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Effects of Crushed Glass Waste as a Fine Aggregate on Properties of Hot Asphalt Mixture

Ahmed D. M. Almuhmdi[1,2*]

Abdulbasit A. Muhmood[2]

Abdulhakim O. Salih[3]

[1]Ministry of Higher Education and Scientific Research, University of Fallujah, Fallujah, Iraq

[2]Department of Building and Construction Engineering Technology, Technical Engineering College / Mosul, Northern Technical University-Mosul, Iraq

[3]Department of Civil Engineering, College of Engineering, Salahaddin University-Erbil, Iraq

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ABSTRACT

The recycling of waste requires large areas; besides recycling wastes to their origin is often economically and environmentally costly. Glass is considered as a solid waste that is difficult to dispose of; it doesn't degrade nor burn. Since glass is a silicic substance with similar properties to aggregates, it can be recycled in asphalt mixtures. This research aims to determine optimum binder content (OBC) of conventional hot asphalt mixture (HMA), (control mixture), and investigate the effect of crushed glass waste (CGW), on its properties. In this work, several percentages of CGW (10%, 15%, 20%, and 25%) have been used as a partial substitution for the weight of fraction size 2.36-0.075mm of natural aggregate to prepare glass-contained asphalt mixtures and compare their properties with the control mixture. Mix design by Marshall method was used, and the properties according to Iraqi standards (SORB/R9,2003), for binder layer, were found, as well as conducting of Retained Marshall stability (RMS), indirect tensile strength (IDT), and tensile strength ratio (TSR), tests on mixtures, as performance tests. The results showed that the OBC of the control mixture was 5% wt., and the Marshall stability and flow values of glass-contained asphalt mixtures were oscillating around the values of the control mixture. The air voids, voids in mineral aggregate, and bulk density were reduced regularly as CGW increased. Also, it was observed from the results that the glass-contained mixtures have good performance properties. However, all results conformed to the standards (SORB/R9, 2003). So, the incorporation of CGW in HMA for the binder layer is feasible.

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* *Corresponding author: E-mail: -* sydik1983@yahoo.com Ministry of Higher Education and Scientific Research, University of Fallujah, Fallujah, Iraq

تأثير نفايات الزجاج المكسر كركام ناعم على خواص خليط الاسفلت الحار

احمد دحام محمد المحمدي / قسم تقنيات هندسة البناء والانشاءات، الكلية التقنية الهندسية/ الموصل، الجامعة التقنية الشمالية، الموصل، العراق
عبد الباسط عبدالعزيز محمود / قسم تقنيات هندسة البناء والانشاءات، الكلية التقنية الهندسية/ الموصل، الجامعة التقنية الشمالية، الموصل، العراق
عبدالحكيم عثمان صالح / قسم الهندسة المدنية، كلية الهندسة، جامعة صلاح الدين، اربيل، العراق

الخلاصة

يهدف هذا البحث إلى تحديد محتوى الرابط الأمثل للخلطة الاسفلتية التقليدية الحارة، (خليط تحكم)، والتحري عن جدوى إستخدام نفايات الزجاج المكسر كركام ناعم في التبليط الاسفلتي، بواسطة دراسة تأثير نفايات الزجاج المكسر على الخصائص الميكانيكية للخلطة الاسفلتية الحارة. في هذه الدراسة، تم استخدام نسب مختلفة من مخلفات الزجاج المكسر (١٠، ١٥، ٢٠، ٢٥٪)، كبديل جزئي عن وزن الركام الطبيعي الناعم العابر منخل رقم ٨ والمتبقي على منخل رقم ٢٠٠ لتحضير خلطات الاسفلت المحتوية على الزجاج المكسر، ومقارنتها مع خليط التحكم. استخدمت طريقة مارشال في تصميم الخلطات وتحديد خصائصها وفقاً للمواصفة العراقية للطرق والجسور وتعديلاتها، (SORB/R9, 2003)، للطبقة الرابطة (نوع II). ايضاً، تم اجراء إختبارات إستقرار مارشال المتبقي و مقاومة الشد الغير مباشر و نسبة مقاومة الشد، كإختبارات اداء، على كل من الخلطة المرجعية و الخلطات الاسفلتية المحتوية على الزجاج ومقارنة النتائج. اظهرت النتائج ان محتوى رابط الاسفلت المثالي لخليط التحكم كان ٥٪ من وزن الخليط . كانت قيم ثبات مارشال و التدفق للخلطات الاسفلتية المحتوية على الزجاج تتأرجح حول قيم خليط التحكم، اما الفراغات الهوائية و الفراغات بين الركام المعدني، والكثافة الظاهرية للخليط، تنخفض بإنتظام مع زيادة نسبة الزجاج. اظهرت النتائج ايضاً، ان الخلطات المحتوية على الزجاج تتمتع بخصائص اداء جيدة. مع ذلك، اظهرت النتائج ان جميع الخلطات مع او بدون زجاج كانت مطابقة للمواصفات العراقية (SORB/R9, 2003)، لذالك، فإن دمج نفايات الزجاج المكسر في الخلطات الاسفلتية الحارة للطبقة الرابطة، امر ممكن من الناحية الفنية وتعتبر طريقة فعّالة للتخلص من النفايات الزجاجية.

الكلمات الدالة: نفايات الزجاج المكسر، محتوى الرابط الأمثل، الخلطات الإسفلتية المحتوية على الزجاج، استقرار مارشال المتبقي، مقاومة الشد الغير مباشر، نسبة مقاومة الشد.

1. INTRODUCTION

With a widening world and the marked growth of haulage volumes, the demand for road networks and suitably designed pavements is increasing. Because obtainable natural resources became rare, so that, incorporation of recycled materials for construction purposes, such as flexible pavement construction, has become commonly [1], all the world waste (glass, scrap tires, plastic materials, demolition materials, etc.) is disposed of in piles and buried, but this is economically and environmentally expensive [2]. On the other hand, the continued depletion of large quantities of the natural aggregate reduces this resource and consumes fuel; therefore, it has a significant impact on the environment. For this reason, the use of waste materials as an alternative for natural aggregates saves energy and reduces the environmental waste [1] [2], as well as improving the engineering properties of asphalt paving in its various layers, including the asphalt binder layer. International collaboration is a principal factor in conserving the environment by diminishing greenhouse gas emissions and save of native natural resources through viable recycled materials exploitation in constructions [3]. Also, wastes recycling in roads construction reduces landfill areas [2]. So, incorporation of wastes materials in pavements is useful in terms of financial cost saving.

Glass is considered a solid waste that is difficult to dispose of; it does not degrade nor burn. Since glass is a silicic substance with similar properties to aggregates, it can be recycled in asphalt mixtures as a partial substitution for fine aggregates or filler. Recycling glass waste from glass factories to produce new glass saves significant energy and natural resources. Recycling glass waste as aggregate in roads may not save energy and resources such as glass manufacturing, but the imbalance between the production of glass and the generated waste may cause encouragement to the use of glass waste as aggregate in road applications and other uses [4]. In many countries of the world, New Zealand, for example, the demand for natural aggregate used in constructions, including roads, is associated with many factors such as low riverbeds, which require governmental licenses; thus, it becomes a valuable resource. The second factor is the problems associated with landfills and cleaning (land area cost, environmental constraints extreme, and moving costs), which may be at high costs in some regions [5]. Studies have shown, in developed countries, that in the antecedent years, the total quantity of crushed glass annually ranges from approximately 10% to 75% of the produced glass [6]. All over the world, nearly 10 million tons of glass waste are produced, 3% to 5% of which is household waste [7].

