Journal of
Engineering Sciences
Faculty of Engineering
Assiut University
مجلة
العلوم الهندسية
كلية الهندسة
جامعة أسيوط
journal homepage: http://jesaun.journals.ekb.eg

Performance evaluation of cement grouted bituminous mixtures incorporating recycled concrete aggregate (RCA) under Egyptian conditions

Received 9 August 2025; Revised 28 September 2025; Accepted 29 September 2025

Mohamed Abd El-Rahman Hafez Mohamed [1]
Sherif Masoud Ahmed El-Badawy [2]
Hassan Abd El- Zaher Hassan Mahdy[3]
Ali Zain El- Abdeen Heikal[4]

Keywords
Construction and Demolition Waste (CDW); Recycled Concrete Aggregate (RCA); Cement Grouted Bituminous Mixture (CGBM); Hamburg Wheel Tracking (HWTT); Dynamic Modulus (E*).

Abstract: The scarcity of natural aggregates, together with the growing volumes of construction and demolition waste (CDW), has intensified sustainability concerns in pavement engineering. While cement grouted bituminous mixtures (CGBM) have been investigated in many studies, most research has relied on natural aggregates, and only limited efforts have addressed the potential of using recycled concrete aggregate (RCA), especially under Egyptian conditions. CGBM is produced by filling an open-graded asphalt skeleton—typically designed with 18–35% air voids—with a specially formulated cement grout. In this work, laboratory experiments were conducted on CGBM prepared with different RCA replacement levels as substitutes for the coarse fraction of natural aggregates. Mixture proportions were established using the Marshall method, and the grout formulations were optimized based on fluidity, compressive strength, and flexural strength. The experimental program included multiple performance tests, such as drain-down, Cantabro abrasion loss, semi-circular bending (SCB), Hamburg wheel tracking (HWTT), dynamic modulus (E*), and flow number (FN). Results revealed that mixtures containing RCA generally matched or exceeded the control (0% RCA), while offering environmental and cost benefits. HWTT demonstrated enhanced rutting resistance, SCB indicated better fracture performance, and RCA incorporation increased stiffness and reduced permanent deformation in FN tests. The influence of RCA gradation was also evident. Multivariate analysis of variance (MANOVA) confirmed the significant impact of RCA content on performance. These findings support the adoption of RCA in CGBM to conserve natural resources, lower costs, and promote sustainable pavement practices consistent with international trends.

1. Introduction

Road transport represents a crucial mode of transportation worldwide. Two major types of pavements, categorized based on material composition, are commonly used in road infrastructure: flexible and

[1] Hafez_mohamed90@yahoo.com Civil Engineering (Public Works) Faculty of Engineering, Ain Shams University, Cairo, Egypt.
[2] sbadawy@mans.edu.eg Professor of Highway and Airport Engineering Faculty of Engineering, Mansoura University, Mansoura, Egypt.
[3] hassan_mahdy@eng.asu.edu.eg Professor of Highway and Airport Engineering Faculty of Engineering, Ain Shams University, Cairo, Egypt.
[4] aheikal@eng.asu.edu.eg Professor of Transportation Planning and Traffic Engineering Faculty of Engineering, Ain Shams University, Cairo, Egypt.

https://doi.org/ 10.21608/jesaun.2025.412268.1666

rigid pavements. Flexible pavements are made of bituminous materials, while rigid pavements are constructed using concrete. Flexible pavements are prone to rutting and fatigue cracking under heavy traffic loads and adverse weather conditions, leading to a shorter service life and more frequent costly maintenance. In contrast, rigid pavements offer greater durability but come with higher construction costs and require longer curing time before opening to traffic. Moreover, they often provide rougher riding quality and higher noise levels (Bonicelli et al.., 2019) [1]. To address the limitations of both flexible and rigid pavements, Semi-Flexible Pavement (SFP) has emerged as a viable pavement alternative. This composite pavement type combines the flexibility of asphalt with the rigidity of concrete, offering improved performance characteristics. SFP, which is CGBM, is manufactured by injecting a cementitious slurry into the voids of an open-graded friction course hot mix asphalt. Typically, CGBM has an air void content ranging from 18% to 35% (ASTM 7064, Kotting et al., 2014; Oliveira et al., 2007) [2-3 and 4]. Using CGBM as a surface course in semi-flexible pavements presents a promising alternative to conventional pavement structures. These mixtures provide enhanced rut resistance, higher load-bearing capacity, and extended service life. They also offer good ride quality due to the absence of joints along with low heat absorption due to their light color [5-6-7-8-9-1-10-11-12]. Due to their superior mechanical properties, CGBM-based pavements are particularly suitable for areas subjected to heavy stationery loads and harsh environmental conditions, such as tunnels, airports, and warehouses (Dhandapani & Mullapudi, 2023; Hassani et al., 2020) [13-14]. **In summary**, this research addresses a critical sustainability challenge: the depletion of natural aggregates and the management of increasing CDW. It fills an important literature gap by systematically assessing RCA within CGBM under Egyptian conditions, with the aim of identifying optimal replacement levels that balance durability, mechanical performance, and sustainability.

2. Literature review

The concept of (SFP) was first introduced in France during the 1950s as a protective measure for asphalt concrete surfaces against damage caused by waste oils and fuels (Van de Ven and Molenaar, 2004) [15]. The term semi-flexible pavement has been referred to by various researchers and developers using different names. For instance, it has been called Asphalt-Portland Cement Concrete Composite (APCCC) by Al-Qadi et al., 1994 [16], Semi-Flexible Composite Mixture by Zhang, Huang, and Goodwin (2013) [17], Semi-Rigid Pavement by Dong Qing Wu and Zhang (2011) [18], Grouted Macadam Composite Material by Hou, Xu, and Huang (2015) [19], and *CGBM* by Bharath et al. (2019) [20]. A review of previous studies identified three primary methods for determining the optimum bitumen content in these types of SPF mixtures. The first method utilizes an empirical formula that calculates the optimal asphalt content based on the specific surface area of the aggregates (Roffe et al., 1989) [21]. The second method involves laboratory tests, including porosity, Cantabro loss (Hou et al., 2016) [22], binder drainage (Koting et al., 2007; Husain et al., 2014) [23-24], and Marshall Procedure (Ling et al., 2009) [25]. The third method, employed by Bharath et al. (2019) [20], involves a drain-down test, where the optimum bitumen content is determined based on a maximum drain-down loss of 0.3%. Thus far, there are no standardized guidelines for the number of blows or gyrations required to compact bituminous mixes with high void content, leading to variations in compaction methods. Some researchers have applied different numbers of Marshall Blows (ranging from 10 to 75) on one or both faces of the specimens [26-27-16-28-24-22-29-25], while others have used a gyratory compactor [30-31]. Researchers have identified and investigated several factors that affect the performance of cementitious grouts such as the aggregate gradation, aggregate type, air void, binder type, and composition of grouting materials.

Increasing the binder content in open-graded asphalt reduces porosity, which in turn restricts grout flow (Hassani et al., 2020) [14]. The use of stiff binders, such as polymer-modified binders, enhances fatigue performance while maintaining the stiffness of CGBM compared to unmodified binders (Oliveira et al., 2006; Setyawan, 2005) [4-32].

Aggregate gradation and type play a crucial role in asphalt mixtures, as they affect the total void volume, which in turn influences mechanical properties such as stability and durability. A review of previous studies identified two main types of blended aggregate gradations used in porous asphalt mixtures. One type has a higher proportion of fine aggregates (less than 4.75 mm) (Sun et al., 2018) [33], while the other uses a higher percentage of coarse aggregates (Setyawan, 2013) [34]. Additionally, various gradation categories are used as per ASTM 7064[2], or single-sized aggregates can be employed (Ding et al., 2011) [35]. The gradation of aggregates in porous asphalt mixes depends on the desired air void content, which typically ranges from 20-30% (Sunil S and Kumar, 2020) [36], 25-32% (Husain et al., 2010, 2014) [28-24], or 18-22% (Alvarez et al., 2010) [37]. Values above 18% are generally considered suitable for grouting purposes. Key factors influencing aggregate gradation selection include the air void ratio and the internal connectivity between voids, which allows the grouting material to flow and penetrate effectively (Setyawan, 2013) [34].

Taghipoor et al. (2024) [5] prepared open-graded asphalt (OGA) mixtures using various gradations, air void contents, fibers, and asphalt binders, and conducted tests such as binder drainage, SCB, Cantabria, HWTT, and indirect tensile strength (ITS). The results showed that SFP had superior resistance to rutting, skid, fire, and moisture damage compared to hot mix asphalt (HMA), which performed better in fracture tests. Overall, SFP mixtures offer a durable alternative to traditional pavements due to their excellent resistance to rutting, moisture, fatigue, fire, and skid [22-38 and 9].

Zhong et al., 2020 [39]. Studied the behavior of grouted open-graded asphalt concrete (GOAC) when combined with latex-modified cement mortar (LCM). They evaluated the fluidity, flexural, and compressive strengths of LCM at different latex dosages, identifying 1.2% as the most effective level. Pull-out and shear evaluations were carried out on the interfaces between LCM-matrix asphalt concrete (MAC) and cement-MAC systems. The findings revealed that incorporating latex enhanced the strength of the cement mortar but led to reduced workability. GOAC exhibited excellent high-temperature stability, strong resistance to moisture, and improved fatigue performance compared with dense asphalt mixtures, although it showed a greater tendency toward brittle cracking. **Wang et al., 2018** [40] incorporated carboxyl latex into the cement grout while applying a warm-mix method to the open-graded asphalt mixture. The modified SFPs were examined through a series of performance tests and contrasted with the unmodified mixtures. The results revealed that carboxyl latex markedly improved rutting resistance and extended fatigue performance. Recent research has also explored methods to enhance the interface between the porous asphalt skeleton and the cement grout. **Xiaoyu et al. (2025)** [41] introduced an interfacial immersion technique using silane coupling agents (SCA) to treat porous asphalt mixtures before grouting. Their results demonstrated notable improvements in dynamic modulus and fracture resistance, particularly for mixes with medium-strength grout. This method enhances the adhesion between the cement grout and asphalt skeleton, thereby reducing brittleness and improving durability.

Additionally, many studies have focused on grouting material formulations [42-43-44-31-45-46-39]. Results indicated that SFPs offer superior performance in terms of anti-rutting and moisture stability compared to conventional asphalt pavements. Higher air void content in OGA mixtures leads to a longer fatigue life (Hou et al., 2016; Yang and Weng, 2015) [22-47] and enhances SFP's resistance to low-temperature cracking compared to traditional asphalt concrete (Ding et al., 2011) [35]. However, the brittleness of the grouting material in SFPs should be considered, as it may increase the likelihood of cracking at low temperatures.

Dhandapani &Mullapudi, 2024 [48]. Focused on evaluating the mechanical properties of CGBM-RAP mixtures (0%, 20%, 35%, and 50%) and comparing them to bituminous concrete (BC) mixes. It was found that permeability decreased with higher Reclaimed asphalt pavement (RAP) content, which hindered complete grout penetration. Grout penetration tests were used to determine the most suitable cement grout. CGBM–RAP mixtures exhibited superior mechanical properties and lower temperature sensitivity compared with CGBM without RAP and conventional bituminous mixtures, due to the increased stiffness from the combined binder and cement grout. The physical properties of the blended binders were closely related to the mechanical performance of CGBM. **Afonso et al. (2016)** [49] evaluated grouted macadam using cold mix asphalt with modified aggregates or RAP, comparing it to hot mix asphalt with natural aggregates. Cementitious grout demonstrated superior mechanical properties, while incorporating 30% milled glass and waste mud further improved performance. Cold mixes also offered benefits such as easier mixing, faster installation, energy efficiency, and lower emissions. **Xie et al. (2021)** [50] studied foamed warm-mix semi-flexible pavement with varying RAP content (0–60%), finding that increased RAP reduced rutting and moisture resistance but improved fatigue and low-temperature cracking resistance. **Zhao and Yang (2023)** [51] compared SFP with and without RAP, concluding that warm mix reclaimed SFP had lower performance in rutting, fatigue, and moisture resistance while also increasing environmental impact and energy consumption. (RAP) properties vary based on source, making it difficult to maintain uniformity across stockpiles. Furthermore, RAP has high moisture content, which complicates storage and handling while increasing fuel consumption during bituminous mixture production (Copeland et al., 2011) [52]. In terms of RAP usage, adding up to 20% has minimal impact as virgin aggregate and binder dominate the mix. However, when RAP content exceeds 20%, the aged binder and reclaimed aggregate significantly affect mix properties, increasing brittleness and fatigue cracking, ultimately raising pavement rehabilitation costs (Zaumanis et al., 2015) [53].

Al-nawasir et al., 2024 [54]. Examined the rutting behavior and moisture resistance of SFP containing ceramic waste powder (CWP) as a sustainable grout. CWP was used as a partial replacement for cement in SFP, with replacement ratios of 15%, 20%, 30%, 40%, and 50%. The performance of SFP was evaluated using ITS and HWTT to assess moisture-related effects. The CWP-modified grout showed excellent results in IT'S and Tensile Strength Ratio (TSR), with higher values compared to the Control Mix (CM). The HWTT results showed that rutting was reduced by 73%-76% for CWP mixes with 20% and 30% replacement, indicating that CWP's high fluidity allowed it to penetrate voids in the porous pavement, forming a dense structure capable of withstanding rutting due to its strong pozzolanic properties.

Zacharia et al. (2020) [55] analyzed how variations in air void levels, water–cement ratios, and aggregate types affect the behavior of cement-grouted macadam mixtures. The materials included crushed natural stone, high-grade brick, and overburnt brick aggregates, tested under three air void conditions (18%, 21%, and 24%) and three different water–cement ratios (0.5, 0.6, and 0.7). The findings indicated that mixes containing 24% voids achieved the best performance, followed by those with 21% and then 18%. In particular, the grouted macadam showed reductions in rut depth up to

35.3% and a 144.5% gain in fatigue life, while also lowering susceptibility to moisture damage compared with traditional mixes.

Bharath et al. (2019) [20]. Developed and evaluated CGBM in both laboratory and field settings, comparing it with conventional dense-graded Bituminous Concrete (BC). The study assessed properties like ITS, Resilient Modulus, and Dynamic Modulus at different temperatures, as well as performance characteristics such as rutting, fracture energy, moisture resistance, oil spillage, and durability. A CGBM test section was laid on-site for performance monitoring. Results indicated that CGBM outperforms conventional bituminous mixes in ITS, Resilient Modulus, Dynamic Modulus, and rutting resistance, though it showed slight reductions in durability and crack resistance due to brittleness. CGBM surpassed conventional bituminous mixes in terms of ITS, Resilient Modulus, Dynamic Modulus, and rutting resistance. However, it exhibited minor drawbacks in durability and crack resistance, largely attributed to its inherent brittleness. The mixes demonstrated stronger resistance to moisture and diesel exposure, and they showed lower sensitivity to temperature variations. Field core samples confirmed that complete grout penetration had been achieved, and Micro-Computed Tomography (Micro-CT) was used to evaluate the connectivity and distribution of air voids within the CGBM structure.

