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Review

Design and performance characteristics of cement grouted bituminous mixtures - a review

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ABSTRACT

Cement grouted bituminous mix (CGBM) is a composite type of pavement surfacing prepared by injecting cementitious grouting material in porous asphalt mixtures under the effect of gravity. Over the past few decades, CGBM is gaining attention due to its numerous advantages over flexible and rigid pavement. Several researchers conducted various laboratory and field studies on CGB mixes using different grouting materials. A comprehensive review of the aggregate gradation, binder type, composition of grouting materials, their effect on the mechanical properties and performance characteristics of CGB mixes, micro-mechanical analysis of CGBM, effect of reclaimed asphalt pavement (RAP) on CGBM are summarized.

1. Introduction

Roads are a crucial form of transportation worldwide. The road infrastructure is constructed employing two types of pavements namely, flexible and rigid pavements. As of the year 2021, the world's road network covered about 6 crores 42 lakh kilometers, which demonstrates the dependency on road transport for the commute of people and goods around the world [1]. Due to the numerous advantages of flexible pavement, nearly 90 % of the total paved road network is constructed using the flexible pavement.

Bituminous mixes are used in the construction of flexible pavement as a base/binder course and as surface course layers. Flexible pavements undergo higher deformation as bituminous mixtures have low flexural strength at high temperatures. Wheel loads are transferred through grain-to-grain contact of the aggregates through the granular structure in flexible pavements. The strength of the flexible pavement depends on the aggregate shape, aggregate interlocking, and cohesion [2,3].

Flexible pavement is more frequently used in road infrastructure as it offers benefits such as reduced driving noise, increased skid resistance, improved driving comfort, quick construction, and simple maintenance. The deformation caused by the traffic load can be partially recovered due to the viscoelastic characteristics of the bituminous mixture [4]. On the other hand, permanent deformation, weaker resistance to aging, oil & fuel spills, chemical attack, and susceptibility to high and low temperatures are some of the significant problems in flexible pavements. These conditions will become a leading cause for pavement distresses like rutting, shoving, ravelling, stripping, etc. Three categories namely, asphalt mix factors, load factors, and environmental factors are the main factors affecting permanent deformation. Factors related to asphalt mixtures include aggregate gradation, binder content, and volumetric properties of the bituminous mixtures. Load-related factors include the type of axle, tire pressure, and duration of loading. Environmental factors include aging, temperature, and presence of moisture. The aging process changes the properties of bitumen, and the action of the water will affect the durability of bituminous mixtures [5–13].

At high temperatures and in the presence of heavier traffic loads, bituminous mixes containing conventional asphalt provide lower resistance to permanent deformation. Various modifiers such as polymer, rubber, and nano-materials can be added to improve the properties of bitumen. Although using these modifiers increases stiffness and improves rut resistance, their usage is restricted because of their low storage stability, poor compatibility, improper blending with asphalt binder, and their higher cost [11].

Rigid pavement consists of cement concrete slabs (with or without reinforcement) as the surface course and base layer that rest on the subgrade. Rigid pavement has higher flexural rigidity and higher

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modulus of elasticity and as a result, these pavements undergo very less deformation under the application of traffic load. The pavement slab disperses wheel load through the slab action. Rigid pavements distribute the traffic load to a larger area and a smaller depth. Joints are necessary to restrict the thermal movement of cement concrete slab [3]. Although rigid pavement offers higher resistance to permanent deformation, its usage is confined by a number of drawbacks. Some of them are longer construction period, high initial and maintenance costs, generation of noise by the joints, poor riding quality, and higher time required to open to traffic [7,8,11,14–17]. For providing adequate drainage in concrete pavements, pervious concrete can be utilized as an alternative pavement construction material in low volume roads [18].

In order to sustain the exponential growth of traffic volume, finding alternatives that can combine the rigidity of concrete pavement and the flexibility of bituminous pavement is necessary to address the shortcomings and improve the performance of the pavements. Performance of the pavements, riding quality, longer service life, and cost-effectiveness are the important factors that need to be considered while choosing an alternative type of pavement. One such alternative is semi-flexible pavement (SFP) containing cement-grouted bituminous mixtures (CGBM) as a surface course.

1.1. *The concept of cement-grouted bituminous mixtures (CGBM)*

Cement grouted bituminous mixture (CGBM) is a composite material consisting of open-graded asphalt mixture injected with cementitious grouting material [19,20]. The construction of CGBM involves two phases. Initially, open-graded asphalt mixtures are prepared with 20 to 35 percent air voids, and in the second stage, cementitious grouting materials are used to fill the voids of the porous asphalt mixtures under the force of gravity. Various grouting materials used by researchers were cement paste, cement mortar, rubber-modified cement mortar, cement asphalt emulsion paste, engineered cement composite mortar, polymer-modified mortar, and high-performance cement paste [17,21–30]. In literature, semi-flexible pavement (SFP) has been referred with different names including semi-rigid pavement (SRP), resin-modified pavement (RMP), semi-flexible composite mixture (SFCM), heavy-duty paving asphalt mixture, densiphalt, conflate, combi-layer, rut-proof pavement and grouted macadam composite material [4,7,9,16,20,22,23,31,32].

In the beginning of the 1950 s, France developed salviacim, a surface course made of porous asphalt mixture grouted with a cement slurry to a depth of 10 mm. Salviacim was created with an intent to provide resistance to petroleum products and it also performed well against rutting [22,33]. Later salviacim evolved into open-graded asphalt mixtures grouted with cementitious mortar [34]. Today, the application of CGB mixes has been extended to various countries like Great Britain, South Africa, Japan, Australia, Singapore, Germany, Italy, England, Netherlands, China, Malaysia, India, and Saudi Arabia in the construction of superhighways, overlays for bridge deck pavements, tunnels, heavily trafficked areas like bus bays, bus terminals, airport aprons, runways, taxiways, parking lots, intersection turning points, loading yards with heavy machinery, warehouses, distribution centers, cargo centers, port *trans*-shipments, gas stations, container depots and locations where high degree of resistance to chemical and petroleum products is required [7,11,25,35–38]. The thickness of cement grouted bituminous layer typically ranged from 30 to 100 mm, depending on the type of application [20,33,39,40].

The surface of SFP is waterproof, joint-less, resilient, long-lasting, and has a better load-bearing capability. In contrast to bituminous mixtures and cement concrete composites, CGBM eliminates the disadvantages of the bituminous mixture by providing greater resistance to permanent deformation, and eliminates the need for joints, and permits the pavement to open to traffic in less than 24 h when compared to the cement concrete mixes [7,11–14,25,30,41]. Although CGBM exhibits minimal rutting and shoving, the grouting material injected into the CGBM imparts higher stiffness, causing the mixture to crack more readily. The cracking resistance is mainly influenced by the quality of grout, elastic modulus, and interfacial bonding characteristics of the grouting material [25]. Several studies have demonstrated that the addition of emulsified asphalt and latex to the cementitious grouting materials improves the adhesion between grouting materials and asphalt mixtures, preventing the development of micro-cracks in the CGBM [17,21,24,26,27,42].

Based on the extensive literature review, it is observed that previous review articles did not present an overview of the design elements of CGB mixes used in various studies. Inadequate comparison of the effect of mechanical properties and performance characteristics of CGB mixes containing various grouting material was observed. Furthermore, researchers did not explore the possibility of the addition of RAP of CGB mixes and failed to summarize the field performance of CGB mixes over the years across various countries. Therefore, the aim of the study is to discuss various aspects related to the influence of the materials used in the CGB mixes. Analyzing the influence of design parameters of porous asphalt mixtures and the selection of cementitious grouting materials. Comparing the effect of various grouting materials on the mechanical properties and performance characteristics of CGB mixes. To understand the micro-mechanical behavior of CGB mixes and the effect of the addition of RAP (reclaimed asphalt pavement) in CGB mixes. Summary of the performance of test sections and field application of CGB mixes around the world is also presented. The current review also presents various research gaps identified through the present review.

1.2. *Review methodology*

The methodology for the proposed study is summarized in the flowchart given in the Fig. 1. The steps below are used to perform a thorough analysis of the literature on cement grouted bituminous mixes (CGBM). Various keywords related to CGB mixes such as cement grouted bituminous mixture, semi-flexible pavement, semi-rigid pavement, reclaimed asphalt pavement (RAP), rutting, fatigue, moisture damage, resistance to petroleum products, grouted macadam, resin modified pavement were identified. Extraction of articles related to the keywords from various standard journals, conference, book chapters were done and classified according to the different categories. Category clustering is used to partition the collected articles according to different categories like conventional grouting materials, modified grouting materials, mechanical properties, rutting, fatigue, low temperature performance, micro-mechanical behaviour of CGBM, addition of RAP in CGBM, field performance of CGBM, construction of trial section of CGB mixes.

Abstract of the literature were reviewed and used to filter the irrelevant literature. Extraction of information was done from each literature based on the categories defined and the interpretations from the literature is presented under different sub-sections. Preparation of relevant tables was done representing different characteristics of porous asphalt mixture, various grouting materials, and their respective flow and strength requirements, and field performance of CGB mixes worldwide. Experimental results of ITS, resilient modulus, rutting, fatigue, moisture damage, and low temperature cracking resistance of CGB mixes obtained by various researchers were compiled and presented in the form of figures. Conclusions were summarized along with the research gaps and future scope of the proposed study. Citation of all the relevant literature selected for the proposed study was done.

Fig. 2 represents the year wise distribution of the publications over the last few decades. Majority of the articles were published in the last decade from 2013 to 2022, which indicates that the research related to CGB mixes has been gaining more attention among the researchers in the recent years and semi-flexible pavement is one of the emerging pavement technologies that is being used worldwide.

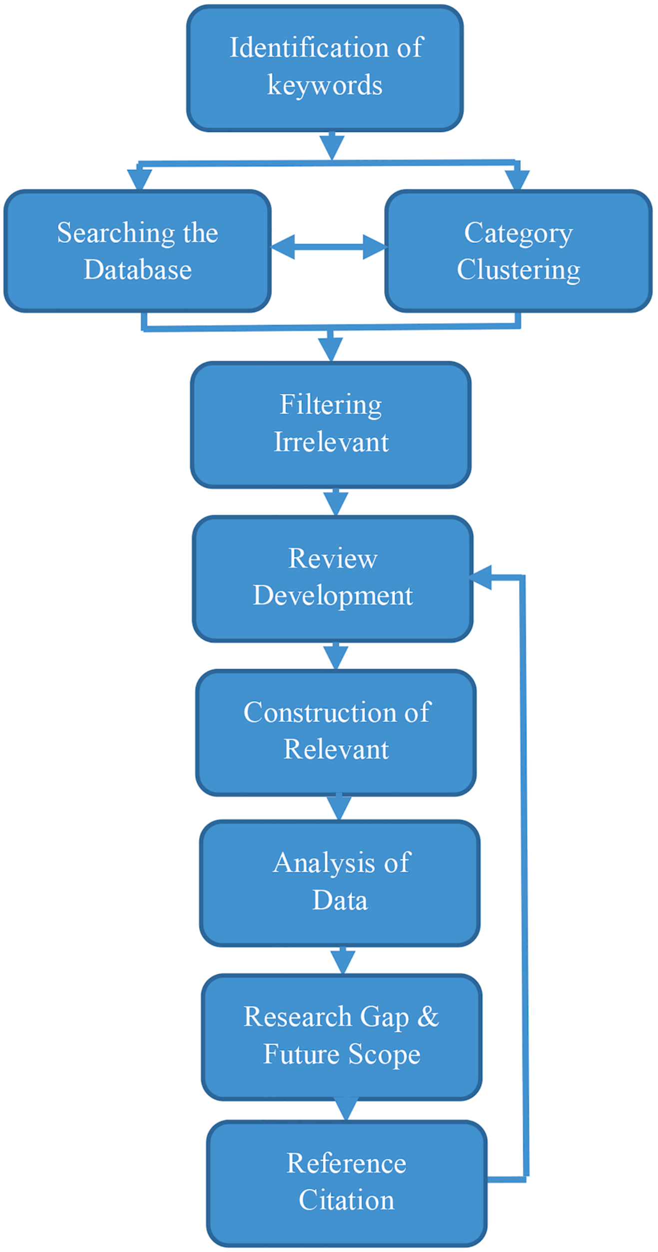


Fig. 1. Flow chart of the proposed study.

2. Influence of materials used to prepare CGB mixes

2.1. Aggregate

Aggregates are the most widely mined minerals on the planet. Common types of aggregates used in road construction include basalt, limestone, granite, dolerite, dolomite, calcareous, and gabbros. The type of aggregates and amount of aggregates used in the pavement construction will depend on the location, climate, traffic load and subgrade conditions [43].

The impact of the aggregate type on the coefficient of thermal expansion had been examined by Anderton (2000) [22]. Crushed limestone and crushed siliceous gravel were utilised to create two sets of RMP (resin-modified pavement) samples. Limestone had lower coefficient of thermal expansion than siliceous gravel which indicates that limestone aggregates have lower susceptibility to temperature when compared to siliceous gravel. Setyawan 2006 [44] studied the effect of aggregate type on the indirect tensile stiffness modulus (ITSM) of CGBM by using carboniferous limestone and dolomite limestone. Dolomite limestone had higher ITSM when compared to carboniferous limestone. In a study done by Oliveira 2006 [45], the influence of aggregate type on the mechanical properties of grouted macadam in terms of ITSM was studied. Two aggregate types namely, limestone and granite aggregates were used in the preparation of CGBM for comparison. According to the findings, grouted macadam with limestone aggregates showed higher stiffness modulus and similar fatigue life when compared to CGBM with granite aggregates. However, limestone has a lower stone polishing value and thus leads to poorer skid resistance limiting its usage in the wearing course. The chemical composition of limestone aggregate is alkaline in nature and granite aggregate is acidic in nature. In addition, the Mohs hardness of granite is higher than limestone, which indicates that limestone has lower skid resistance than granite aggregates [46,47].

Setiawan (2009) [48] investigated the porosity and permeability characteristics of three different aggregate gradations. One gradation with a maximum aggregate size of 14 mm, and two gradations with a maximum aggregate size of 10 mm. The latter two aggregate gradations differ in the proportion of fine aggregates percentage in the gradation. The results indicated that the maximum aggregate size of 14 mm provided higher porosity and higher permeability when compared to the other gradations. Higher porosity and permeability will create a possibility for full-depth penetration of the cementitious grout into the porous asphalt mixture. Another study indicated that the CGB mixtures with lower nominal maximum aggregate size (NMAS) showed superior performance in terms of rutting when compared to the CGB mixtures with higher NMAS, as the lower NMAS mix had better adhesive properties [27]. When compared to the dense graded aggregate gradation, single-sized aggregate gradation had a suitable void structure in the CGB mixes for the full-depth penetration of cementitious grout. Single-sized aggregate gradation had uniform pore size, linear pore channel, and minimal void interlocking. This simple network structure helped the grouting materials to achieve the full-depth penetration of cementitious grout in CGB mixes [49]. The use of mixed recycled aggregate in CGB mixes is recommended in places with non-aggressive environmental conditions [50]. Fig. 3 represents the gradation curve for CGB mixes adopted by various researchers.

2.2. Binder selection

Asphalt (also bitumen) is a petroleum-based liquid or semi-solid obtained from natural deposits or as a residue of solvent extraction from petroleum. Every year, the paving industry uses around 95 % of the total bitumen produced worldwide. Bitumen acts as a binder for aggregates to form bituminous mixtures, also called bituminous concrete or asphalt mixes.

Effect of binder content on CGB mixes was examined by several researchers. As the binder content increases, porosity of the mixture decreases. This will act as a hindrance to the grout to achieve the required degree of penetration. A study compared the use of different binder grades on the properties of porous asphalt mixture. Three different binder grades were used namely, 100 pen (penetration grade) straight run bitumen, 50 pen straight run bitumen, and 7 % SBS (styrene-butadiene styrene) modified bitumen. Binder drainage test was conducted on porous asphalt mixtures for all three binders, results showed that at binder contents greater than 4 %, binder drainage was observed for mixtures with all three binders. All the three mixtures produced similar permeability characteristics. Abrasion loss was the highest for mixtures with 100 pen straight run bitumen and lowest for mixtures with 7 % SBS (Styrene-butadiene Styrene) modified bitumen. Porous asphalt mixture with 50 penetration grade straight run bitumen showed higher indirect tensile strength (ITS) and stiffness values compared to mixtures with other binder types. The addition of loose fibre in porous asphalt mixture lowered the abrasive resistance of the mixture [48]. On contrary, the use of harder binder and reduced binder content in CGB mixes increases the stiffness modulus of the CGB mixes [35]. The polymer-modified CGB

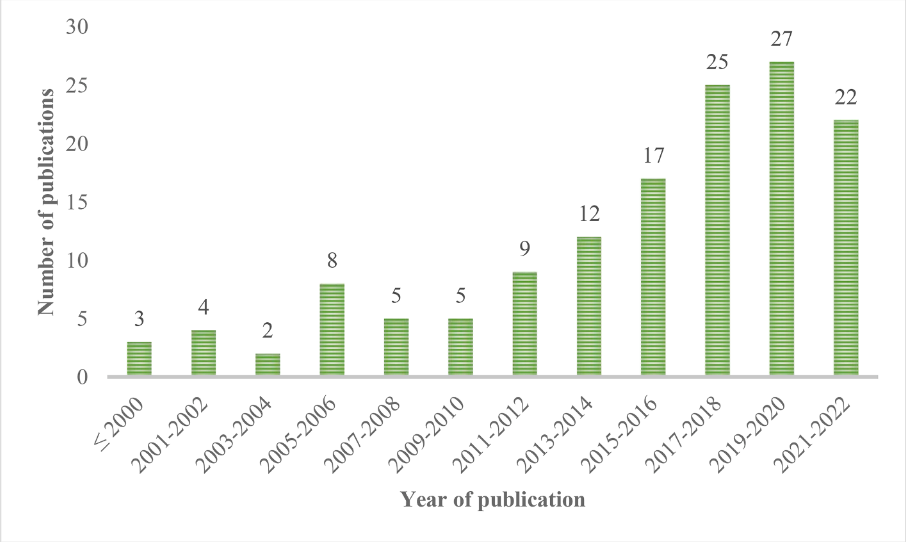


Fig. 2. Year wise distribution of publications.

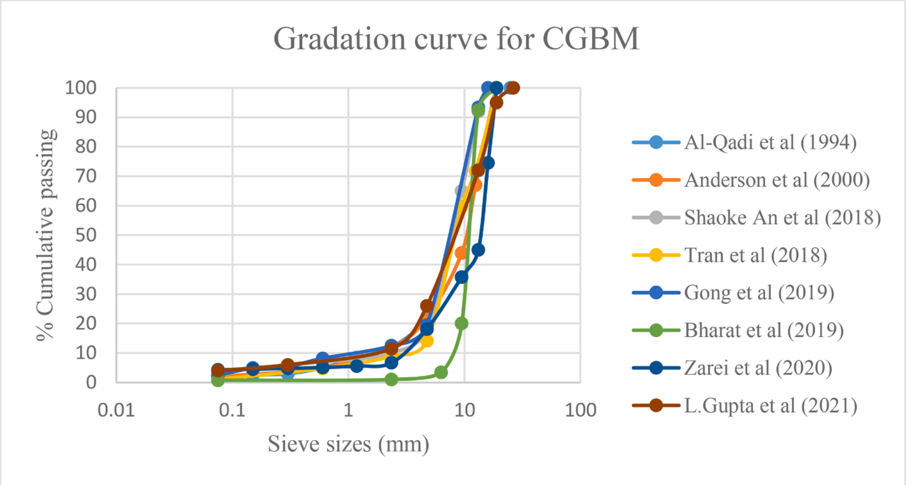


Fig. 3. Gradation curve for CGB mixes.

mixtures outperformed the CGB mixtures prepared using neat bitumen grades in terms of rutting, fatigue, and moisture susceptibility [32,51]. On the other hand, CGB mixtures with fiber-modified asphalt, showed superior fatigue resistance when compared to CGB mixes with polymer-modified asphalt [52]. A study indicated that higher Marshall stability was observed for CGB mixes prepared with the polymer-modified binder (PMB) when compared to CGBM with neat bitumen. The reason is that the increased viscosity of PMB leads to better adhesion between the aggregate particles [53]. Several researchers used polymer-modified bitumen in CGB mixes and inferred satisfactory performance of the CGB mixes in terms of rutting, fatigue, and moisture resistance [25,27,28,54].

