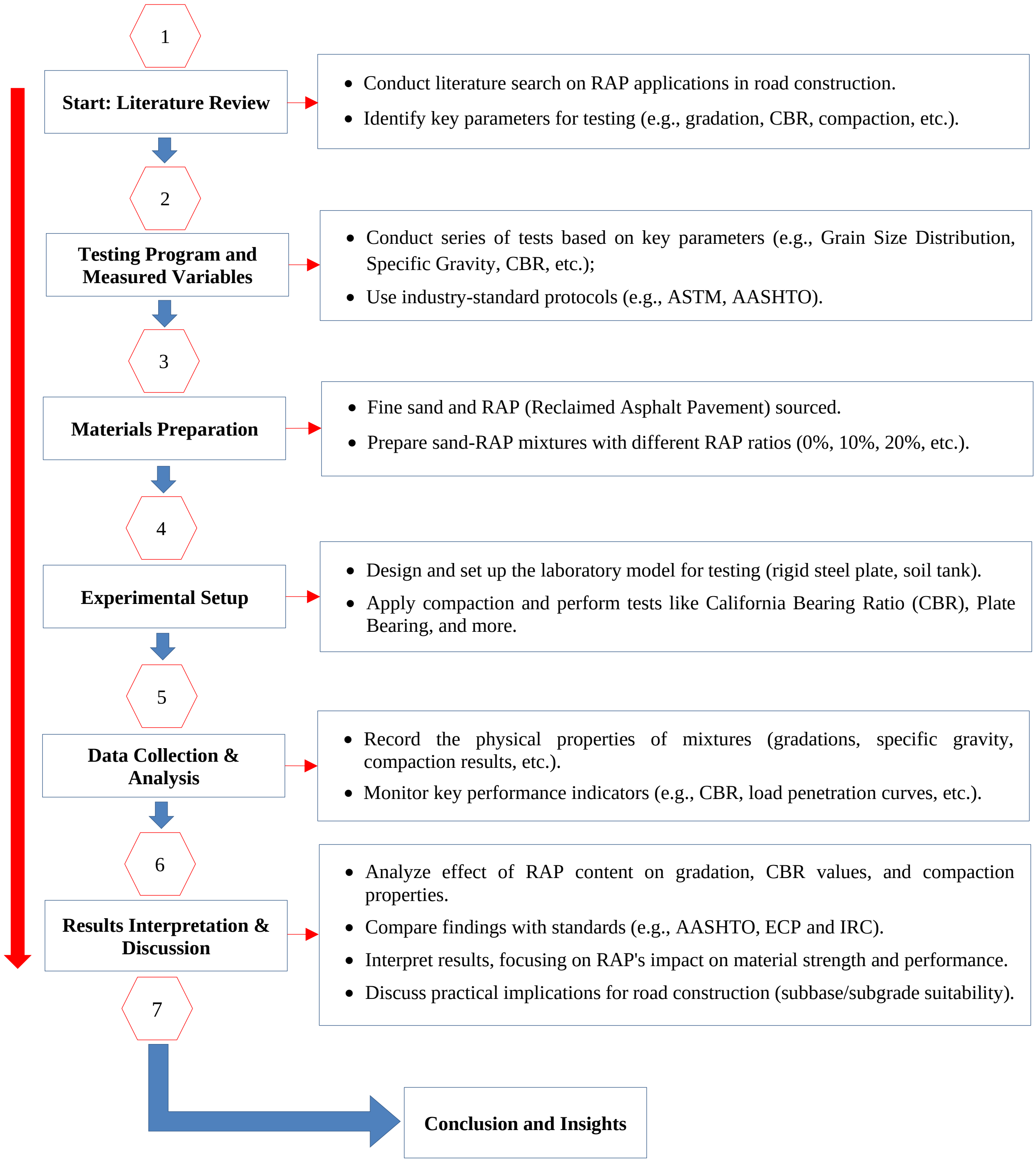


Figure 1. Flowchart of the Research Methodology

4. Testing Program and Measured Variables

A comprehensive testing program was designed to evaluate the physical and mechanical behavior of fine sand and sand-RAP mixtures under varying conditions. Table 1 provides a comprehensive overview of the testing program and key parameters considered in the study. Thirty-eight tests were conducted on sand-RAP mixtures with varying RAP proportions (0%, 10%, 20%, 30%, 40%, 50%, 60%, and 100% by weight). Images of these different mixtures are shown in Figure 2. The experimental program's results will undoubtedly compare to worldwide standards like AASHTO and ECP 104. This evaluation is crucial for subgrade and sub-base layer performance evaluation in road construction. These mixes are tested extensively to ensure they meet or surpass all industry performance criteria, improving infrastructure projects' lifetime and durability.

Table 1. Summary of testing program and key parameters

Series No.	Test Type	Soil State	Variable	Standards Used	Num. of Tests
1.1	Grain Size Distribution (D)	Loose	RAP ratio: 0%, 10%, 20%, 30%, 40%, 50%, 60%, and 100%	ASTM D6913 [51]	8
1.2	Specific Gravity (G_s)	Loose	Fine Sand, RAP	ASTM D854 [52]	2
1.3	Modified Proctor Compaction Test	Compacted	Moisture-density relationship (Wc, γd)	ASTM D698 [53]	8
1.4	California Bearing Ratio (CBR)	Compacted	RAP ratio: 0%, 10%, 20%, 30%, 40%, 50%, 60%, and 100%	ASTM D1883 [54]	8
2.1	Plate Bearing Test (q_u)	Compacted at D_r = 60%	RAP ratio: 0%, 10%, 20%, 30%, 40%, 50%, 60%, and 100%	ASTM D1194 [55] / ECP 104 [56]	8
2.2		Compacted at D_r = 90%	RAP ratio: 0%, 10%, 20%, 30%, 40%, 50%, 60%, and 100%	ASTM D1194 [55] / ECP 104 [56]	8

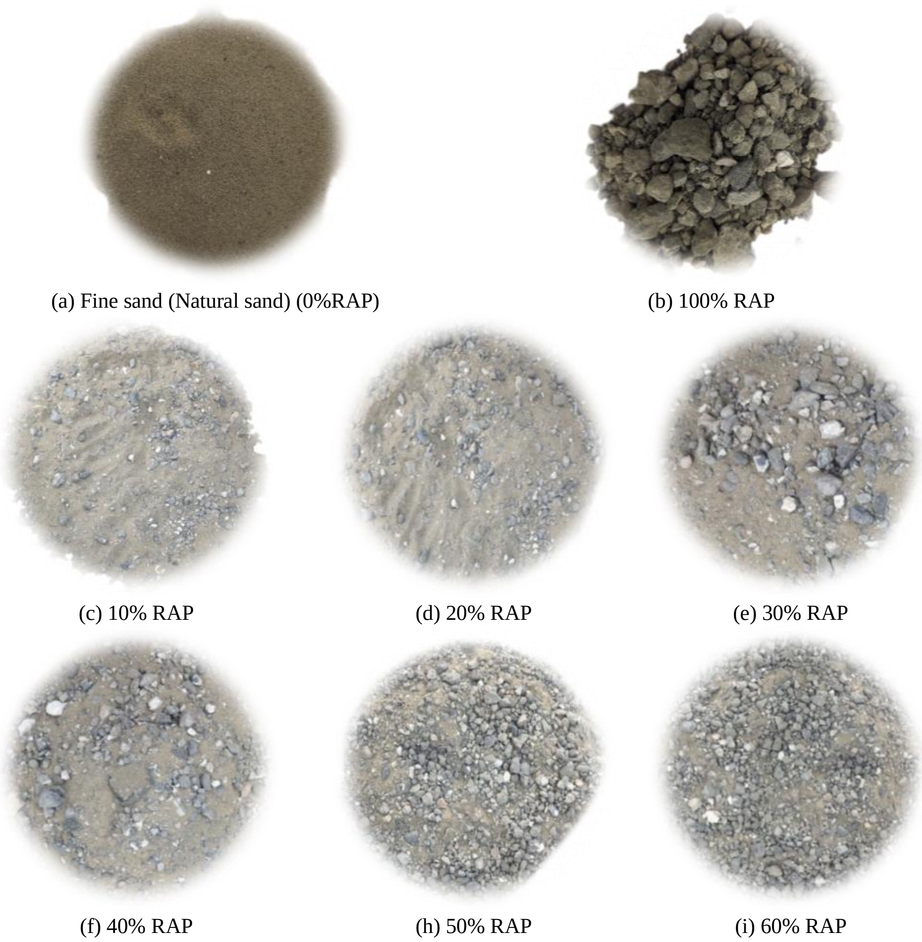


Figure 2. Images of sand-RAP mixtures with varying RAP proportions (R: 0%, 10%, 20%, 30%, 40%, 50%, 60%, and 100% by weight)

Several tests, which are based on Table 1, will be employed to evaluate the physical characteristics of the sand-RAP blends: (1) analysis of the particle size distribution; (2) calculation of specific gravity; (3) evaluation of compaction properties; and (4) the California Bearing Ratio (CBR) test. Two relative densities (60% and 90%) will be evaluated with plate-bearing investigations to further evaluate the bearing capacity and stiffness under varying loads. These tests are designed to assess the performance of various sand-RAP mixtures that are intended for use in road construction, particularly in the subgrade and sub-base layers.

5. Materials Used and Model Description

5.1. Fine Sand

The research utilized fine sand collected near the International Coastal Road in Baltim, Kafr El Sheikh, Egypt, an area recognized for its abundant sand deposits along the Mediterranean coastline. The geotechnical properties of the fine sand were analyzed, and the results are summarized in Table 2. According to the Unified Soil Classification System

(USCS), the sand was classified as SP (Poorly Graded Sand), and under the AASHTO classification system, it was classified as A-3 (Fine Sand). The specific gravity (G_s) was found to be 2.68, and the maximum dry density (MDD) was determined as 17.86 kN/m³ with an optimum moisture content (OMC) of 9.81%. The sand's gradation curve exhibited a coefficient of uniformity (C_u) of 2.80 and a coefficient of curvature (C_c) of 1.73, which aligns with the poorly graded nature of the sand. The sampling location and surrounding region are depicted in Figure 3.

Table 2. An evaluation of the geotechnical properties of natural sand and recycled asphalt pavement (RAP)

Property	Symbol	Unit	Fine sand	RAP
			Average Value	Average Value
Maximum Dry Density	MDD, γ_{dmax}	kN/m³	17.86	20.71
Optimum Moisture Content	OMC	%	9.81	5.80
Minimum Dry Density	γ_{min}	kN/m³	15.00	18.00
Specific Gravity	G_s	-	2.68	2.38
Maximum Void Ratio	e_{max}	-	0.72	0.77
Minimum Void Ratio	e_{min}	-	0.51	0.37
Effective Size	$D_{10\%}$	mm	0.13	1.50
Intermediate Diameter	$D_{30\%}$	mm	0.28	6.00
Mean Size	$D_{60\%}$	mm	0.35	10.25
Coefficient of Uniformity	C_u	-	2.80	6.83
Coefficient of Curvature	C_c	-	1.73	2.34
USCS Classification	-	-	SP (Poorly Graded Sand)	GW
AASHTO Classification	-	-	A-3 (Fine Sand)	A-1-a
USDA Classification	-	-	Sand	Gravel
ISO Classification	-	-	Sand, Poorly Graded (SP)	Gravel, Well-Graded
Dry Density at D_r = 60%	$\gamma_{60\%}$	kN/m³	16.45	19.35
Void Ratio at D_r = 60%	$e_{60\%}$	-	0.60	0.52
Dry Density at D_r = 90%	$\gamma_{90\%}$	kN/m³	17.12	20.15
Void Ratio at D_r = 90%	$e_{90\%}$	-	0.53	0.41

(a) Image from the sample collection location

(b) Location from Google Maps.

