Investigation of the effects of recycled concrete aggregates and emulsified asphalt on the improvement of sandy soil performance

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Abstract

Construction and demolition (C&D) waste significantly contributes to global landfills but has valuable applications in civil engineering. Sandy soils, known for their non-cohesive nature, pose considerable challenges in construction, particularly in embankment and roadbed scenarios. This study examines the impact of Recycled Concrete Aggregates (RCA) and emulsified asphalt on improving the mechanical properties of sandy soils. The results demonstrated that a combination of up to 30% RCA and 25% emulsified asphalt resulted in notable improvements in compressive strength and elastic modulus, achieving average values of 360 kPa and 2.4 MPa, respectively. However, excessive RCA content adversely affects the material's effectiveness. Notably, increased proportions of both additives greatly improved the modulus of elasticity, indicating enhanced resistance to deformation. The binding properties of emulsified asphalt contributed to better cohesion among sand particles, thereby strengthening structural integrity. Conversely, higher RCA percentages were associated with a decrease in fracture energy, raising concerns about material stability and resilience. Overall, the integration of emulsified asphalt and RCA is shown to significantly enhance the mechanical characteristics of sandy soil, making it a viable solution for construction challenges involving non-cohesive soils.

Keywords: *Waste, utilization of recycled materials, recycled concrete aggregates, emulsified asphalt, soil stabilization*

Introduction

The production and extensive use of construction materials, along with the resulting environmental pollution, represent a global challenge. However, the incorporation of recycled materials in infrastructure projects and their reuse serves as a viable solution to mitigate environmental damage, thereby reducing the reliance on new materials in human life and civil infrastructure. Furthermore, suitable soil and substrates for infrastructural development are increasingly scarce due to inadequate physical and mechanical properties. The presence of quicksand in desert and coastal regions poses significant challenges for the construction of pavements and roads. Quicksand, characterized by its loose, water-saturated sand, can undermine structural integrity, leading to unexpected sinkholes and instability[1]. Moreover, its unpredictable behavior complicates the engineering processes, necessitating specialized techniques and materials for effective stabilization. The high variability in moisture content further exacerbates these issues, requiring constant monitoring and maintenance. As a result, projects in these regions often face delays and increased costs, emphasizing the need for thorough geotechnical assessments and innovative engineering solutions to mitigate risks associated with quicksand[2]. The costs associated with the relocation and improvement of sandy soils, commonly found along coastlines and desert regions, are substantial. The advancement of innovative technologies for utilizing loose and sandy soils by enhancing and increasing their strength has always been a focal point for researchers. The application of polymeric materials, particularly emulsified asphalts, has garnered attention as well. These polymers, derived from crude oil and recognized as asphalt, serve as binding and penetrating agents for materials and soil particles. The surface coating of silica aggregates in sandy areas along coastlines and deserts is notably illustrated in Figure 1.

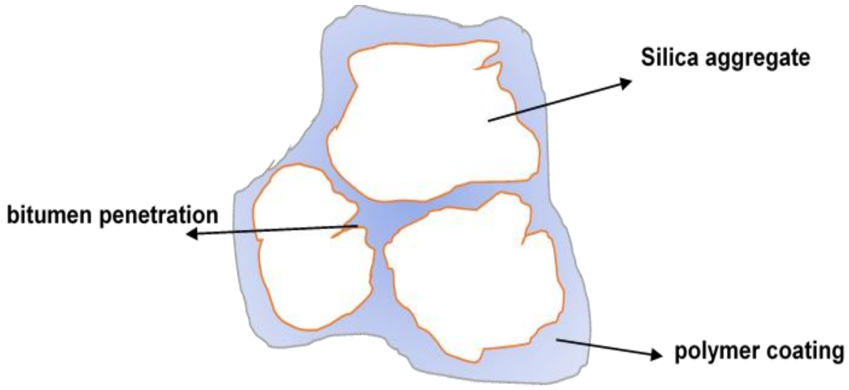

Figure 1: Connection of petrochemical polymers and emulsified asphalt to aggregates

As illustrated in Figure 1, the polymer coating on aggregates enhances their adhesion, thereby ensuring their stability and impermeability. This coating significantly reduces the absorption of water by soil particles, which contributes to the overall mechanical strength and load-bearing capacity of the soil. The use of emulsified asphalt-stabilized sandy soils diminishes the occurrence of rutting and surface deformations in roads and construction sites. Researchers in chemistry and civil engineering have previously focused on weak subsoils treated with binding agents such as cement and lime; the chemical bonds formed by lime and cement sufficiently bind soil particles together[3]. However, a major concern arises from the greenhouse gas emissions, particularly CO_2, associated with the excessive use of these binding agents. Estimates indicate that in 2001, around 16.1 tons of limestone and 4 tons of dolomite were consumed in the United States, leading to the release of approximately 9 tons of carbon dioxide (equating to 2.4 tons of carbon) into the atmosphere[4]. This accounted for 1.7% of the greenhouse gas emissions and 0.13% of total emissions in the U.S. for that year. Industrialized countries face substantial waste challenges, including fly ash, stone dust, plastics, glass, rubber, and construction debris, with ceramic materials, especially crushed concrete and its derivatives, representing the largest volume in the construction industry. Globally, the production of crushed concrete is increasing rapidly, particularly in Iran, Turkey, and China. However, approximately 250,000 tons remain unused annually, while 100 million tons of concrete are utilized for repairs worldwide[5]. Construction and demolition (C&D) waste constitutes a significant portion of landfilled waste globally; nevertheless, these materials have been successfully utilized in various civil engineering applications such as road construction, embankments, drainage pipes, and fill materials. In Australia, for instance, about 8.7 million tons of recycled concrete aggregates, 1.3 million tons of crushed brick, and 1.2 million tons of recycled asphalt are produced annually. Managing this vast quantity of C&D waste poses challenges for urban areas worldwide[6]. Utilizing recycled C&D materials in construction projects presents a sustainable and cost-effective solution, aiding in waste reduction, conserving natural resources, and lowering construction costs. Through further research and innovation, new and beneficial applications for C&D materials in civil engineering can be explored, leveraging their environmental and economic advantages. In Table 1, the advantages and disadvantages of using crushed concrete materials are summarized.

