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A COMPARATIVE ANALYSIS OF RECYCLED AND VIRGIN MATERIALS FOR SUBBASE MIX DESIGNS

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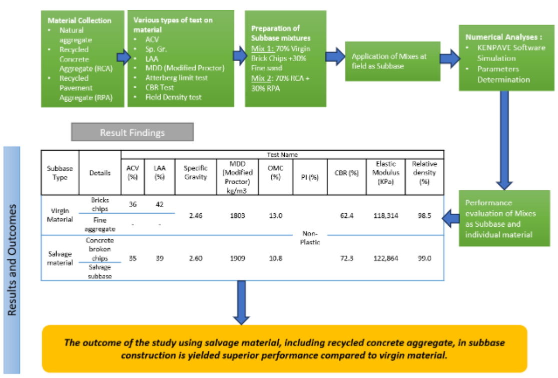
Graphical abstract



Abstract

This study explores the feasibility and benefits of using a mix of 70% concrete broken chips and 30% salvage materials for subbase construction in Bangladesh, offering an innovative alternative to exclusively using virgin resources. Key findings include the salvage materials mix-design achieving lower Los Angeles Abrasion values and higher California Bearing Ratio than virgin materials, indicating superior durability and strength. Additionally, optimal compaction characteristics were observed, with higher maximum dry density and lower optimum moisture content, contributing to environmental sustainability through reduced water consumption. The mix-design's compliance with required gradation standards post-compaction and favorable pavement performance in terms of vertical displacement and shear stress, as per KENPAVE simulations, further validates its effectiveness. This research underscores the potential of incorporating salvaged materials in pavement construction, aligning with sustainable development goals and demonstrating cost-efficiency and reduced landfill usage, while maintaining industry standards.

Keywords: Reclaimed Pavement, Sustainable Development, Recycled Concrete Aggregate, Salvage Materials, Subbase Mix Designs.