There are many studies concerned with incorporating the crushed glass waste into asphalt mixtures; Dalloul [2] studied the incorporation of glass wastes as fine aggregates into hot bituminous mixtures for the binder course of paving. The gradation of crushed glass waste (CGW) was (passed sieve size of 4.75 mm). The crushed glass content was as follows: 2.5%, 5%, 7.5% 10%, 12.5% and 15%, by aggregate weight. Marshall tests showed that the OBC of about 5.1% and indicated the feasibility of using glass aggregates in HMA. However, the optimum percentage of crushed glass was 7.5% by aggregate weight. Anochie-Boateng and George [8] conducted a laboratory study to develop an asphalt concrete mixture containing CGW as a partial substitution for conventional aggregate. The used aggregate gradation for the wear layer has a maximum size of 9.5 mm, and the crushed glass waste gradation is from a sieve size of 4.75 to sieve No. 200. The glass content was 15% by weight of selected fine aggregate. The optimum asphalt content was 5.1% for the glass-contained asphalt mixture, and it was close to the optimum asphalt content of the reference mixture (5%). The results of the volumetric analysis of the glass-contained asphalt mixture showed that they meet the standards of South Africa. Issa [9] elucidated in his research about using crushed glass waste as a partial substitution for natural aggregate in the asphalt mixture that the performance of glass-contained asphalt mixture improved compared to the reference mixture, which consists of conventional materials. The percentages of 5%, 10%, and 15% by weight of aggregate were the contents of the glass that are combined in the mixture. Abu Salem et al. [10] studied using different proportions of crushed glass waste as a partial substitution of the fine natural aggregate in bitumen concrete mixtures, at a maximum size of 2.36 mm for glass particles. In that study, it was investigated how the optimum asphalt binder content was affected by glass waste aggregate and moisture resistance of all mixtures. Testing results showed that the use of glass wastes in hot asphalt mixtures has an effective positive impact, technically and economically. Also, it requires less bitumen content and greater stability and durability than the control mix. The optimum content of crushed glass waste was 10% by weight of fine aggregate, which gives a satisfactory performance of the asphalt concrete mixture. Alhassan et al. [11] accomplished research aimed at studying the use of glass waste in the wear layer. Six percentages of the crushed glass were used as a partial substitution for the fine natural aggregate. The Marshall results indicated that the crushed glass waste resembles the fine natural aggregate. So, glass aggregate can be used in asphalt mixtures with a size of 4.75 mm as a maximum, and that the properties of the mixture were within the specifications. The ideal proportion for crushed glass was 8%. Al-saeedi [12] performed laboratory tests on glass mixtures with different amounts of glass waste as a partial substitution for all sizes of aggregates (from filler to coarse aggregate). The contents of the glass were from 0 to 100% of each sieve portion. All Marshall properties (mechanical and volumetric) conformed to the criteria with all the various contents of the glass excluding the content (100%), which gave a flow value and voids filled with asphalt cement (VFB), below is the minimum standard in the case of using the glass as a filler, and flow value with the contents of 50%,75%, and 100% when using glass as a coarse aggregate is out of the upper limit of specifications.

It is concluded from the findings of the literature reviews that the crushed glass waste can be incorporated into hot asphalt mixtures as part of the natural aggregate, but at a maximal size of 4.75 mm and with a replacement percentage up to 15% of the aggregate, to avoid problems caused by crushed glass. In this study, fewer CGW percentages with a smaller size (passing the sieve No. 8) were used compared to previous studies to obtain better results. Therefore, the study aims to investigate the technical feasibility of using crushed glass waste (CGW). This aim is accomplished by determining the optimum binder content (OBC) of the control mixture (without glass) and conducting a study of the effect of crushed glass waste on the Marshall and some performance properties of asphalt mixtures in comparison with the control mixture. So, it was used four percentages of crushed glass waste (CGW) (10%, 15%, 20%, and 25%) as a partial replacement of fine natural aggregate (fraction size 2.36 - 0.075 mm), as well as natural materials, to prepare Marshall samples according to Iraqi standards (SORB/R9, 2003) for binder layer paving.

It was decided to use these sizes (fraction size 2.36 - 0.075 mm) and proportions of CGW in the binder layer in order to avoid the risks of stripping phenomenon in the mixture and to ensure the glass particles would not break under traffic loads, which may change the selected aggregate gradation because the use of larger sizes increases the potential of stripping, and breaking of glass particles [8], [10].

2. MATERIALS

The source of asphalt cement utilized in this study is from Salaei Group (asphalt plant), in Erbil city – the northern region of Iraq. The grade of asphalt binder is a 40/50 penetration grade, as it was used in making all asphalt mixture samples. Its properties tests were implemented in the Roads Laboratory of the Faculty of Engineering - Salahuddin University in Erbil city. The physical properties of the asphalt binder are presented in Table 1.

Table 1:

Asphalt cement properties

Test type	Units	ASTM specifications	Results	SORB/R9, specification limits for binder layer II
Penetration at 25C°	1/10 mm	D5-06	48.55	40-50
Ductility at 25 C°	cm	D113-07	150	>100
Specific gravity	g/cm3	D 70	1.07	-
Softening point	C°	D 36-95	54	-
Flash point	C°	D 92-90	241	>232

The natural aggregate utilized in this study is brought from Salaei Group (asphalt plant) in Erbil city – the northern region of Iraq. The aggregate (fine and coarse) and filler were found as piles; in the Salaei company, each pile had one size crushed particles, and a certain amount was brought from each pile, then the proportions of each size were tested, as shown in Table 2, and controlled in the laboratory to obtain the required gradation (Fig. 1).