Researchers have demonstrated that the application of emulsified asphalt on sandy soil using a direct shear device leads to an increase in the shear strength parameters C and φ of the sandy soil. Additionally, a study has shown that the mechanical properties of sand, when combined with both cement and polymer, result in a decrease in soil density[9]. Notably, even with an increase in cement content, the dry density remains unchanged. Furthermore, the unconfined compressive strength layer, California Bearing Ratio (CBR), and deviator stress of the stabilized soil sample are found to increase[10]. The impact of adding emulsified asphalt and rubber crumbs to sandy soils has also been investigated using an oedometer, revealing a reduction in permeability, Young's modulus, and internal friction angle, while the volumetric compression coefficient and static soil pressure increase[11].

Table 1: Characteristics, benefits, and drawbacks of crushed concrete aggregate[7,8]

Mechanical and physical properties	**Drawbacks**	**Benefits and useful experiences**
• High water absorption • High initial strength • Low abrasiveness • Potential weakness against impact • Presence of varying sizes and gradation	• Non-uniformity of raw materials • Long-term durability concerns • High volume • Risk of corrosion and degradation	1. Application in soil stabilization and gradation improvement 2. Use as a substitute for natural aggregates 3. Good stability in environmental and moisture conditions 4. Reduction in costs and negative environmental impacts 5. Filling capacity for areas requiring backfill

The objective of stabilizing subgrade soils in road construction, landscaping, and the development of parking lots is to enhance the strength and uniformity of both coarse and fine soils. This stabilization process ensures effective transfer of loads from upper layers to weaker sublayers. This study explores the simultaneous use of recycled crushed concrete from demolished or under-construction buildings, which alters the gradation of the soil. Additionally, the concurrent application of emulsified asphalt contributes to the flexibility of the substructure and subgrade in both road construction and residential complex landscaping.

Experimental part

In this study, windblown desert sand from the outskirts of arid urban areas was collected to determine its particle size distribution and physical quality. As depicted in Fig. 2, the particle size analysis was conducted, and the addition of recycled concrete aggregate with specified sizes and varying percentages modified the grading of this soil. Following the AASHTO soil classification method, this material falls into the SP category, characterized by uniformly graded and relatively fine sand, which is often rated low in terms of its application for landscaping layers and subgrade construction. The sand was extracted from a depth of 0.5 meters beneath the surface. The recycled concrete used in this study originated from remnants of broken samples created in the civil engineering laboratory by researchers. To obtain suitable sizes, the sandy aggregates were initially crushed with a hammer, resulting in particle sizes ranging between 4.75 mm (#4) and 0.425 mm (#40). Since the samples were sourced from laboratory concrete mixtures, they contained no additional impurities and were simply crushed and sieved. To eliminate any potential dust and clay particles, the material was washed with water, soaked for 24 hours, and then dried for four hours at a temperature of 105 ^{o}C. Finer particles below the #200 sieve (0.075mm) were completely removed, while larger sizes were not used due to the difficulty of mixing and the tendency of sand particles to depend on coarser RCA aggregates rather than interlocking. Additionally, particles finer than 0.075 mm were discarded due to the potential for excessive and unregulated impurities. The fines, often regarded as the most challenging aspect of recycled materials, play a crucial role in determining the overall quality and viability of such materials in real-world applications. By analyzing these finer fractions in a manner that mimics on-site conditions, researchers can obtain results that are far more reflective of the actual characteristics encountered in construction projects. This approach would not only align with practical constraints faced during the separation of aggregates in execution projects—where the feasibility of isolating finer material is limited — but also broaden our understanding of how these materials behave under operational conditions.