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1.0 INTRODUCTION

The availability of natural aggregates for infrastructure and pavement construction has been dwindling over the past few decades. Recycling has become more popular because of rising transport costs for delivering aggregates to construction sites. Governments and many private companies are using recycled materials to save resources, protect the environment, and reduce construction costs and waste. Some locations with heavy traffic loads, a second road base layer is placed on top of the subbase layer. The foundation and subbase of flexible pavement are typically made of compacted aggregates. High-quality aggregates are crucial for achieving strong pavement stiffness and effectively distributing traffic loads to the underlying subgrade soil. In South Asia, particularly in Bangladesh, brick aggregate is commonly used for the subbase layer in construction. But brick production is very harmful to the environment [1]. The brick manufacturing industry, reliant on inefficient and polluting coal-fired kilns, maintains an economic equilibrium by supplying cheap construction materials, as revealed by interviews with various stakeholders, but this comes at a significant environmental and health cost, Luby indicating a need for low-cost, efficient solutions to move towards a more sustainable model [2]. Rahman et al. [3] investigated the suitability of recycled construction and demolition materials (crushed brick, recycled concrete aggregate, reclaimed asphalt pavement) as filler materials in permeable pavements, finding them to be effective, especially when combined with geotextiles, although they may be prone to clogging over time. Mujtaba et al. [4] demonstrated that stabilizing reclaimed subbase materials (RSM) with additives like lime, sand, stone dust, and RAP enhances their geotechnical properties, making them suitable for flexible pavement subbases, while reducing the need for virgin materials and promoting cost-effective, eco-friendly construction. Salehi et al. [5] highlighted the need for further study on the environmental and economic impacts of recycled materials in pavement construction, emphasizing that current sustainability analyses are inconsistent and incomplete, particularly regarding long-term viability. Zhao et al. [6] proposed a methodology for assessing the environmental and economic life-cycle benefits of using recycled asphalt pavement (RAP) in highway projects, demonstrating substantial cost savings and environmental impact reductions, with the potential for widespread adoption in similar construction settings. Barbudo et al. [7] investigated the relationship between the constituents of recycled aggregates and their mechanical behavior for road applications, analyzing 31 types of aggregates through characterization and mechanical tests, with results evaluated using ANOVA and correlation analysis. Kang et al. [8] assessed the leaching of inorganic contaminants from fly ash, reclaimed asphalt, and other recycled materials in road construction, finding most substances within safe limits except for aluminum and chromium in certain conditions. Rahman et al. [9] introduced a new mechanistic-empirical method, implemented in the DesignPave program, for calculating base/sub-base thicknesses in concrete block pavement designs, and find that using recycled aggregates doesn't significantly reduce costs, it offers substantial environmental benefits. Bairagi et al. [10] focused on achieving acceptable concrete quality by maximizing the use of recycled aggregate, introducing the term "Replacement ratio" and proposing empirical relations for estimating concrete properties, ultimately suggesting a maximum replacement ratio. Another study of the use of fine recycled concrete aggregates as replacements for natural fine aggregates in structural concrete finds that up to a 30% replacement ratio does not negatively affect the concrete's mechanical properties [11]. Patil et al. [12] employed Multiple Linear Regressions (MLR) and Artificial Neural Networks (ANN) to predict the mechanical properties (e.g., compressive strength, flexural strength, split tensile strength) of 28-day-cured recycled coarse aggregate (RCA) concrete, demonstrating that ANN outperforms MLR in accuracy, offering valuable time and cost-saving prediction models for construction professionals. Among commonly encountered local materials (fly ash, coarse sand, stone dust, and river bed material), stone dust exhibits the highest California Bearing Ratio (CBR), but its dynamic load behavior in triaxial tests is inferior; fly ash has a low CBR but superior stress-strain behavior compared to stone dust, while river bed material (RBM) emerges as the optimal choice for subbase layers in flexible pavements, boasting good CBR, high E-value, resilient modulus, and low permanent strain values [13]. Saberian et al. [14] proposed recycling used face masks with recycled concrete aggregate (RCA) for road construction, demonstrating that blends with up to 3% shredded face mask (SFM) meet strength requirements, with 1% SFM yielding optimal results while higher percentages diminish strength and stiffness. Mohammadinia et al. [15] explored the suitability of cement-treated reclaimed asphalt pavement (RAP), recycled concrete aggregate (RCA), and crushed brick (CB) as environmentally beneficial alternatives for pavement construction, where RAP exhibits the highest strength with 2% cement and 7 or 28 days of curing, while RCA and CB require 4% cement and 28 days of curing, indicating their viability for pavement base/subbase applications. Poon et al. [16] at Hong Kong Polytechnic University found that incorporating 100% recycled concrete aggregates in unbound subbase materials increased optimum moisture content, reduced maximum dry density, and decreased CBR values; additionally, replacing these aggregates with crushed clay brick further amplified these effects, though all subbases met Hong Kong's minimum strength requirements. Puppala et al. [17] investigated the geotechnical characteristics and long-term performance of limestone quarry fines and reclaimed asphalt pavement aggregates, including laboratory tests, field monitoring, and numerical simulations, to assess their efficacy as sustainable materials for base layers. Arulrajah et al. [18] demonstrated that crushed basaltic waste excavation rock, traditionally considered landfill material, meets local road authority specifications, and exhibits favorable geotechnical properties, making it a viable and durable option for pavement subbases. Saberian et al. [19] explored the use of recycled concrete and waste crushed rock blends containing crushed glass and crumb rubber for road base/subbase applications, introducing a simple and quick method to estimate permanent deformation and resilient modulus properties through dynamic tests, revealing a strong correlation with cyclic triaxial test results. Behiry [20] investigated the impact of steel slag quantity on the mechanical properties of blended mixes with crushed limestone aggregates for subbase material in Egypt, revealing improvements in mechanical characteristics, resistance factors, and pavement durability under overweight truck loads. Arshad et al. [21] investigated the suitability of blended materials, comprising 50% and 75% Reclaimed Asphalt Pavement (RAP) with fresh granular materials and Recycled Concrete Aggregate (RCA), for granular base/subbase layers in flexible pavements, revealing notable improvements in resilient modulus with 75% RAP content, but an increase in accumulative strains during cyclic loading. Over 4-years period, monitoring of recycled concrete aggregates in an asphalt-covered road sub-base revealed a decrease in pH of infiltration water [22]. Miranda et al. [23] presented the first full-scale application of alkali-activated fly ash for stabilizing a (sub)base layer, comparing it with soil-cement and soil-lime mixtures, revealing comparable mechanical performance to traditional binders, and highlighting the need for further optimization in this relatively early stage of development. Abedin Khan et al. [24] investigated the physical and mechanical properties of recycled construction and demolition waste aggregates as a viable alternative for pavement base and subbase materials, highlighting their potential for sustainable construction and addressing challenges and future research gaps. Alnedawi et al.[25] evaluated the suitability of recycled concrete aggregate (RCA) as a subbase material for road pavement, demonstrating its strength and fulfilling local road authority requirements, and optimizing its performance with geogrid reinforcement.

