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Review

Application of Glass in Subsurface Pavement Layers: A Comprehensive Review

Salpadoru Tholkamudalige Anupiya. M. Perera, Jiasheng Zhu, Mohammad Saberian, Manlin Liu, Donald Cameron, Tariq Maqsood and Jie Li *

School of Engineering, RMIT University, Melbourne 3000, Australia; s3464242@student.rmit.edu.au (S.T.A.M.P.); s3557884@student.rmit.edu.au (J.Z.); mohammad.boroujeni@rmit.edu.au (M.S.); s3363479@student.rmit.edu.au (M.L.); Donald.Cameron@unisa.edu.au (D.C.); tariq.maqsood@rmit.edu.au (T.M.)
* Correspondence: jie.li@rmit.edu.au

Abstract: Glass-based goods are produced and consumed in relative abundance, making glass a material that is found in most households, thereby leading to its accumulation in alarming quantities throughout the globe and posing an environmental challenge. This being said, glass has been widely acknowledged to possess a variety of desirable physiochemical properties, making it suitable for utilisation as an engineering aggregate. The properties include its non-biodegradable nature, resistance to chemical attack, low water absorption, hydraulic conductivity, temperature-dependent ductility, alterable particle gradation, and its availability in a multitude of forms/chemical compositions. Owing to these properties, glass has been employed in a myriad of civil engineering studies and field trials to assess its efficacy as an engineering aggregate and to provide sustainable management schemes for waste glass. These studies/trials have incorporated glass in many forms, including fine recycled glass (FRG), medium recycled glass (MRG), coarse recycled glass (CRG), glass powder, glass fibres, foamed glass, and glass-based geopolymers. Although the beneficial properties of glass can be exploited in numerous engineering endeavours, this review paper focuses on the possible application of glass to subsurface layers of pavements. In turn, the current study centres on research studies/trials presenting results on the physicochemical, mechanical, and durability aspects of pavement layers (base, subbase, and subgrade) containing pure glass samples or glass as percentage replacements in materials, including but not limited to unbound granular materials (i.e., recycled concrete aggregate (RCA) and crushed rock (CR)) and clay soils. Through the knowledge compiled in this review article, it is reasonable to state that glass shows solid potential as a road pavement material.

Keywords: glass; pavement; base, subbase, and subgrade; clay; sustainability

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1. Introduction

On a global scale, waste materials are becoming increasingly problematic, both environmentally and economically [1,2]. Due to the abundance of waste materials generated every year, landfilling has become a significant environmental problem [3,4]. Landfills are treated as scarce resources. Additionally, road- and transportation-related industries are responsible for consuming large amounts of natural materials. One way to alleviate the environmental impact is to include recycled materials in pavement layers as a sustainable approach [5]. Pavements are an essential structure within the construction industry and apply to various infrastructure systems within the civil sector, such as roads, airstrips, embankments, and footpaths. Naturally sourced construction materials such as sand, gravel, crushed stone, asphalt, and concrete are typically used to construct pavements. The building and construction sector was responsible for the emission of 36% of global final energy-use-related CO_2 emissions in the year 2018 [6]. Hence, there has been a strong demand to investigate alternative sustainable materials that have similar performance to traditional construction aggregates in order to maintain an environmentally sustainable industry [7].

Glass is a material constituent for goods that most individuals have become accustomed to using on a daily basis. It could be in the form of a mirror, a glass bottle, a cellular device screen, a computer screen, windows/doors of dwellings/motor vehicles, or tables. Hence, the global population continues to consume large amounts of glass, which eventually end up as waste glass, generating roughly 130 million tonnes of waste glass each year [8,9]. Furthermore, poor recycling rates have been reported. In mainland China and the USA, only 13% and 28% of glass are recycled, respectively, while producing approximately 40 and 11.54 million tonnes of glass waste per year [10]. Australia consumed about 1.21 million tonnes of glass annually from 2018–2019, with roughly 90% of the consumption being for glass packaging. In this same period, the waste glass generated in Australia was estimated to be 1.16 million tonnes, with a recycling rate of 60% [11]. A large amount of glass waste has been accumulating in landfill sites owing to the substantial amounts generated, poor recycling rates, and the non-biodegradable nature of glass, thereby posing a threat to natural flora and fauna. Table 1 shows the amount of waste glass generated in several countries as well as their recycling and landfilling rates.

Table 1. The amount of waste glass generated in several countries as well as their recycling and landfilling rates [12].

Country	Generation of Waste Glass (Million Tonnes)	Recycling Rate	Landfilling Rate
USA	11.54	13%	75%
Canda	0.75	27%	60%
Australia	1.2	40%	60%
UK	2.4	57%	43%
Germany	2.5	45%	-
India	21	20%	-

The civil and construction industry is identified as a sector with the potential to significantly reduce the problematic accumulation of glass waste in landfill sites. The industry involves projects that can utilise sizeable quantities of glass; this not only has a positive impact by reducing the amount of glass destined to landfill sites but also benefits the natural environment by reducing the use of virgin quarried materials in engineering undertakings [13]. Glass aggregates used in research studies and field trials exist in various forms, including glass cullet/recycled crushed glass (RCG)/waste glass, fine recycled glass (FRG), medium recycled glass (MRG), coarse recycled glass (CRG), glass powder, glass fibres, foamed glass, and glass geopolymers. Glass cullet or recycled crushed glass consists of waste glass that is accumulated in recycling facilities and subjected to mechanical crushing. FRG, MRG, and CRG generally refer to crushed glass that has a maximum particle size of 4.75, 9.50, and 19.00 mm, respectively, while glass powder consists of glass that has undergone extensive mechanical crushing until a powder with an even consistency is achieved, where the specific size is dependent on its intended purpose. Glass fibres are produced via the extruding of thin strands from glass, where these strands are referred to as glass fibres. Varying lengths of glass fibre could be produced during the extrusion process, depending on the requirement. Foamed glass is a lightweight material made through the application of heat to a mix of glass powder and chemical foaming agents. The foamed glass consists of glass cells that are completely sealed, preventing the movement of moisture to and from the glass foam. Glass-based geopolymers are commonly formed by mixing glass powder and an alkaline solution, where the rich silica environment present in the glass powder promotes the geopolymerisation process.

Glass cullet/recycled crushed glass (RCG)/waste glass is a material that is found in abundance, is low in cost, and demonstrates appropriate engineering properties, especially in terms of workability, durability, and hydraulic conductivity [14]. Glass can be utilised as a pavement construction material without the need to alter its properties, requiring approximately 60% less energy to manufacture when compared to common road construction aggregates [15]. Glass cullet generally has less variation in durability parameters compared to that of natural aggregate from one supplier to another [16]. It is also unlikely that replacing up to 10% of natural aggregates with glass cullet would have significant adverse effects on the overall performance of bound and unbound road layer mixtures [17]. RCG is suitable for use as a supplementary pavement subbase material with minimal adverse effects on the environment [18,19]. Up to 15% inclusion of recycled crushed glass has been suggested for use in cement-treated RCG–RCA blends for application in subbase layers of pavements [20,21]. Waste glass (WG) has a hydrophobic nature; hence, the maximum dry density undergoes little change with variation in moisture [22]. Studies revealed that up to 30% of waste glass could be incorporated into subbase layer materials while satisfying the requirements of local authorities [23].

FRG has a particle gradation consistent with a well-graded sand (SW) [24]. Materials with such gradations are generally suited for partial replacement of road aggregate as sample porosity is reduced, thereby improving overall strength characteristics. FRG added to waste rock (WR) aggregate at an optimum rate of 15% by dry mass is found to have adequate strength for use in footpath base layers and has good workability [24]. When added at the same rate to recycled crushed concrete (RCC), the blend showed potential for utilisation in subbase layers of pavements [25,26].

Ground glass-carbide-lime blends could be used to produce hydraulic cement that, in turn, could be utilised for binding sandy soils in geotechnical applications such as the base and subbase of pavements [27].

Glass fibres have beneficial engineering properties such as resistance to chemical attack, insensitivity to variations in moisture, and relatively high tensile strength, making the fibres ideal for utilisation in road layers [28]. The random distribution of glass fibres into the soil matrix aids in improving the strength and resilient properties of the soil–fibre composites [29]. The inclusion of long glass fibres in sand leads to an increase in strength and improves the ductility of the specimens [30].

Recycled glass powder (RGP)-based geopolymer has been studied to evaluate its efficacy in stabilising clay soils [31]. It has been shown that RGP geopolymer characteristics and efficiency in stabilising clayey soils depend upon the molar ratio of the alkaline solution, the initial synthesis temperature, and the period for which curing occurs. RGP is a rich source of silica, thus making it an ideal additive for the alkali–silica reaction (ASR) in RGP-based geopolymer cement [32].

As researchers in today's world, it is vital that all research conducted is in line with sustainability, thereby enabling the preservation of precious and depleting natural resources for future occupants of this planet to utilise. Such an approach not only preserves these resources but also has benefits for the environment through reduced greenhouse gas emissions and, in turn, contributes to a multitude of pro-environmental impacts.

This paper reviews the mechanical, physicochemical, and microstructural properties of various types of recycled waste glass and their blends with road layer materials/aggregates. The paper firstly focuses on the findings concerning the physiochemical properties/tests for pure glass and glass blends, including particle size distribution, specific gravity/density, flakiness index, water absorption, hydraulic conductivity, X-ray fluorescence (XRF)/energy dispersive X-ray, scanning electron microscope (SEM), pH values, organic contents, and leachate testing. Secondly and thirdly, findings on the mechanical strength evaluations for glass blends having the potential for use in base/subbase and subgrade layers of road pavements are discussed. Where knowledge relating to mechanical tests inclusive of compaction, unconfined compressive strength (UCS), California bearing ratio (CBR), Los Angeles abrasion/aggregate crushing value, resilient modulus, permanent deformation, direct shear/triaxial shear, and splitting tensile/in-direct tensile strength are presented. Next, a section consisting of findings concerning field trials of glass blends as pavement aggregate is provided. The remaining sections provide an overall summary of findings, current gaps in research/scope for future studies, and the main conclusions. This comprehensive review will help the research community to efficiently navigate the existing literature on adopting various forms of recycled glass as sustainable road materials. The paper generally shows that glass is ideally suited for use as a supplementary pavement material, owing to its good strength, durability, and resilience to chemical attack.

2. Methodology

The present study aims to conduct a review of current developments in the use of recycled waste glass in various forms for use as supplementary pavement layer materials. A comprehensive literature search is carried out through the use of suitable keywords, including but not limited to glass, road pavement, base, subbase, and subgrade. The literature is obtained from several well-established databases, including Scopus, Springer, Elsevier, Taylor & Francis, and Wiley. Eventually, in excess of 100 relevant articles are identified and explored in the making of this review paper.

3. Findings on Physicochemical Properties of Road Layers Containing Glass

The inclusion of crushed glass into various pavement aggregates results in composites having physicochemical properties unique to each sample composition. This section reveals vital findings observed in the existing literature concerning the physicochemical properties of recycled glass and subsurface pavement layer aggregates containing recycled glass. Thus, the changes in sample characteristics are presented, which are brought about by the introduction of glass into the aggregate mix. Findings for various tests/analyses on physicochemical properties of pure glass samples and specimens containing glass will be discussed herein. The various forms of glass and their potential for use as road aggregates are first briefly introduced in this section. Following this, the commonly assessed physicochemical properties of these composites as observed in the literature are discussed.

Glass cullet's insensitivity to moisture permits its application in various moisture conditions where it improves the drainage characteristics of sandy gravel, indicating its suitability for use in road layers. Between 15% and 30% glass cullet could be used in the base and subbase layers of pavements, respectively [16]. The Federal Highway Administration (FHWA) suggests a maximum use of 15% and 30% RG by weight in road base and subbase, respectively [33]. The recycled glass with a maximum particle size of 4.75 mm is similar to natural quarried aggregates when considering their geotechnical characteristics [34,35]. Up to 15% of RG can be introduced safely into VicRoads Class 3 crushed rock and recycled crushed concrete for use in subbase layers [11,25]. The same percentage of 15% inclusion of FRG in WR is agreed upon by [24] to provide optimum workability and sufficiently high strength for base layers of footpaths. Recycled glass (RG) records specific gravity values that are around 10% lower than those recorded by natural aggregates, thereby allowing the reduction of the surcharge and backfill pressures [26]. Glass has the ability to undergo several cycles of recycling while retaining its chemical properties [35].

Glass fibres demonstrate good ability in resisting deterioration, and their random distribution in soil mixtures can help improve the overall strength and resilience of the composite material [29,36]. The introduction of glass fibres also improves the tensile modulus and flexural modulus of the mixtures, where the use of glass fibre-reinforced soil as a subgrade material not only reduces the thickness of pavement structure by up to 25% but could also positively affect the longevity of the pavement. Glass fibres have a variety of desirable characteristics, including stability against chemicals, moisture insensitivity, relatively high tensile strength, and good stiffness, making them suitable for application in road layers [28].

Foamed glass, when utilised as a replacement for natural mineral base materials, would significantly decrease the pressure experienced by the subgrade layers (by approximately ten folds). Furthermore, foam glass also exhibits an excellent ability to resist the effect of weather, especially with regards to resistance against freeze-thaw damage. Foam glass is particularly useful in constructing roads over soft subgrade soils and stabilising permafrost soil [37]. It is possible to construct up to 60% of the road structure utilising glass foam gravel and glass asphalt. The addition of foamed glass into lime-stabilised Ariake clay caused a reduction of water content, leading to strength enhancement. In addition, the mixtures are reported to be suitable for use in base and subbase layers when comparing results with structural analysis [38].

3.1. Particle Size Distribution (PSD) Curve

This subsection discloses findings relating to the particle size distribution for pure RG and its composites, where recycled glass (RG) would be the first focal point. The particle size distribution of a pavement aggregate has a significant effect on the overall performance of the pavement; therefore, local road authorities identify allowable gradation limits for pavement materials. A pavement aggregate must have a particle gradation within these set limits as aggregates with gradations beyond such limits lead to poor compaction and increased void ratios, thus having detrimental effects on both the performance and longevity of the pavement structure [39].

Pure FRG does not meet the requirements for Type 1 Gradation C road base materials with regards to the ASTM standard [ASTM. 2007] following compaction (Figure 1) [40]. FRG is categorized as a SW material, while the FRG-WR blends containing up to 30% FRG are noted to be SP-SM materials [24]. Grading for pure FRG samples exceeds grading limits, suggesting possible difficulties relating to workability in the field [24]. Recycled glass aggregate obtains grading classification D (AASHTO M 147-65), which is compliant with the base aggregate particle gradation requirements [32]. Fine recycled glass (FRG), medium recycled glass (MRG), and coarse recycled glass (CRG) have the classifications of SW-SWM, GW-GM, and GP according to [41]. Furthermore, CRG (−19 mm) underwent an appreciable change in gradation following compaction efforts, where sand-sized content changed from 2.7% to 9.1% following standard compaction, while a shift from 2.7% to 24.8% occurred after modified compaction effort, whilst the coarse aggregate fraction decreased from 96.4% to 88.8% and from 96.4% to 71.9% with standard and modified compaction [34]. Furthermore, FRG (−4.75 mm) and MRG (−9.5 mm) did not undergo significant change in gradation following the same compaction effort. Samples containing waste glass could experience changes in gradation to a certain degree due to particle breakage caused by vehicular traffic, thus leading to settlement [22], which is an undesirable characteristic of mixtures that incorporate waste glass. PSD for crushed glass [42] reveals a suitable distribution of particle size with a good proportion of fine particles available. The study in [43] shows that FRG undergoes a negligible change in gradation following compaction while MRG experiences small changes in gradation; however, coarse recycled glass (CRG) samples are observed to experience an appreciable shift in gradation due to the breakage of coarser particles during compaction. Owing to this sizeable variation in gradation of CRG, it is suggested to avoid using CRG in high inclusions as well as in base and subbase layers where modified compaction efforts are utilised. No change in classification is observed following compaction for RG, thereby demonstrating stable mechanical behaviour.

Notable post-compaction gradation changes are only observed for pure glass cullet samples, while samples with 15% and 50% cullet in crushed rock show far less change. However, the change in gradation depends on cullet size and percentage inclusion, with increased change in gradation occurring at higher inclusions and larger cullet sizes [16]. Recycled glass (RG) of 4.75 mm minus size is classified as well-graded in accordance with ASCS [41] in the study [25], further stating that particle grading falls within upper and lower boundaries as required by VicRoads. The same conducts post compaction sieve analysis, reporting that minor changes in gradation are observed following the samples undergoing modified compaction effort, thereby indicating good stability of RG during construction activity. PSD of fine recycled glass exhibits stable behaviour, presenting its potential for use in engineering endeavours [33].

RG is classified as well-graded sand containing small amounts of silt-sized material (SW), where the fines content is within the typical range for VicRoads [44]. Furthermore, RG is noted to undergo a minor change in gradation when subjected to modified compaction efforts. RG-RCC blends experienced little to no change in gradation, with fines content between 5.8% and 8.6%, which is within the acceptable limits [26]. The research from [43] reveals that inclusions of greater than 50% RG in crushed rock (CR) would exceed the allowable upper limit of gradation as specified by VicRoads. Furthermore, RG-RCC blends are reported to be primarily well-graded both pre- and post-compaction. Crushed glass is classified as well-graded sand (SW) both pre- and post-compaction, also revealing that CG-CR blends with 12%, 24%, and 45% CG, as well as CG-CR-Rubber blend with 45% CG and 5% rubber, meet the gradation requirements for crushed rock base materials [45].

