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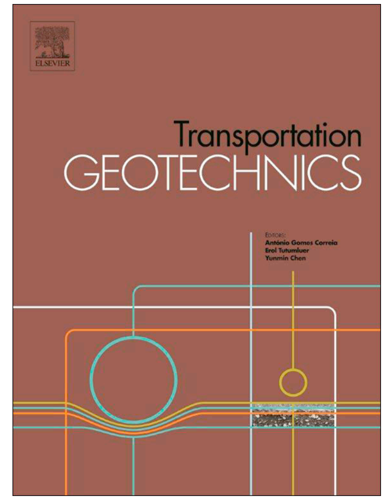

Review Article

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PII: S2214-3912(25)00131-X
DOI: https://doi.org/10.1016/j.trgeo.2025.101612
Reference: TRGEO 101612

To appear in: *Transportation Geotechnics*

Received Date: 7 September 2024
Revised Date: 2 January 2025
Accepted Date: 13 June 2025

Please cite this article as: P. Punetha, S. Nimbalkar, Utilisation of construction and demolition waste and recycled glass for sustainable flexible pavements: A critical review, *Transportation Geotechnics* (2025), doi: https://doi.org/10.1016/j.trgeo.2025.101612

Utilisation of construction and demolition waste and recycled glass for sustainable flexible pavements: A critical review

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

- A critical analysis of the use of recycled aggregates for sustainable construction
- Comprehensive evaluation of physical and mechanical properties of recycled material
- Determination of resilient modulus and permanent deformation of recycled aggregates
- Promotion of broader adoption of aggregates derived from C&D waste and waste glass

Abstract

The heightened pressure on natural resources, coupled with unprecedented levels of waste and pollution, has created an urgent need for sustainable construction practices in the road industry. To this end, the use of recycled aggregates in pavement construction has gained significant attention due to their environmental, economic, and social benefits. However, despite their immense potential, the application of recycled materials in flexible pavements remains limited due to concerns over their long-term performance, variability in properties, environmental impacts and inconsistent specifications. This article provides a critical analysis of the current state of knowledge on the use of recycled aggregates, particularly recycled concrete aggregate (RCA), recycled crushed brick (RCB) and recycled crushed glass (RCG), for sustainable flexible pavement construction. By examining key laboratory and field investigations, this study evaluates the physical and mechanical characteristics of recycled materials and their blends and assess their suitability for use in pavements. While previous studies have demonstrated that recycled aggregates can be effectively used in pavements, their performance is influenced by factors, such as source, composition, gradation, age, degree of compaction, moisture content, and loading conditions. This study also assesses the suitability of predictive models in evaluating the resilient modulus and cumulative permanent deformation of recycled aggregates and their blends under cyclic loading, which could be used in the design of flexible pavements incorporating these materials. The main objective of this review is to promote wider adoption of aggregates derived from construction and demolition waste, as well as waste glass, in flexible pavements.

Keywords: Flexible pavement; recycled concrete aggregate; recycled crushed brick; recycled crushed glass; resilient modulus; permanent deformation

1 Introduction

1.1 Background

A rapid increase in construction activities worldwide has led to the generation of a substantial amount of construction waste. The construction sector alone is responsible for almost half of the consumption of natural resources and about half of the total solid waste generated worldwide [1]. A construction activity impacts the environment at all steps, commencing from the raw material extraction to its processing, manufacturing, and transportation, followed by the construction of the structure, and finally, its demolition. The traditional approach to handling the waste was to dispose it of in landfills, which may lead to severe environmental consequences. Climate change, resource depletion, and biodiversity loss are some of the consequences of human interference with the environment, especially construction activities.

The construction and demolition (C&D) industry is among the largest producers of waste in several countries, including Australia [2], China [3], the United States [4], and those in the European Union [5]. Over the years, C&D waste management has become a critical global issue with significant implications for sustainability and environmental conservation. Many countries are facing challenges in managing the vast quantities of C&D waste generated by rapidly expanding urbanisation and infrastructure development. For instance, in Australia, about 29 million tonnes of C&D waste was generated in 2021, with approximately 22% of this amount being disposed of in landfills [2]. There has been a 73% increase in overall C&D waste generation in Australia since 2007. Although the quantity of waste being disposed has remained relatively constant [2], the accumulation of waste in landfills continues to pose environmental threats. Therefore, further advancements in recycling and waste diversion practices are essential to avoid the need to develop additional landfill facilities that could significantly affect biodiversity and the environment.

C&D waste is a generic term for a diverse range of materials that can end up as high-value materials and resources for new construction after segregation. It is the waste produced by C&D activities, including road and rail construction, maintenance and excavation of land associated with construction activities, conservation, retrofitting and rehabilitation of structures. During construction, waste is primarily generated due to excess material orders, mishandling by unskilled workers and improper material storage, among others. On the other hand, demolition waste is generated when structures reach the end of their life span or are damaged due to natural disasters. The typical C&D waste materials include concrete, bricks, steel, timber, plastics, reclaimed asphalt, cardboard, and smaller quantities of other building materials. In Australia, for instance, 81.6% of the total C&D waste comprises reclaimed asphalt, bricks, concrete, pavers, ceramics, tiles, pottery, plasterboard, cement sheeting, rubber, and soil [2]. In addition, metals and organics contribute to 5.4% and 3% of the total C&D waste generated, respectively.

Alongside a significant amount of waste produced, the construction industry consumes a tremendous quantity of natural resources, including virgin quarried aggregates and fuel. For instance, the average consumption of aggregates in Australia is approximately 7 tonnes per person per annum [6]. While in the United States, over two billion tonnes of natural aggregates are being quarried annually [7]. To preserve the environment, it is inevitable to reduce the exploitation of non-renewable natural resources in the construction industry. The use of recycled materials can reduce the need to quarry more natural aggregates while minimising the amount of waste that is being disposed of in landfills. In addition, it would reduce the need to develop additional landfills in the future, consequently protecting our valuable landscape and environment. Thus, it is essential to promote studies and applications that focus on using recycled materials.

Using recycled materials processed from the C&D waste in road construction and maintenance offers a sustainable and economical alternative to conventional quarry materials. It has been estimated that approximately 8,000 tonnes of C&D waste can be diverted away from the landfill for every kilometre of road constructed using recycled aggregates [8]. The practice of recycling aggregates from C&D waste dates back to ancient civilisations, including the Egyptians, Greeks and Romans [9]. The aggregates derived from the buildings destroyed during the Second World War were used in the post-war reconstruction of infrastructure in Europe [10]. From the 1970s onwards, countries like the United States and the Netherlands began incorporating waste materials, particularly old concrete and masonry, into the base or subbase layers of pavements [11]. In 1971, recycled aggregates were utilised in pavement construction projects in Texas and California [12, 13]. In late 1970s, crushed concrete was used to construct the subbase layer in the Eden's expressway reconstruction project in Chicago [14]. By 1985, several countries including the United States, Japan, the Netherlands, the United Kingdom, and Russia had introduced standards, guidelines or recommendations for using C&D waste and other recycled materials in road construction [15]. Since then, global research into the application of recycled C&D waste in pavements has significantly intensified, leading to further advancements in sustainable construction practices.

In Australia, the use of recycled C&D waste in pavements started around 1986 after a demolition contractor in Victoria began crushing demolished concrete to overcome disposal costs at landfills. By 1989, RCA was being tested for suitability as subbase course materials, and in 1992, VicRoads introduced the standard specification 820 'Crushed concrete for pavement subbase' [16]. By 1996, about 520,000 tonnes of RCA had been utilised in Melbourne, with 39% employed in the subbase layers for deep-strength asphalt pavements [16]. Subsequently, recycling efforts expanded, with Sydney and Melbourne recycling approximately 400,000 and 350,000 tonnes of concrete annually by 2001 [17]. Since 2009, the experimental research at universities further advanced the understanding of the suitability of recycled C&D waste for pavement applications [18-20]. By 2011, 55% of Australia's C&D waste was being recycled, with recycling rates exceeding 75% in some states [6]. Recent developments include a technical note from the Queensland Department of Transport and Main Roads (DTMR) in 2020 [21] and a report from the Australian Road Research Board in 2022 [8], both providing guidance on the use of recycled aggregates in road construction. Additionally, in 2023, Standards Australia launched an initiative to harmonise and improve performance-based standards for recycled materials [22].

In addition to C&D waste, the waste glass can be crushed into cullets and used as a partial replacement for the unbound granular aggregates in pavement construction [23]. This practice is crucial for reducing the amount of waste glass being disposed of in landfills. In Australia alone, 1.5 million tonnes of waste glass was produced in 2021, with approximately 41% ending up in landfills [2]. As the annual generation of waste glass continues to rise, increasing the recycling rate is necessary to avoid the need to construct new landfills.

Despite the growing adoption of recycled materials in road construction, the amount of material being used remains relatively low compared to the large quantities of waste generated. Several factors contribute to the lower utilisation of waste compared to the volume of waste produced. One key challenge is the limited knowledge of the engineering characteristics of aggregates derived from waste, which raises concerns about their long-term performance and durability. Additionally, there is a lack of evidence demonstrating the long-term environmental and performance outcomes of these materials. The variability in the properties of recycled materials also contributes to uncertainty in their application. Environmental concerns, such as the potential for heavy metal contamination in water sources and the corrosive effects of high-pH leachate on underlying metal drainage pipes, further complicate the widespread adoption of recycled aggregates in construction projects.

Consequently, several researchers have attempted to understand the mechanical behaviour of recycled aggregates and assess their suitability for usage in pavements through laboratory and field investigations. This article provides a comprehensive analysis of the current knowledge on the use of recycled aggregates for sustainable flexible pavement construction. Particularly, the physical and mechanical properties of three types of recycled aggregates – recycled concrete aggregates (RCA), recycled crushed brick (RCB) and recycled crushed glass (RCG), are critically examined for application in the construction of flexible pavement layers.

The particle-level properties of recycled aggregates (RCA, RCB, RCG) are first examined, followed by an analysis of their particle assembly properties, with a particular emphasis on pavement applications. Subsequently, the geotechnical properties of blends involving these aggregates and other materials are explored. The long-term performance of these recycled aggregates is then addressed, and the suitability of predictive models for evaluating the resilient modulus and permanent deformation of these aggregates and their blends under cyclic loading is assessed. The values of empirical parameters for different recycled materials and their blends are also determined using the literature data, which could be used by practising engineers for analysis and design of flexible pavements constructed using these materials. Subsequently, field investigations on the application of recycled aggregates in the pavements are reviewed. Finally, the benefits and challenges of using recycled aggregates are discussed along with some strategies that can be adopted by practitioners to overcome the practical obstacles related to the use of recycled materials, such as concerns about long-term durability, environmental impacts, and variability in material properties.

1.2 Significance of review

This review is intended to serve as a guide for researchers, practising engineers and policymakers exploring the use of recycled aggregates, particularly RCA, RCB and RCG, in pavement applications. By critically analysing the micro-scale (i.e., focusing on the structure and arrangement of individual soil particles) and macro-scale (i.e., focusing on the soil sample as a whole) properties of recycled aggregates, along with their geotechnical performance (including short-term and long-term) characteristics, it aims to enhance the understanding of these recycled materials and their potential to improve the sustainability of flexible pavements. Additionally, the assessment of predictive models for evaluating the behaviour of recycled aggregates under cyclic loading would help in the analysis and design of flexible pavement incorporating these materials. By providing a thorough evaluation of laboratory and field investigations (ensuring a balanced focus on each), this review supports the development of more sustainable construction practices and contributes to the global effort to increase recycling and waste diversion in the road construction industry. In addition, this review provides a unique combination of laboratory studies, field performance data, and the evaluation of predictive models, which has not been covered together in previous review articles.

This review also makes an effort to integrate all the scattered data on RCA, RCB, and RCG into a comprehensive resource. By bringing together findings from diverse studies, it aims to assist researchers in identifying knowledge gaps, enabling them to prioritise areas requiring further investigation. For engineers, this resource serves as a practical guide for incorporating sustainable recycled materials into pavement construction by offering insights into material properties, performance, and potential applications. In addition, policymakers can leverage this unified resource to formulate evidence-based guidelines and standards that promote sustainable practices in road construction. By addressing the needs of multiple stakeholders, this review facilitates informed decision-making while also contributing to advancing the adoption of recycled materials, thereby supporting the broader goals of environmental sustainability and resource conservation.

1.3 Review methodology

This literature review employs a systematic methodology to ensure a comprehensive examination of primary research on the use of C&D waste and RCG in flexible pavements. The approach involves systematically identifying, selecting, evaluating, and synthesising high-quality evidence related to the topic.

1.3.1 Search strategy

Publications were searched across three databases, namely, Scopus, Google Scholar and Web of Science, using the following keywords: "construction and demolition waste, flexible pavement, base or subbase, recycled concrete aggregate, crushed brick, recycled glass, geotechnical properties, long-term performance, resilient modulus, permanent deformation, durability, predictive models, field investigation, and machine learning".

1.3.2 Inclusion and exclusion criteria

To maintain focus and relevance, studies explicitly addressing the use of recycled aggregates in pavements were included. The exclusion criteria used were articles published in languages other than English and those unrelated to geotechnical application of recycled aggregates. The titles and abstracts of all the records were scrutinised rigorously, resulting in an initial selection of 72 publications primarily focused on the pavement application of recycled aggregates. Additionally, 86 more publications, comprising journal articles, books, book chapters, conference papers, reports, standards, and webpages, were included, primarily based on their citation relationships with the initially retrieved records (i.e., publications that were either cited by or cited the initial selection).

To minimise subjectivity in the selection process and mitigate the risk of bias, a rigorous screening procedure was adopted to ensure that all included publications were highly relevant to the review objectives. In addition, multiple references were obtained for each topic to reduce reliance on any single source.

1.3.3 Data summarisation

The selected publications were first categorised into three groups: laboratory studies, field investigations, and studies focusing on predictive modelling. Within each category, the studies were further sorted based on the type of recycled aggregate investigated, namely RCA, RCB and RCG. Finally, the studies were classified according to the properties they examined, such as particle size distribution, Atterberg limits, maximum dry density, optimum moisture content, flakiness index, Los Angeles abrasion loss, California bearing ratio (CBR), pH, leachate migration, unconfined compressive strength (UCS), cohesion, friction angle, resilient modulus and permanent deformation accumulation. Data reported in the selected publications were extracted either directly from the text or from graphs using the Plot Digitizer software [24]. The extracted data were systematically compiled and presented for comparison and analysis.

For predictive models, the selection was guided by the prior experience of authors with models for predicting the resilient modulus and permanent deformation accumulation in granular materials [25]. In addition, several machine learning (ML) based predictive techniques were identified and evaluated for their effectiveness in predicting key parameters.

The subsequent section provides an overview of the structure of flexible pavements and the materials used for their construction. This fundamental knowledge is essential for understanding the application and performance of recycled materials in pavements.

2 Flexible pavements

The flexible pavements typically comprise multiple layers constructed using granular and bituminous materials [26]. The imposed wheel load in these pavements is transferred to the underlying granular layers through grain-to-grain contacts. **Figure 1** shows the typical structure of a flexible pavement. The topmost layer in a flexible pavement is termed the surface or wearing course. It usually comprises sprayed seal or asphalt concrete in case of sealed or paved roads. This layer must have adequate toughness to resist distortion under traffic-induced loading and provide a skid-resistant surface. It must be impermeable in order to prevent the ingress of water into the pavement layers and natural subgrade.

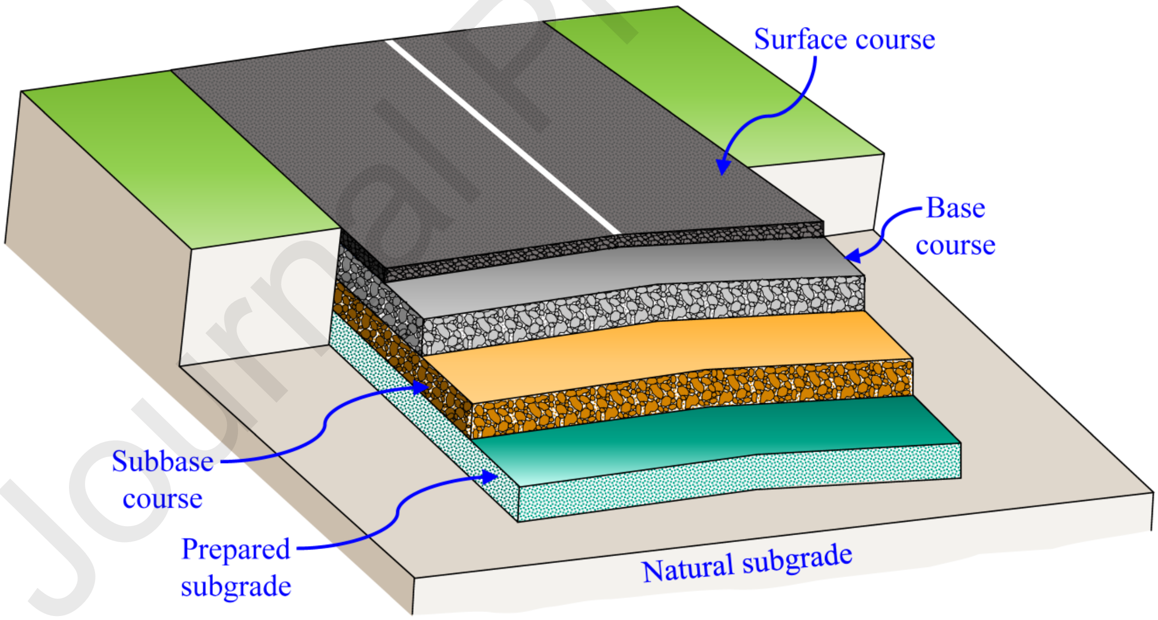

Figure 1 Typical structure of a paved flexible pavement

The base course is provided immediately below the surface course. It is typically constructed using crushed stone, slag or other untreated or stabilised materials. The primary function of this layer is to distribute the loads in such a way that the underlying subgrade does not get highly stressed or undergo significant deformation. It must have a low moisture susceptibility, adequate shrinkage, volume stability, and fatigue properties.

