

Cyclic Behavior and Microstructure of Recycled Concrete Aggregate as a Pavement Base Layer

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Received 22 February 2026; Received in revised form 29 June 2026

Accepted 30 June 2026; Available online 30 June 2026

ABSTRACT

Mechanical analysis of resilient and permanent deformation is critical for pavement design and construction, as repeated traffic loading is the primary factor influencing material stability. This study investigates the cyclic mechanical behavior and microstructural characteristics of Recycled Concrete Aggregate (RCA) to evaluate its suitability as a sustainable pavement base material. Geotechnical characterization classified the RCA as a well-graded gravel (GW) adhering to Department of Highways Thailand Type D specifications, with a maximum dry unit weight of 18.85 kN/m^3 . Multi-stage repeated load triaxial testing was performed to determine resilient modulus and permanent deformation characteristics under varying deviatoric stress states. Results indicated that the RCA exhibits a robust resilient modulus ranging from 125 to 260 MPa. Based on Werkmeister's and shakedown theory, the material remained within the stable Plastic Creep zone (Range B) across all loading stages (150–450 kPa), demonstrating high resistance to incremental collapse. Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) analyses revealed a complex matrix of carbonated adhered mortar and quartz-rich natural aggregates. While the porous interfacial transition zone (ITZ) contributed to elevated water absorption (6.65–7.46%), the non-plastic nature of cementitious fines prevented moisture-induced instability. The integration of macro-mechanical results with micro-scale mineralogical findings validates that RCA provides sufficient structural integrity for high-traffic pavement foundations. This research supports the transition toward a circular economy in the infrastructure sector by providing a technical basis for the large-scale implementation of recycled construction and demolition waste in transportation projects.

Keywords: Permanent deformation; Recycled concrete aggregate; Resilient modulus; Shakedown theory; Werkmeister's criteria

1. Introduction

The rapid expansion of urbanization and infrastructure development worldwide has generated substantial quantities of construction and demolition waste, with concrete waste representing a dominant fraction of this material stream. The reuse of recycled concrete aggregate (RCA) in pavement construction has emerged as a critical sustainable engineering solution that addresses both environmental stewardship and resource conservation challenges [1-3]. In addition to lessening the pressure on landfills and preventing the loss of virgin aggregate supplies, the use of RCA in pavement base and subbase layers supports the circular economy ideals that are becoming more and more important in the construction of contemporary infrastructure [4].

The mechanical and durability performance of unbound granular materials under the repeated traffic loading is fundamental to pavement and structural construction, design, and long-term serviceability [5, 6]. The resilient modulus and permanent deformation characteristics of RCA based pavement layers are critical design parameters that directly influence pavement performance prediction and service life estimation [7]. Previous investigations have established that RCA exhibits distinct mechanical behavior compared to conventional natural aggregates due to its inherent microstructural characteristics, including attached residual mortar, higher porosity, and more angular particle geometry (8-11). Under cyclic loading circumstances, these physical characteristics can have a substantial impact on the buildup of plastic deformation as well as the elastic response [12].

The evaluation of permanent deformation behavior has been extensively studied through repeated load triaxial (RLT) testing, which simulates field stress conditions experienced by pavement

materials [13]. The shakedown theory, originally developed for conventional engineering structures subjected to cyclic loading, has been successfully applied to characterize the long-term deformation behavior of unbound granular materials in pavement systems (2, 14-16). According to this theoretical framework, the permanent deformation response of granular materials can be classified into three distinct ranges: Range A (plastic shakedown), where plastic deformation stabilizes after initial compaction; Range B (plastic creep), characterized by decreasing but persistent strain accumulation; and Range C (incremental collapse), where continuous strain development leads to structural failure. [17] established critical stress thresholds to delineate these shakedown ranges, providing a rational basis for material selection and pavement design [3, 18-20]. However, the applicability of these criteria to recycled materials requires careful validation, as RCA exhibits mechanical characteristics that differ from conventional crushed rock aggregates [18, 19].

Recent studies have demonstrated that RCA can achieve comparable or superior resilient modulus values relative to natural aggregates when properly processed and compacted, particularly under optimized moisture conditions [16, 21]. Nevertheless, the permanent deformation behavior of RCA under extended loading cycles remains a critical concern for pavement design practitioners [22]. [23] emphasized the necessity of characterizing permanent deformation properties specific to regional materials for implementation in mechanistic-empirical pavement design frameworks. The integration of shakedown theory with laboratory-measured permanent strain curves provides a comprehensive approach to evaluating the long-term performance potential of RCA in pavement applications [21, 24].