Cai et al. (2019) [56]. Investigated the reinforcing mechanisms of (SFP), modeled as a double-skeleton structure composed of open-graded asphalt and cement grout. Using the Mori-Tanaka (M-T) model, they identified three key mechanisms: matrix modulus, cement filling effect, and the interlock between the two structures. The study revealed that the reinforcing rate increased with porosity, while the dynamic modulus was more influenced by matrix gradation than by porosity. Additionally, the grouting cement had a negative impact on the loss modulus at high frequencies.

Othman et al. (2020) [57] investigated a new asphalt mixture with reduced asphalt content and enhanced rut resistance for heavy-load areas. Grouting was applied to open-graded asphalt mixtures to create (SFP). Various compaction efforts were used to achieve the necessary air voids, and the mixtures were made with crushed silica limestone, sand, and filler to improve permeability. Asphalt content was determined theoretically and verified through laboratory testing. Marshall Molds were grouted with a mixture of ordinary Portland cement (OPC) and additives. The results showed that grouting reduced bitumen content by 27%-37% and increased rut resistance, stability, and indirect tensile strength by up to three times compared to conventional mixtures. Similarly, **Al-Taher et al. (2015)** [58] focused on developing a semi-flexible mix with lower asphalt content and higher rut resistance. Grouting with OPC and OPC-silica sand mixtures reduced asphalt content by 35%-44% and improved rut resistance and stability by up to three times compared to traditional asphalt mixtures. **Sanad (2022)** [59] evaluated semi-flexible warm asphalt mixtures with high cement mortar and low asphalt content. The grouting process, using a mixture of Portland cement, water, and sand, reduced asphalt content by 52.7%-63.4%, enhancing stability. At high temperatures, the mixture saved 12.5%-16% asphalt and exhibited 3-4 times greater stability. However, it performed 55.5% worse at low temperatures. The material properties were significantly influenced by the gradation. **The previous three studies** did not examine the effect of varying bitumen ratios on the structure of different gradations. While they focused on the injection material, they did not assess the impact on the asphalt structure itself. This was evident in their use of the Marshall method, injecting samples prior to demolding, and applying varying compaction energies (0, 10, 20, and 30). The samples were treated like concrete in terms of preparation, curing, and processing, with the bitumen content theoretically determined and visually inspected in the lab. However, the properties and performance of the open-graded asphalt mix skeleton, particularly its porous structure with a void ratio of 30-40%, have not been explored and require further investigation.

Globally, (CDW) mainly arise from the construction of new structures or the demolition of existing structures. This waste includes various materials such as building components, asphalt, bricks, aggregates, concrete blocks, debris, wood, metals, gypsum, and plastics (Azam et al., 2024; Pasandín and Pérez, 2015) [60-61]. Among these, aggregates, concrete blocks, and clay bricks are increasingly being reused in paving applications. Many aggregates from CDW contain a substantial amount of broken concrete blocks, which vary in physical and mechanical properties based on their source. Managing these large volumes of waste is a challenge due to the scarcity of public landfills and high transportation costs (Jin and Qian, 2015; Oikonomou, Nik. D, 2005) [62-63].

The use of (CDW) as aggregates in (RCA) was first implemented during and after World War II to manage the vast amounts of rubble and debris, particularly in the United Kingdom and Germany **(Wang et al., 2021)** [64].Several studies have investigated the use of recycled concrete aggregates (RCA) as a partial or complete replacement for natural crushed stone in pavement applications [60-65-66-67-68-69-70-71]. RCA has also been explored in asphalt mixtures (cold, hot, or warm) and concrete paving [68-72]. Laboratory tests on asphalt pavements containing RCA include Marshall Tests, IDT, stiffness modulus, fatigue tests, and dynamic modulus (E*). Aytekin and Mardani (2022) and **El-Badawy et al. (2018)** [73] reported that construction and demolition waste (CDW) materials, including RCA, exhibit geotechnical properties comparable to or even better than conventional aggregates. Moreover, RCA has been proven to be suitable as an unbound granular material in pavement foundations, specifically within the base and subbase courses [69-74-75].

Several studies have explored the use of (RCA) in hot mix asphalt (HMA). **Al-Bayati (2024)** [76] found that higher RCA content increased Marshall stability and asphalt demand, with 100% RCA requiring 10.55% more asphalt and 60% RCA achieving the highest stability. Nazal and Ismael (2019) [77] reported that asphalt content peaked at 4.5% for 100% RCA, with 30% RCA was identified as optimal for moisture resistance. El-Tahan et al. (2018) [68] noted that RCA had lower bulk specific gravity and higher water absorption, leading to the use of coarse RCA. Al-Bayati et al. (2018) [78] confirmed that 0–60% coarse RCA met Ontario Ministry of Transportation standards, while Perez and Pasandín (2017) [79] observed that RCA content (0–42%) increased asphalt demand but maintained good fatigue performance. **Razzaq (2016)** [80] found that RCA content up to 58% met stability and strength requirements for varying traffic volumes. Gul and Guler (2014) [81] highlighted that aggregate gradation had a greater impact on resistance to permanent deformation compared to the RCA content. Overall, optimal RCA replacement in HMA ranges from 10% to 50%, as suggested by previous studies [82-83].

El-Tahan et al. (2024) [72] examined the use of (RCA) as a substitute for natural coarse aggregates in warm-mix asphalt (WMA) using wet (adding Sasobit to the asphalt binder) and dry (adding Asphamin to the aggregate) production methods. Nano silica fume (NSF) was tested as an additive, improving stability by up to 35% and enhancing the TSR to meet Egyptian standards. Although WMA showed lower (E*) and (FN) than hot-mix asphalt (HMA), NSF significantly improved these properties, surpassing HMA performance. Covilla-Varela et al. (2023) [84] found that RCA replacement rates of 15%, 30%, and 45%. Reduced environmental impact by lowering natural aggregate consumption and mixing temperatures, though higher RCA content required more asphalt. Martinho et al. (2018) [85] showed that WMA with 60% RCA outperformed HMA, but the use of Sasobit and Reediest as additives reduced rutting resistance and increased moisture sensitivity.

Overall, RCA performed similarly in both WMA and HMA, with WMA requiring extra drying of RCA to address moisture sensitivity issues (Martinho et al., 2012) [86].

Kodekal and Nagakumar (2019) [87] explored the use of (CDW) aggregates (incorporated at 20%, 30%, and 40%) combined with fresh aggregates in an open-graded asphalt mix with 20-30% air voids. The mix was combined with cement grout to enhance the performance of semi-rigid pavements. The study involved selecting suitable gradations and designing cement mortar for fluidity and strength. Performance was evaluated through IDT, rutting, and fatigue tests at various binder contents over 1, 7, and 28 days. The findings showed that incorporating 30% recycled aggregate improved rutting and fatigue resistance, presenting an eco-friendly pavement solution.

The literature studies have shown that the properties of RCA can vary based on its source, highlighting the importance of studying RCA at the local level to avoid inconsistencies in results. However, several challenges hinder their widespread use, including resistance from industry professionals, a shortage of trained technicians, inadequate guidelines for proper waste collection and separation, and a lack of standards and long-term performance data.

A review of the relevant literature indicates that most of the literature studies have focused on CGBM with natural aggregates, with only a few studies incorporating recycled asphalt pavement (RAP) and an even smaller number investigating RCA. Additionally, the percentages of RCA used in these studies are limited.

In summary, previous studies confirm that (RCA) can serve as a sustainable substitute for (NA) in both unbound pavement layers and asphalt mixtures such as CMA, HMA, and WMA. Nevertheless, the properties of RCA play a decisive role in determining the overall quality of the final mixture. Furthermore, its elevated absorption capacity often increases asphalt demand, thereby lowering the effective binder content and raising the overall cost.

Despite the extensive body of research on (SFPs), few investigations have addressed the incorporation of RCA into (CGBM). Studies targeting SFPs under Egyptian conditions are especially scarce, and the role of RCA within asphalt mixtures—particularly in this type of pavement—remains insufficiently explored. Additionally, Egypt is experiencing significant growth in its road network, creating a high demand for construction materials, particularly aggregates. The production of these materials presents both economic and environmental challenges, especially as the country relies heavily on land transportation and faces various issues within its road network. These include high truck traffic volumes and overloading, which lead to pavement distresses such as fatigue cracking and asphalt rutting (Al-Taher et al., 2015; Mohammed et al., 2018) [58-88], reported that the use of RCA can negatively affect pavement performance and longevity. Accordingly, the present study aims to examine semi-flexible pavements injected with cement mortar as a sustainable alternative to conventional asphalt pavements, incorporating RCA. The feasibility and potential application of this approach are evaluated under Egyptian conditions.

3. Materials

a. Aggregates

The natural aggregate (NA) used in this study was crushed limestone sourced from the El Saf quarry in Giza, Egypt, conforming to the Egyptian Code of Practice specifications for road construction. The

RCA was obtained from a demolished building in District 8, Nasr City, Cairo, Egypt (Fig1). The RCA was washed, crushed in the laboratory to a nominal maximum size of 12 mm and sieved into five fractions. The preparation followed the Egyptian Code of Practice (ECP 2020) [89] standards to ensure it meets the gradation requirements in this study. The physical properties of aggregates are listed in Table 1 along with the allowable specification limits. All properties were found to comply with the specified limits, except for the absorption and liquid limit of the fine RCA, which exceeded the acceptable thresholds. These findings are consistent with observations reported in previous literature, highlighting the high absorption characteristics of fine RCA [90-91and 68]. The nominal maximum size was selected in accordance with ECP (2020), relevant ASTM standards, and consistent with previous CGBM studies to ensure uniformity in the skeleton design. Permeability tests further confirmed that the designed open-graded mixtures achieved the target porosity range (18–24%), thereby confirming adequate connected voids for grout penetration.

a) RCA before crushing

b) RCA after Crushing

Fig. 1: RCA before and after the Crushing Process.

Table 1: Physical and mechanical Properties of Natural Aggregate and RCA

Properties	NA (Limestone)	RCA	Specification Limits (ECP-2020)
Bulk specific gravity (Coarse Aggregate) gm/cm3	2.560	2.390	----
Saturated Surface Dry (SSD) Specific Gravity (Coarse Aggregate) gm/cm^3	2.616	2.480	----
Apparent Specific Gravity (Coarse Aggregate) gm/cm3	2.712	2.626	----
Absorption (Coarse Aggregate) %	2.2	5.2	5% max
Fragmentation	0.53	1.32	2% max
Los Angeles abrasion, %	22.8	32.6	40% max
Flat and elongated particles, %	2.5	1.3	10% max
Angularity	96	91	
Bulk specific gravity (Fine Aggregate), gm/cm3	2.545	1.952	
SSD Specific Gravity (Fine Aggregate), gm/cm3	2.582	2.156	
Apparent Specific Gravity (Fine Aggregate), gm/cm3	2.643	2.452	
Absorption (Fine Aggregate) %	1.468	10.43	5 % max
Plasticity index (%)	Non-plastic	Non-plastic	Non-plastic Up to 6% max
Liquid limit (%) Liquid limit (FA)	19.9	38.5	25% max

b. Binder

For preparation of the asphalt mixes, the typical 60/70 penetration grade bitumen was used. It was obtained from Alexandria Petroleum Company (APC), Alexandria, Egypt. The physical properties of the binder are summarized in Table 2.

Table 2: Physical Properties of bitumen

Property	Value	Specification Limits (ECP-2020)
Penetration (25C,100 gm,5 sec)	63	60-70
Rotational viscosity, (cst/s) **135ºC** **150ºC** **165ºC**	 370 291 202	≥ 320 (cst/s) Minimum at 135 °C
Softening point (ring and ball), ºC	50	45-55 °C
Specific gravity at 25° C	1.02	1.00–1.05

c. Grout materials

The materials utilized in this study the grouting material consisted of 42.5-grade OPC, fine sand, and tap water. Several studies used OPC and inferred that OPC provided adequate fluidity and satisfied the strength requirement (Bharath et al., 2019; Dhandapani & Mullapudi, 2023; Gupta & Kumar, 2021; Hassani et al., 2020) [20-13-92-14]. The natural sand used passed entirely through the standard US sieve No. 30 (0.6 mm) to ensure easy penetration into the voids of the porous asphalt mixture. Research studies reported that the use of fine sand aided the complete penetration of the grout throughout the specimen (Luo et al., 2020) [93]. The particle size distribution of the natural sand along with the specification limits as per the ASTM C778 [94] is shown in Fig 2.

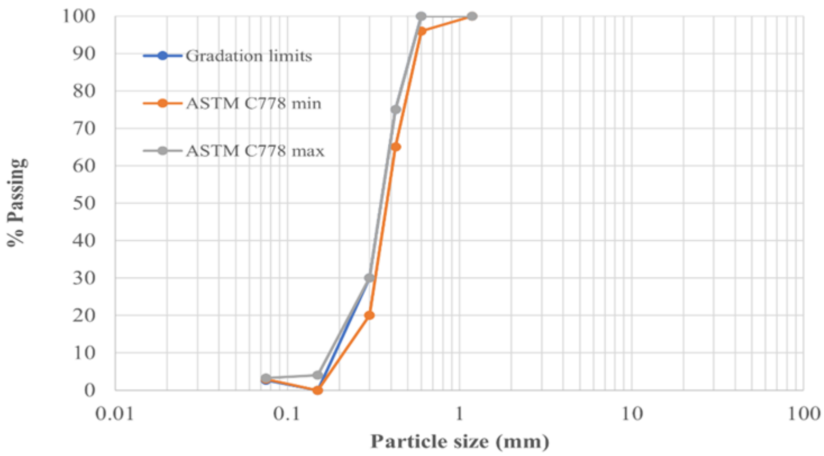


Fig. 2: Gradation used in cement grout mixture according to ASTM Specification.

4. Research Methodology and Experimental Work

The methodology adopted in this study, along with the experimental design, is shown in Figure 3. The routine properties of the materials were first determined in the laboratory. Then, five different CGBM were designed using the classical Marshall method. The design process involved two phases. First, open-graded asphalt mixtures were produced with a minimum air void content of 18%. In the subsequent stage, cement-based grout was introduced into the porous asphalt skeleton. were then applied to penetrate and fill the interconnected voids of the porous asphalt mix under gravity flow. Two types of mixtures were prepared: one using 100% (NA) and the other using 100% (RCA) for the coarse aggregate fraction. Additionally, three other mixes were designed by partially replacing the coarse NA with RCA at proportions of 25%, 50%, and 75%, while maintaining 100% NA for the fine aggregate in all prepared mixes. Fine aggregates are defined as those passing through the U.S. Standard Sieve No. 4 and retained on Sieve No. 200. RCA was incorporated only in the coarse fraction, as the fine RCA exhibited high absorption.

