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Review

A Critical Review of the Utilization of Recycled Glass in Transportation Infrastructure Including Roads and Railways

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Abstract: The global production of waste glass and the challenges associated with its reuse and disposal highlight the urgent need for effective alternatives to prevent the accumulation of landfill. Researchers have already explored the potential of replacing naturally quarried aggregates with waste glass to minimize its accumulation in landfills and the depletion of natural resources. Previous studies have reported that recycled crushed glass (RCG) has a high silica content, angularity, shear strength, and durability, properties which make it a promising material for construction applications. However, there are limited assessments in the existing literature of the performance of RCG as a construction material for transportation infrastructure. This paper reviews the physical, chemical, and geotechnical properties of RCG reported in the literature and compares their findings; it also discusses the existing studies related to its suitability for field applications. This paper also highlights the environmental impact and health concerns of replacing natural aggregates with waste glass by emphasizing its role in sustainable development and the circular economy in the construction of transportation infrastructure.

Keywords: recycled crushed glass; physical properties; chemical properties; engineering performance; transport infrastructures; environmental impacts; health concerns

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Academic Editors: Cinthia Maia Pederneiras, André Augusto Nóbrega Dantas and Catarina Brazão Farinha

Received: 8 March 2025
Revised: 30 March 2025
Accepted: 2 April 2025
Published: 3 April 2025

Citation: Indraratna, B.; Thayananthan, N.; Qi, Y.; Rujikiatkamjorn, C. A Critical Review of the Utilization of Recycled Glass in Transportation Infrastructure Including Roads and Railways. *Sustainability* **2025**, *17*, 3187. https://doi.org/10.3390/su17073187

1. Introduction

Globally, rapid urbanization necessitates the construction of infrastructure such as roads and railways to meet the demands of the growing populations. These activities rely mainly on the use of naturally quarried aggregates extracted from mineral resources. The global demand for natural aggregates has led to the extraction of approximately 40 to 50 billion metric tonnes of crushed rock, sand, and gravel annually, half of which is used for construction purposes [1,2]. This process obviously leads to the depletion of natural resources, the emission of carbon, environmental degradation, the exacerbation of natural disasters, and the destruction of habitats, which can affect nearby ecosystems [3]. In response, the United Nations has implemented sustainability goals such as 9, 11–13, and 15 to clarify the need to adopt sustainable practices in infrastructure construction where naturally quarried materials are heavily utilized.

This is why many researchers have explored the potential of using recycled waste materials such as plastics, glass, rubber, coal wash, steel slag, and demolished construction aggregates as replacements for natural aggregates in road and railway infrastructure. This means using them as fill materials in embankments, backfill for retaining walls [4–10], stabilizing material for soft subgrades and clayey soils [11–14], and load-bearing material in road base, subbase, and subgrade [15,16], as well as ballast, sub-ballast/capping layers, and subgrade in railway constructions [17–24]. The growing interest in these recycled materials is driven by their potential to improve the shear strength, stiffness, and energy absorption, while simultaneously reducing the environmental impact and dependence on natural aggregates.

Unlike other waste materials, reusing/recycling waste glass presents challenges such as (a) breakage during collection and transportation due to its brittle nature, (b) difficulty in sorting broken glass by colour, and (c) the presence of mixed-colour glass with varying chemical compositions. These challenges have led to the high accumulation of waste glass and low recycling rates, thus highlighting the need for alternative applications. According to the Global Statistics and Trends on Glass Recycling Efficiency–2024 [25], around 130 million tonnes (mt) of glass are produced annually from various sectors (container glass, flat glass, tableware, and others) as shown in Figure 1. While this volume of production demands a higher global recycling rate, it still remains low, with an average value of 21% (approximately 27 mt) of the total production of glass [25,26]. Worldwide, China produces the highest amount of waste glass with approximately 23 mt annually, but its recycling rate remains around 40%, highlighting the urgent need for improved waste management strategies [27,28]. Next to China, the most significant contributors to the generation of waste glass include India (21 mt), the USA (11.4 mt), the UK (2.4 mt), Australia (1.1 mt), and Canada (0.75 mt), where recycling rates vary from 27% in the USA to 57% in Australia [29], as shown in Figure 2. In contrast, European countries have achieved a remarkable 80% recycling rate by using efficient waste collection systems, stringent policies, and strong public engagement [30]. This disparity in recycling efficiency emphasizes the urgency to maximize the reuse of waste glass in manufacturing industries and explore alternative applications for recycled glass in order to reduce landfill dependency.

From a civil engineering perspective, incorporating recycled waste glass as a construction aggregate in infrastructure projects offers a promising solution to reduce landfill waste and minimize the dependence on natural aggregates. These efforts align with the principles of a circular economy, which aims to increase circularity from 8.6% in 2021 to 17% by 2030, as reported in the Circularity Gap Report–2021 [31]. Past studies have proved that mixed-coloured glass is not a problem when used as a construction aggregate in civil engineering projects [6,15,32,33]. Moreover, recycled glass can be used as a construction material because of its inert (non-biodegradable) nature and geotechnical properties in comparison to natural aggregates, such as high shear strength, high friction angle, and durability. However, the limited understanding of the geotechnical properties and environmental impacts of recycled glass raises concerns about its widespread use in construction applications, particularly in substructures where it comes into direct contact with the ground. Therefore, this study aims to bridge these knowledge gaps by thoroughly examining its performance, durability, and environmental sustainability to facilitate its practical implementation in civil engineering applications.

Also, while many studies focused on the use of recycled glass as an alternative fine aggregate in the production of cement and concrete [32,34], only a few studies have reviewed its suitability and application in the substructure of roads and railways. This paper therefore aims to review the investigation and application of recycled glass in transportation infrastructure, as discussed in the following sections: (a) physical, chemical, and geotechnical characteristics; (b) applications in various transport infrastructures; (c) field applications; (d) environmental impact and health concerns for long-term use; and (e) recommendations for future research.

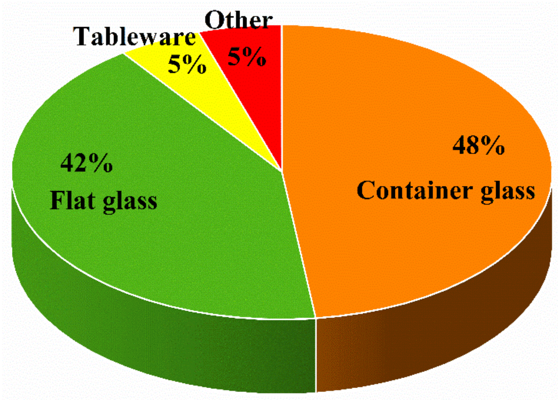

Figure 1. Worldwide production rates of different types of glass (data sourced from [25,35]).

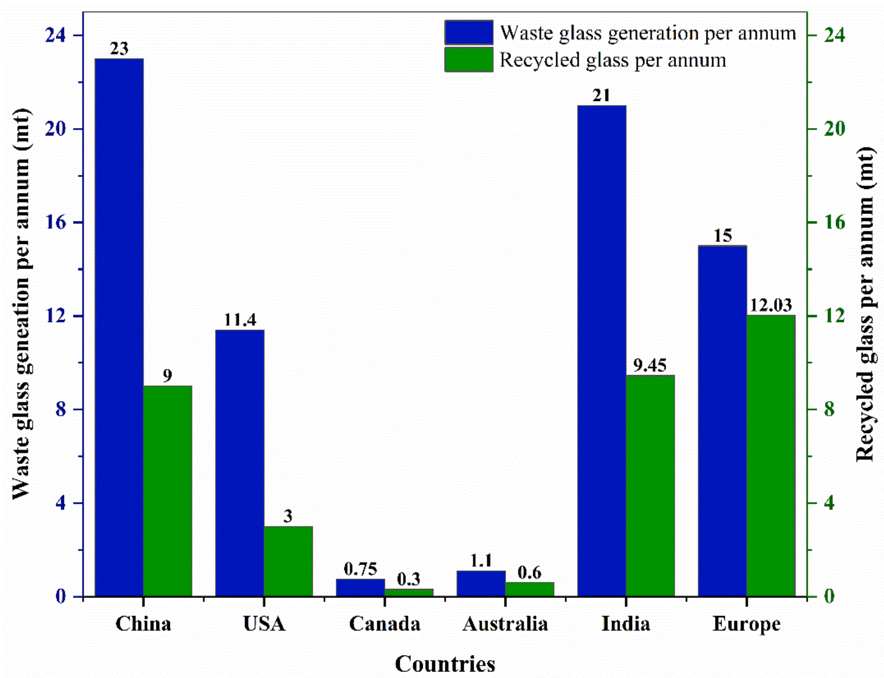

Figure 2. Waste glass generation (mt) and recycled glass (mt) per annum in various countries (data sourced from [27–30]).

2. Physical Properties of Recycled Crushed Glass (RCG)

The characterization of waste glass is essential for its use as an alternative construction material because its physical properties vary based on the source of collection, the methods used for processing (i.e., crushing and screening), and the levels of contamination [36,37]. This section focuses on the key physical characteristics of RCG.

2.1. Particle Size and Gradation

Figure 3 summarizes the particle size range of RCG as reported in the literature. Previous studies commonly used RCG particles that were smaller than 10 mm, with most focusing on well-graded fine particles under 4.75 mm as shown in Figure 3. RCG can be classified into three categories based on the maximum particle size: (a) Fine Recycled Glass (FRG), up to 4.75 mm; (b) Medium Recycled Glass (MRG), up to 9.5 mm; and (c) Coarse Recycled Glass (CRG), up to 19 mm [7], as shown in Figure 4. These terms are used throughout this paper to refer to the range of particle sizes.

Previous studies noted that samples of FRG consist mainly of sand-sized particles and less coarse particles compared to MRG. MRG is mainly a mix of sand and gravel-sized glass particles and a smaller proportion of fine particles. The CRG samples were coarser than the other two types and consisted mainly of flat, elongated gravel-sized particles (flaky particles). Both FRG and MRG were typically characterized by angular-shaped particles. This was further supported by Kazmi et al. [38], who noted that FRG particles (ranging from 0.425 mm to 2.36 mm) are more angular than natural sands. The roundness index of natural sand is 0.55, whereas FRG is 0.32; this indicates a higher angularity for the FRG particles because the roundness index is inversely related to angularity.

A well-graded composition and an increase in coarser particles with higher angularity can enhance the mobilization of frictional resistance in natural aggregates [39]. However, previous studies highlighted that the performance of RCG is sensitive to particle size because its performance deteriorates as the particle size becomes coarser. This decline was primarily attributed to the flaky nature of coarser RCG particles [38]. These findings are further supported by Wartman et al. [6] and Disfani et al. [7], who observed that RCG passing through a 9.5 mm sieve resembles natural sand and gravel due to its angularity and effective interlocking behaviour. This demonstrates that well-graded fine and medium-sized RCG can be an alternative geomaterial in field applications due to its high angularity and better interlocking properties, which are essential for optimal compaction and increasing the shear strength.