Figure 3. Sampling location along the international coastal road near Baltim, Kafr El Sheikh, Egypt

5.2. Reclaimed Asphalt Pavement (RAP)

The study focused on Reclaimed Asphalt Pavement (RAP) sourced from a stockpile over 10 years old, which leads to a stiffer and more stable binder due to reduced volatile components. The aged nature of the RAP offers practical advantages during laboratory testing. It ensures ease of handling, particularly during heating in the oven for moisture content determination or binder recovery. The stable and less volatile binder composition minimizes potential changes to the RAP's properties during testing, leading to consistent and reliable results. The RAP used in this study was classified as GW (Well-Graded Gravel) under the Unified Soil Classification System (USCS) and as A-1-a under the AASHTO classification system. These classifications confirm the material's suitability for use in subgrade and subbase layers. The physical and geotechnical properties of the RAP are summarized in Table 1. The Specific Gravity (G_s) of the RAP was measured as 2.38, slightly lower than that of the fine sand due to the presence of asphalt binder and potential porosity within the aggregate particles.

5.3. Description of the Laboratory Model

The experimental setup comprised a rigid steel plate (250 × 250 mm, 50 mm thick) to simulate a square footing model (B = 250mm), loaded concentrically at its center on the soil sample surface. The RAP-sand mix was housed in a rectangular steel tank (internal dimensions: 1.5 m × 1.5 m × 1 m), constructed from 6 mm thick steel plates reinforced with horizontal stiffeners to avoid lateral deformation during loading. This size adhered to established guidelines [57, 58], which recommend tank dimensions of at least 5–7 times the footing width (B), to ensure that stress and deformation zones did not interfere with the tank walls.

To reduce boundary effects, the tank walls were polished, minimizing friction and enhancing vertical stress transfer [59, 60]. A manual hydraulic loading system (SPX 700-bar pump, 258 kN axial capacity cylinder) applied the load in increments, which were maintained until stabilization was observed (<0.01 mm change over 5 minutes). Vertical displacement was monitored with two dual dial gauges (range: 0-100 mm, and accuracy: 0.01 mm) on opposite sides of the footing. The test setup, including the soil tank dimensions, the compacted layers, the footing plate, and the hydraulic loading system, is illustrated in Figure 4.

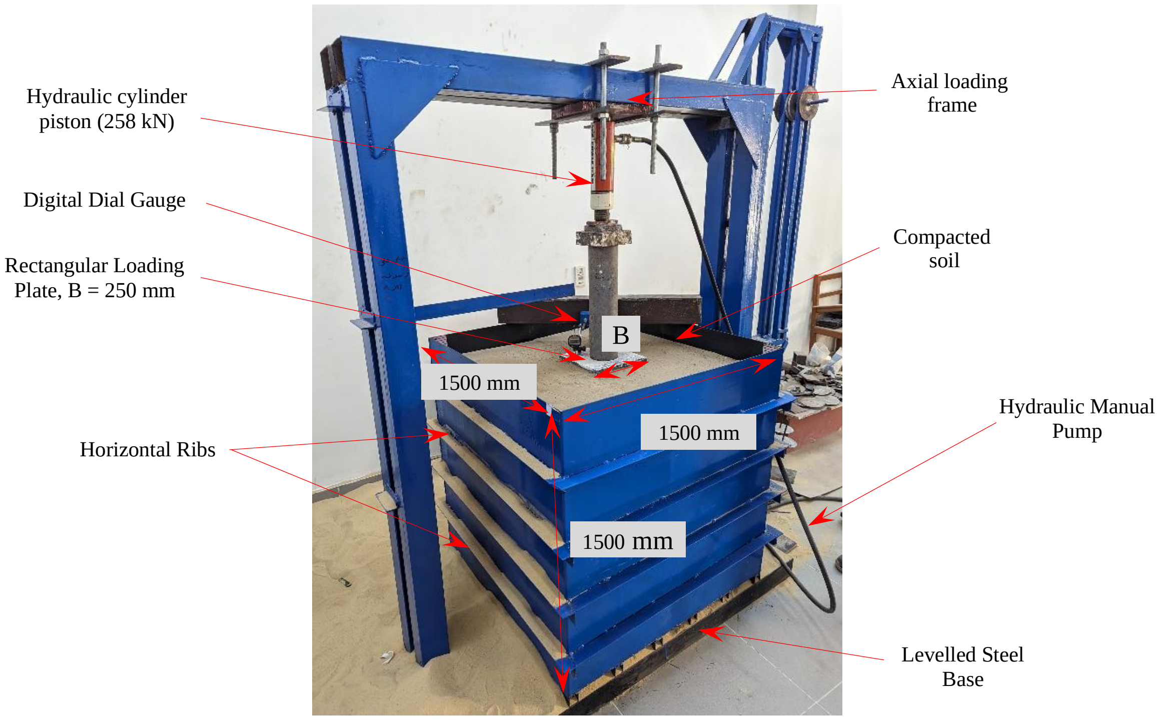


Figure 4. Experimental soil tank and test setup

The RAP-sand mix bed was uniformly prepared by compacting pre-calculated quantities of the mixture into the soil tank in layers of 100 mm thickness, ensuring the target relative density was achieved. Each layer was levelled using a sharpened steel plate. Density verification was performed by collecting samples with metal tins of known volume in accordance with procedures documented in prior studies [59-62].

6. Results and Discussion

6.1. Effect of RAP Addition on Gradation

Figure 5 shows the particle size distribution of the sand-RAP mixtures for different RAP proportions. The curves demonstrate a clear shift toward coarser gradations as RAP content increases, with steeper slopes for the higher RAP blends. The reduction in fines passing the No. 200 sieve with increasing RAP content is evident, aligning with the improved gradation for subbase applications. The incorporation of Reclaimed Asphalt Pavement (RAP) into natural sand significantly alters the gradation profile of the material, shifting it from a predominantly fine distribution to a coarser one. For natural sand, 88.12% of the material passes the No. 40 sieve (0.425 mm) and 4.81% passes the No. 200 sieve (0.074 mm), indicating a high proportion of fine particles. On the other hand, RAP has a much coarser gradation, with 29.31% passing the No. 4 sieve (4.75 mm) and no particles passing the No. 200 sieve. As RAP is blended into the sand, the particle size distribution progressively shifts towards coarser particles. For instance, at 10% RAP, 92.93% of particles pass the No. 4 sieve, while at 60% RAP, this value drops to 57.59%. Similarly, the percentage passing the No. 200 sieve decreases from 4.33% at 10% RAP to 1.93% at 60% RAP. This trend reflects the dominant influence of RAP in reducing fine content and increasing coarser particles in the mixture.

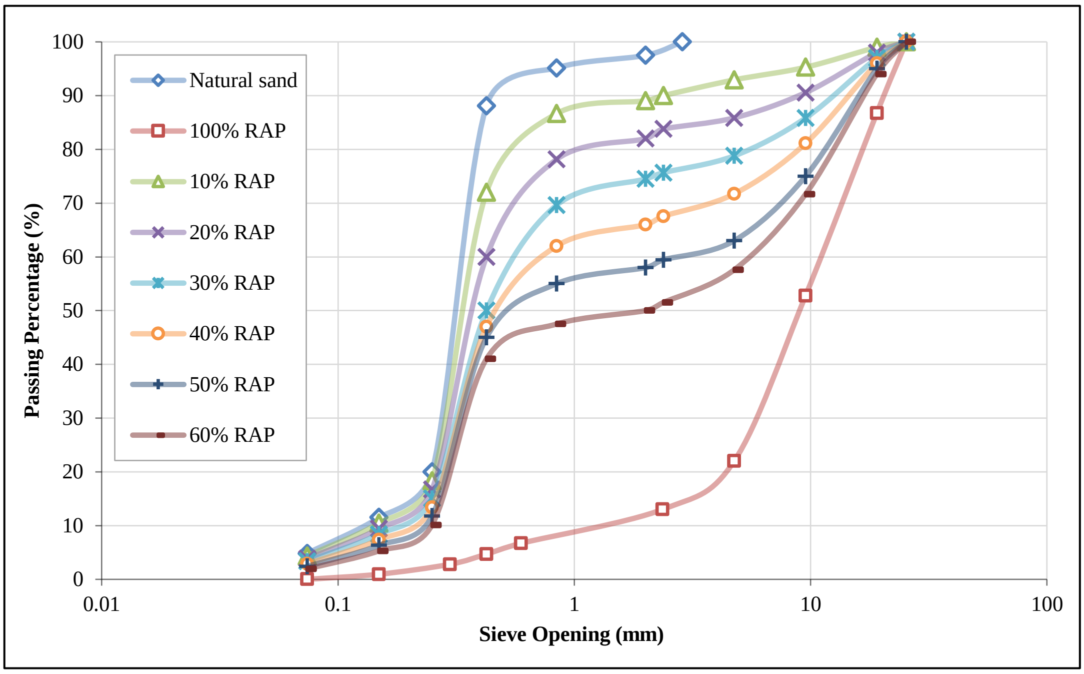


Figure 5. Gradation curves of sand-RAP mixtures

The observed gradation results were compared with the requirements set by ECP 104, IRC: 37-2012, and AASHTO standards for subgrade and subbase applications. For Type A materials, which are commonly used in subbase construction, the acceptable range for particles passing the No. 4 sieve is 35–70%. Mixtures with RAP contents of 50% and 60% satisfy this range, making them suitable for subbase use. Furthermore, the percentage of fines passing the No. 200 sieve remains below the maximum limit of 20% specified by all applicable standards, even at the lowest RAP content of 10%. This compliance with gradation limits demonstrates that the incorporation of RAP enhances the suitability of the sand-RAP mixtures for structural layers in road construction, particularly as RAP content increases beyond 40%.

In terms of ECP 104 and IRC: 37-2012 standards, the gradation of RAP mixtures shows that the addition of RAP results in a soil mix that fits the required specifications for road construction materials. Specifically: (1) RAP mixtures at 40% and 50% RAP fall within the acceptable range for Type A (35-70%). Type B (40-90%) materials, confirming the suitability of RAP for road subbase applications at RAP ratio more than 20%. The RAP mixtures meet the specifications for Types A, B, and C materials (0-15% passing No. 200 sieve), which are suitable for subgrade layers and lower-quality road base applications.

6.2. Effect of RAP Addition on CBR Values

CBR tests are commonly used to evaluate the strength of subgrade soil, subbase, and base materials for road construction. Figure 6 presents the penetration curves for RAP-sand mixtures (CBR Results). The graphs suggest a strong relationship between RAP content and improved load capacity, emphasizing the beneficial reinforcing effect that RAP brings to mixtures. RAP effectively enhances the structural properties of soils, making it a practical choice for road sub-base layers and subgrades.

Using Recycled Asphalt Pavement (RAP) with natural fine sand increases the California Bearing Ratio (CBR) values, strengthening the soil for better weight support. Figures 7 and 8 demonstrate how CBR values and percentage improvement increase with higher RAP content in sand-RAP mixtures.