The evaluated mixture properties included drain-down and permeability before grouting, as well as Marshall volumetric properties, Marshall stability/flow, and Cantabro loss before and after grouting. Furthermore, advanced performance testing was conducted after grouting, including semi-circular bending (SC) to assess fracture resistance, (HWT) to evaluate rutting, (E*) to evaluate mixture stiffness and viscoelastic behavior of the mixtures, and (FN) to evaluate rutting resistance under repeated loading.

Finally, to statistically assess the effect of the cement grout on performance, analyses including using Multivariate Analysis of Variance tests were performed using SPSS**.**

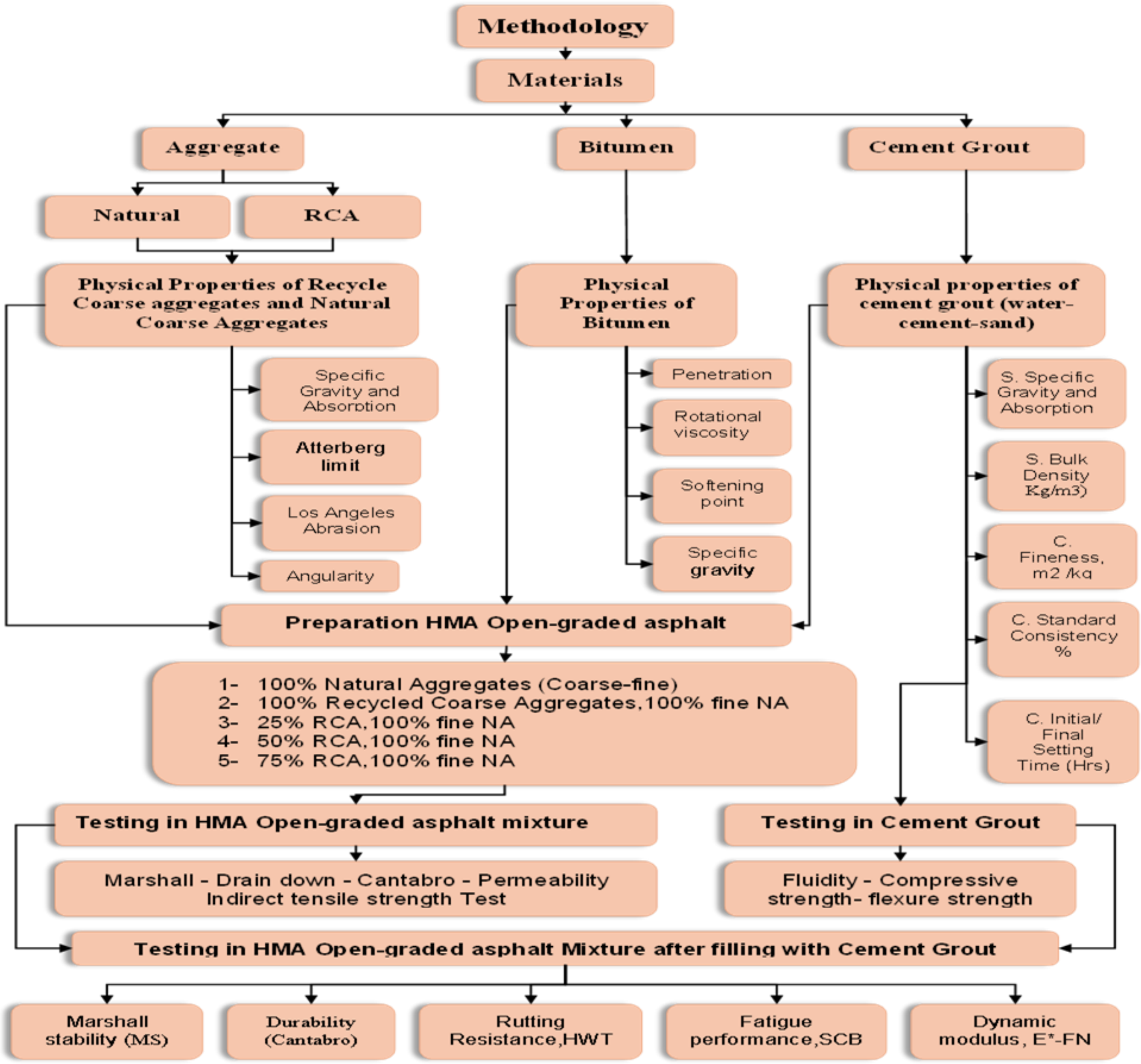


Fig. 3: Outline of experimental work

a. Preparation of porous asphalt mix skeleton

The proportion of air voids in compacted asphalt mixtures is strongly influenced by aggregate gradation. For CGBM, open-graded mixtures are typically recommended, targeting an air void range between (Sunil and Kumar,2020; ASTM7064) [36-2]. The optimal aggregate gradation that achieves the highest void content was selected. The volumetric properties of Gr-I, Gr-II, and Gr-III were analyzed according to ASTM D7064 [2] at a binder content (B.C) of 6%. The study was conducted using five different types of CGBM, each evaluated at the three gradations to identify the best gradation. Fig 4. Shows the gradation size distribution curves for the open graded asphalt mixtures according to ASTM Specification.

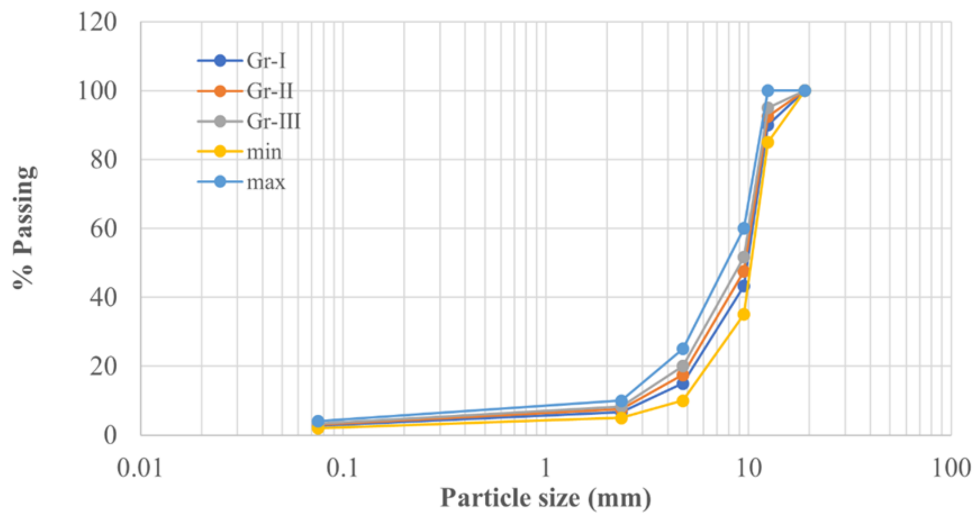


Fig. 4: Gradation curve for open grade asphalt mixture according to ASTM Specification

b. Grout mix design

Cementitious grout plays a vital role in semi-flexible pavement systems by effectively filling and bonding the interconnected voids within the open-graded asphalt matrix (Sunil and Kumar, 2020) [36]. Cement grout is usually designed to ensure adequate flow into the interconnected voids of porous asphalt. Portland cement serves as the primary constituent of the grout. Its workability is evaluated through the fluidity test, while compressive and flexural strengths are determined following ASTM C39/C39M and ASTM C293/C293M [95-96], respectively. Several grouts with varying mass percentages were prepared, using a cement grout ratio of 1.0:0.2:0.6 for cement, sand, and water, respectively, and tested for fluidity, compressive strength, and flexural strength. The test results showed fluidity, compressive strength, and flexural strength values of 12, 17.2 MPa, and 4.3 MPa, respectively. The material proportions and grout design results in this study are consistent with those reported by [97-98-99-100-47-16].

c. Specimen preparation and determination of OBC

In preparing the cylindrical reference samples which contain 100% NA (0%RCA) and the samples which contain (25, 50, 75) % RCA as NA and 100 % RCA for open-graded, Specimens with dimensions of 101.6 mm in diameter and 63.5 mm in height were compacted with 75 blows on each face using a Marshall compactor. After molding, volumetric analysis was carried out to evaluate the characteristics of the mixtures

Determination of the optimal bitumen content was carried out through (i) volumetric evaluation of the mix, (ii) drain down, (iii) permeability, and (iv) Abrasion loss from the prepared open graded bituminous mix samples. All samples are compacted mixes except the drain down sample. Initially, the Optimum Bitumen Content (OBC) was determined by volumetric analysis and then validated through a series of laboratory tests on the investigated open graded bituminous mixtures.

(i) Volumetric evaluation of the mix: generally, require a lower binder content compared to conventional mixes dense mixtures. Bituminous mixtures were prepared with different binder contents ranging from 3.5% to 6.0% by increments of 0.5%. Based on volumetric relationships, OBC was calculated as the average of three bitumen contents, for each gradation from three gradation (Gr-I, Gr-II, Gr-III) as per ASTM 7064[2], which corresponds to maximum stability, maximum unit weight, and a target air voids content.

(ii) Drain down test, in accordance with ASTM D6390 [101], measures the amount of mixture that escapes from the wire basket, which may consist of a binder or fine aggregate. The test procedure involves placing the sample after preparing the specimen was placed in a wire basket, which was set on a pre-weighed plate or other suitable container. The basket, plate, and sample were then kept in a forced-draft oven at 150 °C for one hour. After heating, both the basket with the specimen and the plate or container were removed, and the mass of the plate or container was recorded. including any drained material, is then measured. To ensure the stability of open-graded asphalt (OGA) mixtures, the maximum permissible drain-down should not exceed 0.3% of the total mixture mass as specified by ASTM D7064[2].

(iii) Permeability Test: Permeability was evaluated using a constant head permeameter test, following the guidelines outlined in BS EN 12697-19 [102]. According to previous studies (Saboo et al., 2019) [38] and ASTM D7064 [2], the permeability value should exceed 100 m/day. The test was conducted on the open-graded bituminous mixtures with varying percentages of RCA content (0%, 25%, 50%, 75%, and 100%), as these mixtures facilitate the movement of water through air voids when grouting materials are introduced.

The test procedure, as illustrated in Fig 6, involves sealing the sample with plastic or duct tape to prevent water leakage. Water is introduced from the top of the sample and allowed to exit from the bottom. A standpipe is connected to the system with silicone gel to ensure a tight seal and prevent leaks. The time required for the water level (with a volume of 1735 cm^3) to rise from height h_1 to height h_2 is measured. Based on this data, the permeability of the material is then determined.

(a) (b) (c) (d)

Fig. 6: Permeability test procedure: (a) Schematic of the permeability apparatus Saboo et al., 2019[38] b) permeability apparatus; c) test sample preparation); d) conduct test by monitoring water flow through the specimen.

(iv) Cantabro test was conducted on compacted open-graded friction course specimens to assess their resistance to abrasion loss. The test follows the guidelines of ASTM C131 [103] and AASHTO TP 108-14 [104], using the Los Angeles abrasion machine to measure both abrasion and impact resistance. This test evaluates the abrasion and raveling resistance of porous asphalt samples. According to ASTM D7064 [2], the Cantabro abrasion loss should be less than 20%. The experiment was conducted at 25 ± 5 °C, where each specimen underwent 300 revolutions in the Los Angeles abrasion machine at a speed of 30–33 rpm, performed without steel balls. The samples were weighed before and after testing to calculate the percentage of mass loss.

d. Preparation of CGBM samples

The preparation of CGBM samples began by uniformly filling the Marshall molds with hot bituminous mix, designed with open-graded aggregates, target air voids, and the optimum bitumen content. The mix was then compacted using the appropriate method to achieve optimum density. For open-graded asphalt mixtures before grouting, the Marshall method was applied, with 75 blows on each side to simulate heavy traffic conditions, following previous studies (Zhang et al., 2019) and ECP (2020) [99-89] guidelines. For (CGBM) performance tests, specimens were compacted using a Superpave Gyratory Compactor (SGC), with the number of gyrations (ranging from 45–75 or 75–125) determined through trial and error. Cylindrical porous asphalt specimens were prepared with dimensions of 150 mm × 170 mm for (E*) and (FN) tests, and 150 mm × 63.5 mm for moisture susceptibility (MS), Cantabro loss, (HWT), and (SCB) tests, in accordance with each test's requirements. Once the temperature of the compacted mix reached ambient level or after 24 hours, the porous asphalt mix was demolded, and cementitious grout was poured on the surface to penetrate under gravity, ensuring that the specimens remained nearly free of entrapped air. To avoid any grout leakage from the molds, the corners and edges were sealed from the outside. The porous asphalt skeletons were prepared with a target air-void content of 18–24% prior to grouting. Following injection, post-grout voids were minimized by ensuring complete saturation of the skeleton, and grout penetration was verified through visual inspection of cut specimens, confirming full filling of interconnected voids. All grouted specimens were cured at room temperature (~25 °C) with continuous water spraying to maintain relative humidity above 95%. Mechanical testing, including (E*) and (FN), was carried out at 1, 3, and 7 days to capture the effect of grout hydration on mechanical performance. It should be noted that while the air-void percentage (%AV) was used as a control parameter, groutability depends not only on %AV but also on void connectivity and permeability. Although connectivity indices were not directly measured, their influence was indirectly captured through the performance tests, which reflect the role of pore structure and grout absorption in the mechanical behavior of the mixtures.

e. Laboratory testing

The adequacy of the grout material was assessed based on two primary the evaluation criteria included complete grout penetration through the specimen and adequate compressive strength. Full-depth penetration was directly linked to the grout's flowability or workability, which was assessed using a flow cone test in accordance with ASTM C939 [105]. For compressive and flexural strength evaluation, samples were tested at various water content levels and curing periods of 1, 3, and 7 days according to ASTM C39/C39M and ASTM C293/C293M [95-96], respectively. This analysis was conducted to determine the optimal water content for grout mixing, which would ensure both full-depth grout penetration and sufficient strength of the grout material.

MS test: Marshall stability was determined according to ASTM D 6927–15 [106] guidelines. Marshall stability represents stability and total deformation (flow) of the CGBM mixtures. The Drain-down test, permeability, and Cantabro test are important to assess the characteristics of OGA mixtures used in CGBM. The details of these tests have been thoroughly discussed in the previous sections.

HWTT: The rutting resistance of the CGBM was evaluated using the HWT, in accordance with AASHTO T 324-11 (2015) [107]. Cylindrical specimens (150 mm diameter × 60 mm height) with an air void content of 18% - 24% were compacted using a gyratory compactor to meet the criteria established for this study. The test was conducted at 40 ± 2°C Cin a water bath. This temperature was selected because it falls within the permissible range of AASHTO T 324 (25–70 °C) and has been recommended by FHWA/TX-05/0-1707-7 (Yetkin et al., 2007) [108] to represent realistic pavement service conditions. Previous studies have also shown that rutting performance at 40 °C reflects stiffer binder behavior and provides a conservative estimate for service conditions in Egypt. A 700 N steel wheel load applied to the sample at a rate of 52 passes per minute.