The AASHTO 1993 Guide for Design of Pavement Structures remains a widely utilized empirical-mechanistic design methodology that incorporates material resilient modulus as a fundamental input parameter. The design resilient modulus for aggregate base materials is typically evaluated at a representative stress state ($\sigma = 103.5$ kPa), as recommended by the AASHTO specifications [25]. The accurate characterization of RCA mechanical properties under these standardized conditions is essential for reliable pavement thickness design and performance prediction.

At the microstructural level, the performance of RCA is intrinsically linked to its mineralogical composition, interfacial transition zone (ITZ) characteristics, and pore structure distribution. Advanced microscopy techniques, including scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDX), have proven instrumental in elucidating the microstructural features that govern macroscopic mechanical behavior [26, 27]. Studies employing SEM-EDX analysis have revealed that the ITZ in RCA exhibits distinct compositional gradients and micro-crack patterns that influence both strength and deformation characteristics [19, 28, 29]. The presence of residual calcium hydroxide crystals, C-S-H gel distribution, and microvoid networks in the attached mortar layer significantly affects the aggregate-matrix bonding strength and stress transfer mechanisms under loading [30-33].

The correlation between microstructural characteristics and mechanical performance represents a critical knowledge gap in understanding RCA behavior in pavement applications. While numerous investigations have examined either the macroscopic mechanical properties or the microstructural features of RCA independently, comprehensive studies integrating both scales of analysis remain

limited. Understanding how microstructural parameters such as porosity, ITZ composition, and hydration product morphology influence the resilient modulus and permanent strain accumulation under cyclic loading is essential for optimizing RCA processing methods and establishing quality control criteria.

Despite growing research interest in RCA utilization for pavement construction, several critical aspects warrant further investigation. First, the shakedown behavior of RCA under realistic pavement stress conditions requires systematic evaluation to determine appropriate stress thresholds for various RCA qualities. Second, the specific influence of microstructural characteristics on cyclic deformation response needs quantitative assessment through integrated experimental approaches. Third, the correlation between microscale features and macroscale mechanical parameters must be established to enable microstructure-informed material selection and quality assurance protocols.

This study addresses these research gaps through a comprehensive experimental investigation of RCA behavior under cyclic loading conditions representative of pavement base layer applications. The research objectives are threefold: (1) Evaluate the resilient modulus and permanent deformation of RCA through RLT testing under various stress states; (2) Classify the shakedown behavior according to Werkmeister's criteria; and (3) Characterize microstructural features using SEM-EDX/XRD analysis to establish correlations between hydration product morphology and mechanical performance metrics. The integration of cyclic mechanical testing with microstructural characterization provides a multi-scale understanding of RCA behavior.

The findings of this investigation contribute to the growing body of knowledge on sustainable pavement materials by providing fundamental insights

into the deformation mechanisms of RCA under traffic loading. The establishment of shakedown response classification for RCA, coupled with microstructural analysis, offers a scientific basis for quality assessment and performance prediction. Furthermore, the correlation between microstructural features and macroscopic mechanical properties enables the development of microstructure-based quality control criteria, advancing the reliable implementation of RCA in pavement infrastructure systems.

2. Materials and Methods

2.1 Materials

The 100% Recycled Concrete Aggregate (RCA) used in this research was sourced from construction and demolition waste (CDW) streams in Ubon Ratchathani Province, Thailand, and was prepared to have a negligible residual moisture content of less than 0.3% to ensure experimental consistency. Sieve analysis conducted in accordance with ASTM D422-63 [34] demonstrated that the RCA aligns strictly with the Department of Highways (DOH, Thailand) Type D [35] specifications for premium pavement base materials, establishing the robust mechanical skeleton essential for high-performance infrastructure applications (Fig. 1). By maintaining a well-graded profile comprising 48.6% gravel, 47.9% sand, and a 3.5% non-plastic fine fraction—the material optimizes grain-to-grain contact and minimizes void ratios, which are critical for achieving the high maximum dry density required in structural base layers. Classified as well-graded gravel (GW) under the Unified Soil Classification System (USCS), [36] the RCA exhibited a specific gravity of 2.7, while its mechanical integrity was confirmed by a Los Angeles abrasion value of 38.1% and a flakiness index of 15.6%. These values indicate both sufficient resistance to mechanical degradation and a favorable particle morphology for effective aggregate interlocking. Furthermore,

compaction characteristics derived from the modified Proctor test yielded a maximum dry unit weight of 18.85 kN/m^3 at an optimum moisture content (OMC) of 12.5%. Notably, the elevated water absorption observed in the coarse (6.65%) and fine (7.46%) fractions is a distinctive characteristic attributed to the presence of porous adhered mortar. This microstructural feature underscores the necessity for rigorous moisture management during cyclic loading and pavement design to ensure the material's long-term structural stability.