The subbase course underlies the base course and is typically constructed using local and lower-cost materials than that used in the base course. The reason for providing the subbase course is to achieve economy by replacing the expensive base course material for the entire layer with low-cost materials on top of the subgrade. In addition, it serves as a stable platform for the construction of overlying layers. In the case of an open-graded base course, the subbase course (with more fines) can serve as a filter between the subgrade and the base course.

The subgrade comprises a prepared and natural subgrade. It is a usual practice to scarify and compact the top 150 mm of the natural subgrade layer to serve as a prepared subgrade [26]. However, a layer of selected material can also be provided as the prepared subgrade. The natural subgrade is the naturally occurring material upon which the pavement is built.

Flexible pavements are typically classified into sealed (or paved) and unsealed (or unpaved) roads on the basis of structure. Sealed roads consist of a surface course, base course, subbase course and subgrade (compacted or prepared and natural). The surface course of the sealed road may be constructed using a sprayed seal or asphalt concrete, depending on various factors such as traffic, cost of construction, and available budget.

Unsealed roads are those in which an impermeable surface course is absent, and consequently, they are prone to distress due to adverse climatic conditions. These are constructed when the traffic volume is low and economic considerations cannot justify the use of higher-quality sealed roads [27]. Nevertheless, they form the backbone of growth for several countries. It is a common practice to provide a single base layer that acts as both the wearing and load-bearing layer over the subgrade [28]. However, a subbase course made of lower-quality (marginal) material is often provided for economic reasons and to improve the structural capacity [26, 29, 30].

A wide range of materials can be used to construct different layers of flexible pavements. The selection of the most appropriate material depends on several factors, such as structural requirements, cost, past performance, environmental impact, physical and mechanical properties [31]. Typically, each pavement layer has specific requirements. So, if the recycled materials are used to construct a pavement layer, they must satisfy the requirements for that layer. For instance, the materials to be used in the unbound base layer must have high strength, durability and resistance to permanent deformation. Therefore, to achieve these requirements, the recycled aggregates or their blends must be well graded, angular, possess rough surface texture, must be compacted to high density, have low moisture content, and contain 6% − 12% of cohesive fines [31]. In addition to these physical property requirements, different road agencies specify engineering property requirements that must be satisfied by the pavement materials.

The next section explores the particle-level and assembly-level properties of three types of recycled aggregates and their blends, providing detailed insights into their characteristics and potential applications.

3 Recycled aggregates as pavement materials

Recycled aggregate is a generic term that typically refers to granular material derived from waste. Although waste materials are being studied throughout the world, there is ample scope for understanding their chemical, physical and mechanical behaviour due to their considerable variability. In addition, the common tests used for natural aggregates may not be reliable for evaluating the behaviour of recycled materials and predicting their in-situ performance, particularly for pavement applications [32]. The properties of following three types of recycled aggregates have been critically examined in this section.

3.1 Recycled concrete aggregate (RCA)

RCAs are derived from the concrete waste produced primarily due to the construction, demolition, maintenance, and rehabilitation of concrete structures. These are conglomerates of natural aggregates with mortar and cement paste adhered to them. These aggregates have been commonly used to replace the natural aggregates partially or completely in the different layers of pavements (primarily base and subbase course in sealed roads). These aggregates typically pass nearly all the standard requirements (except soundness) associated with their usage as base and subbase materials. They have also demonstrated similar or superior performance than their natural counterparts [31]. The use of RCA is attractive from the environmental perspective as the production of RCAs can lead to about 65% less greenhouse gas emissions than generating similar virgin aggregates [6].

3.2 Recycled crushed brick (RCB)

RCB is typically derived from the demolition of buildings and other masonry structures. It generally comprises 40−70% brick and 30−60% of materials like mortar, rock, asphalt, and organics, depending on the material source [19, 33]. It can potentially replace natural aggregates for pavement construction and promote sustainability. However, the use of RCB as a pavement material is limited in comparison to RCA due to a lack of specifications or performance-based guidelines or limited knowledge about its behaviour [33]. A few researchers have recommended blending RCB with other aggregates (natural or recycled) to improve its performance in pavement subbase applications [33].

3.3 Recycled crushed glass (RCG)

RCG is a mixture of different coloured glass pieces collected from municipal and industrial waste streams, and it often contains impurities such as organic matter, plastic and metal caps, ceramics (coffee mugs, pottery), paper, and soil [34]. The glass pieces are crushed in a recycling facility to form RCG, which comprises mixed-coloured glass particles that are angular in shape, with a notable percentage of flat and elongated particles. The physical and engineering properties of RCG depend on the waste source (municipal or industrial) and crushing procedure.

Typical applications of RCG include concrete production, asphalt layers, filters, drainage blankets, pavements, backfill for trenches, retaining walls, and buried pipes. It has been used in the construction industry as an embankment fill and drainage since the 1970s, and several specifications have been developed regarding its use [22]. The geotechnical properties of RCG are similar to that of natural sand [35]. However, there are a few issues regarding the quality of glass, which is affected by contaminants. In addition, it is often argued that the potential pollutants present in RCG may spread when it is used in pavements [34].

The subsequent section discusses the properties of RCA, RCB and RCG. The desired properties of these materials depend on the primary function of the pavement layer where they will be incorporated.

3.4 Particle level properties

3.4.1 Gradation

RCA generally comprises sand and gravel-sized fractions [36]; however, their gradation depends on numerous factors, such as the source of concrete waste and the type of crusher used for its manufacture [11]. For instance, the size of RCA derived from structural concrete is different from that of the concrete used to construct a footpath. RCA and its blends must satisfy the grading requirements in order to be used in the base and/or subbase layers of the pavements. **Figure 2** shows the particle size distribution curves of RCA used in past laboratory studies [17, 20, 36-45]. The gradation limits for unbound base and subbase materials, according to current industry practice [46], are also provided in the figure to check their compliance. It is apparent that most of the curves are well-graded and satisfy the limits specified for base or subbase layers [46]. The RCA particles comprise sand and gravel fractions as per the Australian Standard [47], and the average values of d_{10}, d_{30}, d_{50} and d_{60} are 0.25, 1.5, 4.77, and 7.03 mm, respectively. The finer fraction (passing 75 µm sieve) varies between 1.5 to 8%. In addition, the clay content in RCA is usually minimal, which may affect their workability as particle cohesion and a tightly prepared surface are greatly desired in the field [36].

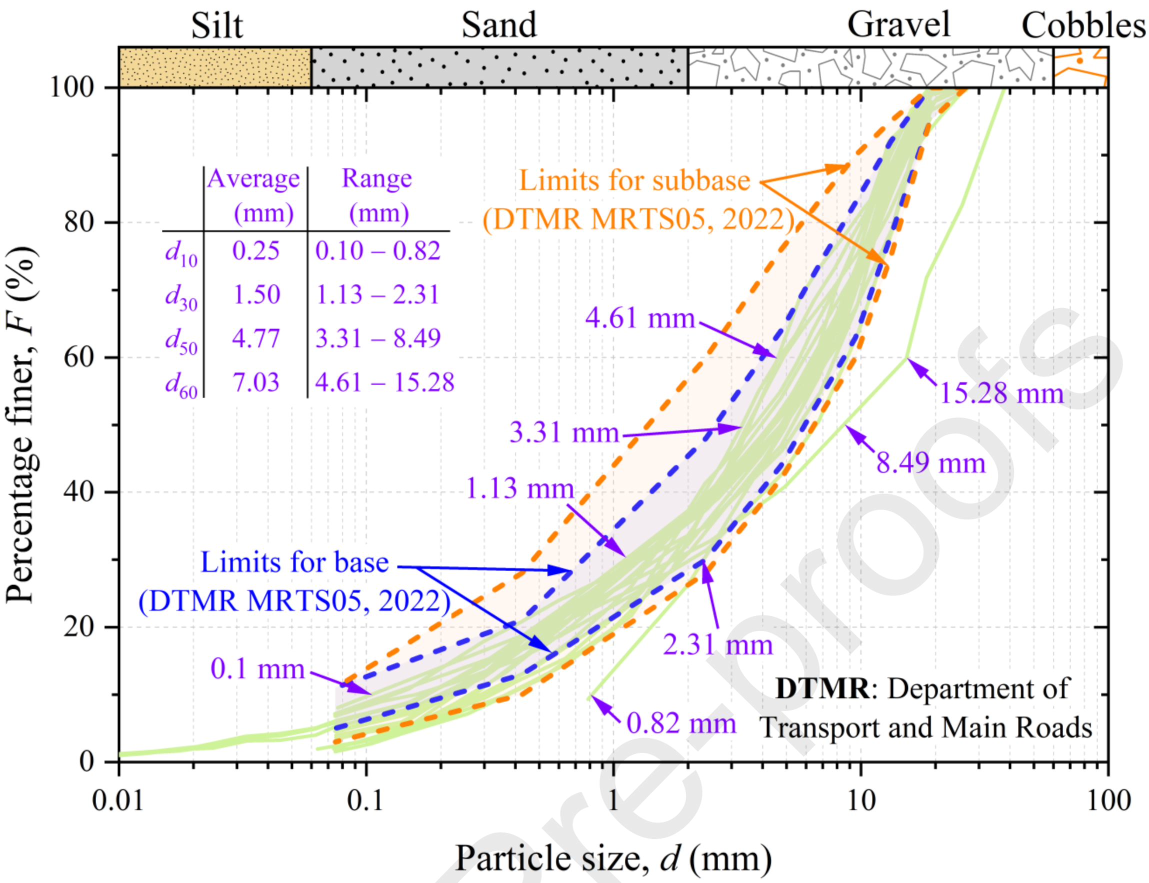

Figure 2 Particle size distribution curves of RCA used in previous studies

RCB typically consists of irregularly shaped particles with particle size ranging from fine dust to large particles. It is typically classified as well-graded gravel with a small amount of fines [36], but its particle size distribution depends on factors such as the crushing process used, source, and the brick manufacturing process, among others. **Figure 3** shows the particle size distribution curves of RCB reported in past studies [36, 38, 48]. The gradation limits for unbound base and subbase materials, according to current industry practice [46], are also provided in the figure to check if the gradation lie within the limits. It is apparent from the figure that all the curves satisfy the limits specified for base or subbase materials. RCB particles comprise sand and gravel fractions as per the Australian Standard [47], and the average values of d_{10}, d_{30}, d_{50} and d_{60} are 0.17, 1.48, 4.93, and 7.18 mm, respectively. The finer fraction (passing 75 µm sieve) varies between 3 to 8%, which is similar to the RCA.

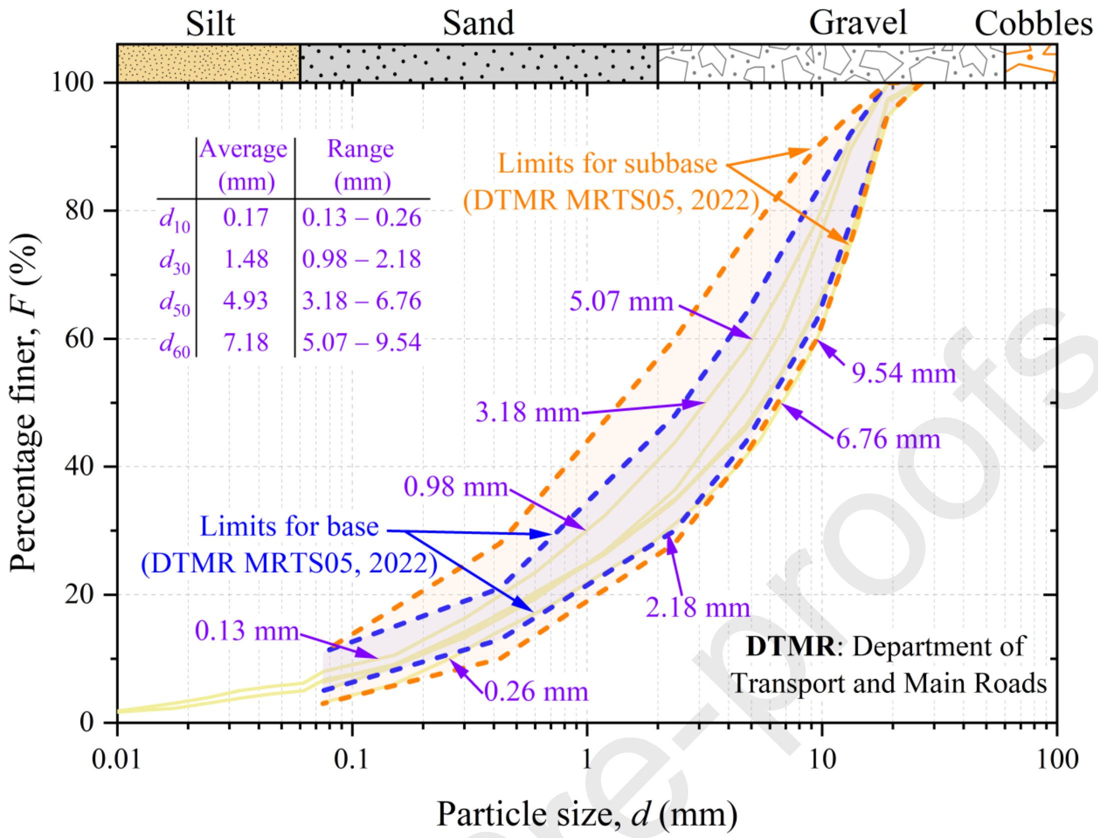

Figure 3 Particle size distribution curves for RCB

RCG is typically classified as a well-graded sand with a small amount of silt-sized particles [34, 40]. **Figure 4** shows the particle size distribution curves of RCG reported in past studies [34, 36, 40, 49-52]. The gradation limits for unbound base and subbase materials according to current industry practice [46] are also provided in the figure to investigate their compliance with the standards. It is apparent that the curves did not satisfy the limits specified for base and subbase materials, therefore RCG alone cannot be used to construct the base or subbase layer and must be blended with other materials. The RCG particles comprise sand and gravel fractions as per the Australian Standard [47] and the average values of d_{10}, d_{30}, d_{50} and d_{60} are 0.66, 1.82, 3.07, and 3.67 mm, respectively. The finer fraction (passing 75 µm sieve) is less than 5%.