This research aims to assess the material properties, performance, and stress evaluations of virgin brick chips, recycled pavement materials (RPM), and recycled concrete aggregate (RCA) in subbase applications. The practical application of these materials as subbase in trial beds, along with the numerical identification of compatibility with international standards, makes this study unique.

2.0 METHODOLOGY

2.1 Outline of Methodology

Figure 1 shows a structured methodology for evaluating the performance of subbase layers using both virgin and recycled materials. Recycled Concrete Aggregate (RCA) and Recycled Pavement Aggregate (RPA). First, materials were collected and subjected to various laboratory tests, such as Aggregate Crushing Value (ACV), Los Angeles Abrasion (LAA), Specific Gravity, and California Bearing Ratio (CBR). Two subbase mixtures were prepared: one with 70% virgin brick chips and 30% fine sand, and another with 70% RCA and 30% RPA. These mixtures were then applied in field trials and analyzed using KENPAVE software for performance simulation. The study demonstrates the effectiveness of recycled materials in subbase construction, promoting sustainable alternatives for road infrastructure.

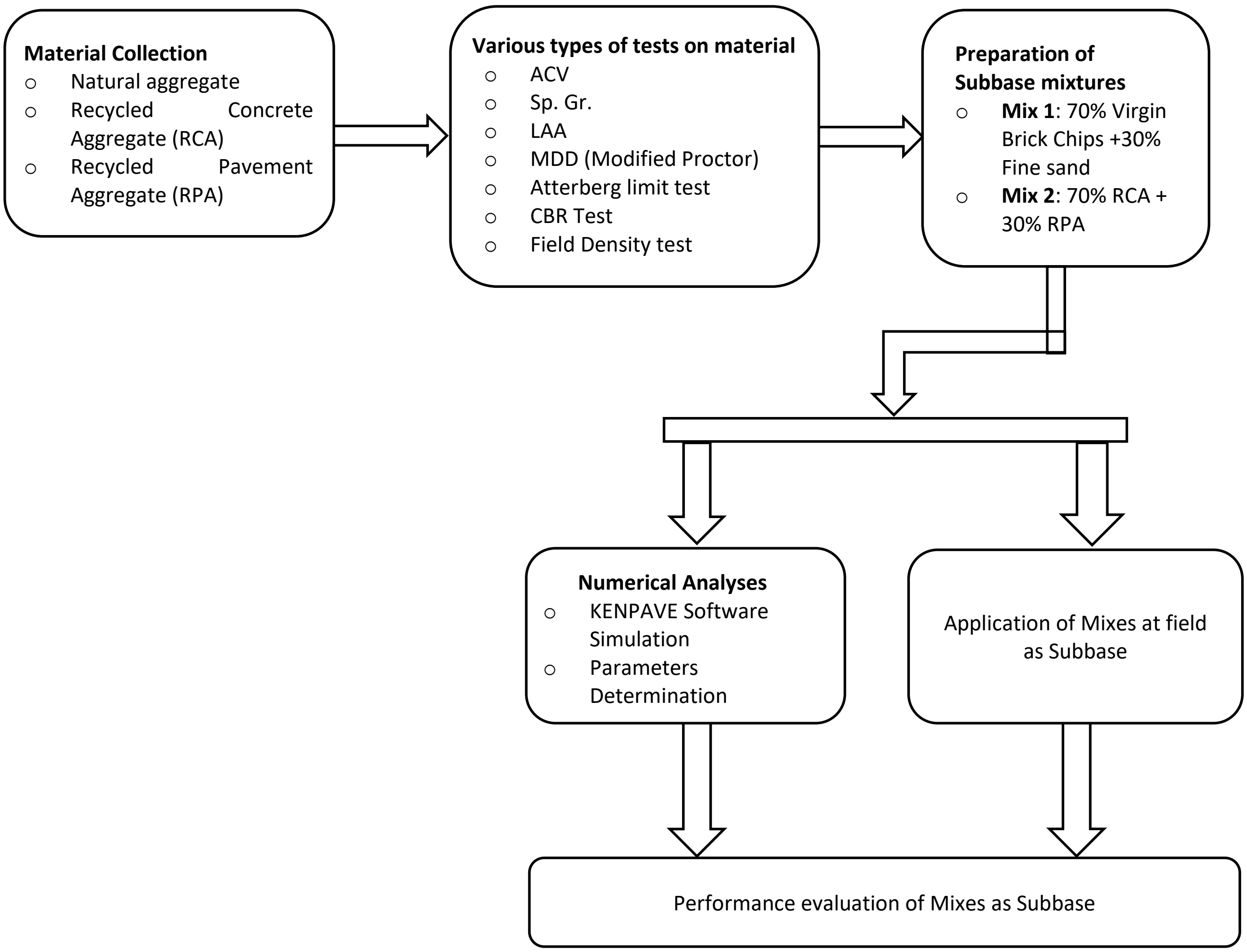


Figure 1 Flow diagram of work methodology

2.2 Materials Collection

The materials were gathered from various sources according to the standard sampling method mentioned in **Table 1**. Mechanically crushed, large aggregates are cleansed of undesirable materials and reduced to an appropriate size. Virgin materials consist of 70% brick chips, and 30% Sylhet sand. Salvage materials consist of 70% broken recycled concrete aggregate (RCA), 30% roadbed recycled pavement aggregate (RPA). The salvaged materials are procured from a project named Greater Dhaka Sustainable Urban Transport Project (GDSUTP): Bus Rapid Transit (BRT), Airport to Gazipur, Bangladesh. All the materials, both virgin and RCA, had to satisfy standard size, fineness, strength, stiffness, abrasion resistance, and soundness provisions up to a specified limit before comparative studies.

2.3 Standard Provisions and Test Codes

Standards from the American Association of State Highway and Transportation Officials (AASHTO), British Standards (BS), and Indian Road Congress (IRC) were followed for aggregate testing in this study. The total tests conducted in the lab and field are listed in Table 1 with their standard code. The results were evaluated using the AASHTO (M-147) standard for Recycled