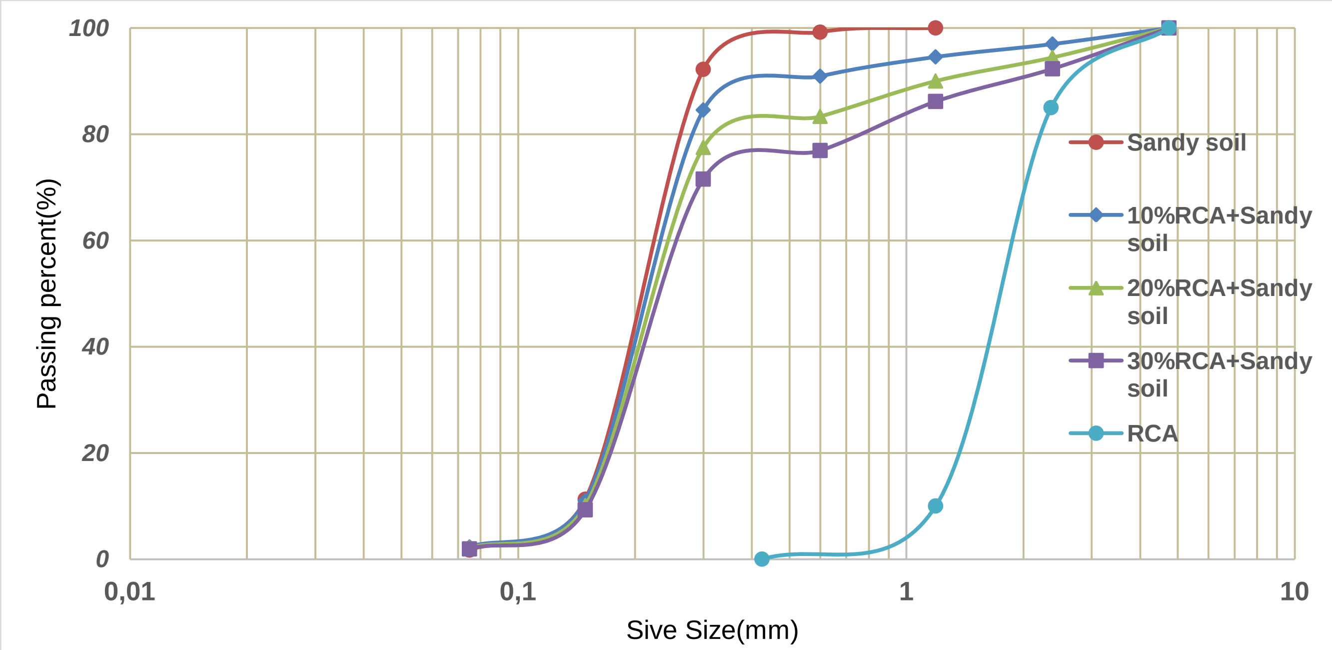

***Figure 2:* Gradation of the base sandy soil and the gradation after the addition of recycled concrete**

The conceptual model of the research process is illustrated in Fig.3, where the strategy of reducing energy consumption and raw material resources is aligned with minimizing the accumulation of construction waste materials. This approach is utilized to stabilize weak substrates in building and road construction. In laboratory testing and sample preparation, emulsified asphalt was considered the primary stabilizing agent, while recycled concrete waste served to enhance soil resistance properties. Laboratory samples were created with varying percentages of recycled concrete waste (10%, 20%, and 30%) and emulsified asphalt (20%, 22.5%, and 25%). The mixing methodology involved blending the soil with the optimal water content (12.5%) before incorporating various emulsified asphalt percentages and subsequently adding the recycled concrete waste. Considering the fine aggregate utilized and its specific surface area, coupled with the incorporation of recycled aggregate as an additive, it was deemed advantageous to employ higher percentages of emulsified asphalt. Preliminary tests indicated that lower percentages of asphalt did not provide the requisite adhesion. The use of Recycled Concrete Aggregate (RCA), in particular, is indicative of a strategic approach aimed at mitigating the environmental burden associated with construction waste. By opting for RCA, we not only aim to repurpose materials that would typically contribute to landfill accumulation but also enhance the sustainability of construction practices. From a scientific perspective, the interaction between the emulsified asphalt and the fine aggregates is significantly influenced by their physical and chemical properties. The fine aggregate's larger specific surface area leads to increased asphalt absorption, requiring a higher binder content to achieve optimal bonding. Moreover, the presence of recycled aggregates can alter the physicochemical behavior of the mix due to the potential for increased porosity and variability in surface texture. This necessitates a careful balance in the formulation to ensure adequate adhesion and performance of the final product. The effectiveness of emulsified asphalt in forming a homogenous matrix can be attributed to its ability to encapsulate the finer aggregates, thereby reducing interparticle voids and enhancing cohesion, which is vital for the mechanical integrity of the composite material.

Once the homogeneity of the mixture was confirmed, the prepared samples were compacted within molds and layered accordingly. Cylindrical soil samples with a diameter of 5 cm and a height of 7.5 cm were employed for the unconfined compressive strength testing. These dimensions were selected to ensure consistency across all experimental trials and to facilitate comparability of results. The size of the samples aligns with standard practices in geotechnical standard test, providing meaningful insights into the mechanical behavior of sandy soils treated with RCA and emulsified asphalt. Thirty soil samples with varying RCA and emulsified asphalt proportions were analyzed to optimize sandy soil performance and stability.

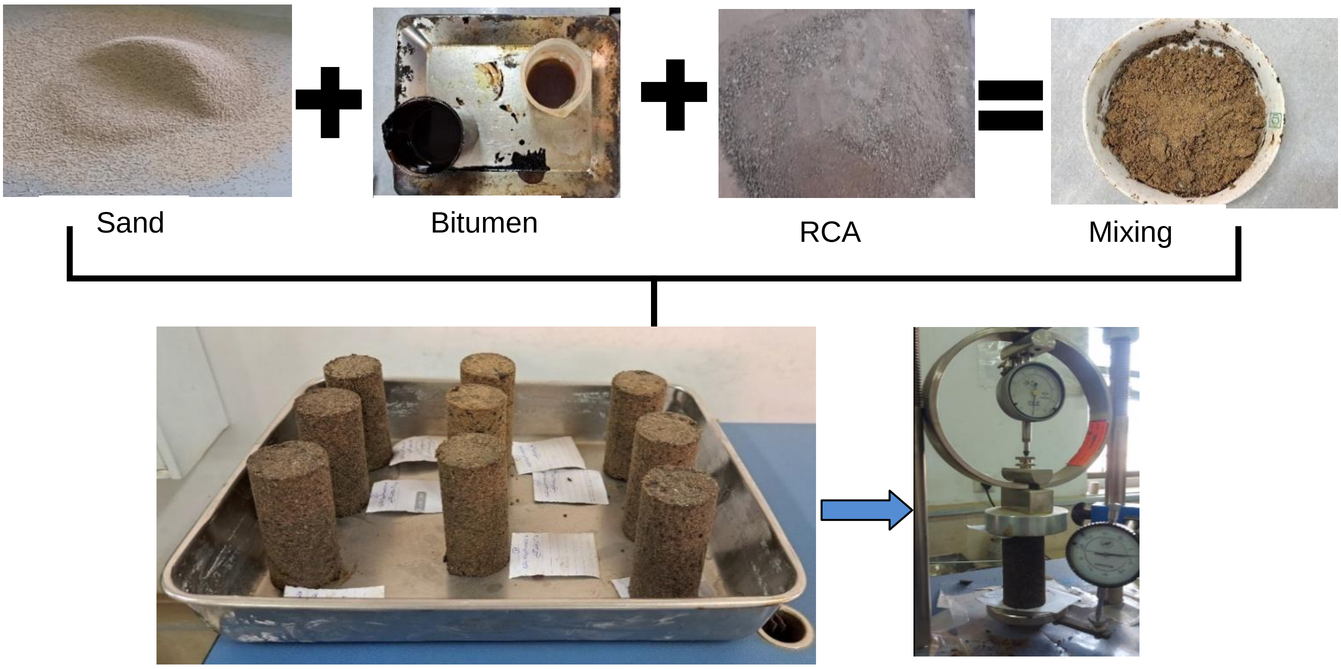

Figure 3: Connection of petrochemical polymers and emulsified asphalt to aggregates

The experimental design included tests for unconfined compressive strength, ultimate load, and strain at failure, as well as the E_{50} modulus and energy at which cylindrical soil samples failed. Following the analysis of results through response surface methodology, an optimal composition of materials and emulsified asphalt RCA was determined. The coding method for the samples was SCxEy, where x represents the percentage of RCA and y indicates the percentage of emulsified asphalt present in the sample. The emulsified asphalt must provide a minimum complete coverage for the mineral particles of the soil, and it is crucial that this coverage is both comprehensive and durable. Therefore, the mixing of soil particles with emulsified asphalt is vital for the quality of stabilization, and the viscosity of the emulsified asphalt used plays a significant role in the performance of the mixture. Numerous studies have reported varying percentages of emulsified asphalt added to soil, ranging from 4% to 25%[12]. The addition of emulsified asphalt initially increases the soil's bulk density, which is later followed by a reduction in bulk density, while also enhancing the optimal moisture content of the soil in both laboratory and field compaction tests.

Results and discussion

Uniaxial compressive strength

The uniaxial compressive strength (q_u) test demonstrated observable stress-strain variations as shown in Fig. 4, following the loading of the samples (an example of stress-strain graph). The samples utilized for examining the uniaxial compressive strength of sand containing recycled concrete aggregate (RCA) and emulsified asphalt clearly indicate that an increase in the percentage of RCA results in enhanced compressive strength. This phenomenon may be attributed to the superior strength of the recycled aggregates, which replace fine sand particles that are naturally rounded. Additionally, the results indicate that as the percentage of emulsified asphalt increases, the compressive strength also rises. This improvement may be due to enhanced adhesion between the sand particles and the reclaimed concrete debris. On average, the increase in compressive strength corresponds to an additional increase of 3% for each percentage of RCA added. Previous studies have also confirmed that a higher percentage of RCA contributes to the increased compressive strength of stabilized soil[9].