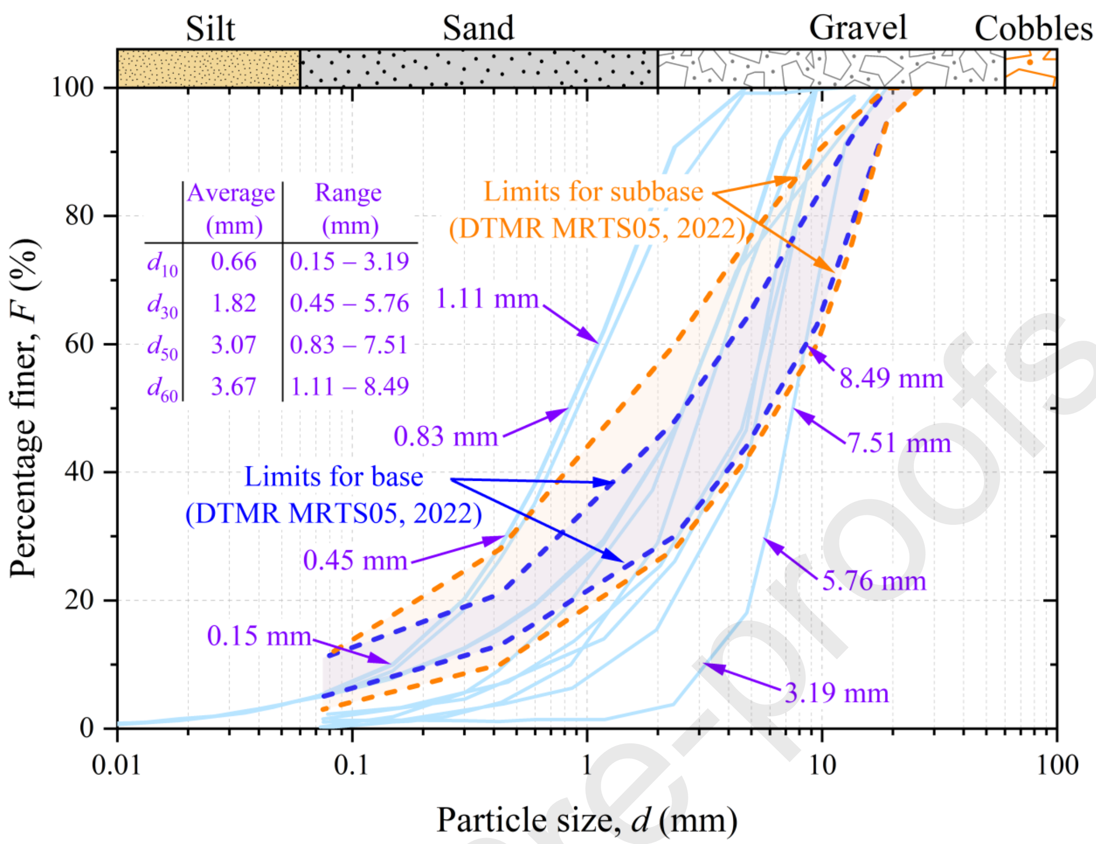

Figure 4 Particle size distribution curves for RCG

3.4.2 Particle shape and texture

The particle shape is a key parameter that influences the properties of granular materials, such as packing ability, shear strength and stiffness [53]. Rounded aggregates undergo more compaction under a given compactive effort as compared to angular aggregates. The shape of RCA depends on the type of crusher used, the number of crushing stages, the shape of aggregates in the original concrete and the amount of adhered mortar. Typically, RCAs have an irregular shape, which is mostly rounded due to the presence of adhered mortar [54]. It may also comprise elongated and flaky particles; however, the percentage of such particles in most of the studies is relatively low, which is evident from the low values of the flakiness index (see **Table A.1**).

The particle texture refers to the small-scale features on the particle surface which affect the shear strength and contact behaviour of the granular material with different interfaces [55]. It represents the local roughness features, such as surface smoothness, the roundness of edges and corners, and the amount of surface irregularities. RCAs typically have a rough surface texture, but it depends on the texture of the original aggregates, the crushing process and the amount of adhered mortar [54, 56].

The shape of RCB depends on the type of crusher used, number of crushing stages and the amount of mortar attached to the bricks. Typically, RCB have an irregular shape which is angular [57]. They also comprise elongated and flaky particles. Their flakiness index value varies in the range of 14% – 25.9% (see **Table A.2**), which is much higher than that for RCA (see **Table A.1**). RCB typically have a rough surface texture, but it also depends on the crushing process and the amount of adhered mortar.

The RCG is produced by crushing and processing waste glass, therefore, its shape is expected to be angular. However, due to the brittleness of RCG, the sharp edges may break, causing the shape to change from angular to subrounded [23]. In addition, the shape also depends on the size of the particles, for instance, coarse RCG typically comprises flaky and elongated particles [23].

RCG is a non-cohesive and unbound substance, and smooth surfaces of RCG aggregates avoid forming strong bonds with other aggregates, such as RCB and RCA. According to the Austroads guideline [58], the RCG particles must be cubic in shape and free from sharp edges and elongated particles to be used for pavement application.

3.4.3 Adhered mortar and cement paste

Since RCA is derived from concrete, a certain amount of mortar from the original concrete remains attached to the natural aggregate particles. The volume percent of the mortar attached to the natural aggregate particles depends on the size fraction and typically increases with decreasing particle size. For instance, Hansen and Narud [59] found that the volume percentage of mortar is between 25% − 35% for 16−32 mm, 39% for 8−16 mm and 58% − 64% for 4−8 mm RCAs. The presence of attached mortar is the primary reason for its high-water absorption capacity, which is attributed to the porous nature of mortar, which allows absorption of more water. The density and specific gravity of the attached mortar are also low and account for the low specific gravity and bulk density of RCA. In addition, the bond between this attached mortar and the natural aggregate is weak, which is further weakened by the crushing process, that generates cracks and fissures in the mortar [60]. It is often argued that RCA exhibits progressively poor performance with an increase in the adhered mortar content [56].

Since RCBs are derived from the masonry, a certain amount of mortar may be attached to the crushed brick particles. The amount of mortar attached to the particles depends on its type and size fraction of crushed brick. For instance, the lime mortar can be easily removed from the bricks during crushing, whereas the cement mortar is difficult to remove [61]. The presence of adhered mortar increases the water absorption capacity of RCB due to its porous nature. The density and specific gravity of the adhered mortar are also low and account for the low specific gravity and bulk density of RCB.

Unlike RCA and RCB, RCG particles typically lack any adhered mortar or cement paste.

3.4.4 Specific gravity, porosity and moisture absorption

The specific gravity of the aggregates is the ratio of their unit weight to the unit weight of water. The specific gravity of RCA typically varies between 2.45 to 2.7 [40, 62, 63], which is slightly smaller than that of the natural aggregates (which typically vary in the range of 2.6 to 2.83 [64]). The porosity of an aggregate is the ratio of the volume of voids to its total volume. It significantly affects the strength and durability of the particle assembly. For instance, higher porosity can lead to (a) weaker aggregates, causing a reduction in the shear strength of the assembly, and (b) more water absorption, rendering the assembly vulnerable to freeze-thaw damage. The porosity and water absorption of the RCA are much higher than the natural aggregates [65]. This is primarily due to the presence of the mortar adhered to the natural aggregates in the case of RCA [66]. Previous investigations have revealed that the water absorption of RCA varies in the range of 1.4% to 13.6% [20, 36, 37, 45, 67-69]. Interestingly, the water absorption is directly proportional to the amount of adhered mortar, i.e., water absorption increases with an increase in mortar content [66].

The specific gravity of RCB typically varies in the range of 2 to 2.67 [36, 62], which is lower than that of the natural aggregates. They typically have a higher porosity than natural aggregates [70]; however, the degree of porosity depends on the type of raw material used to manufacture the original brick and the manufacturing conditions, such as temperature [71]. Previous investigations have revealed that the water absorption of the RCB is in the range of 6.15% to 30.9% [33, 68, 70], which is much higher than the natural aggregates and RCA. This is primarily due to the inherent porous structure of the bricks and the presence of the adhered mortar [68]. This high water-absorption capacity may significantly affect its mechanical performance and require more water during the compaction. In fact, Poon and Chan [68] reported about 28% reduction in the strength of RCB after soaking in water.

The specific gravity of RCG typically ranges between 1.96 to 2.54 [34, 40, 64], which is lower than that of most natural aggregates. A large variation in the values may be attributed to the presence of impurities in RCG and variation in the source. This lower specific gravity results in smaller values of maximum dry density (MDD) than natural aggregates. Crushed glass particles have a negligible porosity, which leads to negligible water absorption [72]. However, the impurities present in RCG, such as paper, could lead to some absorption of moisture [23].

3.4.5 Chemical properties

RCA is alkaline in nature, with a pH value ranging between 8.6 and 13.1, depending on the source and storage time or age. RCA may also have small amounts of heavy metals due to: (a) the use of products, such as fly ash and slag, during the production of concrete [73]; (b) contact with the chemicals during the service life. Chemical analyses performed by several researchers have revealed that the major elements in RCA include aluminium, calcium, iron, magnesium, oxygen, potassium, and sodium [74-76]. It also contains other elements such as arsenic, antimony, barium, cadmium, chromium, cobalt, copper, lead, molybdenum, nickel, selenium, strontium, vanadium, and zinc, albeit in trace quantity [74, 75]. As RCA is a recycled product, some environmental concerns arise from using RCA in the base or subbase courses of the pavements, such as the effect of high pH RCA leachate on groundwater and buried metal pipes.

Crushed bricks made up of clay typically comprise silica, alumina, iron oxide and lime [77]. RCB is alkaline, with a pH value ranging between 9.1 and 10.9, depending on the source. It has a higher water-soluble sulphate content as compared to RCA or natural aggregates. Chemical analyses performed by several researchers have revealed that the major elements in RCB include aluminium, calcium, iron, oxygen, silicon, and sulphur while it also contains trace amounts of elements such as arsenic, barium, chromium, copper, lead, mercury, molybdenum, nickel, selenium, vanadium, and zinc [78, 79].

RCG is alkaline in nature, with a pH typically ranging between 9.6 and 10.1 [34, 35]. This alkalinity may arise due to the leaching of the sodium component of soda lime RCG. Chemical analyses performed by several researchers have revealed that the major elements in RCG include calcium, oxygen, silicon, and sodium, with small amounts of aluminium, chlorine, iron, manganese, magnesium, potassium, titanium, and sulphur [80-83]. It also contains other elements such as aromatic hydrocarbons, arsenic, barium, beryllium, cadmium, chromium, copper, cyanide, lead, mercury, nickel, selenium, silver, and zinc, albeit in trace quantities [34, 84].

3.4.6 Particle crushability

Particle breakage occurs when the stresses imposed on the aggregate particles exceed their strength [85]. It influences the properties of the aggregate assembly, such as shear strength, stress-strain behaviour, compressibility, and hydraulic conductivity or permeability [85, 86]. It depends on several factors, such as the stress level, mineral hardness, particle size, shape and coordination number [85, 87, 88]. Although a significant amount of data related to particle crushability in natural aggregates is available, the data related to RCA is minimal. Some studies have revealed that RCA exhibits a lower crushing strength than natural aggregates [89], which is also responsible for a limited replacement of these aggregates in pavements [90]. Due to low crushing strength, RCA is more susceptible to breakage than natural aggregates. In addition, the magnitude of particle breakage in RCA increases with an increase in angularity and flakiness index [77].

The abrasion value of aggregates is the percentage loss in weight due to abrasion. Los Angeles abrasion (LAA) and Micro-Deval tests are commonly employed to assess the abrasion values of aggregates. A high abrasion value indicates low resistance to abrasion and vice versa. Typically, the materials with low abrasion values are used in the upper pavement layers. It can be observed from **Table A.1** that the LAA loss for RCA typically varies between 21% and

43.6%, with an average value of about 31.7%. This is similar to a typical quarry material, which shows LAA loss of less than 40% [36].

A limited amount of data related to particle crushability in the RCB is available. Some studies suggest that RCB exhibits a lower crushing strength than natural aggregates and RCA [91]. Therefore, it is more susceptible to breakage than the natural aggregates and RCA. It can be observed from **Table A.2** that the LAA loss for RCB typically varies between 35.5% and 49.6%, with an average value of about 40.4%. This value is higher than that for a typical quarry material and RCA [36]. This indicates that RCB has a relatively lower resistance to abrasion than the natural aggregates and RCA.

It has been found that angular RCG experiences more particle crushing than similar less angular materials such as glass beads [92]. In addition, the LAA values for RCG varies in the range of 24% to 42% (see **Table A.3**). These values are affected by the factors such as particle size. Fine and medium-sized RCG typically have LAA values (24.5% − 25.4%) similar to that of crushed rock (24%) and lower than that of RCA (31.7%) [34, 64], whereas the coarse RCG exhibits a higher LAA value of 27.7%.

3.5 Particle assembly properties

3.5.1 Secondary cementation

RCA may contain a small amount of residual unhydrated cement, which reacts with moisture and causes cementation (or secondary cementation or re-cementation). Although there can be strength gain due to cementation, it can be accompanied by a loss of hydraulic conductivity and shrinkage, which might cause reflective cracking in the wearing course of sealed roads. It has been found that the shrinkage strain in RCA increases rapidly during the first seven days, after which the strain increases at a reduced rate till shrinkage stops [20]. Nevertheless, it is often argued that the shrinkage due to secondary cementation would be very slow due to a slow rate of hydration since residual cement is expected to reach the final stage a long time ago [93]. In addition, RCA can be used either in the road subbase or blended with RCG to limit this reflective cracking [8].

3.5.2 Maximum dry density and optimum moisture content

The MDD and optimum moisture content (OMC) are among the most important properties of aggregates for pavement applications. The achievement of MDD and OMC plays an important role in the performance of a pavement layer. During the construction of a pavement, the MDD is employed to specify the target density for the material in a particular layer, while the OMC serves as a guideline to control the moisture content. **Table A.1** shows the mean value, standard deviation and typical range of OMC and MDD for RCA reported in previous studies. RCA has a higher OMC and lower MDD than typical quarried aggregate [68]. The higher OMC is due to the absorption of water by the aggregates owing to their porous nature due to the presence of adhered mortar paste. Therefore, the replacement of natural aggregates with RCA typically increases the OMC of the mix. However, it was found that the energy and effort required to compact RCA is similar to that for crushed aggregate and gravel [45]. **Figure 5** illustrates the values of MDD and OMC for RCA reported in the past studies. It also shows the range for a typical quarry material [36] for comparison. It is apparent from the figure that the MDD and OMC for RCA lie within the range for a typical quarry material. Similarly, **Figure 5** also shows that the MDD and OMC for RCB also lie within the typical range for quarry materials.

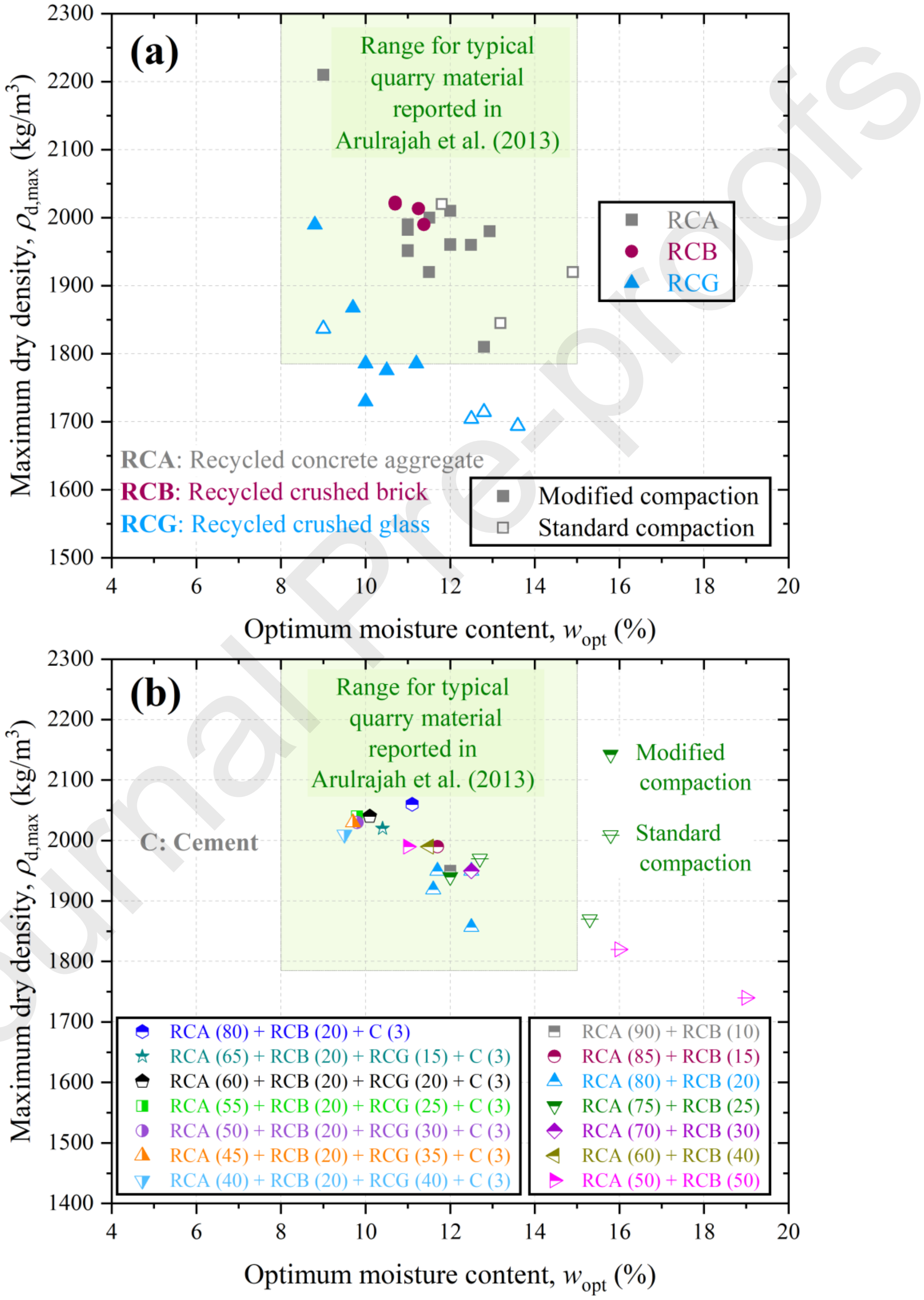

Figure 5 OMC and MDD values reported in past studies for **(a)** RCA, RCB and RCG; **(b)** their blends with other materials

The MDD of RCG varies between 1451 kg/m^3 and 1990 kg/m^3, while the OMC varies in the range of 8% to 13.6% (see **Table A.3**). The moisture-density curves of RCG are relatively flat due to its insensitivity to moisture content. Interestingly, both OMC and MDD of RCG are less sensitive to changes in compaction effort [23]. **Figure 5** illustrates the values of MDD and OMC for RCG reported in previous studies. It is apparent from the figure that the MDD and OMC for RCG in most of the studies lie beyond the range for a typical quarry material. Therefore, RCG alone may be inappropriate for usage in the base and subbase layers of the flexible pavements.