2.3. Grouting material

Grouting material plays a significant role in influencing the performance of the CGB mixtures. Cementitious grouting material is used to fill the voids of the open-graded asphalt mixtures to provide rigidity to the CGB mixes. Grouting material includes cement, sand, fly ash, silica fume, superplasticizer, and admixtures. The main factors that influence the characteristics of the grouting material are the type of cement, gradation of sand, type and dosage of superplasticizer, modifiers used, and optimum water-cement ratio.

2.3.1. Cement

Many researchers employed ordinary Portland cement for the preparation of grouting material and inferred that ordinary Portland cement provides adequate fluidity and strength [10,23,32,35,55,56]. Few researchers conducted their studies using ultra-rapid hardening cement like early strength type cement, retarding strength type cement (with the addition of gypsum) and inferred that these type of cements help in reducing the cracks and shrinkage of the grouting material [4,28,52]. The CGBM with high-strength cement type displayed the best anti-frost properties [4].

2.3.2. Sand

The crushed sand used for the preparation cement mortar needs to pass completely through 0.6 mm in order to have a grout which easily penetrates into the voids of the porous asphalt mixtures and this extra fine sand was chosen to improve the fluidity of the cement mortar [27,57]. The increase in sand content reduced the drying shrinkage of the grouting material. However, the addition of higher proportion of crushed sand led to settlement and segregation of sand from the cement mortar and decreased the compressive strength of the grouting material

[9,57]. Gradation of sand adopted by various researchers to prepare the grouting material that ensured full depth grout penetration and satisfactory strength requirements is presented in Fig. 4.

2.3.3. Pozzolanic materials

Grouting material undergoes two types of reaction when it comes in contact with pozzolanic material like silica fume, fly ash, etc. Initially, cement hydrates and leads to the formation of CSH (calcium silicate hydrate) and $Ca(OH)_2$ (calcium hydroxide), in which CSH is responsible for the strength of the mortar. Later pozzolanic materials undergo a reaction with calcium hydroxide to form more CSH gel, which increases the strength of the grouting material [58]. The addition of fly ash in the cement grout showed better mechanical properties when compared to the pure cement paste [59] Fly ash is employed to reduce early-age shrinkage and temperature rise due to heat of hydration. Fly ash aids to achieve the necessary fluidity for the cementitious grouting materials at lower water contents [57]. The degree of flowability of cementitious grouting materials strongly correlated with the surface area of the material; the larger the surface area, the higher is the flowability [60]. Silica fume is used to reduce the bleeding and segregation in the cement paste [17]. The inclusion of silica fume in the cement mortar up to 5 % showed a significant increase in compressive strength compared to traditional cement mortar [5,6]. Micro silica is added to the grout to provide high initial strength to the grout.

2.3.4. Superplasticizer

To increase the fluidity of the cementitious grouting material without increasing the water/cement ratio, water-reducing admixtures like superplasticizers (such as poly-carboxylic ether-based polymer, naphthalene-based polymer, etc.,) were added to the grout. Superplasticizers alter the properties of grouting material by modifying the heat of hydration, reducing the setting time, and enhancing workability, and durability [12,13]. The flow time of the grouting material is highly influenced by the dosage of superplasticizer and water-cement ratio. A study recommended the use of poly-carboxylic ether-based superplasticizer up to 1 % over naphthalene-based superplasticizer in the grouting material to ensure adequate fluidity [61]. The addition of superplasticizers improved the fluidity of the grouting materials and ensured full-depth penetration of the grout in CGB mixtures. On the other hand, it is also important to note that the excessive addition of superplasticizers reduced the compressive strength of the grouting material [3,62]. An excessive addition of superplasticizer content also leads to segregation and bleeding [63,64].

2.3.5. Admixtures and supplementary materials

Various admixtures, interfacial optimizers and eco-friendly by-products can be added to the cementitious grout as a supplementary material to enhance the properties of the grout and to prevent environmental contamination. Some of the materials used by the researchers are admixtures like latex, accelerating agent, silane coupling agent, interfacial optimizers such as cationic emulsified asphalt, eco-friendly materials like waste polyethylene terephthalate (PET), rice husk ash (RHA), waste rubber tire powder, natural zeolite. A study grouped the waste materials that can be used in green concrete as agricultural, industrial, and municipal waste as shown in Fig. 5. The intrinsic limitations of traditional concrete include the consumption of non-renewable raw materials, low early-age compressive strength, and cause of harmful environmental impact. On the other side, green concrete has many benefits, including enhanced mechanical properties of concrete, low carbon emissions, cost-effectiveness and reduced demand for natural resources [65]. The effect of these materials on the properties on the grouting materials is discussed in the Section 3.2.2.

Table 1 shows the mix composition and properties used by past research studies for the construction of CGBM.

3. Design of cement grouted bituminous mixes

Cement-grouted bituminous mixtures are constructed in two stages. The first stage entails the construction of open-graded asphalt mixtures with 20 % to 35 % air void. The second stage of construction involves the selection of grouting material and injecting it into the voids of the open-graded asphalt mixtures. Depending on the thickness of the OGA

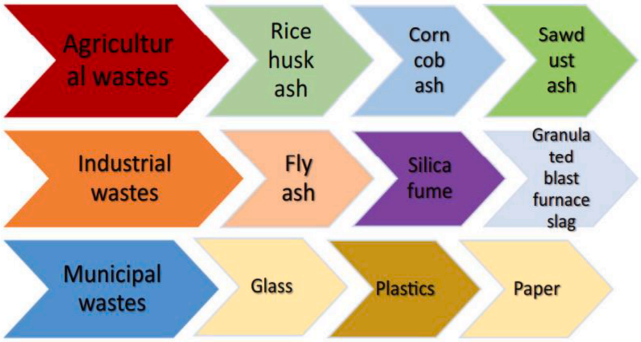


Fig. 5. Classification of waste utilized in green concrete [6 5].

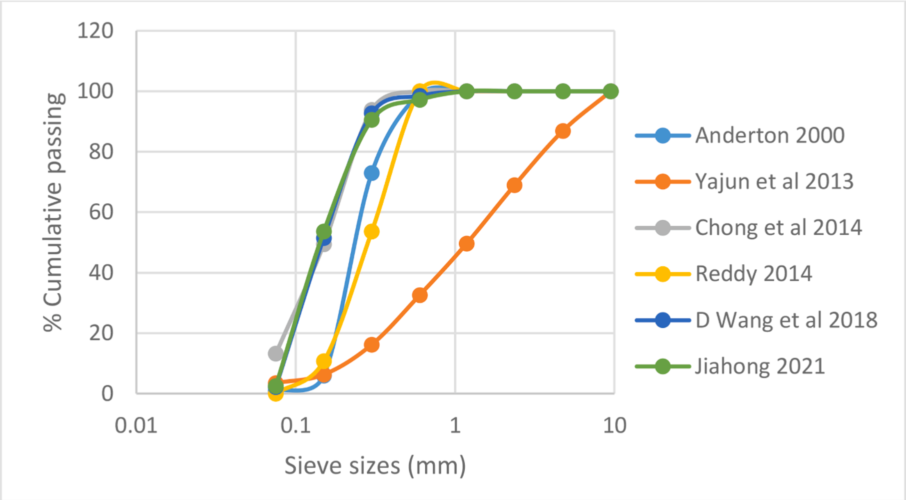


Fig. 4. Gradation of sand adopted in various studies for preparing cement mortar.

Table 1
Mix composition and properties for the construction of CGBM.

Type of Aggregate	Nominal Maximum Aggregate Size (mm)	Binder type	Optimum binder content, %	Air void, %	Type of grouting material	Studies
Dolomite limestone	12.5	Asphalt Cement grade of 20 (AC 20)	4.1	25.3	Resin Modified Cement Grout	AI-Qadi et al 1994 [23]
Limestone	12.5	AC 20	3.8	30	Resin Modified Cement Grout	Anderton 2000 [22]
Basalt, limestone	13.2	Rubber modified asphalt	2.8	30	Rubber modified cementitious grout	Huang Chong et al 2014 [25]
Granite	11	60/70 penetration grade	4.6	20	Cement paste	Karami et al 2017 [10]
Basalt, Limestone	11 (maximum aggregate size)	70/100 penetration grade bitumen	4.5	25	Cement mortar	Corradini et al 2017 [56]
Granite	13 (maximum aggregate size)	Polymer modified asphalt	4	18 – 20	Ultra-rapid hardening cement grout	Bang et al 2017 [4]
Basalt (aggregate), limestone (fillers)	13.2, 16	SBS modified asphalt	3.4, 3.2	22.47, 24.34	Latex modified cement mortar	Sang Luo et al 2018 [27]
Basalt	13	SBS modified asphalt	3.8	24.6	High Performance Cement Mortar	Yazhen Sun et al 2018 [28]
Granite	16	60/70 grade bitumen	4.6, 4.2, 3.8, 3.4	15, 20, 25, 30	Cement Mortar	Wang et al 2018 [66]
Granite	13.2	60/70 grade asphalt	4,3.6,3.3	20,25,28	Engineered Cementitious Composites (ECC) mortar	X. cai et al 2019 [29]
Limestone	13.2	SBS modified asphalt, modified asphalt, fibre-Modified asphalt	3.2,4.2,4.3	25,23,22	Cement mortar	Gong et al 2019 [52]
N/A	13.2	VG 30	2.41	N/A	Polymer modified mortar	Bharath et al 2020 [30]
Limestone	11	60/70 penetration grade	3.2	30	Cementitious grout with polyethylene terephthalate (PET)	Khan et al 2019 [3]
River stone	11 (maximum aggregate size)	60/70 Penetration grade	3	24.95	Cementitious grout with rubber and natural zeolite	Hamzani et al 2019 [68]
Aggregate	13.2	VG-30 (VG - Viscosity Grade)	2.45	24–25	Cementitious grout with fly ash & silica fume	Lokesh Gupta et al 2021 [13]
Limestone, crushed sand	16	80/100 Penetration grade	2.2	26.26	Cement Asphalt Emulsion Paste	Zarei et al 2020 [17]
Basalt	13.2, 19	VG-30 (VG – Viscosity Grade)	2.45, 2.95	24.8, 20.8,	Cementitious grout	Lokesh Gupta et al 2021 [12]

mixtures and the amount of grout injected, the mixture is allowed to cure for a certain period of time to achieve the required strength. The above two stages are detailed in the subsequent sections.

3.1. Preparation of open graded asphalt mixtures

The porous asphalt mixture is prepared with an air void of 20 % – 35 %. Adequate air void in the compacted mixture is necessary for the

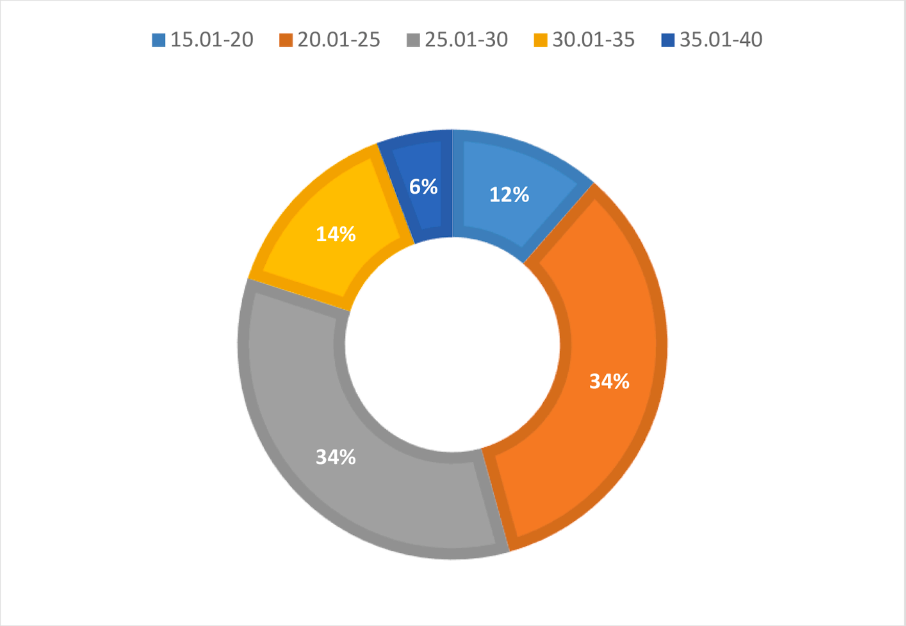


Fig. 6. Air void content of CGB mixes.

proper penetration of cementitious grouting materials. If the air voids in the compacted mixture is on the lower side (less than 15 %), then the grout cannot penetrate to the full depth of the mixture which in turn reduces the strength of the CGBM. On the other hand, if the air void content is too high, then the volume of grout injected will increase which imparts higher rigidity to the mixtures [39]. The air void content of porous asphalt mixtures used by various researchers are grouped into distinct ranges with an interval of 5 % and the number of research studies falling in a range out of the overall literature is calculated as a percentage for each range of air voids as shown in Fig. 6. Based on the classification, it is observed that the requirement of 20 – 35 % air voids in the porous asphalt mixtures ensures full depth penetration of grouting materials.

The following sub sections presents the important design parameters in the preparation of open-graded asphalt mixtures.

3.1.1. *Optimum binder content (OBC)*

The optimum binder content of OGA (open graded asphalt) mixture is determined by conducting the binder drain down test, Cantabro test and permeability test. The criteria used for selecting optimum binder content from the above-mentioned tests are given in the subsequent sections. The optimum binder content of porous asphalt mixtures used by various researchers are grouped into distinct ranges with an interval of 0.5 and the number of research studies falling in the range out of the overall literature is calculated as a percentage for each range of optimum binder content and presented in Fig. 7. It is observed that the optimum binder content of porous asphalt mixture falling in the range of 3 % to 4.5 % by weight of the mixture satisfies the requirement of binder drain down loss, abrasion loss and permeability of the porous asphalt mixtures.

3.1.1.1. Binder drainage test for selection of OBC. Binder drain down test is performed to determine the drain down for the porous asphalt mixture. OGA mixtures have higher potential to drain down loss as the mixtures contain a lower proportion of fine aggregates. The binder drain down increases with increase in the binder content. In addition, as the binder content increases, asphalt film thickness also increases which reduces the porosity of the OGA mixtures. Based on the standards of binder drainage test as per AASHTO T 305 [68], BS EN 12697–18 and ASTM D6390 [69], the binder drain down loss should not be more than 0.3 %. The percentage of drain down for each binder content of porous asphalt mixtures was calculated and a graph was plotted for bitumen content vs binder drain down. The binder content corresponding to 0.3 % drain down was taken as an optimum binder content for the chosen target gradation of porous asphalt mixture [13,30,70]. Fibres such as cellulose fibre, mineral fibre, polyester fibres are added to increase the stability and durability of OGA mixtures by reducing the drain down from the porous asphalt mixtures. The goal of using fibres is to create porous asphalt mixtures with a high binder content that can be transported without the binder drain down as the fibre helps to provide a thicker coating around the aggregates. Also, the usage of fibre prevents segregation in the porous asphalt mixtures, such as varying air void content and resultant premature degradation. Research studies indicate that the amount of fibre to be used in the open graded asphalt mixtures is 0.2 % – 0.5 % [13,48,71,72].

3.1.1.2. Cantabro test. Cantabro test is conducted using a Los Angeles abrasion testing machine to determine the durability of the porous asphalt mixture. Durability evaluation of OGA mixture ensures longer service life and adequate abrasive resistance as CGB mixes are intended to be used in the wearing course. To ensure adequate durability, the abrasion loss is restricted to 20 % [48,71,72]. In a study, the researcher calculated approximate asphalt content based on the asphalt film thickness of 12 μm and aggregate surface area. Author conducted binder drainage test and Cantabro test on three approximate asphalt content of 3.1 %, 3.4 %, 3.7 % for GOAC-13 (grouted open graded asphalt concrete) and 2.9 %, 3.2 %, 3.5 % for GOAC-16. The optimum binder content was 3.4 % for GOAC-13 with an abrasive loss of 14.7 % and 3.2 % for GOAC-16 with an abrasive loss of 18.5 % [27]. Similarly, researchers conducted Cantabro test to determine the OBC of CGB mixes [48,73].

3.1.1.3. Permeability test. Permeability is one of the important properties of open graded asphalt mixtures to ensure adequate air void for the proper injection of the grouting materials. Adequate permeability helps the grout to penetrate to the full depth by means of gravity. Permeability test is done by employing constant head and falling head permeameter and as per EN 12697–19, ASTM D7064/D7064M [74], the permeability of porous asphalt mixtures should meet the minimum requirement of 100 m/day. A study conducted the falling head permeability test on

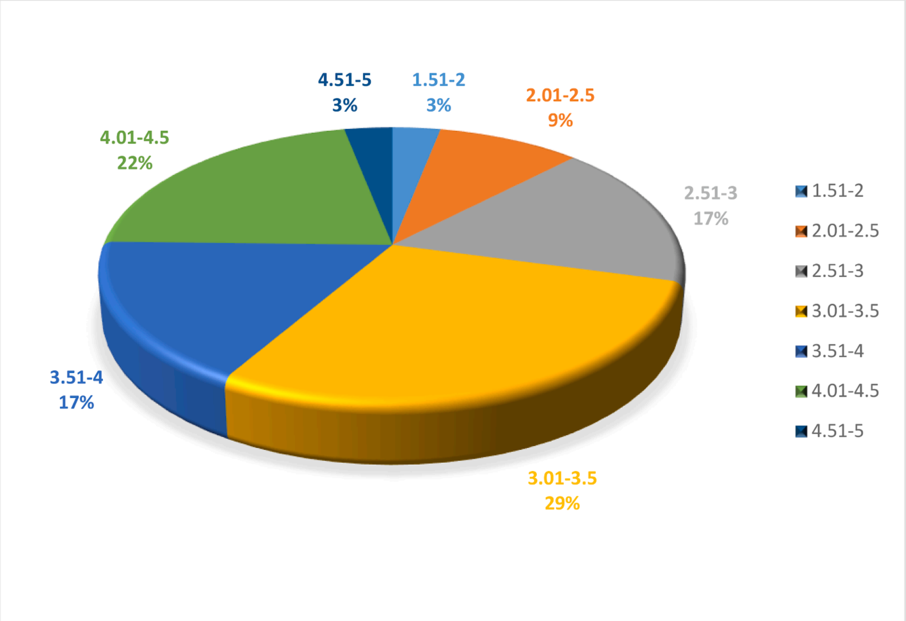


Fig. 7. Binder content of CGB mixes.

porous asphalt mixtures with different aggregate gradation and different binder contents (2 % to 4.5 %) which passed the requirement of binder drain down test. Through permeability test, the study eliminated the porous asphalt mixtures with an aggregate gradation of higher finer percentage (irrespective of binder content) for further study as these mixtures did not pass the permeability criteria of 100 m/day [75]. The permeability of the OGA mixtures correlated well with the packing characteristics of the aggregates. The amount of grout penetrated in the OGA mixtures was in line with the vertical permeability of the porous asphalt mixtures [76].