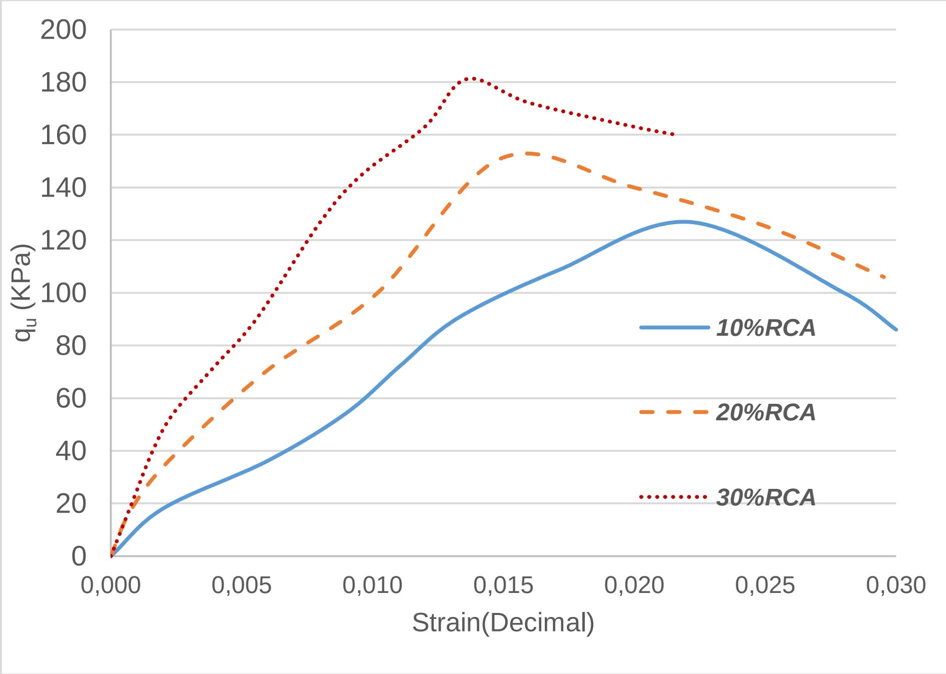

Figure 4: Uniaxial test results of soil stabilized with 20% emulsion bitumen and different percentages of concrete waste

Based on the results presented in the previous figures, it is evident that compacted sandy soils containing RCA and Sand exhibit an increase in emulsion asphalt percentages, whereas an excessive increase in sand can lead to a reduction in strength. The decline in strength due to the rise in sandy soil may be attributed to the adhesive nature of the polymer and the particles constituting the sandy soil, with an overabundance of these materials around the particles potentially increasing the friction between them, thereby resulting in diminished strength. Uniaxial stress increases with higher percentages of emulsion asphalt, accompanied by a corresponding increase in strain, indicative of the brittle behavior of the samples. Although the stress-strain curves are quite similar, there is a notable difference in the maximum uniaxial stress and strain at failure. As the percentage of RCA increases, the strain at failure decreases, which suggests that samples containing higher RCA demonstrate less brittle behavior compared to those with lower emulsion asphalt percentages. Table 2 presents the values of maximum uniaxial stress and strain at the moment of failure (strain at failure) for the stabilized samples.

Table 2: Maximum uniaxial stress and strain at failure for stabilized samples

Sample composition (Mass percentage)		**Maximum uniaxial stress (kPa)**	**Strain at failure (%)**
Emulsion Asphalt (%)	**Recycled Concrete (%)**		
20.0	10	126.8	2.2
	20	151.1	1.5
	30	181.1	1.4
22.5	10	181.0	1.5
	20	226.5	1.3
	30	285.4	1.2
25.0	10	246.4	1.5
	20	291.7	1.4
	30	362.4	1.2

The polymeric nature of the emulsion asphalt can result in added friction among particles when excessive RS is present, which may lead to increased resistance to movement, thereby compromising the overall structural integrity of the mixture. This phenomenon aligns with studies on particle friction and cohesion in geotechnical engineering. Notably, while uniaxial stress increases with emulsion asphalt, samples enriched with RCA demonstrate a reduction in strain at failure, suggesting a transition toward more ductile behavior with higher RCA content. This attenuation of brittleness indicates a complex interplay between the types of recycled aggregates used and their mechanical performance in saturated sandy soils[13].

The data indicates that mixtures containing 20% emulsified asphalt and 10% recycled concrete (RCA) exhibited the highest strain at failure of 2.2%, which suggests a remarkable ductility and resilience in comparison to other formulations, where the strain at failure was comparatively lower, remaining around 1.3% to 1.5%. This phenomenon can be attributed to the unique rheological properties of emulsified asphalt, which possesses a viscoelastic nature, allowing for reversible deformation up to a certain threshold. The interplay between the adhesive characteristics of the asphalt and the aggregate matrix contributes significantly to the composite's overall performance. As the asphalt content increases, the interaction between asphalt and RCA fosters enhanced cohesion and internal friction, thus increasing the maximum uniaxial stress while simultaneously influencing the strain behavior under load. This behavior can be interpreted through the lens of solid mechanics, where the emulsified asphalt matrix serves not only as a binder that imparts lubrication but also as a medium that dissipates energy during deformation, particularly upon reaching failure. As the composition shifts towards higher percentages of asphalt, a critical threshold is observed, beyond which the material's capacity to deform elastically diminishes, resulting in reduced strain values at failure. According to Table 2, the maximum compressive stress observed is 360 kPa. This increase can be mechanically and physically justified by the interaction between the emulsion asphalt and the RCA particles. The emulsion improves adhesion and cohesion within the matrix, reducing microstructural defects and enhancing load transfer efficiency. Simultaneously, the angularity and rough surface texture of RCA contribute to interlocking mechanisms, improving stress distribution and overall resistance.