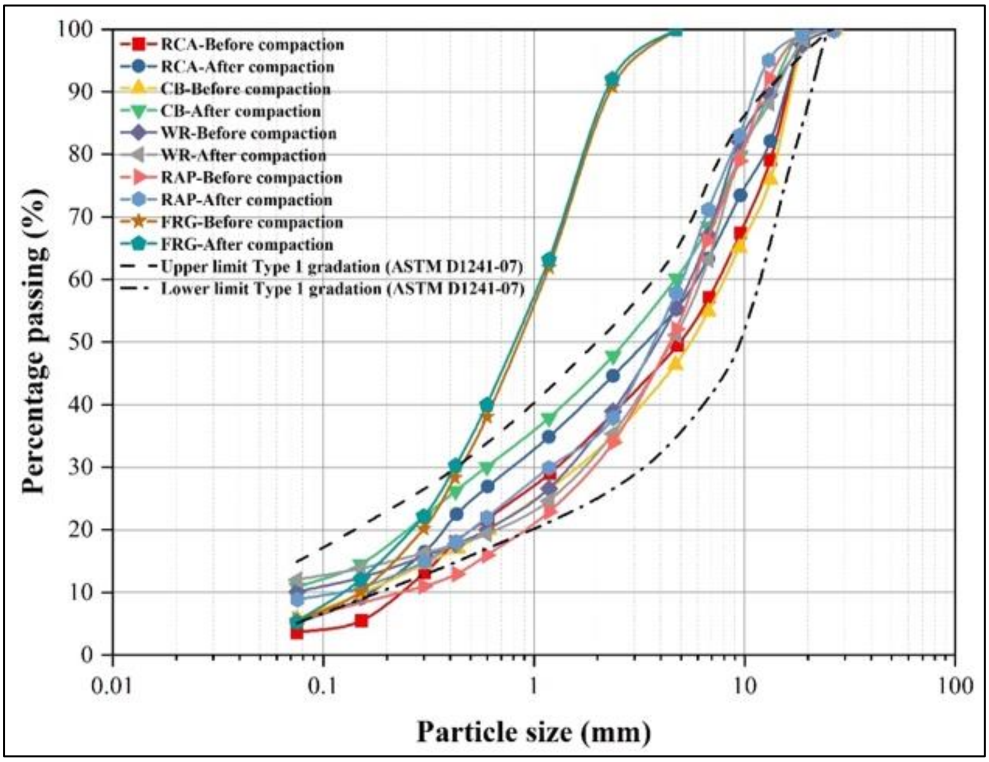


Figure 1. Particle size distribution [40].

RCG-TNZ (M4, AP40) blends up to the inclusion of 30% RCG are compliant with local base course grading limits (TNZ M/4), while inclusions above 30% are non-compliant [46]. Analysis of particle gradation for limestone-cullet blends following compaction reveals that more significant variation in gradation is observed as the percentage of cullet increases [47]. The PSD for RCA samples containing 15% FRG falls within the recommended upper and lower bounds both pre- and post-compaction, where the sample is classified as poorly graded sand [48].

Foamed recycled glass presents a PSD where the gradation of particles is consistent with that for gravel and sand with no fines. The material could be classified as poor and gap-grained according to the coefficient of curvature (C_c) and coefficient of uniformity (C_u) [49,50]. However, the lack of fine particles prevents the use of the material in base/subbase layers without adequate stabilisation.

The gradation values for the control limestone sample are primarily maintained when limestone replacement by the crushed glass is employed. This replacement method allows for the substitution of limestone with crushed glass of similar size, thereby negating effects from variation in particle gradation [51]. This is an interesting approach as the volumetric replacement minimises the gradation variation by replacing an aggregate faction with a faction of the supplementary material consisting of similar-sized particles.

When considering the findings from numerous research studies, it could be concluded that pure RG itself should be avoided in base and subbase layers due to particle breakage during compaction, which leads to an appreciable change in particle gradation. This being said, it is noteworthy to mention that FRG and MRG are found to satisfy gradation and durability requirements following compaction; therefore, they are identified to be the more suitable sizes of glass for utilisation as supplementary pavement aggregates when incorporated with superior aggregates and binders.

3.2. Density/Specific Gravity/Bulk Density

This subsection presents the specific gravity or particle density values recorded by pure glass samples as well as composite samples containing glass in various forms. Aggregates with lower values for specific gravity could be utilised to reduce the burden on underlying pavement layers, although such materials are considered to be of lower quality compared to aggregates with higher specific gravity (i.e., lower compressive strengths, modulus of elasticity) [52]. This being said, the utilisation of aggregates with a lower specific gravity can also be beneficial in reducing freight costs incurred during transport.

The specific gravities of FRG (−4.75 mm), MRG (−9.5 mm), and CRG (−19 mm) are found to be 2.48, 2.5, and 2.5 kN/m^3, respectively, via the studies conducted by [34,43]. Specific gravity values for commercial glass are reported to range between 2.49 to 2.51 kN/m^3, further presenting that the same for natural aggregates lies between 2.65 and 2.68 kN/m^3 [16]. These values for recycled glass are reconfirmed by [24], where FRG is reported to possess a specific gravity of 2.49 kN/m^3. Particle density testing conducted on recycled glass (RG) showed 15% lower specific gravity values compared to those of natural aggregates, recording specific gravity of 2.49 kN/m^3 [25]. Studies conducted by [14,26,53] agree, showing that RG has a specific gravity of 2.49 kN/m^3, also adding that this value is approximately 10% lower than natural aggregates, thus reducing surcharge and backfill pressures. Furthermore, it is worth noting that both RG-CR and RG-RCC blends have specific gravity values close to those recorded by natural aggregates. In addition, the maximum index density of samples containing glass cullet depends significantly on the percentage inclusion of cullet and, to a lesser extent, on the cullet size. Specific gravity values for coarse glass cullet [47] vary between 1.96 and 2.41 kN/m^3, while the same for fine glass cullet is within 2.49 and 2.52 kN/m^3, thereby hinting that the fine glass is a superior aggregate compared to its course counterparts. Research findings from [25] report that RG-CR blends containing up to 50% RG have specific gravities ranging between 2.64 and 2.79 kN/m^3. Results from [47] reveal that the greater the inclusion of crushed glass, the lower the relative density for cullet–limestone blends would be, thereby demonstrating that the addition of glass cullet to limestone reduced the overall quality of pure limestone aggregate. RCA samples containing up to 15% FRG recorded particle density values slightly higher than natural gravel, thus implying that the FRG-RCA composite consists of high-quality aggregates overall [48].

Glass foam gravel records bulk density values in the range from 1.30 to 1.70 kN/m^3, also having in-fill density values between 1.90 and 2.20 kN/m^3 following compaction with small roller compactors [37]. The particle density of foamed recycled glass is observed to be low, ranging from 4.54 to 14.79 kN/m^3, with the finer particle density noted to be nearly three folds of that of the coarser fraction [50].

Glass fibres have specific gravity values of 2.57 kN/m^3 [54]. On the other hand, alkali-resistant glass fibres recorded a slightly higher specific gravity value of 2.7 kN/m^3 [55], indicating a better quality of alkali-resistant glass fibres.

The specific gravity values for expansive soils treated with quarry dust-based geopolymer cement and crushed waste glass (CWG) are observed to increase with increasing inclusions of CWG up to a maximum inclusion of 40% CWG in the study, depicted in Figure 2 [42]. Table 2 provides the specific gravity/bulk density/particle density values of various recycled glass materials.

NB: All tables and text found in the paper would have values converted to the standard SI unit for ease of comparing values across the literature.

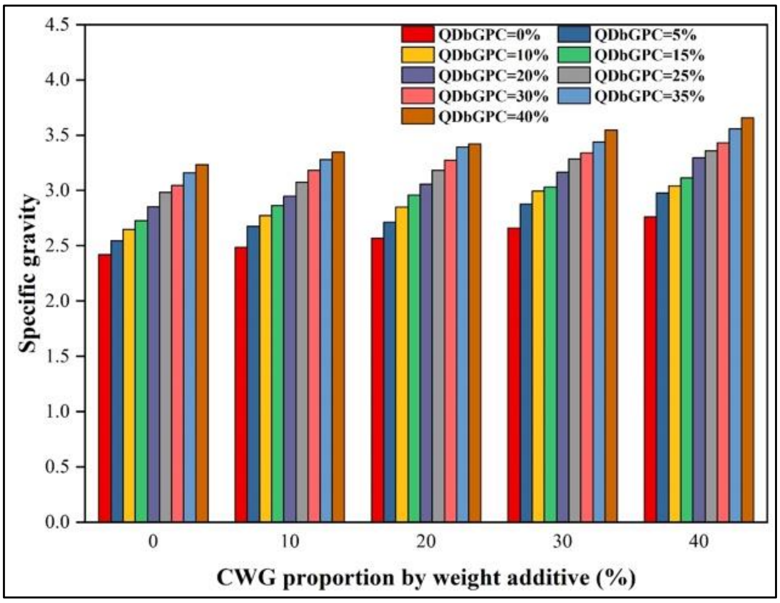


Figure 2. Specific gravity vs CWG% (quarry dust geopolymer cement-CWG) [42].

Table 2. Summary of specific gravity/bulk density/particle density.

Materials	Maximum Glass Inclusion	Specific Gravity/ Bulk Density/ Particle Density (kN/m^3)	Reference
CG	100%	2.49–2.51	[16]
FRG	100%	2.49	[24]
RG	100%	2.49	[14,25,26,53]
FRG	100%	2.48	[43]
MRG	100%	2.50	
CRG	100%	2.50	
CRG	100%	2.49–2.52	[47]
Glass Foam Gravel	100%	1.30–1.70	[37]
Foamed Recycled Glass	100%	4.54–14.79	[50]
Glass Fibres	100%	2.57	[54]
Alkali-Resistant Glass Fibres	100%	2.70	[55]
RG–CR	50%	2.64–2.79	[25]

3.3. Flakiness Index

Flakiness index denotes the percentage (concerning weight) of aggregate that has an average least dimension lower than 0.6 times the mean size of the aggregate sample. This index provides an indication of an aggregates ability to effectively pack together, with flaky aggregates being able to be pack more efficiently than non-flaky ones; hence, flaky aggregates reduce the void ratio of the sample, leading to superior compaction [56].

MRG (−9.5 mm) and CRG (−19 mm) have flakiness index values of 85.4 and 94.7, respectively, thus implying that flakiness is dependent on the degree of processing that the recycled glass has undergone [43]. The smaller aggregates that have been put through greater extents of crushing/processing, in turn, would have lower angularity, hence leading to lower values for the flakiness index [33].

The flakiness index of FRG-WR blends is reported to be 16, thus satisfying the conditions for use in the base layer of footpaths [24]. FRG-RCA and FRG-WR combinations in [57] record flakiness index values of 11 and 16, respectively; thus, the blends are suitable for use in base and subbase layers of pavements when considering flakiness index values. Table 3 summarises the values of the flakiness index of various recycled glass materials.

Table 3. Summary of flakiness index.

Materials	Maximum Glass Inclusion	Flakiness Index	Reference
MRG CRG	100% 100%	85.4 94.7	[43]
FRG-WR	30%	16	[24]
FRG-RCA FRG-WR	50% 50%	11 16	[57]

3.4. Water Absorption

The focal point of this subsection is findings from the literature for water absorption of pure glass samples and composites containing glass. Water absorption values indicate the internal aggregate structure and relative porosity, where materials with higher water absorption values are generally more porous and, thus, less suited for use in road pavement layers [58].

RG recorded lower water absorption values when compared to natural quarried aggregates such as crushed rock (CR), where RG-CR blends with up to 50% RG have water absorption values in the range of 2% to 2.62% [25]. RG–CR blends [26] containing up to 50% RG recorded water absorption values between 2% and 2.70%. The water absorption values for FRG-WR blends [57] containing up to 50% FRG vary from 1.00% to 3.25%, similar to natural aggregates, whereas the same for FRG-RCA blends change between 2% and 8.2%. Furthermore, the pure FRG records a minute value of 1% for water absorption due to small amounts of soil, labels, and other materials. The values for RG-RCC mixtures containing up to 50% RG in [26] are found to be between 4% and 7%, with the water absorption values noted to decrease as the amount of RG increases. Glass has a lower tendency to absorb water; hence, low percentage inclusions of glass in granular demolition waste aggregates have a minimum effect on OMC [59].

The water absorption for foamed recycled glass is very low for the fine particles, where the coarser fraction recorded higher values of approximately 60% [50]. Water absorption values for glass cullet reported in [14] suggest that fine glass cullet has higher water absorption values than the coarse fraction with 4.31% and 2.14% for the finer fraction and the coarser fractions, respectively.

The research from [60] studied the water absorption values for concrete blends containing different glass powder inclusions (6.6% to 45%) and water to cement ratios (0.75 and 0.80), where the water absorption values were found to be in the range of 6.5% to 8.3%.

Considering the above-reported findings, it is possible to deduce that finer glass fractions would record higher water absorption values when compared to the coarser fraction for crushed glass. This being said, the opposite is true for foamed glass, where the coarser fraction recorded higher water absorption values. Table 4 shows the values of water absorption of various recycled glass materials.

Table 4. Summary of water absorption.

Materials	Maximum Glass Inclusion	Water Absorption (%)	Reference
FRG	100%	1.00	[57]
GC (Coarse) GC (Fine)	100% 100%	2.14 4.31	[14]
RG-CR	50%	2.00–2.62	[25]

Table 4. *Cont.*

Materials	Maximum Glass Inclusion	Water Absorption (%)	Reference
RG-CR	50%	2.00–2.70	[26]
FRG-WR	50%	1.0–3.25	[57]
RG-RCC	50%	4.00–7.00	[26]
FRG-RCA	50%	2.0–8.2	[57]
Concrete-Glass Powder	45%	6.5–8.3	[60]

3.5. Hydraulic Conductivity/Permeability

Hydraulic conductivity measures the ability of a liquid to pass through a sample when subjected to a hydraulic gradient. It is a crucial material property that is considered in road layer construction. A mixture with very low permeability would prevent fluid flow through the layer, leading to stagnation and detrimental effects on the pavement layer [61]. On the other hand, a layer comprising material with very high permeability poses the threat of fine material loss by sample drainage, again having damaging effects on the integrity of the pavement. Thus, the material must be within the permissible range of permeability set by local authorities for respective pavement layers. Hydraulic conductivity affects the service life of the pavement as well as the required thickness of the pavement layers [62,63].

The hydraulic conductivity values and related findings for pure glass samples and glass composites as reported in existing literature are presented in this section. Fine recycled glass (FRG) and medium recycled glass (MRG) samples recorded respective hydraulic conductivity values of 1.7×10^{-5} and 2.85×10^{-5} m/s and are classified as materials with "medium" permeability; thus, they are comparable to those of natural aggregates [34,43]. Furthermore, RG is more free-draining than the majority of natural aggregates. The as-received Heller and Stoltzfus glass cullet in [14] have hydraulic conductivity values of 6.45×10^{-4} and 1.61×10^{-4} cm/s, respectively, while the coarser fraction (retained in 2.4 mm sieve) have higher values of 4.91×10^{-3} and 7.22×10^{-4} cm/s; these again are observed to be in the range recorded by typical natural aggregates. Experimental studies conducted on glass cullet–gravelly sand [16] showed that permeability values increased with higher percentage inclusions of cullet and greater cullet size, whilst the permeability values decrease when the compaction effort increases. As mentioned afore, the improvements in permeability with cullet inclusion shed light on the excellent drainage characteristics induced by the glass cullet inclusion.

Results from [57] reveal that according to the constant head method, FRG has hydraulic conductivity of 3.5×10^{-5} m/s, classified as a high permeability material comparable to natural sand, thus implying that varied inclusions of FRG can be incorporated into RCA and WR in order to obtain desired degrees of permeability. Furthermore, the FRG-WR blends studied in [26] are reported to have hydraulic conductivity values similar to natural aggregates. FRG-WR blends are classified as low-permeability materials following studies conducted by [24]. FRG-WR blends are classified as a material with low permeability, having values in the range 6.0×10^{-8} to 9.4×10^{-8} m/s. The hydraulic conductivity values for RCA samples improve with the addition of 15% FRG; however, they are classified as low permeability where the 85RCA-15FRG records a value of 3.8×10^{-7} m/s, whereas the pure RCA sample registers a value of 7.0×10^{-8} [48]. The FRG-RCA [57] blends are classified as low-permeability materials with values ranging from 3.6×10^{-7} to 4.2×10^{-7} m/s.

The addition of greater than 50% CG into dredged material improves the hydraulic conductivity of the dredged material-glass blends. Such materials show suitable permeability values for use in lower layers of road pavements [64]. The inclusion of 0.15% alkali-resistant glass fibre in reclaimed asphalt did not have a notable effect on the hydraulic conductivity values of the blend [55]. The hydraulic conductivity of various glass composites is shown in Table 5.

Table 5. Summary of hydraulic conductivity/permeability.

Materials	Sample Preparation	Maximum Glass Inclusion	Hydraulic Conductivity/Permeability (cm/s)	Reference
Glass cullet (Heller) Glass cullet (Stoltzfus)	OMC and 90% MDD (Modified compaction)	100% 100%	6.45×10^{-4} 1.61×10^{-4}	[14]
FRG MRG	OMC and MDD (Modified compaction)	100% 100%	1.7×10^{-3} 2.85×10^{-3}	[43]
Pure CG (I) Pure CG (II)	OMC and 90% MDD (Modified compaction)	100% 100%	1.61×10^{-4} 6.45×10^{-4}	[53]
FRG	OMC and MDD (Modified compaction)	100%	3.5×10^{-3}	[57]
FRG-RCA	OMC and 98% MDD (Modified compaction)	15%	3.8×10^{-5}	[48]
FRG-RCA FRG-WR	OMC and MDD (Modified compaction)	30% 30%	3.6×10^{-5}–4.2×10^{-5} 6.0×10^{-6}m/s–9.4×10^{-6}	[57]

3.6. X-ray Fluorescence (XRF)/Energy Dispersive X-ray

This section focuses on the results from studies that conduct XRF and energy dispersive X-ray testing on samples containing glass. These tests provide valuable insights into individual aggregate chemical constituents; therefore, it is possible to predict the performance of a composite and enable the elucidation of various experimental observations based on element composition [65,66].