3.1.2. *Compaction effort used by various researchers*

There is no standard that specifies the number of blows that are required to achieve an adequate degree of compaction for the porous asphalt mixtures. Lower number of blows will lead to improper compaction. In contrary to this, if the number of blows tend to be higher, segregation of the mixture happens due to the crushing of aggregates [3]. The minimum number of Marshall blows required to prepare the specimen is the number of blows beyond which there is no noticeable change in the percentage of air voids [16,77,78]. In a study conducted by Raju et al (2014) [79] the specimen was compacted with 25 blows using the Marshall hammer on one face of the specimen to have sufficient air void for grout penetration. Another study indicated that compaction on only one face with 45 number of blows gave better results in terms of achieving the required percentage of air voids [13]. Al-Qadi et al 1994 [23] indicated that the porous asphalt mixtures compacted with 10 blows on both sides was more suitable compared to the increased number of blows. A study inferred that 50 blows on both faces of the CGB mixtures were adequate to produce the required degree of compaction [52]. In another study, open graded asphalt mixture was compacted using 50 number of gyrations with a superpave gyratory compactor (SGC) [80].

3.1.3. *Influence of curing period on the properties of CGBM*

As the curing period of grouting materials increased, the flexural and compressive strength of the grouting materials also increased. A study indicated that the influence of the curing period on the grouting materials showed a higher rate of increase in the flexural strength of the grouting materials than the compressive strength of the grouting material. Shrinkage of the grouting material increases with the extended curing time and a higher rate of shrinkage was observed in the grouting materials within the initial 3 days of curing period. Based on the SCB (semi-circular bending) test, higher tensile strength was observed for CGB mixtures when compared to porous asphalt mixtures. CGB mixtures reached their maximum tensile strength at 4 days of curing beyond which the tensile strength reduced with a further increase in the curing period [80]. An increase in the curing period of CGB mixes (7 and 28 days), increased the Marshall stability of the CGB mixes and improved the resistance to ravelling in the CGB mixes [78,81].

3.2. *Selection of grouting materials for CGB mixes*

Grouting materials play a significant role in determining the performance characteristics of the CGBM. Cementitious grouting materials are used to fill the voids of the open-graded asphalt mixtures to provide rigidity to the CGB mixes. Cement mortar, cement paste, cement asphalt emulsion paste (CAEP), rubber-modified cement grout, polymer-modified cement mortar, and high-performance cementitious grouts were some of the different types of grouting materials used by the researchers in preparing the CGB mixes. The composition of the grouting materials comprises cement, sand, fly ash, silica fume, water, and various additives like superplasticizers, chemical stabilizers, interface modifiers, latex, etc. The main purpose of the grouting materials is to fill the voids of the porous asphalt mixture and to provide adequate strength to the CGB mixture. The main factors that influence the characteristics of the grouting materials include the selection of cement type, gradation of sand, type and dosage of superplasticizer, modifiers, and selection of optimum water-cement ratio. To obtain a homogenous blending, the grouting materials should be mixed properly by manual mixing or by using a mechanical mixer. The optimum dosage of admixtures is determined using trial-and-error approach. The ideal dosage of admixtures is the dosage that ensures easy penetration of grout to full depth of the porous asphalt mixture [11,13]. Fig. 8 & Table 2 show various testing on the grouting material and the mechanical properties for the grouting materials respectively as per IRC: SP:125 (2019) [82].

Due to the variation in air temperature, a higher water-to-cement ratio readily leads to an increase in cracks, as well as deterioration in mechanical properties, and anti-frost properties. To limit the possibility of shrinkage cracking, a lower water-to-cement ratio is preferable. Hence, a minimum water-to-cement ratio that ensures adequate fluidity of the grouting material should be chosen. Furthermore, low water-to-cement ratio can help to prevent the segregation of cementitious grout which results in improving the performance of CGB mixes [5,6,30,67,86]. The water to cement ratio for the grouting materials used by various research studies are grouped into distinct ranges with an interval of 0.05 and the number of literature studies falling in a range out of the overall literature is calculated as a percentage for each group of water-cement ratio as shown in Fig. 9. It is observed that majority of the literature indicated that utilizing a water - cement ratio in the range of 0.3–0.4 and 0.5 – 0.7 ensured adequate fluidity and strength of the grouting material.

The performance and durability of CGB mixtures can be assessed by grout saturation degree (S_g). Grouting saturation degree is an indication of full-depth penetration of grouting materials in the OGA skeleton. Based on several studies, the grouting saturation degree of 90 % and above found to give full depth penetration of the grouting materials [9,11,27,29]. The fluidity of the grouting material obtained by various researchers is classified in the ranges of 0–10 s, 10 – 20 s, 20 – 30 s, 30 – 40 s, greater than 40 s and the number of literature studies falling in a range out of the overall literature is calculated as a percentage for each group of grouting material as shown in Fig. 10. Majority of the researchers concluded that full depth penetration of grout is achieved with a flow time ranges between 10 s to 20 s.

3.2.1. *Effect of various grouting materials on CGBM*

Compared to cement mortar, cement paste displayed superior performance as a grouting material in terms of fluidity and strength whereas cement mortar performed well in terms of lower drying shrinkage due to the presence of sand in the cement mortar [9]. The inclusion of emulsified asphalt in the grouting material improved the cracking resistance of the CGBM, as emulsified asphalt increased the flexural failure strain of the CGB mixtures [17]. The addition of water-based epoxy resin (up to 6 % by weight of cement) in the grouting material decreased the drying shrinkage of the grout but increased the brittleness of the grout and lowered the cracking resistance of the CGB mixes [87]. The addition of rubber powder improved the flow property of the grout but on the other hand reduced the compressive strength of the grouting material [25]. The addition of natural zeolite as a replacement to cement increased the compressive strength of the grouting material [67]. The engineered cement composites with the incorporation of polyvinyl acetate (PVA) showed superior performance in terms of strength characteristics when compared to the conventional cementitious grout [29]. The addition of silane coupling agent underperformed compared to interfacial optimizers like cationic emulsified asphalt, as the use of emulsion improves the interfacial bonding between the cement and asphalt which provided superior performance in terms of high-temperature stability, water stability, and low-temperature crack resistance of the CGBM [88]. The addition of calcium silicate as an accelerating agent in the cementitious grout exhibited superior durability performance when compared to the addition of sodium silicate (as an accelerating agent) in the cement mortar [89].

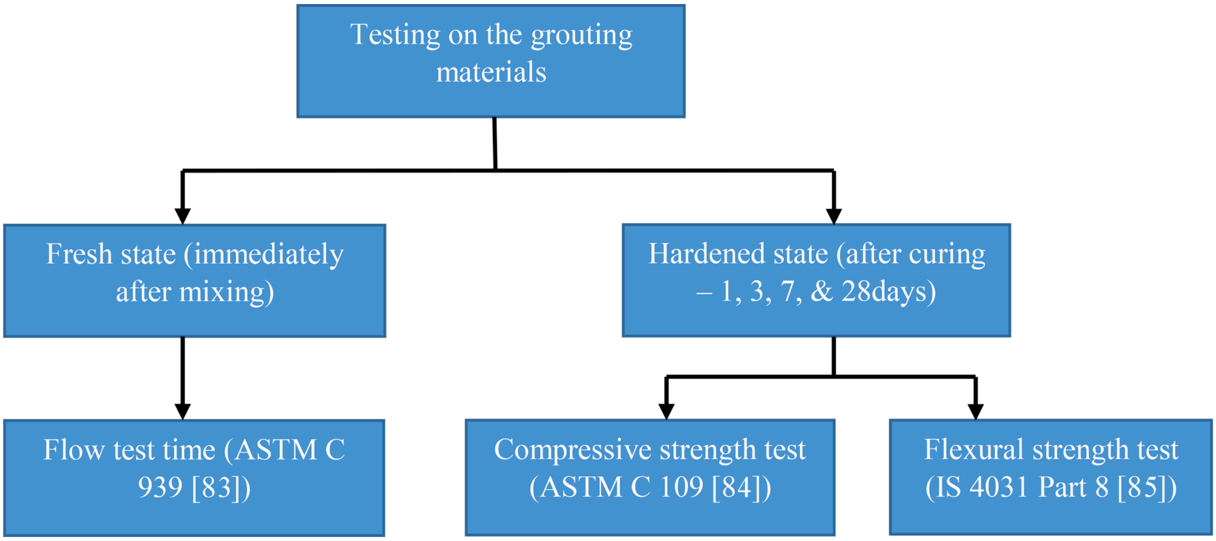


Fig. 8. **Testing of grouting materials (IRC: SP:125–2019)** [82].

Table 2
Mechanical properties of cementitious grout (IRC: SP:125–2019) [82].

Parameters	Requirements
Initial setting time (hours)	4 – 5
Final setting time (hours)	6 – 10
Fluidity (seconds)	20 – 50
Compressive strength (after curing for 28 day) (MPa)	40–100
Flexural strength (after curing for 28 days) (MPa)	5 – 7

3.2.1.1. Latex modified cement mortar. To improve the performance of conventional cement mortar in terms of cracking resistance of the grouting materials, latex modifier is used. The development of micro-cracks in cement mortar was prevented by using a latex film such as styrene butadiene rubber (SBR) or polyvinyl acetate (PVA)) [27]. Latex-modified cement mortar was added to the grouting materials to restrict the development of micro-cracks and to ensure minimum shrinkage in the CGBM. The addition of SBR (Styrene Butadiene Rubber) latex powder decreased the fluidity but enhanced the flexibility of the grout which resulted in higher flexural strength of the grouting materials. At the micro level, cement particles and SBR latex combine together to form a fiber-like hydrated structure which improves the flexibility of cured cement paste. As the ambient temperature varies, the fibre-like structure improved the interface and eliminated the cracks at the contact points between the asphalt mixture skeleton and the cured cement paste. The SBR latex used in the grout decreases the fracture in cementitious grouting material by improving the stability of fresh cement slurry [42]. The SBS (styrene–butadienestyrene) modifier

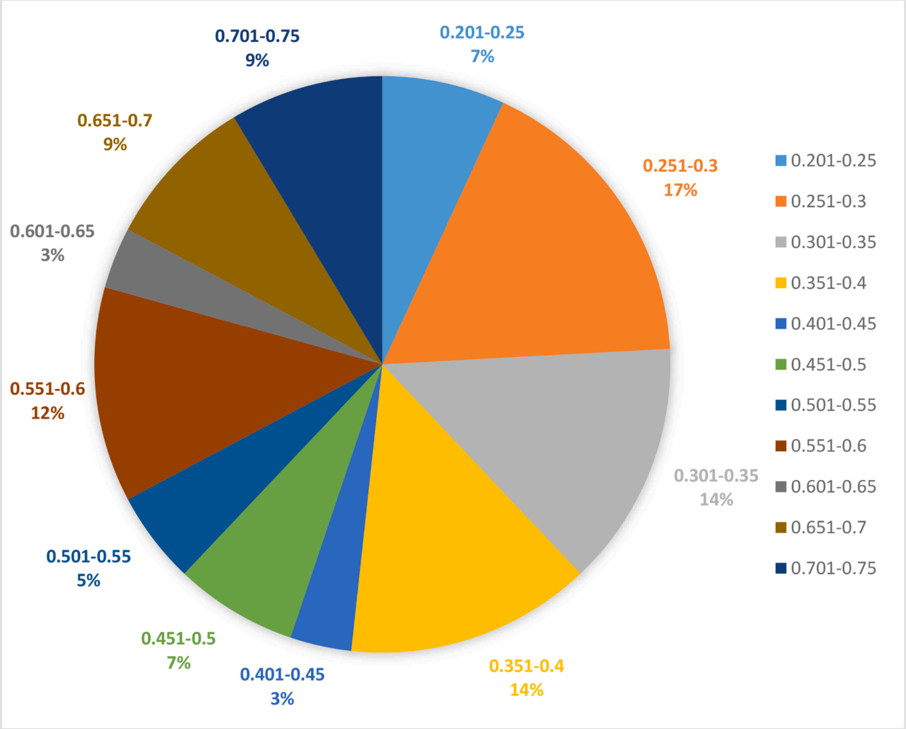


Fig. 9. Water/cement ratio used for preparing grouting material.

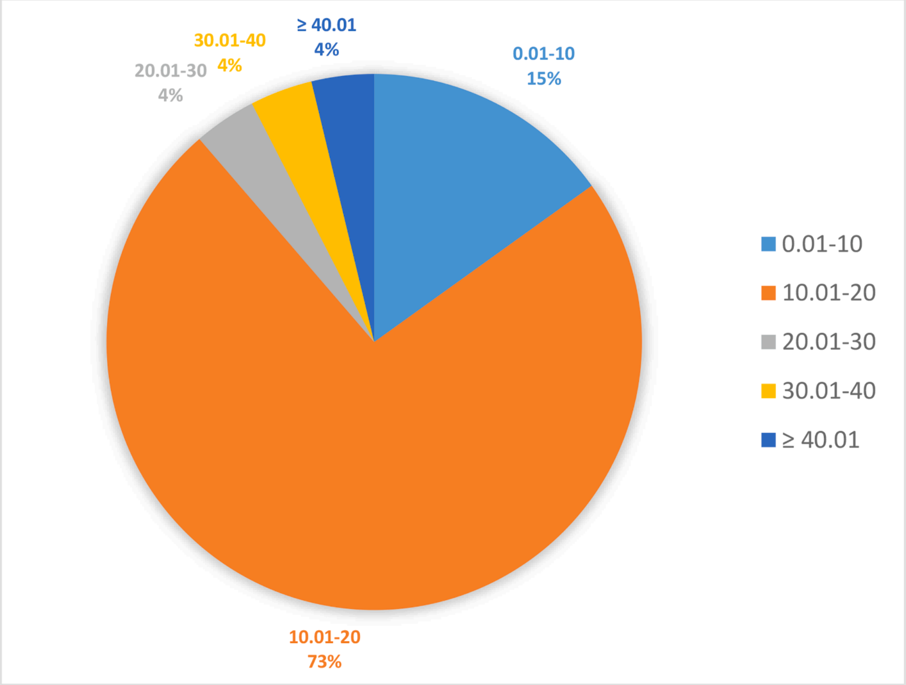


Fig. 10. Fluidity of grouting materials (in seconds).

improved the adhesion between the binder and CSH gel (calcium-silicate-hydrate) [90]. The CGB mixes with latex modified cement mortar showed higher adhesive strength (increase by 34.4 %) and shear strength (increase by 20.6 %) when compared to CGBM with ordinary cement paste [54].

3.2.1.2. Waste PET (polyethylene terephthalate) modified cement mortar. The addition of waste PET plastic waste (up to 30 %) in the conventional bituminous mixtures improved the mechanical properties (Marshall stability) of the PET-modified bituminous mixtures [91]. In addition, the usage of waste plastic can be extended to different layers of pavement. The addition of PET in cemented sand increased the friction angle which results in greater interlocking between the particles. The bearing capacity and stiffness characteristics of the sub-base and base course were not affected up till an addition of 5 % of polyethylene waste granules. The use of PET (0.6 %) saved the initial cost of 8 % in the construction of subgrade [92–95]. Owing to the increased use of PET in various pavement layers, few researchers studied the usage of waste PET in the grouting material and its effect on the mechanical properties of the grouting material in CGB mixes. A study inferred that the replacement of cement and fly ash with waste polyethylene terephthalate (PET) in the grouting mixture imparted better compressive and flexural strength of the grout [3]. The addition of waste polyethylene terephthalate in grouting material decreased the strength of the grout but on the other hand when compared to the addition of normal polyethylene terephthalate in cementitious grout, addition of irradiated polyethylene terephthalate (exposure to 100KGy gamma irradiation) in cementitious grout increased the strength gain of the grouting materials [96]. The mechanical properties of CGB mix (in terms of Marshall stability and indirect tensile strength (ITS)) with 4.75 % irradiated waste PET as a replacement of cement and 2.57 % regular waste PET as a replacement of cement in the formulation of grouting materials were similar and hence higher proportion of irradiated waste PET can be effectively used in the preparation of grouting material as a replacement to cement [97]. The addition of waste polyethylene terephthalate as a partial replacement of cement in grouting materials reduced the fluidity of the cement mortar and increased the drying shrinkage of the grout [98].

3.2.1.3. Supplementary materials. The addition of RHA as a replacement for cement improved the early-age strength of the concrete, helps in the rearrangement of void structure, and aid in reducing the width of the interfacial transition zone between aggregate and cement paste. The pozzolanic activity of RHA depends on the particle size, specific surface area, chemical composition, production process, water-cement ratio, and the content of RHA used as a replacement for cement [99]. On the other hand, the addition of RHA leads to a reduction in workability thereby demanding a higher requirement of water and a higher dosage of superplasticizer [65]. Though, the addition of rice husk ash (RHA) as a replacement for cement in the grouting material reduces the consumption of raw material and decreases environmental contamination, CGB mixes containing RHA decreased the mechanical properties of the mixtures (Marshall stability, ITS). The reason is that the RHA absorbs the binder in the porous asphalt mixture which leads to an insufficient coating of the aggregate particles and inducing higher voids in the CGB mixture [53]. The addition of brick powder waste to the concrete increased the shrinkage due to the hydrophilic nature of brick powder [100]. The addition of fly ash decreased the shrinkage of concrete by 33 % and increased the strength by 20 % [101].

The grouting materials used in various literature are grouped according to the different composition of grout namely, cementitious grouting material, pozzolanic cementitious grouting materials, modified cementitious grouting materials (polymer/rubber), latex-modified cement mortar, and cement asphalt emulsion paste and the number of literature studies using each type of composition in the overall literature is calculated as a percentage for each type of grouting material and presented in Fig. 11. It is observed that the majority of the researchers used cementitious grouting materials (43 %) which include cement, sand, water, and chemical admixtures. In addition, nearly 25 % of the researchers used pozzolanic cementitious grouting material that includes cement, sand, water, chemical and mineral admixtures. The usage of latex-modified cement mortar (15 %), cement asphalt emulsion paste (9 %), and modified cement mortar (polymer/rubber) (8 %) is comparatively less in the overall literature. Table 3 represents the type and characteristics of the grouting materials used by various researchers.

The addition of laterite, calcite, and calcined clay (blended in

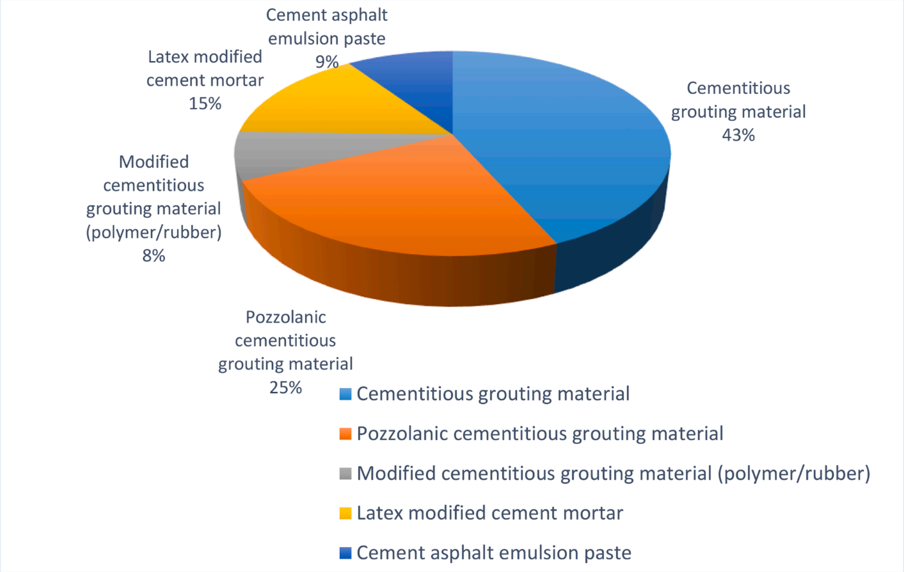


Fig. 11. Different type of grouting materials.

different proportions) as a replacement for cement and the addition of quarry dust as 100 % replacement for river sand minimized the drying shrinkage of sandcrete blocks [102]. Researchers can examine the addition of laterite, calcite, calcined clay and quarry dust as a replacement for cement and sand in the grouting materials of CGB mixes as these materials can provide a positive effect on the drying shrinkage of the grouting material.

