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Compaction Effort Evaluation of Crumb Rubber Modified Hot Mix Asphalt

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Abstract: The primary goal of this study was to obtain the same performance from an asphalt mixture made using a Marshall impact hammer (MIH) as from asphalt made using a Superpave gyratory compactor (SGC). This was due to the expense of Superpave equipment compared with Marshall equipment. A wet process was used to blend the CR with PG 70-16 asphalt. A crushed stone aggregate was used with a 19 mm nominal maximum aggregate size, and the samples were prepared using an SGC and an MIH. The results show that nine percent CR was determined to be the optimum crumb-rubber content (OCRC). In addition, the SGC provided excellent performance in Marshall stability, density, tensile strength, and compressive strength at different numbers of blows and gyrations compared with the MIH. Moreover, the MIH required approximately 21, 21, 18, and 24 extra blows to obtain the same stability, density, tensile strength, and compressive strength, respectively, as the SGC at the design number of gyrations (N_{design}). Furthermore, modified mixtures at the OCRC increased the compressive strength in the range from 16 to 48 percent and had higher values on the index of retained strength than unmodified mixtures. As a result, they provided mixtures with less susceptibility to moisture damage. The significance of this study is that asphalt that performed the same as Superpave samples was obtained using only Marshall equipment.

Keywords: crumb rubber; nominal maximum aggregate size; Superpave gyratory compactor; Marshall impact hammer; moisture sensitivity

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Citation: Qadr, D.B.; Talabany, A.F. Compaction Effort Evaluation of Crumb Rubber Modified Hot Mix Asphalt. *Sustainability* **2023**, *15*, 7839. https://doi.org/10.3390/su15107839

Academic Editors: Shuangqiao Yang, Qingye Li and Dong Tian

Received: 6 April 2023
Revised: 3 May 2023
Accepted: 7 May 2023
Published: 10 May 2023

1. Introduction

A key component of transportation infrastructure is the roadway system. It is challenging to build a road with uniform compaction that is close to the required specifications [1]. However, to construct roads with a sufficient degree of compaction and to provide a long service life, appropriate hot-mix asphalt (HMA) compaction is required [2]. The performance of flexible pavements is greatly influenced by the compaction of the asphalt mixtures. The degree and technique of compaction have significant impacts on mixing characteristics, including the density and air voids. Permanent deformation and fatigue cracking are two pavement performance indicators that are influenced by volumetric analysis and compaction efforts [3].

The results of the evaluation process and the compaction technique that are employed are both factors in how different laboratory compaction methods differ from one another. A mix design procedure's objective is to blend aggregates and asphalt in a way that can deliver the appropriate degree of performance. It is crucial to use realistic methods for assessing the strength of HMA. One of the factors that influences the strength of the HMA is the method used to produce a test sample in the lab that exactly simulates the structure of the paving mixture when it is implemented in the field [4–6].

The quality of the construction methods that are utilized greatly impacts how well asphalt pavement performs. Even if an asphalt mix is well designed and well produced, the performance of the pavement will decrease if the compaction process is not adequate during paving and construction. Consequently, the degree of compaction should be considered one of the primary quality characteristics of HMA throughout design, production, and placement in the field [7–9].

The quality and durability of asphalt are greatly influenced over time by its initial properties, which can result in pavement distresses such as permanent deformation, fatigue cracking, and thermal cracking. In addition to these distresses in asphalt pavement, rapid increases in traffic volume, including high axle loads, and variations in temperature from night to day and from the coldest temperature in winter to the hottest temperature in summer affect the quality of the asphalt. Therefore, asphalt modifications are becoming a necessity in asphalt mix design, specifically using the Superpave mix design method [10].

Researchers have made several attempts in recent decades to create a modifier that would be able to enhance the rheological properties of an asphalt binder. The scholars discovered that adding crumb rubber modifier (CRM) increased the asphalt's elastic component, which indicated that an asphalt mixture would recover when the imposed tension from wheel tracks was removed [11–13].

Prior studies demonstrated that CRM combined with an asphalt mixture provides a pavement mixture that can reduce traffic noise, minimize maintenance costs, decrease the environmental pollution, and increase the resistance to permanent deformation [14] and thermal cracking [15]. As a result, most countries increased their utilization of rubberized asphalt in HMA [16].

Scrap tires are not a recyclable material, and they pollute the environment. The problem is how to dispose of around 1.5 billion scrap tires annually worldwide, which has raised severe environmental concerns in several nations [17–19]. They have been residing in waste areas and pose a hazard to the surrounding environment and to people, plants, and animals. Therefore, the asphalt industry is now focusing on environmentally friendly pavement infrastructure improvements as a substitute for increasing the usage of waste materials and to enhance and improve the performance of HMA [20].

The history of using CRM in asphalt pavements can be traced back to the 1960s in the US. At this time, waste from scrap tires was used as a modifier and was developed by an engineer (Charles McDonald) by mixing crumb rubber (CR) with asphalt to produce a modified mixture. Since then, specialized engineers have conducted a number of empirical tests on CR [21,22]. These experiments determined that adding crumb rubber to an asphalt pavement mixture increased the pavement's durability, skid resistance, resistance to permanent deformation, and resistance to fatigue cracking [23,24].

Additionally, the marketing of CRM has grown, particularly in the United States and across the rest of the world. The majority of laboratory tests demonstrate that the majority of engineering features are enhanced by employing rubberized bitumen in pavement [25].

Generally, there are two kinds of CR, which may be distinguished by the variations in their surface textures and particle sizes. The methods of grinding used to produce ambient or cryogenic rubber cause these variations. Ambient CR is produced using a typical high-powered rubber cracker mill that is configured to produce a crumb rubber with irregular jagged particles. On the other hand, cryogenic CR is produced using chillers to freeze rubber that has previously been crushed into tiny crumbs or chips in order to provide a relatively smooth fracture surface [26].

Normally, there are two methods to produce modified asphalt, which are the wet and dry methods. In the wet method, fine particles of CR in the range of 0.075 mm to 1.2 mm are blended with asphalt at a high temperature before being combined with an aggregate to create CRM asphalt. In the dry method, granulated CR in the range of 0.3 mm to 10 mm is commonly used to replace a tiny amount of aggregate in the appropriate proportion [27].

Compared to the wet method, the dry method is more economical since it uses a large amount of CR and requires less energy for the modifying processes in asphalt plants. However, the dry method is not a powerful method for modifying an asphalt mixture due to a number of unsolved problems, such as the challenge of obtaining a consistent mixture and the consequence of swelling throughout compaction [28]. Furthermore, several previous laboratory and field studies demonstrated that the dry method typically performs poorly or improves asphalt little when compared to the wet process [29].

The degree of CR absorption into the asphalt is one of the fundamental factors affecting the incorporation of CR into asphalt. There are various ways to describe CRM mixing, but the unique way is the reaction between asphalt and CR. The mixing time, mixing temperature, and reaction effort are the primary aspects that should be considered during blending [30].

Typically, there are three classes of mixing temperatures, for example, a low temperature at 160 °C, a medium temperature at 175 °C, and a high interaction temperature at 200 °C. Usually, using CR in the wet process requires a high temperature for blending, but care should be taken to avoid the flash and fire point temperature of the asphalt that is used. Regarding the mixing time, it is recommended to be in the range of 45 to 60 min to enable enough interaction between the asphalt and CR [31].

The main aim of this study was to form a relationship between different compaction methods, the number of gyrations of a Superpave gyratory compactor (SGC), and the number of blows of a Marshall impact hammer (MIH) through a comprehensive laboratory study. Plenty of studies have been conducted comparing Superpave and Marshall mix design methods, but no one has worked on the differentiation in compaction effort in terms of the number of blows from an MIH and the number of gyrations in an SGC. Therefore, the key goal of this study was to obtain the same performance from an asphalt mixture made using an MIH as from asphalt made using an SGC. This was because Superpave equipment is more expensive than Marshall equipment. In addition, CRM was used to assess both mix design compaction efforts and evaluate the performance of HMA using a moisture sensitivity test criteria for the unmodified and modified mixtures.