Table 2:

Aggregates and crushed glass waste properties

property	Natural coarse aggregate	Natural fine aggregate	Dust filler
Bulk specific gravity (OD) (ASTM C 127) & (ASTM C 128)	2.685	2.569	------
Apparent specific gravity (ASTM C 127) & (ASTM C 128)	2.703	2.595	3.018
Absorption % (ASTM C 127), (ASTM C128)	0.3	0.4	------
Angularity % (ASTM D 3398), (ASTM C 1252)	92.8	31.2	N/A
Abrasion%, (ASTM C 131)	16	------	N/A
Sand equivalent % (T176)	------	68.65	------

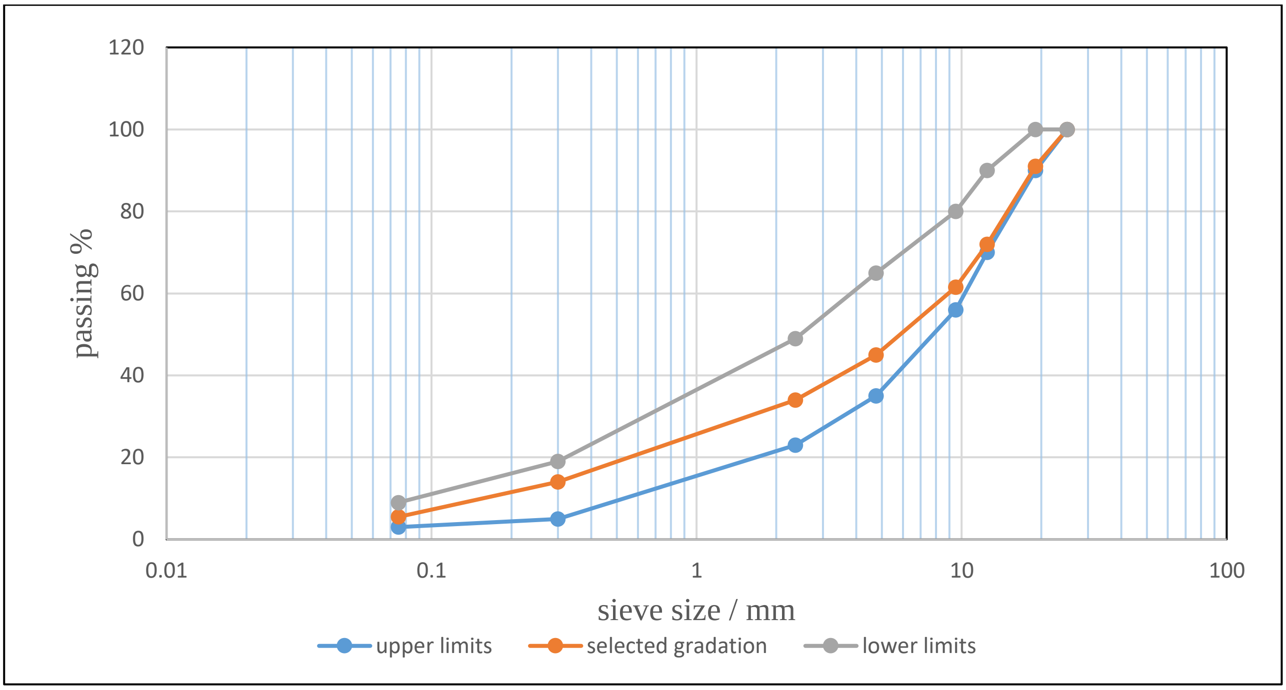


Fig. 1: SORB/R9, 2003 dense-graded gradation limits for binder layer (type II), and used aggregate gradation curves

The glass waste utilized in this study is scrap sheet pieces collected from doors and windows manufacturing workshops. After the glass waste pieces had been cleaned, they were manually broken into smaller pieces and then placed in the Los Angeles apparatus for a certain period in order to obtain the required sizes. After that, sieve analysis was carried out on the standard series of sieves (adopted by SORB/R9, 2003), (No. 3/8 in, No. 4, No. 8 (2.36mm), No. 50 (0.3mm), and No. 200 (0.075mm)). The glass particles, after crushing, are shown in Plate 1.

Plate 1: Glass waste crushing with Los Angeles apparatus.

The gradation of CGW after crushing was found as illustrated in Plate 2 and Fig. 2. The selected sizes of CGW in the present study were retained on sieve No. 50 and the retain on sieve No. 200, to be used as a partial substitution for the fraction with the size of 2.36-0.075mm of natural aggregate, and neglecting of other sizes of CGW. Some properties of the CGW were tested and the result, determined as shown in Table3. It is noted that the specific gravity of the glass particles was by the pycnometer method according to (ASTM C128), and it was 2.33, which is approximately 10% less than the specific gravity of fine natural aggregates.

Plate 2: Sieve sizes for CGW after crushing by Los Angeles apparatus and glass pieces before crushing

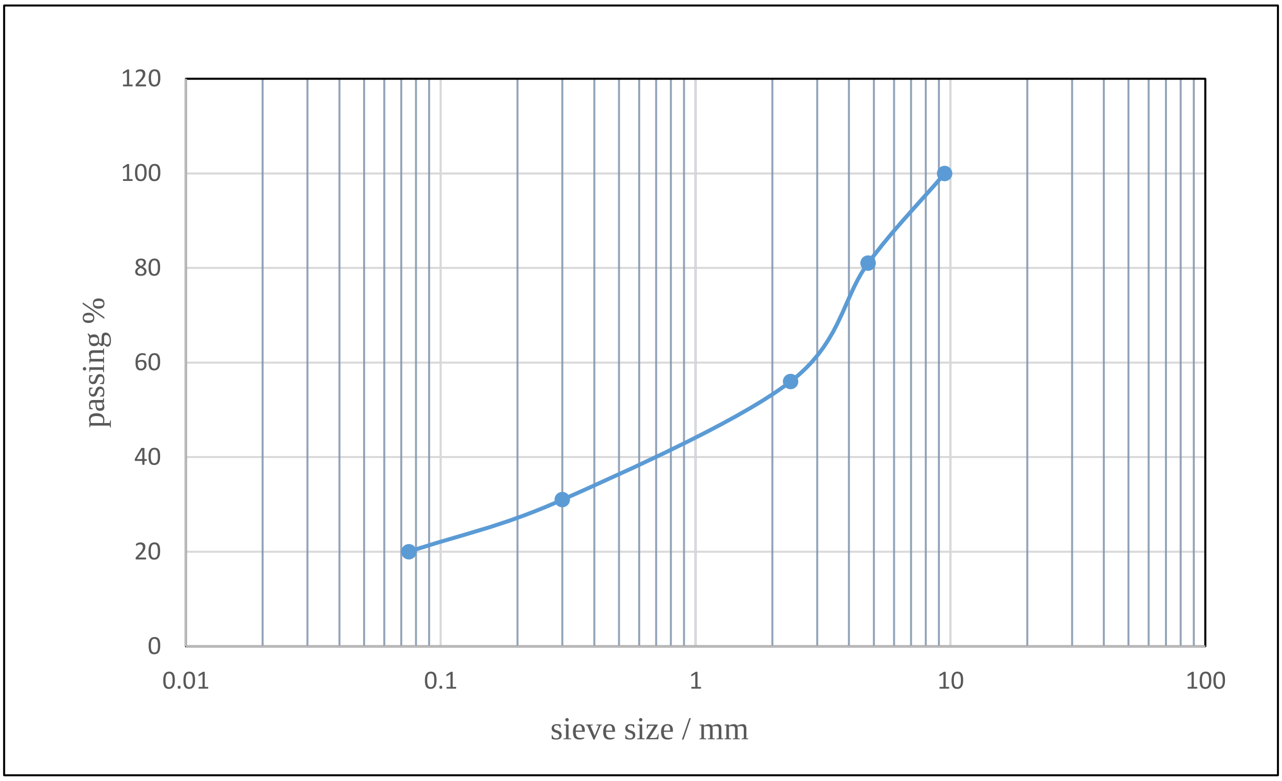


Fig. 2: Sieve analysis curve of glass particles after crushing

Table 3:

Crushed glass waste properties

property	specification	results
Specific gravity	ASTM C128 - 15	2.33
Absorption %	ASTM C128 - 15	0.0
Angularity %	ASTM C1252 - 06	35.62
Sand equivalent %	T176	95

3. EXPERIMENTAL WORKS

3.1. Mix design

Marshall samples for the conventional mixture were prepared and tested according to (ASTM D 6926- 10 & ASTM D6927 – 15, respectively), (Plate 3), according to Iraqi standards (SORB/R9, 2003), for the binder layer. In this study, the asphalt mixtures were prepared with seven binder contents (from 3.5% to 6.5% with 0.5% as an increment), compacted with 75 blows for heavy traffic levels. Three samples were prepared for each asphalt binder content mixed with natural materials only to determine the OBC of the control mixture. Also, samples of glass-contained asphalt mixtures (the mixture components are glass particles and natural materials mixed with asphalt cement) were prepared with each one of the four contents of crushed glass waste (10%, 15%, 20%, and 25%) as a partial replacement of fine natural aggregate (fraction No. 8 - No. 200) mixed by OBC of control mixture.

Plate 3: Prepared Marshall Specimens

The optimum asphalt binder content (OBC) for controlling the asphalt concrete mixture is determined based on the results of Marshall tests and the volumetric properties of the mixtures. The OBC is determined by relying on a higher stability rate, a higher density, and 4% of air voids of the samples by smooth curves representing a relationship of asphalt content versus mixture properties [13], as in Eq. (1).

$$OBC = \frac{S+D+V}{3} \quad \text{..........} (1)$$

Where: *OBC:* optimum binder content; *S:* binder content at maximum stability; *D:* binder content at maximum bulk density; and *V:* binder content at medium air voids content.

The Marshall stability values of the control and glass-contained asphalt mixtures and the associated plastic flow are measured by Marshall apparatus according to specification (ASTM D 6927 - 15). Also, the specific gravity of the sample (Gm), the content of the air voids (Va), the voids between the mineral aggregates (VMA), and the voids filled with asphalt binder (VFB) are calculated.

3.2. Indirect tensile strength (ITS)

The indirect tensile strength test (IDT) is implemented by applying a compressive load by Digital Marshal tester apparatus, along the vertical diametrical plane of a cylindrical specimen (Plate 4), according to (ASTM D6931-12).

Plate 4: Indirect tensile strength test with Marshall tester apparatus

As a result of compression loading (with a loading rate of 50mm/minute), tensile stress is generated perpendicular to the applied compressive load direction, which leads to a splitting failure perpendicular to the direction tensile stress (parallel to compressive load). Dependent on the maximum load which causes the splitting failure of the specimen, the indirect tensile strength (ITS) is determined by Eq. (2).

$$\boldsymbol{ITS} = 2000\, P / \pi t d \quad \ldots\ldots\ldots\ldots (2)$$

Where: *ITS*: indirect tensile strength (KPa), *P:* compressive load (N), *t:* the thickness of test specimen (mm), *d:* diameter of the specimen (mm).

This test is generally used to estimate the cohesive strength of the asphalt concrete mixtures [8], as well as for estimating the potential for rutting or cracking. When the mixture has a higher indirect tensile strength, the asphalt paving can endure the higher strain before failure [14]. In this study, the (IDT) was performed on the glass-contained asphalt mixtures and the control mixture samples at different temperatures (25, 40, and 60 C°), (immersed for 1 hour in the water bath), to estimate potential cracks of the paving.

3.3. *Moisture susceptibility of mixtures*

3.3.1. *Tensile strength ratio*

This test is used to investigate the moisture susceptibility of asphalt mixtures. The tensile strength ratio (TSR) test is an indicator of the adhesion loss between particles of aggregate and asphalt due to water. For this test, two groups of samples are prepared; one group is subjected to indirect tensile testing after being immersed in the water bath at a temperature of 25 C° for 20 minutes (unconditioned samples) and considered as control mixture, and the other is soaked in the water bath at a temperature of 60 C° for 24 hours, (conditioned samples), then immersing it in the water bath for 1 hour at a temperature of 25 C°.

Finally, both groups are tested at 25 C°. The samples are loaded by Digital Marshal tester apparatus, with a compressive load with a rate of 50 mm/ minute, on the vertical plane of the samples (Plate 4), until a split failure occurs in a direction parallel to the direction of the applied compressive load. The indirect tensile strength is calculated by Eq. (2), and the tensile strength ratio is calculated by Eq. (3). The test procedures were done according to (ASTM D4867/D4867M - 09).

$$TSR = \frac{ITS2}{ITS1} * 100 \quad \text{...........} (3)$$

Where: *TSR*: tensile strength ratio %, ITS_2: indirect tensile strength of conditioned samples (KPa), ITS_1: indirect tensile strength of unconditioned samples (KPa).

In this study, the tensile strength ratio of the control mixture and glass-contained asphalt mixtures with different percentages of CGW was tested. Glass particles are hydrophilic because they contain high silica content and have a smooth surface. Therefore, this property may cause the stripping phenomenon in the mixture due to the reduction of the adhesion between asphalt and aggregates [15]. To avoid stripping, hydrated lime was added to mixtures at 2% of the weight of the aggregates as an anti-stripping agent [1], [3], [4], [10]. The results were compared with mixtures without hydrated lime.

3.3.2. Retained Marshall stability

All mixtures are subjected to retained Marshall stability (RMS) test, which can be used to predict the resistance of the mixture to water damage. It is an indication of the moisture susceptibility of the mixture [16]. Six Marshall samples were prepared for each asphalt mixture; Marshall stability ($MS_{uncond.}$) was measured for three of them after being immersed in a water bath by 60 C° for 30 minutes (unconditioned), and other samples ($MS_{cond.}$) were measured after being immersed in a water bath by 60 C° for 24 hours, (conditioned), according to ASTM D1075 method. Then RMS is calculated according to Eq. (4).

$$RMS\% = (MS_{cond.} / MS_{uncond.}) \times 100 \quad \text{...........} (4)$$

Where $MS_{cond.}$: conditioned Marshall stability; $MS_{uncond.}$: unconditioned Marshall stability.

The high value of the retained stability percentage indicates high water resistance. (Shill Bitumen, 2015) [17], set the minimum level of Retained Marshall stability by 75%.