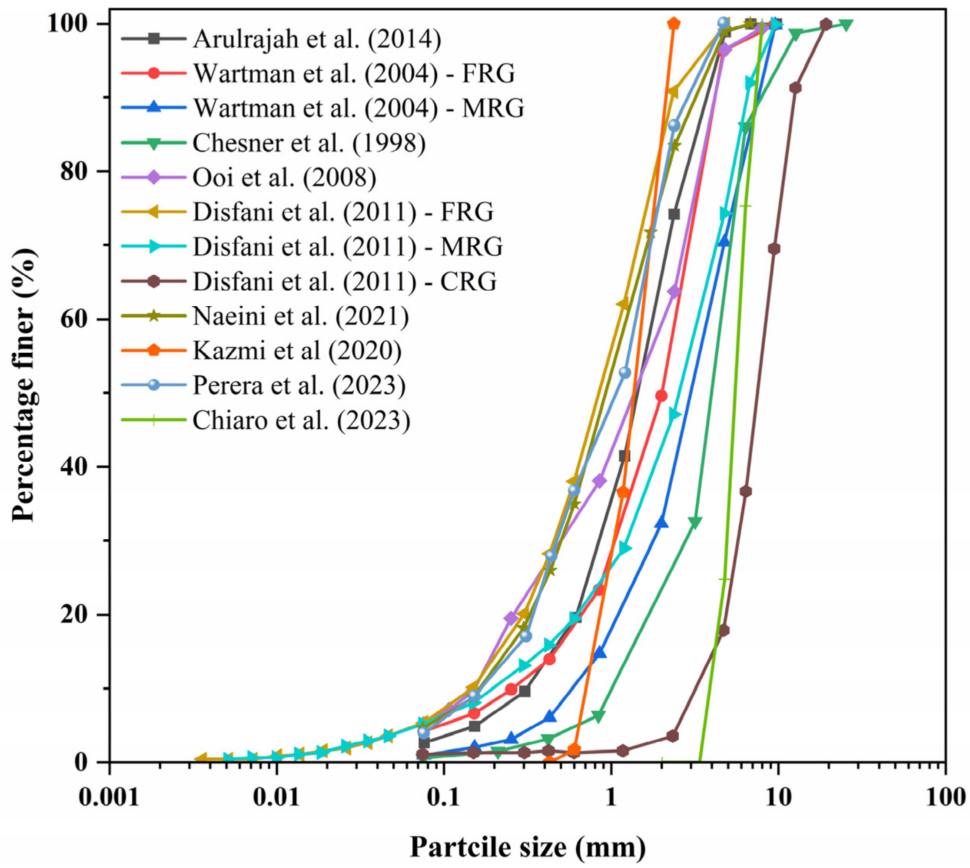

Figure 3. Particle size distribution of RCG utilized in the existing literature studies (data sourced from [6,7,10,16,21,36,38,40,41]).

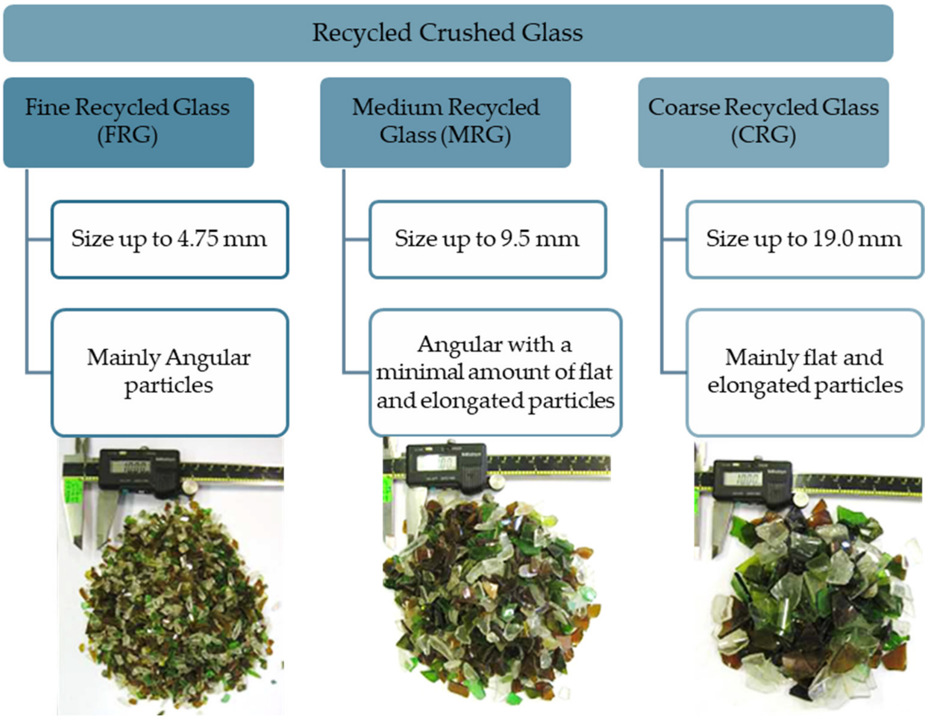

Figure 4. RCG classification based on particle size and shape (modified from [7]).

2.2. Specific Gravity

The specific gravity (G_s) of RCG is essential for calculating the required quantity of fill needed to maintain the required density. Previous studies have reported that the specific gravity of RCG ranges from 2.47 to 2.64 [6,7,10,15,21,38,40,41], as shown in Table 1. This range is consistent with the values of 2.49 to 2.52 provided by Federal Highway Administration (FHWA) guidelines [36]. These values indicate that the specific gravity of CG is approximately 10% lower than most natural aggregates, which typically range from 2.60 to 2.83 [42–44]. This lower specific gravity suggests that RCG can be a viable alternative to natural aggregates because it offers advantages in terms of lightweight and lower transportation costs as well as comparable performance in many applications.

Table 1. Physical properties of RCG.

Properties	Value	References
Specific gravity	2.47–2.64	[6,7,10,15,21,38,40,41]
Los Angeles abrasion (%)	24–27.7	[6,7,15,16,40]

2.3. Durability

The crushing behaviour and particle degradation of construction aggregates pose significant challenges in transportation infrastructure applications. Aggregates used in road and railway construction must possess sufficient hardness and strength to resist abrasion and crushing during construction (i.e., under roller loads) and operation (i.e., under traffic wheel loads). Assessing the suitability of recycled glass as an alternative to natural construction aggregates relies on evaluating the strength and durability of the material. The durability and abrasion resistance of recycled glass can be evaluated utilizing the Los Angeles abrasion test and/or post-compaction sieve analysis.

The Los Angeles (LA) abrasion test (ASTM C131) is widely used in highway and materials engineering to evaluate the durability of construction aggregates by measuring the percentage of mass lost due to abrasion and impact [45]. Previous studies reported that the LA abrasion values of FRG and MRG are between 24 and 27%, as provided in Table 1, which is slightly higher than the natural aggregates, which typically range from 12 to 20% [6]. While this variation was attributed to the higher volume of debris and brittle nature of RCG, these values are still within the 35% and 30% maximum allowable limit specified by the road authorities for road base and subbase. The FHWA [36] reported that CRG particles exhibited a marginal durability ranging from 40 to 45% and recommended additional crushing to improve the particle strength. A sieve analysis conducted by Ooi et al. [40] for MRG demonstrated negligible changes in the gradation curve of RCG before and after modified compaction. This indicates that RCG is a stable material that would be well-suited for engineering applications such as handling, spreading, and compaction [15]. Therefore, the findings of the LA abrasion test and post-compaction sieve analysis reveal that CG would meet the durability requirements needed for use as alternative construction aggregates in transport infrastructure.

3. Chemical Properties of RCG

Glass is primarily composed of silicon dioxide (SiO_2); it is an inorganic and non-crystalline material with a random arrangement of atoms. Natural sand, however, has a higher chemical composition of silica or quartz; the comparisons with glass compositions are listed in Table 2 as determined by X-ray fluorescence (XRF) spectroscopy results from the existing literature. According to these data, the compound "Silica" in glass exhibits characteristics such as hardness, a higher crushing resistance, a high melting point, and chemical inertness [38,46]. The non-biodegradable nature of glass therefore enhances its potential as a suitable alternative for natural aggregate in civil engineering applications [14,21]. Glass is also known for its insulating or heat retention properties (low thermal conductivity), which helps it to decrease the depth to which frost can penetrate when used as construction aggregate in roadworks [36]. To understand how suitable the pH value of recycled glass material to be used as a construction material is, previous studies report that the pH value ranges between 9.6 and 10.1, which indicates an alkaline nature similar to natural aggregates (pH ≈ 9.4) [7,15,16]. Table 2 outlines the chemical composition of different coloured glass compared with natural sand, and Table 3 presents the chemical composition and application of common types of commercial glass [33,36,38,41].

Table 2. Chemical composition of different coloured glass compared to natural sand.

Chemical Composition	Kazmi et al. [38]		Mohajerani et al. [33]				Perera et al. [41]
	Natural Sand (%)	RCG (Mixed Colour) (%)	White Glass (%)	Amber Glass (%)	Green Glass (%)	Brown Glass (%)	RCG (Mixed Colour) (%)
SiO_2	99.81	72.07	69.82	70.66	72.25	72.1	68.14
CaO	0.01	11.09	8.76	9.12	12.35	-	14.15
Na_2O	<0.01	13.73	8.42	8.32	10.54	-	12.51
Al_2O_3	<0.01	1.45	1.02	6.53	2.54	1.74	2.18
Fe_2O_3	0.05	0.34	0.55	2.52	-	0.31	0.92
MgO	0.03	0.69	3.43	1.45	1.18	-	0.74
K_2O	0.01	0.33	0.13	1.03	1.15	-	0.54
TiO_2	0.06	0.05	-	0.27	-	-	0.12
P_2O_5	0.01	0.03	-	0.07	-	-	0.24
MnO	<0.01	0.01	-	-	-	-	0.03
MnO_2	-	-	-	0.04	-	-	-
SO_3	0.01	0.09	0.20	-	-	0.13	0.09
Cr_2O_3	11 ppm	539 ppm	-	-	-	0.01	0.11
V_2O_5	9 ppm	20 ppm	-	-	-	-	-
ZnO	5 ppm	72 ppm	-	-	-	-	0.03
SrO	2 ppm	155 ppm	-	-	-	-	0.03
BaO	26 ppm	355 ppm	-	-	-	-	-

Table 2. *Cont.*

Co_3O_4	42 ppm	26 ppm	-	-	-	-	-
NiO	8 ppm	4 ppm	-	-	-	-	0.01
CuO	<2 ppm	4 ppm	-	-	-	-	0.01

Table 3. Chemical composition and applications of common types of commercial glass.