2. Goals and Objectives

The main goal of this study was to obtain the same performance from an asphalt mixture made using an MIH as from asphalt made using an SGC. This was because of the high cost of the Superpave equipment. Marshall equipment is normally available in most laboratories. A comprehensive laboratory experimental study was used to form the required relationships between SGC and MIH in terms of Marshall stability, tensile strength, compressive strength, and moisture damage. In addition, all the experimental tests of the modified mixture were conducted using the CRM in order to have the best relationships using modified and unmodified mixtures. Moreover, the utilization of waste from scrap tires provided a clean environment. Furthermore, the mechanical properties were improved by increasing the stability and the tensile and compressive strengths of the asphalt mixture.

Limitations

Generally, there have been sufficient studies comparing the Superpave and Marshall mix design methods. The problem is that in the previous studies, the comparison of the compaction effort did not formulate a relationship between the number of blows in the Marshall method and the number of gyrations in the Superpave method. Therefore, the main limitation of this study is the lack of previous data supporting its results.

3. Materials and Methods

The laboratory study started when the materials were collected from three different sources in three different cities (source A in Erbil, source B in Sulaymaniyah, and source C in Duhok) in the north of Iraq. Then, the experimental work was separately initiated based on the standard specifications of the Superpave and Marshall mix design methods, according to the Asphalt Institute [32], for the three sources of aggregate and asphalt cement. The aggregate used for the three sources in this study was a crushed stone, and its consensus properties are shown in Table 1. The asphalt cement used in the study had a performance grade (PG) of PG 70-16, and its physical properties are shown in Table 2. The CR used in the study was from the Iraqi Rubber Company in Baghdad, Iraq. The company used an ambient grinding technique, and the particles of the CR used in the study passed through a 0.3 mm sieve and were retained on a 0.15 mm sieve. After that, the core of the study was initiated through a compaction effort evaluation of HMA for the unmodified and modified mixtures with CR using SGC and a Marshall impact hammer (MIH). Lastly, the performance evaluation of unmodified and modified HMA was carried out by conducting a moisture sensitivity test of the indirect tensile strength and the index of retained strength according to AASHTO T283 [33] and AASHTO T165 [34], respectively, as shown in Figure 1.

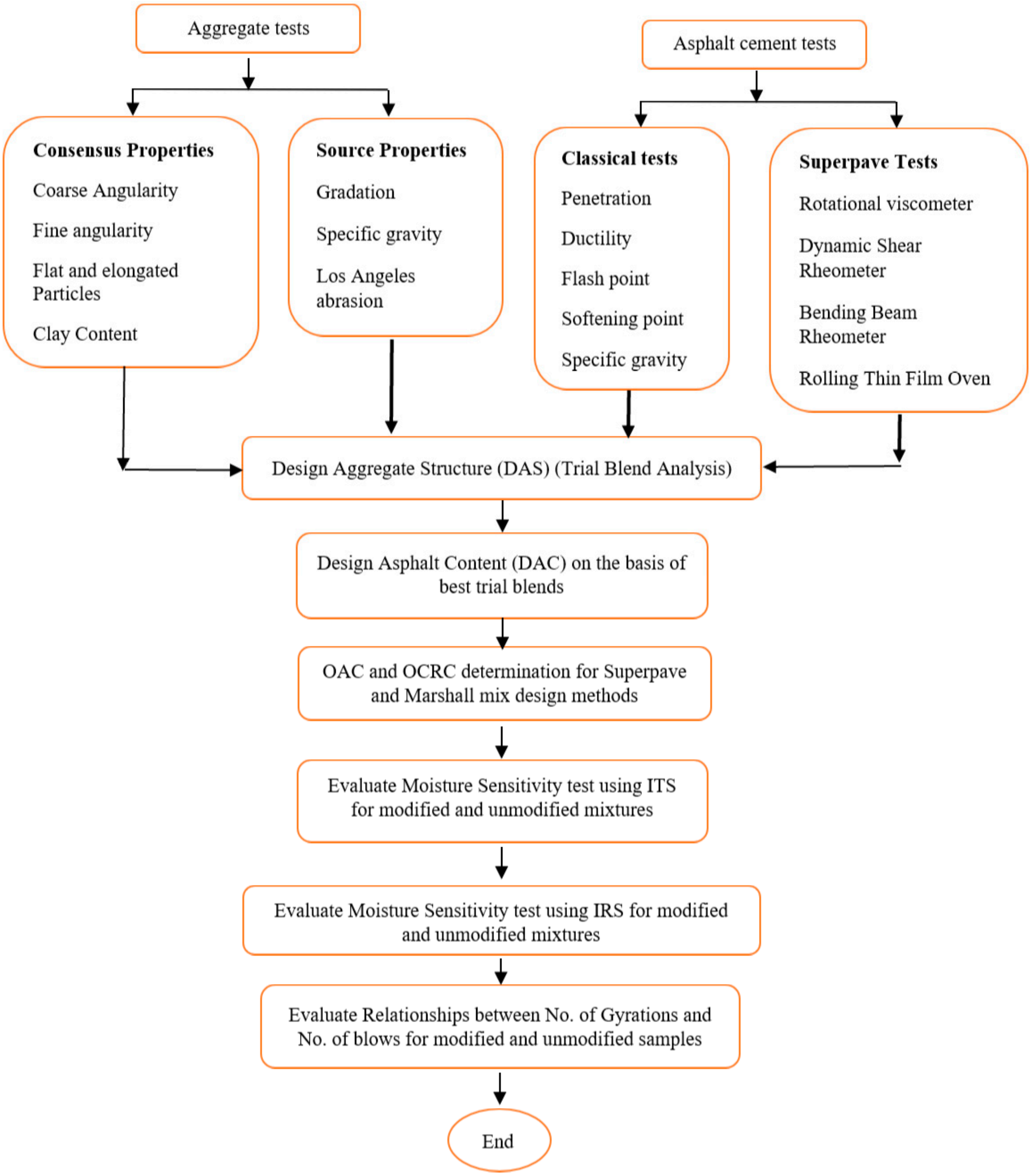


Figure 1. Flowchart of the experimental work.

Table 1. Source and consensus properties of the aggregate used in the study [32].

Aggregate Size	Tests	Standard Specifications	Results			Criteria
			Source A	Source B	Source C	
Coarse aggregate	Bulk specific gravity of coarse aggregate	ASTM C127 [35]	2.675	2.583	2.622	n/a
	Los Angeles abrasion test (%)	ASTM C131 [36]	14	23	18	35% Max.
	Coarse aggregate angularity, at least on fractured face (%)	ASTM D5821 [37]	97	96	97	95% Min.
	Coarse aggregate angularity with more than two fractured faces (%)		95	93	97	90% Min.
	Percentage of flat particles (%)	ASTM D4791 [38]	1	2	1	10% Max.
	Percentage of flat and elongated particles (%)		2	3	0	10% Max.
Fine aggregate	Bulk specific gravity of fine aggregate	ASTM C128 [39]	2.734	2593	2.634	n/a
	Fine aggregate angularity (%)	ASTM C1252 [40]	48	50	49	45% Min.
	Sand equivalent (clay content) (%)	ASTM D2419 [41]	81	80	84	45% Min.

Table 2. Physical properties of the PG 70-16 asphalt cement used in the study [32].

Tests	Standard Specifications	Results			Criteria
		Source A	Source B	Source C	
Flash point (°C)	ASTM D92 [42]	265	260	263	230 Min.
Penetration at 25 °C (0.1 mm)	ASTM D5 [43]	47	48	47	40–50
Softening point (°C)	ASTM D36 [44]	52	51	52	50–58
Ductility at 25 °C (cm)	ASTM D113 [45]	141	133	147	100 Min.
Specific gravity at 25 °C	ASTM D70 [46]	1.01	0.99	1.01	1.01–1.06
Elastic recovery (%)	ASTM D6084 [47]	17	14	15	n/a
Rotational viscosity at 135 °C (Pa·S)	ASTM D4402 [48]	0.572	0.569	0.570	3 Max.
$G^*/\sin\delta$ at 70 °C (not aged) (kPa)	ASTM D7175 [49]	1.32	1.1	1.27	1.0 Min.
$G^*/\sin\delta$ at 70 °C (RTFO) (kPa)		2.42	2.35	2.4	2.2 Min.
$G^*\sin\delta$ at 31 °C (PAV) (MPa)		3.1	3.0	3.09	5.0 Max.
Stiffness at −6 °C (PAV) (MPa)	ASTM D6648 [50]	56	62	60	300 Max.
Slope at −6 °C (PAV)		0.38	0.35	0.39	0.3 Min.