4. RESULTS AND DISCUSSION

4.1. OBC determining of conventional asphalt mixture

Table 4 shows Marshall test results of mixtures with different binder contents, and Fig. 3 illustrates the relationship of asphalt content with mechanical and volumetric properties (stability, flow, air voids, VMA, VFB, and bulk density). The OBC was determined as follows:

- Binder content at maximum stability = 4.9 %
- Binder content at the maximum value of bulk density = 5.3 %
- binder content at medium air voids content = 4.8 %

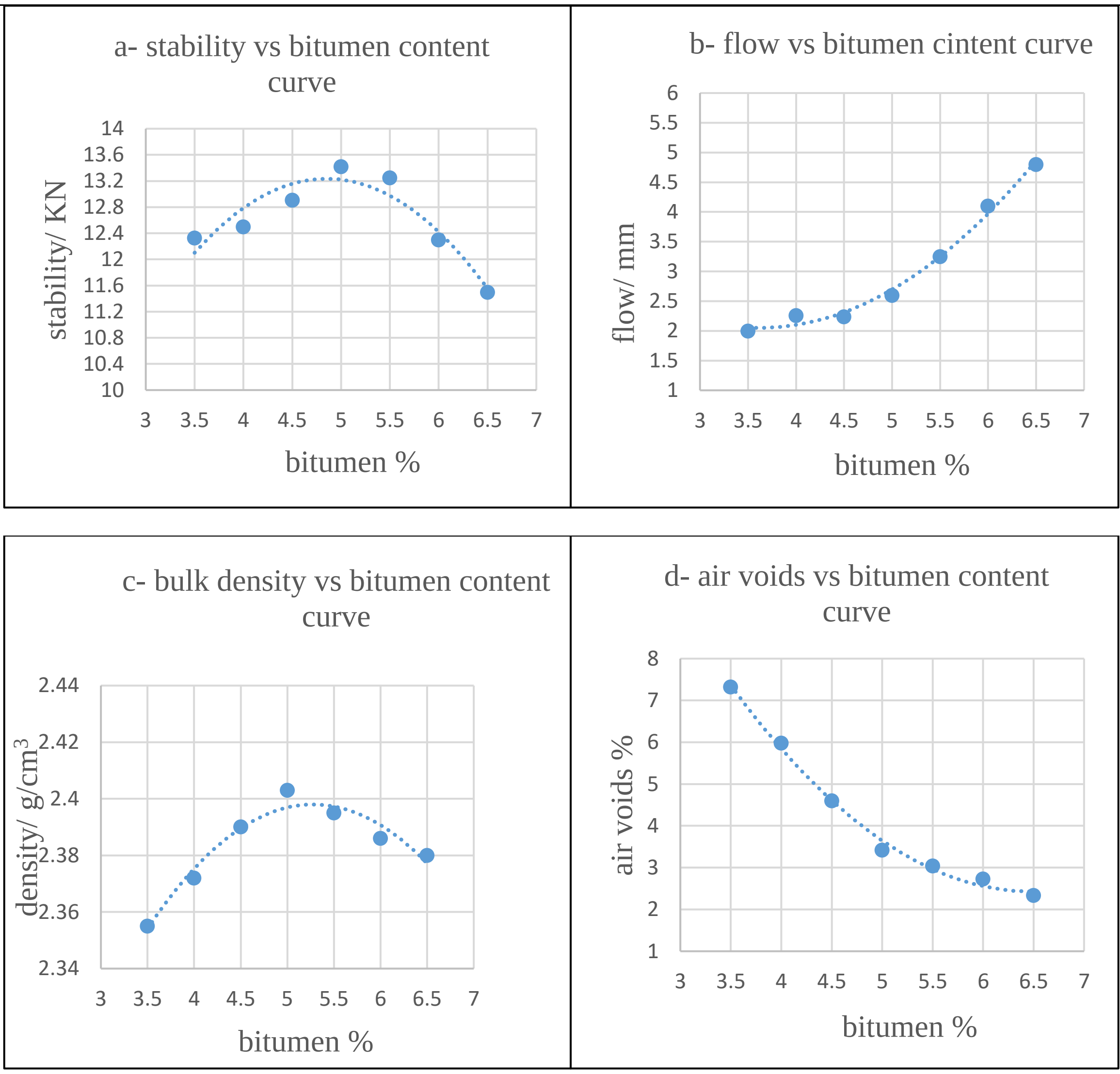
Optimum binder content (OBC) = (4.9 + 5.3 + 4.8)/3 = 5 %

Table 4:

Marshall test results of mixtures without glass waste with different binder contents

OBC %	Stability / KN	Flow / mm	Density/ g/cm³	Air voids %	VMA %	VFB %
3.5	12.33	2	2.355	7.32	14.37	49.06
4	12.5	2.26	2.372	5.98	14.2	57.89
4.5	12.91	2.24	2.39	4.6	14	67.14

5	13.42	2.6	2.403	3.42	13.98	75.54
5.5	13.25	3.25	2.395	3.04	14.72	79.35
6	12.3	4.1	2.386	2.73	15.49	82.4
6.5	11.5	4.8	2.38	2.33	16.15	85.6



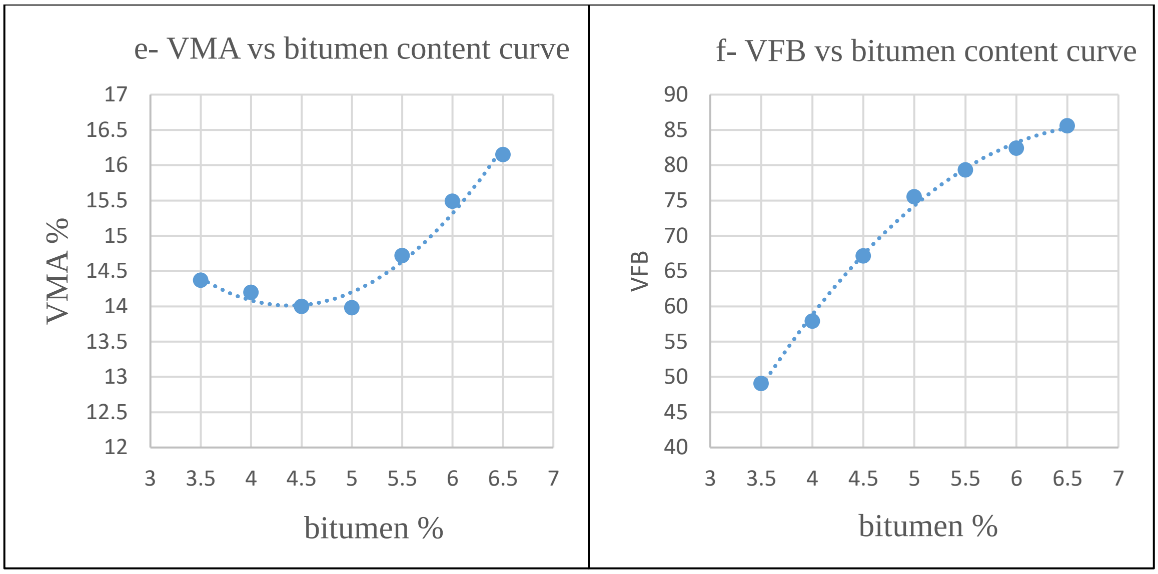


Fig. 3: Curves for relationships of Marshall properties with asphalt content, for trial asphalt mixtures without CGW

The OBC of 5%, by weight of paving mixture, was suitable content mixed with the selected aggregate blend to produce optimum mixture conforms with Iraqi specifications (SORB/R9, 2003) for binder layer paving and considered as control mixture in the present study. The mechanical properties of the optimum conventional mixture were shown in Table 5 and found that all properties meet the limits of the specifications.