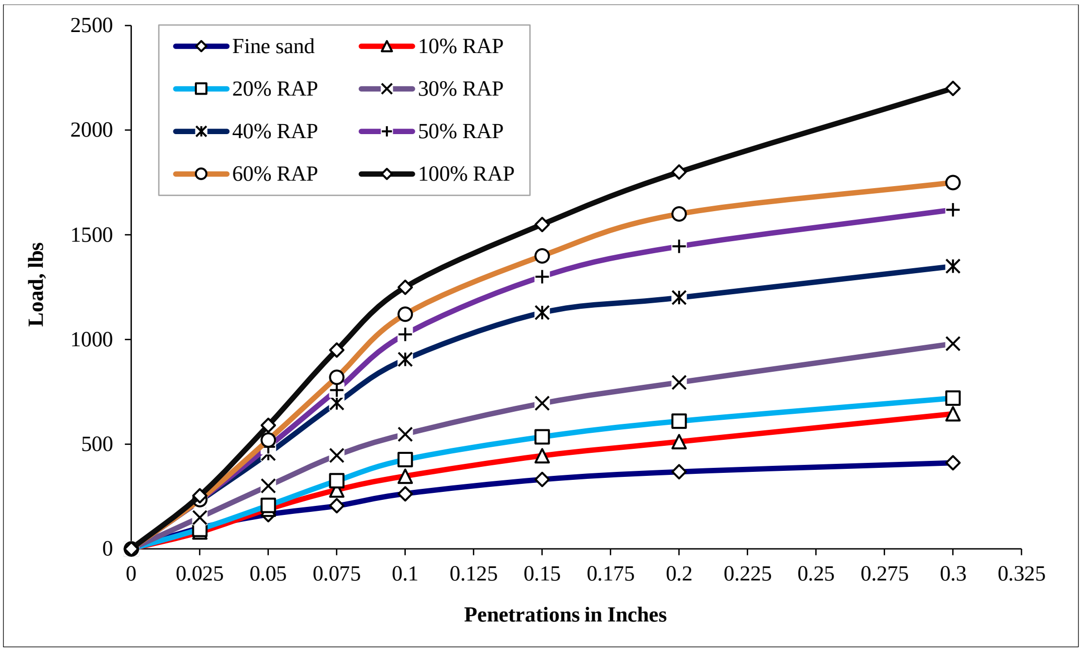


Figure 6. Load penetration curve for RAP-sand mixtures (CBR results)

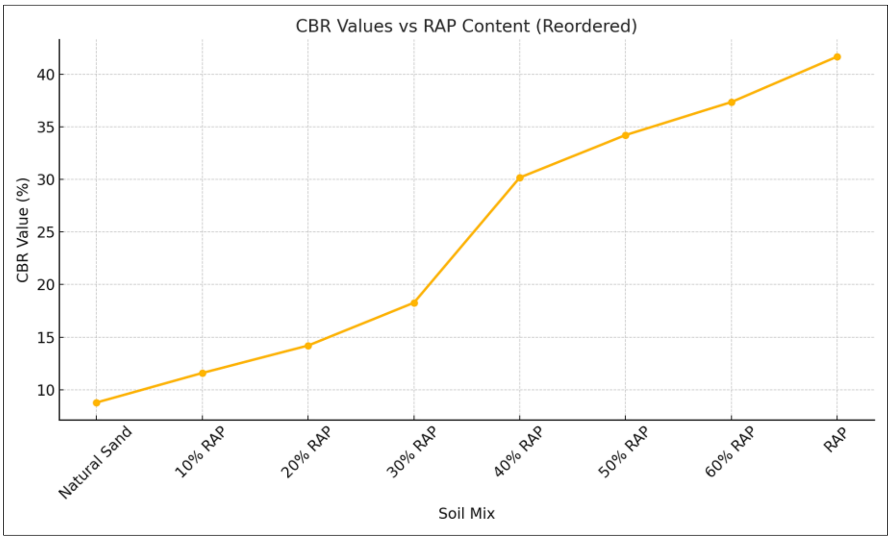


Figure 7. CBR values vs RAP content

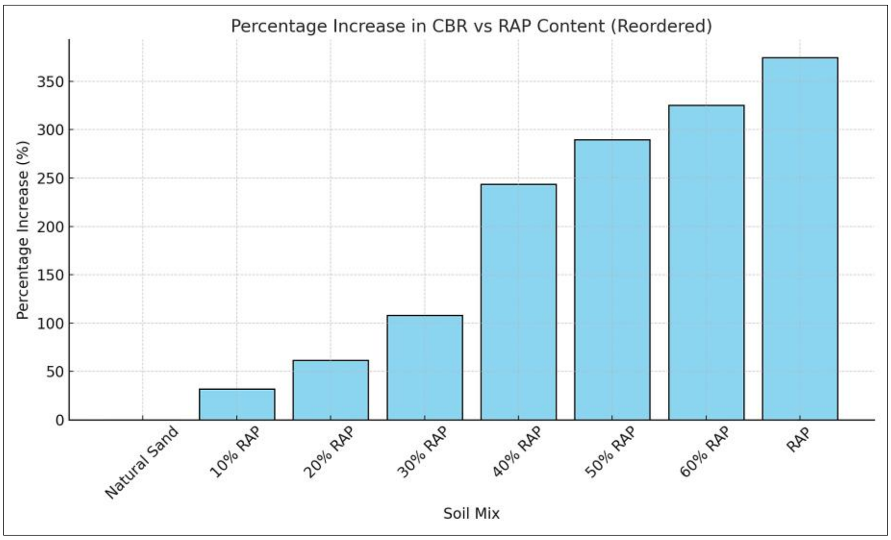


Figure 8. Percentage increase in CBR vs RAP content

The predetermined CBR value of natural sand is 8.78%; by adding only 10% RAP, the CBR rises to 11.59%, a 31.97% increase. The CBR values boost 14.2% and 18.27%, representing increases of 61.74% and 108.05%, when the RAP content increases to 20% and 30%, respectively. These results suggest that even modest amounts of RAP can significantly fortify RAP-sand mixtures, making them more suitable for construction. As RAP percentages continue to climb, the enhancements in CBR values become even more pronounced. At 40% RAP, the CBR reaches 30.17%, a 243.70% increase, while at 50% and 60% RAP, values soar to 34.21% and 37.35%, translating to increases of 289.68% and 325.43%, respectively. Notably, pure RAP achieves a CBR of 41.67%, demonstrating a 374.70% increase over natural sand. This data underscores RAP's effectiveness as a stabilizing agent, highlighting its potential as a sustainable and cost-effective solution for improving RAP-sand properties in heavy-load construction applications. The findings advocate for increased utilization of RAP in construction projects to enhance material performance while promoting sustainability.

The results for 50%, 60%, and 100% RAP indicate a convergence in CBR values, suggesting that while the addition of RAP enhances RAP-sand strength, the benefits diminish at higher percentages. Specifically, the transition from 50% to 60% RAP yields only approximately 9.18% improvement, while moving from 60% to 100% RAP results in around 11.56% improvement. These marginal increases illustrate a plateau effect in performance, where the enhancement in load-bearing capacity becomes less pronounced as RAP content rises.

From an economic perspective, using more than 50% RAP seems less favorable, as the additional costs associated with higher RAP content may not justify the limited improvements in CBR values. Therefore, a 50% RAP mix emerges as the optimal choice, striking a balance between significant strength gains and cost-effectiveness. This approach maximizes the benefits of RAP while minimizing the diminishing returns observed at higher levels, making it a practical solution for construction applications where both performance and budget considerations are critical.

6.2.1. CBR Compatibility Analysis

Table 3 analyzes the California Bearing Ratio (CBR) values for various sand-RAB, providing insight into their suitability for use in subgrade and subbase layers as defined by AASHTO, IRC: 37-2012, and the Egyptian Code for Pavements (ECP 104).

Table 3. Measured CBR and subgrade/subbase standards compatibility

<table>
<tr><th>Material</th><th>Measured CBR (%)</th><th>Subgrade Compatibility</th><th>Sub-base Compatibility</th><th>Specification Limits (CBR) with Standard</th></tr>
<tr><td>Fine sand</td><td>8.78</td><td>Meets low-traffic subgrade (AASHTO, IRC). Below ECP requirement for rural roads.</td><td>Not suitable for sub-base.</td><td rowspan="8"><u>Sub-grade</u>
▪ AASHTO and IRC: ≥5 for low-traffic, ≥10 for higher-traffic areas.
▪ ECP: Strictest for urban areas (≥15); stabilization advised for CBR <10.
<u>Sub-base</u>
▪ AASHTO and IRC: ≥20 for light traffic, ≥30 for high traffic.
▪ ECP: ≥25 for light traffic, ≥40 for high traffic.</td></tr>
<tr><td>100% RAP</td><td>41.67</td><td>Exceeds all subgrade requirements.</td><td>Meets all sub-base requirements.</td></tr>
<tr><td>10% RAP</td><td>11.59</td><td>Suitable for low-traffic subgrade (AASHTO, IRC). Below ECP for durability.</td><td>Not suitable for sub-base.</td></tr>
<tr><td>20% RAP</td><td>14.2</td><td>Suitable for low-traffic subgrade. Marginal for urban (ECP ≥15).</td><td>Not suitable for sub-base.</td></tr>
<tr><td>30% RAP</td><td>18.27</td><td>Meets low-traffic subgrade. Marginal for urban.</td><td>Marginal for light-traffic sub-base (AASHTO and IRC).</td></tr>
<tr><td>40% RAP</td><td>30.17</td><td>Exceeds subgrade requirements.</td><td>Suitable for light traffic; marginal for high traffic sub-base.</td></tr>
<tr><td>50% RAP</td><td>34.21</td><td>Exceeds all subgrade requirements.</td><td rowspan="2">Meets sub-base requirements; marginal for ECP heavy traffic.</td></tr>
<tr><td>60% RAP</td><td>37.35</td><td>Exceeds all subgrade requirements.</td></tr>
</table>

Fine Sand, with a measured CBR of 8.78%, meets the minimum requirements for low-traffic subgrade according to AASHTO and IRC standards. However, it falls short of the stricter ECP standard, which requires a minimum of 8% for rural roads, while it is well below the required limits for urban or heavy-traffic areas. In addition, fine sand should not be used for sub-base layers since it does not have a CBR value high enough to satisfy the 20% minimum requirement for light traffic, according to AASHTO and IRC. All subgrade criteria for low- and high-traffic roads are met by 100% RAP, with a CBR of 41.67%, according to AASHTO, IRC, and ECP standards. It satisfies sub-base standards across the board, even in high-traffic situations where ECP has set a 40% limitation. As a result, 100% RAP is perfect for use as a subgrade and subbase.

With 10% RAP, the CBR obtained is 11.59%, within the permissible range for low-traffic subgrade usage as per AASHTO and IRC guidelines. Nevertheless, it falls short of the ECP specifications, which need increased durability. Because it fails to fulfill even the most basic requirements for light traffic, its CBR value is inadequate for use in any sub-base layer. Under ECP, a minimum CBR of 15% is required for durable subgrades in heavily populated regions; nevertheless, 20% RAP with a CBR of 14.2% satisfies the criteria for low-traffic subgrades but is insufficient for urban applications. Similar to 10% RAP, its CBR falls short of the required minimum, making it inappropriate for use in subbase scenarios. A measured CBR of 18.27% is achieved with 30% RAP, leading to a considerable improvement in performance. Although it is only partially appropriate for use in metropolitan areas, this material satisfies the AASHTO and IRC standards for low-traffic subgrade. According to AASHTO and IRC, sub-base is just passable for light traffic, but it fails miserably when it comes to heavy traffic situations and ECP criteria.

At 40% RAP, meets all subgrade guidelines across AASHTO, IRC, and ECP with a CBR of 30.17 %. Although it is appropriate for sub-base applications in low traffic under AASHTO and IRC, it is still marginal for heavy traffic sub-base needs, especially under ECP, where a minimum CBR of 40% is required. The observed CBR of 34.21% at 50% RAP is higher than all subgrade standards. It satisfies the AASHTO and IRC criteria for light and heavy traffic for sub-base layers. Nevertheless, it is insufficient to meet the requirements of ECP regulations for heavy traffic. Lastly, all subgrade standards under AASHTO, IRC, and ECP have been met by 60% RAP, which has a measured CBR of 37.35%. Although it meets the majority of criteria for sub-base layers, it is only slightly below ECP's high-traffic criterion of 40%.

6.2.2. Best-Achieved Mathematical Model

Important considerations for assessing the present study's validity in light of prior research include the selection criteria for the best-fit mathematical model to examine the impact of RAP addition on CBR values. The coefficient of determination (R^2), mean absolute error (MAE), and root-mean-squared error (RMSE) are essential measures to assess statistical accuracy. Stronger correlations between RAP content and CBR values are indicated by higher R^2, whereas lower MAE and RMSE values reflect better model performance. For the purpose of simplicity and practicality, simpler equations are preferred when there is slight variation in model performance.

To significantly guarantee their usability in real-world situations, models should behave realistically at extreme values, particularly at 0% and 100% RAP addition. Another essential requirement is practical interpretability; models with fewer parameters are simpler for practitioners to grasp and implement successfully, and models that over- or under-predict in certain circumstances may not be acceptable for directing building practices. This study's results are particularly significant in the area of soil stabilization and construction since it fulfills these selection criteria, which not only make it more credible but also provide a solid foundation for comparing them to previous studies.