Sample Preparation

The samples were prepared as follows:

i. After confirming the results of the asphalt cement, the source and consensus properties of the aggregate used in the study were calculated according to the standard specification criteria of the Asphalt Institute [32], as shown in Tables 1 and 2.

ii. Modified bitumen with CR was prepared by mixing bitumen with CR prior to mixing with aggregate at 160–200 °C for 45 min; this was known as the wet process [31].

iii. The Marshall samples were prepared according to ASTM D1559 [51], and the Superpave samples were prepared according to AASHTO TP4 [52].

iv. In total, 64 Superpave Marshall samples were prepared for each source used in the study for the design aggregate structure (DAS), design asphalt content (DAC), optimum asphalt content (OAC), optimum crumb rubber content (OCRC), Marshall stability, indirect tensile strength test (ITS), and index of retained strength test (IRS), as shown in Figure 2.

(**a**) IRS samples

(**b**) OCRC determination samples

(**c**) Marshall stability machine

(**d**) Superpave and Marshall samples

(**e**) SGC

Figure 2. Tested samples.

4. Results and Discussion

4.1. Selection of Design Aggregate Structure (DAS)

The standard Superpave specification criteria were chosen according to a 19 mm nominal maximum aggregate size (NMAS) and for an equivalent single-axle load (ESAL) of 3–10 $\times$ 10^6, as shown in Table 3 [32]. The DASs were selected for each source as follows:

i. Source A: Trial blends 1 and 2 failed the voids filled with asphalt (VFA) criteria. However, these two blends were created with high compaction effort. It is clear in Table 3 that trial blend 3 had all the criteria; therefore, trial blend 3 was selected as a DAS.

ii. Source B: Trial blend 3 failed the percentage of voids in mineral aggregate (VMA) criteria. However, this trial blend was created with high compaction effort. It is shown in Table 3 that trial blends 1 and 2 had all the criteria, but only one trial blend was needed. Therefore, on the basis of the closest values of VMA and VFA to the criteria, it can be observed in Table 3 that trial blend 2 had closer values than trial blend 1; thus, trial blend 2 was selected as a DAS.

iii. Source C: All the trial blends passed the requirements of the Superpave criteria, but in order to choose the best one, it was recommended to select trial blend 1 because all the parameters that were determined in terms of the volumetric analysis were close to the required criteria. Therefore, trial blend 1 was selected as a DAS.

Table 3. Selection of best trial blends [32].

Trial Blends	Sources	Estimated % AC	% Air Voids	% VMA	% VFA	Dust Proportion	% Gmm at N_{max}	Satisfy Criteria	Trial Blend Selection
1	A	3.58	4	16.1	75.2	0.83	96.8	No	
2		4	4	18.6	78.4	1	97.1	No	
3		4.2	4	15.6	74.4	0.75	97.1	Yes	Selected
1	B	4.58	4	15.3	73.85	1.08	96.7	Yes	
2		4.7	4	13.56	70.5	1.06	96	Yes	Selected
3		4.58	4	12.76	68.65	1.05	97	No	
1	C	4.5	4	13.6	70.58	0.98	96.8	Yes	Selected
2		4.66	4	15.32	73.89	0.96	96.9	Yes	
3		4.62	4	13.84	71.1	0.95	96.7	Yes	
Superpave Criterion			4	13% Min.	65–75%	0.6–1.2	98% Max.		

Note: These criteria are according to a 19 mm nominal aggregate size and for an equivalent single-axle load (ESAL) of 3–10 million.

On the basis of these trial blend confirmations, the same selected trial blends were used for the Marshall mix design method.

4.2. Selection of Design Asphalt Content (DAC)

On the basis of the estimated asphalt content for the selected best trial blends shown in Table 3, Superpave recommends selecting four DACs into three parts as follows:

i. Estimated asphalt content;
ii. Estimated asphalt content ± 0.50%;
iii. Estimated asphalt content + 1.0%.

According to the results shown in Table 4, for both HMA design procedures, on the basis of the volumetric analysis and the stability of the mixtures, the OAC was determined for each source and mix design method. It can be observed in Table 4 that the OAC determined using the Marshall method (4.7–4.9%) was higher than that determined using the Superpave method (4.3–4.5%) for all three sources, whereas the Superpave method provided higher stability. This means that the Superpave mix design method is more cost-effective. This result conforms with the previous studies conducted by [53–55]. On the other hand, if the cost of equipment is considered, MIH is much cheaper than SGC.

4.3. Optimum Crumb Rubber Content (OCRC) Determination

In order to determine the OCRC, four percentages of crumb rubber (CR) were used (6, 9, 12, and 15) based on the previous studies of [56,57] and the 3 percent interval was used to obtain accurate results. Normally, in the wet process, less CR content is used compared to the dry process. These percentages of CR were used for each source using both the Marshall and Superpave mix design methods. Figure 3 illustrates that the stability and density of all the mixes increased steadily at six percent CR until it reached a maximum value at nine percent CR. Then, it gradually decreased. Generally, the Superpave mix design provided the maximum Marshall stability and density in all three sources compared to the Marshall mix design. However, both mix designs provided the maximum Marshall stability at nine percent CR. Accordingly, nine percent CR was selected as the OCRC for both mix design methods. Normally, the optimum CR content is selected on the basis of excellent performance, and usually, ranges vary from one study to another, depending on the parameters that are used. This result has trends that are similar to the results of prior studies [58–60].

Table 4. Optimum asphalt content (OAC) determination for Superpave and Marshall mixtures.

Sources	Asphalt Content (%)	Marshall Procedure				Superpave Procedure			
		Air Void (%)	VMA (%)	VFA (%)	Stability (kN)	Air Void (%)	VMA (%)	VFA (%)	Stability (kN)
A	3.7	5.83	14.28	59.16	9.55	5.13	13.93	63.18	17.80
	4.2	4.46	13.03	65.78	13.86	4.18	15.25	75.00	18.90
	4.7	4.03	12.64	68.13	12.67	3.56	18.00	80.20	16.11
	5.2	3.46	12.12	71.48	11.11	2.11	17.36	87.83	12.18
	OAC	4.70				4.30			
B	4.2	6.25	14.45	56.76	15.57	4.43	14.15	68.66	16.72
	4.7	4.28	13.11	67.33	16.88	3.67	12.69	71.10	19.31
	5.2	3.12	12.51	75.09	15.47	3.26	13.13	75.19	18.28
	5.7	2.93	12.80	77.14	12.37	1.97	11.86	83.37	17.28
	OAC	4.75				4.40			
C	4	7.67	14.88	48.48	11.91	4.84	13.12	63.07	12.36
	4.5	5.28	13.13	59.82	12.12	3.96	13.33	65.64	16.52
	5	3.74	12.18	69.32	13.88	2.52	11.93	78.83	15.57
	5.5	3.41	12.35	72.36	11.91	1.61	11.56	86.11	13.62
	OAC	4.9				4.5			