Undertaking an energy-dispersive X-ray in the study [31] to assess the effectiveness of recycled glass powder (RGP)-based geopolymer in stabilising clay soils reveals that RGP is a rich source of silica. In contrast, clay soil has high alumina contents; thus, the two materials provide suitable conditions for efficient geopolymerisation. The energy-dispersive X-ray results confirmed the availability of desirable ratios of silica/alumina and sodium/alumina in the mixtures. These ratios are appropriate for the effective formation of geopolymer gel, hence enabling effective geopolymerisation. XRF analysis (Table 6) reveals that waste glass powder is a rich source of silica, with 72.58% silica by mass [67]. Through the energy-dispersive X-ray and XRF studies undertaken in the literature, it is fair to reveal that glass is a rich source of silica and hence can be supplemented in a material with high amounts of alumina to fulfil conditions required for effective geopolymerisation.

Table 6. XRF analysis for glass powder [32].

Compound/Element	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	MgO	K_2O	SO_3
Content (% weight)	72.58	1.47	0.85	10.49	12.54	0.61	0.4	0.2

3.7. Scanning Electron Microscope (SEM)

The observations relating to images from scanning electron microscopy (SEM) found in the literature are revealed in this section. SEM is utilised to obtain high-resolution images of the aggregates, which are critical when studying surface flaws and inconsistencies. These surface features have a significant influence on the interactions of aggregates within a composite. Furthermore, SEM images are helpful when identifying the formation of chemical products such as those formed during alkali-silica reaction (ASR) and geopolymerisation [68].

Research conducted in [31] undertook SEM to study how recycled glass powder (RGP)-based geopolymers can stabilise clay soils. SEM images from the study depict the formation of a geopolymer gel within the RGP geopolymer-stabilised samples, where an overall increase in sample density is observed owing to geopolymerisation. The increase in UCS and ductility of stabilised materials as the recycled glass powder content increases is explained through the formation of aluminosilicate hydrate gel, as visualized by the SEM images. The formation of the gel holds the aggregate particles intact, thereby enabling more excellent resistance to particle shifting. SEM images from [27,32] reveal that crushed glass aggregate has an irregular shape and jagged edges, indicating the potential to form a matrix with reduced particle sliding (Figures 3 and 4). SEM images obtained for soil stabilised with RGP–calcium carbide residue (CCR) geopolymer present the formation of geopolymer products, thus revealing that RGP–CCR geopolymer is suitable for soil stabilisation [69] (Figure 5).

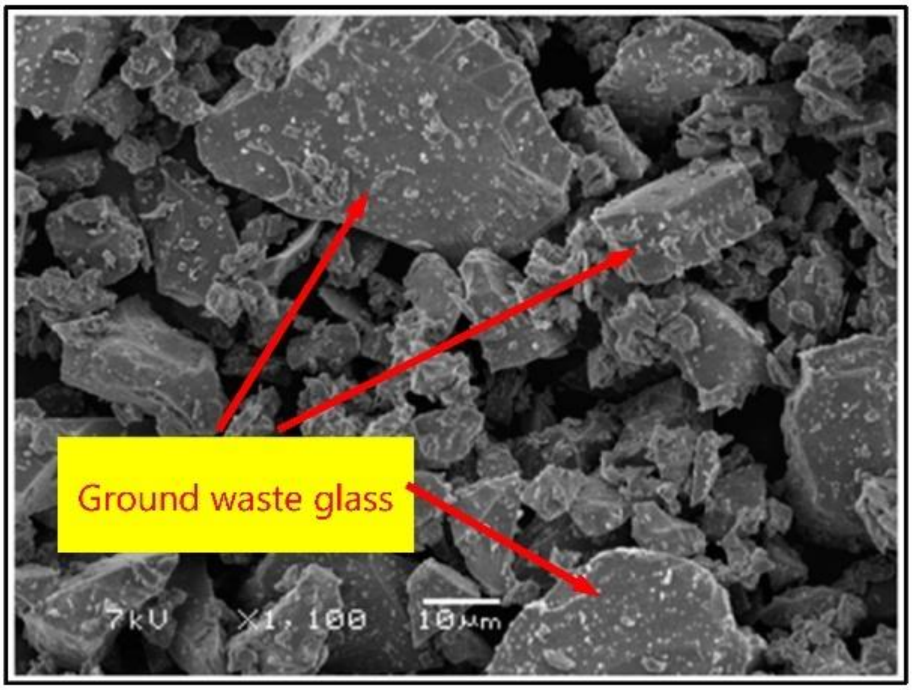


Figure 3. Microphotograph of ground waste glass [27].

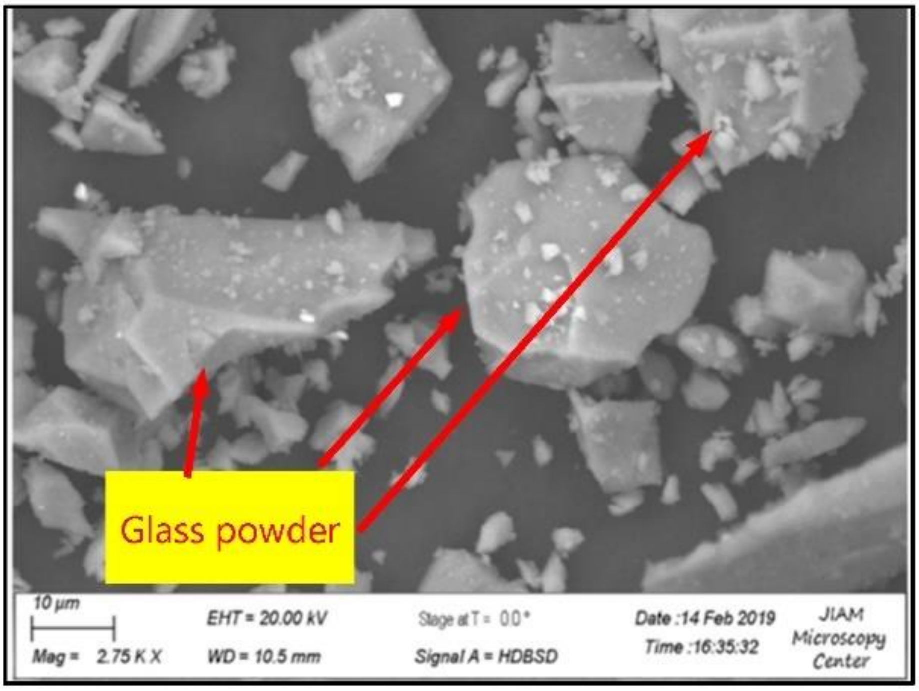


Figure 4. SEM of glass powder [32].

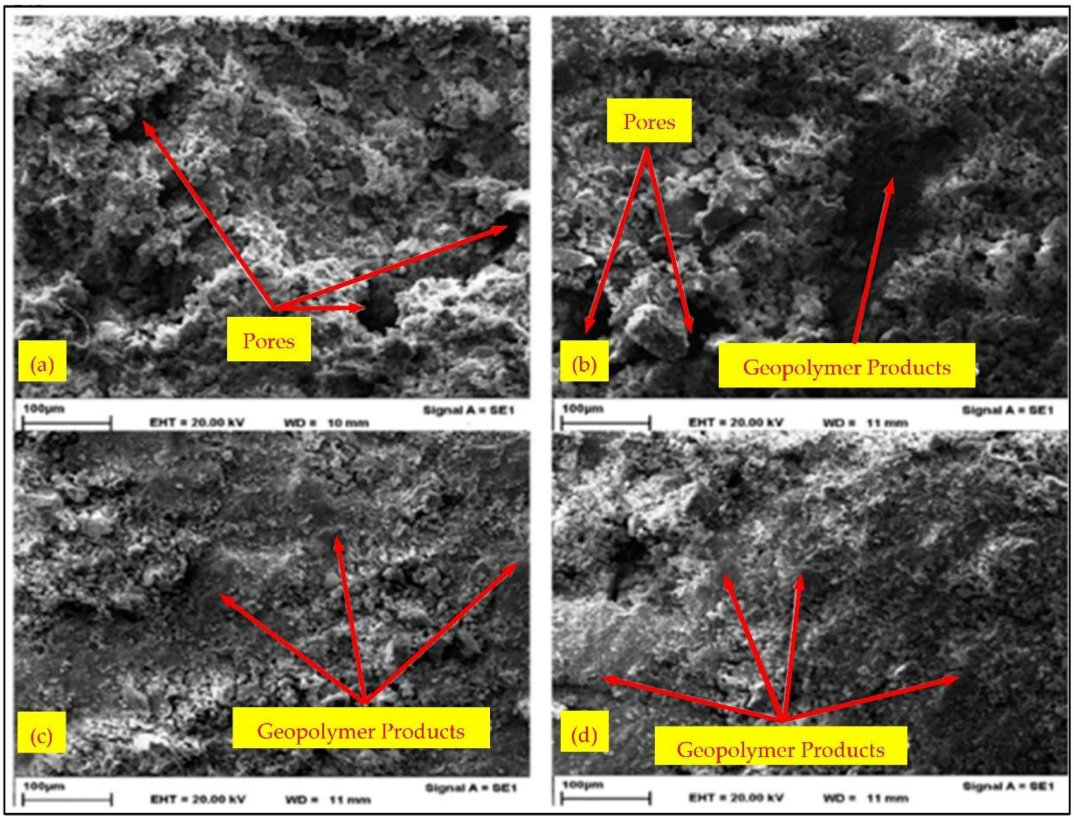


Figure 5. SEM; formation of geopolymer products with increasing glass content: (**a**) C7G0, (**b**) C7G3, (**c**) C7G9, and (**d**) C7G15 [69]. C: calcium carbide residue; G: recycled glass powder; numbers denote the percentage of each additive to the mixture.

The SEM imaging presented in Figures 6 and 7 [70] shows the formation of calcium silica hydrate (CSH) gel in cement-stabilised silty soil containing waste glass powder, where the formation of the dense matrix is observed along with a reduction in porosity of the sample, thereby forming a more dense material.

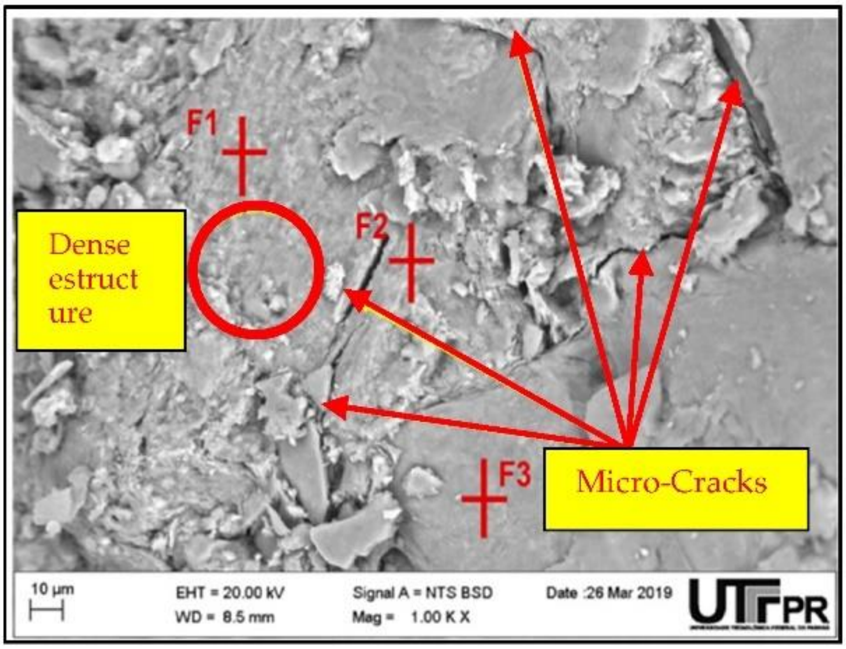


Figure 6. SEM images of compacted blend $\gamma_{159}C_9GP_{30}$ at 28 curing days [70].

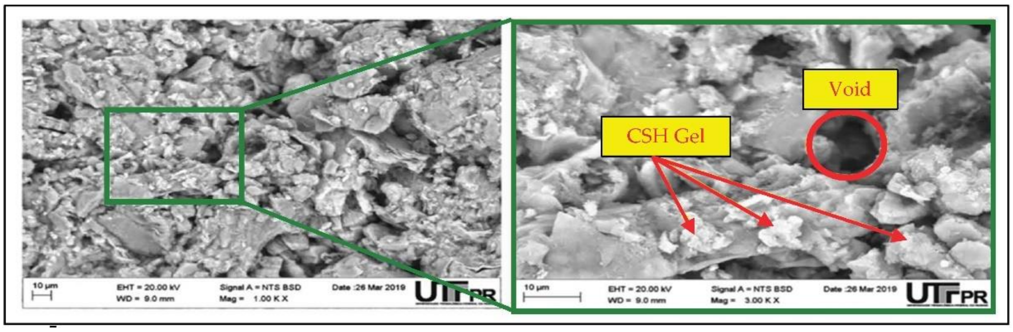


Figure 7. SEM images of compacted blend $\gamma_{145}C_6GP_5$ at 28 curing days [70].

SEM images for 40% PVC-glass mix concrete (containing 75% glass and 25% PVC) depict PVC particles' flocculation together, resulting in the decrease of strength parameters as the PVC-glass mix inclusion increased beyond 20% [71] (Figure 8). The mechanical strength of concrete containing zeolite and waste glass decreases beyond 10% replacement of zeolite/glass, where this reduction could be elucidated by the propagation of hairline fractures through the composite, as observed in the SEM images [72] (Figure 9). SEM is conducted on spent fluorescent lamp glass (SFLG) waste [73], where amorphous CSH gel formation is observed as a result of the presence of $Ca(OH)_2$ and ettringite available in portland cement (PC) and SFLG waste.

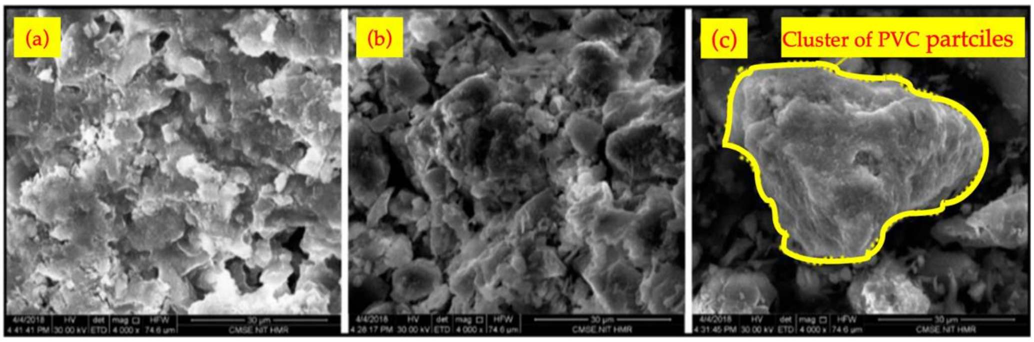


Figure 8. SEM images: (**a**) normal concrete, (**b**) 10%M1, and (**c**) 40%M3 [71].

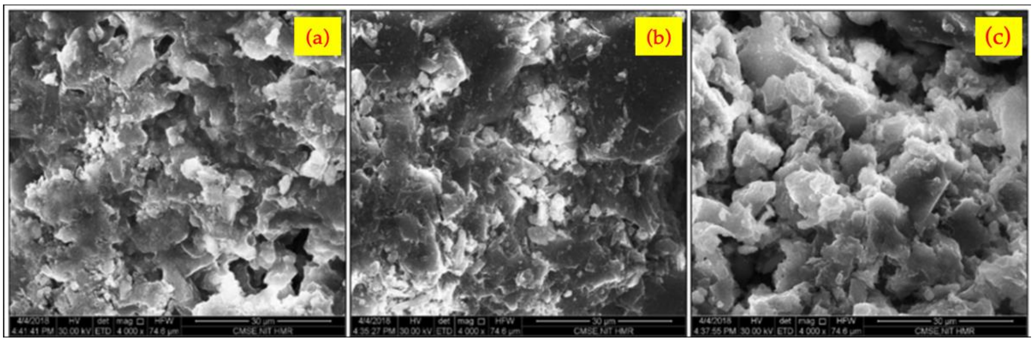


Figure 9. SEM images: (**a**) normal concrete, (**b**) 10G-10Z, and (**c**) 30G-30Z [72].

3.8. pH Value

The pH value provides a measure of the acidity or basicity of a sample. Highly acidic/basic aggregates could increase the probability of adverse reactions occurring within the pavement layer, thus having detrimental effects on the overall performance and integrity of the pavement. Another concern would involve the drainage of acidic/basic material from pavement aggregate into the surroundings, negatively impacting natural flora and fauna. Thus, pavement aggregates must be tested for pH values to assess their suitability for use in road layers. This section will disclose the pH values from existing literature for pure glass aggregates and composites containing glass [74].