3.5.3 California bearing ratio (CBR)

The California bearing ratio (CBR) is the ratio (expressed in percentage) of the load required to cause a specific penetration in any material with a standard circular plunger to that required for corresponding penetration in a standard crushed rock. Although it is an empirical value, it has been widely used to characterise materials owing to its simplicity. **Table A.1** lists the mean, standard deviation and range of CBR values for RCA reported in the past studies. The CBR value of RCA typically varies between 74.2% to 184% depending on various parameters such as testing condition (soaked or unsoaked), compactive effort (standard or modified), material source, and age. **Figure 6** shows the CBR values for RCA and RCB reported in past studies and the range for typical quarry materials [36]. It can be seen from **Figure 6** that the CBR values for RCA and RCB are generally within the range for typical quarry materials (except for the RCA used in [40]). Although the CBR values of RCB are within the range reported for RCA (see **Table A.1**), the variation is smaller, with values typically ranging from 123% to 138%. This small variation is due to a limited number of studies investigating the geotechnical properties of RCB.

Previous studies have reported the CBR values for RCG to lie in the range of 18% – 76%, depending on factors such as the size range and compactive effort (see **Table A.3**). These values are lower than those for RCA and natural aggregates. The CBR values of RCG specimens prepared using the modified compaction are typically much higher than those prepared using the standard compaction [35]. Additionally, the CBR values of medium-sized RCG are much higher than those of fine-sized RCG [35]. **Figure 6** illustrates the CBR values for RCG reported in previous studies. It is apparent from the figure that the CBR values for RCG lie beyond the range for a typical quarry material that is used in the pavement layers.

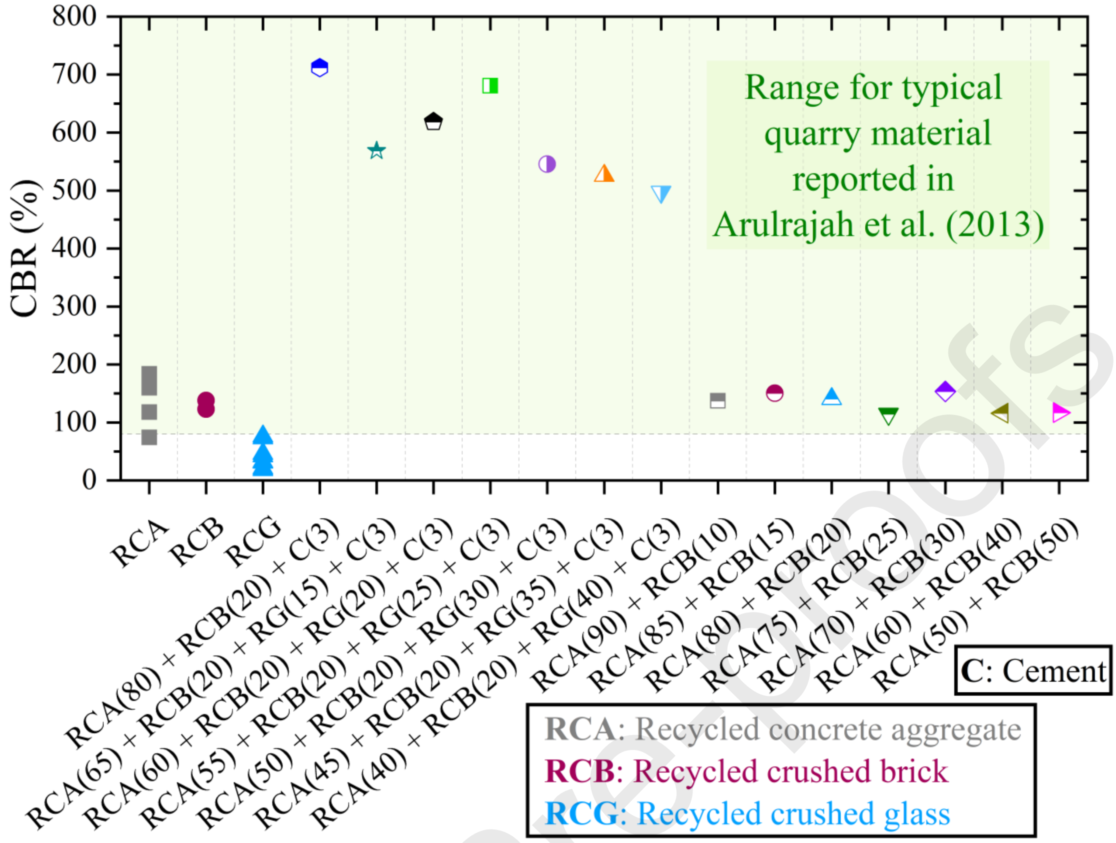

Figure 6 CBR values for recycled aggregates and their blends reported in past studies

3.5.4 Shear strength

Aggregates are the primary load-carrying medium in unbound flexible pavements. Therefore, the shear strength of an aggregate mass is one of the most important properties that governs the design of flexible pavement layers. The shear strength of a granular material is the maximum shear stress that it can withstand without undergoing failure. It is typically represented using the apparent cohesion (c) and friction angle (φ). **Table A.1** lists the mean value, standard deviation and range of c and φ values for RCA reported in past studies. It can be observed that the c values for RCA range between 44 kPa and 169.7 kPa, and the friction angle varies between 41.5° and 57°. **Figure 7** shows the c and φ values for RCA reported in past studies and the range for typical quarry materials [36]. It is apparent from **Figure 7** that the c and φ values for RCA are within the range for typical quarry materials. However, a large variability in the c and φ values reported in the previous studies can be observed. This can be attributed to factors such as difference in the sources, foreign material content, crushing techniques, and testing conditions. It can also be seen from **Figure 7** that the c and φ values for RCB fall within the range for typical quarry materials.

RCG exhibits a φ value in the range of 37° to 48°, depending on parameters such as gradation, angularity, density, test conditions and confining pressure [23, 72]. Similar to cohesionless soil, the friction angle of RCG typically decreases with an increase in confining pressure [35, 84]. **Figure 7** shows the c and φ values for RCG reported in previous studies. It is apparent from the figure that c values for RCG lie beyond the range for a typical quarry material, while its φ values are within the typical range.

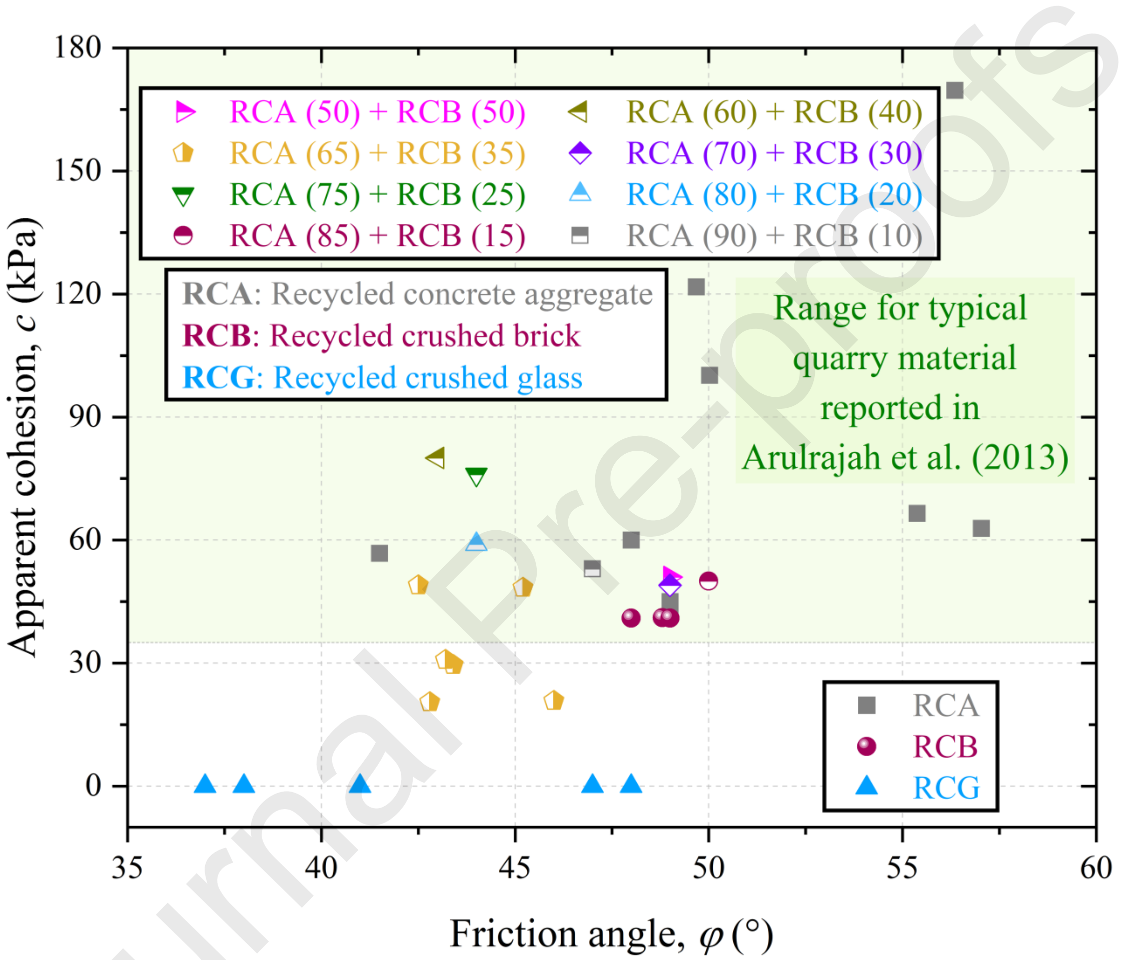

Figure 7 Friction angle and apparent cohesion values for recycled aggregates and their blends reported in past studies

3.5.5 Unconfined compressive strength (UCS)

Unconfined compressive strength is the maximum axial stress that a geomaterial specimen can sustain under zero confining pressure. It is determined using the UCS test, which is considered a special case of triaxial compression test in which $\sigma_2 = \sigma_3 = 0$, where σ_2 and σ_3 are intermediate and minor principal stresses, respectively. **Table A.1** lists the mean value, standard deviation and range of UCS values for RCA reported in the past studies. It can be observed that the UCS value of RCA typically varies in the range of 0.44 MPa to 0.88 MPa, with a mean value of 0.62 MPa. This variation is due to various factors, such as material source, age, gradation, and secondary cementation, among others. In fact, secondary cementation increases the UCS of RCA with time or curing period [20].

3.6 Factors affecting the properties of recycled concrete aggregates

Since RCA is derived from waste, several factors affect its performance. The source is one of the most important factors that influences the properties of RCA, including density, water absorption, pH, stiffness, strength, rehydration ability, and resistance to permanent deformation [20, 37, 94-96]. RCAs derived from high-strength concrete with lower water-cement ratios will exhibit greater density and lower water absorption as compared to those obtained from low-strength concrete, owing to the low porosity of high-strength concrete. Even the properties from the same source might vary temporally [95].

The composition of RCA also influences its performance as an unbound pavement layer. The presence of softer impurities such as wood, plastic and organic matter decreases its density, strength and resilient modulus [17]. The performance of RCA is also affected by the storage time and the amount of mortar attached to the aggregates. For instance, fresh RCA possesses strong self-cementing property, whereas the tendency for secondary cementation decreases with storage time [37]. An increase in adhered mortar content negatively affects its performance by decreasing the density, increasing the water absorption, and reducing the crushing strength [56, 97]. Recycled aggregates may be more prone to change in properties during their service life due to crushing or abrasion of the adhered mortar [56].

3.7 Summary

Thus, the findings from the previous studies demonstrate that RCAs could be used in the base and subbase course of flexible pavements. Their mechanical properties are similar (if not) superior to the natural quarry aggregates and require similar energy and effort for in-situ compaction. However, the main issue with the use of RCA is the adhered mortar, which is responsible for its high water-absorption capacity, lower MDD and higher OMC than the natural aggregates. This mortar may also get detached during the compaction or the construction of the road and modify the in-situ particle size distribution of the mix, thereby modifying the properties. Nevertheless, as RCA possesses some residual or unhydrated cement, there is a tendency for secondary cementation or re-cementation (depending on the age of the aggregate). On one hand, this cementation improves mechanical properties, while on the other hand, it might lead to reflective cracking due to shrinkage associated with the cementation. Reducing this tendency for re-cementation and subsequent crack formation requires blending with other materials such as RCG.

While the properties of RCB are comparable to typical natural aggregates used in the unbound pavement layers, it exhibits inferior properties compared to RCA, such as higher moisture absorption, lower density, and lower abrasion resistance. Consequently, some researchers recommend blending RCB with RCA for pavement subbase applications [93]. Specifically, up to 25% replacement of RCA by RCB has been suggested for subbase layers. In some European countries, about 30% and 10% of RCB blended with RCA are allowed for subbase and base applications, respectively [98].

The findings also reveal that RCG possesses the lowest moisture absorption and sensitivity compared to other recycled aggregates typically used in pavements. Its MDD, CBR, and shear strength are lower than those of typical natural aggregates. Therefore, RCG alone may be inappropriate for usage in the base and subbase layers of the pavement and must be blended with natural or other recycled aggregates.

While individual recycled aggregates such as RCA, RCB, and RCG exhibit distinct properties that influence their standalone application in pavement layers, blending these materials offers a practical approach to mitigating their limitations and enhancing performance. Blends of recycled aggregates are increasingly utilised in real-world pavement construction to achieve optimal mechanical properties while addressing specific challenges such as moisture sensitivity, compaction requirements, and abrasion resistance. The next section discusses about the recycled aggregate blends.

4 Recycled aggregate blends

The recycled aggregates discussed above can be blended together or with other materials to improve their performance or achieve the desired properties. **Table 1** highlights the typical observations from laboratory studies involving recycled aggregate blends. It can be observed from **Table 1** that the addition of bitumen to RCA decreases the water absorption of the blend since bitumen coating covers the mortar pores in RCA. However, the permanent deformation of the blend under repeated loading increases, particularly at high deviatoric stresses. Similarly, the cumulative permanent deformation increases when bitumen is added to RCB. RCA can also be treated with cement for applications as a fully bound subbase for deep-strength asphalt pavements. The addition of cement increases the resilient modulus and UCS of RCA. However, the magnitude of increment in UCS was found to be smaller than that of cement-treated natural aggregate, since natural aggregate typically has more angular particles than RCA [16].

Table 1 Influence of blending RCA and RCB with other materials

Base material	Blending material/additive	Findings	References
RCA	Bitumen	• Increment in permanent deformation accumulated under repeated loading.	[38, 99]

		• Reduction in water absorption.	
RCB	Bitumen	• Increment in cumulative permanent deformation under repeated loading.	[38]
RCA	Cement	• Increment in the resilient modulus, constrained modulus and UCS. • Reduction in the sensitivity of shear strength to confining pressure.	[16, 43, 48]
RCA	Crumb rubber	• Addition by up to 0.5% increases the apparent cohesion; however, the apparent cohesion decreases beyond this percentage.	[41]
RCA	RCG and crumb rubber	• RCA, RCA + 1% crumb rubber + 5% RCG satisfied the permanent deformation requirements to be used as pavement materials for the base and subbase. • Addition of RCG improved the permanent deformation behaviour of the blends under repeated loading.	[42]
RCA	PE plastic granule	• Reduction in CBR, UCS value, and resilient modulus. • Blends with HDPE granules showed better properties (CBR, resilient modulus, UCS) than those with LDPE granules.	[100]
RCA	RCB	• Reduction in MDD and increment in OMC. • Reduction in CBR values (both soaked and unsoaked).	[11, 19, 68, 93-95]

		• Reduction in resilient modulus and increment in permanent deformation accumulated under repeated loading. • Low clay content of the blends may affect the workability. • Up to 25% of RCA can be safely replaced by RCB for pavement subbase application.	
RCA	RCG	• Reduction in OMC, CBR and shear strength. • MDD of blends containing up to 30% RCG is smaller than RCA alone; however, beyond this content (i.e., at 40% or 50% RCG), the MDD increased. • Resilient modulus of the blend containing 10% RCG was the highest, while it decreased with a further increase in RCG content from 10% to 50%.	[40]
RCA	RCB, RCG and cement	• Triple blends that contain up to 15% RCG met the minimum requirements specified in the local road authority specifications.	[39]

Note: PE: Polyethylene; HDPE: high-density polyethylene; LDPE: Low-density polyethylene

It can also be observed from **Table 1** that the OMC increases and MDD decreases on replacing RCA with RCB. This observation is reasonable as RCB exhibits higher water absorption and lower particle density as compared to RCA. The CBR values decrease with an increase in the replacement level of RCA by RCB. In addition, Azam and Cameron [95] reported that the replacement of 20% RCA by RCB (for blends from two different sources) reduced the shrinkage strain by approximately 45% − 59%, decreased the resilient modulus by 7% − 33% and increased the permanent strain by 57% − 83% when compared with RCA alone. Nevertheless, the acceptable level of RCB in the blend (% by dry mass) is quite variable. Some European countries, such as Finland and Denmark, allow a maximum of 20% and 30% RCB blended with RCA for subbase application [98]. For base course application, a maximum of 10% RCB is allowed in Europe. South Africa allows a maximum of 20% RCB for base and subbase applications [98].