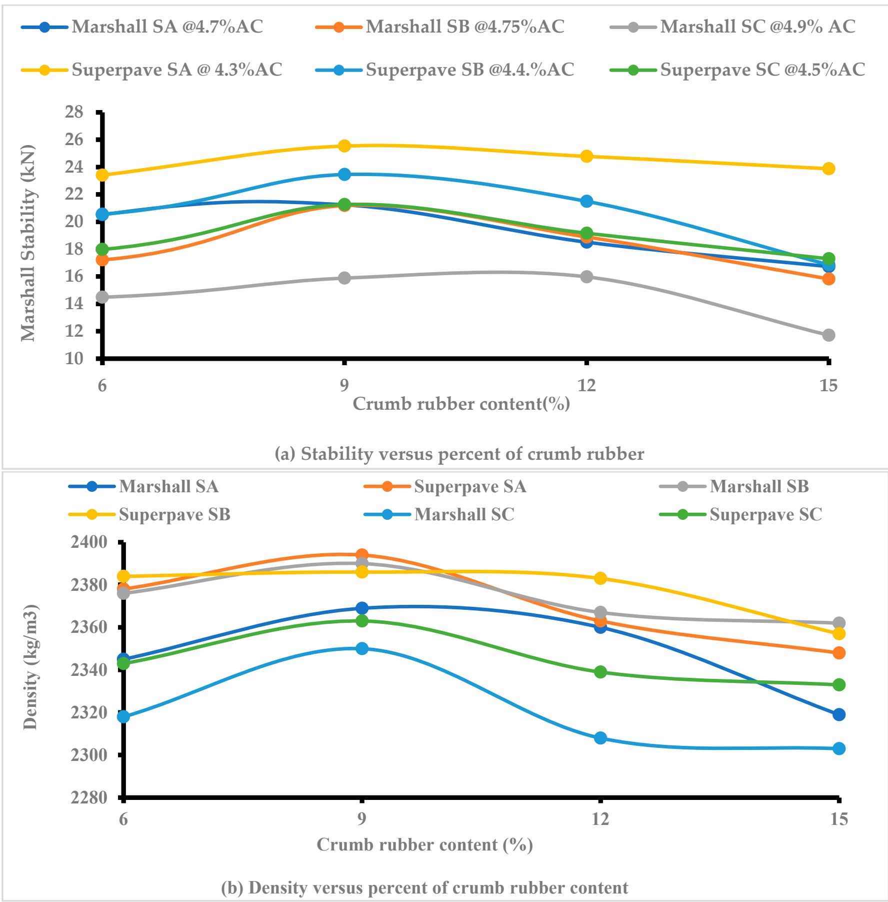


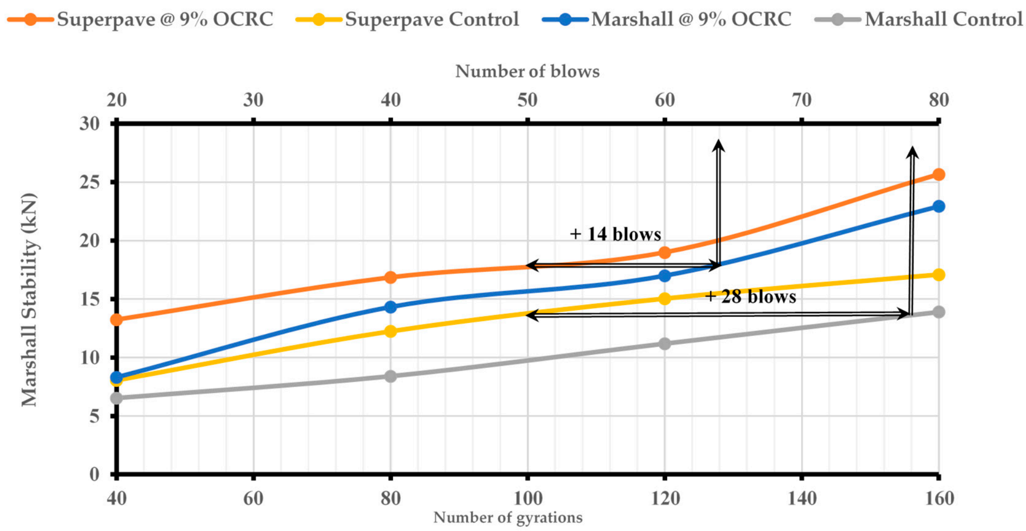
Figure 3. OCRC determination using Marshall stability and density. Note: SA, SB, and SC indicate sources A, B, and C.

4.4. Relationships between SGC and MIH

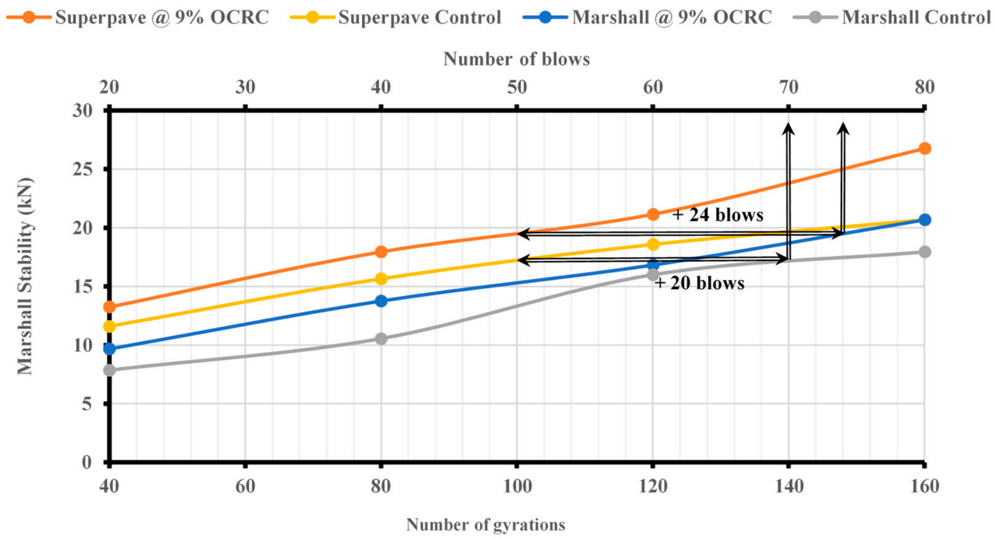
4.4.1. Relationship on the Basis of Marshall Stability

In general, SGC and MIH are directly responsible for increasing the density and Marshall stability of the mixtures in order to provide HMA with a better performance. However, each method had its own different performance, as presented in Figure 4. The responses of each mixture to the different numbers of blows in the Marshall method and the number of gyrations in the Superpave method were different for all three sources (A, B, and C) used in this study.

As shown in Figure 4, the SGC depended on a kneading technique for compaction, and it was performed well to achieve excellent Marshall stability for the mixtures from all sources compared to the MIH. Additionally, even when the modified mixtures at the OCRC were considered, the Superpave samples performed better in the Marshall stability than the Marshall specimens.

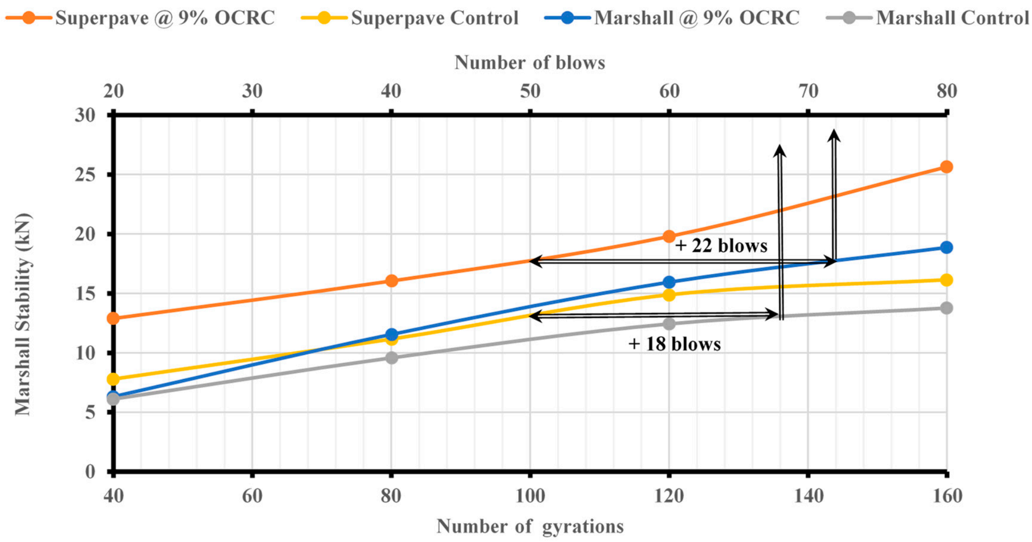


(a) Marshall stability versus number of blows and gyrations for Source A



(b) Marshall stability versus number of blows and gyrations for Source B

Figure 4. *Cont.*



(c) Marshall stability versus number of blows and gyrations for Source C

Figure 4. Effect of CR on Marshall stability at different numbers of blows and gyrations.