Elastic modulus

The elastic modulus, denoted by E, represents the slope of the linear portion of the stress-strain curve for soil. This value indicates how resistant the soil is to deformation. When this slope is calculated at the beginning of the curve, it is referred to as the initial elastic modulus (E_0). However, since this curve is typically not linear, the tangent or secant modulus known as E_{50} is employed instead. To calculate E_{50}, a line is drawn from the origin to the point representing 50% of the ultimate strength, and the slope of this line is considered the secant elastic modulus. The elastic modulus of soil can be determined through laboratory, field, and empirical methods[14]. In laboratory methods, tests such as consolidation, unconfined compressive strength, direct shear, and triaxial compressive strength are used to compute this parameter. Additionally, field tests including field loading, pressuremeter, and dilatometer tests are applied for this purpose. In this research, the results from unconfined compressive strength tests were utilized to determine the secant elastic modulus of stabilized soil. Fig. 5 displays the specifications of the elastic modulus for various percentages of emulsified asphalt and recycled concrete. Regarding the elastic modulus, the maximum value occurs at the specified percentage, as illustrated in Figure 5. This phenomenon can be explained based on material science and solid mechanics principles. The optimal RCA-emulsion ratio leads to a balanced microstructure, where the improved interfacial bonding minimizes voids and microcracks while maintaining sufficient stiffness. This results in an efficient load-bearing capacity without excessive brittleness, thereby achieving the highest modulus at this composition.

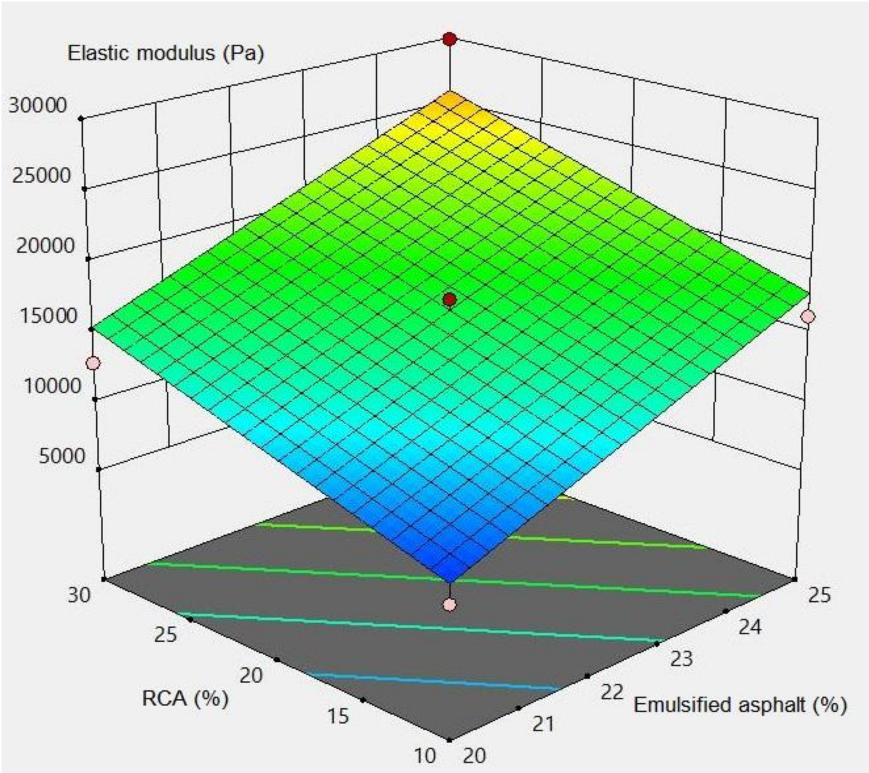

Figure 5: Elastic modulus specifications for stabilized samples

In tests conducted on samples of sand stabilized with emulsified asphalt and recycled concrete, it was observed that an increase in the proportion of emulsified asphalt and recycled concrete in the mixture significantly raised the modulus of elasticity of the samples. This indicates that the addition of emulsified asphalt and recycled concrete improves the mechanical properties of sandy soil, particularly its resistance to deformation. In other words, as the quantity of stabilizing materials increases, the sandy soil exhibits a stiffer behavior and undergoes less deformation under applied loads. As the moisture content increases, the sandy soil exhibits a stiffer behavior and experiences less deformation under applied loads. Research by various scholars has similarly identified enhancements in the mechanical behavior of soil mixtures that include different additives, such as asphalt emulsions and recycled materials. Their findings demonstrate not only increased stiffness but also improvements in other mechanical properties like shear strength and load-bearing capacity[15]. Additionally, researchers have explored the effectiveness of using recycled concrete aggregates in soil stabilization, revealing that their incorporation significantly enhances the overall structural performance of soil mixtures under simulated loading conditions[16]. In the context of the investigation into the effects of Recycled Concrete Aggregates (RCA) and emulsified asphalt on the performance of sandy soils, it is crucial to delve into the interplay between internal friction angles, particle size distribution, and the addition of asphalt as a binding agent. The findings of laboratory tests indicate a positive correlation between the increasing proportions of RCA and the enhancement of both unconfined compressive strength and the elastic modulus of sandy soil mixtures. This improvement can be attributed to the angularity and interlocking ability of RCA, which augments the internal friction angle, thereby providing greater resistance to shear stresses. However, as RCA content exceeds optimal thresholds, a detrimental impact on material resilience is observed, likely due to the fragmentation and altered particle distribution, which can lead to reduced cohesion and increased susceptibility to failure under dynamic loading conditions. Furthermore, the incorporation of emulsified asphalt not only facilitates improved particle binding and cohesion among the sandy matrix but also modifies the gradation characteristics, resulting in a more favorable particle size distribution that enhances the overall mechanical performance. The mechanical and physical behaviors underlying these modifications emphasize the importance of careful consideration of RCA proportions, as excessive amounts can compromise the structural integrity despite the initial benefits observed with moderate inclusion rates.

Energy of fracture

The energy of fracture serves as a pivotal metric in the comprehensive analysis of the fracture behavior of various materials, fundamentally influenced by the applied stress and the corresponding material response. This parameter is crucial as it reflects the inherent resistance of materials to cracking and eventual failure, which are essential considerations in structural applications. The energy required for the failure of a stabilized mixture, for instance, is contingent upon its load-bearing capacity and the extent of displacement it endures under stress. Empirical findings garnered from medium-temperature fracture tests reveal a significant trend: as the percentage of Recycled Concrete Aggregate (RCA) incorporated into the stabilized mixture increases, there is a corresponding rise in the maximum force demanded for the failure of asphalt mixtures. This observation highlights a complex interplay wherein an escalation in RCA content is associated with a higher force requirement for fracture, while simultaneously, the displacement observed diminishes. This dynamic suggests that the increased force cannot adequately offset the reduction in displacement, a relationship that underscores the intricate balance between these two parameters. As depicted in Fig. 6, the energy of fracture experiences a decline with higher RCA percentages, indicating a potential compromise in stability and resilience of the material. Moreover, the inclusion of emulsified asphalt proves to alter the mechanical properties of the stabilized sand mixture, enhancing its pliability, which in turn increases the energy of fracture. This enhancement not only suggests an improvement in material performance under stress but is also observable in similar clay materials treated with emulsified asphalt, reaffirming the significance of additive interactions in modifying the fracture mechanics of composite materials.