Concrete Aggregate (RCA), and the Technical Specification from the Roads and Highway Department of Bangladesh.

Table 1 Test Standards.

SL	Test Name	Standard Code
1	Sampling	AASHTO T 2
2	Gradation	AASHTO T 27
3	ACV	BS 812-110
4	TFV	BS 812-111
5	CBR	AASHTO T 193
6	Liquid limit test	AASHTO T 89
7	PL and Plasticity index test	AASHTO T 90
8	LAA test	AASHTO T 96
9	Passing 0.075mm (No. 200)	AASHTO T 11
10	Moisture content test	AASHTO T 265
11	Moisture-Density relationship Test	AASHTO T 180
12	Field Dry Density Test	IS 2720-28

2.4 Procedure of Field Experimentation

Two distinct subbase mix design materials were collected from reliable sources. The first subbase mix aimed to be designed with virgin brick aggregates along with fine sand. These brick chips were already in suitable sizes, eliminating the need for additional crushing. In contrast, the second subbase mix intended to incorporate salvaged materials sourced from existing road excavation and the demolition of concrete structures such as Road dividers, rigid pavement, bridges, and buildings associated with GDSUTP-BRT, Bangladesh and reclaimed subbase materials. The lab tests were carried out in a lab associated with the GDSUTP Project, Bangladesh on the (N-3) National highway between Dhaka and Mymensingh, Bangladesh. This comprehensive testing procedure aimed to assess various parameters and characteristics of the materials, including their physical properties and suitability for subbase applications. According to the specified standards, each material sample underwent meticulous testing three times to ensure an accurate result. Then the average of the three test results was taken into consideration. Once the test results met the design criteria, two separate subbase mix designs were formulated in the laboratory. In accordance with the designs, materials were uniformly spread by a grader machine to maintain a saturated condition on the 50-meter-long and 5.5-meter-wide trial roadbed. In Figure 2 (g) we can see rolling the materials under an 80 KN specified smooth wheel roller. The field compaction of the subbase mixes was assessed using a Field Dry Density (FDD) test, which provided insights into their compactness and stability under practical conditions. Field dry density (FDD) values were compared with laboratory-modified proctor Maximum dry density (MDD) values to determine the relative density of the trial layers.