Due to the excellent performance achieved by the SGC for the unmodified and modified samples, it was significant to achieve the same performance using the MIH. This could be obtained by fixing the Marshall stability value at the design number of gyration (N_{design}) for the Superpave method, extending the horizontal line to cross the Marshall line and the vertical line to set a new equivalent number of blows that provided the same Marshall stability as the Superpave method at N_{design}, as shown in Figure 4a–c. Based on this technique, the following results were determined:

i. Source A: In order to achieve the same Marshall stability value as the Superpave unmodified sample, the MIH required 78 blows (28 extra blows). However, the modified sample at 9 percent OCRC only required 64 blows (14 extra blows).
ii. Source B: In order to achieve the same Marshall stability value as the Superpave unmodified sample, the MIH required 70 blows (20 extra blows). In addition, the modified sample at 9 percent OCRC required 74 blows (24 extra blows).
iii. Source C: In order to achieve the same Marshall stability value as the Superpave unmodified sample, the MIH sample required 68 blows (18 extra blows). In addition, the modified sample at 9 percent OCRC required 72 blows (22 extra blows).

Consequently, based on the three sources, as illustrated in Figure 4, it can be observed that the average numbers of blows required by the MIH in order to achieve approximately the same Marshall stability as the SGC were 72 blows (22 extra blows) for unmodified mixtures and 70 blows (20 extra blows) for modified mixtures at 9 percent OCRC. This is because the SGC used a kneading technique instead of impacting and compacting the mixtures at rotating angles, which provided a better aggregate skeleton for the asphalt mixtures. The results of this study confirm the results of previous research [54,61–65].

4.4.2. Relationship on the Basis of Density

Generally, the density of HMA increases by increasing the compaction effort. Usually, the density of unmodified mixtures is greater than that of modified mixtures, as demonstrated in Figure 5 for all three sources used in this study. This is due to the effect of the light weight of the CR portion that is used instead of the portion of asphalt cement in the wet process or the aggregate in the dry process.

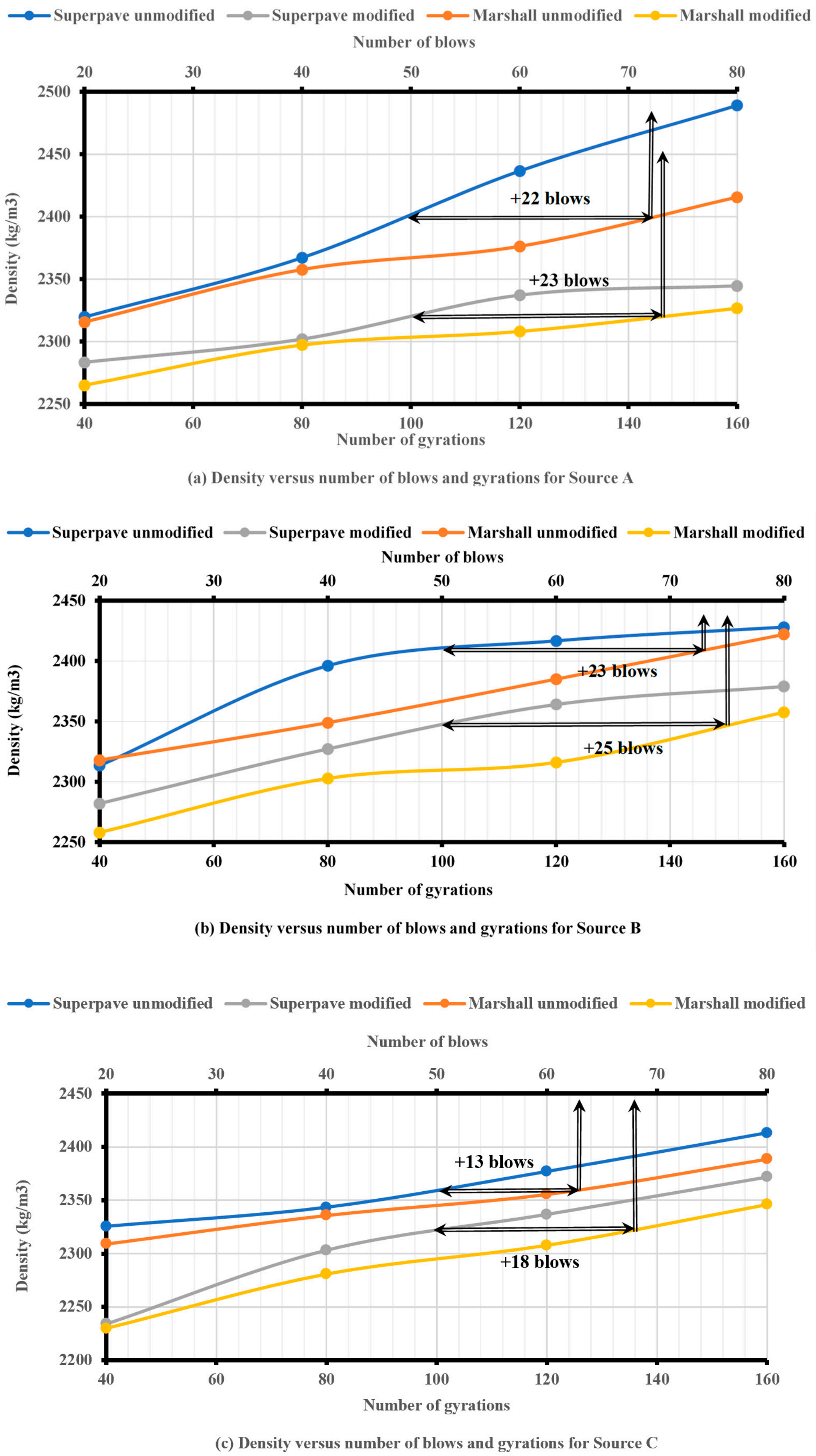


Figure 5. Density versus number of blows and gyrations.

Considering the density determined using the SGC and MIH methods, it can be observed in Figure 5a,b that for the unmodified and modified samples from sources A and B, the Marshall specimens required approximately an average of 73 blows (23 extra blows) in order to obtain the same density as the Superpave specimens at N_{design}. The unmodified and modified specimens from source C required 68 and 63 blows, respectively (18 and 13 extra blows, respectively), as shown in Figure 5c. Accordingly, an average of 71 blows (21 extra blows) was required for all three sources used in this study. The SGC provided higher density and lower air voids than the MIH due to better simulation of field compaction. The results of this study conform with those of previous studies [61,66,67].

4.5. Moisture Sensitivity

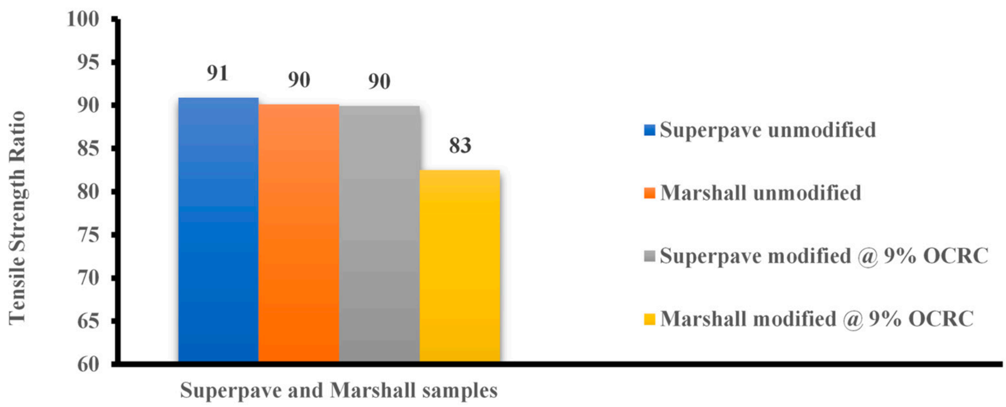
4.5.1. Indirect Tensile Strength (ITS)

The evaluation of HMA in terms of moisture sensitivity can be performed on the basis of ITS test findings, in accordance with the Asphalt Institute's Superpave mix design [32,33]. This test allows for the determination of the mixture's tensile strength for unconditioned and conditioned samples. The tensile strength ratio compares the average of three conditioned samples to the average of three control samples, and the ratio should be greater than 80%.