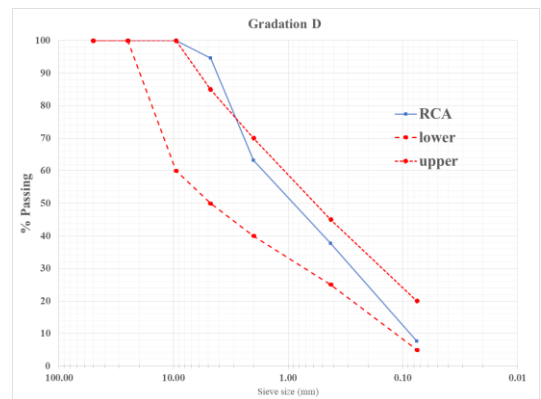


Fig. 1. The particle size distribution of RCA.

2.2 Cyclic triaxial test

The ASTM D1557 [37] modified Proctor compaction test was used to produce the samples, guaranteeing ideal compaction and uniform density throughout the range. For the purpose of compaction testing, the sample was compacted in five layers using a mold that measured 105 mm in diameter by 115 mm in height. Each layer received 25 blows, and the moisture content–dry density correlations were established. The Repeated Load Triaxial Test (RLTT) equipment was used to assess the RCA cyclic behavior. This test was essential for figuring out the long-term permanent deformation characteristics under simulated traffic loading as well as the resilient modulus. To measure the stress-dependency of the stabilized material in a single specimen, a

multi-stage loading methodology was used. In order to replicate the pulse-like characteristics of wheel loads on pavement, the test was carried out at a steady frequency of 1 Hz using a haversine loading waveform. Four successive loading stages at a constant confining pressure of 50 kPa and deviator stress increases of 100 kPa from 150 kPa to 250 kPa, 350 kPa, and 450 kPa comprised the experimental program [4]. To guarantee that the post-compaction phase and the long-term stable (or unstable) strain phases were captured, each stage included 10,000, 20,000, 30,000, and a total of 40,000 cycles per specimen. High-precision Linear Variable Differential Transformers (LVDTs) were used to record axial deformations during the cyclic loading. The laboratory test machine is shown in Fig. 2.



Fig. 2. Cyclic triaxial test machine.

The data made it possible to calculate two key performance indicators: resilient modulus and permanent axial strain. Resilient modulus is defined as the ratio of cyclic deviatoric stress to recoverable

(elastic) axial strain. The cumulative non-recoverable deformation was tracked in the next order permanent axial strain to assess the mixture's shakedown behavior and Werkmeister criteria as shown in Fig. 3. The stability of the material might be determined by comparing the cumulative strain to the permanent axial strain rate.

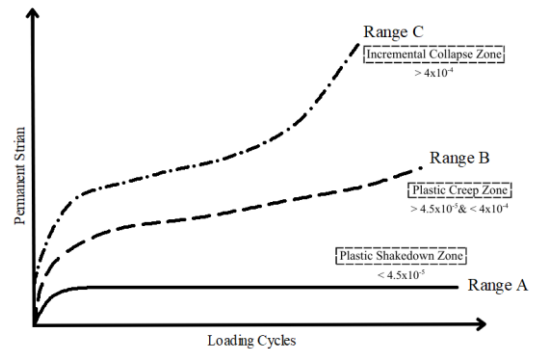


Fig. 3. Shakedown theory and Werkmeister's criteria [38].

For the laboratory test of cyclic loading, the RCA was evaluated with the shakedown theory, and Werkmeister's developed the following criteria to classify these behavioral limits. Werkmeister's justification is shown in Table 1.

Table. 1. Definitions of the Shakedown theory and Werkmeister's behavior classification [39].

Shakedown response	Behavior deformation zone	Werkmeister's criteria
Range A	Plastic shakedown zone	$\epsilon p_{5000} - \epsilon p_{3000} < 4.5 \times 10^{-5}$
Range B	Plastic creep zone	$4.5 \times 10^{-5} < \epsilon p_{5000} - \epsilon p_{3000} < 4.0 \times 10^{-4}$
Range C	Incremental collapse zone	$\epsilon p_{5000} - \epsilon p_{3000} > 4.0 \times 10^{-4}$

2.3 Scanning electron microscopy (SEM-EDX) analysis

Scanning electron microscopy (SEM), Energy Dispersive X-Ray Spectroscopy (EDX), and X-ray Diffraction

(XRD) analysis were employed to visualize the microstructure of the RCA samples at high magnification. This analysis provides insights into the microstructure of RCA, and the SEM examination was conducted on fractured samples post-cyclic triaxial testing to identify the failure mechanisms and to correlate the mechanical test results with the microstructural characteristics. In this step small fragments were taken from the broken samples and then frozen at -195°C by immersion in liquid nitrogen for 5 min and coated with gold prior to conducting SEM (JEOL JSM6400 device) analysis. For laboratory test, the XRD patterns were collected using a diffractometer, with samples being scanned in a 2θ range typically between 5° and 80° . The resultant diffractograms were analyzed to determine the presence of specific crystalline and chemical of the RCA compounds.