Table 1 also shows that replacing RCA with RCG results in a decrease in CBR values, OMC, and shear strength. In addition, the MDD of blends with up to 30% RCG is lower than that of pure RCA. However, at higher RCG contents, the MDD increases, likely due to improved particle packing [40]. Some researchers have also investigated the behaviour of RCA blended with RCB and RCG to limit the effects of rehydration, such as block cracking, and optimise stiffness [39].

Thus, the previous section explored the performance of recycled aggregates after blending or treatment. To ensure their suitability for pavement applications, it is critical to evaluate their behaviour under cyclic or repeated traffic loading. The subsequent section delves into this critical aspect.

5 Performance of recycled aggregates under cyclic loading

The aggregates in the pavement layers are subjected to repeated traffic loading. Therefore, for pavement applications, it is essential to understand the behaviour of recycled aggregates and their blends under repeated or cyclic loading conditions. Typically, the repeated load triaxial (or cyclic triaxial) tests are carried out to study the response of materials under repeated loading conditions. In these tests, the stresses applied to the material vary regularly in magnitude and time and the resilient modulus and accumulation of plastic deformation are of primary interest. These two properties will be discussed in the subsequent sections.

5.1 Resilient modulus of recycled aggregates

The resilient modulus (E_r) is the ratio of the cyclic deviatoric stress (q_{cyc}) to the resilient strain (ε_r) during unloading. It is an essential parameter for the design of pavements. It is usually determined by repeated load triaxial tests in which the confining pressure is kept constant, and the deviator stress is cycled. These tests are carried out at various confining stress and cyclic deviator stress combinations that are representative of the field conditions.

The resilient modulus of RCA typically varies between 118 MPa to 1667 MPa depending on the material source, the amount of foreign materials in RCA, aggregate shape, density, moisture content and stress state, among others [17, 40, 48, 101, 102]. In some cases, its resilient modulus is even higher than that of the natural quarried aggregates due to the cementation provided by unhydrated cement in crushed concrete [16, 17, 20]. Its resilient modulus also increases with a decrease in moisture content; however, the amount of increment depends on the source [20].

The resilient modulus of RCB typically varies between 108 MPa to 519 MPa depending primarily on the source of material, stress state, density, and moisture content [36, 48, 102]. It has been observed that the resilient modulus of RCB decreases with an increase in moisture content [36]. It also increases with an increase in confining stress [48], which is reasonable as the confinement increases the strength and stiffness of a geomaterial.

5.1.1 Prediction of resilient modulus

The resilient modulus of granular materials typically depends on the stress state. Several empirical models have been developed to predict this stress-dependent behaviour of granular materials, which are comprehensively discussed elsewhere [25]. For this study, the following empirical model is used, which was initially proposed by Witczak and Uzan [103] and subsequently modified in the mechanistic-empirical pavement design guide [104]:

$$E_{\mathrm{r}} = k_1 p_{\mathrm{a}} \left(\frac{\theta}{p_{\mathrm{a}}}\right)^{k_2} \left(\frac{\tau_{\mathrm{oct}}}{p_{\mathrm{a}}} + 1\right)^{k_3} \tag{1}$$

where k_1, k_2 and k_3 are empirical parameters; θ and τ_{oct} are bulk and octahedral shear stresses, respectively; p_{a} is the atmospheric pressure. **Table 2** lists the values of parameters k_1, k_2 and k_3 for recycled aggregates and their blends with other materials derived using the data reported in [17, 36, 39, 40, 48, 101, 102, 105]. To evaluate the predictive performance of the empirical model, several statistical metrics are used. These include coefficient of determination (R^2) (Equation 2), and root mean squared error (RMSE) (Equation 3).

$$R^2 = 1 - \frac{\sum_{i=1}^{i=n}\left[(E_{\mathrm{r,p}})_{\mathrm{i}} - (E_{\mathrm{r,m}})_{\mathrm{i}}\right]^2}{\sum_{i=1}^{i=n}\left[(E_{\mathrm{r,p}})_{\mathrm{i}} - \bar{E}_{\mathrm{r,m}}\right]^2} \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{i=n}\left[(E_{\mathrm{r,p}})_{\mathrm{i}} - (E_{\mathrm{r,m}})_{\mathrm{i}}\right]^2}{n}} \tag{3}$$

where $E_{\mathrm{r,p}}$ is the predicted resilient modulus; $E_{\mathrm{r,m}}$ is the measured resilient modulus; n is the number of data sets; $\bar{E}_{\mathrm{r,m}}$ is the average value of measured resilient modulus. In addition to these metrics, analysis of variance test was carried out to determine the significance of the empirical model [106].

Table 2 Values of empirical parameters for different recycled materials and their blends

Material	k_1			k_2			k_3			References
	Mean	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	
RCA	2379	1608	1197 to 5805	0.74	0.26	0.47 to 1.16	-0.37	0.3	-0.01 to -0.89	[17, 40, 48, 101, 102]

RCA + C (2)	13580	–	–	0.20	–	–	0	–	–	[48]
RCA + C (3)	1326	–	–	0.28	–	–	0	–	–	[39]
RCB	1446	305	1207 to 1789	0.47	0.12	0.39 to 0.60	0.13	0.23	-0.01 to 0.39	[36, 48, 102]
RCB + C (2)	7632	–	–	0.42	–	–	0	–	–	[48]
Blends:										
RCA (80) + RCB (20)	1067	162	971 to 1254	0.75	0.06	0.69 to 0.81	-0.17	0.09	-0.11 to -0.28	[105]
RCA (75) + RCB (25)	1454	1420	203 to 2997	1.33	1.08	0.63 to 2.58	-0.82	1.15	-0.15 to -2.14	[93]
RCA (90) + RCG (10)	1887	–	–	0.40	–	–	-0.20	–	–	[40]
RCA (80) + RCG (20)	1626	–	–	0.52	–	–	-0.30	–	–	[40]
RCA (70) + RCG (30)	1246	–	–	0.79	–	–	-0.62	–	–	[40]
RCA (60) + RCG (40)	1363	–	–	0.62	–	–	-0.33	–	–	[40]
RCA (50) + RCG (50)	1053	–	–	0.68	–	–	-0.20	–	–	[40]

RCA (65) + RCB (20) + RCG (15) + C (3)	1404	–	–	0.25	–	–	0	–	–	[39]
RCA (60) + RCB (20) + RCG (20) + C (3)	1557	–	–	0.26	–	–	0	–	–	[39]
RCA (55) + RCB (20) + RCG (25) + C (3)	1524	–	–	0.26	–	–	0	–	–	[39]
RCA (50) + RCB (20) + RCG (30) + C (3)	1447	–	–	0.27	–	–	0	–	–	[39]
RCA (45) + RCB (20) + RCG (35) + C (3)	1754	–	–	0.23	–	–	0	–	–	[39]
RCA (40) + RCB (20) + RCG (40) + C (3)	1615	–	–	0.25	–	–	0	–	–	[39]

SD: Standard deviation

Figures 8 and **9** show a comparison of the measured resilient modulus values and the values predicted using the empirical model. An equality line, representing the condition where the predicted and measured values are identical, is also shown. Datapoints located near this line indicate a good agreement between the measured and predicted values. As can be seen in the figure, the datapoints are closely clustered around the equality line, indicating that the predicted values are in good agreement with the values obtained from the laboratory investigations. In addition, no significant difference is observed in the measured and calculated resilient modulus values, indicated by *p*-values of less than 0.05 at 95% confidence interval (see **Table 3**). Thus, the values of the empirical coefficients provided in **Table 2** can be used to predict the resilient modulus of different recycled materials and their blends with reasonable accuracy. The resilient modulus predicted using Equation 1 can be subsequently employed in computational tools to predict the response of pavements constructed using recycled materials and their blends.

Table 3 Statistical metrics for evaluating the predictive performance

Material	**R^2**	**RMSE**	***p*-value**
RCA	0.92	84.2	0.000000
RCA + C (2)	0.86	71.5	0.000011
RCA + C (3)	0.80	10.0	0.000000
RCB	0.93	14.6	0.000000
RCB + C (2)	0.98	44.4	0.000000
Blends:			
RCA (80) + RCB (20)	0.96	14.4	0.000000
RCA (75) + RCB (25)	0.96	23.8	0.000000
RCA (90) + RCG (10)	0.97	8.4	0.000000
RCA (80) + RCG (20)	0.97	9.2	0.000000
RCA (70) + RCG (30)	0.97	11.7	0.000000
RCA (60) + RCG (40)	0.99	6.3	0.000000
RCA (50) + RCG (50)	0.99	5.1	0.000000
RCA (65) + RCB (20) + RCG (15) + C (3)	0.81	8.9	0.000000
RCA (60) + RCB (20) + RCG (20) + C (3)	0.86	9.1	0.000000

RCA (55) + RCB (20) + RCG (25) + C (3)	0.82	10.0	0.000000
RCA (50) + RCB (20) + RCG (30) + C (3)	0.82	9.5	0.000000
RCA (45) + RCB (20) + RCG (35) + C (3)	0.91	6.7	0.000000
RCA (40) + RCB (20) + RCG (40) + C (3)	0.84	9.4	0.000000

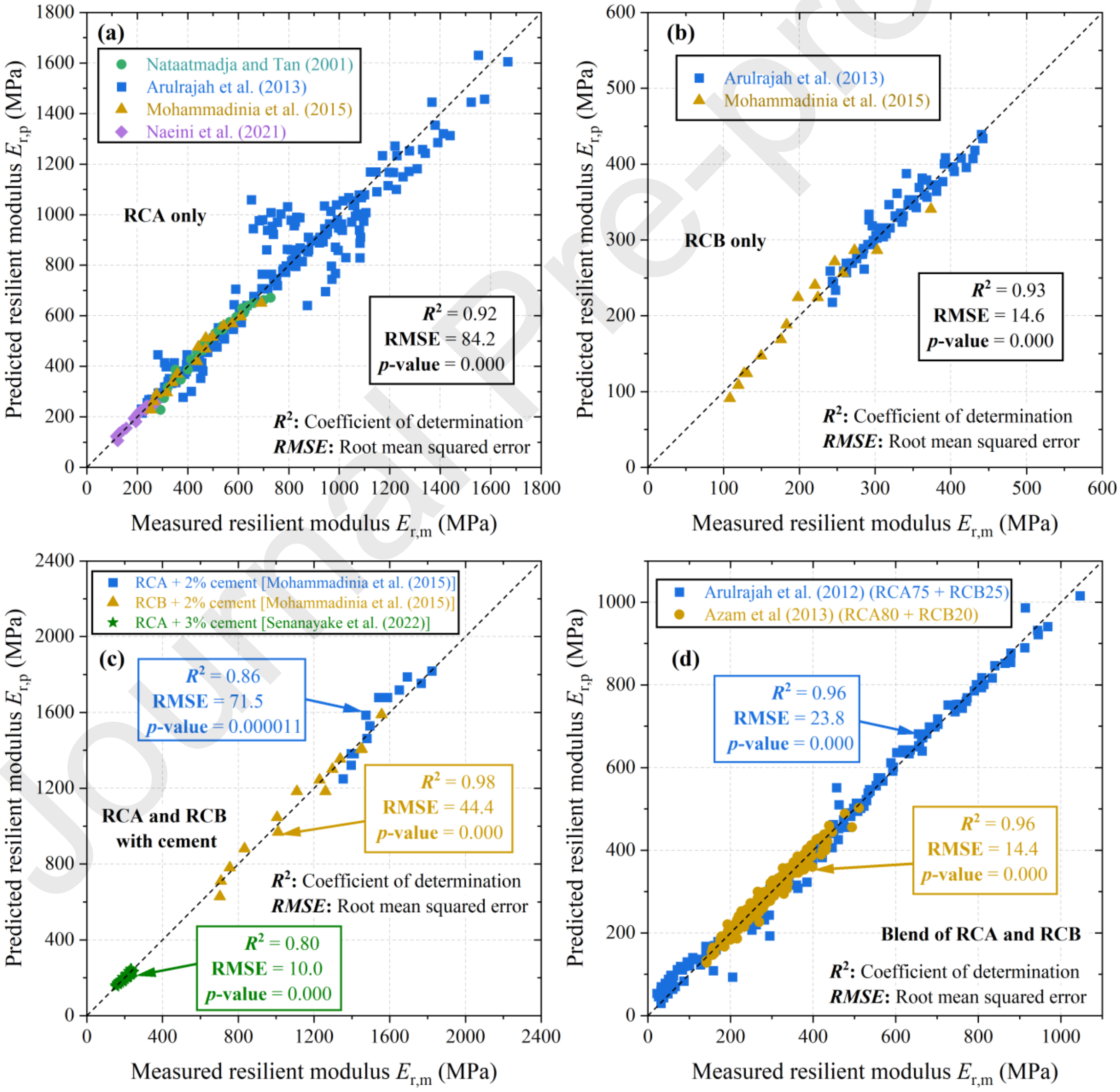

Figure 8 Comparison of measured and predicted resilient modulus values: **(a)** RCA only; **(b)** RCB only; **(c)** RCA and RCB with cement; **(d)** RCA and RCB blend

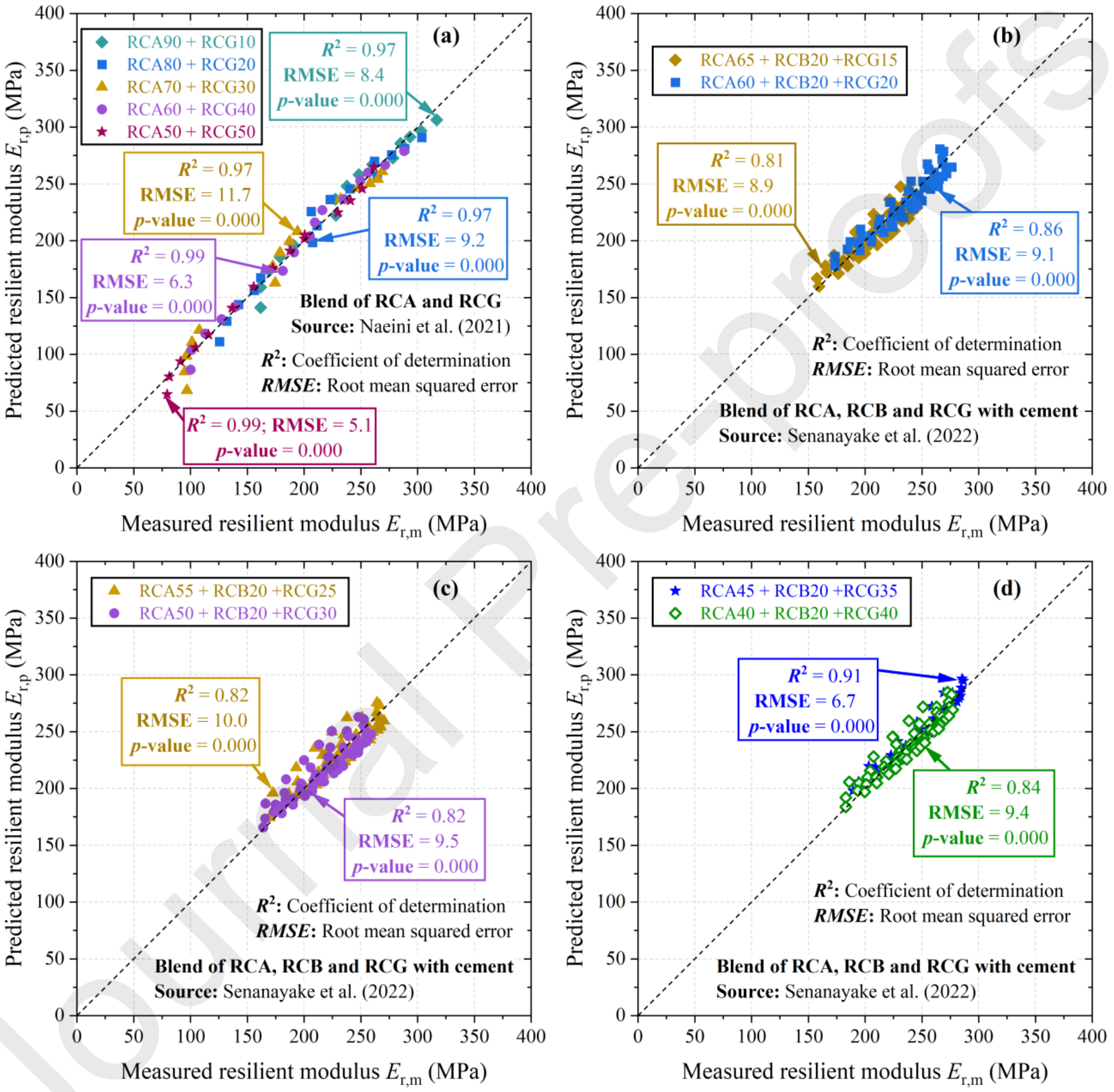

Figure 9 Comparison of predicted and measured resilient modulus values for: **(a)** blend of RCA and RCG; and blends of RCA, RCB and RCG with cement containing **(b)** 15% and 20% RCG; **(c)** 25% and 30% RCG; **(d)** 35% and 40% RCG

5.2 Permanent deformation characteristics of recycled aggregates

For the design of flexible pavements, the prediction of failure is based on determining the amount of rutting, which is a result of accumulated vertical compressive strains throughout the pavement layers. Therefore, it is essential to predict the permanent deformation in a pavement under traffic-induced repeated loads. Often, the permanent strain accumulated in the pavement materials is evaluated by conducting cyclic triaxial tests. The output from this test is used to develop empirical models that can predict the magnitude of permanent deformation.