Chemical Composition	Mohajerani et al. [33]; Chesner et al. [36]			
	Soda-Lime Glass (%)	**Borosilicate Glass (%)**	**Lead Glass (Crystal) (%)**	**Aluminosilicate Glass (%)**
SiO_2	70–75	72–81	54–70	57–64.5
Na_2O	12–17	4–7	7–10	0.5–1.0
CaO	5–12	-	-	8–10
Al_2O_3	0.5–1.5	1–6	1–2	16–24.5
Fe_2O_3	0.06–0.24	-	-	-
MgO	0.1–5	-	-	7–10.5
K_2O	0.1–3	1	2–9	-
Cr_2O_3	0.1	-	-	-
BaO	0.14–0.18	-	-	6
PbO	-	-	15–38	-
B_2O_3	-	11–15	-	4–5
Applications	Windowpanes, light bulbs, bottles, containers, and some types of tableware	Laboratory glassware, cookware, pharmaceuticals, and devices used in space exploration	Electronic parts, colour TV funnel, fine glassware, decorative items, and neon tubing	Glass screen for mobile devices, ignition tubes, resistors, lamps, and fibreglass

4. Geotechnical Properties of RCG

This section focuses on the geotechnical characteristics of RCG that would be used as fine and medium aggregates for road and railway infrastructure. It includes the strength and deformation properties such as the compaction characteristics, shear strength characteristics (i.e., the cohesion and friction angle), the flow properties (i.e., the coefficient of permeability), and the index properties (i.e., the plasticity index).

4.1. Plasticity Index (PI)

Arulrajah et al. [16] and Perera et al. [41] conducted Atterberg limit tests on the fraction of fine particles less than 0.075 mm (No. 200 sieve) of RCG and reported that it exhibits a non-plastic behaviour because its plasticity index is zero, similar to natural sand and gravel. The non-plastic characteristic of RCG is a key property needed for a supplementary material to stabilize expansive or clayey soils due to the moisture-insensitive nature of glass particles. Blending RCG with expansive soils will improve its shear strength and stiffness while reducing the plasticity index, expansive behaviour, and differential settlement. Previous studies also revealed that non-plastic materials like RCG reduce the dependence on traditional additives such as lime or cement while offering a sustainable alternative for soil stabilization [11,12,14,47].

4.2. Hydraulic Conductivity

The hydraulic conductivity of fill materials used in road and railway infrastructure has been a key design factor for practitioners. The permeability coefficients of RCG from the existing literature are shown in Table 4, which indicates how the particle size distribution and gradation played a large role in the hydraulic conductivity of the same material. Well-graded RCG samples with a range of particle sizes exhibited lower permeability coefficients than uniform or poorly graded samples. In practice, the permeability coefficient typically ranges from 10^{-3} to 10^{-5} cm/s for sand and silty sand (low permeability) and 10^{-1} to 10^{-3}

cm/s (medium permeability) for sandy gravel and fine sand, while gravel is classified as highly pervious with values greater than 10^{-1} cm/s [48]. As prior studies indicate [6,7,15,16], most well-graded FRG and MRG samples have a hydraulic behaviour similar to natural sand, silty sand, and sandy gravel, with permeability values from 10^{-3} to 10^{-4} cm/s. The FHWA [36] reported even higher values of up to 6×10^{-2} cm/s for MRG and 2×10^{-1} cm/s for CRG, similar to highly permeable gravel. This level of permeability indicates that RCG is not good at retaining water, so it is well-suited for drainage applications [6]. These findings emphasize the importance of material processing and gradation in optimizing the hydraulic performance of CG for specific engineering applications.

Table 4. Hydraulic conductivity of RCG based on particle size and USCS classification.

Particle Size Range (mm)		USCS Classification	Coefficient of Permeability (cm/s)	References
FRG	0.0035–4.75	SW-SM	1.7×10^{-3}	[7]
	0.075–4.75	SW	1.61×10^{-4}	[6]
			3.3×10^{-3}	[15]
			3.5×10^{-3}	[16]
	0.425–2.36	SP	4.01×10^{-2}	[38]
MRG	0.0035–9.5	SW-SM	2.85×10^{-3}	[7]
	0.075–9.5	SW	6.45×10^{-4}	[6]
		SP	6.20×10^{-2}	[13]
	<6.4		6.0×10^{-2}	[36]
CRG	<19	GW	2.0×10^{-1}	[36]

4.3. Compaction Behaviour

Previous researchers investigated the compaction of RCG using standard and modified compaction tests; the results are summarized in Table 5 and Figure 5. The standard Proctor test reveals that FRG achieved a maximum dry density (MDD) of approximately 16.7 to 17 kN/m^3 at an optimum moisture content (OMC) of 10% to 13.25%, while MRG achieved a relatively higher MDD of 18 kN/m^3 at a lower OMC of 9%. The Modified Proctor test showed improved densities, with FRG achieving an MDD of 17.5–18.3 kN/m^3 at an OMC of 9.7% to 10% and MRG achieving an MDD of 19.5 kN/m^3 at an OMC of 8.8%. These results align with the findings from FHWA [36] and PennDOT [49] which recorded similar modified compaction densities for FRG and MRG. Despite its lower specific gravity and limited water absorption, CG exhibited a compaction that is comparable to natural aggregates (MDD of 19–20 kN/m^3), though with a 10–15% lower maximum density for similar classifications. Disfani et al. [7] identified challenges in compaction for achieving uniform water distribution for CRG due to particle shape and gradation.

Table 5. Compaction properties of RCG based on particle size and compaction effort.

Materials	Standard Compaction Effort		Modified Compaction Effort		References
	MDD (kN/m^3)	OMC (%)	MDD (kN/m^3)	OMC (%)	
FRG ($\leq$4.75 mm)	16.7	12.5	17.5	10.0	[7]
	-	-	18.0	9.2	[15]
	16.8	12.8	18.3	9.7	[6]
	-	-	18.0	9.2	[16]
	17.2	13.25	-	-	[18]
	17.0	10.0	-	-	[41]
			16.9–17.6	-	[49]

Table 5. *Cont.*

Materials	Standard Compaction Effort		Modified Compaction Effort		References
	MDD (kN/m^3)	OMC (%)	MDD (kN/m^3)	OMC (%)	
MRG (≤9.5 mm)	16.6	13.6	17.5	11.2	[6]
	18.0	9.0	19.5	8.8	[7]
	-	-	18.5	9.7	[40]
			17.6–18.4	-	[49]
Crushed rock (≤20 mm)	-	-	22.6	8.7	[15]

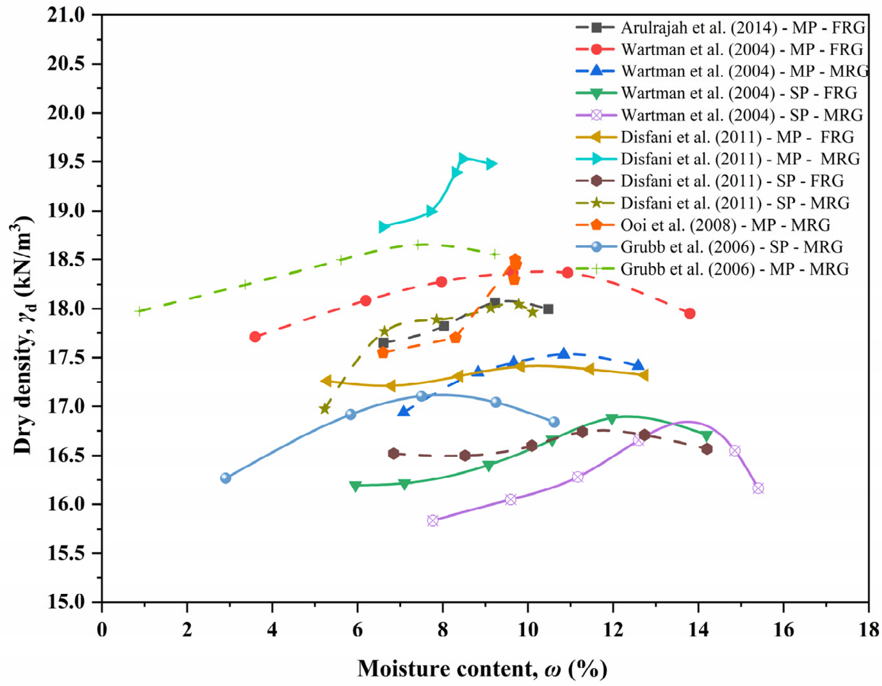

Figure 5. Compaction behaviour of RCG based on particle size and compaction effort (MP—Modified Proctor and SP—Standard Proctor compaction) (data sourced from [6,7,12,16,40]).

The moisture content–density curves with the convex shapes shown in Figure 5 confirm that RCG compacts like natural aggregates. The flatness of the curve suggests stable compaction characteristics and good workability across a range of moisture contents because RCG exhibited less sensitivity to variations in moisture [6]. However, Ooi et al. [40] highlighted a challenge in their study to obtain the wetter points of the compaction curve because the samples could not retain moisture.

4.4. California Bearing Ratio (CBR)

The CBR test is widely used to evaluate the strength and stiffness of soils and subgrade materials in roads and railways. Based on previous studies, the CBR values of RCG, which consider the particle size variations and compaction energy, are summarized in Table 6. The CBR of well-graded FRG ranged from 18 to 25% under the Standard Proctor test, while the MRG ranged from 31 to 32%. Under the Modified Proctor test, the FRG showed CBR values between 42 and 48%, whereas the MRG ranged from 73 to 80%; this demonstrated an increase in strength compared to standard compaction. Studies consistently reported that MRG exhibited higher CBR values than FRG, although both were less than the CBR of crushed rock, as shown in Table 6. The higher CBR of crushed rock was attributed to its greater maximum dry density (MDD), as presented in Table 5, which suggests improved compaction due to a superior particle interlocking which increased its shear strength and load-bearing capacity. These findings emphasize the critical role of compaction energy, particle size, and gradation in influencing the CBR values for road applications. The lower CBR of FRG and MRG compared to crushed rock highlight the need for enhancement strategies such as blending with other materials to optimize the gradation and MDD.

Table 6. Comparison of CBR of RCG based on particle size and compaction effort.

Materials	CBR Value (%)		References
	Using Standard Compaction	Using Modified Compaction	
FRG (≤4.75 mm)	18–21	42–46	[7]
	-	42–46	[15]
	-	47–48	[6]
	-	44	[16]
	25.3	-	[18]
MRG (≤9.5 mm)	31–32	73–76	[7]
	-	75–80	[40]
Crushed rock (≤20 mm)	-	181	[15]

4.5. Shear Strength Behaviour

This section provides the findings from the previous studies that investigated the shear strength behaviour of RCG based on the performed direct shear tests and consolidated drained triaxial tests, and the results are summarized in Table 7.