To calculate the rutting depth, three measurements of the wheel impression (rut) were taken at 5000-pass intervals (at the midpoint, start, and end of the track) using a graduated ruler, and the average values were recorded. The failure criteria for the test were set to either 20,000 repetitions or 12.5 mm of permanent deformation, whichever occurred first. The HWT setup and specimens are shown in Fig 7.

(a) (b) (c) (d) (e)

Fig. 7: HWTT: a) specimens after curing, b) Specimen being cut along edge of the mold using saw, c) Vertical-cut specimens, d) Specimens placed in molds and fixed, ready for testing, e) measurement rut depth

SCB: The SCB test was conducted according to ASTM D8044 [109], to assess the fracture durability of the mixture using fracture mechanics principles. SCB specimens (150 mm radius, 57 mm thickness) with notches of 25, 32, and 38 mm were loaded at a constant displacement rate of 0.5 mm/min at room temperature until failure. The specimens were subjected to three-point bending, with the notches aligned with the loading axis. Sample preparation for the SCB test is shown in Fig 8. As the load increased, cracks started at the notch tip, followed by a drop in load after reaching the peak.

(a) (b) (c) (d)

Fig. 8: SCB test at an intermediate temperature of 25C; a) after curing Cut specimen along the center diameter into two semi- circular specimens with notch; b) cut SCB samples with three notch depths; c) sample preparing for SCB test; d) sample after test

E* and FN tests:

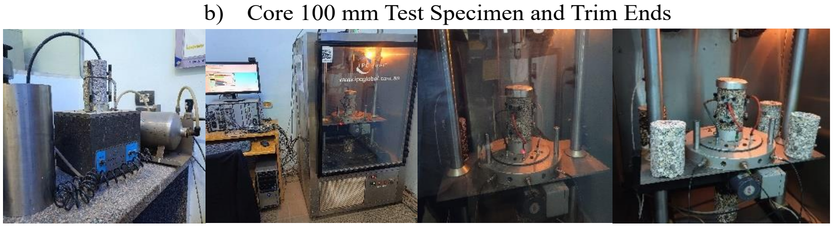
The E* and FN tests are essential for evaluating the performance characteristics of asphalt mixtures. (E*) reflects the stiffness of the mixture under cyclic loading, which is a critical parameter in mechanistic-empirical pavement design. (FN) indicates the mixture's resistance to permanent deformation, providing insight into rutting potential under repeated loads.

In this study, the tests were conducted using the UTM-25 machine in accordance with AASHTO T 378 for (E*) and AASHTO T 342 for FN [110-111]. As shown in Figure 9, the setup includes sample preparation, temperature conditioning, and axial cyclic loading. **(E*) testing** was performed in the strain-controlled mode with a strain amplitude of 50–80 με to ensure that specimens remained within the linear viscoelastic (LVE) range. Axial deformations were measured using three LVDTs mounted on the specimen surface to minimize end effects. (E*) testing was performed at four temperatures—4.4°C, 21.1°C, 37.8°C, and 54.4°C—and six loading frequencies: 25, 10, 5, 1, 0.5, and 0.1 Hz, in line with AASHTO protocols. This range simulates various climate and traffic conditions to characterize the viscoelastic (CGBM). Master curves of (E*) and phase angle (δ) were then developed to comprehensively characterize the viscoelastic response of the mixtures.

(FN) test was performed using the UTM-25 machine in accordance with AASHTO T 342. The test was stress-controlled with a deviator stress of 600 kPa and applied haversine loading (0.1 s load, 0.9 s rest, 1 Hz) under unconfined conditions (confining pressure = 0). (FN) test was carried out at a fixed temperature of 54.4°C, representing a severe loading and thermal condition to assess rutting susceptibility. The FN was identified at the point of minimum permanent strain rate, corresponding to the onset of tertiary flow.

a) Prepare Gyratory Specimen

b) Core 100 mm Test Specimen and Trim Ends



c) Testing Specimens Preparation

Fig. 9: Major Steps and Procedure in UTM-25

5. Results and discussion

a. Suitability of grout materials

To evaluate its performance in (CGBM), a series of laboratory tests were conducted to assess its key engineering properties, including fluidity, compressive strength, and flexural tensile strength, as presented in Table 3.

Fluidity, measured using a flow cone test, assessed the workability and penetrability of the grout within the OGBM skeleton. The results indicated fluidity values between 11 and 12 seconds, which fall within the acceptable range of 10–16 seconds. These values confirm the grout's injectability and ensure sufficient flowability for field applications.

Compressive strength, evaluated at curing ages of 3 and 7 days, showed a notable increase over time—from approximately 12.4 MPa at 3 days to 17.5 MPa at 7 days. These values exceed the minimum strength requirement of 7 MPa for CGBM applications. This ensures both early load-bearing capacity and long-term structural stability. On the other hand, the flexural tensile strength which is indicative of the grout's resistance to cracking under flexural stresses also increased with curing time, reaching up to 4.1 MPa at 7 days. This improvement reflects enhanced elasticity and crack resistance, both of which are essential for the durability of semi-flexible pavement structures.

The results presented in Table 3 confirm that the developed grout mix meets performance expectations in terms of flowability and mechanical strength. The progressive improvement in both compressive and flexural strength demonstrates the grout's effective hardening behavior and compatibility with semi-flexible pavement systems. The obtained results are in agreement with those reported in previous studies [55-99], which reported that optimized grout mixtures with appropriate water-to-cement ratios contribute significantly to improved mechanical performance in grouted macadam pavements. The presented data strongly supports the grout's ability to enhance load distribution, crack resistance, and long-term durability, especially when combined with recycled aggregates in sustainable pavement applications.

Table 3: Engineering performance test results (fluidity - compressive strength - flexural tensile strength)

Cement grout	Fluidity (seconds)	Compressive strength (MPa)			Flexural strength (MPa)		
Performance Test	**Workability**	**Compressive Strength**			**Tensile strength**		
Curing time	0- day	1-day	3-day	7-day	1-day	*3-day*	*7-day*
Test Results mean ± standard deviation	11 ± 0.5	11.2 ± 0.4	12.4 ± 0.5	17.5 ± 0.6	3.3 ± 0.3	*3.7 ± 0.2*	*4.1 ± 0.2*
Requirements Based on previous studies	10-16	7-day (7-35)			7-day (3.7-7.3)		

b. Determination of The Optimum Binder Content (OBC)

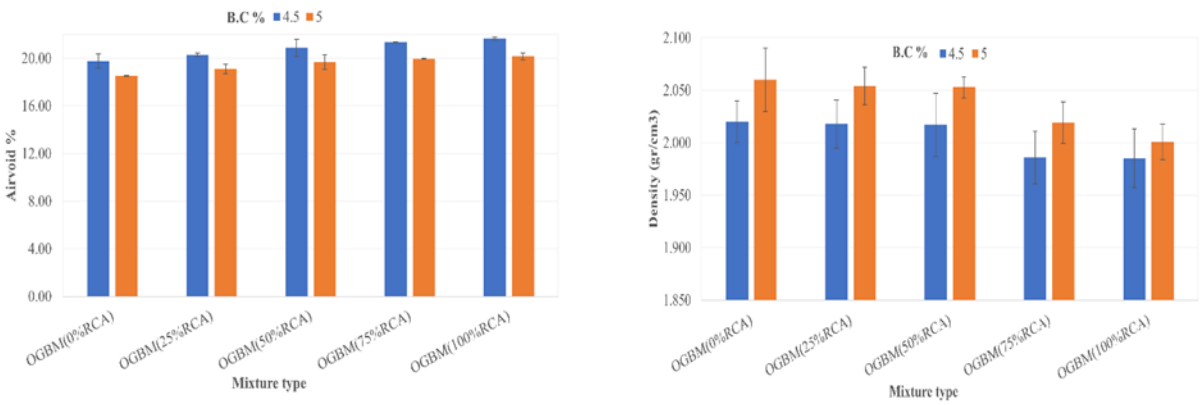
OBC is a critical factor influencing the volumetric and mechanical properties of OGBM before grouting. This phase aimed to identify the binder content that ensures acceptable levels of stability, flow, permeability, drain-down resistance, and abrasion durability. To determine the OBC, a series of trial mixtures were prepared with binder contents ranging from 3.5% to 6.0% with aggregate gradations Gr-I, Gr-II, and Gr-III in accordance with ASTM D7064[2]. Each mixture was evaluated for: Marshall Stability (MS), Marshall Flow (MF), Cantabro Abrasion Loss, Permeability, and Drain-down (%). The OBC was elected based on the mix that achieved the highest air voids while still meeting all critical performance criteria, as shown in Figure 5. To account for possible variability in mixture performance, the Cantabro criterion was conservatively relaxed, consistent with previous findings (Saboo et al., 2019) [38], to avoid rejecting potentially viable mixtures. Based on the results in Table 4, two mixtures met all performance requirements, 4.5% binder content was selected as OBC for up to 25% RCA mixes, and 5.0% for 50%–75% RCA, aligning with both mechanical performance and grout acceptance criteria.

Table 4: Results of MS, MF, drain down, Permeability, and Cantabro abrasion loss with binder contents from 3.5% to 6.0% for OGBM before grout

Bitumen content	Total Air Voids (Va %)	Marshall stability (kg)	Marshall flow (mm)	Drain down (%)	Permeability (m/day)	Abrasion Loss (%)
P1-Gr-I 100% Natural Aggregates (Coarse-fine)						
3.5%	21.1	214.6	2.90	0.098	402.0	68.4
4.0%	20.9	225.2	3.01	0.130	376.5	52.0
4.5%	19.8	310.8	3.20	0.170	323.5	31.3
5.0%	18.5	324.2	3.65	0.251	143.5	20.7
5.5%	16.3	505.6	4.40	0.305	96.5	19.2
6.0%	14.8	479.4	4.01	0.320	85.6	17.0
P2-Gr-III 100% RCA,100% fine NA						
3.5%	23.7	312.4	3.90	0.039	442.0	Failure
4.0%	22.9	440.7	3.70	0.097	396.5	Failure
4.5%	21.7	467.3	3.60	0.108	343.5	77.4
5.0%	20.2	517.5	3.50	0.147	163.5	57.6
5.5%	19.7	529.4	3.75	0.154	97.0	35.7
6.0%	18.1	536.2	3.58	0.259	95.2	22.2
P3-Gr-II 25% RCA,100% fine NA						
3.5%	21.9	239	3.20	0.078	412.0	77.3
4.0%	21.5	285	3.24	0.119	381.0	67.5
4.5%	20.3	360	3.30	0.149	328.0	43.6
5.0%	18.8	384	3.55	0.216	148.0	31.3
5.5%	17.1	482	3.88	0.255	92.0	27.2
6.0%	15.7	475	3.75	0.299	88.0	19.1
P4- Gr-II 50% RCA,100% fine NA						
3.5%	22.8	264	3.50	0.058	422.0	80.3
4.0%	21.7	345	3.47	0.108	386.0	70.5
4.5%	20.5	410	3.40	0.129	334.0	51.6
5.0%	19.0	444	3.60	0.181	153.0	30.3
5.5%	17.9	491	4.09	0.205	87.0	29.2
6.0%	16.3	515	3.88	0.279	76.0	19.5
P5- Gr-III 75%RCA,100% fine NA						
3.5%	23.1	289.0	3.80	0.038	432.0	90.3
4.0%	22.6	405.0	3.60	0.096	391.0	80.5
4.5%	21.4	460.0	3.50	0.106	338.0	63.6
5.0%	19.9	537.5	3.65	0.145	157.0	40.3
5.5%	18.4	579.4	4.31	0.152	98.0	31.2
6.0%	17.4	546.2	3.56	0.257	81.0	20.1
Criteria in this study	18%-24%	-	2 – 4 mm	< 0.3%.	100 m/day	< 50%

Conversely, the 100% RCA mixtures were excluded due to their inability to meet the performance standards established in this study. Mixtures with a binder content of 3.5%–4.0% failed the Cantabro abrasion test, while those with 4.5%–5.0% binder content did not satisfy the Cantabro threshold defined in this research. Furthermore, mixtures containing 5.5%–6.0% binder content failed to meet the minimum acceptable limit for permeability. This criteria was established based on ASTM 7064 standards, ECP 2020, and previous studies simulating local conditions comparable to heavy traffic (Husain et al..,2014; Saboo,Ranjeesh et al..,2019; Hassani et al.., 2020; Sunil S and Kumar,2020; Gong,xiong et al..,2022; Zhao and Yang,2022; Imran khan et al..,2022; Kumar et al.., 2023; Taghipoor et al..,2024) [24-38-14-36-112-113-114-115-5]. Volumetric properties are essential for evaluating the suitability of OGBM prior to grouting. Key indicators including air void content and bulk density are essential for evaluating the suitability of OGBM prior to grouting. Both properties influence the mixture's capacity for grout penetration and its mechanical stability post-grouting. This study assessed the volumetric characteristics of OGBM mixes containing different proportions of RCA of 0%, 25%, 50%, 75%, and 100% at binder contents ranging from 3.5% to 6.0%. Marshall mix design method was employed in this study to evaluate the strength characteristics of the OGBM at selected binder contents.

As illustrated in Figure 10, all mixes-maintained air void contents within the recommended range of 18% to 24%, suitable for grouting applications. This confirms that the selected gradation and binder levels successfully produced a porous skeleton capable of effective grout infiltration. The figure shows a general decrease in air voids with increasing binder content across all RCA levels. The bulk density exhibited a slight decline as the RCA percentage increased, which is attributed to RCA's lower specific gravity compared to NA. Despite this, the densities remained within acceptable limits for SFP applications. Moreover, mixtures with 50% and 75% RCA provided optimal void structures, balancing permeability and mechanical interlock, thus making them promising candidates CGBM use. These findings demonstrate that appropriate binder content and RCA substitution can produce OGBM mixtures that meet volumetric requirements, ensuring both functional porosity for grouting and structural reliability.



(a) (b)

Fig. 10: (a) Variation of air void content and (b) Variation of bulk density for OGBM mixtures incorporating different RCA replacement levels at two binder contents (4.5% and 5.0%). The dashed line indicates the minimum 18% air void threshold required for grouting

The drain-down is a crucial parameter in evaluating the stability of OGBM, particularly when these mixtures are intended for cement grouting in CGBM applications. Excessive binder drain-down during mixing, handling, or compaction can compromise the internal structure of the mixture, leading to insufficient coating, segregation, or reduced mechanical interlock. In this study, the drain-down test was conducted following ASTM D6390 [101]to quantify the amount of binder that drains from the loose mix at elevated temperatures. The test was applied to all mixture types with varying percentages of RCA and binder contents. As shown in Figure 11, the drain-down values for all mixtures were found to be within the acceptable limit of 0.3% as per specification guidelines, confirming that both binder contents were effective in stabilizing the mixtures across different RCA replacement levels. Specifically, Figure 11 indicates a slight increase in drain-down with the increase in binder content from 4.5% to 5.0%, which is expected due to the additional free asphalt. However, the value remained well below the critical limit. The inclusion of RCA had no adverse effect on drain-down, likely due to RCA's high absorption capacity and angular texture, which help retain the binder within the mixture matrix. This behavior suggests that OGBM mixtures with up to 75% RCA substitution can be effectively stabilized with minor adjustments in binder content, ensuring that the mix remains cohesive and structurally reliable during production and placement. Consequently, this supports the use of RCA in semi-flexible pavements without compromising early-stage mixture integrity.