2.5 Various Types of Tests

After appropriate sampling, the initial test gradation was conducted on procured concrete broken chips, recycled pavement materials, and virgin brick chips. The Recycled Concrete Aggregate (RCA) and recycled pavement materials were mixed in the required proportion, while virgin brick chips were combined with sand according to Grading B of AASHTO M-147. The fraction passing the 0.425 mm or No. 40 sieve was checked against the fraction passing the 0.075 mm or No. 200 sieve to meet the subbase criteria of AASHTO M 147. Focus then shifted to individual aggregate properties, testing strength using the ACV test and abrasion resistance using the Los Angeles Abrasion (LAA) Test on six samples. The 4-day soak California Bearing Ratio (CBR) tests, illustrated in Figure 2 ((a-b), assessed the shear strength of both virgin and salvaged subbase mixes. Atterberg limit shown in Figure 2 ((c-d), tests on materials passing a No. 40 or 0.425mm sieve evaluated drainage capacity, liquid limit, and plastic limit. Moisture-Density relationship tests, conducted on eight samples as shown in Figure 2 (e-f) and following the modified Proctor test method, determined the maximum dry density and optimum moisture content. Field Dry Density tests, shown in Figure 2 (h-i), were conducted post-compaction. Comparing the value with maximum dry density we achieved relative density.

2.6 Field Trial Location

The study was practically implemented on two trial beds, each measuring 50 meters in length and 5.5 meters in width, as part of the GDSUTP Project on the Dhaka-Mymensingh Highway (N-3), depicted in Figure 2 (h-i). The compacted thickness of the subbase materials was maintained at 150 mm. The number of passes required for achieving proper compaction was determined on a trial basis using a roller with a capacity of 8 tons or 80 KN.

2.7 Numerical Analyses

KENPAVE/KENLAYER computer program is used for linear elastic analysis, input parameters are traffic load, material properties, thickness of each layer, number of periods, number of load groups etc. In the simulation, an equivalent number of ESALs (Equivalent Single Axle Loads) based on an 80 kN standard axle load was applied in both scenarios, but there was a difference in the resilient modulus between them. This variation in the resilient modulus was particularly noticeable when the pavement's response was measured at various radial coordinates, extending up to 22.86 centimeters from the point of load application. However, in the mechanistic design method, each load group should be considered individually, rather than using ESALs. In this design, the tire pressure and contact radius are calculated considering a 40 kN load on two wheels, rather than simplifying to a single equivalent load. Accordingly tire pressure (contact pressure) of 827.37 KPa and contact radius of 12.192 cm are used in the design. The elastic modulus for both subbase materials, derived from AASHTO 1993, was used in KENPAVE software to analyze Stress and Displacement. The detailed inputs and considerations for this analysis are illustrated in KENPAVE-LGRAPH shown in Figure 3. The data on vertical displacement at the top of the subbase layer provides insights into potential settlement and the overall structural integrity of the pavement. Meanwhile, the shear stress data at the top of the subbase layer informs us about the material's capacity to distribute traffic loads and its resistance to shear deformation. A graphical representation of Vertical Displacement vs Radial Coordinate at the Bottom of the Subbase for Both Virgin and Salvaged Materials and Shear Stress vs. Radial Coordinate at the Top of the Subbase for Both Virgin and Salvaged Materials are presented in Figure 6.

Figure 2: a) Swelling measuring for 4 days Soak CBR of virgin and salvage materials; b) CBR penetration measuring; c) Atterberg limit test (plastic limit) for the 0.425mm passing particles of virgin and salvage materials; d) Liquid Limit (LL) determination of the of virgin and salvage material; e) Molding for Moisture-Density relationship test; f) Modified Proctor compaction of salvage materials; g) Rolling with a standard vibratory roller (8 tons). h) FDD test for subbase layer made of Mix 1; i) FDD test for subbase layer made of Mix 2:

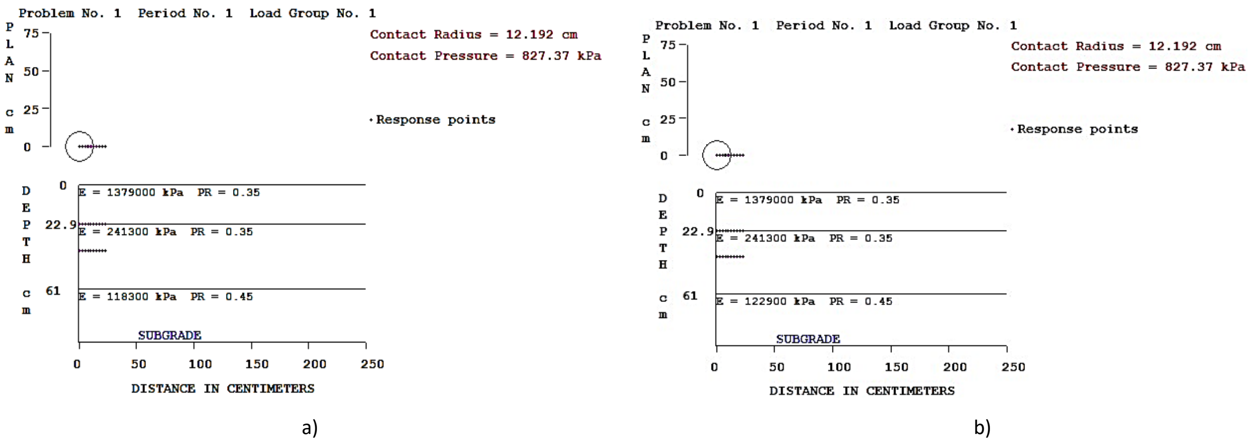


Figure 3 a) KENPAVE -LGRAPH for Pavement using virgin materials; b) KENPAVE -LGRAPH for Pavement using Salvage materials.

3.0 RESULTS AND DISCUSSION

The laboratory test results of the aggregate, as shown in Table 2, were used in two subbase mix designs: one with virgin resources and the other with salvaged materials. These results demonstrated their feasibility and adherence to international (AASHTO M-147) and local road construction guidelines in Bangladesh. We mechanistically analyzed both of the sub base materials performance criteria like vertical displacement and shear stress.

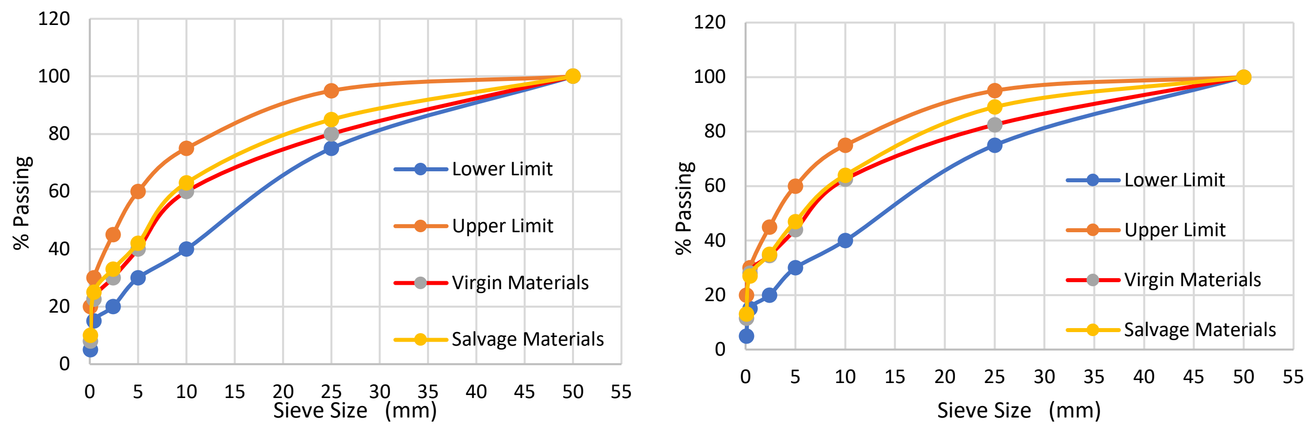
The key findings of this research are summarized below:

1. In the abrasion resistance tests, the mix design with virgin materials achieved a Los Angeles Abrasion (LAA) value of 42%, while the mix with salvaged materials attained an LAA value of 39%. Both results comfortably fall within the maximum allowable limit of 50% as prescribed by AASHTO M-147.
2. Aggregate crushing value (ACV) tests demonstrated that both mix-designs met the maximum limit of 38% (Technical specification, RHD-BD), with the salvage materials mix-design recording a slightly lower ACV value of 35% compared to the mix-design with virgin materials (ACV of 36%), complying with the RHD, BD guideline.
3. The California Bearing Ratio (CBR) test, conducted with a 4-day soak period, revealed that the salvaged material mix design had a CBR value of 72.3%. This significantly exceeds the minimum requirement of 25% as outlined in both AASHTO and RHD technical specification guidelines [26]. In contrast, the virgin mix achieved a CBR value of 62.4%, which aligns with expectations.
4. The gradation analysis results for both before and after the compaction demonstrate that both mix designs satisfied the specified gradation standards (AASHTO M-147), as shown in Figure 4. The X-axis represents sieve sizes, and the Y-axis shows the percentage passing through the sieves. The gradation for virgin subbase materials is indicated by a red line, while for salvaged materials, it is marked with a yellow line. The upper and lower limits on the gradation curve were established according to the specifications of Grading B in AASHTO M-147.
5. In Figure 5 (a & b), the X-axis represents moisture content, while the Y-axis displays the Dry Density values in kilograms per cubic meter (kg/m^3). Additionally, zero air void lines, also known as zero air void curves, are plotted on the MDD graphs. These lines depict a theoretical condition where there are no air voids in the compacted soil, indicating the dry density the soil would have if compacted to 100% of its theoretical maximum density. As shown in Figure 5 (a) and 5(b), the compaction characteristics of the salvage materials mix-design outperformed those of the virgin materials mix-design. The salvage materials mix achieved a higher maximum dry density (MDD) of 1909 kg/m^3 and a lower optimum moisture content (OMC) of 10.8%, indicating more efficient water usage and greater environmental sustainability. In comparison, the MDD for the mix with 70% Virgin Brick Chips and 30% Fine Sand was 1803 kg/m^3.
6. For both virgin and salvaged materials, the fractions passing the 75-µm (No. 200) sieve are 8% and 10% respectively. These values do not exceed two-thirds of the fractions passing the 0.425-mm (No. 40) sieve, which are 15% and 16.66%. This compliance aligns with the specifications of AASHTO M-147.
7. For both virgin and salvage materials the fraction passing the 0.425-mm sieve is non-plastic as prescribed by AASHTO M-147.
8. After compaction of the trial beds, the relative density was found to be 98.5% in virgin material bed and 99.0% in salvage material bed Table 2 Both values satisfy our minimum requirement of 98% (IRC-37-18).
9. The pavement performance simulation using KENPAVE for a 150 mm subbase layer, as shown in Figure 6 (a), revealed that both virgin and salvaged materials exhibited minimal vertical displacement. Specifically, the vertical displacement was 0.287 mm (0.192% of the layer thickness) for virgin materials and 0.282 mm (0.189%) for salvaged materials. These results are within the typical local practice range for maximum subbase deflection, which is between 0.50 to 2.00 mm, considering the layer thickness [27] . This indicates that both types of materials perform effectively, demonstrating strong structural integrity and stability. The results suggest that salvaged materials perform nearly as well as virgin materials, supporting their use for sustainable and cost-effective pavement construction. Overall, the low displacement values reflect high-quality pavement layers capable of withstanding expected loads with minimal

deformation, thus contributing to the pavement's durability and longevity.

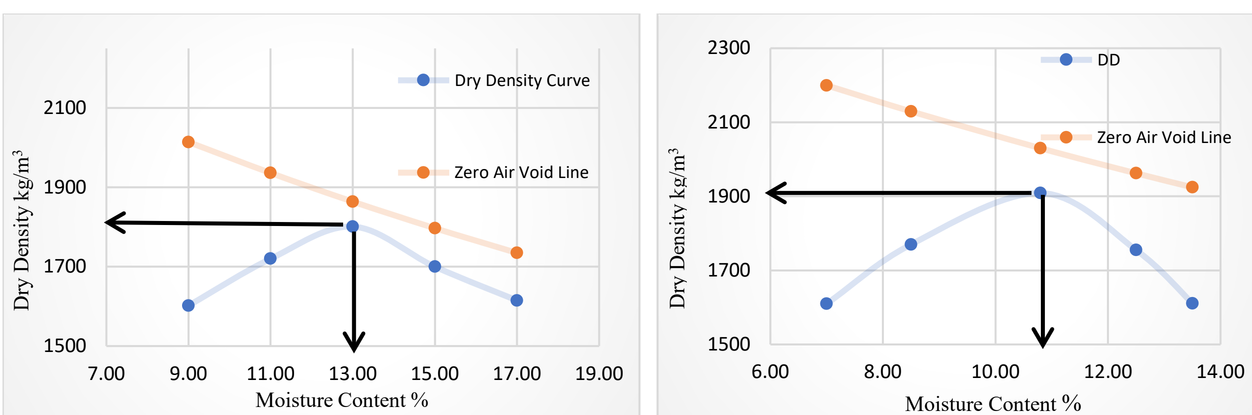
Table 2 Test Results Comparison of Subbase Materials made of virgin and salvage materials.