There are a number of mathematical models that attempt to depict the association between RAP content and CBR values; however, these models all proceed under different assumptions. While linear models perform well for proportional trends, they may oversimplify complicated non-linear conditions if RAP content is assumed to rise at a constant pace, which is not always the case. For datasets showing diminishing returns, the quadratic model is suitable since it captures non-linear patterns and may explain situations where growth rises early before plateauing or reducing. Rapid early growth which slows down with increasing percentages is efficiently shown by the power model, which represents growth that relies on the independent variable increased to a power. Finally, to better depict early decreasing returns, the logarithmic model takes CBR values to climb sharply at lower RAP percentages before gradually leveling out. Finally, to better depict early decreasing returns, the logarithmic model takes CBR values to climb sharply at lower RAP percentages before gradually leveling out. The correlation between RAP content and CBR values, as well as the mathematical models that were fitted, are shown in Figure 9.

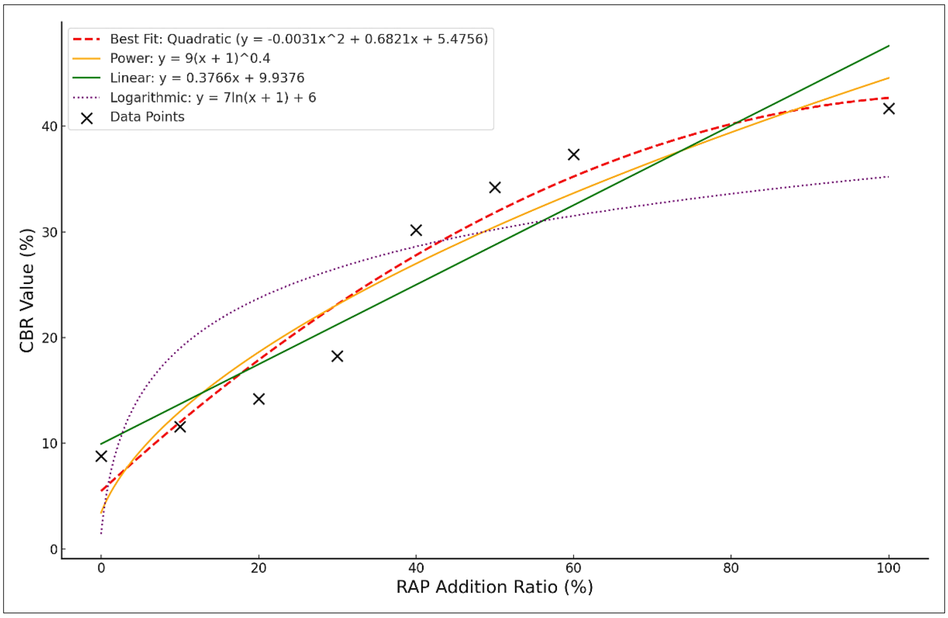


Figure 9. Comparison of RAP content and CBR values employing the best-achieved mathematical model

The effectiveness of four statistical models—Power, Linear Regression, Polynomial (Quadratic), and Logarithmic—for simulating the correlation between RAP percentage and CBR values is assessed and contrasted in Table 4. Each model's effectiveness is evaluated by looking at its formula, R-squared value, MAE, RMSE, and an interpretation of its results. The quadratic equation is the most appropriate option for this dataset. Its R^2 score of 0.9431 is the greatest, accounting for most data fluctuation. Additionally, it exhibits the lowest Mean Absolute Error (MAE) of 2.52 and Root Mean Squared Error (RMSE) of 2.85, indicating minimal prediction errors. The non-linear pattern and plateauing impact seen at higher RAP ratios, as shown by the formula ($y = -0.0031\ x^2 + 0.6821\ x + 5.4756$), are successfully captured by the quadratic framework. The power model is the second-best option with an R^2 of 0.8957, though it is less accurate than the quadratic model. Even though it is simple, the linear approach does not consider diminishing returns, making it score worse ($R^2 = 0.8778$). As the logarithmic equation has the lowest R^2 value of 0.6837, it is inappropriate for this investigation.

Table 4. Comparison of mathematical models

Model	Equation	R^2	MAE	RMSE	Interpretation
Quadratic	$y = -0.0031\ x^2 + 0.6821\ x + 5.4756$	0.9431	2.52	2.85	Best fit: captures non-linear growth and plateauing at higher RAP percentages.
Power	$y = 3.4281\ (x + 1)^{0.5558}$	0.8957	3.69	3.86	Good fit; captures early growth but less accurate at higher RAP percentages.
Linear	$y = 0.3766\ x + 9.9376$	0.8778	3.86	4.18	The simple model fails to capture diminishing returns at higher RAP percentages.
Logarithmic	$y = 7.3282\ \ln(x + 1) + 1.4023$	0.6837	6.30	6.73	Poor fit: underestimates CBR values for higher RAP percentages.

In order to clarify the non-linear correlation between RAP addition and CBR values, the quadratic framework is the best fit for this dataset because of its higher statistical performance. Its precise and interpretable equation successfully captures the plateauing pattern and is handy in practice.

6.2.3. Current Study Validity vs Previous Studies

The findings of this study's quadratic equation were compared to those of previous studies via a thorough examination. Examples include the works of Mishra et al. [63], Taha et al. [64], Seferoglu et al. [65], and Kalpakci et al. [66]. The model's prediction performance was assessed using statistical measures, including Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE). More specifically, the findings show that the quadratic approach captures the non-linear connection between RAP addition and CBR values well and correlates closely with the overall trends in these investigations. As an illustration, compared to Taha et al. [64], the equation showed good prediction ability, achieving an MAE of 1.87 and an RMSE of 2.16. Fortunately, CBR findings may be impacted by varied material qualities and experimental settings, as seen by the variances in MAE and RMSE between research studies. The data points and prior relevant research are compared with the present study's quadratic model in Figure 10.

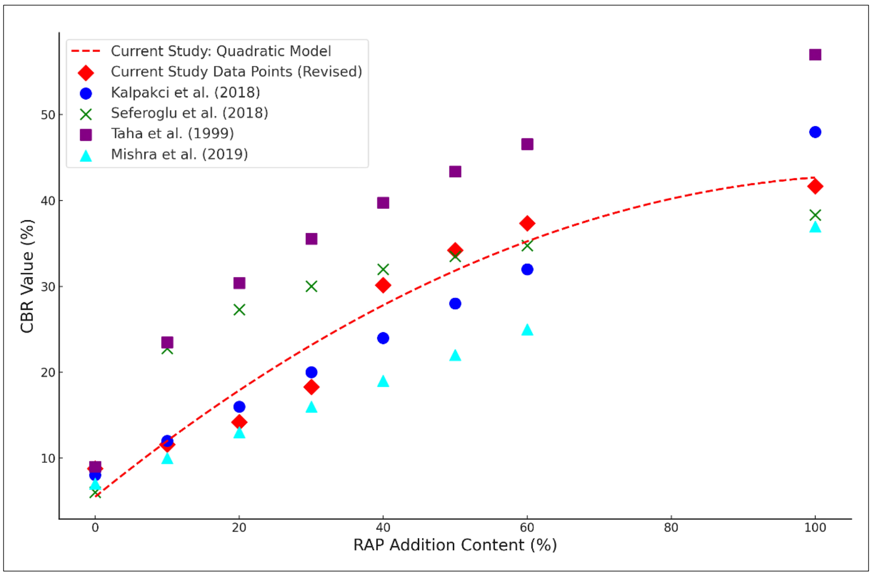


Figure 10. Analysis of the best-fit model in the present study in relation to earlier investigations

Consistent with prior research, the quadratic model accurately predicts that CBR values would rise sharply at the outset and then level off as the RAP % grows. Studies such as Kalpakci et al. [66] and Mishra et al. [63] demonstrated more consistent growth patterns in the early and mid-range RAP proportions. Their differences were more apparent at greater levels when the plateau effects were less noticeable. Consistent with the results of Seferoglu et al. [65] and Taha et al. [64], both likewise show rapid early increase accompanied by declining returns, the quadratic equation robustly represents non-linear manners. In two datasets, Taha et al. [64] and Kalpakci et al. [66], the quadratic equation appears to be highly accurate at predicting CBR values, with lower accuracy ratings. On the other hand, Seferoglu et al. [65] and Mishra et al. [63] had higher errors, which different materials and methods could explain. Variations in predictability show that the model has to be refined, notwithstanding its merits. There are differences between the expected and actual values of CBR due to considerations including differences in RAP gradation, binder concentration, and experimental circumstances.

6.3. Effect of RAP Addition on the Modified Proctor Results

The findings from the modified Proctor test shed light on how the addition of RAP affected the dry density and optimal moisture content (OMC) of the sand-RAP mixes. For different RAP-sand combinations with varied percentages of RAP, Figure 11 demonstrates the relationships between OMC and dry density. A distinct RAP content, ranging from 0% to 100%, is represented by each curve.

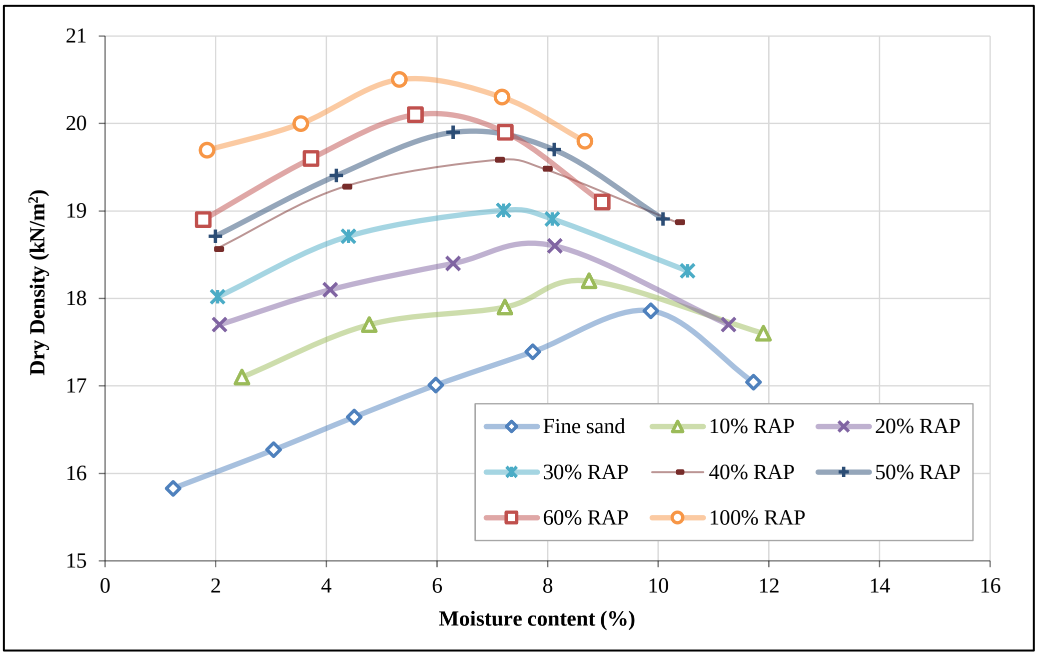


Figure 11. Modified proctor test results for RAP-sand mixtures with varying RAP percentages

For RAP-sand mixes with different RAP percentages, Figures 12 and 13 show the maximum dry density and OMC values as well as the percentage improvements in these measures as RAP content rises. According to the study findings, adding RAP causes the dry density to grow steadily. It improved by 16.42% from 17.8 kN/m³ for fine sand to 20.71 kN/m³ at 100% RAP. The angular and coarse particles of RAP make them interlock better, reducing voids and increasing the density of the soil mix. Between 40% and 100% RAP, the dry density improves by 10% to 16%, which is the sweet spot for the best benefits. The mixtures seem to be well-suited for uses that need high levels of compaction, as shown by the maximum value of 20.71 kN/m³ at 100% RAP.

In terms of the OMC, the data reveal a major drop of 40.94 percent, from 9.81% for fine sand to 5.8% for 100% RAP. This may be ascribed to RAP's hydrophobic characteristics, its diminished ability to absorb water, and the need of its coarse texture for less water to achieve ideal compaction. A significant decrease in OMC transpires between 30% and 100% RAP, indicating the growing influence of RAP's characteristics in the mixture. The lowest OMC at 100% RAP (5.8%) highlights its efficiency in construction environments with limited water availability.

The practical implications of these findings are noteworthy. These blends are perfect for employing as a subgrade or base layer because of its high dry density, which increases its load-bearing capability. The reduction in OMC suggests that RAP-sand combinations need less water during construction, which in turn reduces expenditures and makes them more suitable for use in arid regions. It seems that the best-balanced blends contain 40% to 60% RAP. These blends can lower OMC about 30% and greatly improve dry density (+12%).