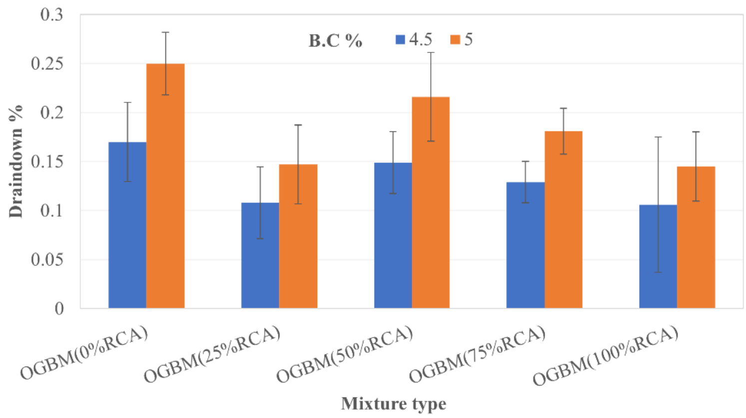


Fig. 11: Drain down Test Results for OGBM at Binder Contents of 4.5 and 5.0%

Permeability is a key performance parameter in CGBM, as it governs the grout's ability to infiltrate the interconnected air voids within the (OGA) skeleton. According to ASTM D7064 [2], a permeability threshold of 100 m/day is required to ensure effective grout penetration. The results, presented in Figure 12, reveal that all mixtures designed with 4.5% to 5.0% binder content exhibited permeability values exceeding the minimum standard. This indicates adequate grout infiltration. Notably, mixtures with higher RCA) content—especially those with 50% and 75% RCA—demonstrated increased permeability. This enhancement is attributed to the angular and rougher surface texture of RCA, which promotes the formation of a more open and interconnected void structure.

These findings underline that the integration of RCA improves not only the sustainability aspects of CGBM but also enhances its functional performance, provided binder content and gradation are optimized to maintain a balance between permeability, mechanical interlock, and grouting efficiency.

The Cantabro abrasion test, conducted according to ASTM D7064 and AASHTO TP 108-14, [2-104] evaluates the raveling resistance of bituminous mixtures by quantifying aggregate loss under mechanical agitation in a Los Angeles abrasion machine (without steel balls). While ASTM sets a maximum abrasion loss of 20% for grouted wearing courses, this threshold is not directly applicable to pre-grouted OGA due to its inherently lower cohesion and higher porosity.

In this study, a relaxed abrasion loss criterion of 50% was adopted for pre-grouted mixtures, aligning with Saboo et al. (2019) [38] to avoid prematurely rejecting potentially viable formulations. Figure 13 illustrates the Cantabro loss before and after grouting for various RCA contents and curing durations. Before Grouting: Abrasion loss increased with higher RCA content due to the angularity, open texture, and reduced inter-particle cohesion of RCA. These traits make the matrix more prone to particle loss under agitation. After Grouting: Grout significantly improved durability across all mixtures, particularly for RCA-rich blends. The interconnected void structure of RCA facilitated deeper grout infiltration, leading to stronger internal bonding.

Moreover, the Abrasion loss decreased progressively with longer curing times (1, 3, and 7 days). This trend is especially evident in 50% and 75% RCA mixes, where improved matrix integrity was achieved over time due to cementitious grout hardening.

The binder contents used—4.5% for 25% RCA and 5.0% for 50% and 75% RCA—provided an effective balance between permeability (required for grout penetration) and durability (measured by abrasion resistance). This agrees with the results of Zachariah et al., 2020[55]. These results confirm that optimized binder content and structured grouting are essential for ensuring mechanical integrity in RCA-based CGBMs.

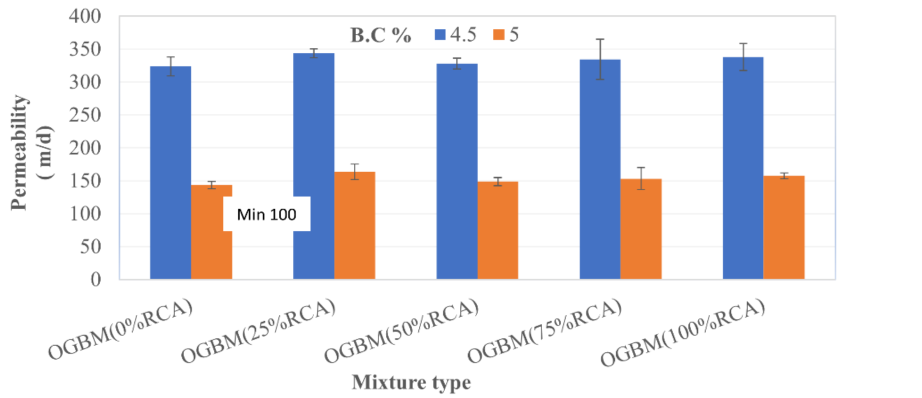
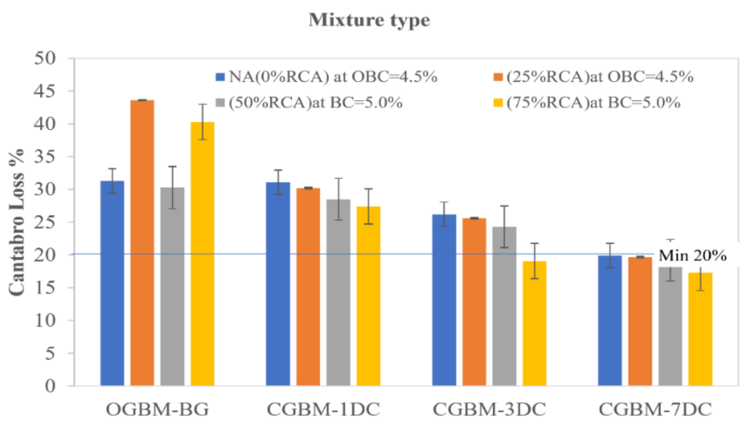


Fig. 12: permeability Test



OGBM-BG Open Grade Bituminous Mixtures before grouted, CGBM-1DC Cement Grout Bituminous Mixtures After 1 Day of Curing, CGBM-3DC Cement Grout Bituminous Mixtures After 3 Day of Curing, CGBM-7DC Cement Grout Bituminous Mixtures After 7 Day of Curing

Fig. 13: Cantabro abrasion loss

c. Marshall stability

Marshall Tests were performed to evaluate the mechanical behavior of grouted bituminous mixtures incorporating varying percentages of RCA. Following grout injection and a 6-hour setting period, specimens were cured via water spraying for 1, 3, and 7 days. A compressive load was applied at a rate of 50 mm/min, and the resulting MS and MF values are presented in Figures 14 and 15, respectively. Figure 14 illustrates a clear positive relationship between RCA content and Marshall stability, both before and after grouting. The data suggest that moderate to high RCA replacement levels (50%–75%), when combined with sufficient curing, yield enhanced stability performance.

The observed improvements are primarily attributed to the angular shape and rough surface texture of RCA, which promotes mechanical interlocking and improved bonding with the cement grout—particularly after extended curing durations. Additionally, binder content played a significant role: mixtures with 25% RCA were maintained at an OBC of 4.5%, while those with 50% and 75% RCA were designed with a higher binder content (OBC = 5.0%) to ensure cohesive matrix formation.

Figure 15 presents the impact of RCA content and curing time on Marshall flow values. Before grouting, flow values increased with higher RCA content—from 3.2 mm at 0% RCA to 3.7 mm at 75% RCA—indicating greater deformability, likely due to the more porous and less dense structure of RCA. After 7 days of curing, flow values generally decreased, reflecting improved stiffness. However, the 75% RCA mix recorded a flow value of 4.3 mm, slightly exceeding the standard limit of 4.0 mm. This may be attributed to differences in aggregate arrangement, internal structure, and bonding between materials. Overall, the obtained MS and MF values fall within the acceptable limits specified in the Egyptian Code of Practice (ECP 2020) [89], confirming the structural adequacy and viability of RCA-based CGBM mixtures as shown previously in Table 4.

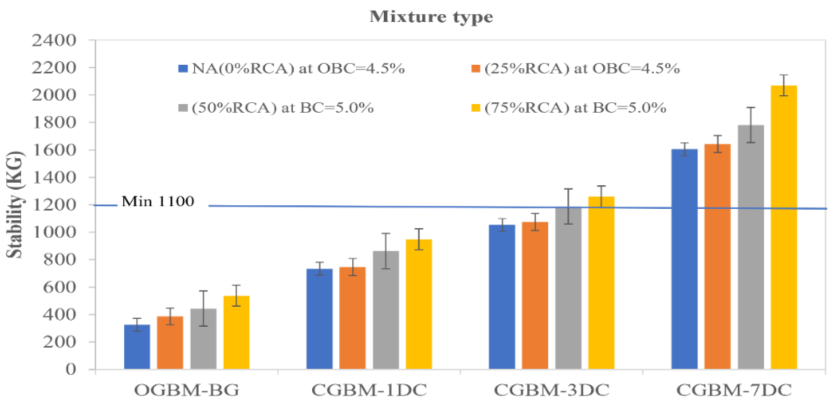


Fig. 14: MS

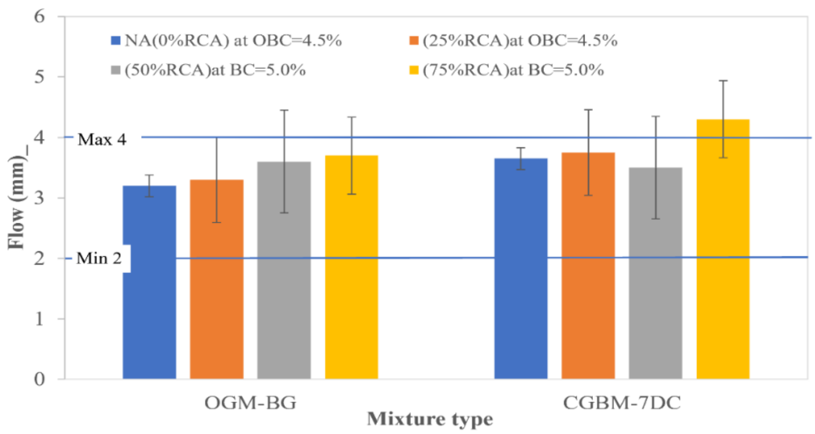


Fig. 15: MF

d. (HWTT):

HWTT, conducted as per AASHTO T 324 [107], was adopted to examine the rutting resistance and moisture sensitivity of CGBM prepared for SFP.

All CGBM mixes containing 0%, 25%, 50%, and 75% RCA maintained rut depths below the AASHTO T 324 allowable threshold of 12.5 mm even after 20,000 load passes as shown in Figure 16. This confirms that all mixes meet the performance criteria for rutting resistance.

Before curing, increasing RCA content led to slightly higher rut depths. This is likely due to the initial porosity and lower cohesion of RCA particles, which can result in early deformation under load. After 7 days of curing, the behavior reversed significantly. The cement grout was fully hardened, filling the interconnected voids and forming a stiff internal skeleton. As a result, rutting resistance improved with higher RCA content. The 50% RCA mix exhibited a 43.2% reduction in rut depth compared to the control mix (0% RCA), while the 75% RCA mix achieved the highest performance, with a 67.6% reduction in rutting. All mixtures with RCA showed comparable or superior resistance to rutting compared to the control mix with 0% RCA.

These improvements are attributed to the angular texture of RCA, which enhances aggregate interlock, Increased surface area for grout bonding due to RCA's porous nature, improved structural post-curing as grout fills and stiffens the mixture matrix. The findings demonstrate that incorporating RCA up to 75% in CGBM enhances rutting resistance after proper curing. The combination of grout penetration and RCA structure offers better load distribution and deformation control. However, this benefit is strongly dependent on curing time. Inadequate curing may negate the advantages of using high RCA content due to delayed stiffness development.

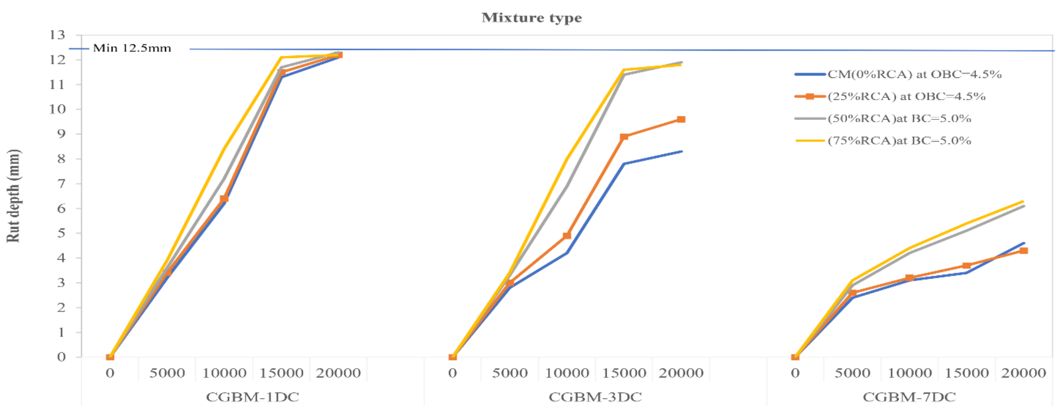


Fig. 16: HWTT

e. SCB:

The SCB test was performed in accordance with ASTM D8044 [109], was employed to evaluate the fracture resistance of CGBM using fracture mechanics principles. Specimens with predefined notch depths were subjected to three-point bending to determine fracture energy, which quantifies the material's resistance to crack initiation and propagation. The results presented in Figure 17 show that as RCA content increased, fracture energy improved. This trend suggests that RCA enhances the aggregate interlock and promotes deeper and more uniform grout penetration, resulting in a stronger bond network within the mix. The increase in fracture energy confirms that mixtures with higher RCA with 50% and 75% content can better resist crack initiation and propagation, contributing to longer pavement life and better performance under heavy loading conditions. While the control mixture (0% RCA) exhibits the lowest fracture energy, highlighting the beneficial role of RCA inclusion.