3. Results and Discussion

3.1 Permanent axial strain behavior of RCA

The permanent axial strain behavior of the RCA under multi-stage cyclic loading, as illustrated in Fig. 4, demonstrates a distinct stress-dependent response that is characteristic of high-quality unbound granular materials. In Stage 1, under a deviatoric stress of 150 kPa, the material undergoes a rapid initial accumulation of axial strain, reaching approximately 1.3×10^{-6} within the first 10,000 cycles. This represents the primary compaction phase where air voids are reduced and aggregate particles rearrange to establish a more stable interlocking configuration. As the deviatoric stress is incrementally increased to 250 kPa, 350 kPa, and 450 kPa in subsequent stages, the cumulative permanent strain continues to rise in a controlled manner, reaching a final value of approximately 3.25×10^{-6} after 40,000 total cycles. The absence of an exponential or sudden vertical increase in the strain curve at the higher stress levels

indicates that the well-graded gravel skeleton (GW) effectively distributes the increased load without experiencing the structural instability associated with incremental collapse

Table. 2. Behavior classification of the RCA.

Stag e	Werkmeister's criteria $\epsilon_{p5000} - \epsilon_{p3000}$	Range	Behavior
1	0.000122803	B	Plastic creep zone
2	0.000074140	B	Plastic creep zone
3	0.000110070	B	Plastic creep zone
4	0.000173820	B	Plastic creep zone

This macroscopic observation is quantitatively supported by the behavior classification presented in Table 2, where all four loading stages are categorized within Range B, designated as the Plastic Creep Zone according to Werkmeister's criteria. Specifically, the calculated strain rate values ($\epsilon_{p5000} - \epsilon_{p3000}$) for Stages 1 through 4 recorded as 0.000122803, 0.000074140, 0.000110070, and 0.000173820, respectively fall consistently between the defined limits of 4.5×10^{-5} and 4.0×10^{-4} . The decrease in the strain rate from Stage 1 to Stage 2 reflects the material's increased stiffness following initial densification, while the subsequent rise in the rate during Stages 3 and 4 is a direct response to the significantly higher deviatoric stresses. This classification confirms that while the plastic deformation does not fully stabilize as it would in Range A (Plastic Shakedown), the rate of strain accumulation remains decreasing and manageable, rather than accelerating toward failure (Range C).

The ability of the RCA to remain within Range B even at a high deviatoric stress of 450 kPa is a critical finding for pavement design practitioners. This steady-state creep response is inherently linked to the physical properties of the material, where the high angularity and a flakiness index of 15.6% facilitate strong particle-to-

particle interlocking. Simultaneously, the porous adhered mortar which accounts for the water absorption values of 6.65–7.46% allows for slight, controlled compressions that contribute to the persistent but non-catastrophic strain observed in the Range B classification. Consequently, the integration of the Fig. 4 strain curves and the Table 2 quantitative limits provide a scientific basis for concluding that this RCA possesses sufficient mechanical integrity and long-term stability for use in premium pavement base layers within the AASHTO 1993 framework.

3.2 Resilient modulus behavior of RCA

The resilient modulus M_r behavior of the RCA throughout the multi-stage cyclic loading regime is presented in Fig. 5, illustrating the material's elastic stiffness response as a function of deviatoric stress and cumulative loading cycles. The results reveal a pronounced stress-dependency, a characteristic typical of unbound granular materials where the elastic response is significantly influenced by the state of confinement and the magnitude of cyclic stress. In the primary loading stage at a deviator stress of 150 kPa, the M_r values initiate at approximately 160 MPa and exhibit a gradual decrease to roughly 125 MPa by the conclusion of the first 10,000 cycles. This initial phase of slight softening may be attributed to the micro-degradation of the porous adhered mortar and the initial settlement of the well-graded gravel matrix. However, as the deviator stress is increased to 250, 350, and finally 450 kPa, the M_r values demonstrate substantial stepwise increments, reaching approximate ranges of 180–200 MPa, 215–230 MPa, and 250–260 MPa, respectively.

This significant increase in stiffness at higher stress levels is a direct consequence of the enhanced aggregate interlocking provided by the GW-classified skeleton and the high maximum dry unit

weight of 18.85 kN/m³ achieved during compaction. Despite the inherent porosity and high water absorption characteristics associated with the attached residual mortar, the RCA maintains a robust and stable resilient response even at the maximum deviator stress of 450 kPa. The achievement of M_r values exceeding 250 MPa at high stress states confirms that the RCA possesses sufficient structural capacity to serve as a high-quality substitute for natural aggregates. Furthermore, the consistency of the resilient response across the extended loading cycles demonstrates that the material can provide reliable long-term support within the AASHTO 1993 pavement design framework, provided that moisture levels are strictly managed to mitigate the potential effects of the porous microstructural features identified in the SEM analysis.