5.2.1 Prediction of permanent deformation

The permanent deformation in the flexible pavement materials is typically predicted using the model proposed by Tseng and Lytton [107].

$$\varepsilon_{\mathrm{p}} = \varepsilon_0 e^{-\left(\frac{\rho}{N}\right)^{\beta}} \tag{4}$$

where ε_{p} is the permanent strain; N is the number of load cycles; ε_0, β and ρ are empirical parameters. These parameters are typically derived using the data from cyclic triaxial tests. **Table 4** lists the values of parameters ε_0, β and ρ for RCA, RCB and RCG and their blends derived using the data reported in previous studies. Other empirical models are also available for predicting the accumulation of permanent deformation in pavement materials, with detailed discussions provided elsewhere [25].

Table 4 Values of empirical coefficients for different recycled materials and their blends

Material	ε_0			ρ			β			**References**
	Mean	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	
RCA	0.53	0.22	0.20 to 1.11	24.13	53.23	1.29 to 204.80	0.23	0.12	0.09 to 0.44	[20, 36, 38, 40]
RCB	0.59	0.23	0.28 to 1.10	38.30	41.41	4.92 to 90.35	0.52	0.39	0.18 to 1.05	[36, 38]
RCA (75) + RCB (25)	0.63	0.27	0.25 to 1.10	10.49	8	3.50 to 19.21	0.27	0.09	0.17 to 0.34	[93]
RCA (90) + RCG (10)	0.45	0.23	0.22 to 0.69	18.59	–	–	0.50	–	–	[40]

RCA (80) + RCG (20)	0.54	0.20	0.34 to 0.74	11.32	–	–	0.46	–	–	[40]
RCA (70) + RCG (30)	0.54	0.25	0.29 to 0.80	8.79	–	–	0.76	–	–	[40]
RCA (60) + RCG (40)	0.73	0.49	0.29 to 1.25	7.35	–	–	0.51	–	–	[40]
RCA (50) + RCG (50)	1.02	0.92	0.26 to 2.05	14.31	–	–	0.46	–	–	[40]
RCA (80) + RCB (20) + C (3)	0.07	0.01	0.06 to 0.08	24.86	–	–	0.78	–	–	[39]
RCA (65) + RCB (20) + RCG (15) + C (3)	0.21	0.02	0.19 to 0.23	0.25	–	–	0.13	–	–	[39]
RCA (60) + RCB (20) + RCG (20) + C (3)	0.12	0.01	0.11 to 0.13	0.27	–	–	0.21	–	–	[39]
RCA (55) + RCB (20) + RCG (25) + C (3)	0.03	0.01	0.03 to 0.04	77.11	–	–	0.79	–	–	[39]
RCA (50) + RCB (20) + RCG (30) + C (3)	0.16	0.01	0.15 to 0.16	427.60	–	–	0.48	–	–	[39]
RCA (45) + RCB (20) + RCG (35) + C (3)	0.27	0.02	0.25 to 0.29	1199	–	–	0.06	–	–	[39]
RCA (40) + RCB (20) + RCG (40) + C (3)	0.23	0.02	0.22 to 0.25	3744	–	–	0.20	–	–	[39]

Figures 10, 11 and **12** show a comparison of the experimental data with the cumulative permanent strain values predicted using the empirical model. Most researchers conducted the multi-stage repeated load (or cyclic) triaxial tests which better simulate the varying stress levels experienced by pavement materials under traffic loading, capturing more realistic performance data. In addition, these tests reduce the number of samples required, resulting in significant time and cost savings in laboratory studies. Multi-stage cyclic triaxial tests are also recommended by current industry standards [108].

As can be seen in the figures, the predicted values are in a reasonable agreement with the values obtained from the laboratory investigations. Thus, the values of the empirical coefficients provided in **Table 4** can be employed to predict the permanent deformation response of different recycled materials and their blends.

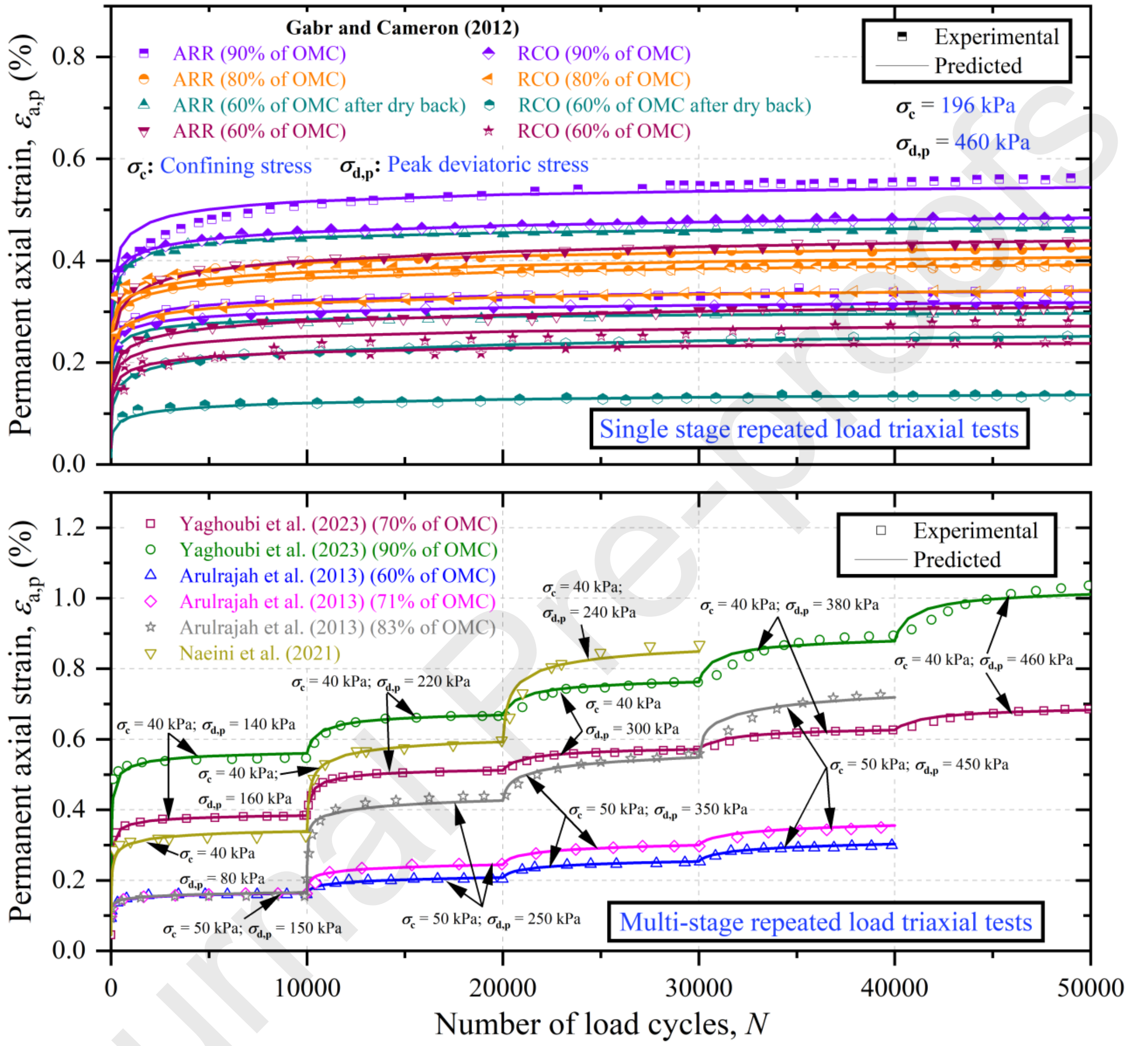

Figure 10 Comparison of measured and predicted permanent axial strain values for RCA

Thus, this section aimed to bridge the gap between laboratory research and practical implementation through the use of predictive models, which are becoming an integral tool in civil engineering. These models enable quick estimation of resilient modulus and cumulative permanent strains, eliminating the need for extensive experimental testing, thereby saving time and resources.

The resilient modulus model (Equation 1) captures the non-linear, stress-dependent behaviour of recycled materials, making it suitable for use in pavement analysis tools. Incorporating this model into design processes facilitates more realistic prediction of stress distribution within the pavement substructure.

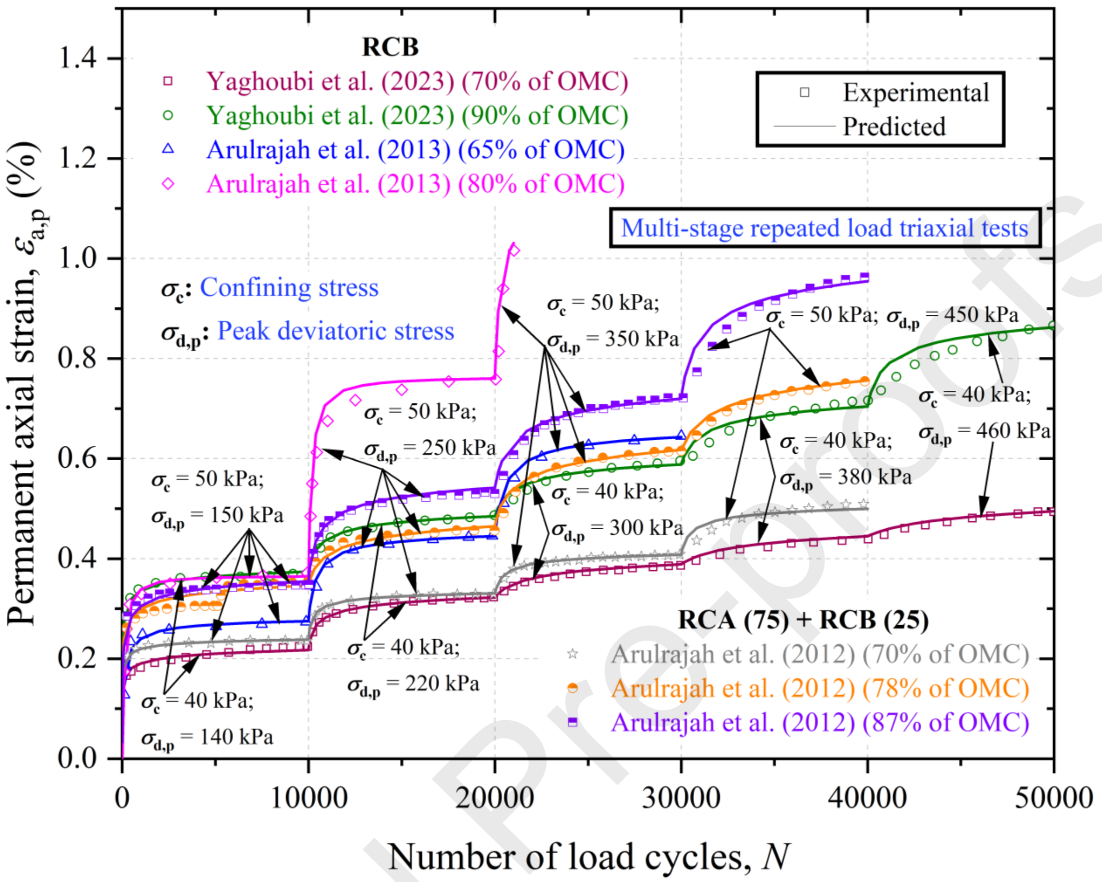

Figure 11 Comparison of measured and predicted permanent axial strain values for RCB and its blend with RCA

The permanent deformation model (Equation 4) can be employed to calculate the permanent strain accumulated in a recycled material layer after a specified number of load cycles. The calculated strain can be compared against acceptable limits established to ensure pavement serviceability and prevent excessive rutting. If the predicted strain exceeds these limits, the thickness of the recycled aggregate layer can be adjusted. Thus, this model can help in effective design of pavements utilising recycled aggregates.

The next section explores recent advancements in machine learning techniques for predicting the resilient modulus and cumulative permanent deformation of recycled materials and their blends.

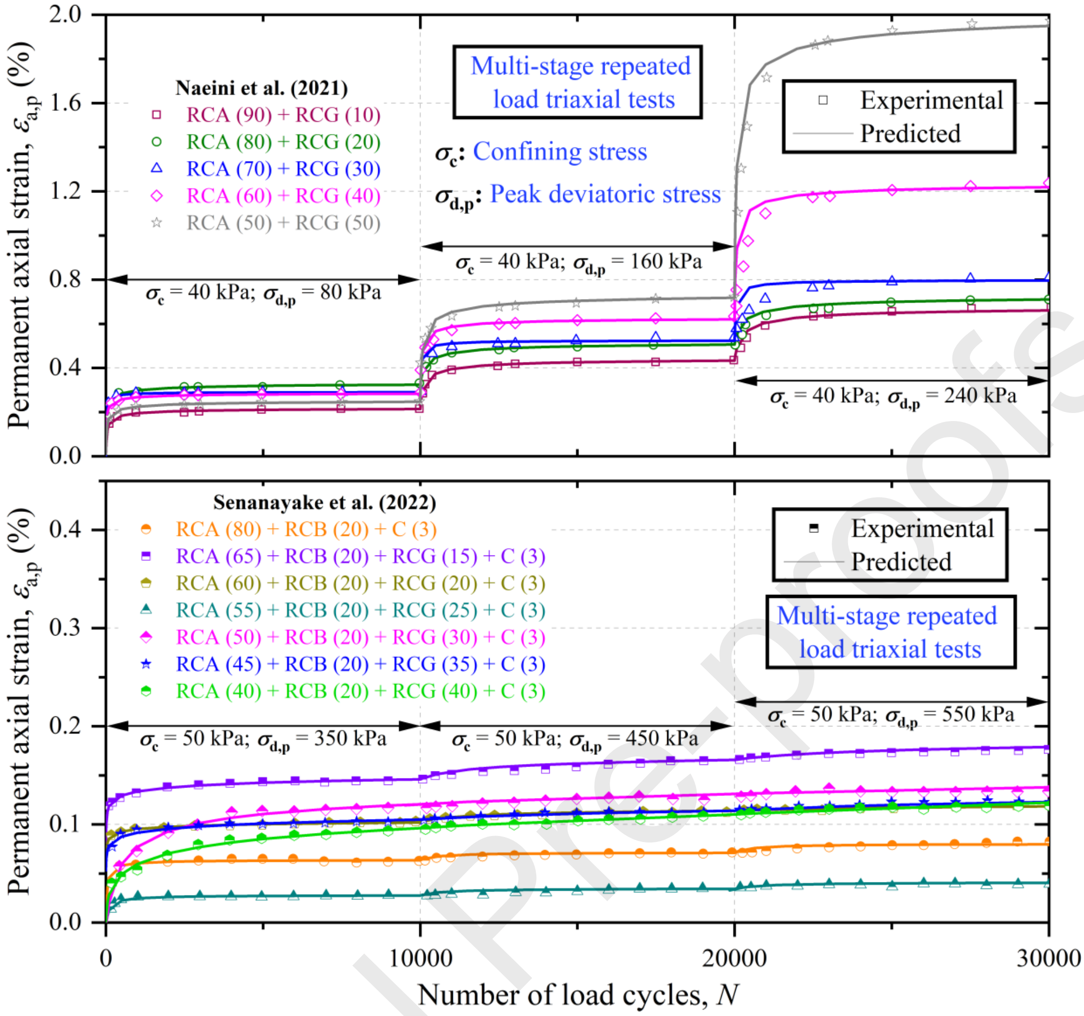

Figure 12 Comparison of measured and predicted permanent axial strain values for recycled aggregate blends

5.3 Recent developments in machine learning techniques

Numerous ML techniques have been developed in recent years to accurately predict the behaviour of pavement materials under cyclic loading conditions. **Table 5** provides a summary of the previous studies on ML techniques. It is apparent that the artificial neural network (ANN) and support vector regression (SVR) are among the most commonly used methods. These techniques have demonstrated reliable predictive performance and are particularly effective in evaluating the resilient modulus and permanent deformation accumulation in unbound granular materials and subgrade soils using key input parameters such as deviatoric stress, bulk stress, moisture content and unconfined compressive strength [109-119].