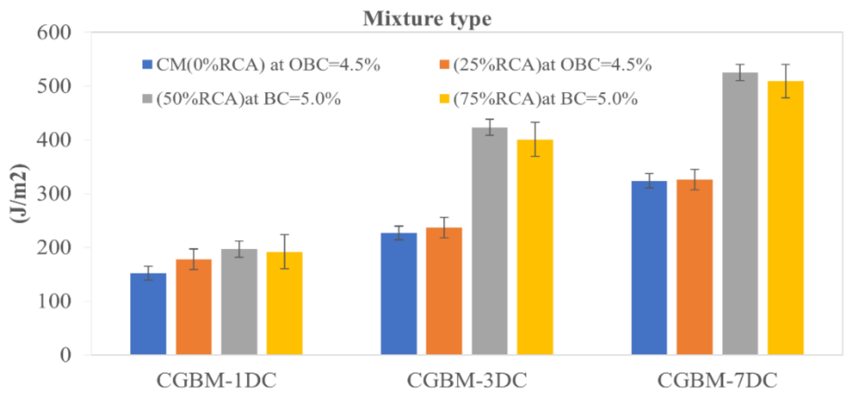


Fig. 17: SCB Test

f. (E*) and (FN) tests:

Figure 18 presents the master curve for (E*) created using the sigmoidal model at a reference temperature of 21°C, following AASHTO R 62[116]. This curve serves as a fundamental tool for characterizing the viscoelastic behavior of asphalt mixtures by relating modulus values to frequency and temperature. The E* values for all CGBM decreased as the temperature increased and frequency decreased, illustrating the expected viscoelastic behavior of asphalt mixtures. At elevated temperatures and lower frequencies—conditions critical for rutting—E* values significantly declined, while the phase angle increased, indicating a greater viscous response and reduced stiffness. The addition of RCA) enhanced the stiffness of CGBM, particularly in mixtures containing 50% and 75% RCA. These mixtures exhibited higher E* values across nearly all temperature–frequency combinations compared to the control mix (0% RCA), demonstrating improved load-bearing capacity and reduced susceptibility to deformation under challenging service conditions. This improvement is linked to the angularity and rough surface texture of RCA, which fosters aggregate interlock and promotes more effective grout penetration and hardening.

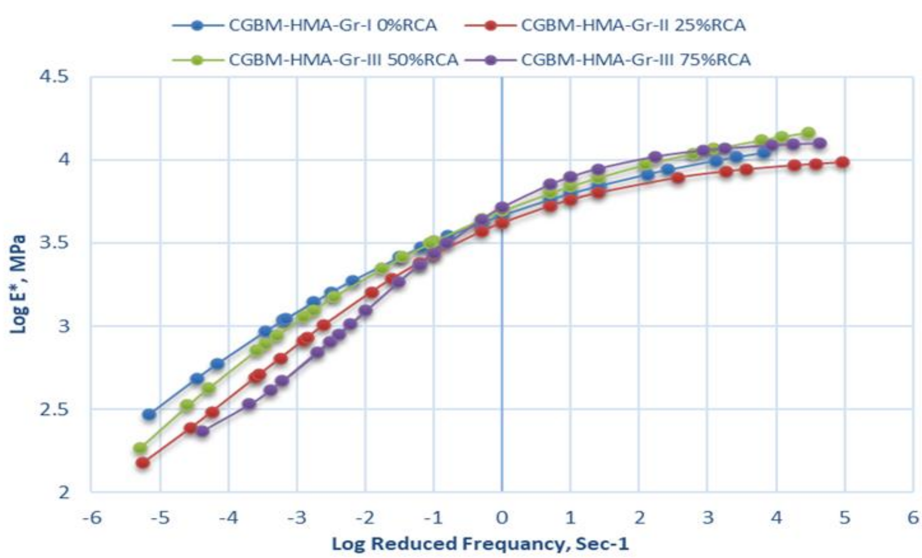


Fig. 18: Dynamic modulus master curve

Figure 19 shows the (FN) results measured at 54.4°C under repeated axial loading. Mixtures with higher RCA content presented lower accumulated permanent strains and elevated FN values, confirming their enhanced resistance to rutting. The 75% RCA mixture achieved the highest FN, indicating a delayed onset of tertiary flow and improved structural integrity under cyclic loading. This behavior reflects the stiffening effect of RCA and the efficacy of the grout in filling and stabilizing the internal matrix.

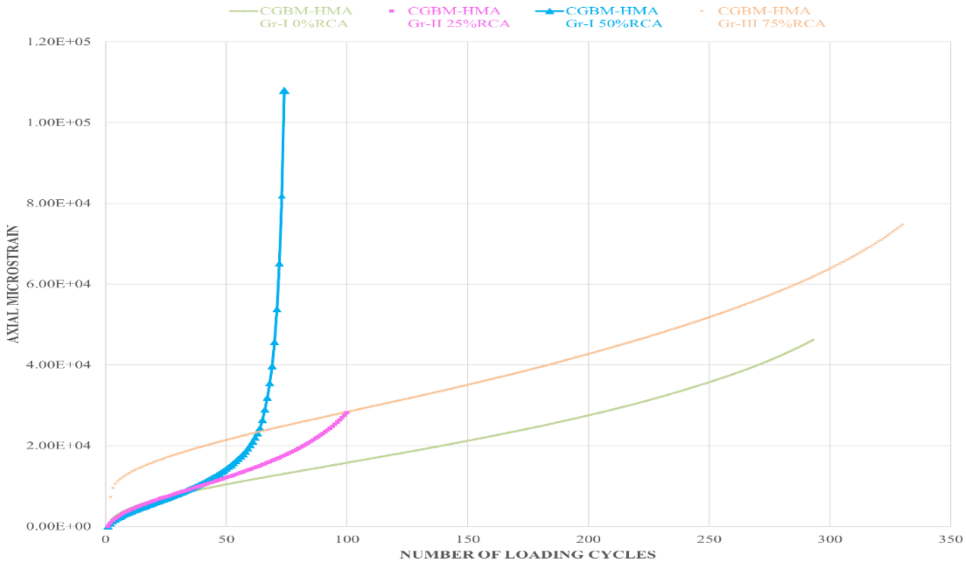


Fig. 19: Axial permanent strains versus the number of loading cycles.

Figures 18 and 19 collectively demonstrate that RCA enhances the structural and functional resilience of CGBM when combined with appropriate binder content and curing duration.

Table 5 provides a comparative summary of the influence of varying (RCA) replacement levels on key mechanical properties of (CGBM). The table highlights the performance trends across different mixtures in terms of stability, durability, rutting resistance, fracture energy, stiffness, and resistance to permanent deformation. This overview facilitates a holistic assessment of each mix and supports the identification of the optimal RCA content for enhanced structural performance.

Table 5 outlines the effect of RCA at various replacement ratios on the key mechanical performance indicators of CGBM. This allows for a clearer evaluation of mixture behavior and supports the selection of the optimal RCA content.

Table 5: summarizing the effect of different mix types (based on %RCA) on key performance parameters:

Mix type	Marshall stability (MS)	Cantabro losses	Rut depth HWTT	Fracture energy (SCB)	Dynamic modulus (E*)	Flow number (FN)
M1 (25%RCA)	↑	↘	↓	↑	↑	↑
M2 (50%RCA)	↑↑	↓↓	↓↓	↑↑	↑↑	↑↑
M3 (75%RCA)	↑↑	↓↓	↓↓↓	↑↑↑	↑↑↑	↑↑↑

Arrow	Meaning
↑	Slight improvement
↑↑	Noticeable improvement
↑↑↑	Significant improvement (best result)
↓	Slight decrease
↓↓	Considerable decrease
↓↓↓	Major decrease (best result)
↘	Moderate or irregular decrease

Statistical analysis.

Statistical analysis was conducted using Multivariate Analysis of Variance (MANOVA) in SPSS at a 95% confidence level to evaluate the effects of RCA content and curing time on CGBM performance. The independent variables included mixture type (0%, 25%, 50%, 75% RCA), curing time (1, 3, 7 days), and binder content (OBC at 4.5%, and BC at 5.0%). The dependent variables assessed were Marshall Stability (kg), Cantabro Loss (%), Rut Depth (mm), and Fracture Energy (J/m²). This statistical approach is suitable for analyzing multiple interrelated dependent variables simultaneously, thereby improving the accuracy of performance evaluation. Table 6 shows the dependent and independent variables considered in statistical analysis.

Table 6: Dependent and independent variables considered in statistical analysis

Independent variable		**Dependent variable**			
CGBM- HMA		**CGBM- HMA**			
Mixture types	Curing time	MS (kg)	Cantabro Loss (%)	Rut (mm) HWTT	Fracture energy SCB
P1-Gr-I 100%NA at OBC=4.5%	1 day 3 days 7 days				
P3-Gr-II 25%RCA at OBC=4.5%					
P4-Gr-II 50%RCA at BC=5.0%					
P5-Gr-III 75%RCA at BC=5.0%					

Table 7 presents, MANOVA results confirmed that all three independent variables—mixture type, curing time, and their interaction—had statistically significant effects ($p \leq 0.001$) on each dependent performance parameter. Both mixture type and curing time significantly influenced all dependent variables ($p < 0.001$). The interaction between these variables also yielded statistically significant differences, indicating that optimal performance was achieved by combinations such as 50–75% RCA with 7-day curing. Key findings showed that the

Stability was significantly enhanced by increased RCA content and longer curing durations ($F = 102.28$ for mixture type; $F = 234.31$ for curing; $p < 0.001$). A strong interaction effect ($F = 31.81$; $p < 0.001$) indicated that optimal performance is achieved when both factors are aligned. The Cantabro Loss, representing abrasion resistance, was highly sensitive to RCA content and curing time ($F = 72.24$ and $F = 99.82$, respectively; $p < 0.001$). RCA initially increased aggregate loss, but extended curing mitigated this effect substantially. Moreover, Rut Depth was notably reduced with increasing RCA content and curing time ($F = 117.91$ and $F = 268.15$, respectively; $p < 0.001$). The 75% RCA mixtures exhibited superior rutting resistance post 7-day curing. Finally, Fracture Energy showed a consistent rise with RCA content and longer curing periods ($F = 80.88$ for mixture type; $F = 167.91$ for curing; $p < 0.001$), reflecting enhanced cracking resistance and grout-aggregate bonding.

The interaction effects between mixture type and curing time were statistically significant for all variables, suggesting that certain RCA blends benefit disproportionately from extended curing—a nuance not captured through univariate analysis. These statistical outcomes validate the structural feasibility of utilizing up to 75% RCA in CGBM, especially when binder content and curing practices are appropriately optimized.

Table 7: MANOVA multivariate Results for SFP

Tests of Between-Subjects Effects							
Source	**Dependent Variable**	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig. (p value)**	**Results**
Corrected Model	Stability (kg)	5823400[a]	11	529400	88.23	.000	Significant
	Cantabro loss (%)	1120.8[b]	11	101.89	42.12	.000	Significant
	Rut (mm)	184.7[c]	11	16.79	94.55	.000	Significant
	Fracture energy (J/m2)	194985.2[d]	11	17726.84	56.34	.000	Significant
Intercept	Stability (kg)	1.14E+08	1	1.14E+08	18958.02	.000	Significant
	Cantabro loss (%)	24975.6	1	24975.6	10329.12	.000	Significant
	Rut (mm)	2115.2	1	2115.2	11910.46	.000	Significant
	Fracture energy (J/m2)	3128300	1	3128300	9945.91	.000	Significant
Mixture	Stability (kg)	1842200	3	614066.7	102.28	.000	Significant
	Cantabro loss (%)	524.1	3	174.7	72.24	.000	Significant
	Rut (mm)	62.8	3	20.93	117.91	.000	Significant
	Fracture energy (J/m2)	76342	3	25447.3	80.88	.000	Significant
curing	Stability (kg)	2814900	2	1407450	234.31	.000	Significant
	Cantabro loss (%)	480.3	2	240.15	99.82	.000	Significant
	Rut (mm)	95.2	2	47.6	268.15	.000	Significant
	Fracture energy (J/m2)	105845	2	52922.5	167.91	.000	Significant
Mixture * curing	Stability (kg)	1161000	6	193500	31.81	.000	Significant
	Cantabro loss (%)	116.4	6	19.4	7.99	.000	Significant
	Rut (mm)	26.7	6	4.45	25.06	.000	Significant
	Fracture energy (J/m2)	27982	6	4663.7	14.82	.000	Significant
a. R Squared = 0.97 (Adjusted R Squared = 0.96)							
b. R Squared = 0.94 (Adjusted R Squared = 0.93)							
c. R Squared = 0.98 (Adjusted R Squared = 0.97)							
d. R Squared = 0.95 (Adjusted R Squared = 0.94)							

6. Summary and Conclusions

This research investigated the feasibility of utilizing (RCA) as a substitute for (NAs) in Cement Grouted Bituminous Mixtures (CGBM-HMA) under Egyptian conditions. RCA was sourced from old, demolished buildings to assess the impact of material degradation on the engineering behavior of the mixtures. The fundamental engineering characteristics of both natural and recycled aggregates were evaluated, as well as for the bitumen and cement grout used in mix preparation. Several mix designs were developed using the conventional Marshall method, with RCA partially replacing the coarse fraction of NAs (retained on the U.S. Standard Sieve No. 4) at substitution rates of 0%, 25%, 50%,75%. The 100% RCA mix was excluded due to its inability to meet the performance criteria set by the study. To evaluate performance, the mixtures were subjected to laboratory tests measuring stability, flow, abrasion loss, rutting resistance, fatigue resistance, (E*), and (FN). Additionally, A comprehensive statistical analysis was conducted to interpret the test results and evaluate the significance of the performance differences among the mixtures.

According to the accomplished Research Methodology and Experimental Work, the following can be concluded from this program:

- (CGBM) with 25–75% (RCA) demonstrated comparable or enhanced performance compared to mixtures with 100% (NA).
- RCA significantly improved Marshall stability, especially at 50% and 75% replacement levels.
- Cantabro abrasion loss was effectively reduced after grouting and curing, indicating improved durability in RCA-based mixes.
- Higher RCA content contributed to better rutting resistance (HWTT) and greater fracture energy (SCB), enhancing overall structural integrity.
- RCA-enhanced mixes showed increased (E)* and (FN) values, indicating better long-term resistance to deformation.
- Statistical analysis (MANOVA) confirmed the significant influence of RCA content and curing time on mechanical and durability performance.
- Utilizing RCA in CGBM supports sustainability by reducing reliance on virgin materials and promoting the recycling of CDW.

Limitations and Future Work

This study confirmed the feasibility of incorporating RCA into CGBM with optimal performance at 25–75% replacement levels under Egyptian conditions. However, the scope was limited to RCA only, while mixed CDW fractions were not examined, and the 100% RCA mix failed to meet the minimum performance thresholds. Long-term ageing, freeze–thaw durability, detailed microstructural analyses, and advanced RCA pretreatment methods (e.g., carbonation, silane coatings, chemical washing) were beyond the scope of this work. Furthermore, the findings are geographically constrained to Egyptian conditions. Future research should therefore address mixed CDW materials, ageing and durability, microstructural and pretreatment techniques, and field-scale validation across diverse climates to establish broader applicability and long-term sustainability.