Among RAP's many benefits is its ability to enhance compaction by increasing the soil's dry density. This enhancement arises from RAP's angular and coarse particle morphology, which facilitates superior interlocking among particles, hence substantially reducing voids in the RAP-sand composition. In comparison to fine sand and other particles with a smoother surface, RAP's sharp, angular edges enhance friction and allow for better interlocking, making them a better compacting agent [63].

Along with improving dry density, RAP also reduces the OMC needed to achieve maximum density during compacting. The reduced need for water during compaction and decreased absorption are due to the hydrophobic properties of RAP, as the asphalt coating on the particles repels water [64, 65]. And since RAP is coarser than tiny particles, it has a lower surface area and uses less water to moisten itself when compacted [66].

Compaction outcomes are further improved by RAP's gradation and void-filling characteristics. When mixed with soil, RAP can improve the overall gradation of the material by filling voids between finer particles, leading to denser packing [64]. Blending RAP with fine-grained soils optimizes the mix's gradation, reducing excessive voids and achieving optimal density [66]. Overall, the use of RAP in sand stabilization not only promotes better compaction but also supports sustainable construction practices by recycling materials and reducing the reliance on natural aggregates.

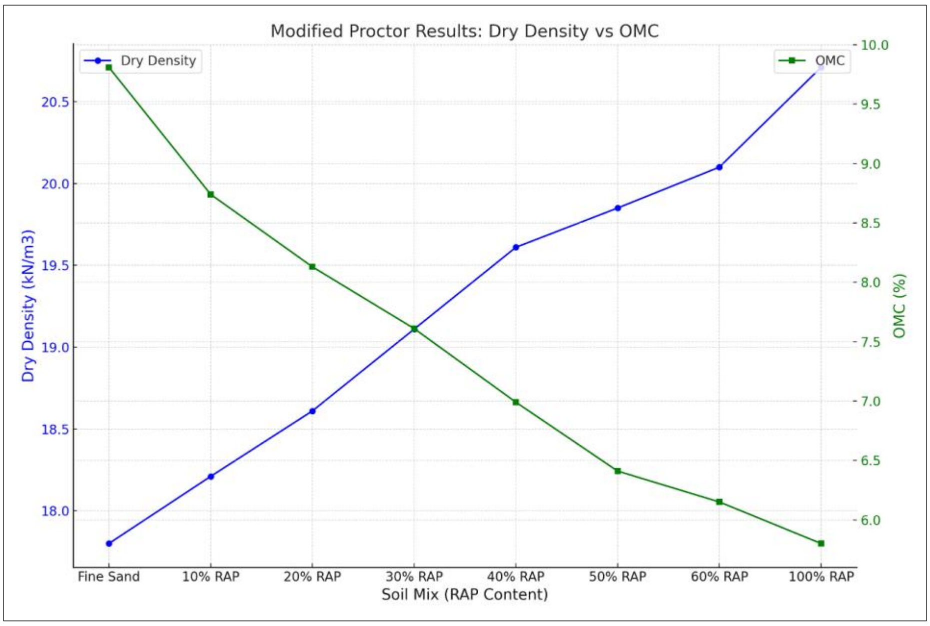


Figure 12. RAP-sand blends' maximal dry density and OMC

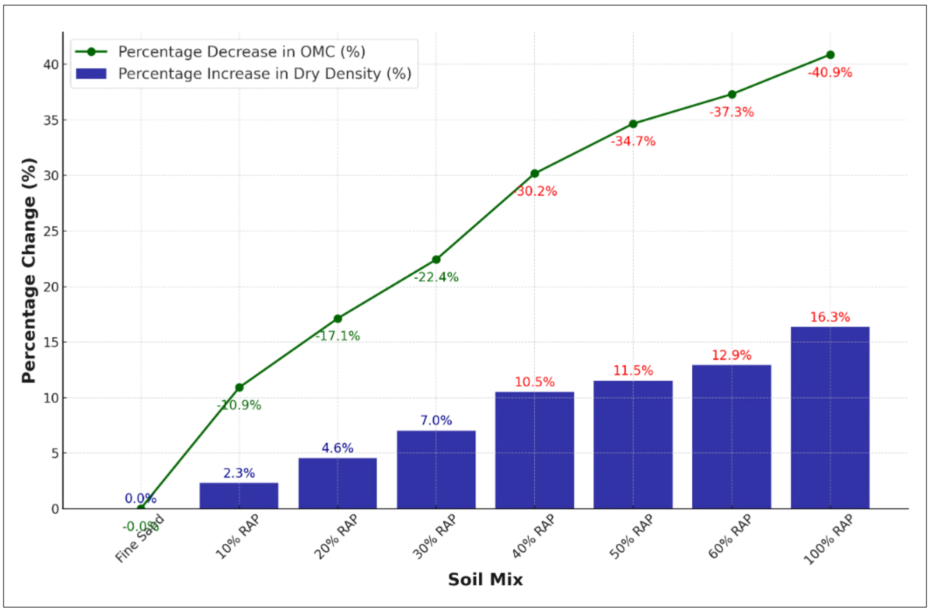
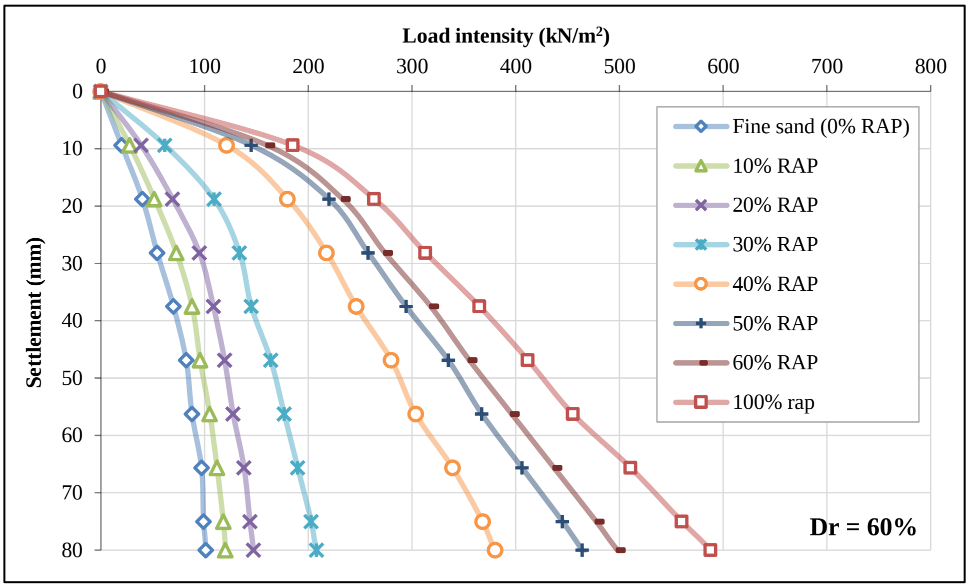


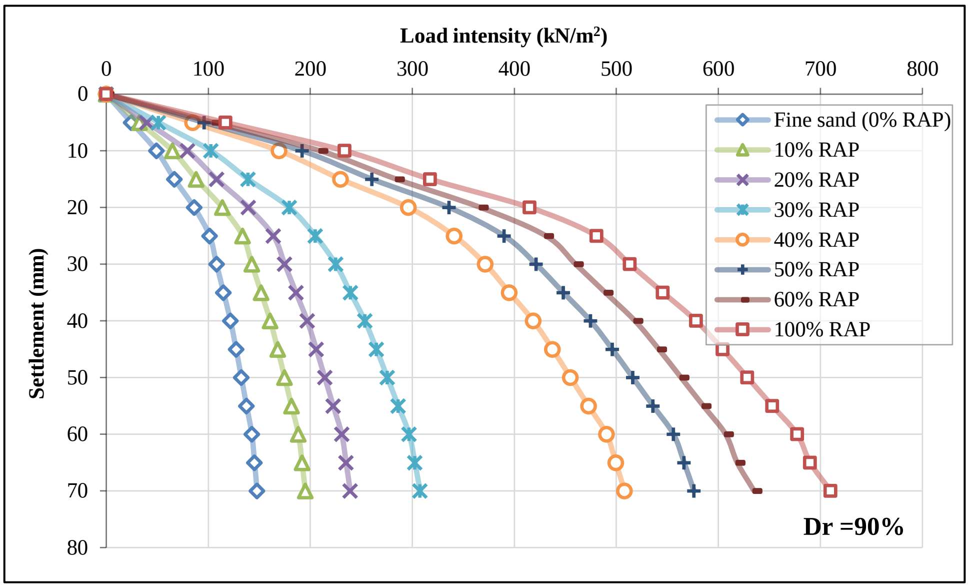
Figure 13. Enhanced compaction indicators as a percentage relative to fine sand

6.4. Results of Plate Bearing Tests

The settlement behaviour of sand-RAP mixes is shown in Figure 13 for two distinct relative densities (D_r = 90% and D_r = 60%) and varied impact intensities. The figures compare settlement (in mm) and load intensity (kN/m²) for various sand-RAP mixtures. As seen in Figure 14, settlement decreases with increasing relative density, while load intensity rises as the proportion of RAP increases, particularly at higher RAP contents. The RAP used in this study was sourced from a stockpile over a decade old, which resulted in a stiffer and more stable binder due to the natural reduction of volatile components. This stable binder composition minimizes changes during testing, ensuring consistent and reliable results.



(a) D_r = 60%.



(b) D_r = 90%.

Figure 14. Load intensity-settlement relations

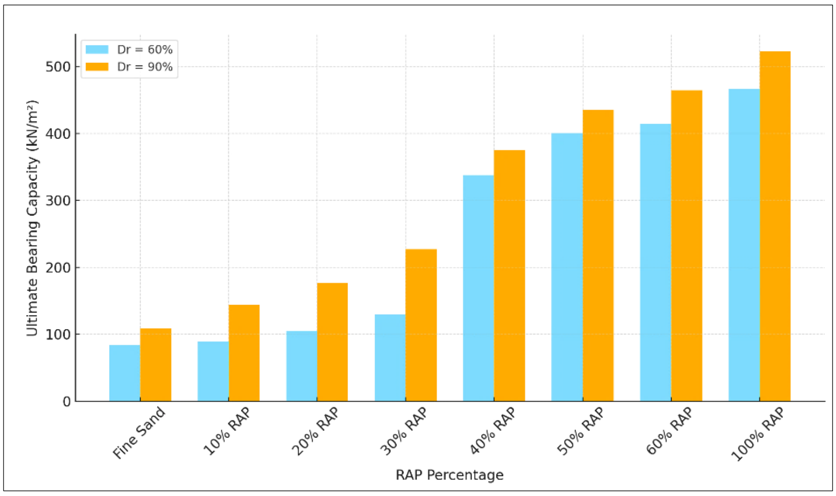
6.4.1. Ultimate Bearing Capacity vs. RAP Content

The bearing capacity of samples calculated using the log-log method from plate load tests provides a reliable estimate of the soil's load-bearing capacity [67]. This method involves plotting the load applied during the test against the corresponding settlement on a log-log scale, allowing for a more accurate interpretation of the data.