Table 5:

Mechanical properties of designed control mixture

Property	Results	SORB/R9, 2003 specifications limits, for binder layer, (type II)	
		Min	Max
Stability / KN	13.25	7	--
Flow / mm	2.6	2	4
Density / g/cm3	2.403	--	--
Air voids %	3.42	3	5
VMA %	13.98	13	--
VFB %	75.54	60	80

4.2. Effect of crushed glass waste on Marshall properties

Four percentages of crushed glass waste were mixed with natural aggregate and 5% binder content to make glass-contained asphalt mixtures and compared with control mixture and Iraqi specifications.

Fig. 4 illustrates that Marshall stability values of glass-contained mixtures meet the Iraqi standards (SORB/R9, 2003) for the binder layer, which defined the minimum limit by 7 KN. Fig. 4 illustrated that the Marshall stability values of these mixtures have increased with the increase of CGW and reduced at 25% CGW, although it has been initially decreased by 2.4%, less than the control mixture. The effect of glass particles, in this study, on Marshall stability is not significant because using small sizes of CGW (passing the 2.36mm sieve), where Marshal stability value is primarily dependent on coarse aggregate. The high values of mixtures stability exhibit high resistance against rutting due to the high angularity of crushed aggregate.

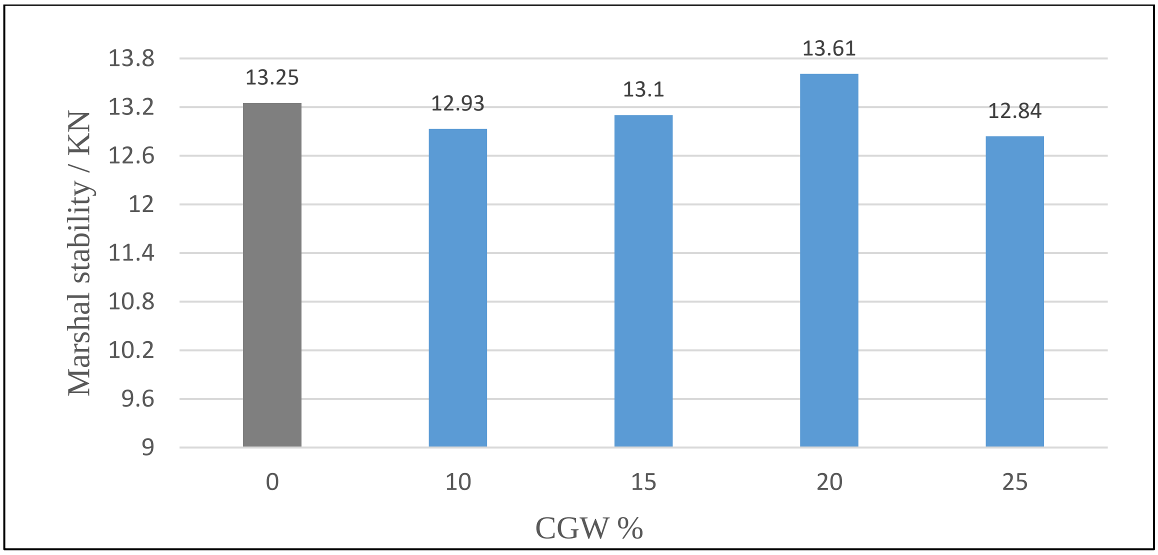


Fig. 4: Marshall stability – CGW relationship

From Fig. 5, which illustrates the Marshall flow-CGW relationship, it was observed that the flow values oscillate at the same value of the control mixture (2.6 mm) because of using the same OBC.

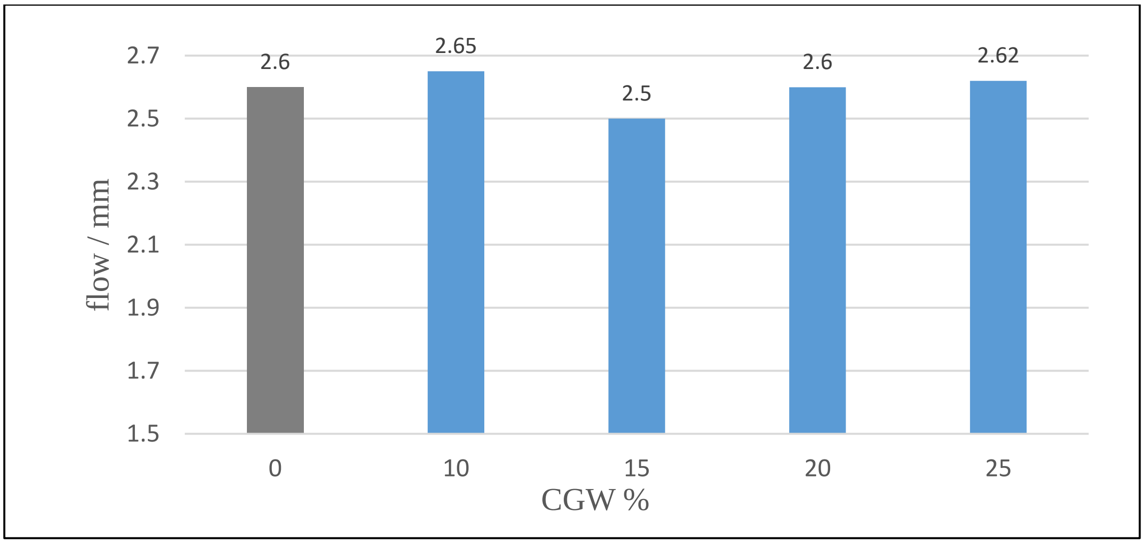


Fig 5: Marshall flow – CGW relationship

As for volumetric properties, the air voids content was decreased regularly as the proportion of glass increased, as illustrated in Fig. 6. The reason is that because the glass is not absorbent for the asphalt; consequently, it leaves an extra abundance of asphalt within the VMA

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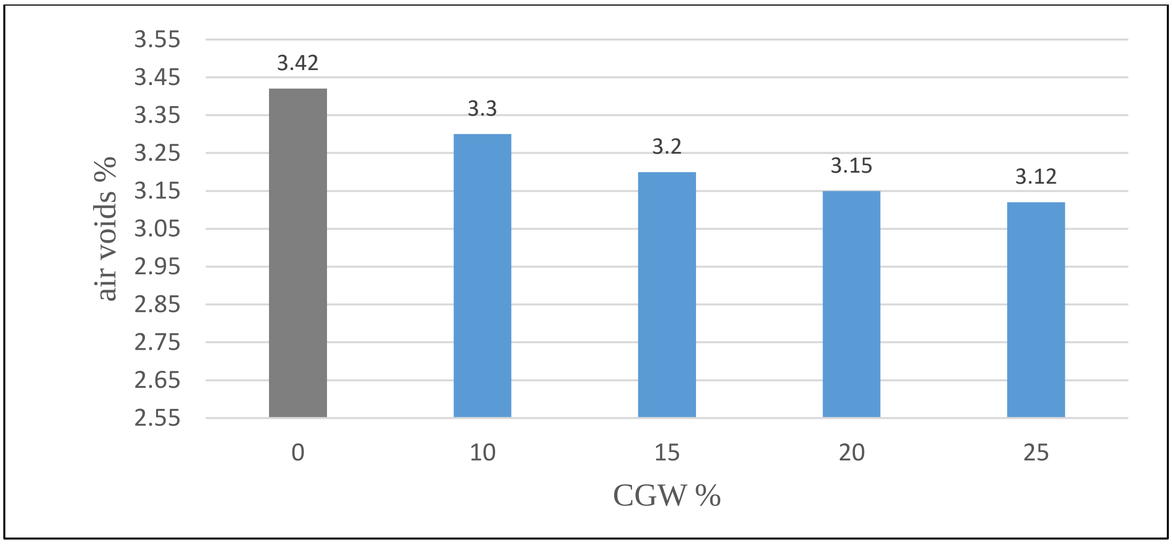