FRG (−4.75 mm), MRG (−9.5 mm), and CRG (−19 mm) exhibited moderate alkalinity with pH values in the range from 9.6 to 10.1 as obtained through the electrometric method [43]. Studies from [34] report pH values for CG that are mostly similar, where FRG and MRG recorded values of 9.87 and 10.14, respectively. Contrasting results are presented by [18], where the pH of water decreases from 9.93 to 7.65 following contact with crushed glass, indicating acid leaching taking place while also revealing that this level of leaching is well within the allowable limits. Thus, it has no adverse effects on the surrounding water bodies when crushed glass is utilised as an aggregate in base layers of pavements. Recycled glass waste (RGW) has a pH value of 7.6 [75]. Research conducted via [57] reveals that FRG is alkaline, recording a pH of 9.6.

The pH for FRG-WR [57] combinations was found to be in the range of 9.57 to 9.71. The pH for RG-CR blends is greater than 7, thereby showing that mixes are alkaline, which agrees with the studies mentioned above [25]. A relatively alkaline nature was observed for FRG-WR blends with pH values between 9.42 and 9.71 [24]. The pH values for RG and RG-RCC mixtures are not found to be within the range designated as hazardous [26]. Thus, they do not have the potential to cause harm to the environment when considering the effects of pH. The FRG-RCA [57] blends recorded pH values in the range 11.14 to 11.33. RCG-RCA blends containing up to 30% RCG had pH values ranging between 11.5 to 11.9 [20].

The introduction of up to 0.15% alkali-resistant glass fibres into cement-treated reclaimed asphalt material had no significant effect on the pH of the blends, where the combinations with 2%, 4%, and 6% cement with glass fibres recorded pH values of approximately 11, which are not in compliance with the range recommended by the Environmental Protection Agency [55]. The pH values for foamed recycled glass were noted to be in the alkali range and comparable to those of construction and demolition materials [50].

When considering the pH values for pure glass and glass composites, as shown above, it can be deemed that the glass-containing composites would generally yield pH values in the alkaline range of the pH spectrum. The pH values of various recycled glass composites and pure glass aggregate are provided in Table 7.

Table 7. Summary of pH values.

Materials	Maximum Inclusion of Glass	pH Value	Reference
FRG MRG	100%	9.87 10.14	[34]
FRG MRG CRG	100%	9.6–10.1	[43]
RGW	100%	7.6	[75]
FRG	100%	9.6	[57]
FRG-WR	30%	9.57–9.71	[57]
FRG-WR	30%	9.42–9.71	[24]
FRG-RCA	30%	11.14–11.33	[57]
RCG-RCA	30%	11.5–11.9	[20]

3.9. Organic Content Tests

The proportion of organic matter in a given sample contributes to the build-up of the voids within samples and influences sample properties such as water-retaining potential, stability of aggregates, and capacity to buffer against acidification [76]. Hence, organic tests are commonly carried out when undertaking studies to assess the suitability of mixtures for use in road pavements.

Organic contents for FRG (−4.75 mm), MRG (−9.5 mm), and CRG (−19 mm) were obtained at 1.3%, 0.5%, and 0.23%, respectively. Further revealing that the more pronounced disparity between the organic contents for FRG and other RG sizes was due to a majority of the debris in FRG being paper, which contributes to the organic content values, while debris for MRG and CRG was more biased towards materials that do not contribute towards the increase of organic content values [34,43]. The recycled glass samples analysed in [18] revealed a total organic content of 0.29%, which is well below the allowable organic content of 5% as governed by the Australian Standards [77]. Studies from [57] presented 0.5% organic content in FRG.

Organic contents ranging from 0.6% to 0.8% were recorded by RG-CR blends [25,26], suggesting stable behaviour for mixtures. Experimental results from [24] present that FRG-WR blends with a maximum inclusion of 30% glass contain minimum organic content values between 0.62% to 0.72% for combinations considered in the study. Organic contents in the range between 1.41% to 2.84% were reported for FRG-RCA blends and between 0.6% to 0.78% in FRG-WR blends [57]. Organic content measured for RCA with 15% FRG was reported at 2.65%, within the total allowable range of organic matter [48]. RG-RCC [25] mixtures have negligible organic materials compared to organic content for common aggregates utilised in base layers of roads. Table 8 provides the organic contents of various blends containing recycled glass.

Table 8. Summary of organic contents.

Materials/Blends	Maximum Inclusion of Glass	Organic Content	Reference
FRG	100%	1.30%	[34,43]
MRG	100%	0.50%	
CRG	100%	0.23%	
FRG	100%	0.50%	[57]
FRG-WR	50%	0.60–0.78%	[57]
FRG-WR	30%	0.62–0.72%	[24]
RG-CR	50%	0.60–0.80%	[25,26]
FRG-RCA	15%	2.65%	[48]
FRG-RCA	50%	1.41–2.84%	[57]

3.10. Leachate Testing (TCLP and SPLP)/Total Contaminant Testing

The leaching of harmful substances such as heavy metals and compounds with extreme pH values pose a significant threat to the natural surroundings. Thus, it is imperative to carry out leachate testing on specimens intended for use in road layers as these extend over vast areas of land and due to the possible risk of direct exposure of the surrounding soil and groundwater to harmful pollutants [63].

Glass cullet (GC) subjected to the Australian Standard Leaching Procedure revealed that the release of heavy metals in both acidic and alkaline buffers is within permissible threshold values, beyond which material would be classified as hazardous [17]. FRG and MRG put through the Australian Standard Leaching Procedure using two buffer solutions (slightly acidic and relatively alkaline) showed that the values are far below the category "C" waste thresholds. As a result, both FRG and MRG can be categorized as low-hazard waste [43]. The Toxicity Characteristic Leachate Procedure (TCLP) and Synthetic Precipitation Leaching Procedure (SPLP) tests were conducted on glass cullet samples in the study [14], where the TCLP detected trace amounts of lead and barium; however, these metals were observed at levels well below the allowable limits for drinking water standards. On the other hand, no detectable amounts of metals were noted through the SPLP testing; thus, it could be deemed that the glass cullet is an environment-friendly aggregate. TCLP results for glass cullet from [16,78] agree, revealing that the leachate levels are below levels deemed hazardous by regulatory bodies and further demonstrate that the values are comparable to those of natural aggregates. According to the total characteristic leachate procedure, RGW has the lowest concentrations of heavy metal leachates among several waste materials, including steel slag, ladle furnace slag, waste foundry sand, and coal ash considered in the study by [79]. The same highlights that RGW leachate levels are within the permissible limits set by local authorities.

Total contaminant (TC) testing conducted in the study by [43] showed that both fine recycled glass and medium recycled glass have contaminant levels well below the allowable limits except concerning chromium, where the values are found to be close to the permissible boundary. Testing conducted to assess the heavy metal leaching from crushed glass [18] revealed that all metal leachate concentrations are comfortably below the threshold limits. However, acid-washed glass samples recorded iron concentrations above the allowable limits, thereby posing a concern regarding using recycled glass in acidic environments.

Total contaminant and Australian Standard Leaching Procedure testing conducted on FRG-RCA samples [48] revealed that all leachate levels are within the permissible limits except for copper and nickel, which pose a slight concern owing to their potential to leach into the surroundings. The case and the study concluded that this does not imply that the same concentration of leachate would make its way into the groundwater table.

Total concentration test results for foamed recycled glass reported that contaminant constituent levels in the sample are well under the allowable threshold limits [50]. Furthermore, leachate testing on foamed recycled glass indicated that the degree of metal leaching is within permissible limits for all metal leachates [50].

4. Application of Glass in Base and Subbase Layers Findings on Mechanical Properties of Samples Containing Glass

4.1. Compaction Test (Standard/Modified)

This section manifests the findings on compaction testing from studies incorporating glass into various aggregates to form composites suitable for use in base and subbase layers of road pavements. The section reports findings for inclusions of different forms of glass into a variety of common road aggregates. Compaction testing is a fundamental engineering test used to determine the most appropriate water content to be added to achieve the highest degree of compaction. This moisture content is referred to as the optimum moisture content (OMC), and at this water content, the sample would record its maximum dry density (MDD). The MDD provides an overall indication of the quality of a mixture where a greater MDD is commonly associated with samples containing higher quality aggregates, thus undergoing a higher degree of compaction, while lower values indicate possible porosity of aggregates [80,81].

Modified compaction testing conducted on FRG-WR blends presented maximum dry density (MDD) in the ranges 2.13 to 2.26 mg/m^3, while the pure FRG recorded MDD of 1.84 mg/m^3 [57]. The MDD of crushed rock (CR) shows a slight decrease with the introduction of CG, while the optimum moisture content (OMC) of the mixture increased slightly. CG blends containing CG in the percentage inclusions considered in the study are regarded as having low water retention, thus improving the overall workability of CR [10,82]. The effect of glass cullet inclusion in CR is studied by [16], where the OMC and MDD were observed to decrease with increasing inclusion of glass cullet in CR. Compaction curves for crushed rock–glass cullet samples [25,26] are relatively flat, indicating moisture insensitivity of mixtures, thus allowing for application in environments prone to drastic changes in moisture. The study conducted by [45] shows that the MDD decreases whilst the OMC increases as the percentage inclusion of CG increases for CR–CG blends.

RG-RCC blends have MDD values that vary between 1.90 to 1.98 mg/m^3 (similar to values for natural aggregates), and in addition, the combinations also demonstrated relative insensitivity to moisture content when undergoing compaction as the RG content increased [26]. The moisture-insensitive nature of the blends mentioned above makes them suitable to be placed in the field, even during wet conditions. Compaction testing on

RCG-base course aggregate blends was performed in [46], with the MDD and the OMC decreasing with increasing RCG inclusion. The control base course sample, 10, 20, and 30% RCG blends record MDD values of 2.34, 2.23, 2.30, and 2.26 mg/m^3, where the same samples have OMC of 5.0%, 4.3%, 4.8%, and 3.89%, respectively. The results from [32] agree, presenting that MDD values decrease as increasing amounts of glass aggregate are introduced to virgin base aggregates, where the MDD value for pure virgin base aggregate is 2.152 g/cm^3 with the value dropping to 2.023 mg/cm^3 upon including 50% crushed glass aggregate. Furthermore, the OMC decreases and the compaction curves become increasingly flattened as the inclusion of glass aggregate increases, indicating increasing insensitivity to moisture for the blends. Modified compaction testing on results from [57] for FRG-RCA blends presented MDD values between 1.90 to 1.98 mg/m^3, where the MDD values are observed to decrease with increasing FRG. On the other hand, the MDD and OMC show little change with the introduction of RCG in cement-treated RCA blends [20], where blends record MDD in the range from 2.008 to 2.018 mg/m^3. Results from [48] concur, where the introduction of 15% FRG to RCA leads to a slight decrease in MDD values, adding that the overall quality of the aggregate, to a great extent, remains constant.

Compaction tests conducted on limestone-glass cullet blends containing up to 30% cullet show that the MDD decreases as the percentage of cullet increases, further revealing that relatively flatter compaction curves are observed as the percentage of cullet is increased [47]. Dry density values for sand-ground glass-carbide lime blends increase as the percentage inclusion of ground glass increases from 10% to 30% [27]. Experimental studies conducted on cement stabilised soil containing 5%, 10%, 15%, 20%, and 30% of recycled glass reveal that an optimum inclusion of 20% glass provides the highest dry density of 2.27 mg/m^3 at a cement inclusion of 3%, further noting that this value is comparable to that of gravel [79]. The same reports that the introduction of glass lowers the moisture sensitivity of the samples in comparison to the natural soil. The introduction of 15% FRG to RCA leads to a slight decrease in MDD values, revealing that the overall quality of the aggregate, to a great extent, remains constant [48].

Considering the findings mentioned above, it is fair to state that the inclusion of glass in common base and subbase aggregates overall leads to a decrease in MDD and OMC while providing relatively flatter compaction curves, indicating an increase in the moisture insensitivity of the composites. Table 9 summarises the effects of various recycled glass on the compaction results of base/subbase materials.

Table 9. Summary of compaction test data.

Materials/Blends	Maximum Glass Inclusion	Sample Preparation	OMC (%)	MDD (mg/m^3)	Reference
GC-CR	50%	Modified compaction	-	1.90–1.98	[25]
FRG-WR	50%	Modified compaction	8.09–9.31	2.13–2.26	[57]
CG-CR-R	5%	Modified compaction	7.75–8.28	2.474–2.443	[82]
RCG-CC (3% cement)	30%	Modified compaction	10.1–10.5	2.008–2.018	[20]
FRG-RCA	50%	Modified compaction	9.41–12.23	1.90–1.98	[57]
RCA-R-CG	5%	Modified compaction	12.32–12.51	2.207–2.222	[82]
Virgin aggregate-glass aggregate-glass powder (geopolymer cement)	80% Glass Aggregate and 10% Glass Powder	Modified compaction	-	2.023–2.152	[32]
RCG-base course	30%	Vibrating hammer compaction	3.89–5.00	2.23–2.34	[46]
Soil-RG-cement (3%)	20%	Modified compaction	5.37	2.27	[79]

4.2. Unconfined Compressive Strength (UCS)

This section presents the unconfined compressive strength (UCS) results from numerous studies where various supplementary inclusions of different glass forms are introduced to several aggregates. The composites considered for this section are deemed suitable for application to base and subbase layers of pavements. The unconfined compressive strength (UCS) test is a commonly conducted strength evaluation procedure that allows for the quantification of the maximum axial stress a right-cylindrical sample can withstand when no confining pressure is exerted. The compressive strength of road aggregates is yet another vital strength property as these materials are subjected to significant compressive stresses due to the weight of the overlying road structure and vehicle-induced loading. Higher UCS values indicate that the aggregate is of higher quality; thus, it is crucial to study the behaviour of these materials under compressive loads [83].

The inclusion of crushed glass in recycled concrete aggregate (RCA) and crushed rock (CR) increased the UCS values, with higher values recorded as the percentage of glass increased up to the maximum inclusion of 5% crushed glass (CG) in the study of [84]. This was explained by the reduction in the porosity of the aggregates with the addition of CG as well as dense packing of CG. The deformability of a specimen measured by the deformability index (ID) decreased with increasing CG inclusion, indicating an increase in specimen stiffness. The inclusion of coarse WG led to reductions in the compressive strength of road aggregates, whilst the introduction of finer WG improved the compressive strength [22,85]. All cement-treated RCG-RCA blends containing up to 30% recycled crushed glass (RCG) recorded UCS values well above the requirements of local authorities for use in pavement subbase applications [20]. Furthermore, the cement-treated RCG-RCA blends recorded values in the range 4.50–5.60 MPa following 7 days of curing and 6.90–8.40 after a curing period of 28 days.

UCS values for 3% cement-stabilised CG-CR blends containing up to 30% RG all comfortably met the minimum requirement of 3.5 MPa, although increasing the percentage of RG led to decreasing UCS [86]. The pure CR specimen recorded a mean 7-day UCS of 6.35-6.77 MPa while the blend with a 30% introduction of RG achieved a UCS of 4.06–4.69 Mpa.

The inclusion of 0.15% alkali-resistant glass fibre into cement-treated reclaimed asphalt did not cause significant changes in the UCS values [55]. The values reported for the blends are comparable to RCA and limestone blends treated with identical amounts of cement. Blends incorporating 0.15% alkali-resistant glass fibre in reclaimed asphalt treated with 2%, 4%, and 6% cement record UCS values of 241.13, 350.16, and 531.62 kPa, respectively. Concrete containing various replacements of the concrete waste aggregate of 30%, 50%, and 100% and 0.25%, 0.50%, and 1.0% glass fibres are subjected to UCS testing in [87], where the samples with up to 0.50% fibre inclusion led to improvements in UCS. Furthermore, it is worth noting that for all concrete waste aggregate contents, the glass fibre inclusion of 0.25% and 0.50% yielded 1.5–4% and 2–7% improvements in UCS, respectively.

Pavement quality concrete in the form of slag-fly ash-based alkali-activated concrete containing glass was studied in [88]. Various inclusions of glass, 0%, 5%, 10%, 15%, 20%, and 25%, are introduced in the study, where the control sample containing 0% glass recorded a compressive strength of 25.2 MPa and where the sample containing the optimum percentage inclusion of 15% glass recorded the highest value of 39.7 MPa following 7 days of curing. The effect of replacing Portland cement (PC) with up to 50% spent fluorescent lamp glass (SFLG) waste was studied in [73]. The UCS values for SFLG blends following 28 days of curing were less than the control PC specimen. However, a 90-day curing period resulted in the SFLG blends containing up to 35% SFLG, achieving UCS values analogous to or greater than the reference control sample.

UCS values are observed to decrease as increased amounts of glass aggregate were introduced to virgin base aggregates bound by the inclusion of 20% glass-powder-based geopolymer [32].

When examining the findings mentioned above, it is rather challenging to arrive at an overall conclusion as the inclusion of various types of glass into different aggregates yields disparate outcomes concerning UCS. This being said, it is safe to state that moderate inclusions of glass below 10% should not have significant adverse effects on the compressive strengths of the blends. Table 10 summarises the range of UCS of various road base/subbase materials/combinations incorporating recycled glass.

Table 10. Summary of UCS values.

Materials/Blends	Maximum Glass Inclusion	Sample Preparation	UCS (MPa)	Reference
Alkali-resistant glass fibre-cement-reclaimed asphalt	0.15%	OMC and MDD (modified compaction)	0.241–0.531	[55]
CG-CR-R CG-RCA-R	5% 5%	OMC and MDD (modified compaction)	0.152–0.210 0.227–0.234	[84]
CG-CC-cement (3% GB cement)	30%	OMC and MDD (modified compaction)	4.50–5.60 (7 days) 6.90–8.40 (28 days)	[20]
GF-limestone-CC	1%	OMC and MDD (modified compaction)	28.2–36.8	[87]
CG-CR-cement (3% GB cement)	30%	OMC and MDD (Proctor compaction)	4.06–4.69	[86]
Slag-fly ash-glass concrete (alkali-activated concrete)	25%	-	25.2–39.7 (7 days)	[88]

4.3. California Bearing Ratio (CBR, Soaked/Unsoaked)

California bearing ratio (CBR) is a penetrative test that measures a material's resistance to penetration by a standard plunger. It is commonly employed to evaluate the performance of base and subgrade courses of roads and to study an aggregate's shear performance compared to a standard sample of crushed rock. The CBR results often contribute to determining the thickness of respective pavements layers to enable the smooth functioning and longevity of road structures. Samples achieving higher maximum dry density (MDD) were identified as having better quality aggregate, often achieving higher CBR values; thus, they are considered to be of better quality [89].