3.3 Permanent axial strain rate of RCA

The relationship between the permanent axial strain rate and the cumulative permanent axial strain is illustrated in Fig. 6, providing a critical diagnostic tool for assessing the long-term stability of the RCA under varied deviatoric stress states. Plotted on a logarithmic scale, the strain rate profiles for all four loading stages exhibit a characteristic steep downward trajectory, which indicates the progressive stabilization of the aggregate matrix through densification and particle reorientation. In the primary stage at a deviator stress of 150 kPa, the strain rate rapidly declines from approximately 100×10^{-6} to a value near 0.1×10^{-6} per cycle as the permanent strain reaches $1,300 \times 10^{-6}$. This behavior corresponds to Werkmeister's Range A (plastic shakedown), where the accumulation of plastic strain effectively ceases after the initial compaction phase. For subsequent stages at 250 kPa, 350 kPa, and 450 kPa, the material displays similar stabilization patterns, with the strain rates consistently dropping toward values below

1.0×10^{-6} per cycle despite the incremental increases in cumulative strain. Notably, while the terminal strain rates for the 350 kPa and 450 kPa stages are higher than those of the initial stage, they do not exhibit any upward curvature or hooking indicative of Range C (incremental collapse).

The maintenance of a decreasing strain rate across all stress levels, even at the maximum deviatoric stress of 450 kPa, verifies that the RCA matrix possesses sufficient inter-particle friction and structural integrity to remain within the plastic shakedown or plastic creep regions. These results mathematically substantiate the suitability of the well-graded RCA for pavement base applications, as the material demonstrates a high capacity to dissipate energy and resist progressive shear failure under cyclic haversine loading. The mechanical performance of the RCA investigated in this study is inextricably linked to its microstructural characteristics and grain-size distribution, which collectively define its suitability as a premium pavement base material.

The observed resilient modulus M_r range of 125-260 MPa and the progression of permanent axial strain from plastic shakedown (Range A) to stable plastic creep (Range B) are consistent with the behavior of high-quality recycled aggregates reported in recent literature [40]. The initial phase of high strain accumulation and slight resilient modulus softening during Stage 1 (150 kPa) reflects the primary deformation stage where the well-graded gravel (GW) matrix undergoes micro-reorientation and densification, a phenomenon characteristic of unbound granular materials with high specific surface

areas [41]. This macro-scale stabilization is supported by the microstructural analysis, where Scanning Electron Microscopy (SEM) reveals that the 6.65–7.46% water absorption is physically localized within the porous adhered mortar and the complex Interfacial Transition Zone (ITZ).

As cyclic loading progresses to higher deviatoric stresses (350-450 kPa), the material's ability to maintain high M_r values and decreasing strain rates, as seen in Figs. 5 and 6, is fundamentally driven by the robust aggregate interlocking of the 48.6% gravel and 47.9% sand fractions. This effective stress distribution within the skeletal matrix offsets the inherent weakness of the porous residual cement paste, which typically serves as the site for micro-crack initiation under excessive moisture or cyclic stress [39]. Furthermore, the non-plastic nature of the minor fine fraction (3.5%) ensures that the material avoids the buildup of pore water pressure, which is critical for preventing the transition into the incremental collapse zone (Range C) that often plagues poorly graded or contaminated recycled aggregates [4].

By satisfying the Department of Highways (DOH) Type D gradation limits, the RCA achieves a high maximum dry unit weight of 18.85 kN/m^3 , creating a dense packing state that maximizes friction and mechanical stability. Ultimately, the synthesis of these multi-scale results validates that while the microstructural porosity necessitates careful moisture management, the macroscopic mechanical integrity of the RCA meets the stringent structural requirements for sustainable, high-performance pavement foundations [21].