4. Mechanical Properties of CGB mixes

4.1. Indirect tensile strength (ITS)

Anderton 2000 [22] used field cores and laboratory-prepared samples to assess various mechanical properties of resin modified pavement (RMP) mix. At low temperatures (5 °C), the ITS values of CGB mixtures were comparable to that of the conventional bituminous mixtures; however, at moderate to high temperatures (25 °C and 40 °C), the ITS values were about two to three times greater than the corresponding ITS values of the bituminous mixtures [33]. Thus, the temperature sensitivity of CGB mixes was lower than that of bituminous mixes. The ITS value of CGB mixes increased with increase in curing period [13]. As indirect tensile strength (ITS) is also a measure of adhesion between the aggregates and bitumen in the bituminous mixture, porous asphalt mixtures containing higher binder content showed greater ITS value when compared with porous asphalt mixtures containing lower binder content [75]. Higher ITS was observed for porous asphalt mixtures compacted using 50 blows on one side, when compared with the mixtures compacted using 25 blows on both sides due to the lower air voids present in mixes compacted using 50 blows on one side and the difference observed was 11 % [71]. Another study indicated that the use of polymer modified-bitumen (PMB) in CGB mixes gave rise to higher indirect tensile strength compared to the conventional CGB mixes at a test temperature of 0 °C, but the trend was observed to be reverse at 20 °C [51]. CGB mixes containing irradiated waste PET (polyethylene terephthalate) and regular waste PET showed similar ITS value, but the ITS value of CGB mixes was higher than bituminous mixes [97]. The ITS value of CGBM with PMB was higher (up to 50 %) than the ITS value of CGBM with neat bitumen. The ITS value of CGBM decreased with the increase in the proportion of RHA (rice husk ash) in the grouting material of CGB mixes [53].

Table 4 presents the abbreviations of CGB mixes containing various grouting materials presented in the Figs. 12,13,15–18 used to compare the mechanical properties and performance characteristics of CGBM mixes.

Fig. 12 indicates the results of ITS of CGB mixes obtained by various researchers. It can be inferred that due to the viscoelastic behaviour of CGB mixes, the reduction in ITS value was observed with the increase in temperature. The ITS value increased with the increase in curing period. CGBM containing cement paste, resin modified mortar, polymer modified mortar and pozzolanic cementitious grout exhibits superior performance in terms of ITS when compared to conventional bituminous mixtures. CGBM containing CAEP, rice husk ash, irradiated PET, marginal aggregates, PSA exhibited moderate performance and needs further investigations.

4.2. Resilient modulus of CGB mixtures

Using laboratory-prepared specimens of CGB mixes and field cores of CGB mixes, resilient modulus and Poisson's ratio were calculated at 5, 25, and 40 °C. The resilient modulus for laboratory prepared CGB mixes was determined to be 19200, 11200, and 5800 MPa, while the Poisson's ratio was determined to be 0.20, 0.26, and 0.28, which corresponds to temperatures of 5, 25 and 40 °C. The resilient moduli for field cores of CGB mixes ranged from 20,700 to 4200 MPa, while the Poisson's ratio values ranged from 0.15 to 0.30. The reduction in resilient modulus and increase in Poisson's ratio, with the rise in temperature reveals the viscoelastic behaviour of the CGB mixes [22]. The resilient modulus of CGB mixes were nearly 3,7 and 10 times higher when compared to that of conventional bituminous mixtures corresponding to the test temperatures of 25 °C, 35 °C and 45 °C respectively. For both CGB mixes and BC mixes, a decrease in resilient modulus value was observed with the increase in test temperature. The rate of reduction in resilient modulus with respect to temperature was higher for conventional bituminous mixtures when compared to that of CGB mixes. Based on the above findings, it can be stated that CGB mixes was less susceptible to temperature when compared to conventional bituminous mixtures [13,30]. A correlation between the void ratio and resilient modulus of CGB mixes was done and it was observed that the resilient modulus increased with an increase in void ratio of the CGB mixture. With the increase in void ratio, the amount of grout penetrated will also increase which in turn increases the rigidity of the mixture thus resulting in higher resilient modulus [111]. Punith et al. [71] compared the resilient modulus of porous asphalt mixtures with the addition of crumb rubber-modified bitumen (CRMB), reclaimed polyethylene-modified bitumen (RPEB)

Table 3
Types & characteristics of grouting materials.

Type of grout	Composition	Superplasticizer	Water/ cement ratio	Fluidity (s)	Compressive strength (MPa)	Flexural strength (MPa)	Studies
Resin modified grout	cement, fly ash, sand, water and prosalvia (PL7) (a commercial resin additive)	–	0.69	8.1	–	–	AI-Qadi et al 1994 [23]
Resin modified grout	Cement, sand, fly ash, water and cross polymer resin	–	0.7	9	22.8 (Day 28)	–	Anderton 2000 [22]
Cement paste	ordinaryportland cement (OPC) , mixed with an additive S, water	polycarboxylic ether polymer,	0.3	14	49.2(Day 1) 95.5 (Day 28)	6.1 (Day 7) 8.2 (Day 28)	Koting et al 2007 [2]
Ordinary cement mortar, Polymer modified cement mortar	Ordinary cement mortar - Cement, fly ash, mineral powder, fine sand and water, Polymer modified cement mortar - Cement, fly ash, mineral powder, fine sand, water, polymer (styrene-butadiene emulsion)	–	–	11.4, 11.1	17.2 (Day 7),12.6 (Day 7)	4.4 (Day 7), 5.9 (Day 7)	Ling et al 2009 [77]
Cement mortar with interfacial modifier	Cement, sand, water, silane coupling agent.	–	–	11.87	29.6 (Day 28)	8.33 (Day 28)	Yang et al. (2011) [103]
Cementitious grout	Cement, fly ash, expansion agent, sand, water and water reducing agent	–	0.1	11.87	29.6 (Day 28)	8.33 (Day 28)	Ding et al. (2011) [49]
CEAM (Cement Emulsified Asphalt Mortar)	Cement, sand, emulsified asphalt, expansive agent, mineral admixture, water with emulsified asphalt to cement (A/C) of 0.3	Naphthalene powder	0.6	13.4	14.7 (Day 3) 25.8 (Day 28)	3.04 (Day 3)5.76 (Day 28)	Huang et al 2012 [24]
Cement mortar	Cement, fine sand, water	Polycarboxylate superplasticizer	0.22	–	93.18 (Day 28)	–	Yajun et al 2013 [104]
Cementitious grout	Cement, Silica fume, water	Polycarboxylate type superplasticizer	0.3	15	57.5(Day 1) 92.5 (Day 28)	6.7 (Day 7) 9.1 (Day 28)	Koting et al 2014 [6]
Rubber modified cement grout (RMCG)	cement, sand, mineral admixture, and expansive agent, water with volume replacement ratio of waste rubber powder (20 %)	naphthalene powder	0.6	16.82	8.2 (1 day)15.4 (7 days)	–	Huang et al 2014 [25]
Cement mortar	Cement, fine sand, water	–	0.75,0.7	14.8, 12.4	24.4 (Day 7), 26.2 (Day 7)	4.45 (Day 7), 3.72 (Day 7)	Yang and Weng (2015) [15]
Cement mortar	Cement, sand, limestone filler, water	Superplastificiser Soicrat	0.2	–	29.9 (Day 28)	8.7 (Day 28)	Cihackova et al 2015 [7]
Latex modified cement mortar	Cement, styrenebutadiene rubber (SBR) latex (2 %), water	polycarboxylene-based superplasticizer (PS)	0.6	10.8	6.1 (Day 3)9.1 (Day 7)32.8 (Day 28)	1.4 (Day 3) 3.5 (Day 7)7.2 (Day 28)	Fang et al 2015 [26]
Cementitious grout	cement, micro silica, fly ash and sand	Polymer based superplasticiser	0.55	6.1	38.6 (Day 56)	6.8 (Day 56)	Reddy (2016) [76]
Cement paste	Cement, water	–	0.5	–	27.6 (Day 7)	–	Karami 2017 [10]
Cementitious grout	cement, fly ash, crushed sand, micro silica, water and admixtures.	–	0.33	20	19.55 (Day 7) 49.58 (Day 14) 59.44 (Day 28)	2.3 (Day 28)	Surana et al 2018 [57]
Latex modified cement mortar	Cement, Sand, fines, latex powder (3 %), water	–	0.72	12.8	2.81 (Day 7)	24.1 (Day 7)	Sang Luo et al 2018 [27]
Cement mortar	Cement, sand, water	super plasticizer was SP-470	0.5	12	–	–	Jatoi et al 2018 [105]
Latex modified Cement mortar	Cement, sand, mineral filler, carbonyl latex (8 %), water	–	0.63	11.63	15.11(Day 7) 22.53 (Day 28)	4.93(Day 7) 6.49 (Day 28)	Wang et al 2018 [42]
CG with waste rubber tire and natural zeolite	Portland cement, sand, natural zeolite (15 %), water	–	0.4	–	15.43 (Day 28)	–	Hamzani et al 2019 [68]
Cementitious grout	ordinary portland cement, fly ash, silica fume, water	polycarboxylic ether	0.32	21	8.93 (Day 7) 12.83 (Day 14)17.03 (Day 28)	–	Gupta et al 2021 [13]
Cementitious grout	Ordinary Portland Cement, Fly ash, Silica Fume, water	–	0.32	33	16 (Day 7)20 (Day14)32 (Day 28)	–	Gupta et al 2021 [12]
Cement grout	Cement, water	–	0.25	11.2	76 (Day 28)	15.5 (Day 28)	Li et al 2022 [106]

and cellulose fibre. The stiffness of the open-graded asphalt mix is lower (nearly-one-half to two-third) compared to that of dense graded asphalt mix as the porous asphalt mixture has higher air void which lowers the mixture's ability to resist the load. The usage of modified bitumen (like CRMB & RPEB) in porous asphalt mix increased the stiffness and showed a higher resilient modulus value when compared with the addition of cellulose fibre in porous asphalt mix.

The results of resilient modulus of CGB mixes obtained by various researchers are presented in Fig. 13. Due to the viscoelastic behaviour of CGB mixes, reduction in resilient modulus value was observed with the

Table 4
Abbreviation for CGB mixes with various grouting materials.

Studies	Abbreviations	
Anderton 2000 [22]	CGBM containing resin modified grout (RMG), 28 days @ 5 °C	CGBM with RMG, 28 days @ 5 °C
	CGBM containing resin modified grout, 28 days @ 25 °C	CGBM with RMG, 28 days @ 25 °C
	CGBM containing resin modified grout, 28 days @ 40 °C	CGBM with RMG, 28 days @ 40 °C
	Conventional bituminous concrete (CBC) with asphalt concrete 20, @ 25 °C	CBC @ 25 °C
Oliveira et al 2006 [35]	Grouted macadam with 4.1 % binder content, 200 pen at −5°C	Grouted macadam with 4.1 % bc, 200 pen at −5°C
	Grouted macadam with 4.1 % binder content, 50 pen at −5°C	Grouted macadam with 4.1 % bc, 50 pen at −5°C
	Grouted macadam with 1.5 % binder content, 200 pen at −5°C	Grouted macadam with 1.5 % bc, 200 pen at −5°C
	Dense bituminous macadam with 50 penetration grade (pen) at −5°C	DBM with 50 pen at −5°C
Oliveira et al 2008 [107]	Grouted macadam with foundation class stiffness 200 Mpa at 20 °C (Upto 50 % stiffness reduction (approximately)	GM with FCS of 200 Mpa at 20 °C (upto 50 % SR)
	CBC with foundation class stiffness 200 Mpa at 20 °C (Upto 50 % stiffness reduction (approximately)	CBC with FCS 200 Mpa at 20 °C (upto 50 % SR)
	Grouted macadam with foundation class stiffness 200 Mpa at 20 °C (Upto 90 % stiffness reduction) (approximately)	GM with FCS of 200 Mpa at 20 °C (upto 90 % SR)
	CBC with foundation class stiffness 200 Mpa at 20 °C (Upto 90 % stiffness reduction (approximately)	CBC with FCS 200 Mpa at 20 °C (upto 90 % SR)
Oliveira et al 2009 [32]	Grouted macadam containing conventional binder of 2 % at 200 με	GM with CB of 2 % at 200 με
	Grouted macadam containing polymer modified binder of 2 % at 200 με	GM with PMB of 2 % at 200 με
Ling et al 2009 [77]	CGBM with rubber modified cement grout	CGBM with RMCG
Yang et al 2011 [103]	CGBM with interfacial modifier (IFM) - silane coupling agent (SCA) at 0.6 %, 0.3 stress ratio at −10 °C	CGBM with IFM-SCA at 0.6 %, 0.3 SR at −10 °C
Chong et al 2012 [24]	CGBM with Cement Emulsified Asphalt Mortar at 0.3 Emulsified asphalt /cement ratio at – 10 °C	CGBM with CEAP, 0.3 SR at −10 °C
Chong et al 2014 [25]	CGBM containing rubber modified cement grout (20 %)	CGBM with RMCG (20 %)
Koting et al 2014 [5]	CGBM containing pozzolanic cementitious grout (PCG), 28 days @ 25 °C	CGBM with PCG, 28 days @ 25 °C
H Zhang et al 2016 [108]	CGBM with cement slurry	CGBM with CS
Hou et al 2016 [16]	CGBM containing cement slurry (CS with crushed limestone powder) 28 days @ 25 °C	CGBM with CS, 28 days @ 25 °C
Karami et al 2017 [10]	CGBM containing cement paste @ 90 days	CGBM with CP @ 90 days
Corradini et al 2017 [56]	CGBM with cement mortar (CM) at 20C with a stress level of 500 kPa	CGBM with CM at 20 °C, 500 kPa
J Cai et al 2017 [8]	CGBM containing high performance cement paste @ 24 % air void	CGBM with HPCP @ 24 % AV
D Wang et al 2018 [42]		CGBM with CLMCM @ 28 % AV
	CGBM containing carboxyl latex modified cement mortar @ 32 % air void	
	CGBM containing carboxyl Latex modified cement mortar @ 24 % air void	CGBM with CLMCM @ 24 % AV
	CGBM containing unmodified cement mortar @ 32 % air void	CGBM with UCM @ 28 % AV
	CGBM containing unmodified cement mortar @ 24 % air void	CGBM with UCM @ 24 % AV
Xu Cai et al 2019 [29]	CGBM containing engineered cement composite (ECC) mortar with 25 % air void, 28 days at – 10 °C	CGBM with ECC, 25 % AV, 28 days at – 10 °C
	CGBM containing engineered cement composite (ECC) mortar with 25 % air void, 7 days at – 10 °C	CGBM with ECC, 25 % AV, 7 days at – 10 °C
Zarei et al 2020 [17]	CGBM with CAEP (cement asphalt emulsion paste) of 20 % AE/C (asphalt emulsion/cement)	CGBM with CAEP of 20 % AE/C
Bharat et al 2020 [30]	CGBM containing polymer modified mortar	CGBM with PMM
Zhang et al 2020 [109]	CGBM containing pozzolanic cementitious grouting material	CGBM with PCG
Luo et al 2020 [27]	CGBM with latex modified cement mortar of NMAS 13	CGBM with LMCM of NMAS 13
K zhong et al 2020 [54]	Polymer modified CGBM with latex modified cement mortar, of NMAS 16,28 days @ 25 °C	PCGBM with LMCM, NMAS 16, 28 days @ 25 °C
	CGBM contanining SBS-latex modified cement mortar with NMAS 16 at stress ratio of 0.5	CGBM with SBS-LMCM, NMAS 16 at SR of 0.5
	CGBM contanining conventional binder-latex modified cement mortar with NMAS 16 at stress ratio of 0.5	CGBM with CB-LMCM, NMAS 16 at SR of 0.5
Luo et al 2020 [27]	CGBM containing latex modified cement mortar of NMAS 13 with stress ratio of 0.5 at 15 °C	CGBM with LMCM of NMAS 13, SR of 0.5 at 15 °C
	Conventional Bituminous Concrete (CBC) of NMAS 13 with stress ratio of 0.5 at 15 °C	CBC of NMAS 13, SR of 0.5 at 15 °C
Khan et al 2021 [96]	CGBM with Irradiated PET, 28 days @ 25 °C	CGBM with IrPET, 28 days @ 25 °C
Humeidawi et al 2021 [53]	CGBM containing 10 % RHA 90 % OPC, 28 days @ 25 °C	CGBM with 10 % RHA 90 %OPC, 28 days @ 25 °C
Shukla et al 2021 [70]	CGBM with polymer modified grout (PMG), 28 days @ 25 °C	CGBM with PMG, 28 days @ 25 °C
Hlail et al 2021 [60]	CGBM containing paper sludge ash (PSA),28 days @ 25 °C	CGBM with PSA, 28 days @ 25 °C
Basim H. Al-Humeidawi et al 2021 [53]	Polymer modified CGBM with 10 % RHA 90 %OPC,28 days @ 25 °C	PMCGBM with 10 % RHA,90 % OPC, 28 days @ 25 °C
Basim H. Al-Humeidawi et al 2021 [53]	CGBM containing 10 % RHA 90 % OPC, 28 days @ 25 °C	CGBM with 10 % RHA 90 % OPC, 28 days @ 25 °C
Gupta et al 2021 [13]	CGBM containing pozzolanic cementitious grout (PCG), 28 days @ 25 °C	CGBM with PCG, 28 days @ 25 °C
	CGBM containing pozzolanic cementitious grout, 7 days @ 25 °C	CGBM with PCG, 7 days @ 25 °C
		CGBM with PCG, Lab

(continued on next page)

Table 4 (*continued*)

Studies	Abbreviations	
Gupta et al 2021 [12]	CGBM containing pozzolanic cementitious grout, (laboratory produced)	
	CGBM containing pozzolanic cementitious grout, (field cored)	CGBM with PCG, field cored
Kaushik et al 2022 [81]	CGBM with marginal aggregate, 28 days @ 25 °C	CGBM with MA, 28 days @ 25 °C
	Conventional bituminous concrete (BC), @ 25 °C	CBC @ 25 °C
Li et al 2022 [106]	CGBM containing cement paste (CP), 28 days @ 25 °C	CGBM with CP, 28 days @ 25 °C
Khan et al 2022 [110]	CGBM containing regular PET, stress level of 640 kPa @ 25 °C	CGBM with regular PET, 640 kPa @ 25 °C
	CGBM containing irradiated PET, stress level of 640 kPa @ 25 °C	CGBM with IrPET, 640 kPa @ 25 °C

increase in temperature. CGBM with polymer modified grout, resin modified grout, pozzolanic cementitious grout showed higher resilient modulus when compared with the conventional bituminous mixtures. In addition, CGBM containing marginal aggregates displayed lower resilient modulus than CGB mixes containing virgin aggregates, however CGBM with marginal aggregates had higher resilient modulus than conventional bituminous mixtures.