CBR testing on GC-CR revealed that the inclusion of 15% glass cullet (GC) produces results comparable to those of pure crushed rock (CR) samples [16]. However, the same showed that an increase of said percentage to 50% resulted in notable reductions in CBR values. CBR testing results from [33] for CR mixed with up to 50% CG recorded CBR values between 42% to 125%, further noting that lower inclusions of glass (15%) obtained CBR values similar to pure CR samples. CBR testing was conducted on FRG-WR blends in [24], where all FRG-WR mixtures containing up to a maximum inclusion of 30% FRG met the minimum CBR value of 40% required for use in the base layer of footpaths. All CG-CR blends from [25,26] containing up to 50% CG met the minimum requirement of 80% for VicRoads Class 3 subbase materials. The introduction of up to 50% RG in CR [23] resulted in the blends achieving CBR values in the range of 121% and 199%, which is well above the base and subbase layers' requirements. FRG-WR mixes, including up to 50% FRG [57], had CBR values in the range of 121% to 170%, where all blends satisfied CBR requirements for use in base and subbase layers of road pavements. Studies conducted on Class 2 CR revealed that incorporation of CG causes significant increases in CBR values from 133% to 144% [84], where the gain was interpreted by the decreasing void ratio due to the introduction of CG. All mixtures are noted to satisfy requirements for aggregates used in the base layer of roads. RG–CR blends treated with 3% cement and up to 30% RG were studied by [86], where CBR values are noted to decrease with increasing inclusions of recycled glass (RG). However, all blends meet the minimum CBR requirements as governed by local road authorities. The pure CR sample achieved CBR values of 919–980%, while the mixture containing 30% recorded CBR values of 707–717%.

All CG-RCC blends from [26] recorded CBR values ranging from 98% to 203%. It is worthy of mention that the CBR values recorded are markedly more significant than the minimum requirement as per VicRoads specifications for Class 3 materials. Cement-treated RCG-RCA blends containing up to 30% RCG recorded very high CBR values in the range from 458% to 596% [20], where these values again comfortably satisfy the requirements for road pavement aggregates. The introduction of FRG to RCA reduced CBR values, although 15% of FRG in RCA met the CBR requirements for use in bases for footpaths [48]. Inclusion of up to 50% FRG in RCA [57] led to CBR values in the range of 98% to 203%, which are well above the requirements for road layer aggregates.

The inclusion of 10% glass aggregate to virgin base aggregate (gravel and hard limestone) led to a minor reduction in the CBR value compared to that of the pure virgin aggregate. However, further inclusion of glass aggregate led to a more significant CBR decrease [32], where virgin aggregate-glass blends containing up to 50% glass recorded CBR values in the range from 40% to 99%. The decrease in CBR was attributed to the lower interlocking performance of glass than the virgin aggregate (VA) because of the smooth surfaces of glass and the breakage of glass particles during testing. The same reports that virgin aggregate-glass blends treated with glass powder-fly ash geopolymer had high CBR values ranging from 298% to 512%, presenting that geopolymer binding led to drastic improvements of CBR values. Although the geopolymer-treated blends with higher glass inclusions recorded lower CBR values, all geopolymer-treated mixtures recorded satisfactorily high CBR values for use in base layers of pavements [32]. Cement-stabilised soil incorporating recycled glass contents of 5%, 10%, 15%, 20%, and 30% showed an increase in CBR values as the percentage inclusion of glass increased, where the CBR values achieved were 130.93%, 143.26%, 147.97%, 153.26%, and 159.85%, respectively, at a cement inclusion of 3% [79]. The same further notes that the CBR values recorded by all cement-stabilised soil samples containing glass meet the minimum requirements of 80% and thus can be used in the base layers of light haul roads.

The CBR results for pure foamed recycled glass satisfied Victorian road authority requirements as structural fill for road embankments. The material exhibits behaviour that is not common to coarse-grained soils, where the aggregate shows both peak and ultimate loads when a penetrative force is applied [50], hinting at the possibility of using foamed recycled glass in road layers when mixed with higher quality aggregates.

Including glass in different aggregates leads to distinct results; however, it is safe to state that an overall inclusion of up to 15% glass is not expected to deteriorate the CBR values of the composites significantly. A summary of the CBR results of samples containing glass is provided in Table 11.

Table 11. Summary of CBR values.

Materials/Blends	Maximum Glass Inclusion	Sample Preparation	CBR	Reference
RCG-RCA-cement (3% Cement)	30%	OMC and MDD (modified compaction)	458–596%	[20]
Gravel/hard lime stone (virgin agg)-RG -glass powder geopolymer	50%	OMC and MDD (modified compaction) Four-day soaked	298–512%	[32]
CG-CR	50%	OMC and MDD (modified compaction)	42–125%	[33]
FRG-WR	50%	OMC and MDD (modified compaction) Four-day soaked	121–170%	[57]
RG-CR	30%	OMC and MDD (modified compaction) Four-day soaked	121–199%	[23]

Table 11. *Cont.*

Materials/Blends	Maximum Glass Inclusion	Sample Preparation	CBR	Reference
CG-CR-R	5%	OMC and MDD (modified compaction)	133–144%	[84]
RG-CR-cement (3% cement)	30%	OMC and MDD (modified compaction) Four-day soaked	707–717%	[86]
FRG-RCA	50%	OMC and MDD (modified compaction) Four-day soaked	98–203%	[57]
CG-RCA-R	5%	OMC and MDD (modified compaction)	147–164%	[84]
RG-cement-soil (Up to 3% cement)	30%	OMC and MDD (Proctor compaction)	130.93–159.85%	[79]

4.4. Los Angeles Abrasion/Aggregate Crushing Value

The Los Angeles abrasion and aggregate crushing value tests indicate the quality of aggregates in terms of their ability to resist abrasion and changes in gradation. Resisting breakage when subjected to forces is a fundamental material characteristic and is especially important in the case of road aggregates that undergo repeated vehicular loading. Lower losses indicate aggregates with superior resistance to mechanical abrasion; therefore, these tests are undertaken to evaluate the suitability of any material for use in the construction of roads [90].

Pure glass cullet of 1/4″ size recorded losses of 29.9%, while the 3/4″ registered a value of 41.7%; thus, it is not as mechanically sound as crushed rock (CR) associated with a Los Angeles abrasion value of 13.6% [16]. This being said, the pure glass samples are noted to be close to those of typical limiting values of LA abrasion according to limits set by the Washington Department of Transportation. Pure crushed glass (CG) recorded losses of 24% to 25%, according to Los Angeles abrasion testing conducted in [53]. Abrasion losses for FRG and MRG were noted to be 24.8% and 25.4% [34], respectively, possessing values similar to CR (24%) and below RCA (28%). Coarse recycled glass (CRG), on the other hand, recorded higher losses of 27.7% [43]. The soundness of RG compared to that of CR was far lower, where RG reported nearly twice the losses reported by CR [78]. The study conducted in [32] shows that RG recorded a Los Angeles abrasion value of 38.7%. The Los Angeles abrasion study from [26] reports that RG by itself has a wear value of 27%. Glass cullet has Los Angeles values falling between 24% and 25%, for the finer sample and coarser sample, respectively, noting the values are well within the range of 10% to 35% for typical natural aggregates [14].

CR-RG blends have abrasion losses between 23% to 25%, which are within the acceptable VicRoads Los Angeles limit of 35% for crushed aggregates used in base and subbase layers of pavements [23,26]. FRG-WR blends tested in [57] were reported to have losses in the range of 23% to 25%, further presenting that the values are within the range for use in base and subbase layers of pavements. The introduction of up to 5% crushed glass to crushed rock (CR) containing 1% rubber in [59] revealed losses in the range 23.7–24.86, indicating that crushed glass is a suitable aggregate for use in subbase layers of pavements. FRG-WR blends recorded losses of around 25%, which is well below the maximum allowable value of 60% for base layers of footpaths [24].

RG-RCC blends studied in [26] possessed Los Angeles abrasion values from 28% to 32%, which are within VicRoads' 35% acceptable limit. The research conducted by [57] reported losses ranging from 28% to 32% for FRG-RCA blends, adding that the values are within the suitable range for base and subbase aggregates. Studies from [59] include up to 5% RG in RCA containing 1% rubber where losses in the range 32.9–34.2% are recorded for the blends, thereby indicating a slight improvement in the durability of RCA as crushed glass is introduced. The FRG-CA composite containing 15% FRG registered an abrasion loss of 32%, within the allowable loss for footpath base aggregate [48].

Pure foamed recycled glass recorded a very high Los Angeles abrasion value of 94%, indicating low particle strength. Thus, exceeding the maximum Los Angeles abrasion value of 40% is generally considered the upper margin for pavement base and subbase applications [50]. A summary of Los Angeles and aggregate crushing values of different recycled glass and the mixture of glass with aggregates for base/subbase applications are provided in Table 12.

Table 12. Summary of Los Angeles abrasion/aggregate crushing value.

Materials/Blends	Maximum Glass Inclusion	Los Angeles Abrasion/Aggregate Crushing Value	Reference
RG	100%	27%	[26]
Glass cullet	100%	29.9–41.7%	[16]
RCG	100%	38.7%	[32]
FRG MRG CRG	100% 100% 100%	24.8% 25.4% 27.7%	[34]
CG	100%	24–25%	[53]
RG-CR	50%	23–25%	[26]
RG-CR-R	5%	23.7–24.86%	[59]
FRG-RCA	15%	32%	[48]
RG-RCA	50%	28–32%	[57]
CG-RCA-R	5%	32.9–34.2	[59]

4.5. Resilient Modulus

The triaxial testing procedure is followed to experimentally obtain resilient modulus values, where a repeated impulse load of fixed magnitude is applied in progressive cycles with varying magnitudes assigned to each loading cycle [91,92]. Such loading allows for a more efficient simulation of material deformation and performance under moving vehicular loads; thus, the resilient modulus is a critical parameter for pavement materials [93]. Higher values of resilient modulus are often associated with aggregates of superior quality.

Resilient modulus values could not be determined for pure RG samples due to the failure of specimens shortly after the start of the testing [43].

Resilient modulus testing was conducted on crushed rock (CR) samples containing 1% rubber and varying percentages of 1%, 3%, and 5% crushed glass in [84], where the introduction of higher contents of CG caused a notable increase in resilient modulus, from 96.1 to 131 MPa as the inclusion of glass increased from 1% to 5%. The increase in the resilient modulus was attributed to the reduction of the porosity of the samples with an addition of CG as well as the dense packing of the CG blends. Furthermore, all samples met minimum requirements for use in base and subbase layers of pavements. Research conducted in [23] indicates that up to 30% inclusion of FRG in CR yields resilient modulus values comparable to those of natural subbase aggregate. In contrast, findings from [16] revealed reductions in resilient modulus values upon the addition of 15% and 50% glass cullet to crushed rock, with more significant reductions observed as the cullet content increased. The resilient modulus values are in the range 22.4–33.5 MPa as the percentage of glass cullet increases from 15% to 50%. However, the same states that including up to 50% glass cullet in crushed rock is appropriate for standard pavement design. Resilient modulus values for RG-CR blends are comparable to those of natural aggregates and are noted to be primarily insensitive to moisture [26]. An increase in resilient modulus values was noted up to the inclusion of 24% CG in CR, while further increasing the %CG led to a decrease in the values [45]. The resilient modulus values from [86] for RG-CR blends stabilised with 3% cement after a curing period of 7 days present that an optimum inclusion of 20% RG achieved the highest values for RG-CR combinations, where the 20% RG blend recorded values in the range 169–256 MPa whilst the cement-treated pure CR sample presented values in the range 176–278 MPa. Thereby showing that the inclusion of RG in CR leads to a decrease in resilient modulus values, although the blends meet the requirements for use in road pavement layers.

RG-RCC blends possess resilient modulus values that are much higher than natural aggregates [26]. Furthermore, resilient modulus values for RG-RCC are noted to be sensitive to both moisture content and %RG, where higher moisture contents and %RG leads to a decrease in resilient modulus values. The resilient modulus values for FRG-RCA blends studied in [57] were noted to be sensitive to both moisture content and percentage inclusion of FRG, where higher inclusions of FRG generally lead to lower resilient modulus. This observation could possibly be elucidated through the reduction in the amount of unreacted cement in the RCA blends as FRG was introduced, where higher glass inclusions led to a greater reduction in the relative unreacted cement available, thus leading to lower strength. All cement-treated RCG–RCA blends from [20] with up to 30% recycled crushed glass (RCG) inclusion record resilient modulus values within the required range for bound quarry subbase materials of local authorities, where the blend containing 10% RCG recorded the highest resilient modulus values in the range 352.04–505.70 MPa while the sample containing 30% RCG presented a value in the range 209.71–437.24 MPa. The reduction in resilient modulus values as the RCG content was increased from 10% to 30% could be explained through the lower durability of RCG compared to RCA where higher inclusions of RCG led to reductions in the resilient modulus values. Resilient modulus testing was undertaken on RCA containing 1% rubber and varied percentage inclusions of 1%, 3%, and 5% CG in [59,84], where the resilient modulus values were observed to increase as the glass inclusion increases, with the values increasing from 169 to 192 MPa as the %CG increased from 1% to 5%.

Studies on RG and caliche (conventional subbase granular aggregate) blends reveal that the resilient modulus values increase with the inclusion of up to 30% RG [94]. Results of the repeated load triaxial tests conducted by [46] reflect that the addition of up to 30% RCG (−9.5 mm) in TNZ M4 AP40 (common base course) has an insignificant effect on the performance of blends concerning rutting depth. Table 13 summarises the resilient modulus values for samples containing glass that are suitable for utilisation in base and subbase layers of road pavements.

Table 13. Summary of resilient modulus.

Materials/Blends	Maximum Glass Inclusion	Sample Preparation	Resilient Modulus (MPa)	Reference
RG	100%	OMC and MDD (modified compaction)	-	[43]
RG-CR-R	5%	OMC and MDD (modified compaction)	96.1–131	[84]
GC-CR	50%	OMC and MDD (modified compaction)	154.44–230.97	[16]
RG-CR-cement (3% cement)	30%	OMC and MDD (Proctor compaction)	142–278	[86]
RCG-CC (3% cement)	30%	OMC and MDD (modified compaction)	209.71–505.70	[20]
RG-RCA-R	5%	OMC and MDD (modified compaction)	169–192	[59,84]

4.6. Permanent Deformation

Permanent deformation is commonly evaluated using the triaxial machine, and it is mainly similar to the resilient modulus procedure where repeated rapid cyclic loading is applied. The significant difference between the resilient modulus and permanent deformation comes down to recoverable strain vs. irrecoverable strain, where permanent deformation values reflect on deformation that is considered as "plastic/permanent" or irrecoverable. Deformation that is permanent is highly undesirable for mixtures intended to be used in the construction of road layers, as this would adversely affect the performance of the road structure. Hence, this test is widely incorporated in testing schemes employed to evaluate the appropriateness of a given material for use within the network of roads [95].

Repeated load triaxial tests were conducted on RG-CR blends in [26], where the permanent deformation values were observed to increase as the amount of RG in the mixture increased, further noting that the values for RG-CR blends were sensitive to moisture content. Studies conducted by [23] revealed that permanent deformation values for FRG-CR mixtures with up to 30% FRG achieve permanent deformation values comparable to natural subbase aggregates. Studies conducted in [20] agreed that an overall trend of increasing permanent deformation is observed as the percentage inclusion of RCG increases. On the other hand, repeated load triaxial test results from [45] for CR–CG blends showed that permanent deformation values decreased as the %CG increased, thereby revealing that the inclusion of crushed glass (CG) increases the stability of the crushed rock (CR). Permanent deformation values for FRG-WR blends from [57] showed sensitivity to the moisture content in the range 60–90% of OMC and fine recycled glass (FRG) content, where higher FRG inclusions led to a potential increase in the recorded permanent strain.

CR and RCA samples with CG mainly demonstrated plastic creep behaviour with respect to permanent deformation according to the Werkmeister criteria [7], while this behaviour changed from plastic creep to plastic shakedown at higher percentage inclusions of CG [59,82]. This shift in permanent deformation behaviour is especially significant as it aids in improving the performance of the materials against dynamic loading, similar to what is applied by vehicular traffic. A majority of mixes satisfy requirements in terms of permanent deformation for use in base/subbase layers of pavements.

Permanent deformation testing carried out on RG-RCC blends [26] reveals that the RG-RCC combinations have much smaller permanent deformation values than natural subbase aggregates. Permanent strain values for FRG-RCA blends in [57] were insensitive to both moisture content and FRG content. Permanent deformation testing was undertaken using the repeated load triaxial machine on RCA incorporating RG where 10%, 30%, 50%, and 70% RG were introduced into the RCA [96]. The results obtained from the permanent deformation testing revealed that the maximum permanent strain accumulated increased as an increasing amount of RG was introduced, with the 10%, 30%, 50%, and 70% RG blends recording maximum permanent strain of 0.52%, 0.56%, 0.75%, and 1.18%. Furthermore, the permanent strain is noted to increase significantly as the RG content rises beyond 30%. The fraction of recoverable strain increased with the introduction of RG into limestone aggregate; however, the permanent deformation results did not show a consistent trend with the variation of RG [51].