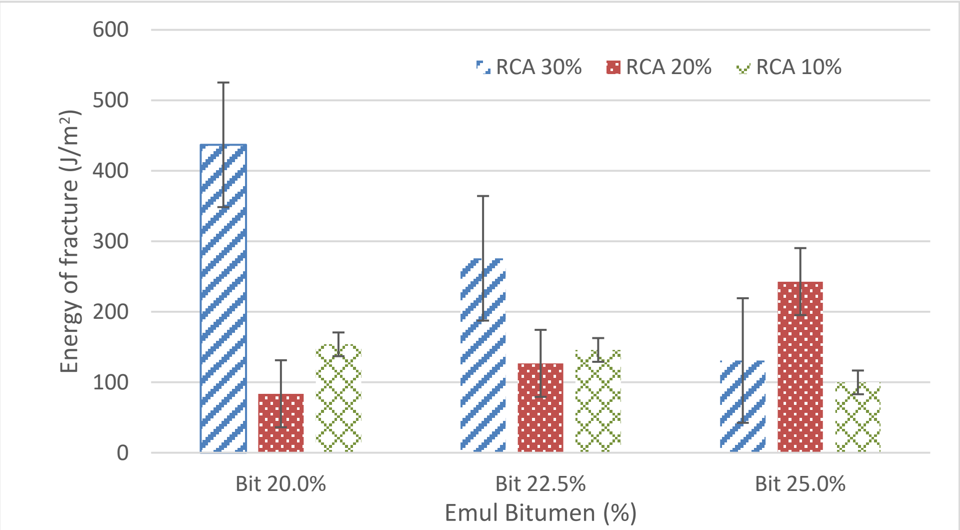

Figure 6: Effects of emulsion percentages and RCA variability on energy fracture

Fracture mechanism and crack propagation

Emulsified asphalt enhances the cohesion between soil particles and fills the interstitial spaces, thereby improving the tensile and shear strength of the soil while preventing crack propagation. Higher-viscosity, more adhesive emulsified asphalts typically result in a reduction of the crack angle. Recycled concrete serves as a reinforcing network within the soil, enhancing its tensile and shear strength and impeding the spread of cracks. The characteristics of concrete particles within the soil, including their size, shape, and distribution, play a significant role in determining the angle of cracks. To analyze the fracture mechanism and crack propagation during uniaxial compressive resistance testing, several methods can be utilized. These include direct observation of the failure surface post-fracture and measuring the crack angle through techniques such as direct measurement or image analysis. One of the most significant effects of soil stabilization with emulsified asphalt and recycled concrete is the reduction of the internal friction angle, consequently leading to a decrease in the crack angle. This indicates that as the amount of stabilizing materials increases, the soil becomes more robust and exhibits less propensity for high-angle cracking. Stabilization leads to a more uniform distribution of cracks within the sample, preventing the formation of large and sudden cracks. Figure 7 illustrates an example of crack propagation following uniaxial testing.

Figure 7: The propagation of cracks in the sample post-failure

It can be concluded that increasing the percentages of emulsified asphalt and recycled concrete also results in reduced crack angles. Fig. 8, demonstrates the decrease in crack angles with the increasing percentages of emulsified asphalt and RCA.