Moisture damage is one of the most significant causes that lead flexible pavement to be distressed after construction while exposing it to heavy rainfall and temperature variations. Figures 6a, 7a and 8a demonstrate that the tensile strength ratios (TSRs) of the samples conformed to the standard specifications of the Superpave, which should be more than 80 percent, except the conditioned Marshall sample modified at 9 percent OCRC from Source B, which failed the TSR. This may have been due to the effect of the compaction method, which did not form a strong skeleton in the asphalt mixture compared to Superpave kneading, but the result was very close to the specification, as shown in Figure 7a.

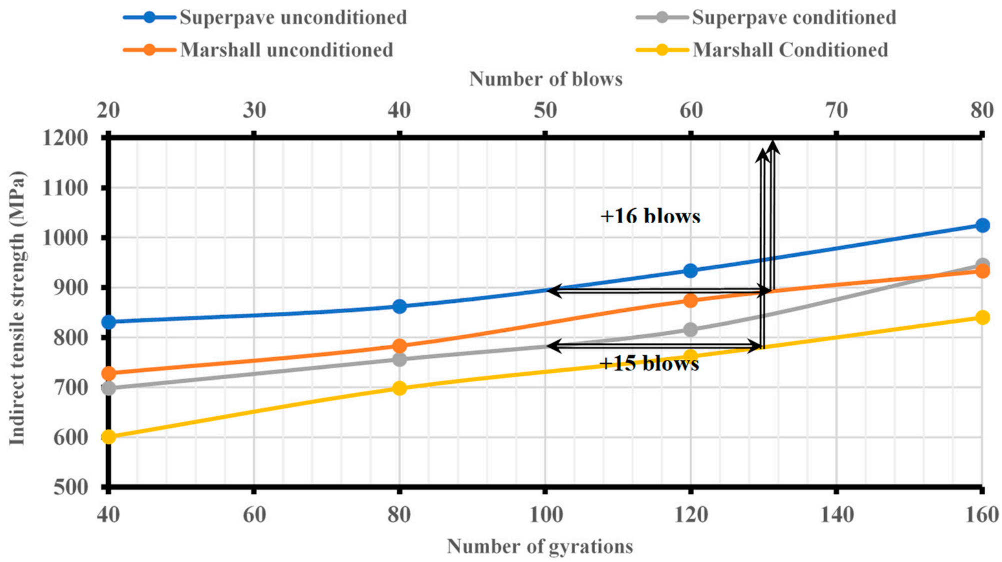
It can be observed in Figures 6b,c, 7b,c and 8b,c that the CRM had a positive effect on the performance of the HMA and increased the tensile strength of the Superpave and Marshall unconditioned and conditioned samples. However, it is difficult to perceive whether the effect of the CRM increased or decreased the number of extra blows required by the Marshall impact hammer to achieve the same tensile strength as with the SGC.

Consequently, the required number of extra blows decreased for the conditioned and unconditioned specimens from sources B and C, as shown in Figures 7b,c and 8b,c. On the other hand, for specimens from source A, the required number of extra blows required to obtain the same tensile strength as with the SGC increased, as shown in Figure 6b,c. Therefore, the required number of extra blows depended on which compaction technique was more influenced by CRM and may also have depended on the percentage of asphalt content, the aggregate gradation, and the source of the material.

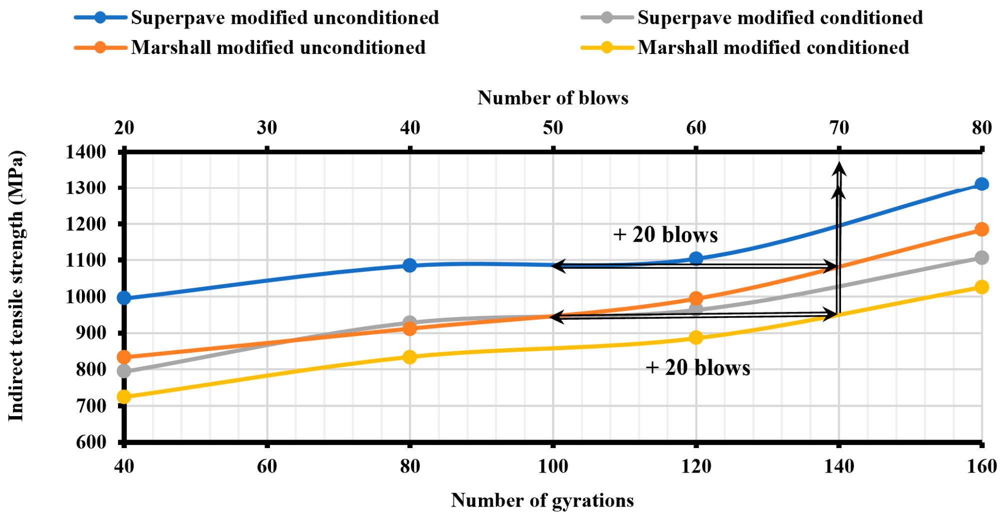


(a) TSR for modified and unmodified samples Source A

Figure 6. *Cont.*

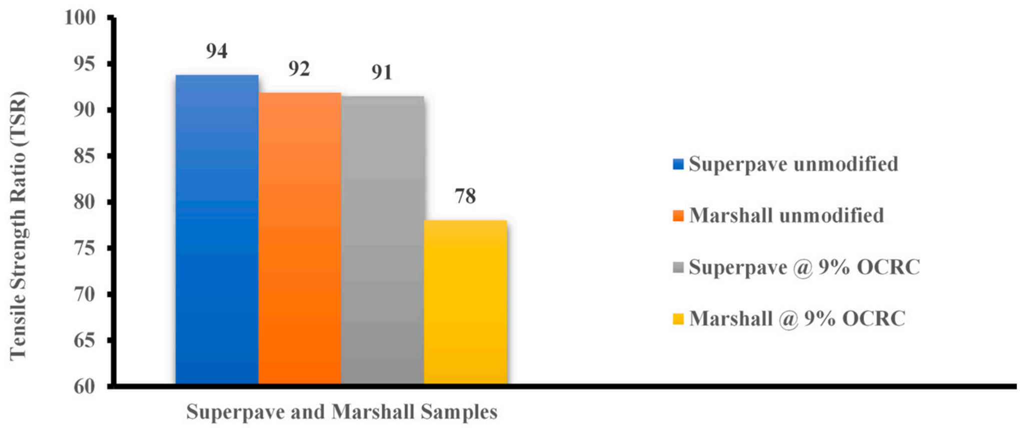


(b) Indirect Tensile Strength versus number of blows and gyrations Source A



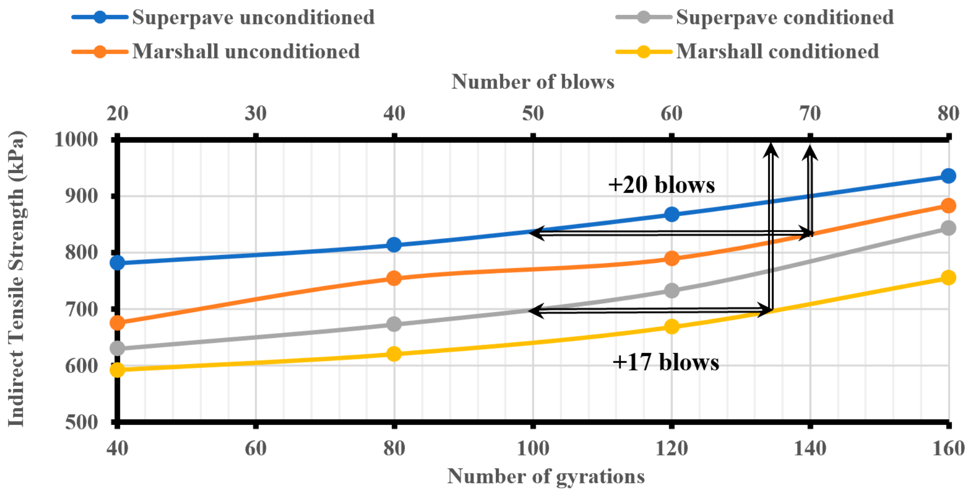
(c) Indirect Tensile Strength versus number of blows and gyrations Source A

Figure 6. Effect of CR on indirect tensile strength and its ratio for source A.