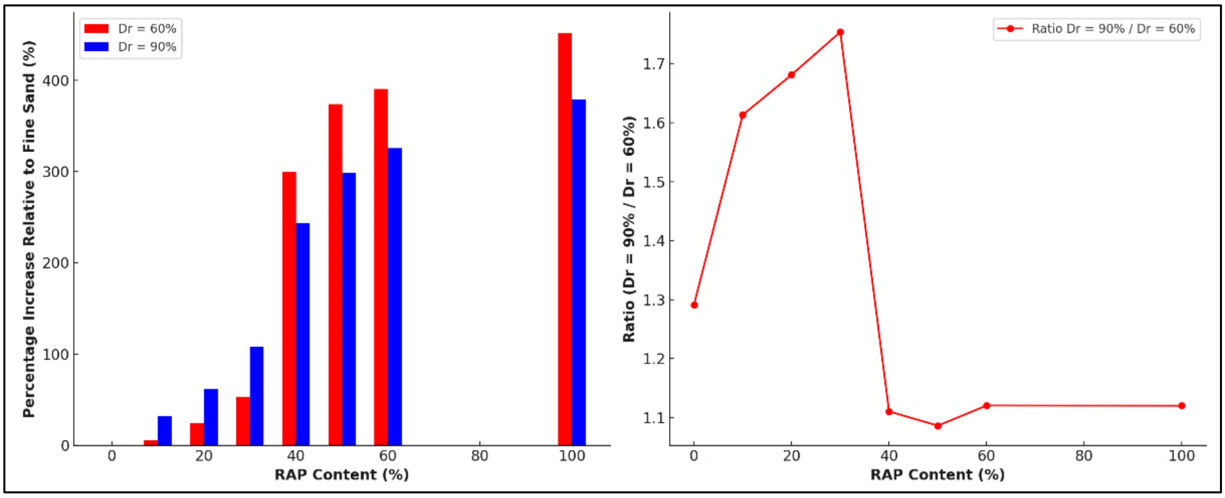
Figures 15 highlight the substantial improvements in ultimate bearing capacity when incorporating RAP into fine sand, with notable differences across both density conditions (D_r = 60% and D_r = 90%). By comparing the percentage increase relative to fine sand and analyzing the ratio of D_r = 90% to D_r = 60%, we gain deeper insights into the influence of RAP content.

For both densities, the ultimate bearing capacity increases consistently as the RAP content rises (Figure 15a). At D_r = 60%, the bearing capacity starts at 84.5 kN/m² for fine sand (0% RAP) and climbs gradually until 30% RAP, where it experiences a sharp increase from 129.5 kN/m² to 337.64 kN/m² at 40% RAP. The growth continues steadily, peaking at 466.12 kN/m² for 100% RAP. Similarly, for D_r = 90%, the initial bearing capacity of 109.12 kN/m² for fine sand rises significantly with increasing RAP, reaching a maximum value of 517.91 kN/m² at 100% RAP. The steepest increase is observed between 30% and 40% RAP for both densities, indicating a critical threshold where RAP contributes heavily to strength enhancement.

When comparing the two densities, the ultimate bearing capacity for D_r = 90% consistently exceeds that of D_r = 60% at all RAP levels. This is expected due to the higher compaction density, which enhances the soil's resistance to deformation. Interestingly, the difference in bearing capacity between the two densities narrows slightly at higher RAP contents, suggesting that the benefits of RAP might be more pronounced under less compacted conditions as the RAP content increases.



(a)



(b) (c)

Figure 15. (a) Ultimate bearing capacity vs RAP percentage, (b) increase ratios in ultimate bearing capacity relative to fine sand across various RAP content levels, (c) ratios of ultimate bearing capacity between D_r = 90% and D_r = 60%.

A notable finding is the significant improvement in soil strength with RAP inclusion, particularly at levels of 40% RAP and higher. For instance, at 50% RAP, the ultimate bearing capacity is approximately 400.48 kN/m² for D_r = 60%, which rises to 425.19 kN/m² for D_r = 90%. This trend underscores the potential of RAP to enhance soil performance, especially when used in higher proportions.

The inclusion of RAP leads to progressively greater percentage increases in ultimate bearing capacity compared to the baseline fine sand condition (Figure 15-b). At D_r = 60%, the increase is modest at lower RAP contents, with a 5.68% improvement observed at 10% RAP. However, as RAP content increases, the improvements become significant, reaching a remarkable 299.53% at 40% RAP and culminating in a 451.52% increase at 100% RAP. Similarly, for D_r = 90%, the percentage improvements are even more pronounced at lower RAP contents, with a 31.96% increase at 10% RAP. The trend continues, with a 243.69% increase at 40% RAP and a peak improvement of 374.58% at 100% RAP. This indicates that higher densities amplify the benefits of RAP inclusion, particularly at lower RAP levels.

The comparison of ultimate bearing capacity ratios between D_r = 90% and D_r = 60% reveals interesting trends (Figure 15c). At 0% RAP (fine sand), the ratio is 1.29, indicating a significant advantage for the higher density condition due to improved soil compaction. However, as RAP content increases, the ratio steadily declines, reaching 1.11 at 100% RAP. This diminishing ratio suggests that as RAP content rises, its inherent strength contribution becomes a dominant factor, reducing the relative influence of density. Thus, while higher density consistently enhances soil strength, the benefit is less pronounced at very high RAP levels.

6.4.2. Stiffness of RAP-Sand blends

Stiffness is a fundamental property that measures a material's ability to resist deformation when subjected to an applied load. In the context of geotechnical engineering, stiffness quantifies how much settlement or displacement occurs in response to an increase in load intensity. Higher levels of stiffness indicate less settlement under a given load, whereas lower values indicate more deformation. Soil stiffness (k) is a crucial property for understanding its behaviour under various loading conditions; it is calculated using load intensity-settlement curves with a specific formula. The formula can be written as:

$$\mathrm{k}\left(\frac{kN}{m^2}\text{ per mm}\right) = \frac{\Delta\, Load\ Intensity\ (\frac{kN}{m^2})}{\Delta\, Settlement\ (mm)} \tag{1}$$

The formula indicates that Δ Load Intensity is the change in load between two points on the curve and Δ Settlement is the variation in settlement that corresponds to it. By analyzing these curves, stiffness can be calculated as the slope of the curve at different segments. Slope steepness is a measure of stiffness; a steeper slope means less deformation for the same level of applied stress. The sand-RAP stiffness trends of different soil mixtures as a function of % RAP are shown in Figure 16. The values displayed in this figure were derived from the load intensity-settlement curves presented in Figure 14. This investigation elucidates the correlation between RAP levels and the resultant stiffness of soil mixtures, particularly for each relative density.

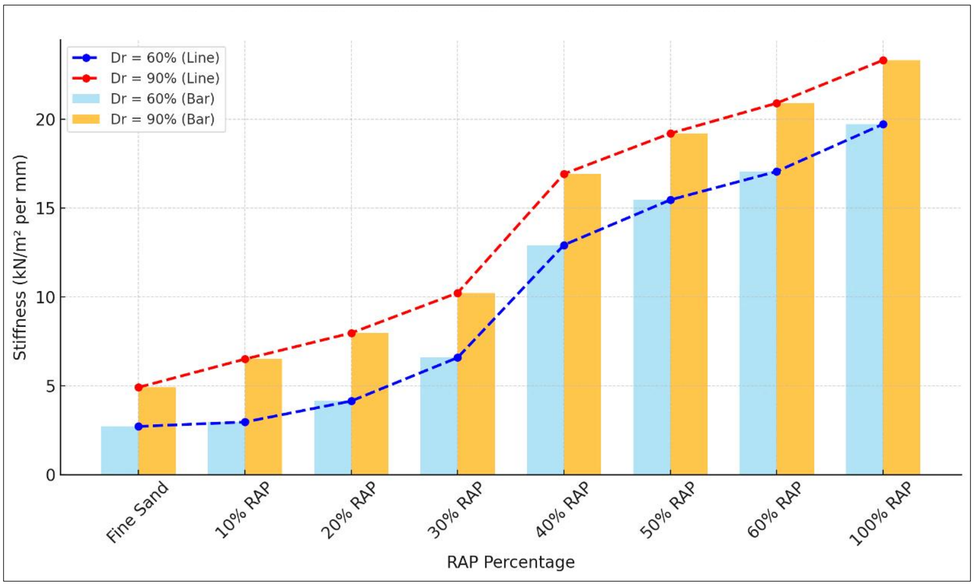


Figure 16. Graphing sand-rap stiffness versus percentage

The analysis reveals that a rise in the fraction of RAP is associated with a significant improvement in the soil's stiffness for both relative densities (D_r = 60% and D_r = 90%). Particularly, at D_r = 60% and D_r = 90%, the stiffness measurements for fine sand devoid of RAP are 2.71 kN/m² per mm and 4.91 kN/m² per mm, respectively. Alternatively, at D_r = 60% and 90%, respectively, the stiffness achieves its maximum values of 19.73 kN/m² per mm and 23.33 kN/m² per mm at 100% RAP. The pronounced disparity underscores the beneficial effects of RAP in improving soil behavior. Since the interlocking structure of RAP particles improves load distribution and reduces settling, raising the % RAP increases stiffness. The sharp and uneven surface of RAP particles, in contrast to the smooth and relatively tiny friction angle of fine sand, increases shear resistance and enhances particle interlock.

Additionally, the findings show that regardless of the ratio of RAP, the stiffness is continuously greater when the relative density is 90% (dense state) than when it is 60% (loose state). In the case of 50% RAP, for illustration, the stiffness rises from 15.47 kN/m² per mm at D_r = 60% to 19.21 kN/m² per mm at D_r = 90%. Stiffness also increases with 100% RAP, moving from 19.73 kN/m² per mm at D_r = 60% to 23.33 kN/m² per mm at D_r = 90%. This conclusion highlights how the soil's mechanical characteristics are greatly affected by its relative density. As the relative density increases, the void ratio decreases, increasing the interparticle friction and the soil's interlocking capability and, therefore, the stiffness. Moreover, at higher RAP percentages, the compaction-induced stiffening is especially noticeable, as the resistance to deformation is maximized when particles are tightly compacted. Ultimately, RAP mixes are more suited for load-bearing applications when their relative densities are increased.

The performance statistics for fine sand blended with varying percentages of Recycled Asphalt Pavement (RAP) reveal significant improvements over baseline values. The baseline measurements for D_r = 60% and D_r = 90% are 2.71 and 4.91, respectively. These values serve as the control for assessing the effects of increasing RAP percentages. As the percentage of RAP increases, notable enhancements are observed in both D_r = 60% and D_r = 90%. At 10% RAP, the D_r = 60% value slightly increases to 2.96, reflecting a 9.1% improvement, while D_r = 90% rises more significantly to 6.50, marking a 32.4% improvement. The trend continues to strengthen with higher RAP percentages. At 20% RAP, the D_r = 60% value increases to 4.14, demonstrating a substantial 52.8% improvement, and D_r = 90% reaches 7.97, which is a 62.3% improvement. The most remarkable changes occur at the higher RAP percentages. For instance, at 30% RAP, D_r = 60% grows to 6.58, achieving a 143% improvement, while D_r = 90% climbs to 10.23, reflecting a 108.4% improvement. This upward trajectory continues, with D_r = 60% jumping to 12.93 at 40% RAP, representing a staggering 377.1% improvement. Simultaneously, D_r = 90% reaches 16.93, marking a 244.8% improvement. Further increases in RAP content show continued benefits. At 50% RAP, D_r = 60% moderately increases to 15.47, indicating a 471% improvement, and D_r = 90% advances to 19.21, with a 291% improvement. The trend is even more pronounced at 60% RAP, where D_r = 60% rises to 17.07, reflecting a 530% improvement, and D_r = 90% grows to 20.91, indicating a 326% improvement.

The analysis of performance trends between various percentages of Recycled Asphalt Pavement (RAP) reveals some important insights (Figure 17), particularly when comparing 50% RAP to 60% RAP and 60% RAP to 100% RAP. When evaluating the performance values for 50% RAP and 60% RAP, the differences are relatively modest. For D_r = 60%, the value for 50% RAP is 15.47, while it increases to 17.07 at 60% RAP. Similarly, for D_r = 90%, the values are 19.21 for 50% RAP compared to 20.91 for 60% RAP. The percentage improvements between these two levels of RAP indicate a gradual increase, suggesting that while there is a performance benefit in moving from 50% to 60% RAP, the enhancement is not as dramatic as seen with lower RAP percentages. In contrast, the comparison between 60% RAP and 100% RAP reveals a more pronounced stability in performance. The values at 60% RAP—17.07 for D_r = 60% and 20.91 for D_r = 90%—are significantly closer to those at 100% RAP, which are 19.73 and 23.33, respectively. This trend indicates that as RAP content increases to higher levels, specifically from 60% to 100%, the performance improvements begin to taper off, reflecting diminishing returns. Overall, these observations highlight that while increasing RAP content generally enhances performance, the rate of improvement decreases as RAP levels rise, particularly beyond 50% RAP. This suggests that at higher RAP concentrations, the benefits become less pronounced, indicating a stabilization of performance metrics.