Subbase Type	Details	Test Name								
		ACV (%)	LAA (%)	Specific Gravity	MDD (Modified Proctor) kg/m³	OMC (%)	PI (%)	CBR (%)	Elastic Modulus (kPa)	Relative density (%)
Mix 1: 70% Virgin Brick Chips +30% Fine sand	Bricks chips	36	42	2.46	1803	13.0	Non-Plastic	62.4	118,314	98.5
	Fine aggregate	-	-							
Mix 2: 70% RCA + 30% RPA	Concrete broken chips	35	39	2.60	1909	10.8		72.3	122,864	99.0
	Salvage subbase									



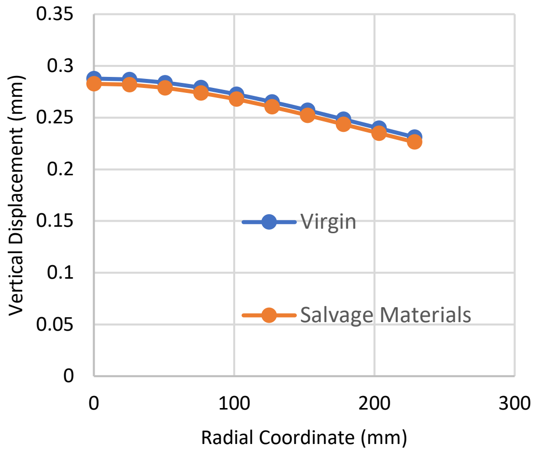
a) b)

Figure 4 a) Combined Gradation of Two Subbase Design Mixes Before Compaction; b) Combined Gradation of Two Subbase Design Mixes after Compaction.



a) b)

Figure 5 (a) Dry Density vs. Moisture content relationship for Subbase materials of virgin aggregates; (b) Dry Density vs. Moisture Content relationship for subbase materials of Salvage aggregates



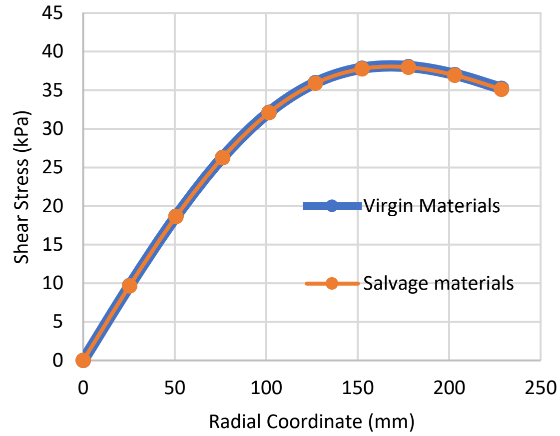


Figure 6 a) Vertical Displacement vs Radial Coordinate at the Bottom of the Subbase for Both Virgin and Salvaged Materials. b) Shear Stress vs. Radial Coordinate at the Top of the Subbase for Both Virgin and Salvaged Materials.

10. The analysis at a radial distance of 228.6 mm revealed that the maximum shear stress at the top of the 150 mm subbase layer was 38.07 kPa for virgin material and 37.98 kPa for salvaged material, both measured 177.8 mm from the load center. These shear stress values, which resulted in maximum strains of 0.000426 for virgin material and 0.000425 for salvaged material, are well below the typical range of 200 to 500 kPa for subbase materials. These results are depicted in Figure 6(b). This result is significant because it demonstrates that both virgin and salvaged materials are performing effectively under the applied loads, as they exhibit shear stresses and strains far below the threshold for subbase material performance. This indicates that the subbase layer has adequate resistance to shear deformation, which is crucial for maintaining structural integrity and preventing premature failure of the pavement. The low shear stress and strain values suggest that both materials offer similar performance and stability, which supports the use of salvaged materials as a viable alternative to virgin materials in terms of shear resistance and overall pavement durability. This information is important for ensuring that the pavement design meets the necessary performance criteria and can sustain the expected loads over time.

4.0 CONCLUSION

The study demonstrates that using a mix of 70% recycle concrete broken chips (RCA) and 30% recycle subbase materials (RPA) for subbase construction is both feasible and beneficial, as an alternative to solely using virgin resources. All test results aligned with the local specifications set by the Roads and Highways Department of Bangladesh and the International standards of AASHTO. The analysis of pavement performance confirmed that this mix design meets necessary specifications, highlighting its effectiveness for pavement construction. This approach supports sustainable development through cost efficiency and reduced landfill usage, while maintaining compliance with industry standards.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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