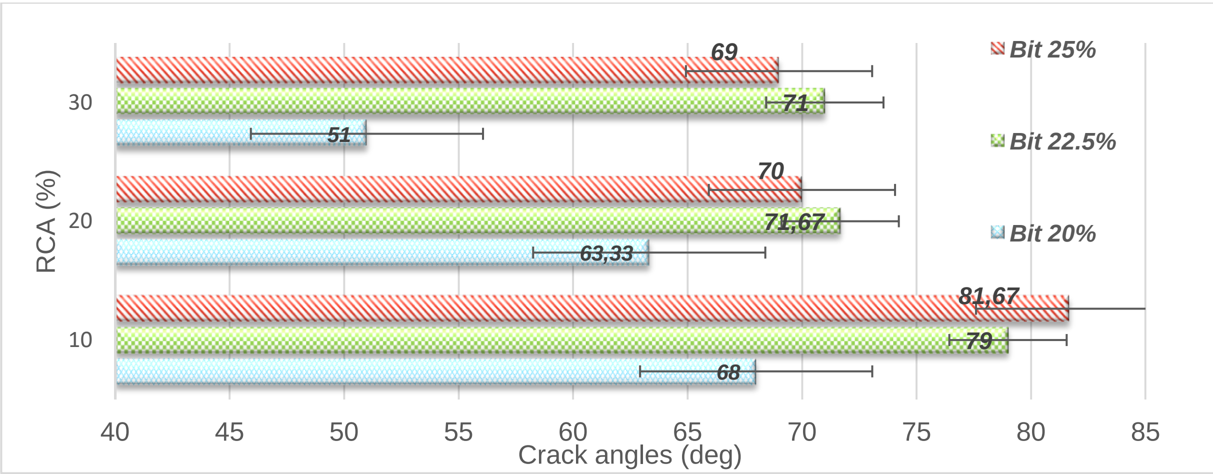

Figure 8: Crack angles of stabilized samples

This paper examines the advantageous outcomes of these resources and contrasts results from recent academic publications that emphasize their influence on stabilization efficacy. Emulsified asphalt, known for its binding properties, enhances the cohesion among sand particles, leading to improved structural integrity. The introduction of recycled concrete aggregates (RCA) further bolsters this effect RCA not only enhances binding capacity but also reduces waste generated from construction activities, thereby supporting sustainability. Research conducted by scholars shows that using emulsified asphalt together with RCA for soil stabilization leads to a significant reduction in cracking — an indicator of improved stability — compared to conventional stabilization methods. Their study reveals a linear correlation where increasing the percentage of emulsified asphalt combined with RCA consistently results in tighter crack angles, thereby improving the material's resistance to environmental stresses[17]. Research indicates that emulsified asphalt, when enhanced with 12% by weight of processed rubber powder, yields an effective emulsion and improves storage stability. Exceeding this concentration leads to uneven distribution, negatively impacting the integrity of the mixture. Notably, the 12% rubber powder dosage significantly enhances the residual strength of evaporated asphalt, thereby improving its performance at high temperatures, which is crucial for the durability of pavements. The use of rubber powder in road construction underscores its role as an environmentally friendly solution for tire disposal, while simultaneously contributing to sustainable road infrastructure[18]. In previous studies, the fracture properties of Cement Emulsified Asphalt Mortar at service temperature were examined under mixed-mode I & II fracture conditions. Experiments using Semi-Circular Bending (SCB) specimens evaluated the mixed-mode fracture energy, with the volume fractions of mortar constituents considered as independent variables. A D-Optimal mixture design was utilized to optimize the experimental approach, leading to the development of a regression model that correlates fracture energy with mortar components. The optimal mix design for maximizing fracture energy was identified, revealing that both cement and asphalt significantly impacted energy variations. Higher asphalt emulsion-to-cement ratios were found to decrease the maximum load capacity while increasing deformation[19]. Results indicated that as the emulsified asphalt content increased, the crack angles showed a corresponding reduction. The authors assert that the reduction in crack angles not only enhances the durability of wind-sand structures but also prolongs the lifecycle of pavement built in such environments. This phenomenon can be explained by examining the underlying mechanisms that influence stress distribution within the stabilized composite material. The application of emulsified asphalt fosters the development of a cohesive network that interlocks effectively with surrounding sand particles. When external stresses are applied to the pavement, the elastic properties of the asphalt facilitate energy dissipation and redistribution throughout the material. This process significantly reduces the likelihood of crack initiation at acute angles, which are known to be critical points of vulnerability in pavement structures. Furthermore, the incorporation of recycled concrete aggregate (RCA) into the mix enhances this system by providing a rougher surface texture that improves particle interlock. The increased interfacial friction between the aggregates promotes effective load distribution, thus mitigating stress concentration points that typically lead to the formation of cracks. These combined effects result in a more resilient pavement structure, capable of withstanding the harsh environmental conditions often encountered in wind-sand environments. Ultimately, understanding the interplay between emulsified asphalt and RCA in influencing crack angle reduction offers valuable insights into the engineering design of sustainable and durable infrastructural components in challenging terrains.

Interaction mechanism between soil, bitumen, and RCA

The behavior of sandy soils can be described through various soil mechanics relationships, including the Mohr-Coulomb failure criterion[20] (as relation 1):

$$\tau = C + \sigma \times \tan(\emptyset) \qquad (1)$$

- τ = shear strength of the soil
- c_c = cohesion
- σ_σ = normal stress
- ϕ_ϕ = angle of internal friction

The incorporation of bitumen alters both the cohesion c_c and the angle of internal friction ϕ_ϕ by providing a binding mechanism at the particle interfaces. The result is a composite material with enhanced shear strength, suitable for construction applications such as road subgrades and embankments. When bitumen coats sandy particles, it forms a thin layer that modifies the surface characteristics of the sand. This coating plays a crucial role in increasing the adhesion between particles. The interlocking effect generated by bitumen further increases the frictional resistance. The modified Mohr-Coulomb failure criterion (as relation 2) can be applied here as well:

$$\tau = C_{Bit} + \sigma \times \tan(\emptyset_{RCA}) \qquad (2)$$

where: C_{Bit} and $\emptyset_{RCA}$ are the cohesion and angle of internal friction for the bitumen-modified RCA.

The binding mechanism primarily works through the reduction of moisture penetration and the alteration of surface properties, which enhances inter-particle friction. Incorporating recycled concrete aggregates into construction and civil engineering applications presents an opportunity to promote sustainability within the industry. However, RCA often exhibits a higher porosity and weaker inter-particle bonding compared to natural aggregates. The interaction of bitumen with RCA can significantly enhance its mechanical properties. Bitumen coats the surface of RCA, similar to its interaction with sandy particles, leading to improved adhesion between aggregates. Notably, the similarities in results across the other mixtures suggest that the mechanical responses are influenced by the intrinsic behaviors of the materials involved. Understanding the rheological properties of the emulsified asphalt, as well as its reversible and elastic behavior upon failure, is paramount when assessing the solid mechanics and physical behavior of sandy soils stabilized with emulsified asphalt. The relationship described by the

Mohr-Coulomb failure criterion (Relation 1) provides a foundational framework for analyzing shear strength dynamics, which are indeed modified through the incorporation of bitumen, as indicated by the subsequent modified criterion (Relation 2). Specifically, the enhancement of both cohesion (C_{Bit}) and the angle of internal friction ($\emptyset_{RCA}$) is attributable to the binding mechanisms at the particle interfaces, which are intensified by the presence of bitumen. This interaction not only reduces moisture penetration but also significantly enhances inter-particle friction, thereby improving the overall mechanical properties of the composite material. It is critical, however, to acknowledge the limitations in accessing triaxial and dynamic triaxial loading equipment for comprehensive investigations. Therefore, it is recommended that future research prioritize further examination of these parameters to validate the obtained results and substantiate the applicability of using sandy soil-modified Emulsion/RCA in field projects, while also demonstrating the practical realism of Relations 1 and 2 through thorough laboratory investigations.

The process of bitumen application results in a composite material exhibiting superior performance characteristics when compared to unmodified RCA. Emulsified bitumen, when combined with fine grains in sand, results in the formation of bituminous mastic as Fig. 9 and what is in the schematic Figure 1, although the overall strength of these mastics may be compromised in specific regions due to variations in composition or application techniques, their utilization in conjunction with recycled concrete aggregates has demonstrated a significant improvement in bond strength. This enhancement is attributed to the compatibility of the mastic with the aggregates, which promotes better adhesion and cohesion, ultimately leading to improved performance in pavement and construction applications. This study demonstrates that incorporating emulsified asphalt and RCA improves soil stability and strength, necessitating precise additive management for optimal results (as Table 3).

Table 3: Benefits and drawbacks of emulsified asphalt and recycled concrete aggregates

Aspect	Benefits	Drawbacks
Compressive Strength	Improved mechanical properties of sandy soils	Excessive RCA contents can compromise stability
Elastic Modulus	Enhanced material performance	Requires careful consideration of additive ratios
Environmental Impact	Promotes sustainability through recycling	Potential variability in material properties
Construction Efficiency	Reduces the need for traditional materials	May require specific handling or application methods

This study emphasizes that the integration of emulsified asphalt and RCA leads to significantly enhanced soil stability, tensile strength, and overall structural performance. However, careful attention must be given to additive proportions to ensure optimal effectiveness.