Won et al. [109] used five machine learning algorithms, including K-nearest neighbour, random forest, neural network, extreme gradient boosting, and decision tree to predict the permanent strain accumulation in unbound base aggregates. All these methods showed a good prediction accuracy [109]. Ghorbani et al. [110] employed ANN machine learning model to predict the permanent deformation and resilient modulus of RCA blended with RCG for road substructure. Oskooei et al. [117] used the multi-layer perceptron (MLP) to evaluate the resilient modulus of bound and unbound recycled materials in pavement. Wu et al. [118] used MLP and long short-term memory (LSTM) techniques, to predict the stress-strain behaviour of granular materials under repeated loading.

Ghorbani et al. [119] predicted the resilient modulus and permanent deformation accumulation of RCA mixed with RAP by using the SVR technique with three different kernels. The hybrid least square support vector machines (LSSVM) approach has also been utilised to predict the resilient modulus of subgrade. This method provides a higher degree of precision, contrasting alternative to conventional ML methods like ANN [41].

Table 5 Summary of published studies on machine learning techniques

Reference	**Type of material**	**Method**	**Parameters evaluated**
Won et al. [109]	Unbound base aggregates	K-nearest neighbour, neural network, decision tree, random forest, extreme gradient boosting	Permanent strain accumulation
Ghorbani et al. [110]	RCA and RCG	Artificial neural network (ANN)	Resilient modulus and permanent strain accumulation
Oskooei et al. [117]	C&D [RCA, RCB, reclaimed asphalt pavement (RAP)] with natural aggregates	ANN, multi-layer perceptron, back propagation neural network (BPNN)	Resilient modulus
Saha et al. [120]	Unbound base granular material	BPNN	Resilient modulus
Ghorbani et al. [119]	RAP and RCA in base/subbase	Support vector regression (SVR) (linear, radial basis	Resilient modulus and permanent

		function, polynomial), random forest regression	strain accumulation
Heidarabadizadeh et al. [121]	Non-cohesive subgrade soil, unbound subbase material	Support vector machine (SVM) hybridised with colliding bodies optimisation, ANN	Resilient modulus

These ML techniques have demonstrated significant potential in accurately predicting the behaviour of pavement materials under cyclic loading conditions. Methods such as ANN, SVR, and hybrid models like LSSVM have proven highly effective in modelling critical parameters, including resilient modulus and permanent deformation under repeated loading. These advancements highlight the transformative role of ML in addressing complex geotechnical challenges, enabling data-driven insights that surpass the capabilities of traditional methods. Future research should focus on refining these models and leveraging advancements in data availability and computational power to further enhance the predictive accuracy and practical applicability of ML techniques.

After examining the performance of recycled aggregates under cyclic loading conditions, it is essential to explore the key durability factors, including freeze-thaw resistance, sulphate soundness, and temperature effects, among others. The next section delves into these factors, highlighting their significance for the sustainable application of recycled aggregates.

6 Long-term durability of recycled aggregates

Durability refers to the ability of a material to endure over extended periods with minimal degradation and low maintenance requirements. It is a key indicator of sustainability of a material, as durable materials help conserve resources and minimise waste, thereby reducing their environmental impact [9].

For recycled aggregates to be durable, they must possess adequate shear strength, permeability, soundness, and resistance to freeze-thaw damage. Insufficient permeability can lead to water accumulation, causing increased pore water pressure under repeated traffic loading. This, in turn, can reduce the shear strength and stiffness of pavement layers constructed using recycled aggregates. Therefore, ensuring adequate permeability is essential to prevent water accumulation in pavement layers. Among the various recycled aggregates typically used in pavements, RCG exhibits the highest permeability, which is comparable to or even superior than that of natural aggregates [34]. For RCA, contrasting results have been observed. Some studies reported that the permeability of RCA is higher than the natural aggregates [122], while others suggest the opposite [123].

The pavement performance can also be significantly affected by freeze-thaw cycles, especially in regions with cold climate. Freezing causes expansion of water present inside the pores of aggregates, leading to significant tensile stresses. If the aggregates possess low freeze-thaw resistance, these stresses can cause fragmentation and degradation. Zhang et al. [124] investigated the influence of freeze–thaw cycles on the resilient modulus of recycled C&D waste. It was observed that the freeze and thaw cycles decrease the resilient modulus of recycled C&D waste. Soleimanbeigi et al. [125] observed an initial decrease in the resilient modulus of RCA with an increase in the number of freeze-thaw cycles. However, after 20 cycles, the resilient modulus increased due to secondary cementation. Saberian and Li [126] reported that the resilient modulus of RCA subjected to a one-day freezing and one-day thawing cycle was higher than that of RCA without freeze-thaw exposure. In addition, the resilient modulus after thawing and freezing cycle was significantly higher compared to RCA without thaw-freeze exposure.

The durability of recycled aggregates can also be assessed using the sulphate soundness test, which measures their resistance to disintegration under simulated weathering conditions. In this test, aggregates are subjected to repeated cycles of immersion in a sulphate solution (typically, sodium or magnesium sulphate) followed by drying. The weight loss of aggregates is recorded after repeated cycles, with lower weight loss indicating better durability and suitability for pavement applications. The natural aggregates typically show low sulphate soundness values, usually below 3% [127]. However, RCA exhibits higher sulphate soundness values due to the presence of weak and porous cement mortar adhered to the aggregates. Nevertheless, the sulphate soundness value of RCA is typically below 20% [68, 127-129], reflecting good resistance to weathering.

Temperature is another factor influencing the long-term performance of recycled aggregates. Ghorbani et al. [130] investigated the effect of temperature on the permanent deformation characteristics of blends containing RCA and RAP. The temperature was varied between 5°C to 50°C to study its influence. The results revealed that blends with higher RAP content (60% and 80%) showed a decrease in cumulative plastic strain with a reduction in temperature. For blends with lower RAP content (20% and 40%), while cumulative plastic strain increased at 50°C, the deformation stabilised more rapidly compared to other temperatures. In addition, for these blends (with 20% and 40% RAP), the cumulative permanent strain was higher at 5°C compared to 20°C. This was attributed to the slower curing process in RCA blends at low temperatures, which led to increased permanent strain. A sensitivity analysis revealed that both RAP content and temperature significantly influenced the permanent strain of RCA-RAP blends. However, the number of load cycles emerged as the most critical factor affecting the permanent strain.

The self-cementing properties of the recycled aggregates, especially RCA, also play a key role in their durability. The aggregates with a stronger tendency for self-cementation are typically more durable due to reduced permanent deformation and increased resilient modulus over time. Wang et al. [131] studied the influence of varying levels of self-cementing properties on resilient modulus and permanent deformation characteristics of RCA after different curing durations. It was observed that RCAs with a higher tendency for self-cementation exhibited reduced permanent deformation and increased resilient modulus with an increase in curing time, making it an excellent material for use in unbound pavement layers. However, cyclic loading from traffic was observed to partially damage the bonds formed between particles, thereby diminishing the effects of self-cementation. Therefore, further research is required to better understand the long-term behaviour of RCA, particularly under the effects of cyclic loading and extended curing periods.

Thus, recycled aggregates demonstrate promising durability characteristics but require careful consideration of factors such as permeability, freeze–thaw resistance, sulphate soundness, temperature effects, and self-cementation. While current studies highlight their potential for sustainable applications, further research is required to fully understand their long-term behaviour under varying environmental and loading conditions.

The previous sections examined the properties of recycled aggregates obtained from laboratory experiments. The next section shifts focus to their field performance, presenting results from case studies and real-world applications.

7 Field investigations on the use of recycled aggregates

Several field investigations have been carried out to investigate the performance of recycled aggregates in pavement applications. de Rezende et al. [132] investigated the performance of asphalt pavement in Goias, Brazil, over a period of eight years. The pavement was constructed using aggregates derived from C&D waste (in subbase and base layers) sourced from demolished buildings and laboratory concrete specimens. Tests were carried out to obtain the water content, density, deflections, and in-situ penetration resistance. The water content and dry density were obtained using the speedy and sand cone, respectively, and also using the nuclear density tests. The dynamic cone penetration, Penetrometre Autonome Numerique Dynamique Assite par Ordinatur (PANDA) (to get the end or tip resistance values along the depth), plate bearing (on the surface course), and Benkelman beam tests (on the surface course) were also carried out. It was observed that the pavements constructed using recycled aggregates showed similar performance to those constructed using natural quarried material.

Chini et al. [67] studied the performance of RCA for use as a base material for HMA pavements and as an aggregate in Portland cement concrete (PCC) pavements using the actual dual-wheel loading at the University of Central Florida’s circular accelerated test track. The thickness of the base course of the experimental pavement section was varied depending on the percentage replacement of the aggregates. It was reported that the pavements constructed using RCA performed similar to those with natural aggregates.

Jiménez et al. [133] investigated the performance and environmental impact of using a low-quality recycled aggregate with low embodied energy from non-selected C&D waste processing in unsealed pavement construction. The experimental road was divided into two 100-m long sections. These sections comprised natural soil (subgrade), base and surface courses. The recycled aggregates mixed with natural aggregates were used to construct the surface course. The Young's modulus of the pavements constructed using recycled aggregate increased with time. This was attributed to the pozzolanic activity or the remaining hydraulic potential of cement in the concrete or the mortar. The bearing capacity was found to decrease over time for the control or reference pavement. In addition, the leaching tests showed that the mixed recycled aggregates do not have a greater leaching risk than natural aggregates. Although the sulphate content or leached concentration was high in the case of mixed C&D waste, the amount was non-hazardous as per the European Union (EU) landfill classification acceptance criteria.

Paul [16] presented a case study on the use of RCA by VicRoads as a fully bound pavement subbase for deep-strength asphalt pavements. It was reported that the performance of RCA is similar to class 3 crushed rock either in bound or unbound pavement subbase. The testing of field cores indicated that the stabilised materials have some moisture sensitivity.

Park [45] conducted laboratory and field investigations to evaluate the performance of dry and wet RCA as base and subbase materials for concrete pavement. The falling weight deflectometer (FWD) was used to measure the deflection of pavement sections constructed with RCA base and subbase. The FWD results indicated that the performance of concrete pavements with RCA base/subbase was similar to those with natural aggregates as base/subbase.

Main Roads Western Australia (MRWA) utilised over 30,000 tonnes of recycled C&D waste in a road widening project in Perth [134]. The recycled waste was used to construct the subbase course in full-depth asphalt pavement. Initial investigations on road performance indicated that the roads constructed using recycled materials were durable and could withstand moderate traffic from construction vehicles [134].

Tavira et al. [135] investigated the long-term performance of an experimental pavement section in Spain constructed using recycled aggregates derived from demolition waste. The study involved two sections of 170 m and 180 m length, where recycled aggregates were used in the base and subbase layers. These aggregates were deemed non-hazardous under the European Landfill directive, posing no environmental risk. Static plate bearing tests were conducted during the construction, while falling weight deflectometer tests were performed at various stages, i.e., during construction, at its completion and during the service period. In addition, the international roughness index (IRI) was measured using a laser profiler over a seven-year period post construction. It was observed that recycled aggregates exhibited higher bearing capacity compared to natural aggregates. Pavement section with a base layer of recycled aggregates showed lower deflection than that with natural aggregates. Overall, the pavement constructed using recycled aggregates demonstrated acceptable structural performance and stability over time, which was evidenced by small IRI values.

Zhang et al. [136] studied the long-term seasonal performance of pavement bases constructed with recycled aggregates derived from C&D waste in the United States. Falling weight deflectometer tests were conducted to measure pavement deflection and assess seasonal variations in the base layer modulus. In addition, the ride quality of the pavement was monitored through IRI and rutting depth measurements. The findings revealed that recycled aggregates exhibited a higher modulus compared to natural aggregates. It was also found that climatic factors have more significant influence on the long-term performance of the pavement base than traffic loading. In terms of ride quality, the pavement section constructed with recycled aggregates performed comparably to that constructed with natural aggregates.

Pourkhorshidi et al. [137] examined the behaviour of a trial pavement constructed in Italy using different types of recycled C&D waste (used in the base layer). The study revealed that recycled aggregates containing weak components, such as brick particles and tiles, exhibited stiffness increase only during the initial passes of vibrating roller. This stiffness gain was attributed to particle breakage and changes in particle size distribution. In contrast, recycled aggregates with strong components such as crushed high strength concrete, demonstrated a progressive increase in stiffness throughout the construction phase. In addition, the rate of stiffness gain during successive passes of the vibratory roller varied among different recycled materials owing to the differences in their strength and brittleness.

Thus, the field investigations demonstrate that the performance of roads constructed using recycled materials is similar to those constructed using natural aggregates. Despite these encouraging results, recycled materials are not being utilised at their full potential. This is due to several reasons that are discussed in the next section.

8 Impediments to the use of recycled aggregates

Several barriers hinder the adoption of recycled aggregates in flexible pavements [16, 22, 35, 57, 75, 102, 138]:

- A misconception still exists in the industry that recycled materials are inferior to natural quarried materials, largely due to limited knowledge of the engineering characteristics of recycled aggregates for pavement applications.
- There is limited information regarding the long-term durability of recycled aggregates in service. In addition, evidence demonstrating the long-term environmental and performance outcomes of these materials is relatively scarce.
- Some stakeholders have concerns about the environmental effects of using recycled material, which negatively impacts their acceptance.
- There is inconsistent information on the allowable proportions of recycled materials and their long-term performance in unbound pavement layers. Industry standards often provide only the maximum permissible limits, with limited guidance on selecting appropriate percentages of different aggregates in blends.

- Minimum requirements for natural aggregates are based on their established performance history, whereas comprehensive data on the in-situ performance of recycled materials is still required.
- The availability of recycled material suppliers near a project site can be limited compared to the quarry sources. When suppliers are distant, the additional haulage costs can significantly offset the cost advantage of recycled materials. In addition, maintaining consistent product quality and performance standards can be challenging for the suppliers.
- Recycled materials exhibit inherent variability in their properties, partly due to their affinity for water due to the presence of cement mortar and other foreign materials. Therefore, the use of recycled materials necessitates stringent quality control and extensive laboratory testing in comparison to natural aggregates.
- Lack of reliable tools for predicting the long-term in-service performance of recycled aggregates and their blends.
- Possibility of leaching of hazardous materials, especially after rainfall. This risk can be mitigated by ensuring that recycled aggregates contain negligible amounts of harmful compounds, such as organic compounds, ions, and heavy metals.
- Environmental concerns, such as the transportation of heavy metals to water sources or the impact of high-pH leachate on corrosion of underlying metal drainage pipes.
- Some recycled aggregates are classified as waste, requiring compliance with regulations regarding special infrastructure for their storage. In contrast, the natural aggregates do not require such infrastructure.

Thus, the full potential of recycled aggregates remains untapped due to several industry barriers, including misconceptions about material behaviour, limited long-term performance data, and inconsistent guidance on the use of recycled aggregates. Despite these impediments, the use of recycled aggregates in pavements is highly desirable due to the benefits outlined in the next section.

9 Environmental, economic and social impact of recycled aggregates

9.1 Environmental impact

The use of recycled aggregates must not affect the groundwater or the neighbouring environment. Therefore, it is essential to evaluate the contaminant concentration in the water that might seep through the recycled aggregates in pavements during its service life. This is typically estimated using a leaching test which provides information about the potential impact that a project will have on groundwater during their service life [139, 140]. A leaching test is vital to ensure that the water seeping through the recycled material would not pose a threat to the surrounding environment (groundwater or water streams). This is ensured by comparing the tested concentration of the contaminants, such as heavy metals, with the guidelines specified by various government agencies regarding requirements for fill or various categories of waste materials. **Table 6** provides an example of the threshold limits for different contaminants set out by EPA Victoria [141].

Table 6 Threshold limit for various contaminants (sourced from [141, 142])

Contaminant	Total concentration (mg/kg)		ASLP threshold for solid inert waste (mg/L)
	Fill material (maximum)	**Solid inert waste (threshold)**	
Arsenic	20	500	0.35
Barium	–	6,250	35
Beryllium	–	100	0.5
Cadmium	3	100	0.1
Chromium (VI)	1	500	2.5
Copper	100	5,000	100
Lead	300	1,500	0.5
Mercury	1	75	0.05
Nickel	60	3,000	1
Selenium	10	50	0.5
Silver	10	180	5
Zinc	200	35,000	150
Cyanide (total)	50	2,500	4
Benzene	1	4	0.05
Benzo (a) pyrene	1	5	0.0005

Polycyclic aromatic hydrocarbons	20	50	–

ASLP: Australian standard leaching procedure

Some studies have found that aggregates derived from C&D waste do not pose a higher leaching risk than natural aggregates [78, 133]. This is attributed to the total concentration of contaminants in recycled C&D waste being below the established threshold limits [78]. In addition, the ASLP values for these aggregates have been found to be below the thresholds for hazardous waste [78]. Research also indicates that RCG does not pose any leaching hazard throughout its service life in pavement applications [34].