4.5.1. Direct Shear Test

Wartman et al. [6] conducted direct shear tests to investigate the non-linear shear strength of RCG using the Mohr–Coulomb failure envelope. With zero cohesion to emphasize material non-linearity, especially in angular particles like RCG, they found internal friction angles ranging from 47° to 62° under normal stresses of 0 to 200 kPa. These values exceed the friction angles of 51° to 53° reported by FHWA [36] for RCG materials. Consequently, researchers studied the Mohr–Coulomb failure envelopes of RCG, which exhibits zero cohesion, and found a decreasing trend in the friction angle with increasing confining stress, as shown in Figure 6. This emphasizes the need for careful selection of strength parameters in the design. Despite this decrease in the friction angle, the RCG is comparable to, or exceeded, the natural soil and aggregates. The study also noted that the RCG demonstrated dilatant behaviour during shearing where higher confining stresses led to increased dilatancy [6,7]. MRG exhibits a 10–15% higher internal friction angle than FRG due to higher particle interlocking and larger particle size. The friction angles of FRG and MRG resemble dense sand or gravel, which indicates their potential for geotechnical applications.

It is interesting to note that, albeit crushed glasses present a relatively lower CBR value compared to natural aggregates, i.e., crushed rock (Table 6), their friction angle are similar or even superior to conventional materials. This is because CBR is influenced by factors such as particle packing, stiffness, density, and resistance to localized deformation; well-graded crushed rock compacts more efficiently, forming a denser structure with better load distribution, resulting in a higher CBR value (Ali et al. [15]); in contrast, RCG particles are more brittle and tend to have a high void ratio due to their irregular shapes and poor packing efficiency; as a result, under CBR testing, the material compresses more easily, reducing its ability to resist deformation. However, its angular particles and rough surface contribute to a high friction angle, which enhances shear resistance.

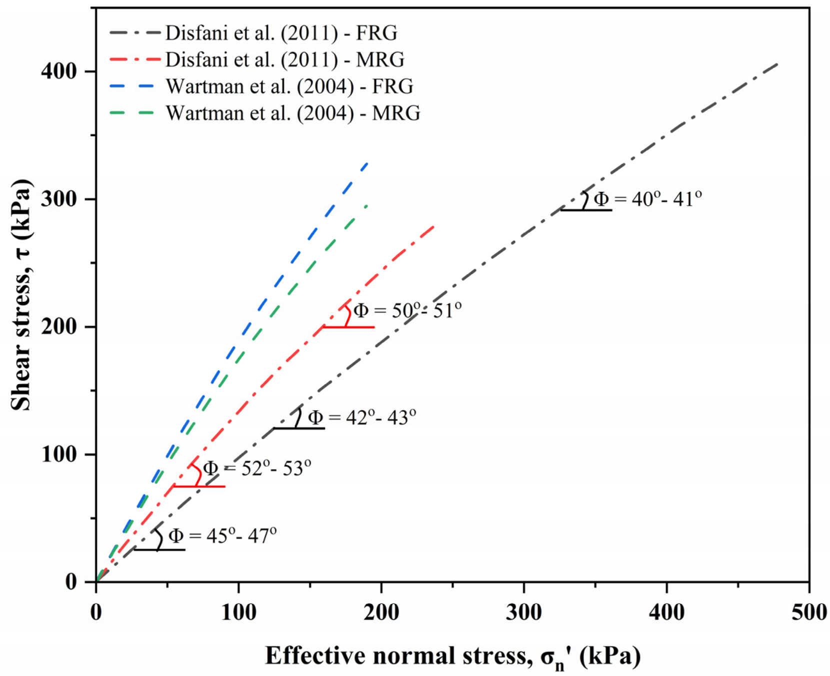

Figure 6. Mohr–Coulomb failure envelopes from direct shear tests on compacted CG samples (data sourced from [6,7]).

Meanwhile, Disfani et al. [7] observed an apparent cohesion in the FRG and MRG samples due to the effect of surface tension in the granular particles, the influence of water [50], and particles of debris. Recently, Chiaro et al. [10] investigated the shear strength of 2 to 8 mm particles of pure green glass under dry conditions. They found that, while the glass particles exhibited stiffness (unlike gravel), they were also easily crushed under higher normal stresses. This suggests that the shear strength characteristics of glass are influenced by particle breakage under load, which highlights the importance of considering particle breakage as a critical parameter when shear testing these mixtures. Overall, these studies provide insights into the shear strength of CG that is influenced by particle size, gradation, applied pressure, and particle breakage.

Table 7. Shear strength properties of RCG.

Properties	USCS Classification	Value	References
Direct Shear Test—Friction angle, °	SW	47–62 FRG: 40–47 MRG: 50–53	[6] [7,15] [7,51]
	SP	34–51	[51,52]
	GP	45–54	[49,52]
Drained Triaxial Test—Friction angle, °	SW	47–48 37–48 FRG: 35–40 MRG: 41–42	[6] [49] [7]
	SP	31–37	[12]
	GP	44–45	[49]

4.5.2. Triaxial Test

Previous studies used consolidated drained triaxial tests to investigate the geotechnical characteristics of RCG materials [6,7]. The deviator stress–axial strain trends from these past studies are compared in Figure 7a with the applied confining pressures in the brackets. The results indicate that at all levels of confining pressure there is a gradual increase in peak stress (failure stress) followed by a slight decrease in residual stress with limited strain softening. This stress–strain behaviour of dense sand is typical because there is a decrease in strength following peak strain [52]. However, this gradual increase in deviatoric stress leading to peak strength and the subsequent slow decline to residual stress (ultimate stress) resembles the behaviour of loose sand; from this, they noted that the behaviour of FRG and MRG resembles the characteristics of dense and loose sand. Wartman et al. [6] observed a peak deviator stress at 5–8% of axial strain for the FRG sample and a slightly higher strain (7–10%) for the MRG sample. Disfani et al. [7] observed a consistent increase in strain (8–18.5%) at failure with increasing confining stress for FRG and MRG; the result for MRG is shown in Figure 7a.

The volumetric behaviour from both studies is shown in Figure 7b. Wartman et al. [6] observed an increase in dilation with an increasing confining stress (27–140 kPa), the FRG samples exhibiting greater dilation due to their higher relative density. Conversely, Disfani et al. [7] found that the MRG samples demonstrated contraction at higher confining pressures (>120kPa) and initial contraction followed by dilation at lower confining pressures (≤120 kPa). Increasing contraction occurred with increasing confining stress, which is consistent with the characteristics of loose sand [53]; this suggests there is a transition from dense to loose sand-like conditions due to initial contraction followed by dilation. A similar volumetric response occurred in FRG samples.

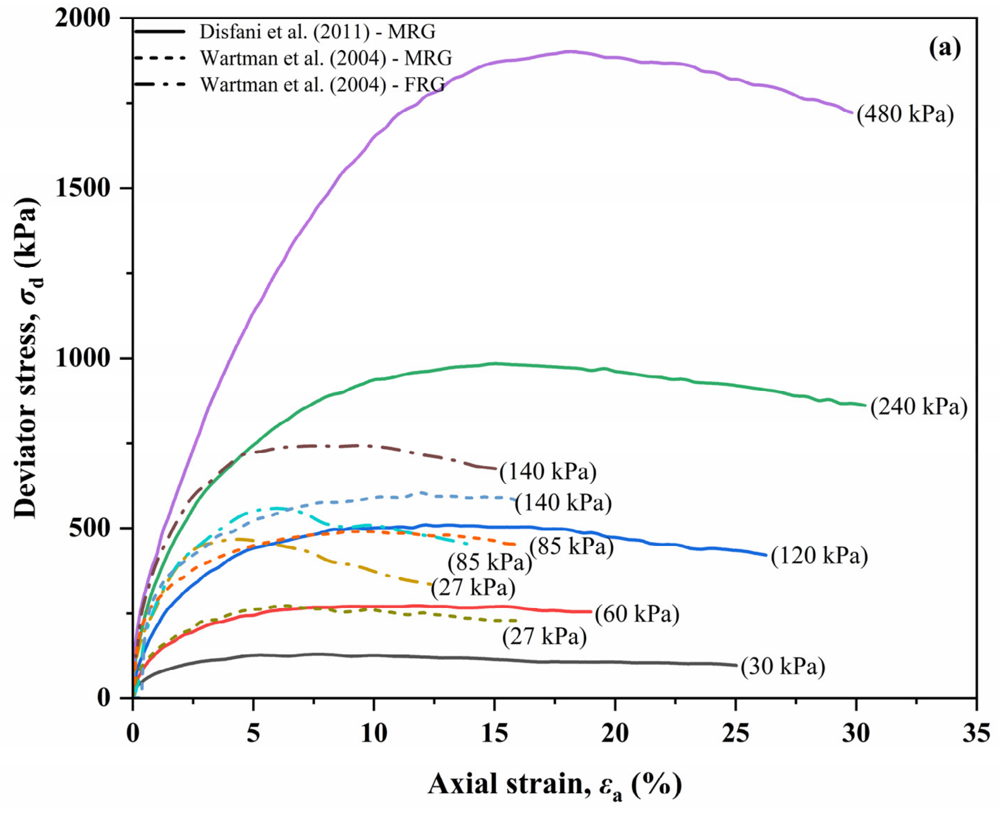

Figure 7. *Cont.*

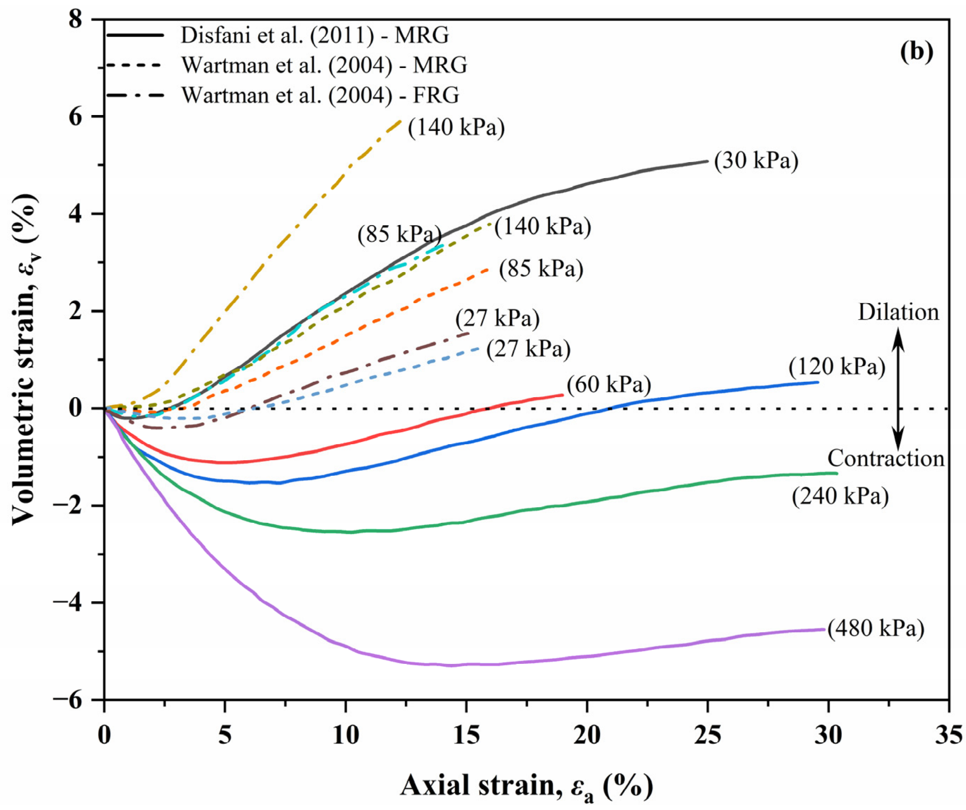

Figure 7. Response of compacted crushed glass in CD triaxial tests for (**a**) changes in deviator stress and (**b**) changes in volume with axial strains (data sourced from [6,7]).