References

[1] Bonicelli. A, Preciado. J, Rueda. A, Duarte. A Semi-Flexible Material: A Solution for High-Performance Pavement Infrastructures, MS&E 471 (3) (2019) 032062, DOI:10.1088/1757-899X/471/3/032062.

[2] ASTM D7064/D7064M-08, Standard Practice for Open-Graded Friction Course (OGFC) Mix Design, ASTM International, West Conshohochen, PA, 2013.

[3] Koting, S.; Karim, M.R.; Mahmud, H.B.; Hamid, A.; Anjang, N. Mechanical Properties of Cement-Bitumen Composites for Semi-Flexible Pavement Surfacing. Balt. J. Road Bridge Eng. 2014, 9, 191–199.

[4] Oliveira. J.R.M, Grouted macadam: material characterization for pavement design, University of Nottingham, 2006. Doctoral dissertation.

[5] Taghipoor, M., Hassani, A., Karimi, M.M., 2024. Investigation of material composition, design, and performance of open-graded asphalt mixtures for semi-flexible pavement: A comprehensive experimental study. J. Traffic Transp. Eng. (Engl. Ed.) 2024; 11 (1): 92e116.

[6] Chen, Z., Qiao, J., Yang, X., Sun, Y., Sun, D. "A review of grouting materials for pouring semi-flexible pavement: Materials, design and performance", Construction and Building Materials, 379,131235, 2023.

[7] Abdulsahib, I.; Hilal, M.; Fattah, M Semi-Flexible Pavement: A Review of Design and Performance Evaluation. E3S Web of Conferences 427, 03001 (2023), ICGEE 2023.

[8] Guosheng. Li Huan. Xiong, Qi Ren, Xiaoguang. Z and Libao Wu.2022 Experimental Study and Performance Characterization of Semi-Flexible Pavements, Coatings 2022, 12, 241.

[9] Taghipoor, M., Hassani, A., Karimi, M.M., 2021. Development of procedure for design and preparation of open-raded asphalt mixture used in semi-flexible pavement. Construction and Building Materials 306, 124884.

[10] Shaoke An; Changfa Ai, Dongya Ren, Ali Rahman, and Yanjun Qiu.2018, Laboratory and Field Evaluation of a Novel Cement Grout Asphalt Composite, J. Mater. Civ. Eng., 2018, 30(8): 04018179.

[11] Tran, T.N, Tai, H., Son Nguyen. K., Nguyen. N. T.2018. Semi-flexible Material: The Sustainable Alternative for the Use of Conventional Road Materials in Heavy-Duty Pavement.

[12] Cihackova. P, Hyzl. P, Stehlik. D, Dasek. O, Šernas. O, A. Vaitkus, 2015 Performance characteristics of the open-graded asphalt concrete filled with a special cement grout, Balt. J. Road Bridg. Eng. 10 (2015) 316–324.

[13] Dhandapani, B. P and Mullapudi, R.S,(2024) Cement-grouted bituminous mixtures containing reclaimed asphalt pavement material: design and mechanical properties, Road Materials And Pavement Design, https://doi.org/10.1080/14680629.2024.2430379.

[14] Hassani, A.; Taghipoor, M.; Karimi, M.M. A state of the art of semi-flexible pavements: Introduction, design, and performance.Constr. Build. Mater. 2020, 253, 119196, https://doi.org/10.1016/j.conbuildmat.2020.119196.

[15] Van de Ven, M. F.; Molenaar, A. A. 2004. Mechanical Characterization of Combi-Layer, Journal of the Association of Asphalt Paving Technologists 73: 1–22.

[16] Al-Qadi, I., H. Gouru, and R. Weyers, Asphalt Portland cement concrete composite: laboratory evaluation. Journal of Transportation Engineering, 1994. 120(1): 94-108.

[17] Zhang, S., Huang, & Goodwin. (2013). Evaluation of semi-flexible composite mixture using indirect tensile tests. Paper presented at the TRB Annual Meeting, Washington, DC.

[18] Dong Qing Wu, Daud, Yanli Zhang (2011). The semi-rigid pavement with higher performances for roads and parking aprons, CAFEO 29, Sustainable Urbanization – Engineering Challenges and Opportunities 27-30 November 2011, The Rizqun International Hotel, Brunei Darussalam.

[19] Hou. S, T. Xu, K. Huang, (2016). Investigation into engineering properties and strength mechanism of grouted macadam composite materials, Int. J. Pavement Eng. 17 (2016) 878-886,

[20] Bharath.G, Manoj Shukla, M. N. Nagabushana, Satish Chandra & Amit Shaw, (2019) Laboratory and field evaluation of cement grouted bituminous mixes, Road Materials and Pavement Design, 21:6, 1694-1712, DOI: 10.1080/14680629.2019.1567375

[21] Roffe, J.C., Salviacim–introducing the pavement. Jean Lafebvre Enterprise, Paris, France, 1989.

[22] Shuguang Hou, Tao Xu & Kai Huang (2016) Investigation into engineering properties and strength mechanism of grouted macadam composite materials, International Journal of Pavement Engineering, 17:10, 878-886, DOI: 10.1080/10298436.2015.1024467.

[23] Koting, S., M.R. Karim, and H. Mahmud. The Properties of bituminous mixtures for semi-flexible pavement. In Proceedings of the Eastern Asia Society for Transportation Studies Vol. 6 (The 7th International Conference of Eastern Asia Society for Transportation Studies, 2007). 2007. Eastern Asia Society for Transportation Studies.

[24] Husain, N. M., Karim, M. R., Mahmud, H. B., & Koting, S. (2014). Effects of aggregate gradation on the physical properties of semi flexible pavement. Advances in Materials Science and Engineering.

[25] Ling, TQ., Zhao, ZJ., Xiong, CH., Dong, YY., Liu, YY., The Application of Semi-Flexible Pavement on Heavy Traffic Roads. International Journal of Pavement Research and Technology, 2009. 2(5): 211-217.

[26] Anderton G.L., 1996, User's Guide: Resin Modified Pavement, U.S. Army Engineer Waterways Experiment Station Vicksburg MS Geotechnical Lab.

[27] Anderton G.L., 2000, "Engineering Properties of Resin Modified Pavement (RMP) for Mechanistic Design", US Army Engineer Research and Development Centre ERDC/GL TR-00-2, Vicksburg, MS-USA.

[28] Husain, N. M., Mahmud, M. R., Karim, & Hamid, N. B. A. A. (2010). Effects of aggregate gradations on properties of grouted Macadam composite pavement. Paper presented at the Proceeding of 2nd International Conference on Chemical, Biological and Environmental Engineering, Cairo, Egypt

[29] Khan, I. (2010). Mix design for cement grouted bituminous macadam (Unpublished M. Tech thesis). IIT Kanpur, Kanpur, India.

[30] Gawedzinski, M. J. (2008). Evaluation of semi-flexible (Resin modified) pavement (report no I2008-1).

[31] Hassan, K. E., Setyawan, A., & Zoorob, S. E. (2002). Effect of cementitious grouts on the properties of Semi-flexible bituminous pavements, performance of bituminous and Hydraulic materials in pavements. Proceedings of the Fourth European Symposium on performance of bituminous and Hydraulic materials in pavements, Bitmat 4, Nottingham, UK.

[32] Setyawan. A Development of semi-flexible heavy-duty pavements, University of Leeds, 2005. Doctoral dissertation.

[33] Sun, Y., Cheng, Y., Ding, M., Yuan, X., Wang, J., 2018.Research on Properties of High-Performance Cement Mortar for Semi-flexible Pavement. Advances in Materials Science and Engineering, 2018.

[34] Setyawan, A., 2013.Assessing the Compressive Strength Properties of Semi-Flexible Pavements. Procedia Engineering, 54: 863-874.

[35] Ding, Q. J., Sun, Z., Shen, F., & Huang, S. L. (2011). The performance analysis of semi-flexible pavement by the volume parameter of matrix asphalt mixture. Advanced Materials Research, 168, 351–356.

[36] Sunil. S, M.S.N. Kumar, 2020.Laboratory evaluation of engineering and strength properties for semi rigid mixtures, IOP Conf. Series: Material Science and Engineering,1006,2020,012034. doi:10.1088/1757-899X/1006/1/012034.

[37] Alvarez, A.E., A.E. Martin, and C. Estakhri, Drainability of permeable friction course mixtures. Journal of Materials in Civil Engineering, 2010. 22(6): 556-564. doi.org/10.1061/(ASCE)MT.1943-5533.0000053.

[38] Saboo, N., Khalpada, V., Prasanta K. Sahu, Radhakrishnan R., & Gupta. A., Optimal proportioning of grout constituents using mathematical programming for semi flexible pavement. International Journal of Pavement Research and Technology, 2019. 12(3): 297-306.

[39] Zhong. K, Sun. M. Z, Zhang. M, Qin. Y. J, Li. Y.D, (2020). Interfacial and mechanical performance of grouted open-graded asphalt concrete with latex modified cement mortar, Construction and Building Materials 234.

[40] Wang, D.; Liang, X.; Jiang, C.; Pan, Y.2018. Impact analysis of carboxyl latex on the performance of semi-flexible pavement using warm-mix technology. Constr. Build. Mater. 2018, 179, 566–575.

[41] Xiaoyu Liu, KuangHuai Wu, Giovanni Giacomello, Yunpeng Yue a, Fengming Ren, Xu Cai a, Marco Pasetto.2025. Enhancing cracking resistance in semi-flexible pavements using an interfacial immersion method, Case Studies in Construction Materials 22 (2025) e04311

[42] Cai, J., Pei, J., Luo, Q., Zhang, J., Li, R., Chen, X., 2017. Comprehensive service properties evaluation of composite grouting materials with high-performance cement paste for semi-flexible pavement. Construction and Building Materials, 153: p. 544-556.

[43] Fang, B., T. Xu, and S. Shi, 2015. Laboratory study on cement slurry formulation and its strength mechanism for semi-flexible pavement: ASTM International.

[44] Gong. M, Xiong. Z, Chen. H, Deng .C, Chen. X, J. Yang, H. Zhu, J. (2019) .Hong, Evaluation on the cracking resistance of semi-flexible pavement mixture by laboratory research and field validation, Construction and Building Materials 207-387–395

[45] Koting, S.; Karim, M.R.; Mahmud, H.B.; Hamid, A.; Anjang, N. Mechanical Properties of Cement-Bitumen Composites for Semi-Flexible Pavement Surfacing. Balt. J. Road Bridge Eng. 2014, 9, 191–199.

[46] Pei. J, Cai. J, Zou. D, Zhang. J, R. Li, X. Chen, L. Jin, (2016). Design and performance validation of high-performance cement paste as a grouting material for semiflexible pavement, Construction and Building Materials 126 - 206–217.

[47] Yang. B, X. Weng, (2015). The influence on the durability of semi-flexible airport pavement materials to cyclic wheel load test, Constr. Build. Mater. 98 - 171-175, https://doi.org/10.1016/j.conbuildmat.2015.08.092.

[48] Dhandapani, B. P and Mullapudi, R.S,(2024) Cement-grouted bituminous mixtures containing reclaimed asphalt pavement material: design and mechanical properties, Road Materials And Pavement Design, https://doi.org/10.1080/14680629.2024.2430379.

[49] Afonso. M.L, M. Dinis-Almeida, L.A. Pereira-de-Oliveira, J. Castro-Gomes, S. E. Zoorob, (2016). Development of a semi-flexible heavy duty pavement surfacing incorporating recycled and waste aggregates–Preliminary study, Constr. Build. Mater. 102 - 155–161.

[50] Xie, J., Huang, W., Hu, B., Xiao, Z., Hassan, H. M. Z., & Wu, K. (2021). Study on the road performance of foamed warm-mixed reclaimed semi-flexible asphalt pavement material. Materials, 14(18), 5379. https://doi.org/10.3390/ma14185379.

[51] Zhao, W., & Yang, Q. (2023). Life cycle assessment and multi-index performance evaluation of semi-flexible pavement after composite modification by using fly ash, rubber particles, warm mixing asphalt and recycled asphalt pavement. Construction and Building Materials, 364, 129945.