5. Properties of CGB mixtures

5.1. *Resistance to petroleum products*

Asphalt pavements are very sensitive to the fuel spill which reduces the durability of the pavement to a large extent due the attack by petroleum products. When fuel spills on the asphalt pavement, the bitumen softens and segregation of aggregates can be observed which leads to ravelling type of distresses in the surface of the pavement. Airport aprons, BRT (bus rapid transit) stations, tunnels, bridge deck pavements, industrial areas, toll plazas, intersections, and parking lots are some of the places with a higher possibility of the attack of petroleum products due to slow-moving traffic and heavy stationary loads. In the case of CGBM, the cementitious grouting material acts as a coating around the asphalt mixture, thus providing greater resistance to fuel spills [11]. There is no proper method to evaluate the resistance to petroleum products. A study examined the resistance to petroleum products by conducting ITS test on samples conditioned in diesel for 24 h by complete submergence. BC and CGB mixes were used in the study to examine the resistance to petroleum products and the results of CGB mixes were compared with the conventional bituminous mixture. TSR (tensile strength ratio) was adopted as a measure to indicate the retained stability of the mixtures. The CGB mixes had a better TSR value of 92.21 % when compared to asphalt mixtures which had a TSR value of 63.98 % [30]. In another study, the ratio of the mass of the mixture before and after soaking in diesel oil for seven days was used to assess the response of the CGB mixture to petroleum products. After being submerged in diesel oil, the loss of the material was 0.3 % of its original mass [112]. Similarly, in another study resistance to fuel spillage was evaluated in terms of mass loss after immersion in diesel oil for 7 days. The mass loss of CGB mixes (less than 6 %) was significantly lower when compared to the mass loss of HMA mixes (greater than 20 %) [97]. Thus, experimental results from various literature indicated that CGB mixes showed higher resistance to fuel spillage when compared to bituminous mixes.

5.2. *Fire resistance*

Fire safety is a major concern in tunnels. The intensity of fire in tunnels will be aggravated due to the presence of asphalt pavement. As bitumen is a by-product of crude oil, when it is exposed to high temperatures it causes severe damage to the surroundings. The tunnel

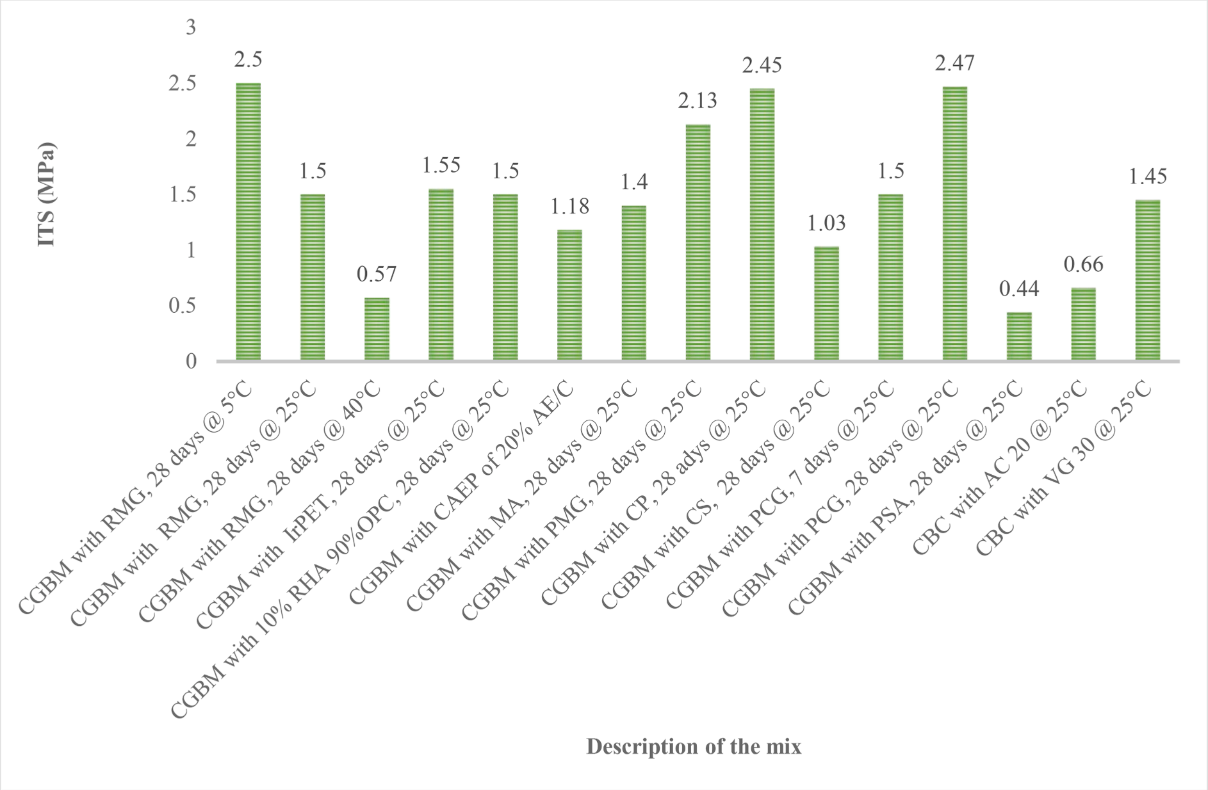


Fig. 12. Results of ITS of CGBM obtained by various researchers.

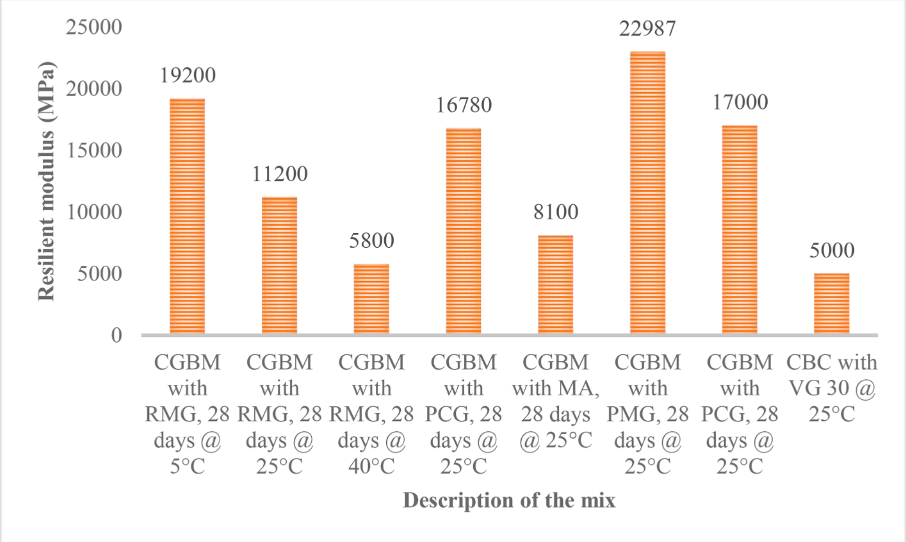


Fig. 13. Results of resilient modulus of CGBM obtained by various researchers.

Fig. 14. Equipment used for fire testing [113].

temperature can raise up to 800 °C from the heat generated from the asphalt pavement. In addition, the emission of smoke during the fire exposure causes oxygen deficit and reduced vision to the people which hampers the possibility to escape from the tunnel. In addition to this, the smoke produces harmful fumes which are dangerous to inhale and leads to serious health issues and causes irrecoverable loss to the people and the environment. Taking concrete pavements into consideration, the effect of fire propagation will be lower comparing to that of asphalt pavement and comparatively concrete pavements emit minimal toxic gases. A study was done to evaluate the fire resistance of different types of pavement materials namely, asphalt mixtures, cement concrete mixtures and CGBM. Tunnel fires are identified by the quick spread of fire and presence of high temperature; the study was carried out to examine these two phenomena individually. Fig. 14 presents the equipment that is used for fire testing. Fire test was done using gas cooker by exposing the specimen up to a temperature of 400°C. High temperature tests were performed by increasing the temperature of the specimen in an oven or heating element up to a temperature of 850°C. During the testing process, a portable smoke analyser was used to evaluate the emission level of smoke. Compressive strength test was performed to evaluate the mechanical properties of the specimens before and after the exposure to fire and high temperature conditioning. The results indicated that in the presence of fire, asphalt mixtures emitted larger smoke while this behaviour was not observed in cement concrete mixtures and CGB mixes. On exposure to fire, asphalt pavement temperatures reached to higher values when compared to other type of mixtures. When considering the effect on the mechanical properties of the specimen on the exposure to fire, asphalt mixture showed a larger reduction in strength when compared to that of cement concrete mixtures and CGB mixes. Among the three, asphalt mixture was worst performing, cement concrete pavement was best performing on exposure to fire and CGB mixes showed better mechanical properties than bituminous mixture in the application of tunnel and its usage will be advantageous for the repair and overlay of the existing pavements [113]. Further studies are needed to analyse the response on the properties of CGB mixtures at different temperatures upon exposure to fire.

5.3. *Skid resistance*

Skid resistance is indicated in terms of the macro texture and micro texture of the pavement. The skid resistance increases with the increase in the macro-texture (wavelength from 0.5 mm to 50 mm) and micro-

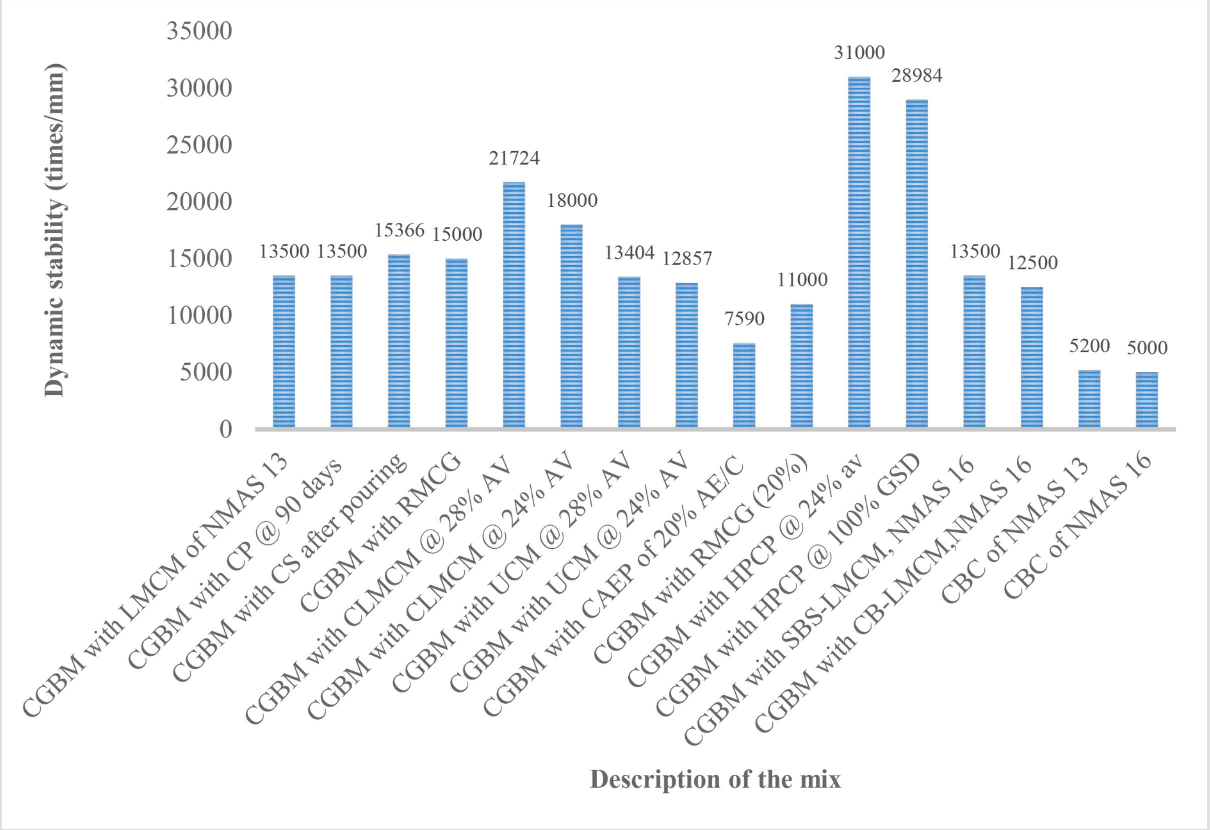


Fig. 15. Results of dynamic stability obtained by various researchers.

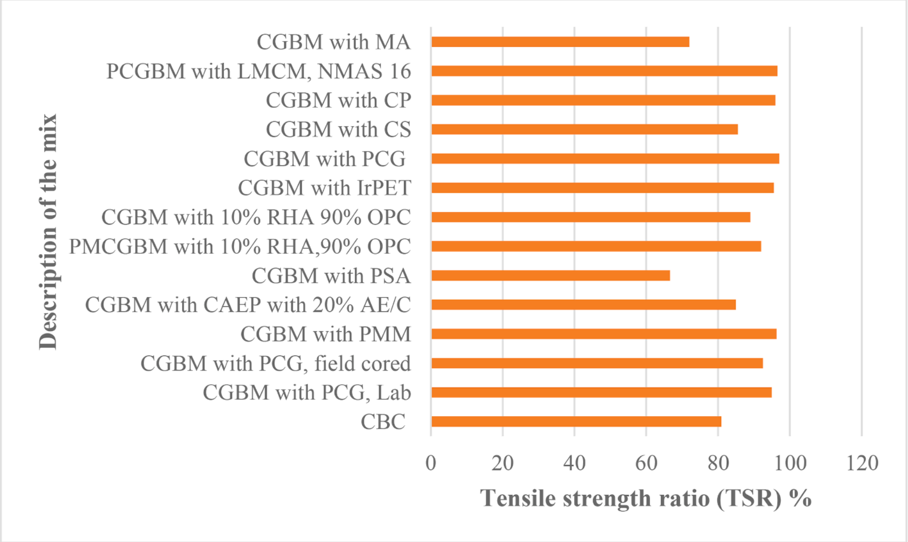


Fig. 16. Results of TSR values of CGBM obtained by various researchers.

texture (wavelength from 0 mm to 0.5 mm) of the surface of the pavement. The skid resistance of CGB mixtures was evaluated by calculating the mean depth value and pendulum test for macro texture and micro texture respectively. The results revealed that CGB mixtures provided acceptable skid resistance and surface texture [7]. Another study indicated that the CGB mixtures had satisfactory skid resistance with an average surface texture depth of 0.82 mm [112]. Bharath et al. 2019 [30] conducted a study to evaluate the skid resistance of CGB mixtures for wet and dry conditions. The skid resistance was measured using British pendulum tester in terms of BPN (British pendulum number). The measured BPN value for CGB mixes in wet condition was 60 and BPN value for dry condition was 70, which satisfied the permissible BPN requirement of 55. Battey and Whittington (2007) [40] compared the performance of three alternative pavement construction techniques by constructing test sections: resin modified pavement (RMP), hot mix asphalt (HMA) with PG (performance grade) 82–22 polymer modifier binder and ultra-thin white topping. The performance of the test sections was tracked for five years. By the end of fourth year, the skid resistance

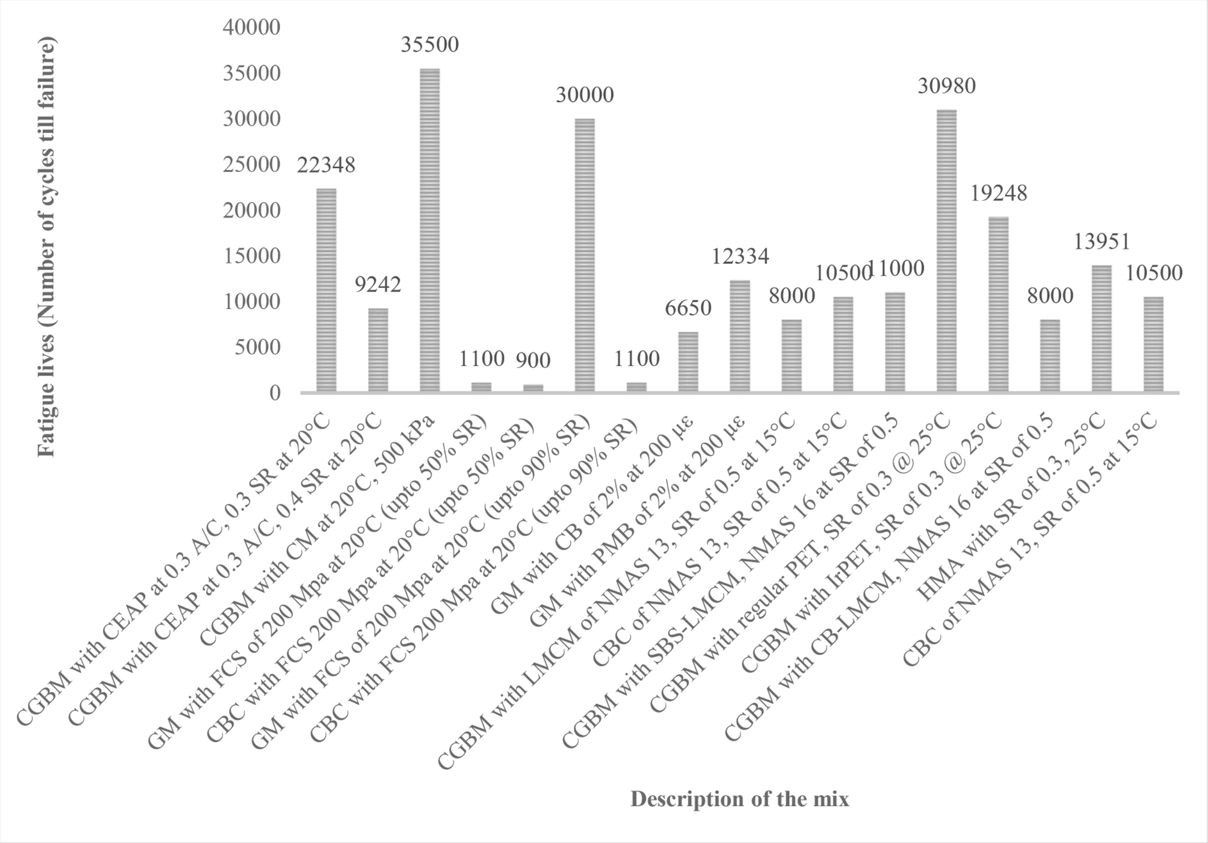


Fig. 17. Fatigue lives of mixture obtained by various researchers.

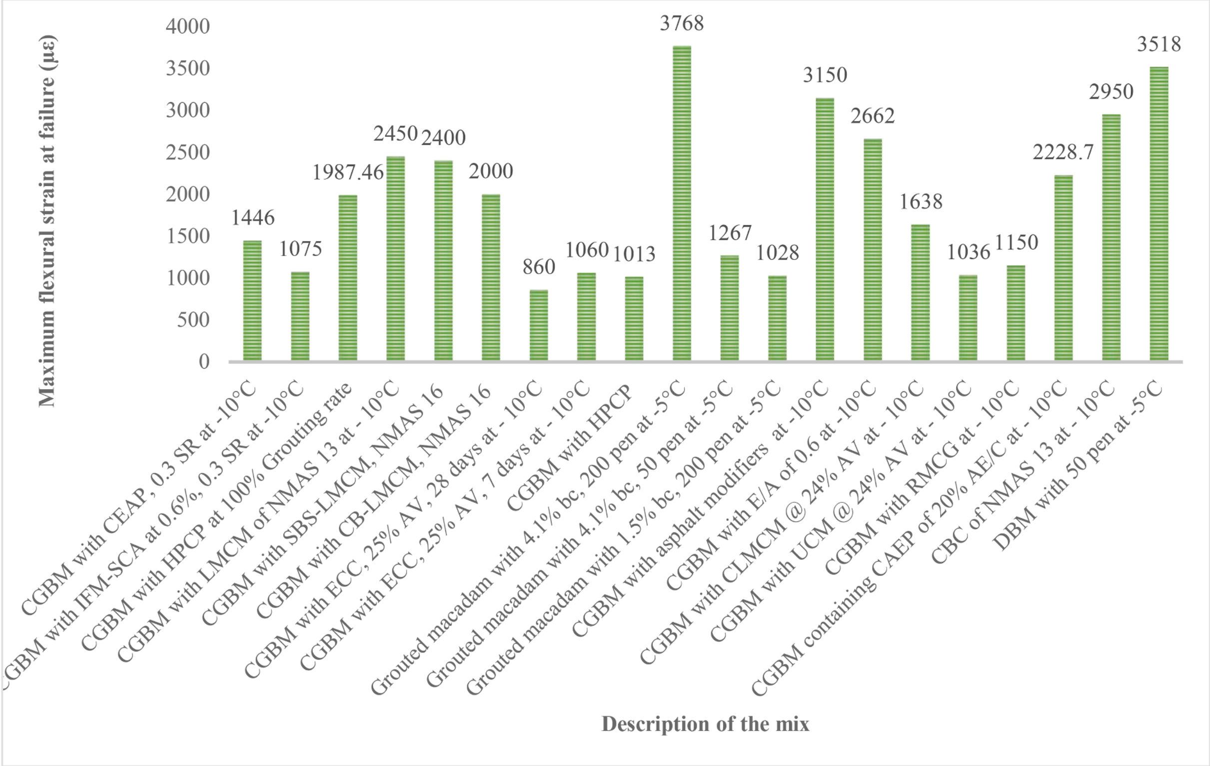


Fig. 18. Maximum flexural strain at failure of the mixture obtained by various researchers.

value (in terms of friction number) of the CGB mixes, HMA, and ultra-thin white topping pavement was 30, 28.1 and 40 respectively against the standard requirement of 35, indicating that CGB mixtures provided slightly higher skid resistance when compared to HMA mixes. The inclusion of calcined clay, saw dust ash, superplasticizer, laterite and crystalline-based admixture in different proportions improved the skid resistance of the concrete [114,115]. Researchers can effectively use the calcined clay, saw dust ash, laterite and crystalline-based admixture to improve the skid resistance of CGB mixes.