While both studies report a relative density of 90%, difference in particle size distribution (as shown in Figure 3), particularly the presence of fines, likely plays a key role in their inverse volumetric strain behaviour. The material in the Disfani et al. [7] study contains a higher proportion of fine particles, which act as fillers during particle rearrangement. Upon loading, these fines facilitate greater compression, resulting in a contractive behaviour and leading to an even denser state. In contrast, the material in the Wartman et al. [6] study contains fewer fines, limiting its compressibility and causing it to exhibit a more dilative behaviour under loading.

The shear strength parameters for the linear Mohr–Coulomb envelope are shown in Figure 8 [6,7]. Past studies found that the internal friction angles determined through triaxial shear tests were approximately 10–20% less for glass materials compared to direct shear tests; this was probably due to differences in the boundary condition (how stress is applied during testing) and the lower dry unit weight of triaxial samples to avoid damaging the membrane. Wartman et al. [6] reported friction angles of around 47–48° for crushed glass, while Disfani et al. [7] found values of approximately 38° for FRG and 41° for MRG. Both studies also identified an apparent cohesion that was probably influenced by the linear representation of the failure envelope, potential non-linear failure, and contaminants such as adhesive materials (i.e., label glue) [6]. The triaxial test results are considered to be more representative of field conditions and are therefore recommended for RCG design applications. According to Arulrajah et al. [16], FRG had a drained cohesion of 0 kPa and the lowest drained friction angle of 38°, which is similar to coarse sand with minimal cohesion. These results demonstrate the reasonably appropriate engineering characteristics of RCG and its potential as an alternative to natural aggregates for transportation infrastructure such as embankment fill, subbase and subgrade materials, and railway sub-ballast and subgrade.

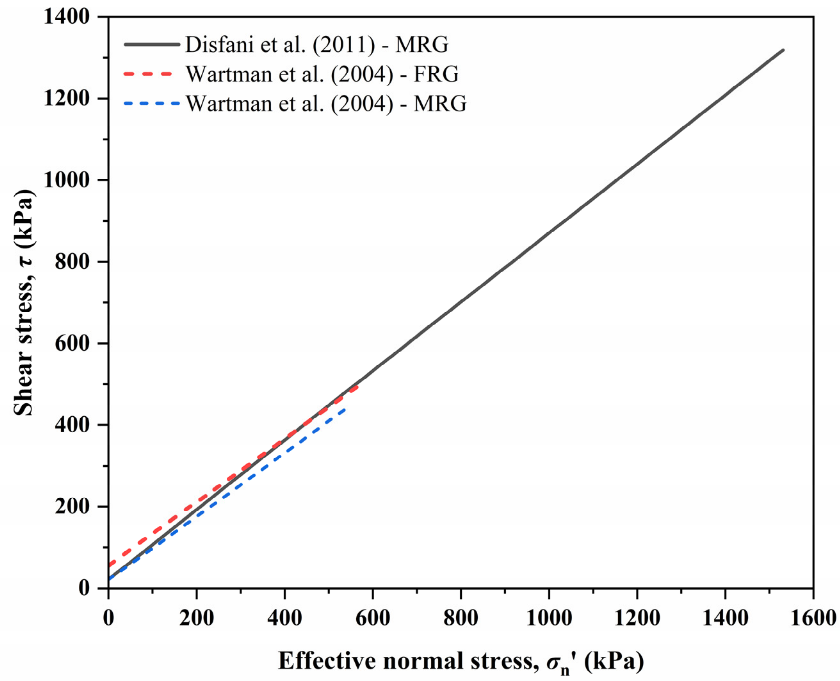

Figure 8. Mohr–Coulomb failure envelopes from CD triaxial tests on compacted CG samples (data sourced from [6,7]).

5. Applications of RCG in Transport Infrastructures

Given this unique combination of properties as outlined in the previous sections, RCG emerges as a promising raw material for geotechnical engineering applications because it is an environment-friendly, cost-effective, and widely available alternative to natural aggregates. The subsequent sections will further explore its utilization in transportation infrastructure projects to evaluate its long-term performance and engineering characteristics.

5.1. Applications as a Stabilizing Agent in Clayey Soils

Most saturated clays are generally soft and prone to yield quickly at lower stress levels due to their weak shear strength. Specifically, the volumetric changes of expansive clay due to its high swelling and shrinkage, low bearing capacity, and high compressibility make it a challenging material to use for constructing road and railway subgrade. One of the practical solutions used to enhance the shear strength and stiffness of these problematic soils is mechanical stabilization using foreign additives. Researchers investigated the effect of adding sand-sized crushed glass particles to clay as a stabilization technique and found it helps to mitigate the adverse properties of soft and expansive clays, while making soft clay a stiffer material for transportation infrastructure foundations and subgrade. Some previous studies investigated the use of waste glass in various forms, such as glass powder, residue, fine particles, and cullet (crushed glass), to enhance the performance of different types of clay, as well as low, medium, and high-plasticity clay [13,41,54].

Past studies showed that incorporating RCG into clay soils significantly influences their compaction characteristics, particularly MDD and OMC, as shown in Figure 9. Grubb et al. [12] and Malasavage et al. [13] observed a significant improvement in the compaction and workability of high-plasticity clays as the MDD increased and the OMC decreased with the addition of 20–80% MRG. Incorporating up to 20% of FRG into low-plasticity clays led to a slight increase in MDD and a marginal reduction in OMC [41]. The effect of adding 10%, 20%, and 25% of powdered glass to high and low-plasticity clays was also investigated [54]. There was a clear increase in MDD for high-plasticity clays with up to 25% of powdered glass, while low-plasticity clays exhibited a significant increase in

MDD with up to 10% of powdered glass; there was only a slight increase afterwards, as shown in Figure 9. These changes are primarily due to the low water absorption properties of RCG.

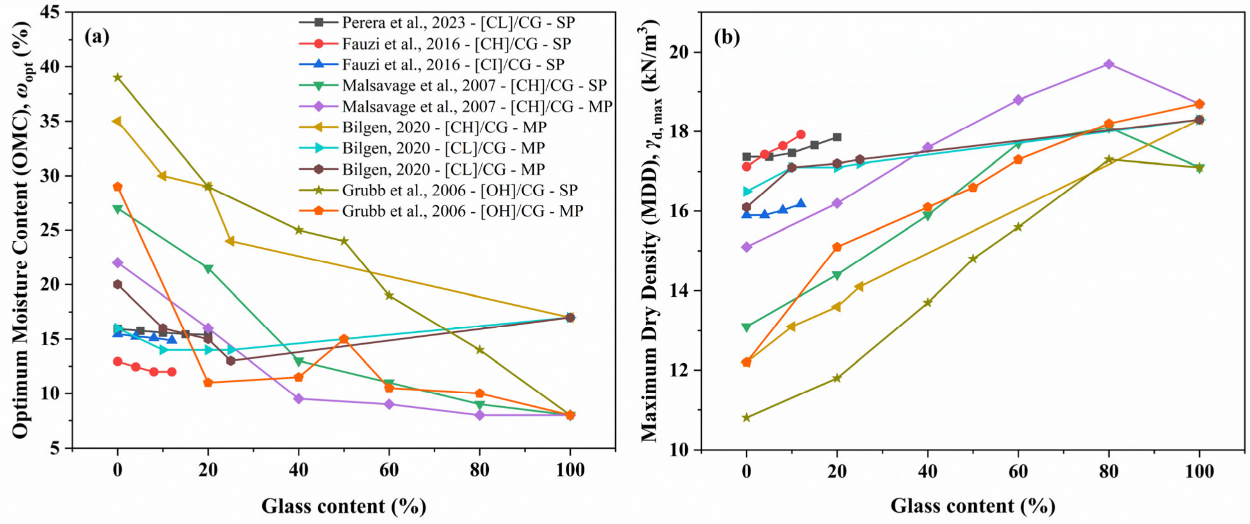

Figure 9. Variation of (**a**) OMC and (**b**) MDD with the addition of RCG in various clayey soils based on the existing literature (MP—Modified Proctor and SP—Standard Proctor compaction) (data sourced from [12,13,41,54,55]).

Previous studies also showed that incorporating RCG into problematic soils can reduce their potential swelling, shrinkage, and compressibility. In a low-plasticity clay, an optimal amount of 15% FRG led to a 28% reduction in swelling–shrinkage potential [41], and a high-plasticity clay exhibited a 33% decrease in compressibility with 40% of MRG [13], while the addition of 20% MRG in high-plasticity organic silt reduced the compressibility by 50% [12]. These enhancements were primarily attributed to the low water absorption of RCG and the angular and rough surface texture of RCG particles. These characteristics promote effective interlocking and denser packing within the clay–glass blend which increases the frictional resistance between clay and glass particles and mitigates the heaving and shrinkage of clay soils.

Past studies also reported improvements in geotechnical properties such as the California Bearing Ratio (CBR), the unconfined compressive strength (UCS), the porosity, the hydraulic conductivity, and the shear strength (in terms of the friction angle), as well as the resilient modulus (M_r), as recycled glass particles were incorporated into clay [13,41,54–56]. Variations of CBR values and shear strength parameters with the amounts of RCG are shown in Figure 10. Moreover, the inclusion of RCG also led to higher yield and peak stresses in the stress–strain curve while reducing the dilation in expansive clays [14,47]. These findings further reinforce the potential of RCG as an additive for soft soil that will enhance its geotechnical properties.

Notably, Grubb et al. [11] conducted a field study to assess the effectiveness of MRG combined with dredged material as an embankment fill. They found that incorporating 20–80% of MRG increased its dry densities by 1.5–5.5 kN/m^3 in field conditions; this surpasses the levels of density achievable with traditional stabilization additives such as Portland cement, fly ash, or lime. Moreover, RCG significantly enhanced the workability of dredged material, which facilitated construction with standard equipment and a minimum number of crew. These improvements increased the load-bearing capacity, reduced the settlement, and mitigated the expansive behaviour of clays containing Montmorillonite minerals—a key factor in preventing damage to roads and highways built on expansive clay subgrades.