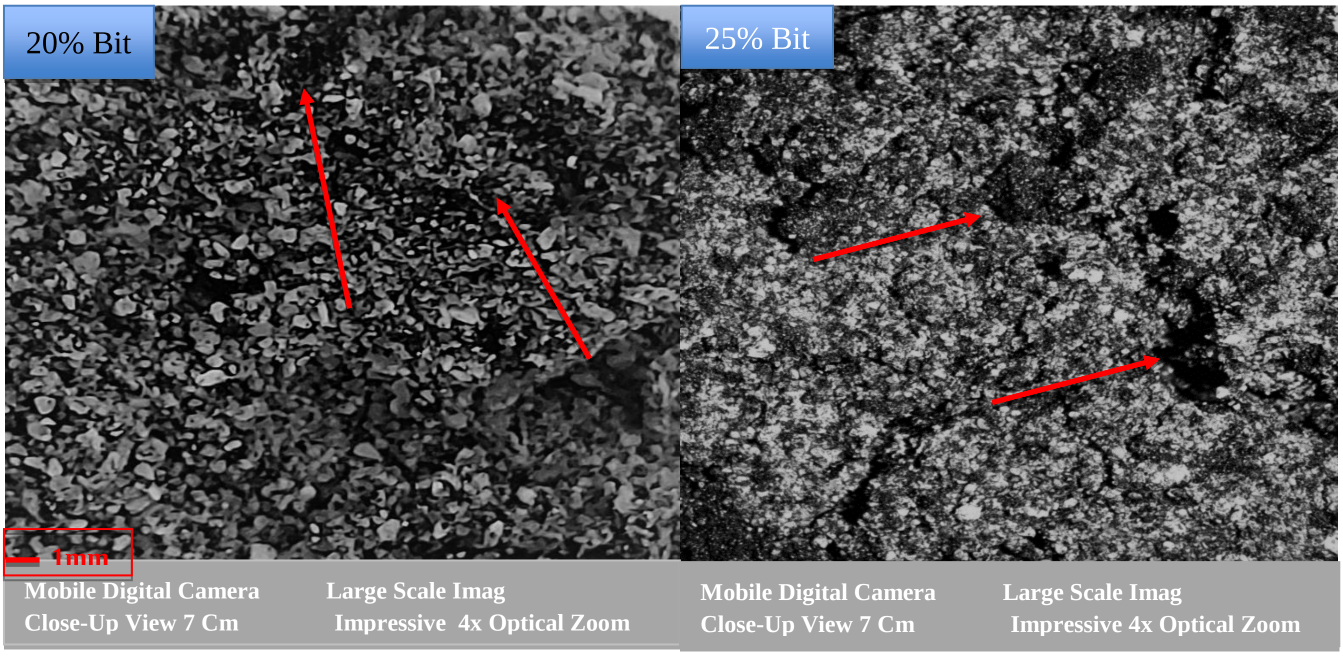

Figure 9: Large-scale image depicting two various concentrations of bitumen emulsion, with arrows indicating the presence of bitumen and fine grain

Conclusions

This investigation highlights the significant potential of utilizing Recycled Concrete Aggregates (RCA) in combination with emulsified asphalt to improve the performance of sandy soils. Given the challenges posed by the non-cohesive nature of these soils in construction applications, the findings suggest that incorporating up to 30% RCA and 25% emulsified asphalt can substantially enhance the mechanical properties, leading to notable increases in both compressive strength and elastic modulus.

- The results indicate that optimal combinations can significantly improve compressive strength and elasticity, providing a promising approach to addressing the inherent challenges posed by non-cohesive soils in construction applications.
- Furthermore, the study reveals that excessive proportions of RCA can compromise material stability, emphasizing the need for careful consideration of additive ratios.
- In conclusion, the study demonstrates that the inclusion of emulsified asphalt and recycled concrete significantly enhances the elastic modulus of sandy soil, leading to improved structural stability.
- The significant impact of emulsified asphalt on enhancing the pliability and energy of fracture in stabilized mixtures emphasizes the importance of additive interactions. Future research should continue to explore these dynamics to optimize material performance in various structural applications, ultimately contributing to more sustainable engineering practices.
- In summary, the incorporation of emulsified asphalt and recycled concrete aggregates significantly enhances soil stability through improved tensile and shear strength, leading to reduced crack angles and a more resilient structural performance.
- The positive correlations drawn from recent research indicate that increasing the percentages of these stabilizing materials yields favorable outcomes in crack propagation and overall material integrity.

The research highlights the effective use of Recycled Concrete Aggregates (RCA) and emulsified asphalt as stabilizers for sandy soils, significantly improving their mechanical properties, including compressive strength and elastic modulus. This approach addresses the challenges posed by non-cohesive soils in construction. Future studies should focus on determining optimal additive ratios to mitigate stability issues from excessive RCA, as well as exploring other binding agents for enhanced material performance, ultimately promoting sustainable practices in civil engineering.

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Vyšetřování účinků recyklovaného betonového kameniva a emulgovaného asfaltu na zlepšení vlastností písčitých půd

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Souhrn

Stavební a demoliční odpady (C&DW) významně přispívají k celosvětovým skládkám, ale mají cenné využití ve stavebním inženýrství. Písčité půdy, známé svou nesoudržnou povahou, představují velké výzvy ve stavebnictví, zejména v případě hrází a podkladů silnic. Tato studie zkoumá vliv recyklovaného betonového kameniva (RCA) a emulgovaného asfaltu na zlepšení mechanických vlastností písčitých půd.

Výsledky ukázaly, že kombinace až 30 % recyklovaného betonového kameniva (RCA) a 25 % emulzního asfaltu vedla k významným zlepšením pevnosti v tlaku a modulu pružnosti, přičemž průměrné hodnoty dosáhly 360 kPa a 2,4 MPa. Avšak nadměrný obsah RCA negativně ovlivňuje účinnost materiálu. Zvýšené podíly obou příměsí výrazně zlepšily modul pružnosti, což svědčí o zvýšené odolnosti proti deformacím. Pojivové vlastnosti emulgovaného asfaltu přispěly k lepší soudržnosti mezi částicemi písku, čímž posílily strukturální integritu. Naopak vyšší podíl RCA byl spojen se snížením lomové energie při porušení, což vyvolává obavy o stabilitu a odolnost materiálu. Celkově se přidání emulgovaného asfaltu a RCA projevilo na významném zlepšení mechanických vlastností písčité půdy, což z ní činí životaschopné řešení stavebních problémů spojených s nesoudržnými půdami.

Klíčová slova: *Stavební a demoliční odpady, využití recyklovaných materiálů, recyklované betonové kamenivo, emulgovaný asfalt, stabilizace půdy*