5.4. Ravelling resistance of CGB mixes

Cantabro durability test is used to determine the ravelling resistance of CGB mixes in terms of abrasive loss of CGB mixes. A study revealed that the CGB mixes were 10 times more susceptible to abrasion loss compared to the bituminous concrete mixtures as the average weight loss for CGBM was 16.1 % while in the BC mix, the abrasive loss was 1.7 % [30]. Another study indicated that the abrasive loss of 7 and 28 days cured CGB mixes was 60.5 % and 19.2 % whereas the abrasive loss of bituminous mixture was 8.1 %. With the increase in curing period of CGB mixes, the abrasive resistance of CGB mixes increases due to the development of stronger bond between the cement and the asphalt mixture with time [81]. In line with the above results, a study concluded that CGBM had an abrasive loss of about 14 % while BC mixture had an abrasive loss of 3.89 % [12]. The abrasive loss of CGBM was 15.13 % against the requirement of the maximum abrasive loss of 20 % as per ASTM D7064/D7064M [74] which in turn indicated that CGB mixes provide adequate resistance to wear and tear in the surface of the pavement. CGB mixes tend to disintegrate due to the presence of grouting material in the porous asphalt mixture. A higher abrasive loss of CGB mixes when compared to bituminous mixtures indicates weaker bonding and inadequate adhesion between the grouting material and the asphalt mixture [13]. A study concluded that the replacement of OPC (ordinary Portland cement) with silica fume up to 5 % (by weight of cement) in the grouting material effectively increased the abrasive resistance of CGB mixes when compared to the CGB mixes prepared with 100 % OPC grouting material. The reason was that the addition of silica fume increased the bonding in the composite mixture and strength of the grouting material which in turn increased the ravelling resistance of CGB mixes [6].

6. Performance studies on CGB mixes

6.1. Rutting characteristics

Rutting is the permanent deformation in the surface layer originating in the surface/subgrade of the pavement. Due to the lower stiffness of the bituminous mixture at high temperatures, rutting becomes more critical during the summer season of the initial years of the pavement life.

The CGB mixtures showed significantly lower rut depth, nearly 1/10 when compared to the bituminous mixtures. Even after 12 months, no rutting was observed in the field trial section constructed using CGBM. The cementitious grouting material in the CGBM provides rigidity to the mixture which results in very minimal plastic deformation under loading [30]. Several studies concluded that CGB mixtures showed greater rutting resistance when compared to conventional asphalt mixtures which helps in reducing the maintenance cost and aids in increasing the service life of the pavement [12,27,39,73,76,79,106,107,116,117]. A decrease in rutting resistance of CGBM was observed with increase in binder content in the porous asphalt mixture as higher binder content resulted in lower air voids which led to poorer grout penetration into the porous asphalt mixture [76]. The curing period of CGB mixes plays an important role in providing the rut resistance of CGBM. Rut progression curve of CGB mixtures with a curing period of 7 days was significantly different compared to the CGB mixtures cured with 90 and 270 days. Due to the hydration process of the grouting materials, the CGB mixtures with longer curing period had a higher rut resistance when compared to the CGBM with shorter curing period [10]. The rut resistance of GOAC-13 (grouted open asphalt concrete with nominal maximum aggregate size of 13 mm) was higher than GOAC-16, as GOAC-16 had a weaker cohesion due to the lower proportion of fine aggregate and hence deformation was higher for GOAC-16 when compared to GOAC-13 [27]. The rutting test of composite cement-asphalt mixture was conducted at a temperature of 60°C. The results indicated that the rutting resistance was significantly higher for bituminous mixtures with the injection of cementitious grout when compared to bituminous mixtures without cementitious grout [108]. The CGBM with marginal aggregates showed lower temperature susceptibility and better high temperature stability when compared to conventional bituminous mixture [81].

The CGB mixes containing polymer-modified bitumen showed higher resistance to rutting when compared with dense graded bituminous mixture, as the polymer molecules in the CGB mixes provide greater elasticity to the mixture which leads to lower permanent deformation under the application of loading [51]. The rubber-modified CGB mixes provided greater rutting resistance than asphalt mixtures as the dynamic stability of CGB mixes containing rubber-modified binder was 15,000 cycles/mm, whereas the dynamic stability of the bituminous mixture was 2000 cycles/mm. The presence of hardened cement paste in the CGB mixtures provides higher stability to the CGB mixes when compared to the conventional bituminous mixes [77]. The high-temperature rutting resistance of modified CGB mixes (with the addition of carboxyl latex) was higher when compared to the unmodified CGB mixes, as the addition of carboxyl latex in grouting materials filled the micro-cracks present in cement mortar of CGB mixes. In addition, carboxyl latex absorbed the fracture energy required for the expansion of the defects and micro-cracks in the cement mortar. The addition of carboxyl latex in CGB mixes improved the adhesion between the cement mortar and porous asphalt mixture which enhanced the internal stability of the CGB mixes [42]. In general, polymer-modified asphalt concrete (PMAC) was considered an optimal solution for surface courses than conventional bituminous mixture due to the ability of PMAC to resist deformation under heavy loads at high pavement service temperatures. In a study done by Tran et al. [118], the results revealed that the rut depth of CGB mixtures was 2.5 times lower than PMAC, which indicates that CGB mixtures have greater rut resistance than PMAC.

A study inferred that greater rutting resistance was observed for CGB mixes with pure cement paste (CP) when compared to CGB mixes containing cement asphalt emulsion paste (CAEP) as CAEP exhibits higher viscoelastic and temperature-dependent behavior. When compared with asphalt mixtures, higher rut resistance was observed for CGB mixes with the addition of CAEP up to an asphalt emulsion to cement (AE/C) ratio of 0.4 [17]. The addition of waste rubber powder in the grouting material for CGB mixes increased the rut depth and reduced the rut resistance of CGB mixes [25]. The rut resistance of CGB mixtures containing high-performance cement paste was higher compared to that of the CGB mixtures containing pure cement paste [8].

The results of dynamic stability of the CGBM and BC (bituminous concrete) mixture obtained by various researchers are shown in the Fig. 15. CGB mixes with higher grouting saturation degree, SBS modified asphalt, high performance cement paste, latex modified cement mortar has higher rutting resistance than conventional CGB mixes (CGBM containing cement paste and cement slurry). The usage of cement asphalt emulsion paste as a grouting material decreased the rutting resistance of CGB mixes. Irrespective of the grouting materials used, CGB mixes exhibited superior rutting resistance than conventional bituminous mixtures due to the stiffness of the grouting materials.

6.2. Moisture damage resistance of CGB mixes

Moisture susceptibility is one of the important performance characteristics of the bituminous mixtures indicating the durability of the pavement during its service life. Moisture resistance is generally examined in terms of RMS (residual Marshall stability) and TSR (tensile strength ratio). CGB mixes had a higher tensile strength ratio (TSR) of 96 % in comparison to the BC mix which had a TSR value of 80 % as moisture-induced damage was minimized in CGB mixes due to the highly impervious structure of the composite material. Cement acts as an anti-stripping agent by restricting the entry of water into the air voids of the CGB mixes by forming a coating around the porous asphalt mixture. The presence of water in the surface of the pavement along with repetitive traffic load adversely affects the binder coating around the aggregate, which leads to reduction in the strength of the mixture. Due to moisture damage, the ITS value of conditioned specimen was lower than the ITS value of unconditioned specimen for both CGB mixtures and BC mixtures [12,30,55,79]. CGB mixtures with high viscosity modified asphalt showed higher resistance to water damage when compared to CGB mixtures with 70 penetration grade petroleum asphalt [119]. A study determined the moisture susceptibility of the CGB mixes in terms of retained Marshall stability (RMS) and tensile strength ratio (TSR). The RMS of CGB mixtures and BC mixes was 110.1 % and 87.8 % respectively. The TSR values of CGB mixtures and bituminous mixes were 85.5 % and 81.8 % respectively [120]. In line with the above results, a study evaluated the resistance to moisture damage in terms of tensile strength ratio (TSR). TSR value of CGB mixes was 95 % whereas the TSR value of HMA mixes was 87.6 % which indicated that CGB mixes provide superior resistance to moisture damage when compared to HMA mixes [97].

A study compared the TSR value of CGB mixtures prepared using various binder contents used to prepare the porous asphalt mixtures. At smaller binder contents (2 % & 3 %), the TSR values of the CGB mixtures were nearly equal to 100 % as the quantity of grout penetrated was higher and CGB mixtures with the grouting material had gained strength after moisture curing at 60 C. On the other hand, despite of the decrease in the quantity of grout penetrated in CGBM at higher binder contents (4 % & 5 %) moisture resistance was higher for the composite mixtures due to the increased film thickness around the aggregates [76]. Marshall stability test was conducted on saturated composite cement-asphalt mixture to evaluate the moisture damage resistance of the CGB mixes. The results inferred that the Marshall stability of saturated CGBM and unsaturated CGBM were nearly same and CGBM had significantly higher moisture resistance [108]. Higher TSR were observed for CGB mixes prepared with PMB when compared to CGBM with neat bitumen as PMB improves the adhesion in the mixture [53]. TSR value of CGBM with latex modified cement mortar was higher when compared to CGBM with ordinary cement mortar and the increase was by 5.6 % [54].

CGB mixes with rubber-modified asphalt showed superior resistance to moisture damage when compared with the rubber-modified bituminous mixtures [77]. By the use of polymer-modified binder in the CGB mixtures, greater resistance to moisture damage was observed compared with the conventional asphalt mixture and the addition of paper sludge ash and silica fume in the cementitious grout of CGB mixes showed superior water stability when compared to the CGB mixes with conventional cementitious grouting material [54,60]. The RMS value of CGB mixtures containing CAEP (cement asphalt emulsion paste) was lower than the CGB mixtures containing CP (pure cement paste). At high temperatures, the mechanical properties of CGBM with CAEP showed higher susceptibility to moisture damage compared to that of CGBM with CP. On the other hand, the TSR value of CGB mixtures with CAEP was higher compared to the CGB mixtures with pure CP. CGBM with CAEP exhibited higher resistance to frost damage when compared to CGBM with CP. The reason was that due to the viscoelastic behavior of CAEP, CGB mixes with CAEP absorb more freeze–thaw energy than CGBM with CP. In addition, due to the hydrophobicity of asphalt, the water absorptivity of CAEP was lower than that of CP [17]. A study reported that higher moisture resistance was observed for CGBM with latex-modified cement mortar when compared to conventional asphalt concrete. Higher moisture resistance of latex-modified CGBM was attributed to the higher tensile strength of the latex-modified cement mortar [27]. TSR values of CGB mixtures containing high-performance cement paste were greater than that of CGB mixtures containing pure cement paste. At the same air void content, CGB mixes with high-performance cement paste had higher fluidity and higher volume of cement mortar when compared to CGB mixes with pure cement paste. With the increase in fluidity and volume, the quantity of grout penetration will be higher which results in higher rigidity of the mixture [8].

Fig. 16 shows the TSR values of CGB mixes obtained by various researchers. Polymer modified CGB mixes showed higher moisture resistance than CGB mixes containing unmodified binder. CGB mixes containing cement paste, cement slurry, CAEP, latex modified cement mortar, irradiated PET cement mortar, polymer modified cement mortar, pozzolanic cementitious grout, RHA (10 %) modified grout exhibited superior moisture resistance than conventional bituminous mixture. CGB mixes containing PSA, marginal aggregates underperformed when compared with conventional bituminous mixture.

6.3. *Fatigue performance*

Lower fatigue resistance was observed in CGB mixtures when compared to conventional asphalt concrete as CGB mixtures had a weak interfacial bonding between the asphalt – aggregate skeleton and the cement mortar [24,87]. At stress levels of 400 kPa & 500 kPa, CGB mixtures exhibited higher fatigue lives (nearly 5 times) when compared to the conventional BC. On further increasing the stress levels beyond 500 kPa, the fatigue resistance of CGB mixtures was reduced to a larger extent [53]. Laboratory tests and examination of pavement sections of CGB mixtures indicated that fatigue performance increased with the increase in binder content as the CGBM mixtures with smaller binder content exhibited higher stiffness and smaller failure tensile strains [69]. Also, the failure tensile strain decreased with decrease in the temperature [70]. CGBM laid over an existing pavement showed a greater fatigue life which resulted in reduction in the maintenance cost per year [12]. A study reported that the fatigue performance of CGB mixes was underestimated by using traditional failure fatigue criteria (50 % reduction in initial stiffness) as the study observed higher fatigue life in CGB mixes than the dense bituminous macadam (DBM) with the calculation of fatigue lives with a failure criterion of 90 % reduction in initial stiffness. The reason was that beyond 50 % reduction in initial stiffness, the rate of stiffness loss increased rapidly in DBM whereas the rate of reduction in stiffness loss happened gradually with time in case of CGB mixes. This clearly showed that in contrast to conventional bituminous mixtures, CGB mixes continue to perform well beyond the traditional failure fatigue criteria (50 % reduction in initial stiffness) [107].

The use of polymer-modified binder in CGB mixes showed higher fatigue resistance when compared to the conventional CGB mixtures and asphalt concrete mixes [32,49]. In a study, CGBM with styrene butadiene styrene (SBS) modified asphalt mixture of optimal asphalt content (OAC) of 3.2 %, CGBM with modified asphalt (MA) of OAC 4.2 %, and CGBM with fiber (lignin fibre) incorporated modified asphalt (MAF) of OAC 4.3 % were employed to compare the performance of CGB mixtures. Among the three mixtures, CGBM with SBS modified asphalt mixture had the highest tensile strength but lowest fracture energy. Higher fracture energy produces higher fatigue resistance. Both CGBM with modified asphalt (at 15° C) and CGBM with fiber modified asphalt (at 25° C) produced higher fracture energy than SBS modified asphalt mixture. CGBM with MA (modified asphalt) and CGBM with MAF (fibre-modified asphalt) had higher asphalt content and exhibited a ductile behaviour by producing adequate adhesion between the bitumen and cement mortar in the CGB mixture which resulted in higher fatigue resistance than CGB mixes with SBS modified asphalt [50]. A study evaluated porous asphalt mixtures containing three different binders namely, CRMB (crumb rubber modified binder), RPEB (reclaimed polyethylene modified binder), and the addition of cellulose fiber in the 60/70 Penetration grade bitumen. By using modified binders (CRMB & RPEB) in porous asphalt mixtures, asphalt film thickness increased, which resulted in higher adhesion in the porous asphalt mixtures. The results indicated that fatigue resistance was higher for porous asphalt mixtures with modified bitumen when compared to the porous asphalt mixtures with fiber added 60/70 grade bitumen. When compared to porous asphalt mixtures compacted with 25 blows on each side, a higher fatigue life (12 – 18 % increase) was observed in porous asphalt mixtures compacted with 50 blows on one side [65]. On increase of the stress levels, the fatigue resistance of CGB mixtures decreased at a faster rate when compared to the bituminous mixes due to the presence of grouting materials in CGB mixtures. This drop-in fatigue resistance of CGB mixes can be minimized with the addition of an interfacial modifier. A study used silane coupling agent (water-based epoxy resin) as a modifier in the CGB mixes. This modifier enhanced the flexibility of the CGB mixes which effectively increased the fatigue resistance of the CGB mixes [87].

A latex-modified cement mortar was used as a grouting material to improve the flexibility of the CGB mixtures. As the CGB mixtures have a stiffer skeleton, it has lower ability to deform under heavy loads, when compared to the conventional asphalt concrete which results in lower fatigue performance of CGBM than bituminous mixture [27]. The addition of latex-modified cement mortar in CGBM showed higher fatigue resistance at higher stress levels and nearly similar fatigue performance at lower stress levels when compared to dense graded asphalt mixtures [52].

The results of fatigue lives of CGB mixes and bituminous mixes obtained by various researchers is shown in Fig. 17. Higher fatigue lives were observed for CGB mixes containing polymer modified binder, latex modified cement mortar, PET waste (irradiated and regular), CAEP (at lower stress levels), cement mortar, fatigue lives with a failure criterion of 90 % stiffness reduction when compared to conventional bituminous mixture. CGB mixes with lower binder content reduces the fatigue resistance of CGB mixes. Limited studies are available about the fatigue performance of CGB mixes and results contradict with each other, therefore further studies are needed to understand the fatigue behaviour of CGB mixes using various grouting materials.

6.4. Low temperature performance of CGBM

For an adequate low-temperature cracking resistance of the CGB mixtures, the expansion and contraction stress (internal stress) of the cement mortar should be less than the ultimate tensile strain of the CGB mixture. This internal stress can be reduced, by using porous asphalt mixtures with higher air voids and grouting materials having lower volumetric variations [101]. A study evaluated the susceptibility of thermal induced cracking for CGB mixtures and compared with dense bituminous macadam (DBM) containing 50 pen grade bitumen. The temperature-induced cracking resistance of the CGB mixtures was comparable to that of dense graded bituminous mixtures. The thermal cracking resistance decreased when the CGB mixtures were prepared with stiffer binders [35]. The CGBM prepared with asphalt modifiers (styrene–butadienestyrene (SBS), hydrocarbon resins, rubber oil, and amine polymers) enhanced the low-temperature flexural failure strain of CGBM which results in higher cracking resistance at low temperatures when compared to conventional CGBM [67]. The weak Van Edward force between the cement and asphalt is the main reason for the cracking of the CGB mixes, as the Van Edward force cannot resist the internal stress that is caused by the shrinkage of the cement mortar and thermal expansion of the asphalt. When the internal stress exceeds the interfacial bonding strength or tensile strength, CGB mixes tend to crack. To increase the bonding force between the cement mortar and the asphalt mixture, a water borne epoxy-emulsified asphalt was added to the cement mortar. The study used small bending beam test at -10° C to examine the cracking resistance of the CGB mixes with the addition of water borne epoxy-emulsified asphalt. The specimen with higher bending strain and smaller stiffness modulus could provide better low temperature cracking resistance. Without the addition of water borne epoxy-emulsified asphalt in CGB mixes, the maximum bending strain was below 1000 με and stiffness modulus was 8442 MPa. With an E/A ratio (water borne epoxy to emulsified asphalt) of 0.6, maximum bending strain (2662 με) and smaller stiffness modulus (2322 MPa) was observed. Beyond a E/A ratio of 0.6, due to the brittleness of the cured epoxy, low temperature cracking resistance of CGB mixes was reduced [92]. With the increase in amount of grouting material in the pores of the open graded asphalt mixtures, the brittleness of the CGB mixes increased which resulted in higher flexural strength and lower flexural strain of the CGB mixes [28]. Adding ECC (poly vinyl acetate – engineered cement composite fiber) into cement mortar increased the toughness of the CGBM and resistance to fatigue cracking [29].