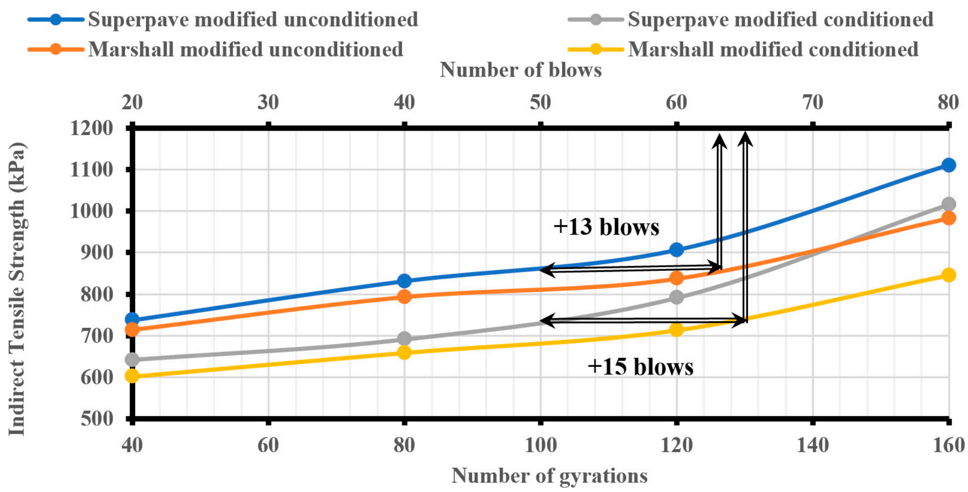


(a) TSR for modified and unmodified samples Source B

Figure 7. *Cont.*

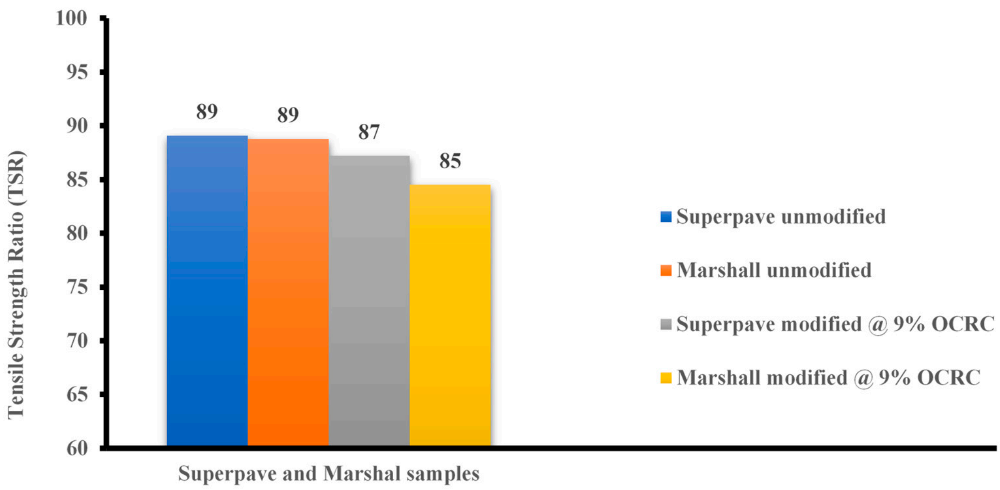


(b) indirect tensile strength versus number of blows and gyration Source B



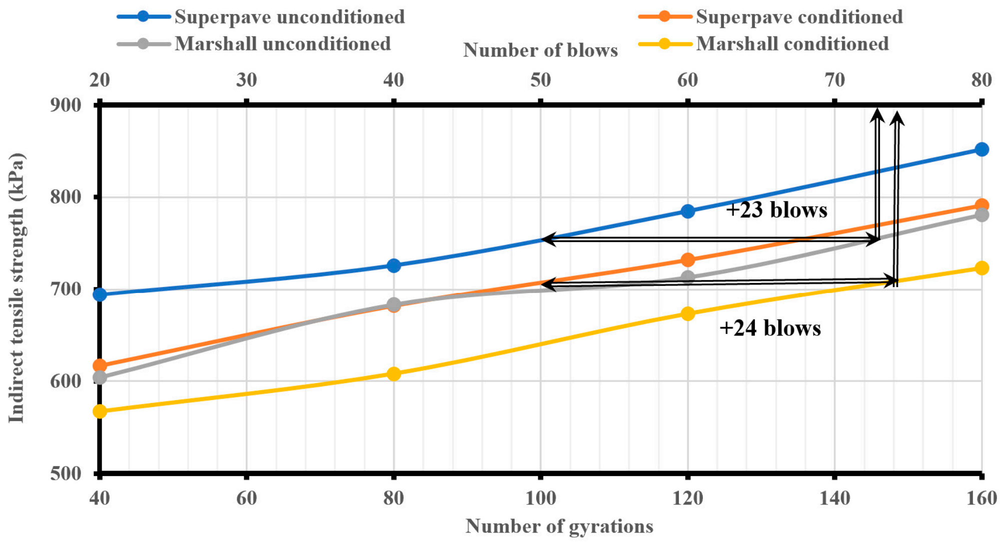
(c) indirect tensile strength versus number of blows and gyration Source B

Figure 7. Effect of CR on indirect tensile strength and its ratio for source B.

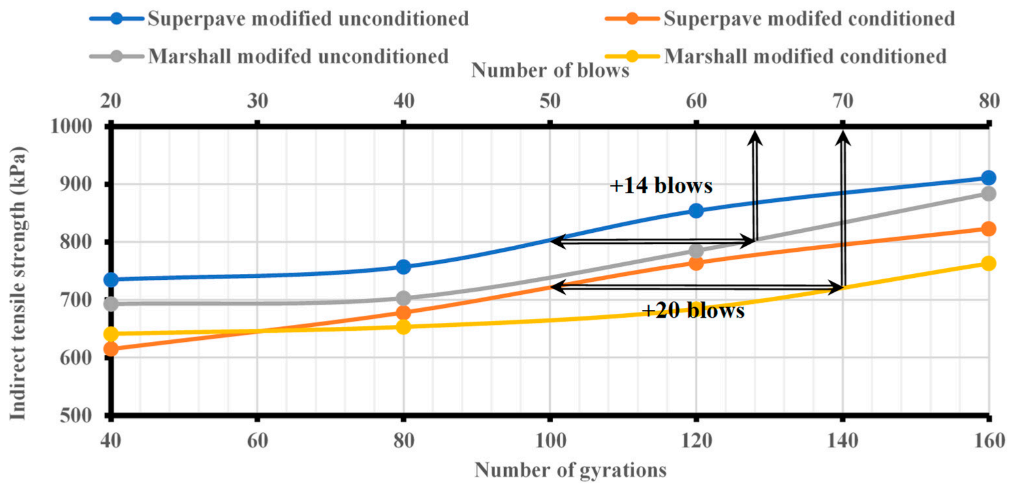


(a) TSR for modified and unmodified samples Source C

Figure 8. *Cont.*



(b) indirect tensile strength versus number of blows and gyration Source C



(c) indirect tensile strength versus number of blows and gyration Source C

Figure 8. Effect of CR on indirect tensile strength and its ratio for source C.

In addition, the improvement of HMA with CRM not only increased the tensile strength but also formed relationships among different techniques of compaction, and it might decrease the required compaction effort. Overall, on the basis of the results shown in Figures 6b,c, 7b,c and 8b,c, the MIH required approximately an average of 67 blows (17 extra blows) in order to obtain the same tensile strength as the SGC at N_{design} for modified mixtures and an average of 69 blows (19 extra blows) for the unmodified mixtures, as averages of all three sources used in this study. The superiority of Superpave samples compared to Marshall samples was due to the fact that in the SGC method, the interaction between aggregate particles created a stronger bond, and the kneading technique during compaction also increased the shear strength of the asphalt mixture. Previous studies confirmed the results of this study, such as [54,61–63,65].

4.5.2. Index of Retained Strength (IRS)

The loss of compressive strength resulted from the influence of water on HMA for the conditioned sample. The conditioned compressive strength to unconditioned compressive strength ratio is known as the IRS. The IRS is one of the parameters, next to ITS, that is used to assess an asphalt mixture's moisture susceptibility. The lower the ratio, the more susceptible a mixture is to moisture. This test was carried out according to ASTM D1075 [68] and AASHTO T165 [34].