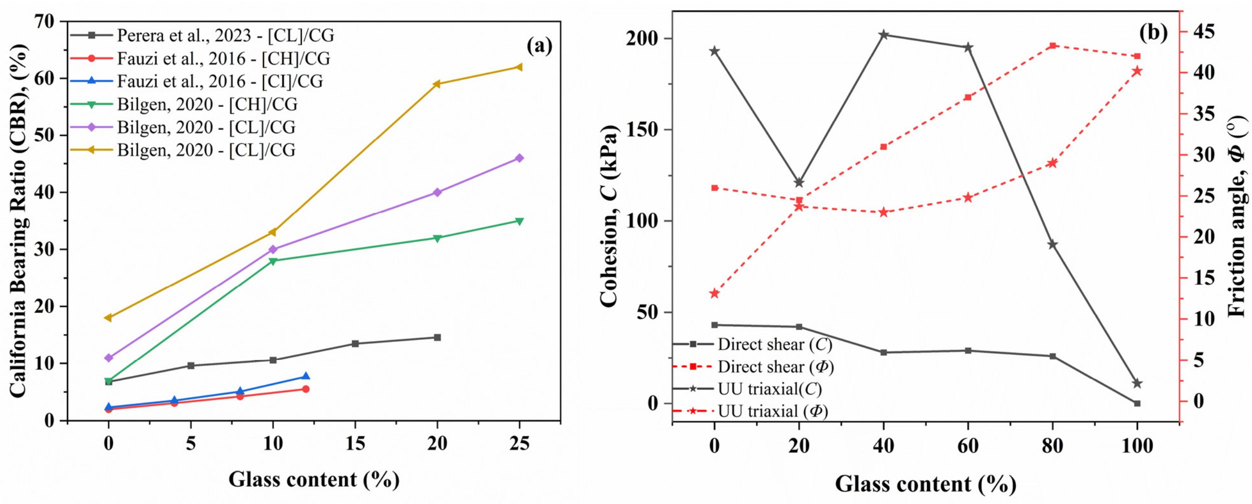

Figure 10. Variation of (**a**) CBR based on different studies (data sourced from [41,54,55]) and (**b**) shear strength parameters (data sourced from [13]) with the addition of CG in various clayey soils.

5.2. Applications of RCG in Railways

While several studies investigated the use of a variety of recycled materials in railway substructures [17,19,20,22–24,57], very few studies examined the suitability of RCG as a supplementary material for railway capping layers [18,21]. The capping or sub-ballast layer is a compacted aggregate layer positioned between the ballast and subgrade in the railway substructure [58,59]; it functions as a structural layer by mitigating the cyclic stresses transferred from the ballast to the subgrade, thus ensuring that the subgrade can sustain these loads over the period of its service life [59]. This layer is exposed to surface water, rainfall, and complex cyclic loadings with high deviator stresses at low confinement levels [17]; since this can lead to instability, there is a need to do the performance-based evaluations of capping materials.

Naeini et al. [18] examined the suitability of blends made from recycled concrete aggregates (RCA) and RCG for railway capping layers. These materials (RCA and RCG) had maximum particle sizes of 20 mm and 5 mm, respectively, and 0–50% of RCG was mixed with RCA by weight. According to the Australian standards [60,61], capping materials should have a CBR value exceeding 50% because it is a key strength parameter used by the construction industry to evaluate the suitability of granular materials for railway capping layers. However, incorporating RCG into RCA reduced the CBR values [18], probably because the shear strength of RCG particles is lower than RCA [16]. Specifically, the CBR values decreased from 74.24% to 48% as the amount of glass increased from 0% to 50%. However, while those blends with up to 40% RCG still satisfied the minimum CBR requirements, all the blends met the Los Angeles abrasion threshold of less than 50, a specification typically adopted for capping materials [59,62].

The Standard Proctor Compaction tests revealed that the OMC of the RCA/RCG blends decreased as the amount of RCG increased; it remained relatively unchanged from 40% to 50% RCG (Figure 11). Similarly, the MDD initially decreased with up to 30% RCG, but then it increased markedly with the addition of 40% and 50% of RCG, as shown in Figure 11. This shift can be attributed to a transition in the structure of the blend as it evolved from a coarse-grain-supported matrix to a fine-grain-supported matrix. In this configuration, the sand-sized particles of RCG and RCA fill the voids between the coarse particles and thus reduce the overall porosity of the mixture.

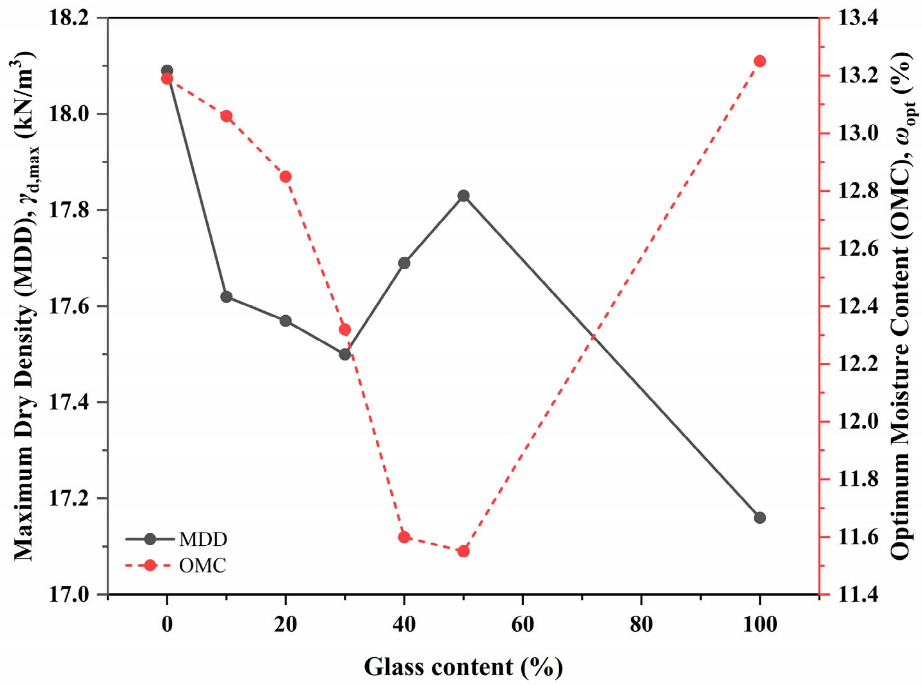

Figure 11. Variation of MDD and OMC with the addition of RCG in RCA/RCG blends (data sourced from [21]).

Later, Naeini et al. [21] analyzed the static and cyclic behaviour of these mixtures to identify the optimal composition for railway capping layers. A multi-stage triaxial test was carried out to investigate the stress–strain behaviour and variations in shear strength of the RCA/RCG blends. The results showed that, at all confinement levels, the peak deviatoric stress (q_{peak}) decreased as the amount of RCG increased from 10% to 40%; this was mainly due to the lower shear strength of RCG particles relative to RCA. Interestingly, blends with 40% and 50% RCG exhibited similar q_{peak} values, as shown in Figure 12, likely due to the increased dominance of sand-sized glass particles within the matrix. Additionally, the axial strain corresponding to q_{peak} increases with larger amounts of RCG at all confinement levels, reflecting a transition to greater ductility (due to the reduced strain-softening of RCG) [40]. This behaviour can be attributed to the reduced brittleness of the RCA and increased interactions among RCG particles within the force chain skeleton. The volumetric strain responses revealed minimal compression for the blends under an initial confinement of 10 kPa, with the impact of the amount of RCG being limited at this level. However, as the amount of RCG increased, the dilation of these blends decreased significantly due to the lower dilation of RCG compared to RCA. This reduction in dilation further highlights the shift in mechanical behaviour as the blend composition changes.

The inclusion of RCG into the RCA/RCG blends reduced cohesion due to the non-cohesive nature of RCG, as shown in Figure 13 [18,21]. Interestingly, the frictional resistance of the blends remained higher than pure RCA (≈42°) when the amount of RCG was up to 30% (>42°). However, with 40% and 50% of RCG, the friction angle decreased to approximately 40°, as shown in Figure 13. This shift is attributed to the dominance of contact forces between the RCG particles within the matrix which altered the mechanical behaviour of the blend and helped to reduce the overall frictional resistance.

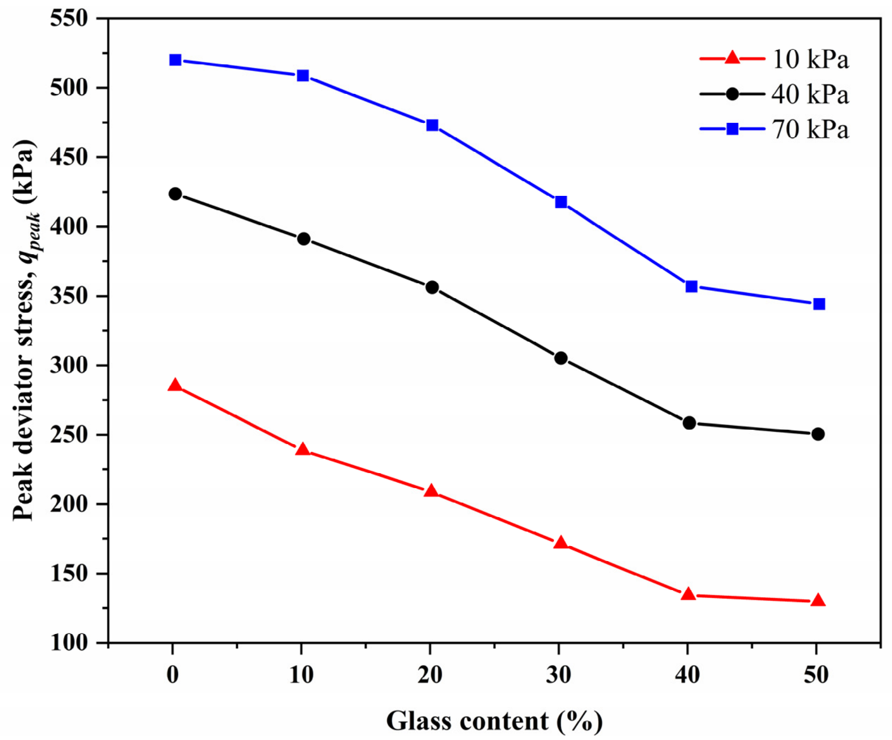

Figure 12. Variation of peak deviator stress with the addition of RCG in RCA/RCG blends under various confining pressures (data sourced from [21]).