A study indicated that the influence of matrix porosity had a significant impact on the low-temperature cracking resistance of the CGBM. After the addition of carboxyl latex into the cement mortar, the influence of the void fraction on the performance of CGBM was greatly reduced and low temperature cracking resistance was improved. The reason was that the carboxyl latex reduced the brittleness of the mortar, and strengthened the bonding force between the asphalt matrix and the mortar, thereby increasing the integrity of the mixture [42]. A study was conducted to check the possibility of using waste rubber powder in the grout to reduce the stiffness of the CGB mixes. The result indicated that higher failure tensile strain was observed with the increase in the volume of the rubber powder in the grouting material. The higher tensile strain indicated a better low-temperature cracking resistance. Thus, the addition of rubber powder to the grout enhanced the cracking resistance of CGBM [25]. The flexural failure strain of CGB mixtures with pure cement paste (CP) was lower than the CGB mixtures with cement asphalt emulsion paste (CAEP). The reason was that the addition of asphalt emulsion to the cement paste improved the bonding interface which resulted in higher flexibility of the mixture and increased the flexural failure strain increased by 1.47 times when compared to CGB mixtures with pure cement paste. CGB mixes with CAEP at 20 % of AE/C (asphalt emulsion/cement) content indicated a better low-temperature cracking resistance when compared to CGB mixes with CP [17,24]. The addition of emulsified asphalt and silica fume into the grouting material of CGBM increased the flexibility of the cement mortar which resulted in improved low-temperature cracking resistance of the CGB mixtures [87]. CGBM containing high-performance cement paste showed a higher low-temperature cracking resistance when compared to the CGBM containing pure cement paste as mixes prepared with higher performance cement paste had a greater failure tensile strain compared to the CGBM with pure cement paste. But in both cases, the failure tensile strain of CGB mixes was lower when compared to the bituminous mixtures [8].

Maximum failure flexural strain of CGB mixes at low temperature obtained by various researchers is given in the Fig. 18. The higher flexural failure strain of CGB mixes indicates the enhanced low temperature cracking resistance of CGB mixes. Higher binder content increased the low temperature cracking resistance of CGB mixes. As the curing period of CGB mixes increases, brittleness of the mixture increases leading to a reduction in the low temperature cracking resistance of CGB mixes. CGB mixes with latex modified cement mortar, asphalt modifiers, cement asphalt emulsion paste, polymer modified asphalt showed better performance in terms of low temperature cracking resistance of CGB mixes when compared to conventional CGB mixes. The inclusion of interfacial modifiers, various flexible admixtures aid in improving the low temperature cracking resistance of CGB mixes. However, further studies are needed to identify the materials required to improve the flexibility of CGB mixes at lower temperatures.

7. Micro-mechanical and adhesion characteristics of CGB mixes

7.1. Digital image processing and numerical modelling

Digital image processing technology was used to examine the interfacial bonding performance of CGB mixes at different curing periods. Images of the fracture surface of CGBM specimen were processed to identify the different components of the mixtures like cement mortar, asphalt, and the interface at different curing ages. As the curing period increased, the interaction between the mortar and the asphalt increased thereby increasing the stress accumulation in the mortar which led to cracking in the grout. On the other hand, the prolonged curing period emulsified the asphalt due to the intrusion of moisture and decreased the cohesive bonding in the asphalt which led to the failure of the asphalt surface [119].

The internal stresses produced in the CGB mixes were the main reason for the cause of cracking in the CGB mixes. The internal stresses in the CGB mixes are produced due to the expansion and contraction stresses in the cement mortar. A study analysed the internal stresses produced in the CGB mixes containing a range of air voids (15 %, 20 %, 25 %, and 30 %) using numerical simulation by employing the finite element method. To construct a model for CGB mixture, researcher processed the image by employing a CCD digital camera to capture the pictures of CGBM specimens with various air voids (15 %, 20 %, 25 %, 30 %). These images were processed to define the exact position of cement mortar, matrix, and air voids by incorporating into the AutoCAD software. The AutoCAD pictures were fed into the finite element software (ABAQUS) and the respective material properties were defined. The results indicated that for the CGB mixture with 15 % air voids, the contraction deformation of 0.2 % produced an internal stress of 0.46 MPa whereas the expansion deformation of 0.2 % produced an internal stress of 0.16 MPa. The contraction deformation in the cement mortar produced a higher internal stress when compared to the same amount of expansion deformation in the cement mortar. Therefore, contraction deformation is a critical factor in examining the cracking resistance of CGB mixtures. By increasing the air voids in the CGB mixes, a reduction in cracking potential was observed. On the other hand, higher air voids increased the expansion deformation of the cement mortar, but this increase in expansion deformation had minimal effect on the increase in the internal stresses in the CGB mixes. The study concluded that the porous asphalt mixture with higher air voids and grouting material having lower volumetric variations providing greater resistance against cracking of the CGB mixtures [66].

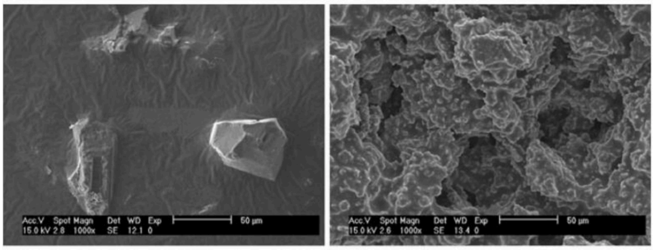
In another study, the micro-mechanical analysis of recycled CGB mixtures was done with the addition of reclaimed asphalt pavement (RAP) material using ANSYS software. Four material phases namely virgin aggregate, asphalt binder, cement paste, and reclaimed aggregate were analysed individually for their transverse failure strain using a linear elastic model. The exact position of each material phases were identified individually using DIP and fed into the ANSYS software for numerical simulation. The study inferred that on loading, the cracking probability of virgin aggregate was lower than the reclaimed aggregate. As asphalt is a viscoelastic material, it attained the highest failure strain and lost the cohesive force. The strength of the cement paste was also reduced due to the high concentration of stress in the interconnected pores of the CGBM [121]. Thus, DIP helps to identify the cracking portion of the fractured surface of the CGB mixes and numerical modelling helped to quantify the stresses and strains that are developed in the CGB mixes during loading.

7.2. Imaging techniques

The morphology of CGB mixes was analysed using a scanning electron microscope (SEM) to understand the micro-mechanical performance of the specimen under varied stresses and environmental conditions. Based on the SEM analysis, it was concluded that the hydration of cement paste formed a thicker coating around the aggregate and the asphalt film which increased the interfacial strength of the composite material. The spatial crystalline lattice network of the hardened cement paste provides better adhesion between the asphalt mixture and the grouting material [16]. A study evaluated the performance of CGB mixtures by constructing trial sections of CGB mixes in the field. ’Micro-computed tomography’ was utilized to examine the air void content of field-cored specimens. The air void content of the field cored CGB mixes were found to be 3.16 % and the obtained air voids indicated the interconnected and closed air voids in the CGB mixes which could not be filled with the grouting material [30]. Micro-mechanical analysis of asphalt mastics and cement asphalt mastics (CAM) was carried out using environmental scanning electron microscopy (ESEM). The results indicated that the asphalt mastics had no air voids due to the absence of water, and the surface of asphalt mastic was smoother with little texture. On the other hand, cement asphalt mastics (CAM) had tiny air voids with a coarser surface texture that were evenly distributed due to the hydration process between the cement and water phase in the cement asphalt mastics as shown in Fig. 19 [122]. The microstructural analysis of cement mortar with various percentages of asphalt (0 %, 5 %, 20 %, 30 %) was studied. It can be inferred that the hydration of the pure cement paste was higher due to the absence of asphalt, resulting in higher stiffness and lower flexibility. As the asphalt content increased, the flake-like structure was observed and the flexibility of the cement mortar was improved. The air voids which were available due to the hydration process of cement and water were effectively occupied by the asphalt. Up till an addition of 20 % asphalt in cement mortar, the performance of the grouting material was improved and adequate flexibility was observed. Beyond 20 % asphalt content, a block-like structure was formed and the properties of asphalt affected the performance of cement mortar. Although flexibility of the asphalt increased, cement hydration process of the cement mortar decreased [108]. Another study indicated that the initiation of cracks was observed mainly in the cement mortar near the cement-asphalt interface. As the cement is a stress-tolerant material and asphalt is a strain-tolerant material, the interfacial zone of cement and asphalt undergoes higher stress concentration and reaches its failure limit early due to shrinkage of the grout and the application of external load [123].

7.3. X-ray diffraction & Fourier-transform infrared (FTIR) spectroscopy

From X-ray diffraction (XRD) analysis, a study concluded that the hydration process of CAM (cement asphalt mastics) was delayed due to the presence of asphaltic emulsion when compared to the hydration process of pure cement paste. Similar peaks as present in normal cement paste in the diffraction pattern were observed which indicates the characterization of cement minerals and the hydration process of cement mortar as shown in the Fig. 20(a), no new crystalline materials were formed in CAM. Attenuated total refraction method was used to capture FTIR data. The absorption peaks of cement asphalt mastic (CAM) represented the superposition of the absorption peaks of unhydrated cement, cement paste, and residual asphalt at the same places according to the absorbance bands of the respective materials as



Asphalt mastic Cement asphalt mastic

Fig. 19. ESEM images of asphalt emulsion mastic and CAM [122].

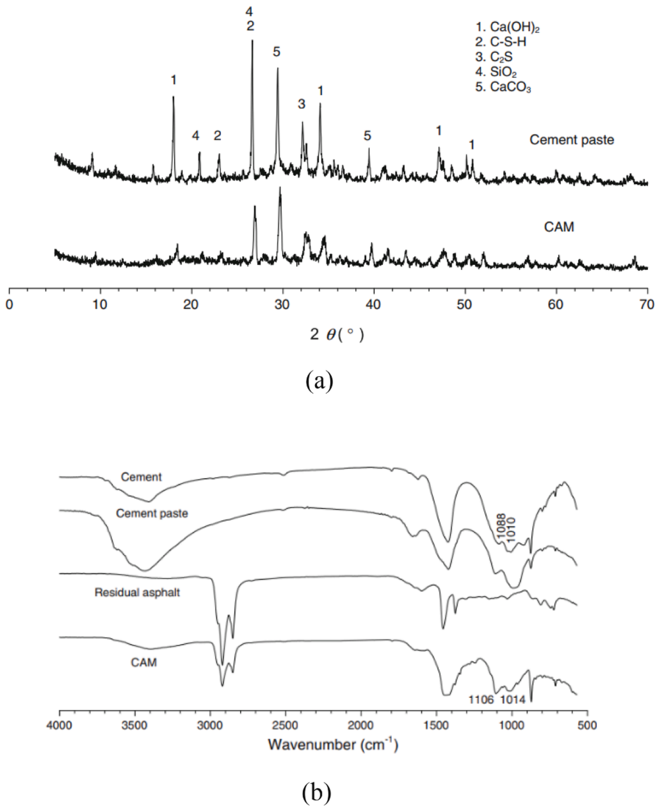


Fig. 20. (a) XRD results for CAM and cement paste; (b) FTIR results for various materials [122].

shown in Fig. 20 (b), which indicated no new functional groups were formed. The results of the XRD and FTIR investigations showed that the cement asphalt mastics did not develop any new crystalline compounds or functional groups. Hence, it can be inferred that the interaction mechanism of grouting materials and asphalt binder is a physical process [122].

7.4. Cohesive and adhesive properties of CGB mixes

To examine the interfacial bonding strength of the CGB mixes, pull-off tensile test was conducted. When the applied load exceeds the adhesive strength or cohesive strength of the CGBM mixes, failure occurs on the interface between the hardened cement paste and the porous asphalt mixture. The pull-off tensile strength test was conducted on CGB mixes with pure cement paste and CGB mixes with cement asphalt emulsion paste (CEAP). The adhesive strength of the CGBM with CEAP increased with increase in asphalt emulsion content of the grouting material. As a result of the improved adhesion, the interface failure between the aggregate and the grouting paste was minimized. The adhesive strength of CGBM with CAEP was higher compared to CGBM with pure cement paste [17,24]. The internal friction of the asphalt mix skeleton, network structure of hardened cement paste, and adhesion between porous asphalt mix and the grouting materials are the important factors that contribute to the strength of the CGB mixture. The adhesion between the cement particles, aggregate, and bitumen increases as the hydration process of the cement progresses. SEM analysis was used to understand the microstructural pattern of CGB mixes with the addition of water-borne epoxy-emulsified asphalt. Three different phases were analysed namely, pure cement hydration, hydration of cement with the addition of emulsified asphalt and hydration of cement with the addition of asphalt. During the hydration process of cement, the formation of C—S—H (calcium-silicate-hydrate) hydrogels and needle shaped ettringite with lot of pores were observed in pure cement hydration (Fig. 21 (a)) and hydration of cement with the addition of asphalt (Fig. 21(c)), whereas a more compact grouting system was observed in hydration of cement with the addition of emulsified asphalt as seen in Fig. 21 (b), as the C—S—H hydrogel combined with cured epoxy without the formation of ettringite. The microcosmic pattern of cement with the addition of emulsified asphalt and asphalt was captured (Fig. 21(d)) and it was observed that asphalt acts as a continuous phase, cured epoxy as dispersed phase and cluster of CSH hydrogels acts as a bonding system. The hydration of composite grouting system (cement + emulsified asphalt + asphalt) was still more compacted and no obvious pores were observed when compared to the hydration of individual phases (cement, cement + emulsified asphalt, cement + asphalt). From the Fig. 12(d), it is clear that the cured epoxy enhanced the interfacial adhesion between the grouting material and asphalt matrix [120]. The inclusion of an interfacial modifier (silane coupling agent) improved the adhesion near the interface of the CGBM and reduced the concentration of local stress which results in improved resistance to cracking of CGB mixes [103].

8. Performance of semi flexible pavement with CGB mix as a surface layer

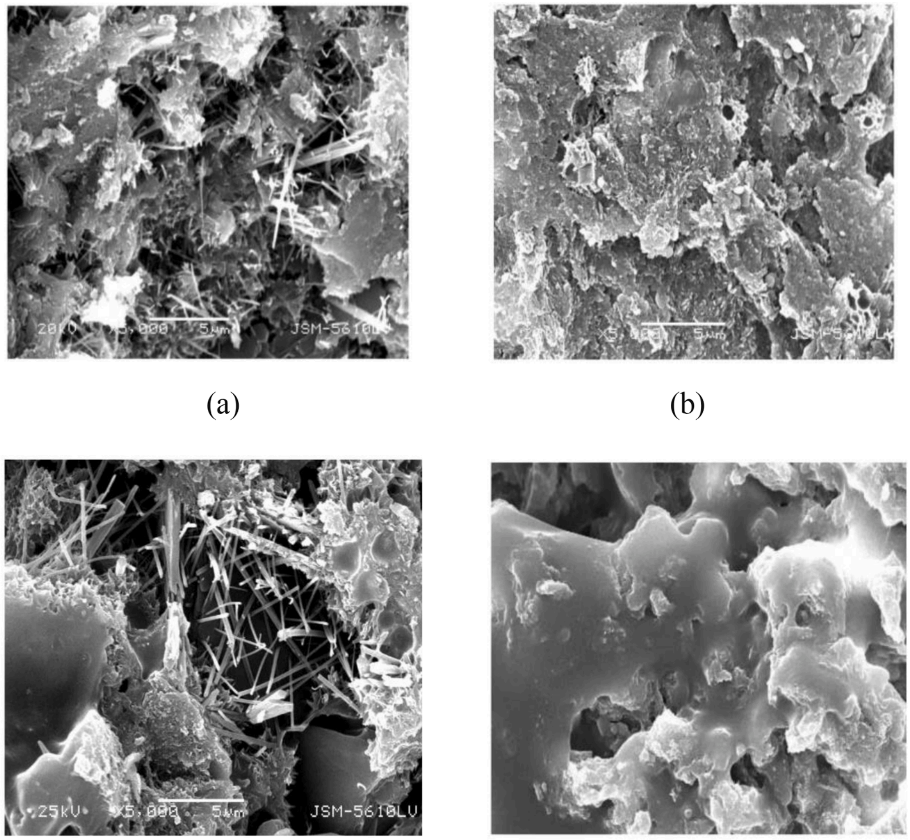
CGBM as a surface layer was first used in the early 1960 s in France as a part of SFP, where the CGBM was chosen as a replacement for Portland cement concrete composite [7,17]. The usage of the CGB mixture as a surface layer is majorly in overlay applications. CGB mixes have been used for various applications in the paving industry and their performance is reported by several research studies. The construction and performance of CGBM in various countries are presented in Table 5.

9. Usage of RAP in CGB mixes and potential challenges

9.1. RAP properties in general

Reclaimed asphalt pavement (RAP) material is the asphalt mixture removed from the existing pavement after the completion of service life which consists of reclaimed aggregate and aged asphalt. The RAP material is produced by the milling of the existing pavement layers during the reconstruction or overlay operations of the pavement. RAP is most typically utilized in reclaimed asphalt paving as an alternative for new aggregate and virgin asphalt binder in the bituminous binder course or surface course, and its usage can be extended to granular base or sub-base, and embankment materials [126]. The proper utilization of RAP material provides greater economic and environmental benefits by reusing valuable non-renewable resources (aggregate and asphalt) and reducing the disposal and dumping in the form of waste materials. Overviewing the project cost of paving the bituminous mixtures, the cost spent on purchasing the virgin materials takes a higher percentage of the total cost when compared to the cost spent on plant production, transportation of the materials, and paving the mixture. Among the raw materials needed for the construction of the pavement, asphalt is the material having higher cost. The usage of RAP materials will reduce the need for virgin asphalt binders by replacing certain portion of bitumen with aged binders in the new reclaimed asphalt mixes [127]. The quality of the RAP material removed from a particular site is influenced by the material used for the original construction, environmental conditions and the milling process (type of milling machine, speed, and depth of milling) [128–130]. With the increase of RAP content in new formulations of recycled asphalt mixtures, the stiffness of the mixture increases which results in higher resistance to rutting and lower sensitivity to water damage. However, the increased stiffness of RAP material increases the brittleness of the recycled bituminous mixture making it more susceptible to fatigue cracking and less resistant to low-temperature cracking [131].

Rejuvenators or virgin binders of lower viscosity grade can be used in an optimum proportion to reduce the stiffness of the RAP materials



(a) (b)

(c) (d)

Fig. 21. SEM image of a) pure cement hydration b) cement + emulsified asphalt c) cement + asphalt d) cement + emulsified asphalt + asphalt [120].

which improves the cracking resistance of the reclaimed asphalt mixtures. In comparison to organic rejuvenators, petroleum rejuvenators required a higher dosage to soften the aged RAP binder. The type of rejuvenator and the mixing procedure of the rejuvenator with the binder play a significant role in determining the volumetric properties of the new formulated recycled mixtures [127,132,133]. The performance characteristics of recycled asphalt mixes varies with respect to the percentage of RAP materials blended with the virgin aggregate and virgin binder [131,134–137]. The addition of a lower viscosity grade binder with the RAP material reduces the stiffness of the RAP material and enhanced the cracking resistance of the RAP mixture [139,138]. Higher fracture energy was observed for RAP mixtures blended with a soft virgin binder. On the other hand, the addition of soft virgin binder led to a higher creep compliance and a decrease in rut resistance. The study concluded that in order to have a durable mixture with the addition of RAP, virgin binder content should be increased by 0.1 % for every 10 % increase in RAP binder, up to 30 % RAP binder into the new formulation mixtures. Beyond a 30 % of RAP binder content, soft virgin binder grades shall be used to provide adequate resistance to cracking [131]. The fractionation of RAP materials allows to utilize higher proportion of RAP percentage in newly formulated recycled mixtures. RAP obtained from multiple sources can be combined and blended into a virgin asphalt mixture only if the materials are uniformly processed and met the required criteria of passing the penetration and softening point test of the aged RAP binder [70,127–129,139]. A study indicated that the addition of 25 % RAP materials along with 0.26 % of glass fibre to the bituminous mixture showed good performance characteristics of the recycled mixture and the economic evaluation was carried out for the same indicated that the cost spent on paving can be saved up to 21 % [140]. A study analyzed the reclaiming of artificially aged crumb-rubber modified asphalt mixtures and recommended the optimum usage of 35 % RAP materials in new reclaimed asphalt mixes [136]. Similarly, Sharma et al 2018 [141] recommended the usage of RAP material in DBM mixes up to 35 %. Hyzl et al., [135] recommended usage of RAP in SMA (Stone Mastic Asphalt) of 30 % without any negative impacts.