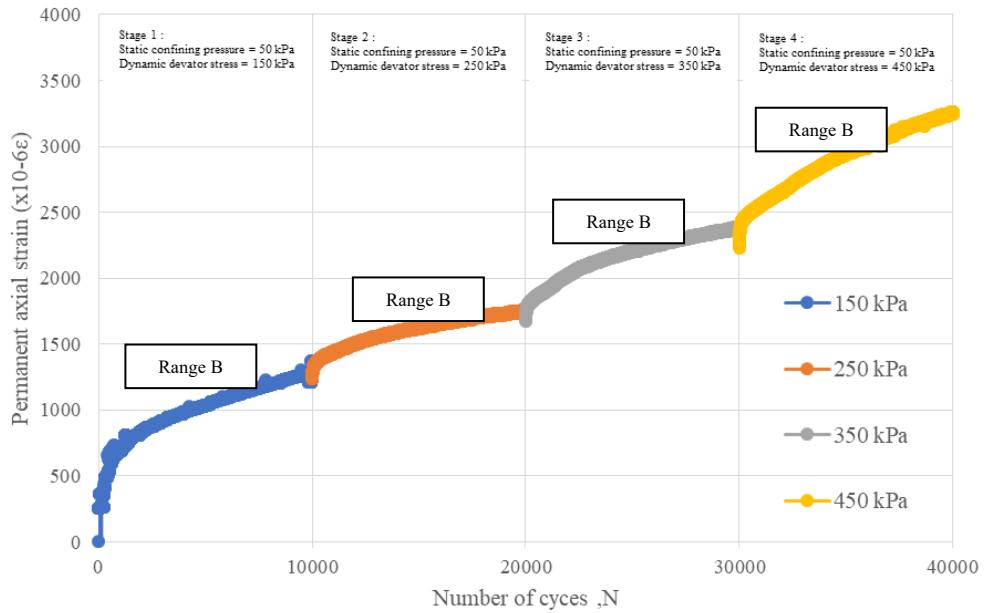


Fig. 4. Permanent axial strain testing of RCA.

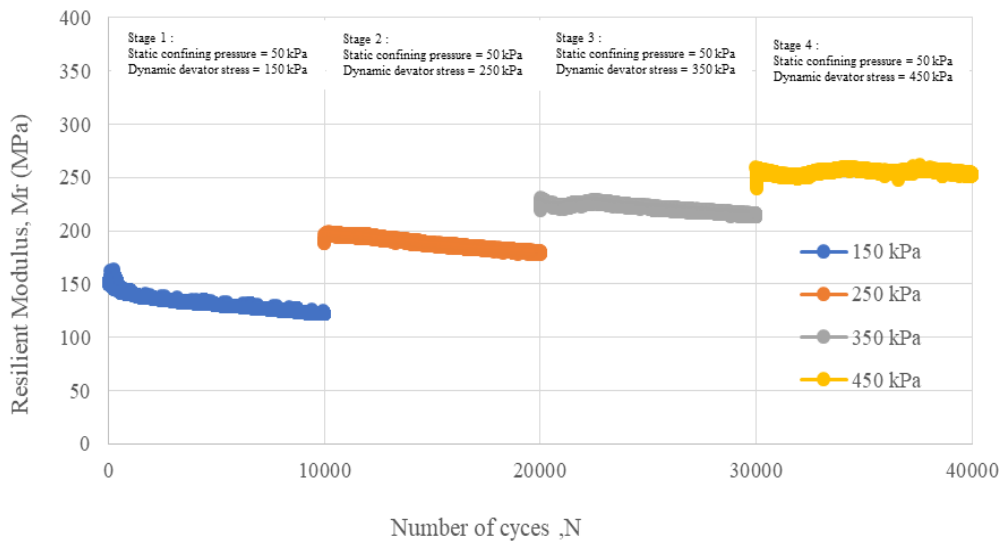


Fig. 5. Resilient modulus testing of RCA.

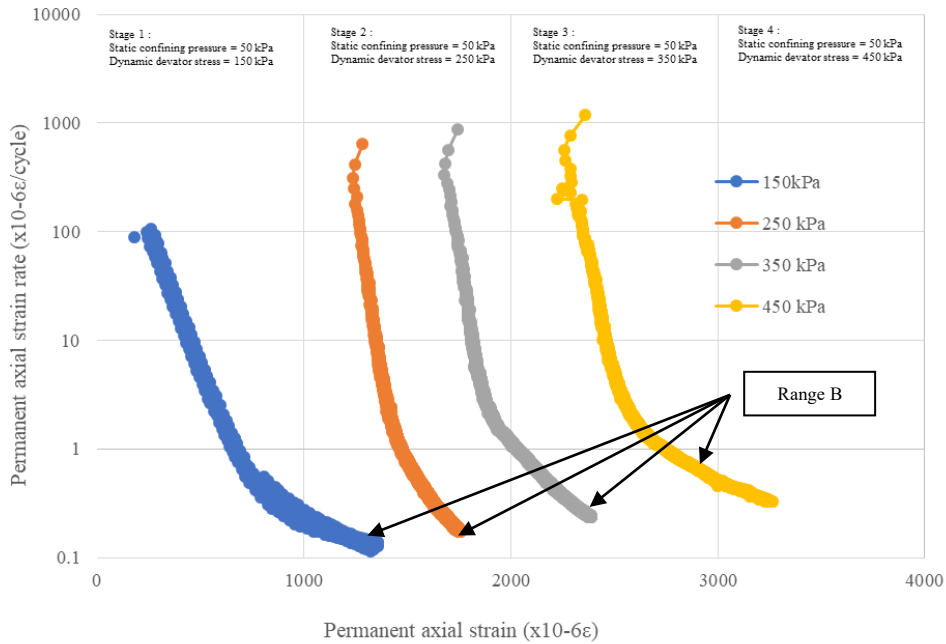


Fig. 6. Permanent axial strain rate of RCA.