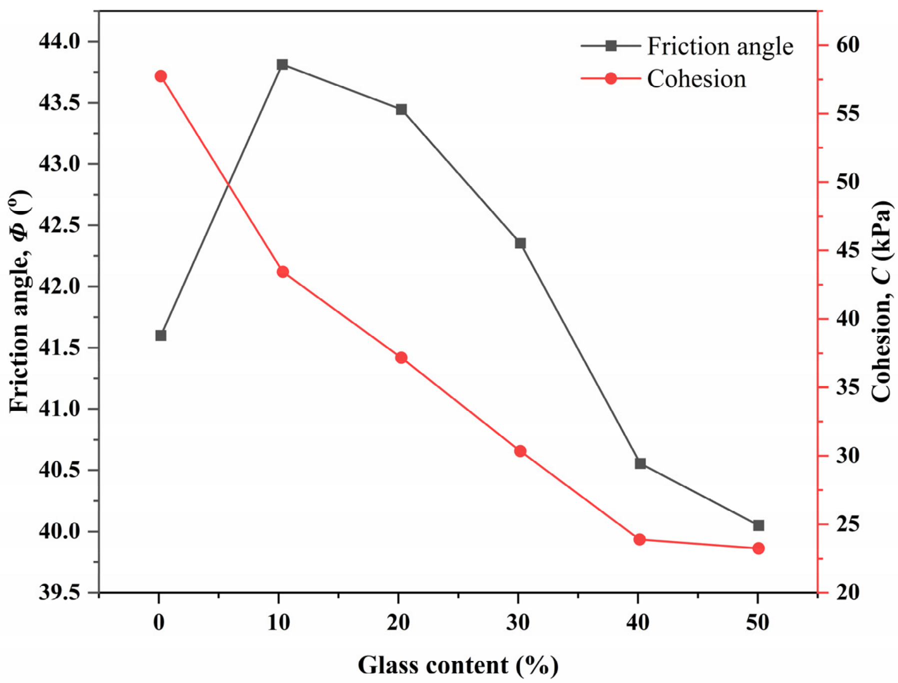

Figure 13. Variation of shear strength parameters with the addition of RCG in RCA/RCG blends (data sourced from [21]).

The stiffness of capping materials is a critical factor in determining the thickness of the railway capping layer under cyclic loading conditions [57]. The stiffness is usually evaluated by measuring the resilient modulus (M_r), which represents the ratio between the maximum deviatoric stress (q_{max}) and the corresponding recoverable axial strain (ε_a). Naeini et al. [18,21] utilized a repeated load triaxial testing protocol and multi-stage cyclic permanent deformation tests to assess the M_r of RCA/RCG blends used as capping materials. Their findings revealed that the highest M_r value was achieved with a blend containing 10% RCG; this blend had a better frictional resistance than pure RCA. However, as the amount of RCG increased from 10% to 50% there was a decreasing trend in the M_r value. Importantly, all the tested blends exhibited higher M_r values than the minimum requirement for capping materials because they ranged between 55 and 105 MPa [62]. This indicates that the RCG blends would provide comparable or even higher stiffness than conventional capping materials.

Overall, blends with 10–20% RCG were optimal alternatives to conventional capping materials because they offered a balance of high stiffness and strength, while complying with the required performance standards. These findings highlight the potential of incorporating recycled glass into railway infrastructure without compromising mechanical performance. Despite these promising findings, the review still highlighted the limited use of RCG as a supplementary material for railway substructures. This underscores the need for further research and wider adoption of RCG materials to enhance the performance and sustainability of railway infrastructure.

5.3. Applications of RCG in Road Substructure

Existing studies highlighted the extensive research carried out on the feasibility of using RCG to replace natural aggregates in roadwork and earthwork applications [6,7,15,40,43]. These findings indicate that RCG, either alone or mixed with natural or recycled aggregates like crushed rock and concrete, is suitable for load-bearing material in road pavement and subbase layers, fill material in embankments, and trenches and backfill material in retaining walls, as tabulated in Table 8. These findings also suggest that recycled glass is a viable material for free-draining applications such as filters and drainage blankets [6,43].

A field trial of an asphalt footpath in Victoria, Australia, demonstrated that adding FRG to the crushed rock base enhanced its workability and compaction but reduced its strength; however, a 15% FRG blend yielded optimal performance with high strength compared to the parent rock [63]. Further research studies confirmed that recycled glass in pavement subbase layers (Class 3) meets engineering standards and regulatory requirements when combined with up to 30% of crushed rock by mass [15]. Arulrajah et al. [16] stated that, while blends of RCG with 20% FRG and recycled concrete aggregate (RCA) or waste rock show promising performance for subbase applications, they do not fully meet the standards for pavement bases. The physical and geotechnical properties of RCG indicate that it is suitable for fill material in structural and non-structural applications because the density of recycled glass is lower than natural aggregate; this then reduces the lateral pressure on retaining walls, an effect that can lead to a more economical design for the retaining walls. Clean Washington Center [43] suggests that up to 30% of recycled glass can be used for stationary load backfills, but this percentage is limited to 15% for fluctuating loads. Also, up to 100% of recycled glass can be used as a backfill for non-structural applications.

Previous studies demonstrated that sand–tyre shred mixtures enhance the shear strength, which makes them suitable for embankments subjected to heavy loads [64]. Similarly, FRG exhibits the same strength characteristics as sand [7,40], which suggests it could be with tyre crumbs as a lightweight fill material in highway embankments. Research by Disfani et al. [9] identified the optimum amount of tyre crumbs is from 10 to 20% under a high level of confinement and from 20 to 30% under a low level of confinement; these amounts would ensure adequate shear strength, stiffness, and compressibility for lightweight highway embankments.

Table 8. Summary of applications of recycled glass as a replacement for natural aggregates in roadworks and earthworks based on existing studies.

Study	Materials	Application	Glass Content (%)
[43]	Recycled glass	Stationary load backfills Fluctuating load backfills Non-structural backfills	Up to 30% Up to 15% Up to 100%
[40]	Recycled glass	Load-bearing material in road pavements, backfill material in trenches, and behind the retaining walls	-
[32]	FRG	Road embankment fills, pipeline beddings, and road subbase layers	-
[63]	FRG with crushed rock	Footpath trial (asphalt shared path)	Limited to 15%
[6,7]	FRG and MRG	Filling material in trenches, behind the retaining walls, road pavements, and embankment fills	-
[15]	Recycled glass with crushed rock	Road pavement subbase	Up to 30% (by weight)
[16]	FRG with RCA and FRG with waste rock	Road pavement subbase	20%
[9]	FRG and tyre crumbs	Lightweight backfill/embankment fills	FRG from 70% to 90%
[65]	FRG and crushed limestone	Granular base layer (MG20)	Up to 11.4% (by volume)
[10]	Glass, gravel, and rubber	Structural fills	Up to 60% (by volume)

Furthermore, RCG has a high friction angle, and when properly graded, it will develop a substantial shear strength under appropriate relative density and confining stress conditions. This characteristic makes RCG a viable material for compacted aggregate foundations and ground improvement techniques such as sand compaction piles, vibro-replacement, and vibro-flotation, particularly in transportation infrastructure applications [40].

6. Field Applications—A Way Forward

Since 1998, RCG has been utilized as an aggregate substitute in asphalt paving for highways [36] where it gained traction worldwide as a sustainable alternative to natural aggregates. In the USA, several state departments of transportation have published regulations and specifications to facilitate the use of RCG in roadwork applications such as bases, subbases, embankments, structural fills, and utility trench fills [40,43]. No data were reported in Australia about using RCG in roadworks until the year 2000, and even by 2009, its use was limited with only 3–5% of recovered glass permitted in granular products due to knowledge gaps in geotechnical properties and environmental concerns [66]. However, from 2011 the state of Victoria has used fine RCG in asphalt mixes for intermediate and base courses and from 2018 in general concrete pavements. The Western Roads Upgrade incorporated 190 million recycled glass bottles into sections of roads and structures such as bridges and culverts; here they achieved a 65% reduction in carbon emissions and also conserved natural resources. In the state of New South Wales [67], the Albion Park Rail bypass recycled 30 million glass bottles in a 98 km upgrade, with 10% RCG used in the asphalt base layer. Additionally, a Canterbury-Bankstown trial road utilized a subbase mix of 30% RCG and 70% crushed concrete [67,68]. As well as road construction, RCG has been used as bedding materials for underground cables and drainage, diverting large amounts of waste from landfills and reducing the reliance on natural resources. Glass can be recycled endlessly without any loss in quality, which makes it an ideal construction material for a circular economy. However, challenges such as low glass waste generation in small communities, proper recovery, processing, and maintaining a consistent supply of waste glass still remain unresolved in many regions worldwide.

7. Environmental Impacts and Health Concerns

The use of RCG in road and railway substructures has emerged as a sustainable alternative that offers geotechnical and engineering properties comparable to natural aggregates. This innovation not only reduces our reliance on natural resources and diverts large quantities of waste from landfills, but it also helps to lower carbon emissions. For instance, utilizing recycled glass can reduce CO_2 emissions by 46.7% compared to quarry-derived sand in construction projects [69]. Despite these advantages, however, the broader adoption of RCG is still limited due to concerns about leaching, contamination, and the need for quality control. Quality control is very important for addressing environmental concerns such as variations in the origins of waste streams and methods of processing; moreover, quality control highlights the importance of standardizing protocols to ensure consistent quality and reduce risks such as contaminated debris and odours [43,66,68]. Moreover, since the performance of recycled materials in substructure applications is influenced by environmental factors such as rain and the moisture content, it is very important to understand leachable concentrations and the possible emission of contaminants. In light of this, studies on the environmental consequences of using RCG have been thoroughly reviewed and discussed [6,43,70].

In 1998, the Clean Washington Center [43] investigated the broader chemical properties of glass cullet leachate by assessing the suitability of RCG as a construction aggregate. Parameters such as Biochemical Oxygen Demand, Total Phosphorus (TP), and Total Kjeldahl Nitrogen (TKN) were found to decrease over time, so they posed no environmental risks. Furthermore, concentrations of suspended and dissolved solids were so low they were difficult to measure and were not expected to cause any environmental concerns. Additionally, Total Organic Carbon (TOC), pH, and total concentrations of chromium, copper, zinc, nickel, Selenium, and lead, etc., were similar to or lower than those found in naturally occurring soils such as granite. However, they did not investigate heavy metal leaching using advanced testing methods. This gap in evaluating leaching risks was addressed later by Wartman et al. [6] and Disfani et al. [70]; they provided a more comprehensive understanding of heavy metal leaching and reaffirmed the environmental viability of RCG in road construction applications.

Leaching tests provided valuable insights into the environmental safety of using RCG as an alternative construction aggregate in road substructures [6,70]. Wartman et al. [6] utilized the Toxicity Characteristic Leaching Procedure (TCLP) and Synthetic Precipitation Leaching Procedure (SPLP) to simulate metals leaching under landfill and the condition of soils using U.S. EPA guidelines. As shown in Table A1 (attached in Appendix A), concentrations of heavy metals in RCG were well below hazardous waste thresholds and US EPA drinking water standards, albeit their assessment was limited to a few heavy metals and a single buffer solution. Disfani et al. [70] then carried out more comprehensive tests that are outlined in the EPA Victoria [71,72]; this included the Total Concentration [60] and Australian Standard Leaching Procedure (ASLP) under both acidic and alkaline conditions (using two buffer solutions). Their findings revealed that concentrations of contaminant in FRG and MRG were well below thresholds for solid inert waste and hazardous waste, even under extreme conditions such as acid rain, as given in Table A1. These results confirm that RCG poses negligible leachate hazards to surface or groundwater during its service life and fulfils the environmental standards set by EPA Victoria for fill materials, provided it is properly processed to remove contaminants such as heavy metals and organic debris. Both studies underscore the compliance of RCG with environmental standards, thus supporting its safe application as a sustainable material in geotechnical applications. To further mitigate environmental risks, EPA Victoria [73] recommended the strategic placement of RCG in capped or elevated applications such as beneath sealed road surfaces or in overpasses. These approaches will reduce exposure to environmental elements such as rainwater infiltration and minimize the potential for contaminants to migrate into surface or groundwater. Overall, comprehensive leachate testing and adhering to processing standards must be followed up before applying RCG materials in road and railway substructures, in order to minimize environmental risks.