[52] Copeland.A, Reclaimed asphalt pavement in asphalt mixtures: State of the practice, No. FHWA-HRT-11-021, United States. Federal Highway Administration. Offce of Research, Development, and Technology, 2011.
[53] Zaumanis.M, R.B. Mallick, Review of very high-content reclaimed asphalt use in plant-produced pavements: state of the art, Int. J. Pavement Eng. 16 (1) (2015) 39–55.
[54] Al-Nawasir, R., Al-Humeidawi, B., Shubbar, A. "Influence of Sustainable Grout Material on the Moisture Damage of Semi-flexible Pavement", Periodica Polytechnica Civil Engineering, 68(3), pp. 961–973, 2024. https://doi.org/10.3311/PPci.23373.
[55] Zachariah. J. P, P.P. Sarkar, D. Nandi, A study on the properties of cement grouted open-graded bituminous concrete with brick as aggregates, Construction and building materials 256 (2020) 119436.
[56] Cai. X, Zhang .H, Zhang. J, Chen. X, J. Yang, and J. Hong, 2019 "Investigation on reinforcing mechanisms of semi-flexible pavement material through micromechanical model," Construction and Building Materials, vol. 198, pp. 732–741.
[57] Othman M.Gamal,Z.Hussein,and A. Abu El-Maaty,Evaluation of semi-flexible pavement performance, journal of Al-Azhar University Engineering Sector, Vol.15, no.54, pp.100-111,2020,
[58] Al-Taher. M.G, Mohamady A., Attia M.I, Shalaby M.A., 2015. Technical Evaluation of Using Grouting for Producing Semi-Flexible Asphalt Concrete Mixtures. MEJ. Mansoura Engineering Journal, 40(4):22-38.
[59] Sanad, A.M (2022). Performance analysis of semi-flexible bituminous mixture manufactured by warm mixing technique and its comparison with traditional hot asphalt mixture [Unpublished master's thesis]. University of Cairo.
[60] Azam, Gabr, Ezzat, Arab, Alshammari, Alotaib and Zeiada.2024 Life cycle assessment and pavement performance of recycled aggregates in road construction, Case Studies in Construction Materials 20 - e03062.
[61] Pasandin, A.R. and Perez, I., 2015. Overview of Bituminous Mixtures Made with Recycled Concrete Aggregates. Construction and Building Materials, 74, pp.151-161.
[62] Jin, Ruoyu, and Qian Chen. "Investigation of Concrete Recycling in the U.S. Construction Industry." Procedia Engineering 118 (2015): 894-901.
[63] Oikonomou, Nik.D. "Recycled Concrete Aggregates." Cement and Concrete Composites 27, no. 2 (February 2005): 315-318.
[64] Wang, B., L. Yan, Q. Fu, and B. Kasal. 2021. "A comprehensive review on recycled aggregate and recycled aggregate concrete." Resour. Conserv. Recycl. 171 (Aug): 105565. https://doi.org/10.1016/j.resconrec.2021.
[65] Aytekin, Mardani and Sema.,2023. Performance assessment of recycled waste materials for use in unbound pavement Layers: A case study from Turkey, Construction and Building Materials 402 - 133004.
[66] Zou, Sun, Liu and Zhang., (2020). Influence factors on using recycled concrete aggregate in foamed asphalt mixtures based on tensile strength and moisture resistance, Construction and Building Materials, 265, 120363.
[67] Adegoke D.D, T. O. Ogundairo1, D.O Olukanni and O.M. Olofinnade,2019, Application of Recycled Waste Materials for Highway Construction: Prospect and Challenges, Journal of Physics: Conference Series 1378 (2019) 022058.
[68] El-Tahan, D., Gabr, A., El-Badawy, S., and Shetawy, M. (2018) Evaluation of Recycled Concrete Aggregate in Asphalt Mixes, Innovative Infrastructure Solutions 3:20 DOI: 10.1007/s41062-018-0126-7.
[69] Arisha, A., Gabr, A., El-Badawy, S. and Shwally, S., 2016. Using Blends of Construction& Demolition Waste Materials and Recycled Clay Masonry Brick in Pavement. Procedia Engineering, 143, pp.1317-1324.
[70] Arulrajah, A., M. Piratheepan, and M. Disfani. Reclaimed Asphalt Pavement and Recycled Concrete Aggregate Blends in Pavement Subbases: Laboratory and Field Evaluation. Journal of Materials in Civil Engineering, Vol. 26, No. 2, 2014, pp. 349-357.
[71] Behiry, A.E.A.E.M., 2013. Utilization of Cement Treated Recycled Concrete Aggregates as Base or Subbase Layer in Egypt. Ain Shams Engineering Journal, 4(4), pp.661-673.
[72] El-Tahan, D.; Gabr, A.; Samer Dessouky, S; and El-Badawy, S., (2024) Study of the Performance of Warm-Mix Asphalt Containing Recycled Concrete as a Coarse Aggregate in Egypt and the Middle East.
[73] El-Badawy SM, Gabr AR, Abdel Hakim RT., 2018 Recycled Materials and by-Products for Pavement Construction. In: Martínez LMT, Kharissova OV, Kharisov BI (eds)Handbook of ecomaterials. Springer, New York, pp 1-22.
[74] Gabr AR, Cameron DA (2012) Properties of recycled concrete aggregate for unbound pavement construction. J Mater Civ Eng 24(6):754–764.

[75] Poon CS, Chan D (2006) Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. Constr Build Mater 20(8):578–585.
[76] Al-Bayati, (2024). Rutting Performance of Asphalt Mixtures Containing Recycled Concrete Aggregate and Reinforced by Carbon Fibers. MS Thesis. Department of Civil Engineering, University of Baghdad, Ministry of Higher Education and Scientific Research, Republic of Iraq.
[77] Nazal and Ismael., 2019. Evaluation of the Moisture Susceptibility of Asphalt Mixtures containing Demolished Concrete Waste Materials, Civil Engineering Journal Vol. 5, No. 4.
[78] Al-Bayati HKA, Tighe SL, Achebe J (2018) Infuence of recycled concrete aggregate on volumetric properties of hot mix asphalt. Resour Conserv Recycl 130:200–214.
[79] Pérez, I. and Pasandín, A.R., 2017. Moisture Damage Resistance of Hot-Mix Asphalt Made with Recycled Concrete Aggregates and Crumb Rubber. Journal of Cleaner Production, 165, pp.405-414.
[80] Razzaq, A.K., 2016. Possibility of Utilizing Recycled Concrete Aggregates in HMA Mixture. Kufa journal of Engineering, 7(3).
[81] Gul WA, Guler M (2014) Rutting susceptibility of asphalt concrete with recycled concrete aggregate using revised Marshall procedure. Constr Build Mater 55:341–349.
[82] Paranavithana, S. and Mohajerani, A., 2006. Effects of Recycled Concrete Aggregates on Properties of Asphalt Concrete. Resources, Conservation and Recycling, 48(1), pp.1- 12.
[83] Mills-Beale, J. and You, Z., 2010. The Mechanical Properties of Asphalt Mixtures with Recycled Concrete Aggregates. Construction and Building Materials, 24(3), pp.230- 235.
[84] Covilla-Varela, E., E. Turbay, R. Polo-Mendoza, G. Martínez-Arguelles, and J. Cantero-Durango. 2023. “Recycled concrete aggregates (RCA)-based asphalt mixtures: A performance-related evaluation with sustainability-criteria verification.” Constr. Build. Mater. 403 (Nov).
[85] Martinho, F. C. G., L. G. Picado-Santos, and S. D. Capitao. 2018. “Influence of recycled concrete and steel slag aggregates on warm-mix asphalt properties.” Constr. Build. Mater. 185 (Oct): 684–696. https://doi.org/10.1016/j.conbuildmat.2018.07.041.
[86] Martinho, F., S. Capitão, and L. Picado-Santos. 2012. “Sustainable pavements: Warm asphalt mixtures made with recycled aggregates from different industrial by-products.” In Proc., Atas do EPAM4-4th European Pavement and Asset Management Conf. Zagreb, Croatia: Hrvatsko Asfaltersko Društvo
[87] Kodekal Shankar, Sunil S, M S Nagakumar,2019 Performance Studies on Semi Rigid Mixes with Incorporation of Construction and Demolition Aggregates, Colloquium on Transportation Systems Engineering and Management (CTSEM)-, India
[88] Mohammed A. Mahmoud, Ammar A. Shubber and Aqeel Raheem Jabur, Effect of Using Recycled Waste Concrete Materials On Rutting Behavior of HMA, International Journal of Civil Engineering and Technology, 9(4), 2018, pp. 697-709.
[89] ECP (Egyptian Code of Practice). 2020. "Egyptian Code of Practice for Urban and Rural Roads, edition 1: Road Materials and Their Tests (Part Four)." Ministry of Housing, Utilities and Urban Communities, Cairo, Egypt.
[90] Mohammadinia, A., Arulrajah, A., Sanjayan, J., Disfani, M.M., Bo, M.W. and Darmawan, S., 2014. Laboratory Evaluation of the Use of Cement-Treated Construction and Demolition Materials in Pavement Base and Subbase Applications.Journal of Materials in Civil Engineering, 27(6), p.04014186.
[91] Gómez-Meijide, B., Pérez, I. and Pasandín, A.R., 2016. Recycled Construction and Demolition Waste in Cold Asphalt Mixtures: Evolutionary Properties. Journal of Cleaner Production, 112, pp.588-598.
[92] Gupta. L, Kumar. R, Recarpeting using cement grouted bituminous mix in urban flexible pavement: a laboratory and feld evaluation, Aust. J. Civ. Eng. 00(2021) 1–12, https://doi.org/10.1080/14488353.2021.1896125.
[93] Luo. S, Yang. X, Zhong. K, Yin J.2020, Open-graded asphalt concrete grouted by latex modified cement mortar.Road Materials and Pavement Design, 21(1): 61-77, https://doi.org/10.1080/14680629.2018.1479290.
[94] ASTM C778 - 13, Standard Specification for Standard Sand, ASTM International, West Conshohochen, PA, 2013.
[95] ASTM, C39/C39 M - 21 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.
[96] ASTM, C293/C293M-10 Standard Test Method for Flexural Strength of Concrete, 2007.
[97] Guo, X. and P. Hao, Influential Factors and Evaluation Methods of the Performance of Grouted SemiFlexible Pavement (GSP)-A Review. Applied Sciences, 2021. 11(15).
[98] Corradini. A, G. Cerni, A. D'Alessandro, F. Ubertini, Improved understanding of grouted mixture fatigue

behavior under indirect tensile test configuration, Constr. Build. Mater. 155 (2017) 910-918.

[99] Zhang. H, S. Liang, Y. Ma, X. Fu, Study on the mechanical performance and application of the composite cement-asphalt mixture, Int. J. Pavement Eng. 20 (1) (2019) 44-52.

[100] Zhang, J., J Cai, J Pei, R Li, X Chen., Formulation and performance comparison of grouting materials for semi-flexible pavement. Construction and Building Materials, 2016; 115: 582-592

[101] ASTM, D6390 Standard Method of Test For Determination of Draindown Characteristics In Un-Compacted Asphalt Mixtures, 1997

[102] BSI, BS EN 12697-19 Bituminous mixtures -Test Methods for Hot Mix Asphalt asphalt-Part 19: Permeability of specimen, 2012.

[103] ASTM, C131-06 Standard test method for resistance to degradation of smallsize coarse aggregate by abrasion and impact in the Los Angeles machine,2006.

[104] AASHTO TP 108, Standard Method of Test for Abrasion Loss of Asphalt Mixture Specimens 2014.

[105] ASTM, C939/C939M Standard Test Method for Flow of Grout for Preplaced Aggregate Concrete (Flow Cone Method), 2002.

[106] ASTM, D6927-15 Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures, 2015.

[107] AASHTO, T324, Standard method of test for Hamburg wheel-track testing of compacted hot mix asphalt, (HMA) (2011).

[108] Yetkin Yildirim, Priyantha W. Jayawickrama, M. Shabbir Hossain, Abdulrahman Alhabshi, Cenk Yildirim, Andre de Fortier Smit, and Dallas Little,2007, HAMBURG WHEEL-TRACKING DATABASE ANALYSIS, FHWA/TX-05/0-1707-7.

[109] ASTM D8044, 2016. Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance Using the Semi-circular Bend Test (SCB) at Intermediate Temperatures.D8044-16. ASTM International, West Conshohocken.

[110] AASHTO T 378. (2017). Standard method of test for determining the dynamic modulus and flow number for asphalt mixtures using the Asphalt Mixture Performance Tester (AMPT). American Association of State and Highway Transportation Officials, Washington, DC, USA.

[111] AASHTO T 342. (2011). Standard method of test for determining dynamic modulus of Hot-Mix asphalt concrete mixtures. American Association of State and Highway Transportation Officials, Washington, DC, USA.

[112] Gong. M, Xiong. Z, Deng .C, Peng. G, Jiang.L, Hong. J. (2022). Investigation on the impacts of gradation type and compaction level on the pavement performance of semi-flexible pavement mixture, Construction and Building Materials 324 (2022) 126562

[113] Zhao, W., & Yang, Q. (2022). Study on the applicability of asphalt concrete skeleton in the semi-flexible pavement, Construction and Building Materials 327 (2022) 126923.

[114] Imran Khan. M, Muslich, Sutanto M.H, Yusoff. N.I, Salah E. Zoorob, Waqas Rafiq, Mujahid Ali, Roman Fediuk and Nikolai Ivanovich Vatin.2022. Cementitious Grouts for Semi-Flexible Pavement Surfaces A Review Materials 2022, 15, 5466. https://doi.org/10.3390/ma15155466

[115] Kumar, D. H., Chinnabhandar, R. K., Chiranjeevi, K., Shankar, A.U. R. "Effect of aggregate gradation and bitumen type on mechanical properties of semi-flexible asphalt mixtures", Case Studies inConstruction Materials, 18, e02025, 2023

[116] AASHTO R 62. (2013). Standard practice for developing dynamic modulus master curves for asphalt mixtures. American Association of State and Highway Transportation Officials, Washington, DC, USA.

تقييم أداء خلطات البيتومين المحقونة بالمونة الاسمنتية باستخدام ركام مخلفات الهدم والبناء المعاد تدويره

الملخص

إن استنزاف الركام الطبيعي والزيادة السريعة في مخلفات البناء والهدم (CDW) قد خلقا تحديات ملحة تتعلق بالاستدامة في مجال إنشاء الأرصفة. معظم الأبحاث السابقة حول الخلطات البيتومينية المحقونة بالإسمنت (CGBM)اقتصرت على استخدام الركام الطبيعي، مع قلة قليلة من الدراسات التي تناولت جدوى دمج الركام الخرساني المعاد تدويره(RCA) ، خصوصًا في ظل الظروف المصرية. تُعد الخلطة البيتومينية المحقونة بالإسمنت (CGBM) نوعًا مركبًا من الأرصفة يتم إنتاجه من خلال حقن ملاط إسمنتي داخل هيكل إسفلتي مفتوح التدرج يحتوي على نسبة فراغات هوائية تتراوح بين ١٨–٣٥ % .

تهدف هذه الدراسة إلى تقييم الأداء المعملي للـ CGBM المصنَّعة بنسب مختلفة من الركام الخرساني المعاد تدويره (RCA) المستخرج من مخلفات البناء والهدم. حيث استُبدل الجزء الخشن من الركام الطبيعي (NA) بنسب ٠٪، ٢٥٪، ٥٠٪، ٧٥٪، و١٠٠٪. تم تصميم جميع الخلطات باستخدام طريقة مارشال التقليدية، بينما أُعد الملاط الإسمنتي على أساس اختبارات السيولة ومقاومة الضغط والانحناء.

تم تقييم الأداء من خلال اختبارات النضح، فقدان الكانتابرو، الانحناء النصفي(SCB) ، تتبع العجلة هامبورغ (HWTT)، معامل المرونة الديناميكي(E*) ، واختبار رقم الانسياب .(FN) أظهرت النتائج أن الخلطات المحتوية على RCA قدمت أداءً مماثلاً أو متفوقًا على الخلطة المرجعية(0% RCA) ، مع تحقيق فوائد بيئية واقتصادية. فقد أظهرت نتائج HWTT تحسنًا ملحوظًا في مقاومة التخدد للخلطات المحتوية علىRCA ، بينما أشارت اختبارات SCB إلى زيادة مقاومة التشقق. كما حققت خلطات RCA قيمًا أعلى لمعامل المرونة الديناميكي وانخفاضًا في التشوه الدائم باختبار .FN

كان للتدرج الحبيبي للـ RCA تأثير ملحوظ على الأداء الميكانيكي. وُجد أن مستويات الاستبدال المثلى تتراوح بين ٢٥٪ و٧٥٪، حيث أظهرت نسبة ٧٥ RCA %أفضل مزيج من مقاومة التآكل، مقاومة التخدد، والثبات. أما الخلطة المحتوية على ١٠٠ RCA %فلم تحقق متطلبات الأداء في هذه الدراسة. وأكد التحليل الإحصائي باستخدام تحليل التباين متعدد المتغيرات (MANOVA) أن محتوى RCA له تأثير معنوي على الأداء.

تدعم النتائج استخدام RCA في الـ CGBM كوسيلة لخفض تكاليف إنشاء الطرق، والحفاظ على الموارد الطبيعية، وتعزيز الاستدامة بما يتماشى مع الاتجاهات العالمية نحو إنشاءات أكثر خضرة وابتكارًا.