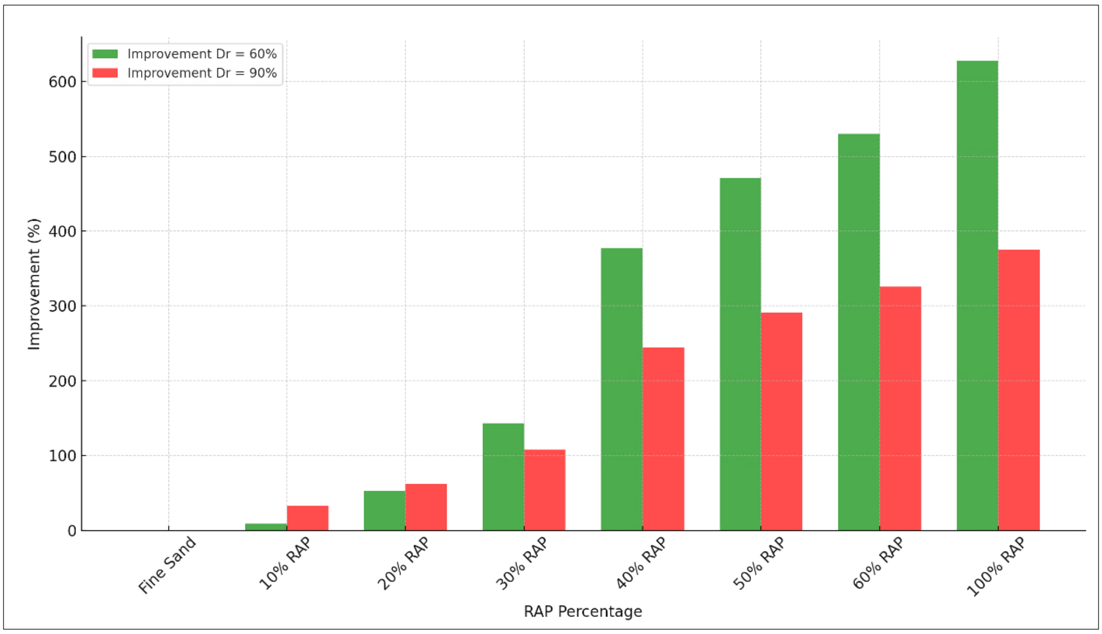


Figure 17. Improvement ratios across RAP percentages

7. Conclusions

The primary objective of this study was to assess the physical and mechanical behavior of fine sand and sand-RAP mixtures to determine their suitability for use in subgrade and subbase layers in road construction. A detailed experimental program analyzed key parameters, including gradation, specific gravity, compaction characteristics, California Bearing Ratio (CBR), stiffness, and bearing capacity. The mixtures were tested with varying RAP contents (0%, 10%, 20%, 30%, 40%, 50%, 60%, and 100% by weight) and evaluated for compliance with AASHTO and ECP 104 standards. A total of 38 tests, including physical and plate-bearing tests, were performed on sand-RAP mixtures under static loading conditions at two relative densities (Dr = 60% and 90%). Based on the results and analysis, the following conclusions highlight the key findings of this study.

- Integrating RAP into fine sand shifts its gradation to a coarser profile (A-1 classification), meeting ECP 104, IRC: 37-2012, and AASHTO standards for subgrade types A, B, and C. Mixtures with 50–60% RAP fall within acceptable ranges for subbase use, confirming their suitability for road construction.
- RAP levels beyond 50% show diminishing returns, with 50% marking an optimal balance point. At this level, significant improvements in CBR values, dry density, and reduced OMC ensure efficient compaction and enhanced bearing capacity, making it ideal for high-performance, moisture-sensitive construction applications.
- Adding RAP to natural sand significantly boosts CBR values, starting from 8.78% for natural fine sand. A 10% RAP addition raises CBR to 11.59%, while 20% and 30% RAP increase it to 14.2% and 18.27%, respectively.
- Beyond 40% RAP, CBR improvements taper, with 50% RAP yielding 34.21% and 60% RAP reaching 37.35% (max 41.67% at 100% RAP). Diminishing returns beyond 50% RAP suggest capping content for optimal strength and cost efficiency in road construction.
- While fine sand and low RAP blends (10%-20%) are only suitable for low-traffic subgrade applications, they fail to meet the CBR requirements for sub-base layers. Higher RAP contents (40%-60%) show significantly improved in CBR performance, meeting all subgrade and sub-base requirements for light and moderate traffic. However, only 100% of RAP fully complies with all subgrade and sub-base standards.
- The quadratic model emerges as the best-fit mathematical model for analyzing the relationship between RAP content and CBR values, achieving the highest R^2 (0.9431) and the lowest MAE (2.52) and RMSE (2.85). It aligns closely with prior research and provides a robust framework for advancing studies in soil stabilization and construction.
- Mixtures with 40% to 60% RAP exhibit significantly greater improvements in dry density, achieving increases of 12% to 16% compared to fine sand. This range also shows a substantial reduction in OMC, often decreasing by 30% or more. These characteristics make higher RAP mixtures more effective for applications requiring improved load-bearing capacity and stability, especially in water-limited environments.
- The inclusion of RAP in fine sand improves bearing capacity across all RAP levels, with trends varying by content and density. In the 10% to 30% RAP range, capacity grows moderately, from 5.68% to 53.27% at Dr = 60% and from 31.96% to 81.86% at Dr = 90%. At higher RAP levels, particularly in the 40% to 60% range, growth becomes significant, with increases from 299.53% to 411.83% at Dr = 60% and from 243.69% to 318.43% at Dr = 90%. These findings underscore 40% RAP as the critical point where notable performance gains are achieved.
- The ultimate bearing capacity ratio (Dr = 90% / Dr = 60%) initially increases, peaking at 1.77 around 30% RAP, indicating a significant advantage of higher density at moderate RAP levels. However, beyond 30% RAP, the ratio drops sharply and stabilizes near 1.11 from 40% RAP onwards, reflecting the diminishing influence of density as RAP's inherent strength becomes the dominant factor at higher contents.
- RAP inclusion significantly improves stiffness, with peak gains between 40% and 60% RAP. At Dr = 60%, stiffness rises by 530% (17.07 kN/m² per mm), while Dr = 90% achieves a 326% increase (20.91 kN/m² per mm). Initial gains at 10%-30% RAP are steady, with increases up to 143% at Dr = 60% and 108.4% at Dr = 90%, but beyond 50% RAP, diminishing returns emerge. Optimizing RAP content at 40%-60% ensures superior stiffness and performance for construction applications.

8. Declarations

8.1. Author Contributions

Conceptualization, A.B. and M.H.Z.; methodology, A.B. and M.H.Z.; software, M.E.; validation, A.B., M.H.Z., and M.E.; formal analysis, M.H.Z. and M.E.; investigation, M.H.Z. and M.E.; resources, M.H.Z. and M.E.; data curation, M.H.Z.; writing—original draft preparation, M.H.Z. and M.E.; writing—review and editing, A.B.; visualization, A.B. and M.E.; supervision, A.B., S.F., and M.H.Z.; project administration, A.B.; funding acquisition, A.B., M.H.Z., S.F., and M.E. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

8.4. Acknowledgements

The authors sincerely thank the Geotechnical Engineering Laboratory at Kafr El-Sheikh University for their essential support throughout this research. The laboratory's contributions, particularly in providing the necessary equipment and expertise for the experimental work, were pivotal to the successful completion of this study.

8.5. Conflicts of Interest

The authors declare no conflict of interest.

8.6. Competing interests

The authors declare that they have no competing interests.

9. References

[1] Li, L., Zhang, Y., & Tian, Y. (2024). The Application of Fine Sand in Subgrades: A Review. Applied Sciences (Switzerland), 14(15), 6722. doi:10.3390/app14156722.

[2] Mukiza, E., Zhang, L., Liu, X., & Zhang, N. (2019). Utilization of red mud in road base and subgrade materials: A review. Resources, Conservation and Recycling, 141, 187–199. doi:10.1016/j.resconrec.2018.10.031.

[3] Xiao, J., Juang, C. H., Xu, C., Li, X., & Wang, L. (2014). Strength and deformation characteristics of compacted silt from the lower reaches of the Yellow River of China under monotonic and repeated loading. Engineering Geology, 178, 49–57. doi:10.1016/j.enggeo.2014.06.008.

[4] USDA. (1999). Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys (2nd Ed.). U.S. Government Printing Office (USDA), Washington, United States. doi:10.1097/00010694-197704000-00011.

[5] ASTM D2487-17. (2020). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International, Pennsylvania, United States. doi:10.1520/D2487-17.

[6] Mahvash, S., López-Querol, S., & Bahadori-Jahromi, A. (2018). Effect of fly ash on the bearing capacity of stabilised fine sand. Proceedings of the Institution of Civil Engineers: Ground Improvement, 171(2), 82–95. doi:10.1680/jgrim.17.00036.

[7] Anvari, S. M., & Shooshpasha, I. (2016). Influence of size of granulated rubber on bearing capacity of fine-grained sand. Arabian Journal of Geosciences, 9(18), 707. doi:10.1007/s12517-016-2744-8.

[8] Badrawi Attia, E. (2024). Influence of Geogrid-Axial Stiffness on Bearing Capacity of Geogrid-Reinforced Fine Sand. Port-Said Engineering Research Journal, 28(2), 41-49. doi:10.21608/pserj.2024.253870.1298.

[9] Van Den Berg, J. H., Van Gelder, A., & Mastbergen, D. R. (2002). The importance of breaching as a mechanism of subaqueous slope failure in fine sand. Sedimentology, 49(1), 81–95. doi:10.1111/j.1525-139X.2006.00168.x-i1.

[10] Martin, B. E., Chen, W., Song, B., & Akers, S. A. (2009). Moisture effects on the high strain-rate behavior of sand. Mechanics of Materials, 41(6), 786–798. doi:10.1016/j.mechmat.2009.01.014.

[11] Hatten, J., & Liles, G. (2019). A 'healthy' balance – The role of physical and chemical properties in maintaining forest soil function in a changing world. Global Change and Forest Soils, 373–396, Elsevier, Amsterdam, Netherlands. doi:10.1016/b978-0-444-63998-1.00015-x.

[12] Holtz, R. D. (2001). Construction Materials: Soil and Natural Materials. Encyclopedia of Materials: Science and Technology, 1559–1563, Elsevier, Amsterdam, Netherlands. doi:10.1016/b0-08-043152-6/00278-3.

[13] Archibong, G. A., Sunday, E. U., Akudike, J. C., Okeke, O. C., & Amadi, C. (2020). A review of the principles and methods of soil stabilization. International Journal of Advanced Academic Research| Sciences, 6(3), 2488-9849.

[14] Plati, C., & Tsakoumaki, M. (2023). Life Cycle Assessment (LCA) of Alternative Pavement Rehabilitation Solutions: A Case Study. Sustainability (Switzerland), 15(3), 2129. doi:10.3390/su15032129.

[15] Zang, Y. X., Gong, W., Xie, H., Liu, B. L., & Chen, H. L. (2015). Chemical sand stabilization: A review of material, mechanism, and problems. Environmental Technology Reviews, 4(1), 119–132. doi:10.1080/21622515.2015.1105307.

[16] Tao, G., Yuan, J., Chen, Q., Peng, W., Yu, R., & Basack, S. (2021). Chemical stabilization of calcareous sand by polyurethane foam adhesive. Construction and Building Materials, 295, 123609. doi:10.1016/j.conbuildmat.2021.123609.

[17] Szendefy, J. (2013). Impact of the soil-stabilization with lime. Proceedings of the 18th international conference on soil mechanics and geotechnical engineering, 2-6 September, 2013, Paris, France.

[18] Wang, S., Zhang, X., Zhang, P., & Chen, Z. (2023). Strength Performance and Stabilization Mechanism of Fine Sandy Soils Stabilized with Cement and Metakaolin. Sustainability (Switzerland), 15(4), 3431. doi:10.3390/su15043431.

[19] Markiewicz, A., Koda, E., & Kawalec, J. (2022). Geosynthetics for Filtration and Stabilisation: A Review. Polymers, 14(24), 5492. doi:10.3390/polym14245492.