In addition to environmental concerns, the use of RCG as a sustainable alternative in construction materials also raises questions about health risks related to physical handling and inhalation. Physical injuries such as cuts and punctures are a concern when handling crushed glass; however, studies show that the crushing process reduces the sharpness of glass particles, which makes them safer and comparable to natural aggregates. Past research indicates that RCG passing through a 9.5 mm sieve poses minimal risk of injury [11,12,37]. The inhalation of glass dust is another concern, but unlike natural sand which contains harmful crystalline silica, glass dust contains amorphous silica which is biologically inert and non-carcinogenic [43]. Despite this, exposure to fine particles during construction still requires precautionary measures such as wearing dust masks and the proper monitoring of job sites. Even though the health risks from recycled glass are lower than from natural aggregates, appropriate safety measures, such as gloves, dust masks, and eyewear, are essential to mitigate health and inhalation risks [37]. Nevertheless, further research and consistent regulations are necessary to ensure the safe and widespread adoption of RCG in infrastructure projects.

8. Limitations of the Study

This review paper primarily focuses on the application of RCG in granular layers of roads and railways and does not explore its potential uses in concrete, cement, or asphalt mixes. Hence, the thermal stability, binding properties, and behaviour of RCG in combination with binding materials have not been addressed.

9. Conclusions and Future Recommendations

The utilization of RCG in transportation infrastructure presents a promising solution for sustainable construction by reducing reliance on natural aggregates and addressing critical waste management challenges. This review summarizes the suitability of RCG (FRG and MRG), which exhibits comparable physical, chemical, and geotechnical properties to conventional materials and industry specifications, making it suitable for diverse applications in transportation infrastructure components, such as road base, subbase, subgrade, railway capping, and embankment fills. Also, this paper discussed the effectiveness of RCG in improving the engineering properties of expansive clays as a stabilizing agent, which further reinforces its potential in geotechnical applications.

The key findings are concluded below:

- The properties of RCG can vary significantly due to differences in material suppliers, particle sizes, shape, gradation, and the presence of debris.
- Well-graded RCG particles passing through a 9.5 mm sieve can replace natural aggregates, maintain angularity, and improve their interlocking behaviour, while showing high shear strength and friction angles like natural sand and gravels.
- The specific gravity of RCG is approximately 10% lower than most natural aggregates (2.60 to 2.83).

- Los Angeles (LA) abrasion values for RCG range from 24% to 27%, which is slightly higher than natural aggregates (12–20%), but still within acceptable limits for road bases and subbases set by the road authorities.
- Direct shear tests indicated that the shear strength of RCG is influenced by particle size, applied pressure, and particle breakage. The friction angles of FRG and MRG resemble well-graded dense sands or gravels, thus demonstrating their potential suitability for geotechnical applications.
- Triaxial shear tests indicated that the internal friction angles of RCG materials were approximately 10–20% lower than the direct shear tests, due to differences in boundary conditions. Since triaxial tests better simulate field conditions, they are recommended for the design and application of RCG in engineering projects.
- The use of RCG significantly improves the engineering properties of expansive clays by enhancing its workability, CBR, porosity, hydraulic conductivity, shear strength, and resilient modulus, while reducing the swelling–shrinkage potential, compressibility, and dilation behaviour.
- The addition of up to 80% RCG increases the dry density of dredged material under field conditions, thus achieving higher density levels than traditional stabilization additives such as Portland cement, fly ash, or lime.
- Blending RCG with RCA up to 40% meets the CBR requirements and achieves a stiffness that is comparable to conventional capping materials. Furthermore, the addition of RCG (up to 30%) enhances the friction angle and improves the ductility of the blend compared to pure RCA, contributing to greater stability and overall performance in railway capping applications.

In addition to the advantages from a technical perspective, the utilization of RCG offers substantial environmental benefits, including a significant reduction in landfill waste, lowering the carbon emissions, and promoting the conservation of natural resources. The existing studies report that comprehensive leaching assessments (i.e., TCLP, SPLP, ASLP, and Total Concentration) for the RCG exhibit minimal contamination risks, ensuring its safe use under various environmental conditions, such as exposure to acid rain. On the other hand, RCG passing 9.5 mm poses minimal risk of physical injury, and unlike natural sand, they are free from crystalline silica, making it a suitable and safer alternative for construction works, which contributes to improved occupational health and safety standards.

From an industrial perspective, the adoption of RCG in roadworks and railway substructures offers a cost-effective, resource-efficient solution that meets engineering performance standards while reducing reliance on virgin aggregates. Its successful implementation in large-scale infrastructure projects demonstrates its practical viability and potential for broader industry adoption. Additionally, RCG aligns with circular economy principles by promoting material reuse, minimizing waste, lowering raw material extraction costs, and enhancing resource sustainability in construction. However, continued research, industry collaboration, improved waste management systems, and regulatory advancements are essential to optimizing its application and maximizing its long-term impact on sustainable construction.

Future research should focus on optimizing processing techniques, evaluating the long-term durability and thermal stability of RCG, and assessing its feasibility for complete replacement in both structural and non-structural layers. The development of standardized guidelines will be essential to facilitate the large-scale adoption of RCG in transportation infrastructure. Furthermore, research should investigate the environmental benefits of RCG, particularly its potential to reduce carbon emissions, conserve natural resources, and contribute to sustainable development. Additionally, there is limited research on RCG as a standalone granular material and its specific applications in railway substructures, underscoring the need for further investigation in these areas. Moreover, future studies should analyze the post-construction engineering performance of RCG in large-scale applications to better understand its long-term durability. Addressing these knowledge gaps will support the broader utilization of RCG as a viable alternative to natural aggregates, advancing the transition toward more circular and environmentally sustainable practices in the construction industry.

Author Contributions: Conceptualization, B.I., Y.Q. and N.T.; methodology, B.I., Y.Q. and N.T.; investigation, Y.Q. and N.T.; and data curation, N.T.; writing—original draft preparation, N.T. and Y.Q.; writing—review and editing, N.T., Y.Q., B.I. and C.R.; supervision, B.I., C.R. and Y.Q.; funding acquisition, B.I., C.R. and Y.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Australian Research Council Discovery Project (ARCDP220102862) and Linkage Project (LP200200915). Significant financial support from Sydney Trains, Transport for NSW, SMEC, Bently Systems, Bestech Australia, and other industry organizations over the years is gratefully appreciated.

Data Availability Statement: The data presented in this study are openly available as indicated from the cited references.

Acknowledgments: The authors would like to acknowledge the financial support from the Australian Research Council for ARCLP200200915 and ARCDP220102862. The authors would also like to express appreciation for the technical and financial support from industry partners, including Sydney Trains, Bentley Systems Pty. Limited, SMEC Australia Pty. Limited, and Bestech Australia Pty. Limited.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Summarized comparison of various leaching procedures and total concentration test results of recycled glass wastes along with the existing threshold values of fill material, inert solid waste, hazardous waste, and drinking water.

References	Wartman et al. [6]				EPA Victoria [72,73]			Disfani et al. [70]					
Contaminant	Hazardous Waste Thresholds (mg/L)	US EPA (1999) Potable Water Standard (mg/L)	TCLP (mg/L)	SPLP (mg/L)	Maximum TC for Fill Material (mg/L)	Threshold for Solid Inert Waste		FRG			MRG		
						TC (mg/kg)	ASLP (mg/L)	TC (mg/kg)	ASLP (Acet) (mg/L)	ASLP ((Borate) (mg/L)	TC (mg/kg)	ASLP (Acet) (mg/L)	ASLP ((Borate) (mg/L)
Arsenic	5.0	0.05	<0.1	<0.1	20	500	0.35	<5	<0.01	<0.1	<5	<0.01	<0.1
Barium	100	2.0	0.151	<0.1	-	6250	35	6	0.1	<0.1	53	0.31	0.1
Beryllium	-	-	-	-	-	100	0.5	<5	<0.01	<0.1	<5	<0.01	<0.1
Cadmium	1.0	0.005	<0.01	<0.01	3	100	0.1	0.5	0.004	<0.02	<0.2	0.004	<0.02
Chromium	5.0	0.1	0.0772	<0.03	1	500	2.5	<5	<0.01	<0.1	11	0.01	<0.1
Copper	-	-	-	-	100	5000	100	6	0.12	<0.1	6	0.06	<0.1
Lead	5.0	0.015	0.128	<0.1	300	1500	0.5	12	0.19	<0.1	72	0.4	<0.1

Table A1. *Cont.*

References	Wartman et al. [6]				EPA Victoria [72,73]			Disfani et al. [70]					
						Threshold for Solid Inert Waste		FRG			MRG		
Contaminant	Hazardous Waste Thresholds (mg/L)	US EPA (1999) Potable Water Standard (mg/L)	TCLP (mg/L)	SPLP (mg/L)	Maximum TC for Fill Material (mg/L)	TC (mg/kg)	ASLP (mg/L)	TC (mg/kg)	ASLP (Acet) (mg/L)	ASLP ((Borate) (mg/L)	TC (mg/kg)	ASLP (Acet) (mg/L)	ASLP ((Borate) (mg/L)
Mercury	0.2	0.002	<0.0002	0.00024	1	75	0.05	<0.05	<0.001	<0.01	<0.05	<0.001	<0.01
Nickel	-	-	-	-	60	3000	1	<5	<0.01	<0.1	<5	<0.01	<0.1
Selenium	1.0	0.05	<0.2	<0.2	10	50	0.5	<5	<0.01	<0.1	<5	<0.01	<0.1
Silver	5.0	0.05	<0.02	<0.02	10	180	5	<5	<0.01	<0.1	7	<0.01	<0.1
Zinc	-	-	-	-	200	35,000	150	34	0.79	0.1	70	1.6	<0.1
Cyanide	-	-	-	-	50	2500	4	<5	<0.05	<0.5	<0.5	<0.05	<0.05
Monocyclic aromatic hydrocarbons	-	-	-	-	7	50	N/A	<0.1	<0.001	<0.001	<0.1	<0.001	<0.001
Monocyclic aromatic Benzene	-	-	-	-	1	4	0.05	<0.1	<0.001	<0.001	<0.1	<0.001	<0.001
Polycyclic aromatic hydrocarbons	-	-	-	-	20	50	N/A	<0.1	<0.01	<0.01	<0.1	<0.01	<0.01
Benzo (a) pyrene	-	-	-	-	1	5	0.0005	<0.1	<0.001	<0.001	<0.1	<0.001	<0.001
PAHs (total)	-	-	-	-	N/A	50	N/A	<0.1	<0.001	<0.001	<0.1	<0.001	<0.001

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