Considering the findings mentioned above, it can be concluded that the inclusion of glass in base and subbase aggregate overall leads to an increase in permanent deformation, which is undesirable for materials used in road layers. This being said, it is noteworthy that even though an increase in permanent deformation is observed with the inclusion of glass, the addition of up to 15% glass should not significantly reduce the performance of the road aggregate mix.

4.7. Direct Shear Test and Triaxial Shear

This section will focus on the findings relating to shear parameters for composites where various glass forms are introduced to different pavement aggregates. Shear testing is a widely undertaken geotechnical test that evaluates the ability of a material to resist shear forces, in other words, the shear strength of the material. The resistance of aggregates to sliding forces is critical when focusing on pavement layer materials, as such forces are commonly exerted on roads induced by vehicular loading [97]. Materials with higher shear strength are more desirable for utilisation in road pavement layers as they positively influence the service life of the pavement structure [98].

RG shows the variation of internal friction angles between 55° and 46° at the normal stress values of 25 and 400 kPa, respectively [26]; however, the RG samples show a shortcoming in terms of interparticle cohesion resistance. The RG-CR blends from [26] recorded internal frictional angles ranging from 41.3° to 50.3°, values of cohesion between 5 kPa (100% RG) and 69.6 kPa (100% CR), and cohesion values of 31 to 59.3 kPa for mixed blends; thus, it is fair to state that all RG-CR mixes report high shear strength. Large direct shear test testing was carried out on CR samples containing 1% rubber along with varied percentage inclusions of 1%, 3%, and 5% waste crushed glass (WCG) in [5], where the blends had internal friction angles ranging between 43.26° and 44.10°. Furthermore, the cohesion values were observed to increase with the introduction of WCG to the CR samples containing rubber.

Large direct shear test testing was performed on RCA samples containing 1% rubber together with inclusions of 1%, 3%, and 5% waste crushed glass (WCG) in [6], where the blends had internal friction angles between 43.89° to 47.73°. Furthermore, the cohesion values increased as WCG was introduced into the mixture. Further adding that 3% WCG best enhanced the overall shear performance of the WCG-R-RCA blends. Direct shear testing was conducted on RG-RCC blends in [26] containing up to 50% RG where the mixtures had internal frictional angles (Mohr-Coulomb) ranging from 44.7° to 51° and cohesion values from 33.4 to 91.2 kPa.

Consolidated drained (CD) Triaxial test conducted on RG-RCC blends in [26] indicated strain-softening behaviour for the mixes and have similar confining pressure and peak strength relationship seen in RG–CR combinations. Another finding is that peak deviator stress decreased as %RG increased.

The foam glass gravel recorded a relatively high angle of internal friction of 45°, thus allowing for efficient mobilisation of load distribution within the road layer [37]. Foamed recycled glass [50] demonstrated a high degree of dilatant behaviour, which is noted to be unusual for coarse-grained materials. The material also records cohesion and friction angle values of 23.36 kPa and 54.7°, respectively, making it suitable as a lightweight fill (comparable to dense gravel material). The relatively high shear parameters, especially the high friction angle of foamed recycled glass, indicate suitability for use in subbase layers when stabilised with superior aggregates.

The shear strength decreased as a higher percentage of recycled glass (RG) was introduced into limestone aggregate, this being attributed to the smoother surface and lower angularity of RG, thus leading to weaker particle interaction within the limestone-RG matrix [51].

Considering the findings from the literature as mentioned above, it can be deemed that the introduction of glass does not have significant adverse effects on the shear parameters of the glass-base and subbase aggregate blends. Table 14 shows the cohesion and angle of friction for road base and subbase materials with glass.

Table 14. Summary of shear values.

Materials/Blends	Maximum Glass Inclusion	Sample Preparation	Cohesion (kPa)	Angle of Friction	Reference
WCG-CR-1%R	5%	OMC and MDD (modified compaction)	31.47–41.66	44.73–46.48°	[6]
RG-CR	50%	OMC and 95% MDD (vibrating hammer compaction)	31.0–59.3	41.3–50.3°	[26]

Table 14. *Cont.*

Materials/Blends	Maximum Glass Inclusion	Sample Preparation	Cohesion (kPa)	Angle of Friction	Reference
FRG-WR	50%	OMC and MDD (modified compaction)/triaxial shear	31–59	47–50°	[57]
WCG-RCA-1% rubber	5%	OMC and MDD (modified compaction)	10.17- 13.37	43.26–47.73°	[6]
RG-RCC	50%	OMC and 95% MDD (vibrating hammer compaction)	33.4–63.2	44.7–51°	[26]
FRG-RCA	50%	OMC and MDD (modified compaction)/triaxial shear	33–63	45–48°	[57]

5. Application of Glass in Subgrade Layer Aggregates Findings on Mechanical Properties of Samples Containing Glass

5.1. Compaction

This section would first focus on the compaction test findings for pure recycled glass (RG) from the literature, following which the results for blends consisting of RG and subgrade aggregate blends would be presented.

The compaction curve for only RG is convex in shape, showing similarity to that of natural aggregates; however, it is noteworthy that the curve for RG is flatter, thereby indicating relative insensitivity to moisture [14,35]. The as-received cullet samples for Heller and Stoltzfus in [14] achieved maximum dry density (MDD) values of 1.72 and 1.79 mg/m^3, respectively, following standard compaction effort. FRG and MRG studied in [34] record MDD of 1.70 and 1.83 mg/m^3 with standard compaction effort, whereas the same values for modified compaction are 1.78 and 1.99 mg/m^3; the higher MDD for MRG indicates superior compaction.

Replacement of soil with crushed soda–lime glass at various percentages by weight increased MDD, where the higher the percentage inclusion of glass, the higher the MDD [99,100]. Compaction test results for FRG-biosolid blends show an increase in MDD value as the %FRG increased [34]. Lower percentage inclusions of glass cullet in gravelly sand [16] recorded higher maximum density values. The blends containing up to 50% glass cullet had MDD in the range of 2.15 to 2.23 mg/m^3. The introduction of 20% lead-free panel glass and funnel glass [101] into the soil matrix increased the MDD of the soil, where the 20% lead-free panel glass-soil achieved MDD of 1.804 mg/m^3 while the 20% funnel glass–soil blend recorded a slightly higher maximum dry density of 1.820 mg/m^3. Mechanical soil stabilisation work was undertaken in [102] utilising 10%, 20%, and 30% RG inclusions in expansive soil showed that the MDD of the soil increased as the amount of recycled glass added was increased. The pure clay and blends with 10%, 20%, and 30% RG achieved MDD values of 1.457, 1.520, 1.559 and 1.585 mg/m^3, respectively. Furthermore, the optimum moisture content (OMC) for mixtures decreased as the glass introduced increased, indicating increased moisture insensitivity of blends as the glass content was increased. MDD results for expansive clay and waste glass powder (WGP) combinations [103] agree with the above as the MDD values increased up to 1.94 mg/m^3 at an optimum inclusion of 15% WGP, beyond which further increasing the %WGP led to a decrease in the MDD. The same presents that the OMCs for the blends decreased continuously as the %WGP increased, indicating increased moisture insensitivity of combinations brought about by the introduction of glass. MDD of kaolinite soils and quarry fines mixtures shows an increase with the addition of CG [104]. This increase could be elucidated by improving the gradation of particles in the mix with the introduction of crushed glass (CG). The effect of incorporating powdered glass in fat clay was studied in [105], where samples with glass powder inclusions in the range of 0% to 14% were assessed. The compaction test results for the fat clay-glass powder blends revealed MDD values in the range 1.86 to 1.93 mg/m^3 and OMC in the range 18.2% to 14.8%; furthermore, the MDD was observed to increase with increasing glass inclusion up to a maximum inclusion of 12%, beyond which further introduction of glass led to lower MDD while the OMC continues to decrease with increasing glass powder.

The OMC increased with the introduction of glass fibres into a cohesive soil matrix [28]. This change is associated with the increased void ratio caused by the addition of glass fibres. The increase in voids allows higher water retaining within the fibre–soil matrix. The introduction of alkali-resistant (AR) and electronic-grade glass fibres to clay soils reduced the dry density of the mixture, indicating reduced workability and degree of compaction achieved [106], where the MDD decreased from 2.05 to 1.83 mg/m^3 and 2.05 to 1.81 mg/m^3 as 1% AR and electronic-grade glass fibres were introduced, respectively. The optimum moisture content (OMC) of cement reinforced sandy soil [29] increased while the maximum dry density (MDD) decreased when the percentage inclusion of glass fibre was increased. This decrease in the MDD is attributed to the lower density of glass fibre than sandy soil, and the increase in OMC is explained by the greater surface area of particle contact as the fibres are added.

Introduction of crushed waste glass (CWG) to expansive soil stabilised with quarry dust-based geopolymer cement (QDbGPC) in [42] causes reductions in OMC values while increasing the MDD values, further revealing that at a 40% inclusion of QDbGPC, the MDD increases from 1.85 to 4.54 mg/cm^3 as the CWG% increases from 0 to 40%.

Concerning the findings mentioned above, it is safe to state that the inclusion of glass into subgrade aggregates leads to an overall increase in MDD and decrease in OMC, which indicates superior compaction and increased workability of blends. Table 15 summarises the MDD values for the various mixtures.

Table 15. Summary of compaction test data.

Materials/Blends	Maximum Glass Inclusion	MDD (mg/m^3)	Reference
Glass cullet (Heller)	100%	1.72	[14]
Glass cullet (Stoltzfus)	100%	1.79	
FRG (standard compaction)	100%	1.72	[34]
MRG (standard compaction)	100%	1.84	
FRG (modified compaction)	100%	1.78	
MRG (modified compaction)	100%	1.99	
Glass cullet-gravelly sand	50%	2.15–2.23	[16]
RG-soil	80% Glass Aggregate and 10% Glass Powder	1.46–1.59	[32]
CWG-soil-QDbGPC	40%	1.85–4.54	[42]
Lead-free panel glass-soil	20%	1.804	[101]
Funnel glass-soil	20%	1.820	
WGP-soil	25%	1.94	[103]
Fat clay-glass powder	14%	1.87–1.94	[105]
Soil	0%	2.05	[106]
AR glass Fibre–soil	1%	1.84	
E glass Fibre–soil	1%	1.82	

5.2. *Unconfined Compressive Strength (UCS)*

This section focuses on findings to aid in evaluating the suitability of the glass to be incorporated as supplementary material in pavement subgrade aggregates. Various glass forms are included in the studies considered, including glass cullet, glass powder, glass fibres, foaming glass, and glass-based geopolymers. This section, however, does not reflect on pure glass samples as the samples fail prior to commencement of the testing shortly after de-moulding.

The compressive strength of cement-stabilised soil containing recycled glass improved with increasing inclusions of recycled glass up to an optimum inclusion of 10%, for which a compressive strength of 6.25 MPa was recorded, which is much higher than the compressive strength of gravel at 0.44 MPa, although increasing the glass content beyond 10% led to a decrease in the sample's compressive strength [79]. Such improvements in the compressive strength presented the potential for cement-stabilised soil containing waste glass to be used in base layers of roads. Incorporating waste glass powder (WGP) in expansive clay [103] increased UCS values by up to 360.10 KPa at an optimum inclusion of 15% WGP; further increasing the WGP content resulted in a decrease in UCS. The inclusion of soda–lime glass in expansive clay soil led to improved UCS values, where the improvement increased with the higher inclusion of glass at 12%, which was the maximum replacement tested in the study [99,100]. The soda-lime glass powder (GP)-clay blends containing up to 12% glass had UCS values between 0.239–0.584 MPa [99]. UCS testing was conducted on fat clay stabilised with varied inclusions of glass powder up to a maximum inclusion of 14% in [105], where the unconfined compressive strength values were observed to increase with greater inclusions of glass up to an optimum inclusion of 12% and then decreased as higher amounts of glass were added. The UCS values for the clay-glass blends following 7-day curing increased from 636.4 KPa for the control sample to a maximum of 801.7 KPa for the 12% glass samples.

The incorporation of glass fibres into cement-reinforced sandy soil led to greater unconfined compressive strength (UCS) values as the percentage introduction of glass increased up to an optimum value of 3% [29]. UCS testing was undertaken on low plasticity clay (CL)-glass fibre (GF) blends in the study [54], where differing percentage inclusions of 0.25%, 0.5%, 0.75%, and 1% GF, as well as varying lengths of 10, 20 and 30 mm fibres, were added to the CL clay. The study revealed that including up to 1% GF in CL improved the peak strength and allowed the samples to reach greater axial strains at failure, thus showing greater ductility. The UCS value for the pure CL sample at OMC was recorded as 138 kPa, while the GF–CL blends with 0.25%, 0.5%, 0.75%, and 1% of 20 mm fibres (optimum length) provided UCS values of 187, 239, 280, and 262 kPa, respectively. These improvements could be attributed to adhesion frictional resistance of the soil–fibre matrix and the build-up of tensile forces of resistance as the glass fibres are stretched due to compression. The study [54] further reported that the UCS values of the GF-CL blends are sensitive to both moisture content as well as MDD, where the UCS increased as the MDD was increased and as the water content was increased up to OMC, beyond which a decrease in UCS was observed. Alkali-resistant and electronic-grade glass fibres of 0.25%, 0.50%, 0.75%, and 1.0% were added to reinforce clay soil [106], where the soil–glass fibre blend containing 0.75% fibres led to the greatest improvement for both alkali-resistant and electronic-grade glass fibres where the alkali-resistant and electronic-grade glass fibres led to an improvement of 60% and 48%, respectively. UCS tests were conducted on expansive clay stabilised with up to 1% glass fibres of length 30 mm in [107], where the UCS was observed to increase upon introducing the glass fibres. The samples were prepared at three different dry densities of 1.25, 1.34, and 1.40 mg/m^3, where the 0.25%, 0.50%, 0.75%, and 1.0% fibre inclusions recorded values of 0.019, 0.023, 0.035, and 0.060 MPa for 1.25 mg/m^3 blend; 0.037, 0.059, 0.076, and 0.096 MPa for 1.34 mg/m^3; and 0.043, 0.065, 0.109, and 0.147 MPa for the 1.40 mg/m^3 sample, respectively. Furthermore, the highest ductility was recorded at a fibre inclusion of 0.50%. Lime-stabilised Ariake clay had little change in UCS when up to 25% foaming waste glass (FWG) was introduced at low lime content [38]; however, a notable increase in UCS was observed when an increased proportion of foaming glass was added at high lime contents. The FWG-clay-lime blends containing 5%, 10%, 15%, and 20% lime recorded UCS approximately within the ranges of 0.69–0.73, 1.40–1.66, 1.61–1.87, and 1.70–1.91 MPa, respectively. Furthermore, revealing that longer curing times also led to higher UCS results.

The UCS values of up to 25% RGP geopolymer-stabilised clay soils showed improvement compared to the unstabilised control sample [31]. The 7-day UCS values for RGP geopolymer–clay with 2M NaOH (sodium hydroxide) for blends with 3%, 6%, 9%, 12%, 15%, 20%, and 25% recycled glass powder (RGP) were approximately 0.52, 0.57, 0.66, 0.72, 0.83, 0.75, and 0.73 MPa. Furthermore, the samples stabilised with %RGP > 9% achieved superior UCS results to clay soil stabilised with 5% ordinary Portland cement, where samples with RGP content greater than 9% yielded UCS values greater than 2 MPa following a 91-day curing period. Using a higher molar ratio NaOH solution up to an optimum of 3 M provided higher UCS values due to more efficient geopolymerisation. Increasing RGP from 0% to 9% led to a near 60% increase in UCS values. The highest failure strain was obtained by 15% RGP inclusion for all curing periods. The UCS testing was carried out on RGP-calcium carbide residue (CCR)-stabilised clay sample containing up to 9% glass from [69], where the UCS was observed to increase compared to the control clay sample. Furthermore, the UCS values and failure strain (%) increased with increasing RGP inclusions up to an optimum inclusion of 15%. The blends for RGP–CCR–clay geopolymer recorded 7-day approximate UCS values of 1.49, 1.69, 1.83, 1.93, 2.14, and 2.04 for RGP contents of 3%, 6%, 9%, 12%, 15%, and 20%, respectively. The increase in the failure strain can be associated with improved ductility brought about by RGP–CCR geopolymer stabilisation of the soil. Compressive strength of 2.38 MPa was recorded for limestone stabilised with 8% glass waste binder [108].

Through the findings from the literature as mentioned above, it is reasonable to presume that the inclusion of glass in its many forms, including crushed glass, glass powder, glass fibres, foaming glass, and glass-based geopolymer, leads to an increase in UCS values of the subgrade aggregates. Thus, glass is a suitable supplementary material for use in subgrade layers of pavements when considering UCS improvements. Table 16 presents a summary of the UCS values for studies containing samples with glass that is suitable for application in the subgrade layers of pavements, where exact UCS values have been presented.

Table 16. Summary of UCS values.