3.3 SEM, EDX, and XRD analysis of RCA

The microstructural morphology and elemental composition of the RCA, as visualized through the SEM and EDX analysis in Fig. 7, provide the fundamental scientific explanation for the cyclic mechanical performance observed in the RLT testing. The SEM micrographs depict highly angular particles with a complex, heterogeneous surface texture characterized by a porous, crystalline crust of residual cement mortar adhered to the original natural aggregate. This micro-porosity and the presence of micro-voids within the old Interfacial Transition Zone (ITZ) directly account for the relatively high water absorption values of 6.65% for coarse and 7.46% for fine fractions. However, the inherent angularity of these particles, evidenced by a favorable flakiness index of 15.6%, facilitates robust aggregate interlocking. This interlocking mechanism is the primary driver behind the high

resilient modulus values M_r reaching up to 260 MPa and the material's ability to maintain structural stability within the plastic shakedown and creep regions (Ranges A and B) under significant deviatoric stresses.

The chemical composition provided in the EDX spectra further elucidates the material's stability; the high concentrations of Calcium (Ca), reaching a maximum of 67.89% in Spectrum 5, and Oxygen (O), peaking at 57.46% in Spectrum 1, confirm the prevalence of cementitious hydration products such as Calcium-Silicate-Hydrate (C-S-H) gel and Calcium hydroxide. The substantial Carbon (C) content of 55.81% in Spectrum 4 indicates significant carbonation of the residual paste, a process known to enhance the stiffness and durability of recycled aggregates over time. Furthermore, the presence of these cementitious remnants in the minor 3.5% fines fraction ensures its non-plastic character, which is critical for preventing the development of pore water

pressure and the resulting "pumping" effect during cyclic loading. By validating that the fines are composed of stable mineralogical components rather than expansive clay minerals, the SEM-EDX results confirm that the RCA matrix can withstand repeated traffic loads without transitioning into the incremental collapse zone (Range C).

This multi-scale synthesis linking the chemical stability of the hydration products and the physical interlocking of the well-

graded gravel (GW) skeleton demonstrates that the RCA possesses the necessary microstructural integrity to function as a sustainable, high performance substitute for virgin aggregates in pavement base layers. The X-ray diffraction (XRD) patterns illustrated in Fig. 8 provide the crystallographic confirmation of the RCA mineralogical stability, which serves as the fundamental basis for its mechanical performance under cyclic loading.

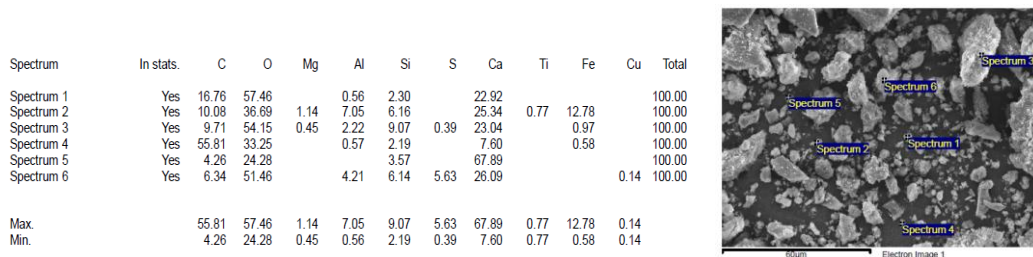


Fig. 7. SEM and EDX analysis of RCA.