However, other studies have reported instances where leaching of certain elements, such as Aluminium, Barium, Chromium, Iron, Molybdenum, Sodim, Nickel, Antimony and Strontium, exceeded local risk-based thresholds for groundwater in some RCA samples. Nevertheless, the reported values in most cases were within the same order of magnitude as the thresholds [75].

The pH of RCA leachate is generally higher compared to that of natural aggregates [75]. If this high-pH leachate reaches an aquifer, groundwater dilution and carbonation typically mitigate its impact on groundwater pH [75]. However, the use of RCA may pose risks in sensitive environments with limited potential for dilution and pH neutralisation [75].

The use of RCB in asphalt may also pose some environmental challenges. Its higher compaction temperature requirements lead to increased energy consumption and greater greenhouse gas emissions [143].

Nevertheless, the use of recycled aggregates offers several environmental benefits, including reduced waste disposal into landfills, lower greenhouse gas emissions [144, 145] associated with the production and disposal of new and waste materials, respectively, and conservation of energy and water resources [144, 146, 147]. Recycled aggregates reduce the demand for virgin aggregates, thereby preserving natural landscapes and protecting local ecosystems by reducing the need for new quarry sites. This, in turn, helps prevent habitat destruction, soil erosion and wildlife disruption.

9.2 Economic impact

Using recycled aggregates can lower project costs by reducing the amount of waste being disposed of in landfills, which saves the landfill levy [148], storage, transportation, and long-term monitoring expenses. When the recycled aggregates suppliers are near the project site, they can be more cost-effective than virgin aggregates, resulting in significant cost savings for road construction and maintenance [134]. Local government agencies may also offer incentives or tax benefits for utilising recycled materials in infrastructure development projects, further reducing the project expenditure. Additionally, the reduced demand for natural aggregates results in cost savings associated with the exploration, land acquisition and development of new quarry sites.

The adoption of recycled aggregates can also create job opportunities in the recycling sector. These jobs can range from waste collection and processing to the manufacture of recycled products, which contributes to local economic development and community welfare. For instance, in Australia, it has been estimated that 9.2 jobs are created for every 10,000 tonnes of waste recycled, compared to just 2.8 jobs for the same amount of waste disposed of in a landfill [149].

9.3 Social impact

The use of recycled aggregates in flexible pavements also demonstrates a commitment to environmental conservation and responsible resource management, enhancing community satisfaction and promoting civic pride. Recycling helps conserve natural resources for future generations and thus, promotes sustainability. In addition, the reduction in greenhouse gas emissions and pollutants associated with the extraction, production, and transportation of virgin aggregates has positive impacts on human health. Finally, using recycled aggregates helps reduce noise and vibrations associated with quarrying operations, contributing to better living conditions for nearby communities.

Thus, the use of recycled aggregates in flexible pavement construction presents a sustainable and economically viable alternative to traditional materials. These materials not only offer substantial environmental benefits, such as reducing landfill waste, conserving natural resources, and protecting ecosystems, but also provide significant cost savings in project execution. Furthermore, the adoption of recycled aggregates fosters job creation in the recycling sector, contributing to local economic growth and community well-being. Given these compelling benefits, further research efforts are needed to overcome the impediments (discussed in the next section) and advance the widespread adoption of recycled aggregates in pavement construction, paving the way toward more sustainable infrastructure solutions.

10 Overcoming practical obstacles related to the use of recycled materials

Several techniques are being developed to address the obstacles associated with the use of recycled aggregates, especially the concerns regarding long-term durability, environmental impact and material variability. The durability of recycled aggregates, particularly RCA, can be enhanced through pre-treatment using thermal [150, 151] and chemical methods [152, 153]. In the thermal method, RCA is heated to a temperature sufficient to weaken the mortar adhered to the natural aggregate particles, which can then be removed through mechanical rubbing [150]. In chemical methods, acidic solvents are used to weaken and remove the adhered mortar, improving the quality of RCA [152, 153]. Additionally, use of additives such as cement can further improve the long-term performance of these aggregates [14].

To address environmental concerns, it is crucial to ensure that recycled aggregates contain negligible amounts of harmful substances, such as organic compounds, ions, and heavy metals. This can be achieved through: (a) proper material segregation at demolition or recycling sites to avoid contamination, (b) comprehensive chemical and leaching tests [34, 75] and (c) pre-treatment through washing, thermal or chemical methods. Batch testing should also be conducted to ensure material consistency and quality. Other techniques, such as installing impermeable barriers beneath the recycled aggregate layer [154] and creating specialised drainage paths to bypass the recycled aggregate layer [155] can also be employed to minimise soil or groundwater contamination.

Continuous monitoring of the environmental impact is also essential for roads constructed using recycled materials [155]. This includes regular measurement of pH levels and the concentration of potential contaminants in the soil or groundwater near the construction site. The data collected from such projects can be analysed to identify and address potential issues proactively, thereby minimising environmental risks.

Material variability can be minimised by sourcing recycled aggregates from consistent, reliable and certified suppliers which operate under recognised quality assurance standards [156]. Additional measures include segregation at the source, implementing rigorous quality control in sorting waste, and maintaining uniformity throughout the recycling process [9, 157]. Techniques such as grouping recycled aggregates based on similar material characteristics [158], as well as washing and pre-treatment, can also be employed to achieve a consistent material quality.

11 Research gaps

The following research gaps have been identified based on the extensive review of the literature:

- Although the feasibility of using RCA as a base course material has been investigated relatively well, few studies have been conducted on the suitability of RCA-RCB or RCA-RCG blends for subbase or base-course applications. RCB and RCG usually possess inferior engineering properties as compared to RCA; however, when blended with RCA, they might prevent the occurrence of reflective cracking. In addition, RCB can be more fragile undergoing substantial particle degradation (i.e. abrasion, splitting and fragmentation) compared to RCA. This degradation effect in RCB requires further investigation.
- Limited studies have investigated the performance of RCA, RCB, and RCG triple blends. A better understanding of their performance is essential to justify an increase in their allowable percentage for use in pavement construction and maintenance. In

addition, the influence of the blending technique on the properties of recycled aggregate blends needs to be investigated.

- Most of the studies have been carried out to assess the performance of recycled aggregates for applications in sealed or paved roads, whereas limited studies have investigated their potential application in unsealed or unpaved roads. A probable reason for this could be the concern regarding the contaminant concentration in the water that inevitably seeps through the recycled aggregates in the case of unsealed roads.
- Although the use of recycled material blends has now been permitted in pavements [21, 46], only the maximum limit of each recycled constituent to be used is specified, and the optimum percentage still needs to be determined. In addition, there is no guideline for selecting the percentage of various constituents in the blend.
- Current industry standards only set maximum replacement limits for recycled aggregates in pavement applications, which might be insufficient to completely recover the waste that is being generated annually. To increase the utilisation of recycled materials, their effectiveness at replacement levels exceeding the allowable limits must be demonstrated through rigorous field and laboratory investigations.
- The long-term performance of recycled materials needs to be comprehensively investigated, especially under realistic moving loads. This could be achieved by performing accelerated loading tests on pavements constructed using recycled aggregates and their blends.
- The studies on the permeability of recycled materials and their blends are limited. In addition, the influence of principal stress rotation on the behaviour of recycled materials is not clearly understood.
- Laboratory investigations typically focus on estimating the apparent cohesion and friction angles of recycled aggregates while overlooking their volumetric behaviour. Further research is needed to understand the shear-induced volumetric behaviour of recycled aggregates, often linked to the volumetric changes caused by compaction. This understanding is essential for developing accurate constitutive models for recycled materials and their blends. These constitutive models can be subsequently employed to predict the response of pavements constructed using recycled materials and their blends using numerical methods.
- Most of the properties measured in the laboratory are obtained by preparing samples at their OMC. Although it might be acceptable for blends with flatter OMC-density curves that tend to be less sensitive to water content, it may cause performance issues for blends with a sharp OMC-density curve that tend to be sensitive to the moisture content. The moisture levels in pavements may fluctuate due to material type, for example, RCB may absorb more water than RCA. The moisture in pavements may also fluctuate due to seasonal changes. It is therefore essential to study the behaviour of blends at various moisture contents.
- Most studies ignore the end-of-life use of recycled materials, i.e., their utilisation after the design life is achieved. This aspect must be addressed in future projects.

The following are the recommendations for future research:

- Establishment of comprehensive performance-based guidelines and specifications for using different types of recycled aggregates and their blends in pavement construction.
- Advanced sensors can be employed for real-time monitoring of the performance of recycled materials in pavements. These sensors would continuously collect data, which

can be analysed using data-driven techniques to identify performance patterns and assess the long-term behaviour of recycled materials. Such insights could facilitate the development of adaptive pavement management strategies tailored to recycled materials.

- Standardised methodologies for long-term field monitoring of recycled pavement materials under various traffic loads and climatic conditions should be developed. These methodologies would enable the creation of universally accepted performance benchmarks and guidelines, promoting consistent and reliable use of recycled materials in pavements.
- Artificial intelligence and machine learning techniques can be employed to analyse large datasets obtained from laboratory and field tests on recycled materials. These approaches can identify complex performance patterns and provide accurate predictions of resilient modulus and permanent deformation under varying loads, environmental conditions and material compositions.
- Existing machine learning models should be refined, leveraging advancements in data availability and computational power to further improve their accuracy and reliability.
- Predictive models could also be integrated into digital twin frameworks to enable real-time simulation of the behaviour of pavements constructed with recycled aggregates under cyclic loading. This integration would provide dynamic updates based on real world data and help optimise pavement performance during the design and maintenance phases.

12 Concluding remarks

The use of recycled aggregates in pavement construction has gained significant attention due to their environmental, economic, and social benefits. This article provided a comprehensive evaluation of the physical and mechanical properties of recycled aggregates, particularly RCA, RCB and RCG, in the context of flexible pavement construction. It examined particle-level and assembly properties, as well as the long-term performance of these materials and their blends, providing critical insights into their effectiveness as flexible pavement materials. By leveraging empirical models for predicting resilient modulus and permanent deformation characteristics under cyclic loading, this study offers a practical approach to incorporate recycled materials in flexible pavement analysis and design. The following conclusions can be drawn from this study:

- RCA has demonstrated significant potential as a substitute for natural aggregates in base and subbase layers of flexible pavements. Despite variability in its properties, RCA often meets or exceeds standard requirements, sometimes performing comparably to or even better than natural aggregates. Notably, RCA benefits from secondary cementation, which can enhance strength and stiffness over time, although it may require careful management to prevent issues such as shrinkage-induced cracking. However, challenges such as the presence of adhered mortar, which influences its engineering characteristics, still needs to be addressed.
- RCB offers both opportunities and challenges as an alternative material for pavement construction. While its particle level properties generally meet the criteria for unbound base and subbase materials, its high-water absorption capacity, due to its porous nature, poses challenges for compaction and may affect its mechanical performance. The presence of adhered mortar further exacerbates these issues, influencing its engineering

behaviour. In comparison to RCA, it exhibits a lower density, higher moisture absorption, and inferior abrasion resistance. These limitations underscore the importance of blending RCB with other aggregates to enhance its overall performance.

- RCG stands out due to its unique properties, including insensitivity of dry density to moisture content variations. It exhibits lower MDD, CBR, and shear strength compared to typical natural aggregates. Consequently, blending RCG with natural or other recycled aggregates is recommended to enhance its performance and achieve suitable engineering properties.
- Blending recycled aggregates with other materials often addresses some of the challenges associated with individual materials. For instance, blending RCA with bitumen reduces water absorption but may increase permanent deformation under repeated loading. Adding cement to RCA improves its mechanical properties, though the gains are less pronounced compared to natural aggregates. Similarly, blending RCA with RCB and RCG, alongside additives like cement, has shown to mitigate issues such as shrinkage-induced cracking, thereby enhancing overall performance.
- Previous studies reveal considerable variability in the resilient modulus of recycled aggregates, influenced by factors such as composition, source, moisture content and stress state. Notably, RCA often exhibits a higher resilient modulus than natural aggregates, primarily due to the secondary cementation of unhydrated cement. The empirical model used to predict resilient modulus provides predictions that closely match laboratory data, validating its application for performance evaluation of various recycled materials and their blends.
- The cumulative permanent deformation in recycled aggregates and their blends is influenced by several factors, including aggregate type, source, moisture content, and stress state, among others. The empirical model for predicting permanent deformation provides reasonable predictions, affirming its utility in assessing the long-term performance of recycled aggregate and their blends.
- Field investigations consistently demonstrate that pavements constructed using recycled aggregates exhibit performance comparable to those built with natural quarried materials. Some studies demonstrated that recycled aggregates not only maintained performance but also had a lower environmental impact, with leaching tests indicating non-hazardous levels of contaminants. These findings indicate that recycled aggregates are a viable alternative to natural materials, offering comparable performance in various pavement applications.

Despite these positive outcomes, the full potential of recycled materials remains underutilised. Challenges such as variability in material quality and conservative industry practices continue to hinder broader adoption. Addressing these issues through improved quality control, updated guidelines, a better understanding of engineering characteristics and long-term performance, and increased awareness of the benefits of recycled aggregates could facilitate more widespread use in flexible pavement construction.

Acknowledgements

The authors thank the anonymous reviewers for their valuable comments and suggestions to improve the technical merit of this study.

CRediT authorship contribution statement

Piyush Punetha: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Software, Visualisation, Writing – original draft.

Sanjay Nimbalkar: Conceptualisation, Funding acquisition, Resources, Supervision, Visualisation, Writing – review and editing.

Funding sources

This work was financially supported by the SmartCrete CRC and the industry partners (the Scenic Rim Regional Council, Queensland, Australia; and the Queensland Government Department of Environment and Science, Queensland, Australia) [SmartCrete CRC 21.PP.0120 project, 2023].

Declaration of competing interest

The authors declare no known competing financial interests or personal relationships.

Data availability statement

Data will be made available on reasonable request.

Appendix A. Mechanical Properties of Recycled Aggregates Reported in Literature

Tables A.1, **A.2** and **A.3** list the properties of RCA, RCB and RCG reported in past studies, respectively.

Table A.1 Properties of recycled concrete aggregates reported in past studies

Property	**Unit**	**Mean value**	**Standard deviation**	**Typical range**	**References**
Liquid limit (LL)	%	28	6.2	23 – 35	[20, 42]
Maximum dry density (MDD)	kg/m^3	1967	83	1810 – 2210	[19, 20, 36, 37, 40, 42, 44, 45, 48, 68, 102]
Optimum moisture content (OMC)	%	11.9	1.2	9 – 14.9	[19, 20, 36, 37, 40, 42, 44, 45, 48, 68, 102]
Flakiness index	%	13.1	2.9	11 – 16.4	[18, 42, 48]
Los Angeles abrasion loss	%	31.7	6.4	21 – 43.6	[17, 18, 20, 37, 40, 45, 48, 67, 99]
pH	–	11	1.5	8.6 – 13.1	[18-20, 37, 48, 75]
California bearing ratio (CBR)	%	140.5	38.4	74.2 – 184	[18, 19, 40, 100]
Unconfined compressive strength (UCS)	MPa	0.62	0.2	0.44 – 0.88	[20, 43, 100]
Apparent cohesion, *c*	kPa	80.8	42	44 – 169.7	[36, 37, 40, 43]
Friction angle, *φ*	°	50.9	5.2	41.5 – 57	[36, 37, 40, 43]

Table A.2 Properties of recycled crushed brick reported in past studies

Property	Unit	Mean value	Standard deviation	Typical range	References
Maximum dry density (MDD)	kg/m^3	2013	14	1990 – 2022	[36, 48, 102]
Optimum moisture content (OMC)	%	11	0.36	10.7 – 11.4	[36, 48, 102]
Flakiness index	%	20	8.4	14 – 25.9	[33, 48]
Los Angeles abrasion loss	%	40.4	8	35.5 – 49.6	[33, 48, 70]
pH	–	9.7	1	9.1 – 10.9	[36, 48]
California bearing ratio (CBR)	%	131	10.6	123 – 138	[33]
Apparent cohesion, c	kPa	41	–	–	[93]
Friction angle, φ	°	49	–	–	[93]

Table A.3 Properties of recycled crushed glass reported in past studies

Property	Unit	Mean value	Standard deviation	Typical range	References
Maximum dry density (MDD)	kg/m^3	1747	174	1451 – 1990	[35, 36, 41, 50, 51, 64, 72, 84]
Optimum moisture content (OMC)	%	10.3	1.9	8 – 13.6	[35, 36, 41, 51, 64, 84]
Flakiness index#	%	90.1	6.6	85.4 – 94.7	[35]
Los Angeles abrasion loss	%	27.6	5.7	24 – 42	[35, 36, 50, 64, 84]
pH	–	9.9	0.3	9.6 – 10.1	[35]
California bearing ratio (CBR)	%	42.4	21.9	18 – 76	[34, 35]
Apparent cohesion	kPa	0	–	–	[35, 51]
Friction angle	°	41.3	5	37 – 48	[35, 51, 84]

#For medium and coarse RCG

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