Materials/Blends	Maximum Glass Inclusion	Sample Preparation	UCS (MPa)	Reference
RG-soil-cement (Up to 3% cement)	30%	OMC and MDD (vibrating hammer compaction)	3.43–6.62	[79]
GP-clay	12%	OMC and MDD (standard compaction)	0.239–0.584	[99]
WGP–clay	25%	OMC and MDD (standard compaction)	0.205–0.360	[103]
GP-clay	14%	OMC and MDD (modified compaction)	0.636–0.801 (7 days)	[105]
GF-clay	1%	OMC and MDD (standard compaction)	0.187–0.280 (Optimum Length= 20 mm)	[54]
GF-soil (1.25 mg/m^3) GF-soil (1.34 mg/m^3) GF-soil (1.40 mg/m^3)	1% 1% 1%	Prepared at varied dry densities of1.25, 1.34, and 1.40 mg/m^3	0.019–0.065 0.037–0.096 0.043–0.147 (Approximately)	[107]

Table 16. *Cont.*

Materials/Blends	Maximum Glass Inclusion	Sample Preparation	UCS (MPa)	Reference
FWG-clay (5% Lime)	25%	OMC and MDD (standard compaction)	0.69–0.73	[38]
FWG-clay (10% Lime)	25%		1.40–1.66	
FWG-clay (15% Lime)	25%		1.61–1.87	
FWG-clay (20% Lime)	25%		1.70–1.91	
RGP geopolymer-clay (2M NaOH)	25%	OMC and MDD (standard compaction)	0.52–0.83 (Approximately)	[31]
RGP-CCR-clay geopolymer	20%	OMC and MDD (standard compaction)	1.49–2.14 (Approximately)	[69]

5.3. California Bearing Ratio (CBR, Soaked/Unsoaked)

This section assesses the effectiveness of incorporating glass in subgrade layer materials with direct reference to California bearing ratio (CBR) values, where CBR results attained in studies that incorporate glass in many forms into conventional subgrade aggregates are disclosed. The section evaluates CBR values for pure glass samples as well as glass–subgrade aggregate composites.

Fine recycled glass (FRG) and medium recycled glass (MRG) recorded CBR values in the range 18–21% and 31–32% for standard compaction effort while achieving 42–46% and 73–76% when subjected to modified compaction effort, respectively [34]. The finding is explained by better compaction and higher particle contact for MRG [43]. Studies [17,109] also concurred, revealing that CBR values for glass cullet (GC) varied depending on their gradation, with mixed gravel and sand-sized GC recording higher CBR values than sand-sized GC samples. The gravel and sand-sized GC were noted to be more responsive to the compaction effort, thus allowing for a greater degree of density control. Furthermore, the extent to which the flakiness of particles affects CBR values is also lower for the gravel and sand-sized GC mixture. Furthermore, the CBR values for GC are comparable to natural aggregates bearing similar particle gradations. Glass cullet (GC) records CBR values greater than 15%, satisfying requirements for road subgrade aggregates, with values of 20% and 44% achieved for standard and modified compaction, respectively, thus not requiring a capping layer [17]. GC could also be used as capping layer material over weak natural subgrades.

The introduction of soda-lime glass into clayey soil increased the CBR values, a trend showing the higher the inclusion, the higher the CBR up to a maximum inclusion of 12% [99,100]. Studies conducted on FRG-biosolids present that the CBR of the blends increased as the %FRG increased, further adding that the increase was more pronounced at inclusions above 40% [34]. The CBR values for expansive WGP–soil blends are in partial agreement, where CBR was noted to increase as the %WGP was increased from 0% to an optimum inclusion of 15%, where further addition of WGP led to a decrease in CBR values [103]. The introduction of 20% lead-free panel glass and funnel glass in the soil increased CBR values to 6.9% and 7.3%, respectively, while the control soil sample recorded only 6.4% [101], further revealing that 20% inclusion of both glass types met the CBR requirements for use in the pavement subgrade layer. The introduction of glass powder into fat clay [105] improved CBR values up to an optimum inclusion of 12%, beyond which further increasing glass powder content resulted in a reduction in CBR. Raising the glass powder inclusion from 0% to 12% led to an improvement of CBR from 1.8% to 7.7%, whereas increasing the glass powder to 14% reduced the CBR value. Stabilisation of clay with glass was studied by [110], where an increase in CBR values was observed as higher contents of the glass were introduced. As a result, the inclusion of glass in the soil improved subgrade-related properties, thereby implying that glass is a feasible aggregate for use in subgrade layers of road pavements.

The effect of introducing varied inclusions of glass fibres (0.25%, 0.50%, 0.75%, and 1.00%) and varying lengths (10, 20, and 30 mm) was studied in [28]. An increase in CBR values for glass fibre-stabilised cohesive soils was observed up to an optimum inclusion of 0.75% of 20 mm fibre; inclusions beyond this point led to reductions in CBR. This phenomenon is elucidated through the higher tensile strength of the glass fibres that aid in the effective interlocking of the soil–fibre matrix, thereby assisting in resisting the movement of particles. However, as the percentage inclusion of glass fibre increased beyond 0.75%, the interaction of fibre–fibre particles dominated over the more effective fibre–soil interaction, thus leading to reductions in CBR. Unsoaked CBR values were noted to improve up to an optimum inclusion of 0.75% fibre, where the optimum fibre length was observed to be 20 mm, and the unreinforced sample recorded 8.06% CBR while the sample reinforced with 0.75% of 20 mm fibres achieved the highest CBR of 22.31%. The four-day soaked CBR value of the unreinforced specimen was 2.89% (poor subgrade); in contrast, the values for fibre-stabilised specimens increased to a maximum value of 8.23% (good subgrade), which was again achieved at a 20% inclusion of 0.75 mm fibres. Additionally, CBR decreases with the increasing soaking periods [28]. CBR values for expansive clay was observed to increase with the introduction of glass fibres of length 30 mm, where the inclusion of 1% fibre increased the CBR to 9.6%, whereas the control clay sample only achieved a CBR of 1.6% [107]. The addition of foaming waste glass into lime-stabilised Ariake clay led to a significant increase in CBR values, where the addition of 25% foaming glass increased the CBR values by 65% and 72% for 7 days and 28 days of curing, respectively [38].

The effect of introducing recycled glass (RG) to coffee ground geopolymer was studied by [44], where various percentages of coffee grounds (25%, 50%, and 75%) were replaced by RG along with an inclusion of 30% fly ash or ground granulated blast furnace slag (GGBFS) to produce recycled glass-coffee ground geopolymer. The CBR results revealed a positive correlation for CBR value and coffee ground replacement by RG, where the CBR values were observed to increase with increasing percentage inclusions of RG, further reporting that all coffee ground-recycled glass geopolymer compositions achieved CBR values above the minimum requirement for pavement subgrade.

Considering the above-mentioned findings gathered from the literature, the addition of moderate quantities of glass (<20%) in its many forms into subgrade materials is justified, as the CBR values are noted to increase with the introduction of glass. Therefore, glass is suitable for being utilised as a supplementary subgrade material for road pavement construction. Table 17 summarises the CBR values for samples containing glass that are ideal for use in subgrade layers of road pavements.

Table 17. Summary of CBR values.

Material/Blends	Maximum Glass Inclusion	Sample Preparation	CBR	Reference
FRG MRG	100% 100%	OMC and MDD (standard compaction)	18–21% 31–32%	[34]
FRG MRG	100% 100%	OMC and MDD (modified compaction)	42–46% 73–76%	[34]
GC GC	100% 100%	OMC and MDD (standard compaction) OMC and MDD (modified compaction	20% 44%	[17]
GP–clay	12%	OMC and MDD (standard compaction)	2.4–5.8% (Approximately)	[99]
Lead-free panel glass-clay Funnel glass-clay	20% 20%	OMC and MDD (Proctor compaction)	6.9% 7.3%	[101]
WGP-soil	25%	OMC and MDD (standard compaction)	5.6–12.2% (Approximately)	[103]
GP-clay	14%	OMC and MDD (standard compaction)	2.5–7.6% (Approximately)	[105]

Table 17. *Cont.*

Material/Blends	Maximum Glass Inclusion	Sample Preparation	CBR	Reference
GF-soil GF-soil	1% 1%	OMC and MDD (standard compaction) OMC and MDD (standard compaction)	22.31% (0.75%, unsoaked) 8.23% (0.75%, four-day soaked)	[28]
GF-soil	1%	OMC and MDD (standard compaction)	4.3–9.6%	[107]
FRG-biosolids FRG-biosolids	90% 90%	OMC and MDD (standard compaction) OMC and MDD (modified compaction)	3.9–10.8% (Approximately) 7.10–25.0% (Approximately)	[34]
RG-coffee grounds-30% fly ash/GGBFS RG-coffee grounds-30% Slag	50% 50%	OMC and MDD (modified compaction) OMC and MDD (modified compaction)	11.0–15.0% (Approximately, four-day soaked) 25.0–35.0% (Approximately, four-day soaked)	[44]

5.4. Direct Shear Test and Triaxial Shear

This section details the findings relating to shear parameters for pure glass as well as glass-subgrade aggregate composites. The shear parameters are obtained through two main items of testing equipment, namely, direct shear and triaxial shear. The resistance of aggregates to sliding forces is especially important when focusing on pavement materials, as such forces are commonly exerted on roads through vehicular loading.

Direct shear testing on fine recycled glass (FRG) [34] revealed that the internal friction angle decreased from 47° to 40° as the applied normal stress increased from 30 to 480 kPa, comparable to that of dense sand containing angular grains. Both FRG (−4.75 mm) and MRG (−9.5 mm) manifest slight vertical contractions at the start of the direct shear testing, followed by vertical expansions until the testing was completed. Furthermore, dilatancy in volumetric strain and axial strain correlation was experienced at low effective confining stresses, while compression was experienced at effective confining stresses higher than 100 kPa. Direct shear analysis conducted on RG [43] with respect to shear shows repeating stress vs. horizontal deformation pattern for each stress level considered, where a peak value was attained followed by levelling out. The peak shear value achieved was observed to increase with increasing normal stress. Furthermore, when considering vertical/horizontal displacements during the shearing of FRG, dilatant shear behaviour similar to that of dense sand was observed, where FRG samples underwent contraction during the start of the shearing followed by dilation. This dilation was more pronounced at lower normal stress values, while the contraction during the initial stage was more noticeable at higher normal stress values. FRG recorded internal friction angles of 45° to 47°, 42° to 43°, and 40° to 41° when normal stresses in the ranges of 30–120, 60–240, and 120 to 480 kPa were applied, respectively. MRG, on the other hand, obtained higher internal friction angles of 52° to 53° and 50° to 51° with the application of normal stress in the ranges of 30–120 and 60–240 kPa, respectively. This indicates that the internal friction angles for medium recycled glass (MRG) are approximately 15% higher than those of FRG. It is worth mentioning that FRG and MRG both achieved angles of internal friction that are comparable to the values of well-graded natural sand. Direct shear testing was undertaken on glass cullet samples in [14], where the as-received cullet of Heller and Stoltzfus resembled the shear behaviour observed by the natural aggregates. However, variations in stress were observed at the early stage of shearing for the coarse fraction (greater than 2.4 mm); this could be explained by the unstable arrangement of coarse glass, which consequently leads to the reorientation of glass particles during the early stage of the test. The friction angles for Heller and Stoltzfus glass cullet as received were 56° and 61° while the same for the coarse fraction (>2.4 mm) were 48° and 54°, respectively. This suggests a possible correlation between cullet size and frictional angle, where the greater the cullet size, the lower the friction angle. The same reveals that the lowest friction angle of 48° exceeds the values achieved by typical natural aggregates. The same study conducted triaxial shear testing on glass cullet where strain hardening behaviour was observed. The friction angles obtained through triaxial shear testing for the as-received Heller and Stoltzfus glass cullet was noted to be 46° and 47°, while the same values for the coarse fraction were found to be 44° and 45°, thereby confirming that glass cullet records satisfactory angles of friction comparable to common natural aggregates. The same reveals that MRG showed more desirable shear performance in comparison to FRG.

The research from [43] conducted triaxial shear testing on RG where the frictional angles obtained via the triaxial test were reported to be 10–15% and 15–20% lower than the values obtained by direct shear test for FRG and MRG, respectively. Slightly lower levels of compaction partly caused the reduction for the triaxial test samples. The internal friction angles obtained via triaxial test for FRG were 40°, 38°, and 35° and MRG were 42°, 41°, and 41° for stress ranges of 30–120, 60–240, and 120–480 kPa, respectively.

Direct shear test results for FRG-biosolid blends showed an increase in the internal friction angles from 10° to 43° as the %FRG was increased from 0% to 50%, while leading to a slight decrease as the %FRG was increased from 50% to 70% and again increasing as the %FRG was increased beyond 70% [34]. The same adds that cohesion values for FRG-biosolid blends were observed to increase up to 30% FRG, followed by a decreasing trend as the %FRG was increased further. The study concludes that the optimum inclusion of FRG in FRG-biosolid blends was 40%, where the highest shear strength results were obtained at all normal stress levels. Shear testing conducted on expansive clay containing WGP [103] revealed that the friction angle increased from 19.80° to 31.87°, whereas the cohesion values decreased from 39.13 to 31.68 KPa as the waste glass powder (WGP) content increased from 0% to 25%.

Stabilisation of problematic soils by adding recycled glass fibres (RGF) and glass powder was evaluated by [111], where significant improvements in shear strength, particularly in terms of internal frictional angles, were observed with the addition of both RGF and glass powder. The improvement in shear behaviour was associated with the formation of a stable soil-fibre matrix, thereby aiding to uphold the cohesion of the soil particles. Shear values of the samples were also noted to be affected by wetting and drying cycles. Shear strength testing was conducted on expansive soil stabilised with up to 1% glass fibres and compacted at varied dry densities [112], reporting that the internal friction angles and cohesion values of the blends increased as glass fibres were added up to an optimum inclusion of 0.75%, beyond which further inclusion of fibres led to a decrease in the friction angles for all blends. In addition, it was observed that cohesion values decreased as the dry density increased where the GF–soil combinations recorded cohesion values and internal friction angles in the ranges of 9.0–30.0 and 2.70–10.33, respectively. The effect of introducing glass fibres to sand was assessed in [113] where five distinct fibre inclusions of 0.5%, 1%, 2%, 3%, and 4% and three lengths of 10, 20, and 30 mm fibres were utilised in the study. Furthermore, the GF–sand blends were compacted at various relative densities of 35%, 65%, and 85%. The results of the study identified that the optimum length of fibre was 20 mm, while the optimum inclusion was found to be 4%, which was the maximum fibre inclusion in the study. In addition, the shear parameters were noted to improve when blends were compacted at higher relative densities. The combinations achieved cohesion and internal friction angles between 42–233 kPa and 32.8–36.7°.

Friction angles obtained through direct shear testing in [16] for cullet-gravelly sand samples range between 49° and 53°, indicating that the cullet has similar interparticle frictional behaviour to natural aggregates. The normal and shear stress at the point of failure increased for cement-reinforced sandy soil when glass fibres were added to the mixture. This was associated with the increase in cohesion and the internal angle of friction due to interactions of sandy soil-glass fibre particles [29].

The introduction of crushed waste glass (CWG) and geopolymer stabilisation of expansive soil improved cohesion values and the angle of friction. However, it was noted that the addition of geopolymer cement significantly improved the previously recorded values. At the same time, the introduction of CWG caused a slight decrease in the improvement brought about by geopolymer cement [42]. Table 18 provides a summary of the shear results discussed in this section.

Table 18. Summary of shear results.

Materials/Blends	Maximum Glass Inclusion	Sample Preparation	Cohesion (kPa)	Angle of Friction	Reference
RG	100%	OMC and 95% MDD (vibrating hammer compaction)	-	46–55°	[26]
FRG	100%	OMC and MDD (standard compaction)	-	40–47°	[34]
FRG	100%	OMC and MDD (standard compaction)	-	40–47°	[43]
Glass cullet (Heller) Glass cullet (Stoltzfus)	100% 100%	OMC and MDD (modified compaction) from direct shear	-	56° (Fine) 48° (Coarse) 61° (Fine) 54° (Coarse)	[14]
Glass cullet (Heller) Glass cullet (Stoltzfus)	100% 100%	OMC and 90% MDD (modified compaction) from triaxial shear	-	47° (Fine) 45° (Coarse) 46° (Fine) 44° (Coarse)	[14]
Cullet-gravelly Sand	50%	OMC and 95% MDD (vibrating hammer compaction)/direct shear	-	49–53°	[16]
FRG-biosolids	90%	OMC and MDD (standard compaction)	9.8–33.6	37.2–46.6° (Approximately)	[34]
CWG-soil-QDbGPC (up to 40%)	40%	OMC and MDD (standard compaction)	-	20.2–60.1 (Approximately)	[42]
WGP-soil	25%	OMC and MDD (standard compaction)	31.7–38.6	21.2–31.9° (Approximately)	[103]
GF-soil	1%	OMC and varied MDD (standard compaction)	9.0–30.0 (Approximately)	2.70–10.33 (Approximately)	[112]
GF-sand	4%	OMC and varied MDD (standard compaction)	42–233	32.8–36.7°	[113]

5.5. Compressive Splitting/Split-Tensile Strength (Indirect-Tensile)

The addition of foaming waste glass to lime-stabilised clay improved the compressive splitting strength of the mixture. The study also revealed that the effect of adding foaming waste glass was more pronounced in samples that were allowed to cure for 28 days as opposed to those cured for only 7 days [38]. Research testing on cemented silty soil containing glass powder revealed improvement in the split-tensile strength of specimens by introducing 5%, 15%, and 30% glass powder and increasing the curing period from 7 days to 90 days [70].

5.6. Resilient Modulus

Replacing coffee grounds with recycled glass (RG) in coffee ground geopolymers positively correlated with the resilient modulus values (M_r), where resilient modulus values increased with increasing RG, implying that the addition of RG led to increased material stiffness [44].

RG was utilised in percentage inclusions of 10%, 20%, and 30% to stabilise an expansive soil in the study conducted by [102], where the control clay sample recorded an average resilient modulus of 52.0 MPa while the 10%, 20%, and 30% mixtures achieved values of 65.5, 95.9 and 110.7 MPa, respectively. Compared to the unstabilised control expansive soil sample, the 30% sample presented a resilient modulus increase of 113%. The increase in resilient moduli with the addition of RG was associated with the shift of clay soil to sandy-clay soil due to the addition of sand-sized RG particles. Up to 18% of Glass A (1.18–4.75 mm), Glass B (0.08–1.18 mm), and Glass C (<0.08 mm) was added to roadbed clay [114], where resilient modulus values were noted to improve with increasing percentage of glass up to maximum inclusion of 18%. The M_r values for control soil were noted to be approximately 33.2 MPa while the values for 18% inclusion of Glasses A, B, and C resulted in M_r of roughly 81.0, 122.9, and 135.0 MPa, respectively.