In Japan, on average 47 % of RAP materials were reused for road construction purposes. As per Japanese standard, in order to use RAP materials in the surface course or binder course, the binder content of RAP materials should be at least 3.7 %, penetration value of the aged RAP binder should be a minimum of 20 dmm (deci millimeter) and the dust content in RAP material should not exceed 5 %. The RAP materials which fail the above criteria will be used in unbound base layers. The cost of utilizing rejuvenators in the reclaimed asphalt mixture was reported to be roughly the same as that of the cost of using softer virgin binder grades in the reclaimed asphalt mixture [129]. In France and Germany, in order to use RAP material in the surface course or binder course the penetration value of aged RAP binder should be greater than 5 dmm and 15 dmm respectively, and the softening point of aged binder is restricted to 77°C and 70°C respectively [142]. In Belgium, in order to use RAP material in the surface course or binder course the penetration value of aged RAP binder should be greater than 10 dmm (EN 13108–8 (2005).

Coming to the addition of RAP material in CGB mixes, the cement mortar covers the aged bituminous mixtures and prevents the secondary aging of the binder present in the mix, which ensures an increased service life. In a study micro-mechanical analysis of recycled CGB mixes was done. Four material phases namely virgin aggregate, asphalt binder, cement paste, and reclaimed aggregate were analyzed individually using a linear elastic model. From the micromechanical analysis, the study inferred that the cracking potential was higher for reclaimed aggregate

Table 5
Construction of SFP as a wearing course.

Country	Place of construction	Period of inspection	Type of SFP as a wearing course	Thickness of SFP	Performance of the pavement	Studies
United States of America (Site Inspection in 1995)	Fuel storage area, Malmstrom Air Force Base (AFB), Montana	2 years & 3 months old	Resin Modified Pavement (RMP)	N/A	No visible surface damage or structural damage in CGB mixes was observed due to fuel or oil spills. Three types of pavement cracking were observed. Interconnected and parallel cracking was seen as one type of cracking. The second type of cracking was observed along the longitudinal construction joints with a crack width of 8 mm approximately. Thermally-induced transverse cracking was observed as a third type of crack and ran along the center of the roadway.	Anderton 2000 [22]
	Storage areas at McChord AFB, Washington	4 years old	RMP	N/A	The RMP had been proven to be resistant to damage from heavy forklift movements and heavy point loads. Almost no ruts, fissures, or other surface damage were found at this location.	
	Aircraft parking aprons at Pope Air Force Base, North Carolina	17 months old	RMP in Snack bar apron	50 mm	Few hairline cracks on the surface were observed. The surface texture was found to be uniform and had adequate skid resistance.	
			RMP in Operations apron	50 mm	Reflective cracking and parallel cracking were observed along the RMP/PCC interface.	
			RMP in hanger apron	50 mm	No cracking was observed. The performance of RMP in the hangar apron was best when compared to the snack bar apron and operations apron because of the full-depth reconstruction while the other sites were only overlaid with RMP over PCC pavement.	
	Warm-up apron, Fort Campbell Army Airfield, Kentucky	3 years and 3 months old	RMP	50 mm	During the inspection, slight spalling of the joints between the RMP and PCC taxiway, and reflective cracking were observed. A single incident on skid resistance (sliding of aircraft) during a heavy rain storm was observed.	
United States of America (Testing on-field cored samples compared with laboratory-prepared CGB mixtures and BC samples)	Airfield taxiways, Altus Air Force Base, Oklahoma (1995)	24 months old when tested	RMP	50 mm	Indicated full-depth penetration of grout in all field core samples. Based on the laboratory test on the field cored samples, at low pavement temperatures, RMP seems to have roughly the same indirect tensile strength as asphalt concrete, but at moderate to high pavement temperatures, RMP had two to three times higher tensile strength than bituminous pavement. RMP also showed a decrease in tensile strength with the increase in temperature due to the temperature susceptibility of bitumen present in the CGB mixes.	
	Re-fueling pads on an airfield parking apron at McChord AFB, Washington (1996)	14 months old	RMP	40 mm		
Denmark	Copenhagen Airport	N/A	SFP (for Static load) Heavy Duty (HD) SFP (for heavy static load)	50 mm 90–100 mm	Test conducted on trial sections of CGBM indicated that the stiffness of the CGBM did not significantly depend on temperature and frequency when compared to bituminous mixtures. These experimental conclusions led to the construction of SFP & HD-SFP.In comparison to conventional concrete pavements, the advantages of HD-SFP were cost-effectiveness with savings of up to 50 %, easiness in construction, and the avoidance of reflection joints.	Mayer et al 2001 [19]
United States of America (Test sections)	Signalized intersection at Corinth, Mississippi	5 years	Ultra-thin white topping, Resin Modified Pavement,	76.2 mm, 50.8 mm,	The performance of CGBM was observed for five years on all three test sections. The ranking was given to all	Battey and Whittington (2007) [40]

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Table 5 (*continued*)

Country	Place of construction	Period of inspection	Type of SFP as a wearing course	Thickness of SFP	Performance of the pavement	Studies
			HMA with PG 82–22 polymer modified	Two layers of 50.8 mm	three test sections based on the performance of the pavement in terms of skid resistance, ease of construction, rutting, cost, IRI (international roughness index), and PCR (pavement condition rating). Among the three, RMP was ranked as the last option for usage in the surface course because of the poor skid resistance. On the other hand, RMP performed superior to other pavements in terms of rutting resistance.	
Lithuania	Experimental pavement structures - Wearing course, Vilnius City	5 years	Confalt (cement grouted bituminous mixture)	40 mm	From the performance analysis carried out over 5 years, it was observed that among the constructed (27 different types) pavement structures, confalt had the minimal rut depth and highest bearing capacity. On the other hand, longitudinal and transverse cracks appeared on the surface of the CGBM.	Vaitkus et al 2012 [124]
India (Test sections)	Accelerated pavement test facility, IIT Kharagpur	4 months	Cement Grouted Bituminous Mixtures (CGBM) – 5 test sections, Bituminous mixture (1 test section)	43 mm, 34 mm, 34 mm, 39 mm, 41.5 mm, 35 mm	At the end of 4 months of loading (10,000 load applications on both ways), no cracking was observed in any of the pavement sections. Higher resilient modulus, higher rutting resistance, and lower damage due to petroleum products were observed for CGBM test sections when compared with the test section consisting of bituminous layers. Among the 5 test sections of CGB mixtures, CGBM with lower binder content was more prone to abrasion loss.	Reddy (2016) [76]
China (Trial section)	Golden Lotus Avenue and District D of Liangli Steel City in Chengdu.	1 year	SFP (manual grouting)	40 mm	In both cases of the field-core samples, the stability and tensile strength of the SFP were higher when compared to bituminous mixtures.	An et al 2018 [73]
	Shenxianshu BRT station in Chengdu		SFP (Mechanized grouting)		Compared to CGBM with manual grouting, CGBM with mechanized grouting generated results closer to laboratory-prepared CGB mixtures.	
Singapore	Heavy loading yard (2005)	12 years	Semi-rigid pavement (SRP)	50 mm	Polymer-modified cement mortar which was used in the construction of CGB mixtures had good penetrability and adequate strength. SRP performed well irrespective of chemical/oil attacks. Even after 12 years of construction, the SRP was performing well without rutting. This indicated that SRP serves as a durable and long-lasting pavement.	Wu et al 2018 [125]
	AYE expressway (2011)	6 years	SRP	N/A	No defects were found on the surface of the SRP and all the junctions were in good operational conditions	Wu et al 2018 [125]
	Changi Airport parking aprons (2007)	13 years	SRP	50 mm	No serious defects were observed and performed well.	Y Zhang et al 2020 [37]
	Runway entry taxiways at Changi Airport (2010)	10 years	SRP (for improvement and resurfacing)	150 mm (75 mm/layer, 2 layers)		
	Bus depot of Tuas West MRT station (2015)	5 years	SRP (laid on water proofing membrane)	100 mm (50 mm/layer, 2 layers)		
India (Test sections)	Surat, Gujarat	1 year	SFP	40 mm	After a year of construction, no rutting was seen in the field section of CGB mixes. The CGBM surface was proven to have sufficient skid resistance in both dry and wet conditions.	Bharath et al 2020 [30]
India (Trial sections)	SVNIT (Sardar Vallabhbhai National Institute of Technology Surat,) Surat, Gujrat	1 year	CGBM	N/A	After one year of construction, no distresses or defects were seen on the pavement	Gupta et al 2021 [13]

compared to virgin aggregate. By the use of a modified functional rejuvenator in reclaimed CGBM, the failure tensile strain of the mixture increased which led to improved fatigue life of the reclaimed mixture. The initial failure happened in the interfacial zone of aged asphalt binder and hardened cement paste [121]. A study compared the CGB mixtures prepared using RAP material with the conventional hot mix asphalt. The usage of polycarboxylate-based admixture improved the durability of the CGB mixture. The reclaimed CGB mixtures showed greater compressive strength and higher resistance to rutting [72]. In a study, RAP material that were passing 4.75 mm sieve size were removed, and retained portions were taken for further addition in the CGB mixtures. Two kinds of micromechanical analyses were done by considering the reclaimed CGBM with and without interface. The compressive strain in the cement mortar-asphalt mastic interface was greater when compared to CGB mixtures without the interface, as in the cement mortar-asphalt mastic interface the load distribution occurred after the failure of the interface structure [123].

In a study, grouted macadam was produced by cold mix asphalt mixtures using altered aggregate or reclaimed asphalt pavement (RAP). The performance of these cold mix asphalt mixture was compared with a hot mix porous asphalt mixture containing natural aggregates. Cementitious grout and geo-polymeric grout were used as a grouting material in cold asphalt mixture and hot asphalt mixture. The Marshall stability and stiffness modulus of grouted macadam produced by cold mixture containing RAP (with cementitious grout) were lower than hot mix asphalt mixture (with cementitious grout). The compressive strength and resistance to permanent deformation were higher for grouted macadam produced by cold mixture containing RAP (with cementitious grout) when compared to cold mixture containing altered granite (with cementitious grout). Irrespective of mixtures (hot mix asphalt mixture or cold mix asphalt mixture) when compared to the geo-polymeric grout, cementitious grout showed better performance in terms of stiffness modulus, compressive strength, stability and resistance to permanent deformation [143].

9.2. Cohesion and adhesion properties of RAP in CGB mixes

A study conducted split tensile test on CGB mixtures with the inclusion of RAP materials and compared the performance of recycled CGB mixtures without a rejuvenator, reclaimed CGBM with conventional rejuvenators, and modified functional rejuvenator. The results concluded that the CGBM with a modified functional rejuvenator showed higher yield stress as the cohesion of the aged binder improved and gave rise to greater failure surface strain. This improved cohesion aided in increasing the cracking resistance of the recycled CGB mixture. As bitumen is a viscoelastic material, the failure occurred by gradually attaining excessive transverse deformation and losing the cohesive strength. During the deformation of the binder, the interface between the cement paste and the asphalt had undergone higher stress accumulation and caused early cracking in the mixture. The performance of recycled CGBM was influenced by the cohesive strength of the aged binder and the strength of the cement paste [121]. A study compared reclaimed CGB mixes with three different asphalt adhesion interfaces namely, the new aggregate-asphalt mastic interface, reclaimed aggregate-asphalt mastic interface, and cement mortar-asphalt mastic interface. The interface properties were obtained by the pull-off tensile test. Finite element analysis was done by incorporating the interface properties of the composite mixtures to identify the interfacial properties. The interface modulus of the cement mortar-asphalt mastic interface was identified as weaker when compared to other interfaces [123]. A study evaluated the work of adhesion (between the cement mortar and binder) and work of cohesion (within the blended binder (RAP and virgin binder)) in terms of surface free energy using contact angle measured with goniometer. The work of adhesion and work of cohesion decreased with the increase in RAP content. The work of cohesion within the binder was nearly twice when compared to the work of adhesion between the cement grout and binder. This indicated that the interface between the cement mortar and binder was the weakest zone for the initiation of crack in the CGB mixes when compared to the fatigue of the binder [144].

9.3. Challenges in using higher RAP content

The addition of RAP material up to 20 % into the mixes will have minimal effect on recycled asphalt mixture as the properties of virgin aggregate and virgin binder will dominate the prepared mixtures. Many state transportation agencies use RAP up to 20 % without any complication in the procedure of mix design of RAP mixtures. If the addition of RAP material in reclaimed mixes increased beyond 20 %, then the reclaimed aggregate and aged binder will start showing significant effect on the mixture depending on the percentage of RAP materials added. The reclaimed aggregate of the RAP material has lower compressive strength when compared to virgin aggregate. The behavior of the aged RAP binder will be different when compared to the virgin binder due to the aging of the RAP binder, the light fractions like maltenes would be converted by asphaltenes. Increase in the asphaltenes in the aged RAP binder will contribute to higher stiffness of the recycled asphalt mixture. At higher RAP content, the mixture exhibits brittleness which leads to premature failure of the pavement (in fatigue cracking) and increases the rehabilitation costs of the pavement. The addition of a rejuvenator or a soft-grade virgin binder to the RAP mixes will help the RAP binder to restore its properties and aids in blending. Also, with the excessive addition of a rejuvenator or soft binder, the blended binder will become over-softened and will lead to poor rut resistance of the recycled asphalt mixture [127,128,131,145]. Hence optimum dosage selection of rejuvenator is important. As the properties of RAP materials will differ for different sources, maintaining homogeneity between various stockpiles will be a cumbersome process [127,128].

The RAP material will have a higher proportion of fines due to the milling of the existing bituminous layer. When compared to a coarser proportion of RAP materials, the finer proportion of RAP material contains a higher percentage of aged RAP binder due to the larger specific surface area of fine aggregate, and the finer proportion of RAP materials will limit the maximum utilization of RAP percentage in the RAP mixes. According to the survey conducted by Ministry of Transportation of Ontario (MTO), Canada, the usage of a higher percentage of RAP in reclaimed asphalt mixtures is greater in places of base courses or light traffic roadways. Few state transportation departments did not permit the usage of RAP in surface course due to certain reasons like lack of expertise, unsatisfied past experiences and the requirement of adequate frictional characteristics of the mixture. Storing and handling of RAP stockpiles is very difficult since RAP holds higher moisture content and leads to higher fuel consumption during the production of bituminous mixtures [127,128].

The percentage of RAP in reclaimed mixtures can be increased by adopting appropriate gradation for a particular RAP source or by using a suitable RAP source for the selected gradation [70]. CGB mixtures are usually stiffer when compared to neat bituminous mixtures. The usage of RAP in CGB mixture will further increase the stiffness of the mixture leading to premature failures of the pavements and lowering the resistance to cracking. The possibility of the usage of RAP in CGB mixtures needs to be further evaluated in order to select the appropriate binder, RAP content, and type of admixture for increasing the percentage of RAP material usage.

10. Conclusions

The aim of the paper is to provide a comprehensive understanding of the materials that are used in CGB mixes, the design of porous asphalt mixtures and selection of grouting materials, mechanical properties and performance characteristics of CGBM, micromechanical analysis of CGB mixtures, the influence on the addition of RAP in the CGBM, and performance of CGBM as a wearing course in various countries. The paper provides systematic overview of the literature/research done in the domain of cement grouted bituminous mixes and semi-flexible pavements. As the entire work in the domain is presented and certain gaps are identified, the paper can show a path for future research work.

The selection of suitable aggregate gradations and the type of binder used in the porous asphalt mixture play a significant role in determining the performance of the CGB mixes. Cement, sand, fly ash, silica fume, rice husk ash, rubber powder, and various chemical admixtures are some of the materials of the grouting material that are added to enhance the properties of CGB mixture. Superplasticizers were used to increase the fluidity of the grouting material by reducing the water-cement ratio of the grouting materials. Latex was added to the grout to enhance the cracking resistance of the grouting material by providing adequate flexibility to the grout. The design of CGB mixes involves the preparation of open-graded asphalt mixtures with an air void content of 20 – 35 % and the injection of cementitious grouting material in the voids of the porous asphalt mixture. Apart from the usage of conventional cementitious grouting material in CGBM, high-performance cement paste, rubber-modified cement grout, cement asphalt emulsion paste (CAEP), polymer-modified cement mortar, and latex-modified cement mortar were used in CGB mixes for the improved performance of the grouting materials.

CGB mixtures showed superior performance in terms of higher resistance to rutting, and higher resistance to moisture damage when compared to conventional bituminous mixtures. CGBM provides adequate skid resistance and surface texture. CGB mixtures provide higher resistance to petroleum products, higher resistance on exposure to fire, and resist the attack of chemicals when compared to conventional bituminous pavements in places of slow-moving traffic/heavy stationary load like re-fuelling stations, tunnels, heavy loading yards, parking lots, and intersections. A lower fatigue resistance of CGB mixes was observed when compared to the conventional bituminous mixture due to the weak interfacial bonding between the cement grout and the asphalt mixture. The usage of cement asphalt emulsion paste (CAEP) as a grouting material in CGB mixes improved the fatigue resistance of CGB mixtures. The addition of polymer-modified cement mortar and latex-modified cement mortar in CGB mixtures outperformed conventional CGB mixtures in terms of resistance to abrasion, rutting, fatigue, and moisture damage.

Imaging techniques like scanning electron microscope (SEM), and X-ray ct scan (computed tomography) was used to understand the micro-structural behavior of CGB mixes. X-ray diffraction and FTIR were used for the identification of new crystalline compounds and the formation of new functional groups in cement asphalt mastics respectively. The micro-mechanical analysis of CGB mixtures with the addition of RAP was studied. The reclaimed aggregate had a greater potential for cracking when compared to the virgin aggregate. Also, the initial failure occurred in the interfacial zone of aged asphalt binder and hardened cement paste. The inclusion of a modified rejuvenator in the RAP mixtures combined with CGBM improved the cohesive and adhesive properties of the CGB mixtures.

The following are some of the suggestions for future research regarding the cement grouted bituminous mixes and semi-flexible pavements.

- Usage of interfacial modifiers to improve the fatigue resistance of the cement grouted bituminous mixes should be studied.
- Usage of industrial/municipal waste or byproducts as a replacement for cement in the grouting materials of CGB mixes needs to be studied. Furthermore, the effect of various aggregate shapes on CGB mixes needs to be examined.
- Feasibility of using RAP material in CGBM has to be studied in order to come up with the composition of the mixes which will perform equally or better than the conventional CGBM/bituminous mixes.
- Employing the advanced techniques like imaging techniques for the evaluation of cohesion and adhesion properties that will help in identifying the type of interfacial modifiers with scientific reasoning. Such studies have to be taken up to improve the CGB mix composition.
- Field test sections needs to be constructed and monitored for real time traffic loading and environmental conditions for the CGB mixes containing interfacial modifiers
- Life cycle analysis of the semi flexible pavements needs to be done in order to understand the overall perspective of choosing it over a rigid or flexible pavement.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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