[20] Andavan, S., & Kumar, B. M. (2020). Case study on soil stabilization by using bitumen emulsions – A review. Materials Today: Proceedings, 22, 1200–1202. doi:10.1016/j.matpr.2019.12.121.

[21] Rezaeimalek, S., Nasouri, A., Huang, J., Bin-Shafique, S., & Gilazghi, S. T. (2017). Comparison of short-term and long-term performances for polymer-stabilized sand and clay. Journal of Traffic and Transportation Engineering, 4(2), 145–155. doi:10.1016/j.jtte.2017.01.003.

[22] Vidal, R., Moliner, E., Martínez, G., & Rubio, M. C. (2013). Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. Resources, Conservation and Recycling, 74, 101–114. doi:10.1016/j.resconrec.2013.02.018.

[23] Aurangzeb, Q., & Al-Qadi, I. L. (2014). Asphalt pavements with high reclaimed asphalt pavement content: Economic and environmental perspectives. Transportation Research Record, 2456(1), 161–169. doi:10.3141/2456-16.

[24] Willis, J.R. (2015). Effect of recycled materials on pavement Life-Cycle Assessment: A case study. Proceedings of the 94th Annual Meeting of the Transportation Research Board, 11–15 January, 2015 Washington, United States.

[25] Bloom, E., Canton, A., Ahlman, A. P., & Edil, T. (2017). Life cycle assessment of highway reconstruction: A case study. Proceedings of the 96th Transportation Research Board Annual Meeting, 8–12 January, 2017, Washington, United States.

[26] Gruber, M. R., & Hofko, B. (2023). Life Cycle Assessment of Greenhouse Gas Emissions from Recycled Asphalt Pavement Production. Sustainability (Switzerland), 15(5), 4529. doi:10.3390/su15054629.

[27] EAPA. (2022). Asphalt in figures 2022. European Asphalt Pavement Association (EAPA), Brussels, Belgium.

[28] Williams, B.A., Willis, J.R., & Shacat, J. (2020). Asphalt pavement industry survey on recycled materials and warm-mix asphalt usage: 2020. National Asphalt Pavement Association: Greenbelt, United States.

[29] Yousefdoost, S., Rebbechi, J., & Petho, L. (2016). P57: Implementing the use of reclaimed asphalt pavement (RAP) in TMR-registered dense-graded asphalt mixes. Project No: PRP16033, National Centre of Excellence (NACOE), Fortitude Valley, United Kingdom.

[30] ARRB. (2022). Best Practice Expert Advice on the Use of Recycled Materials in Road and Rail Infrastructure: Part A Technical Review and Assessment. Australian Road Research Board (ARRB), Melbourne, Australia.

[31] SABITA. (2021). Use of Reclaimed Asphalt in the Production of Asphalt, TRH 21. Southern African Bitumen Association (SABITA), Pinelands, South Africa.

[32] 32-Mousa, E., El-Badawy, S., & Azam, A. (2021). Evaluation of reclaimed asphalt pavement as base/subbase material in Egypt. Transportation Geotechnics, 26, 100414. doi:10.1016/j.trgeo.2020.100414.

[33] Cubas, M., Correa, E., Benavides, W., Suclupe, R., & Arriola, G. (2025). Modified Asphalt Mixtures Incorporating Pulverized Recycled Rubber and Recycled Asphalt Pavement. Civil Engineering Journal (Iran), 11(2), 420–436. doi:10.28991/CEJ-2025-011-02-02.

[34] Chfat, A. H. Z., Yaacob, H., Kamaruddin, N. M., Al-Saffar, Z. H., & Jaya, R. P. (2024). Performance of Asphalt Mixtures Modified with Nano-Eggshell Powder. Civil Engineering Journal, 10(11), 3699-3720. doi:10.28991/CEJ-2024-010-11-016.

[35] Suddeepong, A., Akkharawongwhatthana, K., Horpibulsuk, S., Buritatum, A., Hoy, M., Yaowarat, T., Pongsri, N., Chinkulkijniwat, A., Arulrajah, A., & Horpibulsuk, J. (2024). Polyethylene Terephthalate Modified Asphalt Concrete with Blended Recycled Aggregates: Analysis and Assessment. Civil Engineering Journal (Iran), 10(11), 3569–3588. doi:10.28991/CEJ-2024-010-11-08.

[36] Tsakoumaki, M., & Plati, C. (2024). A Critical Overview of Using Reclaimed Asphalt Pavement (RAP) in Road Pavement Construction. Infrastructures, 9(8), 128. doi:10.3390/infrastructures9080128.

[37] Tarsi, G., Tataranni, P., & Sangiorgi, C. (2020). The challenges of using reclaimed asphalt pavement for new asphalt mixtures: A review. Materials, 13(18), 4052. doi:10.3390/ma13184052.

[38] Zhang, K., Huchet, F., & Hobbs, A. (2019). A review of thermal processes in the production and their influences on performance of asphalt mixtures with reclaimed asphalt pavement (RAP). Construction and Building Materials, 206, 609–619. doi:10.1016/j.conbuildmat.2019.02.057.

[39] Hung, V. Q., Jayarathne, A., Gallage, C., Dawes, L., Egodawatta, P., & Jayakody, S. (2024). Leaching characteristics of metals from recycled concrete aggregates (RCA) and reclaimed asphalt pavements (RAP). Heliyon, 10(9), e30407. doi:10.1016/j.heliyon.2024.e30407.

[40] Al-Shujairi, A. O., Al-Taie, A. J., & Al-Mosawe, H. M. (2021). Review on applications of RAP in civil engineering. IOP Conference Series: Materials Science and Engineering, 1105(1), 012092. doi:10.1088/1757-899x/1105/1/012092.

[41] Puppala, A. J., Saride, S., & Williammee, R. (2012). Sustainable Reuse of Limestone Quarry Fines and RAP in Pavement Base/Subbase Layers. Journal of Materials in Civil Engineering, 24(4), 418–429. doi:10.1061/(asce)mt.1943-5533.0000404.

[42] Mousa, R. M., & Mousa, M. R. (2019). Cost–Benefit Analysis of RAP–Sand Blend Applications in Road Construction. Transportation Research Record, 2673(2), 415–426. doi:10.1177/0361198118823495.

[43] Buhari, B. M., Jose, A., Muhammed, A., Abhilash, S., & Shaji, S. (2025). Experimental Investigation on Concrete using RAP & QBP as Aggregates. AIP Conference Proceedings, 3280(1), 30007. doi:10.1063/5.0247522.

[44] Tiza, M. T., Agunwamba, J., Okafor, F., & Solomon, S. (2025). Prediction and Optimization of Compressive Strength of Cement Concrete with Box-Behnken Model. Journal of International Environmental Application and Science, 20(1), 56-69

[45] Suddeepong, A., Intra, A., Horpibulsuk, S., Suksiripattanapong, C., Arulrajah, A., & Shen, J. S. (2018). Durability against wetting-drying cycles for cement-stabilized reclaimed asphalt pavement blended with crushed rock. Soils and Foundations, 58(2), 333–343. doi:10.1016/j.sandf.2018.02.017.

[46] Miao, Y., Wang, S., Guo, L., Zheng, X., Huang, Y., & Wang, L. (2018). Effect of temperature on deformation properties of unbound granular materials containing fine RAP. Construction and Building Materials, 169, 443–451. doi:10.1016/j.conbuildmat.2018.02.154.

[47] Adhikari, S., Khattak, M. J., & Adhikari, B. (2020). Mechanical characteristics of Soil-RAP-Geopolymer mixtures for road base and subbase layers. International Journal of Pavement Engineering, 21(4), 483–496. doi:10.1080/10298436.2018.1492131.

[48] Hasan, M. M., Islam, M. R., & Tarefder, R. A. (2018). Characterization of subgrade soil mixed with recycled asphalt pavement. Journal of Traffic and Transportation Engineering (English Edition), 5(3), 207–214. doi:10.1016/j.jtte.2017.03.007.

[49] Suebsuk, J., Suksan, A., & Horpibulsuk, S. (2014). Strength assessment of cement treated soil-reclaimed asphalt pavement (RAP) mixture. International Journal of GEOMATE, 6(2), 878–884. doi:10.21660/2014.12.3262.

[50] Lima, D., Arrieta-Baldovino, J., & Izzo, R. L. S. (2023). Sustainable Use of Recycled Asphalt Pavement in Soil Stabilization. Civil Engineering Journal (Iran), 9(9), 2315–2329. doi:10.28991/CEJ-2023-09-09-016.

[51] ASTM D6913/D6913M-17. (2021). Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. ASTM International, Pennsylvania, United States. doi:10.1520/D6913_D6913M-17.

[52] ASTM D854-23. (2000). Standard Test Methods for Specific Gravity of Soil Solids by the Water Displacement Method. ASTM International. ASTM International, Pennsylvania, United States. doi:10.1520/D0854-23.

[53] ASTM D698-12(2021). (2012). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3)). ASTM International, Pennsylvania, United States. doi:10.1520/D0698-12R21.

[54] ASTM D1883-21. (2021). Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. ASTM International, Pennsylvania, United States. doi:10.1520/D1883-21.

[55] ASTM D1194-94. (2017). Standard Test Method for Bearing Capacity of Soil for Static Load and Spread Footings (Withdrawn 2003). ASTM International, Pennsylvania, United States.

[56] ECP-104. (2018). Egyptian Code of Practice for Urban and Rural Roads, edition 1: Road materials and their tests (part four). Housing and Building National Research Center (HBRC), Cairo, Egypt.

[57] Das, B. M., & Sivakugan, N. (2018). Principles of Foundation Engineering. Cengage Learning, Boston, United States.

[58] Bowles, J. E., & Guo, Y. (1996). Foundation Analysis and Design. McGraw-Hill, New York, United States

[59] Vinod, P., Bhaskar, A. B., & Sreehari, S. (2009). Behaviour of a square model footing on loose sand reinforced with braided coir rope. Geotextiles and Geomembranes, 27(6), 464–474. doi:10.1016/j.geotexmem.2009.08.001.

[60] El Sawwaf, M., & Nazir, A. (2012). Behavior of Eccentrically Loaded Small-Scale Ring Footings Resting on Reinforced Layered Soil. Journal of Geotechnical and Geoenvironmental Engineering, 138(3), 376–384. doi:10.1061/(asce)gt.1943-5606.0000593.

[61] Azzam, W. R., & Elwakil, A. Z. (2017). Performance of Axially Loaded-Piled Retaining Wall: Experimental and Numerical Analysis. International Journal of Geomechanics, 17(2). doi:10.1061/(asce)gm.1943-5622.0000710.

[62] Mayne, P. W. (2007). In-situ test calibrations for evaluating soil parameters. Characterisation and Engineering Properties of Natural Soils, 3–4, 1601–1652, Taylor & Francis Group, London, United Kingdom. doi:10.1201/noe0415426916.ch2.

[63] Mishra, S., Sachdeva, S. N., & Manocha, R. (2019). Subgrade Soil Stabilization Using Stone Dust and Coarse Aggregate: A Cost Effective Approach. International Journal of Geosynthetics and Ground Engineering, 5(3), 1–11. doi:10.1007/s40891-019-0171-0.

[64] Taha, R., Ali, G., Basma, A., & Al-Turk, O. (1999). Evaluation of Reclaimed Asphalt Pavement Aggregate in Road Bases and Subbases. Transportation Research Record: Journal of the Transportation Research Board, 1652(1), 264–269. doi:10.3141/1652-33.

[65] Seferoğlu, A. G., Seferoğlu, M. T., & Akpinar, M. V. (2018). Investigation of the Effect of Recycled Asphalt Pavement Material on Permeability and Bearing Capacity in the Base Layer. Advances in Civil Engineering, 2018(1), 2860213. doi:10.1155/2018/2860213.

[66] Kalpakci, V., Faeq, R., & Canakci, H. (2018). Compaction and CBR properties of RAP/sand blends in Iraq. Arabian Journal of Geosciences, 11(21), 1–7. doi:10.1007/s12517-018-4033-1.

[67] De Beer, E. E. (1970). Experimental determination of the shape factors and the bearing capacity factors of sand. Geotechnique, 20(4), 387–411. doi:10.1680/geot.1970.20.4.387.