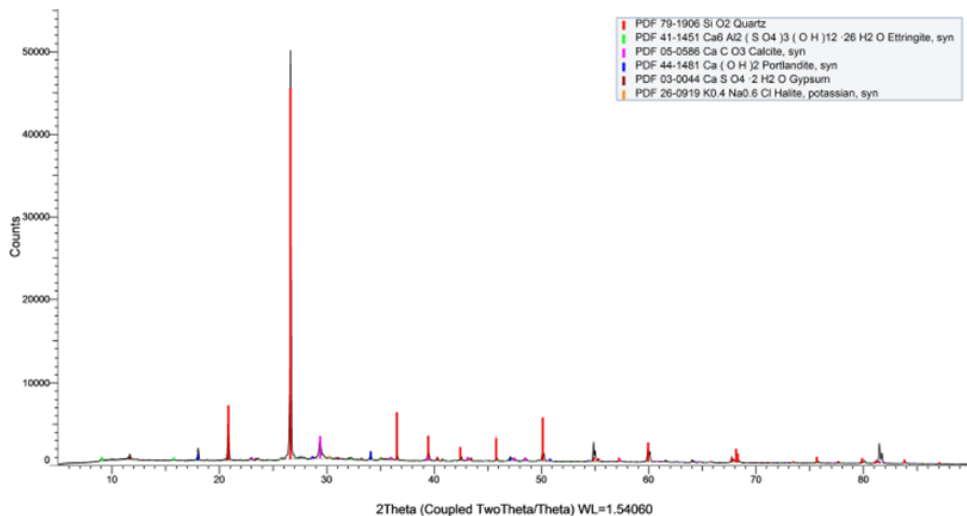


Fig. 8. XRD analysis of RCA.

The most prominent diffraction peak, observed at approximately 26.6° with 2° theta, corresponds to quartz (SiO_2), reflecting the high mineralogical quality of the original natural aggregates and the dominant sand fraction within the RCA matrix. This dominance of silica-based minerals provides the primary structural

stiffness and high resilient modulus values reaching 260 MPa, as identified in the macroscopic testing, because these minerals maintain high inter-particle friction and do not undergo significant mechanical degradation under deviatoric stresses.

Furthermore, the identification of Calcite (CaCO_3) peaks aligns perfectly with

the substantial carbon content detected in the EDX analysis, specifically Spectrum 4, confirming that the adhered mortar has undergone extensive carbonation. This process is scientifically significant as it densifies the porous cement paste and strengthens the Interfacial Transition Zone (ITZ) observed in the SEM micrographs, thereby reducing the risk of micro-crack propagation during repetitive traffic loads.

The presence of hydration products such as Portlandite (Ca(OH)_2) and Ettringite, alongside traces of Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), validates the residual cementitious nature of the material which contributes to the non-plastic character of the minor 3.5% fines fraction. Unlike natural subgrade soils which may contain expansive clay minerals, the crystalline structure of these cementitious remnants ensures that the fine particles do not induce moisture-sensitive instability or pore-water pressure buildup. This chemical stability directly supports the material's behavior within the plastic shakedown and plastic creep zones (Range A and B), as the absence of plastic fines prevents the "pumping" effect and the subsequent transition into the incremental collapse zone (Range C) even at high stress levels of 450 kPa. Consequently, the integration of these XRD results with the previous SEM-EDX and cyclic triaxial data demonstrates that the RCA possesses both the chemical and mechanical integrity required for long-term serviceability in sustainable pavement foundations.

4. Conclusion

This study provides a comprehensive multi-scale evaluation of Recycled Concrete Aggregate (RCA), effectively linking its microstructural characteristics to its macroscopic mechanical performance under cyclic traffic loading. The physical and geotechnical characterization confirms that the RCA is classified as a well-graded gravel (GW) that

adheres strictly to the Department of Highways (DOH) Thailand Type D specifications, providing a robust skeletal matrix with a maximum dry unit weight of 18.85 kN/m^3 . Through multi-stage repeated load triaxial (RLT) testing, the material demonstrated a high degree of structural integrity, exhibiting stress-dependent resilient modulus values ranging from 125 to 260 MPa. The application of Werkmeister's and shakedown theory quantitatively verified that the RCA remains within the stable Plastic Creep zone (Range B) across all tested stress states, from 150 to 450 kPa, with no evidence of transitioning into the incremental collapse zone (Range C). This stability is scientifically substantiated by the SEM-EDX and XRD analyses, which identified the presence of carbonated adhered mortar and a quartz-dominant mineralogy. Although the porous nature of the Interfacial Transition Zone (ITZ) contributes to elevated water absorption, the non-plastic character of the cementitious fines prevents the buildup of pore water pressure and subsequent mechanical failure.

The integration of these findings demonstrates that the RCA investigated in this study possesses the necessary mechanical and chemical stability to function as a high-performance, sustainable alternative to virgin aggregates in pavement base layers. The results satisfy the technical requirements for resilient and durable infrastructure while contributing significantly to the circular economy by repurposing construction and demolition waste. Ultimately, the multi-scale methodology employed here provides a reliable framework for assessing recycled materials, ensuring that their implementation in the transportation sector is supported by both structural performance and microstructural validation.

Acknowledgements

For laboratory SEM-EDX and XRD testing, the author is extremely grateful to the ISI laboratory and Testing and Certification Service Unit (LSU), Sirindhorn Engineering Development Building, Analytical Instruments Research Center, Suranaree University of Technology.

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