Fig. 6: Air voids – CGW relationship

Fig. 7 displays the results of VMA percentages. The percentages of the VMA for glass-contained asphalt mixtures did not differ much from the VMA of the control mixture and are within the limits of the Iraqi standard (SORB / R9,2003) for binder layer paving, which was set at 13% as a minimum. The bulk density also decreased as glass content increased (Fig. 8) because the crushed glass has a bulk density less than fine natural aggregate by about 9.3%.

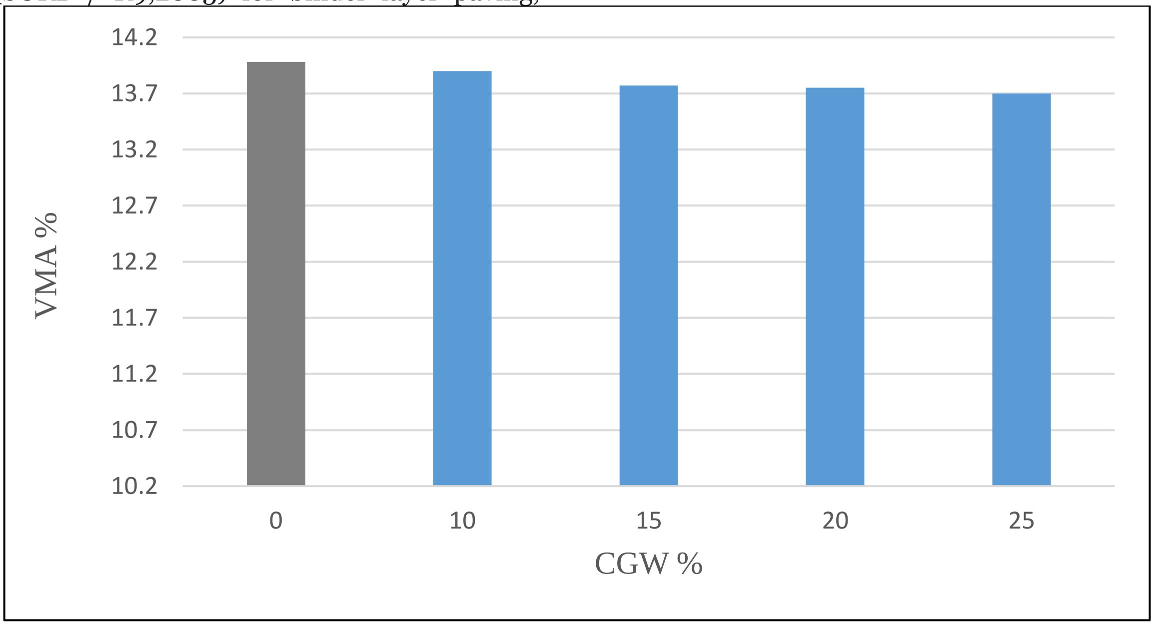

Fig. 7: VMA – CGW relationship

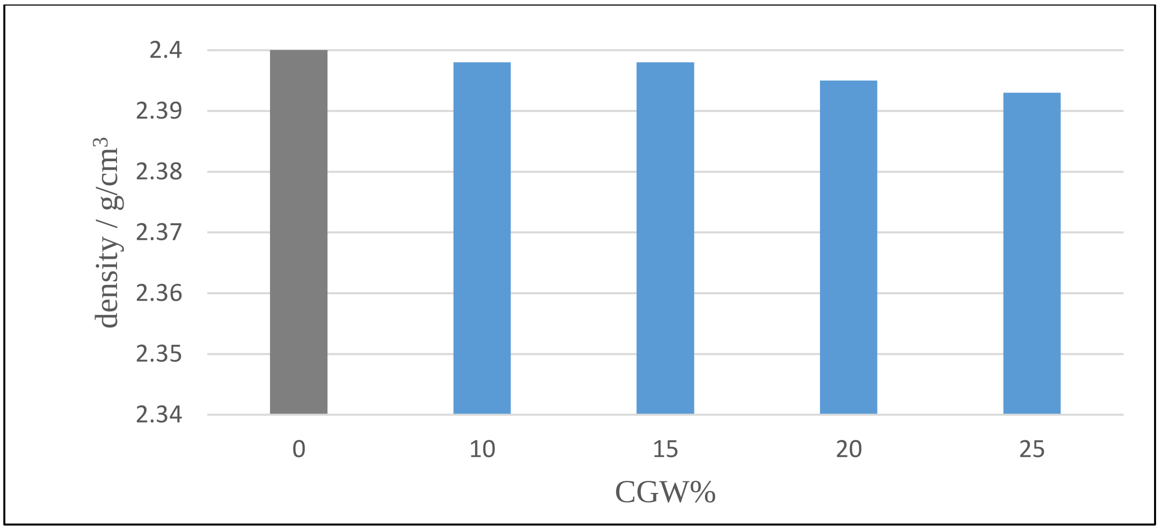

Fig. 8: Density – CGW relationship

4.3. *Effect of crushed glass waste on indirect tensile strength*

Fig. 9 shows the results of the indirect tensile strength test for the control and glass-contained mixtures with three temperatures (25, 40, and 60 C°). Indirect tensile strength (ITS) results showed that the mixtures of glass-contained mixtures had acceptable performance properties and were comparable to the control mixture because of using glass particles in small sizes and little doses. The figure showed that the strengths of the glass-contained mixtures decreased slightly with the high dosage of crushed glass at CGW of 25% due to the slipping of glass particles together as one block at a high dosage of crushed glass. Fig. 9 shows that increasing temperature causes remarkably decreasing the strength of mixtures, but the effect of temperature change on the strength of glass-contained mixtures, did not differ greatly from its effect on the strength of the control mixture.