5.7. Swelling–Shrinkage

The replacement of coffee grounds by RG in coffee ground geopolymers had an inverse relationship with linear swelling, where greater inclusions of RG led to the lower linear swelling of the samples following a 4-day soak period [44]. Limestone samples stabilised with a pozzolanic binder containing waste glass showed minor swelling of 0.09% [108].

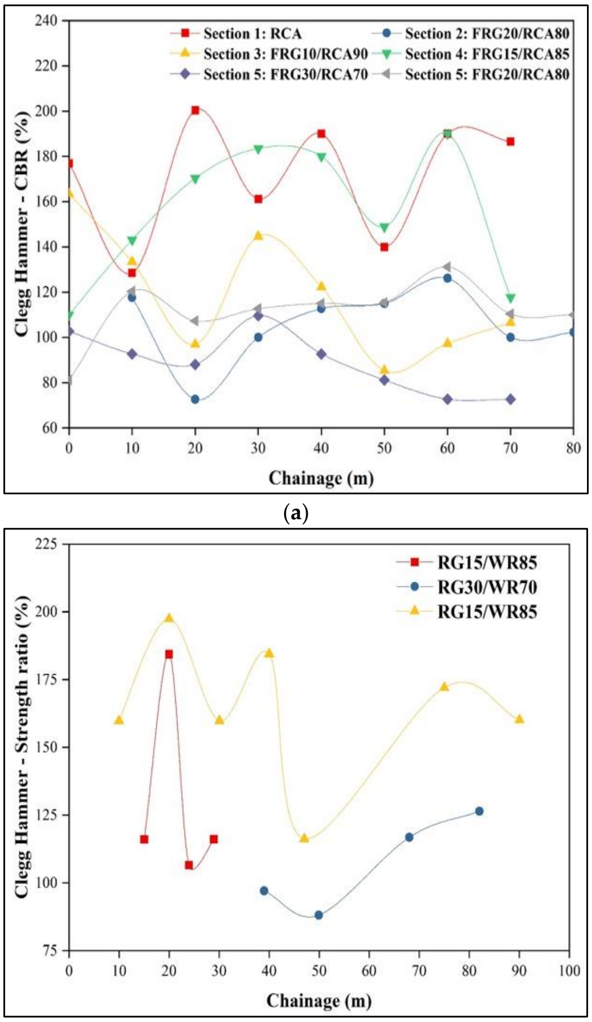
The introduction of waste glass powder (WGP) to expansive clay reduced free swelling, where the inclusion of 25% WGP caused the free swelling to significantly decrease by 83.3% compared to the control expansive clay sample [103]. One-dimensional consolidation tests were conducted on fat clay–glass powder blends by [105], where the swell index was observed to decrease from 0.043 to 0.012 as 14% glass powder was added to the fat clay. The introduction of up to 1% of 30 mm long glass fibres into expansive clay led to a significant decrease in the swell potential of samples [107], where a greater inclusion of fibres caused a higher reduction in the swell potential. The control expansive clay records a swelling potential of approximately 18.74%, with the introduction of 1% fibre decreasing the swelling potential to about 4.0%.

6. In-Field Trials for Road Layers with Glass

A study involving a trial of road layer sections containing waste glass (WG) and low-grade aggregate as well as sections with only low-grade aggregates (control) revealed that surface ravelling of the base was reduced upon inclusion of WG [19,115]. The WG sections also had comparable rebound deflection to that of the control sections.

Field testing was conducted via the construction of several sections of unbound granular pavement layers composed of up to 30% RG in RG–CR and RG-RCC blends, where it was reported that certain sections did not comply with the required minimum thickness, thereby shedding light on possible challenges when constructing pavement layers with RG-CR and RG-RCC blends [26]. The field study notes that %RG above 20% led to lower field densities, thus proposing RG inclusions be capped at a maximum of 20%. Furthermore, it was reported that RG-RCC blends achieved higher field densities compared to RG-CR blends. CBR values obtained via on-field Clegg hammer tests met the minimum required value of 80% for most trial subbase sections, while several sections failed to meet the more stringent requirement of 100% for base layers. Hence, it is recommended that higher %RG blends be limited for use in subbase layers. Furthermore, the 20% RG in CR and RCC was suggested to be the most suitable blend, where RG-RCC combinations were noted to have slightly superior performance over RG-CR blends based on the field trial results. This being said, in terms of workability, 15% RG with CR/RCC was noted to be the least challenging of the blends to place, as determined by the best compaction results.

Trial base sections of FRG-RCA and FRG-WR blends (up to 30% FRG inclusions) as well RCA and WR control sections were decided upon for field trials [57]. Four sections were constructed with FRG-RCA blends (with 10%, 15%, 20%, and 30% FRG) and three sections consisting of FRG-WR mixtures (with 10%, 20%, and 30% FRG). Two additional sections were constructed as control sections, one consisting entirely of RCA and the other entirely of WR. The FRG-RCA blend sections showed a propensity to undergo ravelling when compared to the FRG/WR sections, which appeared to be tighter following compaction. In general, blends with 15% FRG inclusion had optimum workability for both RCA and WR. Field densities for FRG-WR sections were higher than the FRG-RCA blends, consistent with laboratory testing results, thus confirming that the FRG-WR blends are of slightly higher quality. It is worthy of note that the field densities were in the range of 96–100% of MDD. Furthermore, the blends with 30% inclusion of FRG showed the lowest density ratios for both FRG-RCA and FRG-WR blends, indicating possible challenges relating to workability as the FRG content increased. The base layers were slightly under the minimum requirement of 100% mean density ratio, except for the FRG15-RCA85 section. All trial base sections were noted to satisfy dry back requirements before placement of the asphalt layer. Soaked field CBR values obtained via field Clegg hammer test indicated that all sections met the CBR requirement of 100% for base layers except for FRG10–WR90 and FRG-RCA blends with 10%, 20%, and 30% FRG (Figure 10a). However, in general, all sections met the CBR requirement of 80% for subbase layers of pavements except for short sections of FRG10-WR90, FRG20-RCA80, and FRG30-RCA70.



(**a**)

(**b**)

Figure 10. Clegg impact hammer results of (**a**) FRG-RCA/WR blends [57] and (**b**) RG-WR blends [24].

FRG-WR blends and WR were considered in [24] for field trials as base layers in footpaths, where mixtures containing 15% and 30% FRG achieved in-field relative compaction levels of 94% and 93%, respectively, which fulfiled the specified relative compaction levels of 92%. Furthermore, the variation of dry density ratios along chainage was insignificant, indicating that uniform compaction could be achieved in the field. Clegg hammer tests were conducted to determine in-field CBR values and obtain strength ratios relating to the required CBR of 28% following field compaction. The sections made of the blend containing 15% FRG recorded Clegg impact values between 18 and 25, which translates to CBR values in the range 30–52%, converting to strength ratios of 106–184% (Figure 10b). The sections containing the 30% FRG blend achieved Clegg impact values between 16 to 20, translating to 25–35% and 88–126% in terms of strength ratios. In addition to this, it is worthy of mention that the section with 15% FRG achieved a high compaction ratio and that the addition of 15% FRG to WR significantly improved the workability while only minutely reducing the strength of the base layer; thus, a maximum inclusion of 15% FRG was suggested for use in WR for use in base layers.

RCA–FRG blends containing 15% FRG were used as a footpath base layer aggregate [48]. Field testing of RCA aggregate containing 15% FRG showed that the samples have good workability and underwent adequate compaction, allowing for a stiff surface. As a result, the field compacted layer had similar MDD to the laboratory-tested samples, recording MDD of 2.01 mg/cm^3 where adequate relative field compaction was achieved throughout the chainage length. The field CBR determined via the Clegg Hammer test revealed that the minimum CBR of 20% required for footpath bases was achieved throughout the chainage length. The trial concluded that 85RCA–15FRG is a viable aggregate for use in the base layers of footpaths.

7. Summary Table for Strength Parameters of Blends

Table 19 summarises the improvements of geotechnical properties of soil mixtures by the inclusion of recycled glass in terms of the UCS, CBR, Los Angeles abrasion, resilient modulus, permanent deformation, and shear strength.

Table 19. Summary table for key strength and resilient parameters.

	Suitable Glass Content That Best Enhances Respective Parameters					
Materials/Blends	**UCS**	**CBR**	**Los Angeles Abrasion**	**Resilient Modulus**	**Permanent Deformation**	**Shear**
RG-CR/WR	10%	15%	50%	15%	10%	15%
RG-CR-R	5%	5%	5%	5%	5%	3%
RG-RCA/RCC/CC	20%	10%	15%	10%	10%	15%
RG-RCA-R	5%	3%	5%	5%	5%	3%
RG-soil-cement	10%	-	-	-	-	-
RG-clay/soil	10%	12%	-	30%	-	15%
GF-clay/soil	0.75%	1%	-	-	-	0.75%
GP-geopolymer	15%	20%	-	20%	-	40%

8. Current Gaps in Research and Scope for Future Research

Upon re-examining the findings from the extensive literature considered in this review paper, it is evident that there is a shortage of studies that address crucial aspects for glass-pavement aggregate composites, including the following:

1. Studies considered in this review incorporated glass in a variety of common road aggregates while also subjecting these composites to a series of physicochemical and mechanical strength tests. However, little knowledge exists about the life cycle cost of utilising glass in pavements, especially in terms of life cycle cost assessments, including freight costs and maintenance. Such studies in the future would allow for a comparison to be made between implementation and maintenance costs for glass composites and common aggregate pavement layers. Subsequently, it would be

possible to deem whether the usage of glass as a supplementary pavement aggregate is economically feasible when considering the collection, transportation, preparation, and maintenance costs.

2. Perusal of the literature also shows that a majority of the studies make random substitutions of glass into regular road materials without considering the volumetric replacement of aggregates with glass. Volumetric replacement refers to replacing regular aggregates with glass consisting of similar gradation to aggregates it replaces. This would aid in obtaining a more reliable understanding of how the inclusion of glass as a material affects the experimental results as volumetric replacement negates the effects induced by the shifting of particle gradation caused by the introduction of a material with very different particle sizes.
3. It is evident from the findings of this review that there is a lack of permanent deformation testing conducted. Permanent deformation is a key test when assessing the long-term performance and durability of glass composites as pavement aggregates, hence allowing an evaluation of the service life of the blends. This being said, it is helpful to keep in mind that the lack of enthusiasm to undertake permanent deformation testing could be due to the complexity of the test, the high cost involved, and the longer duration required to test a single specimen.
4. Glass fibre utilisation is observed to provide an interesting finding via the improvement of tensile-resistant forces in the mixtures. However, there is a lack of studies for cement-treated glass fibre–soil blends, which has the potential to make an overall sound material when considering the compressive strength induced by the addition of cement and the good tensile strength brought about by the inclusion of glass fibres.
5. Glass powder-based geopolymers, when added to both soil and common road aggregates, provide remarkable improvement. However, there is a lack of literature on leachate studies on glass powder geopolymer blends. Such studies need to be performed in the future to assess the suitability of blends as road aggregates in sensitive environments. Furthermore, these blends should be subjected to freeze–thaw and wetting–drying cycle testing to evaluate the potential to be used in harsh climatic conditions. Energy dispersive spectroscopy (EDS), X-ray fluorescence and micro-CT studies are also suggested to attain an in-depth understanding of how variations in glass powder content and chemical additives affect the degree of geopolymerisation, thus allowing an in-depth understanding of the binding mechanism.
6. Resilient modulus testing was found to be relatively scarce when considering the inclusion of various forms of glass in soil. The resilient modulus is a crucial value for pavement aggregates that indicates the behaviour of the aggregates under vehicular loading. Hence, it is suggested that further resilient modulus testing is to be carried out on glass-soil blends in future studies.

9. Conclusions

Upon reviewing the existing literature, it is evident that glass can be utilised as a sustainable supplementary pavement material that could be introduced in a variety of forms into a diverse range of pavement aggregates where the material composites yield adequate strength and resilience characteristics as governed by the respective road/engineering authorities. The research studies considered in this review introduce glass in various distinct forms; fine recycled glass (FRG), medium recycled glass (MRG), coarse recycled glass (CRG), glass powder, glass fibres, foamed glass, and glass-based geopolymers. It is worthy of note that each form of glass has unique properties, allowing its composites to achieve contrasting strength and characteristic parameters. Glass in its many forms, as mentioned previously, can be introduced to a series of conventional pavement aggregates, including recycled concrete aggregate (RCA), crushed rock/waste rock (CR/WR), clay/soil, silty-sand, gravel, and limestone. The addition of glass to pavement aggregates/soils would generally provide favourable strength properties. Moreover, the adoption of glass as a sustainable road material can induce environmental benefits through reduced usage of virgin quarried materials and offer a sustainable alternative to continuous stockpiling of glass waste in hazardous landfill sites.

The following conclusions may be drawn from the literature examined;

1. A percentage inclusion by weight of 15% fine recycled glass (FRG) and medium recycled glass (MRG) can be safely introduced to both recycled concrete aggregate (RCA) as well as crushed rock (CR)/waste rock (WR), where the composite samples overall satisfy the minimum strength, durability, and resilience requirements for base and subbase layer aggregates. Coarse recycled glass (CRG), on the other hand, does not perform as well as FRG and MRG, as high inclusions adversely affect the strength of the blends. The introduction of CRG at high inclusions poses the risk of particle breakage during compaction, increasing finer glass content, thus pushing the particle size distributions out of the recommended gradation limits. Therefore, the use of CRG at high inclusions is not encouraged, especially when utilised in base and subbase layers.
2. Crushed glass (CG) inclusion in soils reduces OMC while improving the maximum dry density, indicating that CG contributes to superior compaction. The inclusion of 10% recycled glass (RG) and waste glass powder (WGP) can be safely added to clay soil, where the strength and durability results are observed to improve. The introduction of RG improves the unconfined compressive strength (UCS), California bearing ratio (CBR), and resilient modulus values, which are vital strength and resilient parameters for pavement layers. In addition, the introduction of CG to soils also results in improved shear performance in terms of higher values for the angle of internal friction of the mixtures. Furthermore, a 10% inclusion of RG into the soil generally meets the minimum strength requirements for use in the subgrade layers of pavements.
3. Incorporating glass fibres in soil overall leads to an increase in optimum moisture content (OMC) of samples, which can be elucidated by the high surface area of fibres leading to decreased workability, hence requiring a higher water content. The addition of fibres leads to increased compressive strength and higher CBR values while also increasing shear parameters such as shear stress and angle of internal friction for the glass fibre-soil mixtures. The increased strength parameters can be explained by the build-up of resistive tensile forces due to the stretching of fibres as the sample experiences load-induced stresses.
4. Foamed glass presents unique dilatant behaviour when subjected to shear testing, which is unusual for coarse-grained aggregates. The material also exhibits a relatively high internal friction angle, which would be favourable for efficiently mobilising loads within the sample. This being said, foamed waste glass is only recommended for use in pavement layers as a supplementary material along with high-quality aggregates, owing to its poor durability, as shown by very high Los Angeles abrasion values.
5. The addition of glass powder–fly ash geopolymer to virgin subbase aggregates leads to drastic improvements in CBR, where the mixtures satisfy the CBR requirements for base layer aggregates of pavements. Glass powder is a rich source of silica, while the fly ash is a good source of alumina, providing appropriate conditions for the alumina–silica reaction (ASR) to take place efficiently.
6. The addition of glass-based geopolymers and alkaline-activated recycled glass powder (RGP) to soil leads to higher UCS, CBR, and resilient modulus values. The improvement in the mechanical strength of the soil can be explained using the energy dispersive X-ray, X-ray fluorescence (XRF), and scanning electron microscope (SEM) test data. The energy dispersive X-ray and XRF data reveal high amounts of silica in glass powder while the soil is noted to be a good source of alumina, thereby allowing for a favourable environment for the effective ASR to occur, thus, improving the strength of the mixtures. The SEM images further prove this by depicting the formation of CSH gel and geopolymer products for soil–geopolymer combinations.

In light of the findings mentioned above, it is fair to state that glass in its many forms should be considered for utilisation as a supplementary material in road pavement layers. This provides improved material composites and induces environmental benefits through the reduced reliance on virgin quarried materials and provides a sustainable alternative to continuous stockpiling of glass waste in hazardous landfill sites.

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Abbreviations/Acronyms

AR	Alkali-resistant
CBR	California bearing ratio
C_c	Coefficient of curvature
CD	Consolidated drained
CG/CWG	Crushed glass/crushed waste glass
CR	Crushed rock
Cu	Coefficient of uniformity
FRG	Fine recycled glass
GC	Glass cullet
GF	Glass fibre
GGBFS	Ground granulated blast furnace slag
MDD	Maximum dry density
Mr	Resilient modulus
MRG	Medium recycled glass
OMC	Optimum moisture content
PSD	Particle size distribution
RCA	Recycled concrete aggregate
RCC	Recycled crushed concrete
RG	Recycled glass
RGF	Recycled glass fibre
RGW	Recycled glass waste
SEM	Scanning electron microscope
SFLG	Spent fluorescent lamp glass
SPLP	Synthetic precipitation leaching procedure
TCLP	Toxicity characteristic leaching procedure
TNZ	Transit New Zealand
UCS	Unconfined compressive strength
XRF	X-ray fluorescence

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