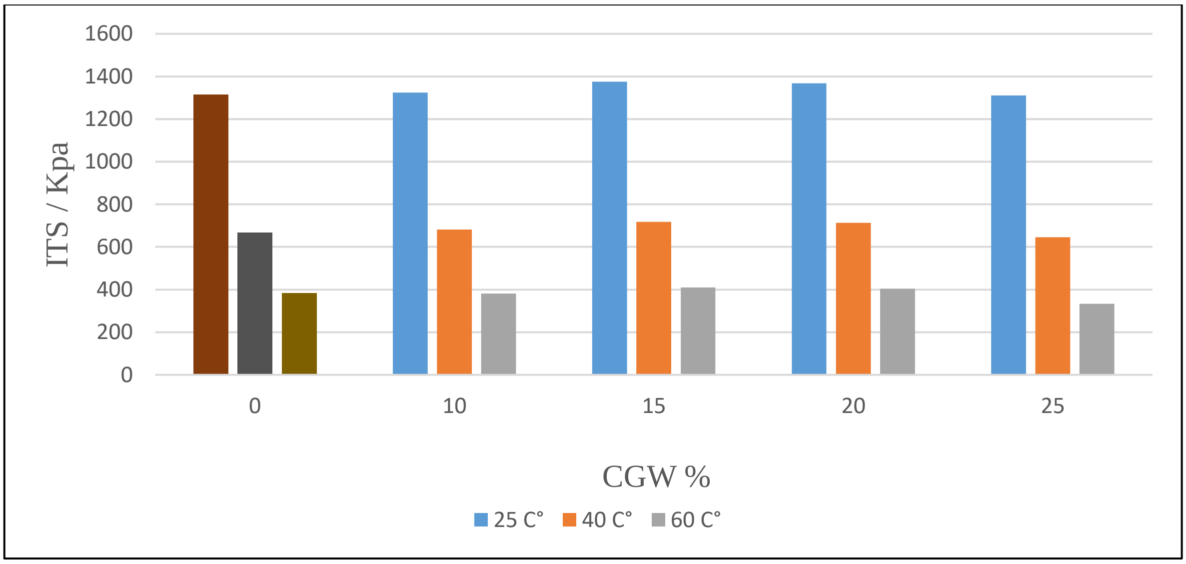

Fig. 9: Indirect tensile strength vs. crushed glass percentages

However, some studies have indicated that the ITS values below of about 1000 KPa tend to rut (flexible pavement), but ITS values more than 1700 KPa, may tend to brittleness at 25 C° [8]. Depending on this range (1000-1700KPa), it can be deduced that glass-contained asphalt mixtures have good rutting performance. ITS results at different temperatures (25, 40, and 60 C°) indicate the reduction of glass-contained mixtures stiffness with increasing temperatures within acceptable limits, also indicate good resistance to rutting.

4.4. Effect of crushed glass waste on moisture resistance

4.4.1. Tensile strength ratio test results

The results of the tensile strength ratio test are shown in Fig. 10. It was noticed that the lowest tensile strength ratio of the mixture was with the CGW of 25%, and the highest was for the control mixture, without glass. Fig. 10 shows the tensile strength ratio decreases with increasing the crushed glass content because the glass particles are not absorbent for the asphalt and are poor in terms of adhesion with the asphalt. It has been shown that the efficiency of hydrated lime in improving the TSR for glass-contained asphalt mixtures is more than that for the control mixture, especially at CGW content of 20 and 25%, because the control mixture contains natural materials that have good adhesion properties with the asphalt. However, all mixtures with and without crushed glass have sufficient TSR according to (Asphalt Institute, MS-2, 7th edition), which set the minimum ratio of 80%.

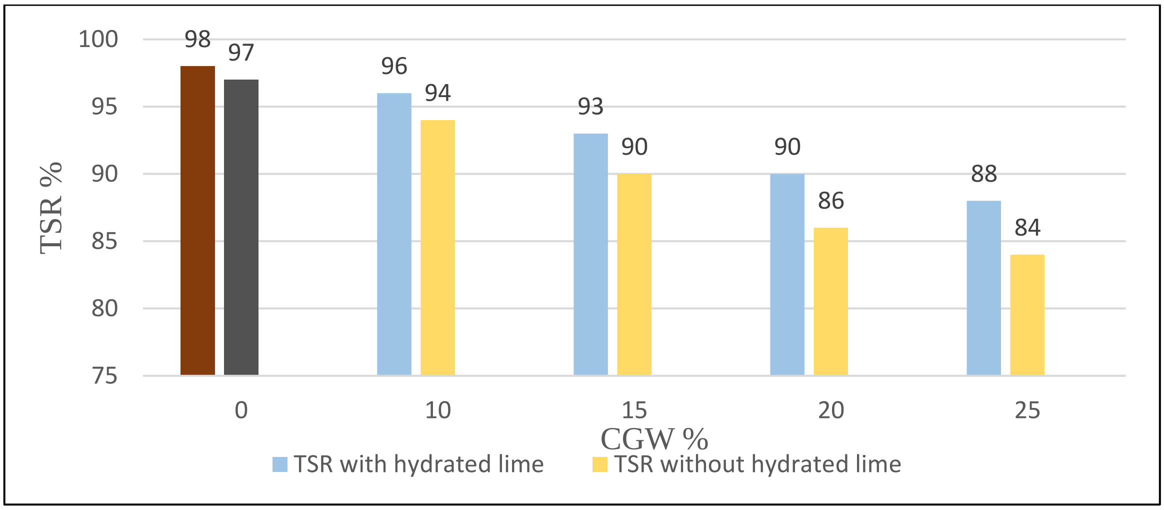

Fig. 10: Tensile strength ratio (TSR) vs. crushed glass waste percentages

4.4.2. Retained Marshall stability test results

Table 7 shows the results of retained Marshall stability (RMS) test. The test showed that the glass-contained asphalt mixtures have satisfactory moisture resistance, according to (Shill Bitumen Handbook, 2015) [17]. The RMS percentages were reduced with increasing glass content. In comparison with the control mixture, the RMS percentage reduced from 82% (without glass) to 76.87% with 25% glass content.

Table 6: Retained Marshall stability test results

CGW %	MSuncon. / KN	MScon. / KN	RMS %
0	13.42	11	82
10	12.93	10.36	80.12
15	13.1	10.51	80.23
20	13.61	10.68	78.47
25	12.84	9.87	76.87

5. CONCLUSIONS

It should be noted that the main objective of this study is to investigate the technical feasibility of recycling the glass waste in hot asphalt mixtures for the binder layer, and this requires that the glass-contained asphalt mixtures possess satisfactory properties according to the limits of the Iraqi specifications (SORB/R9, 2003), for the binder layer. Depending on the results of laboratory tests of the glass-contained asphalt and control mixtures, the following can be concluded:

1. Using crushed glass as a substitution for fine sand is technically feasible. The glass-contained asphalt mixtures have mechanical properties close to conventional hot asphalt mixtures; thus, adopting glass waste in a flexible pavement reduces depletion of natural resources. This economically and environmentally effective way for glass waste recycling, in case factories concerning collecting and crushing of glass waste, is available.
2. The General trend of crushed glass waste with these percentages and glass particles size which passed sieve 2.36 mm, towards increasing of Marshall stability (except at 25% glass, where stability dropped), and reducing density, air voids, and VMA.
3. All the mixtures with all percentages of CGW in the present study succeeded under RMS, and ITS tests, which indicates acceptable moisture sensitivity, and the other properties were also accepted.
4. The glass-contained asphalt mixtures had acceptable performance properties in terms of the indirect tensile strength (ITS), with different temperatures, where the strength increases as the CGW increases till CGW of 15%, then decrease. Thus, it is an acceptable indicator of good mixtures performance in terms of stiffness and rutting resistance.

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