Effect of the Number of Blows and Gyrations on the Compressive Strength

The compressive strength of the Superpave and Marshall samples was increased by increasing the number of blows and gyrations for unmodified, modified, unconditioned, and conditioned samples from all three sources used in this study. However, the Superpave samples had higher compressive strength values than the Marshall samples with an equivalent number of blows, as shown in Figures 9–11. The number of extra blows required by the MIH in order to obtain the same compressive strength as with the SGC at N_{design} was approximately the same for sources A and B, and it was around 76 blows (26 extra blows). However, source C required a lower number of extra blows (around 71 blows (21 extra blows)). As a result, an average of 74 blows (24 extra blows) was required by all three sources in order to obtain the same compressive strength as with the SGC at N_{design}, as demonstrated in Figures 9–11. The superiority of the Superpave samples over Marshall samples can be attributed to the fact that in SGC, the interaction between aggregate particles created stronger bonds, and the technique of kneading used during compaction improved the compressive strength of the asphalt mixture. The results of this study have a trend similar to the results of previous studies, such as [64,69].

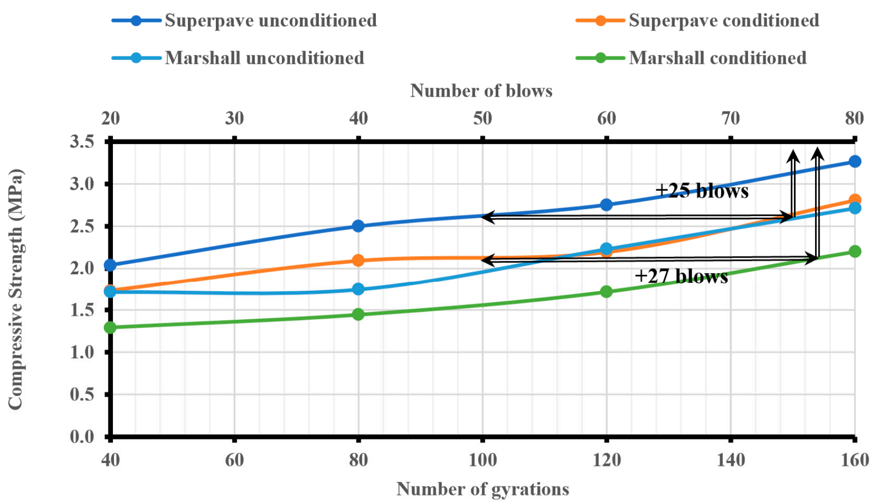
Effect of CRM on the IRS at Different Numbers of Blows and Gyrations

Generally, the techniques of compaction procedures have a great effect on IRS results. As shown in Figure 12, there was a significant difference between the Superpave and Marshall mix design results in terms of the IRS percentage. The Superpave mix design had better results, but overall, both mix designs had reasonably acceptable results; however, the Marshall design failed to satisfy the criteria of 80 percent IRS at four compaction levels for unmodified specimens from sources A, B, and C.

Additionally, due to the fact that the modified samples provided a higher IRS percentage and a higher compressive strength than the unmodified samples, as shown in Figures 9–12, it was demonstrated that adding CRM, in addition to increasing the compressive strength, provides a mixture with a high susceptibility to moisture damage.

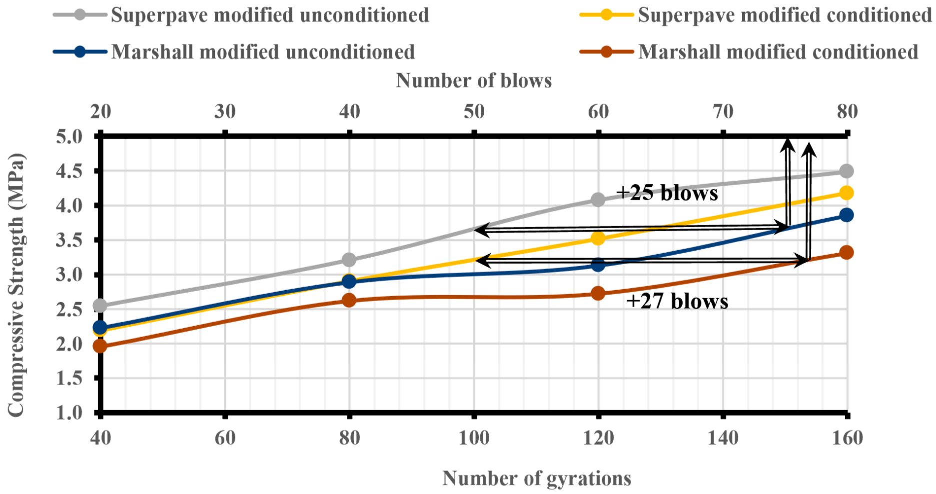
Effect of CRM on Compressive Strength

The modified Superpave and Marshall samples provided greater compressive strength than the unmodified specimens from all three sources used in this study, as shown in Table 5. This test was carried out according to ASTM D1075 [68] and AASHTO T165 [34].



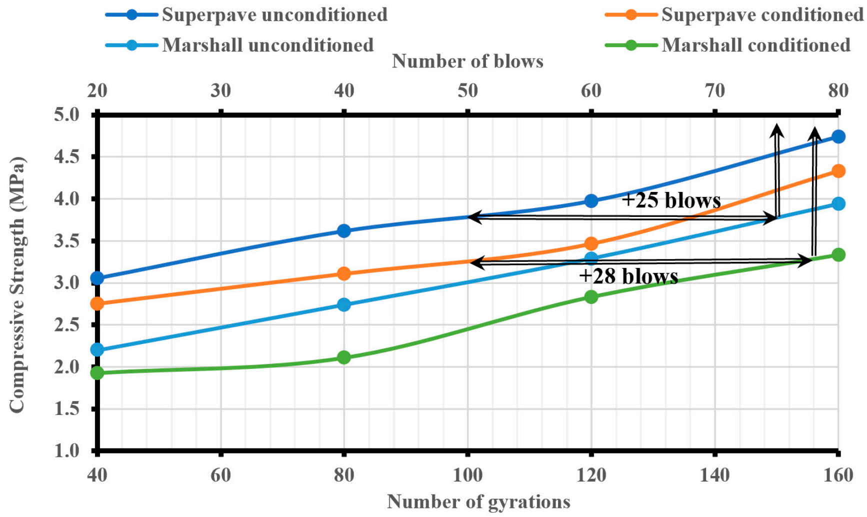
(a) compressive strength versus number of blows and gyrations Source A

Figure 9. *Cont.*

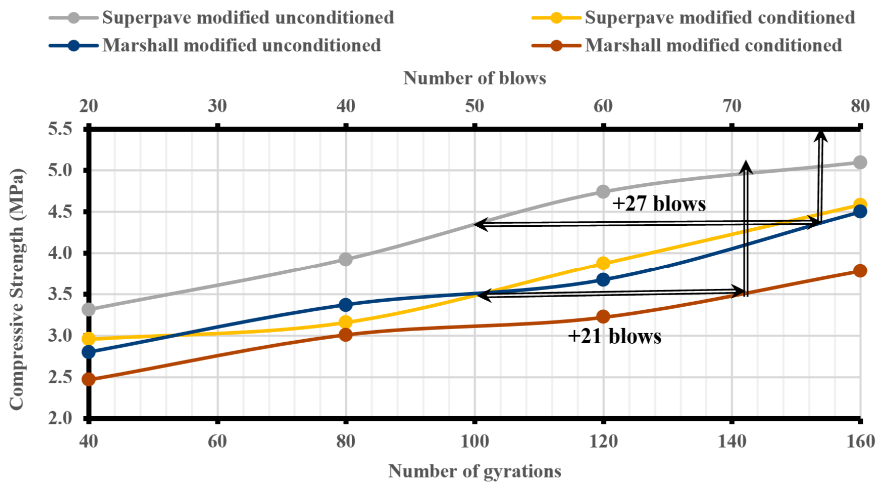


(b) compressive strength versus number of blows and gyrations Source A

Figure 9. Effect of CR on compressive strength for source A.

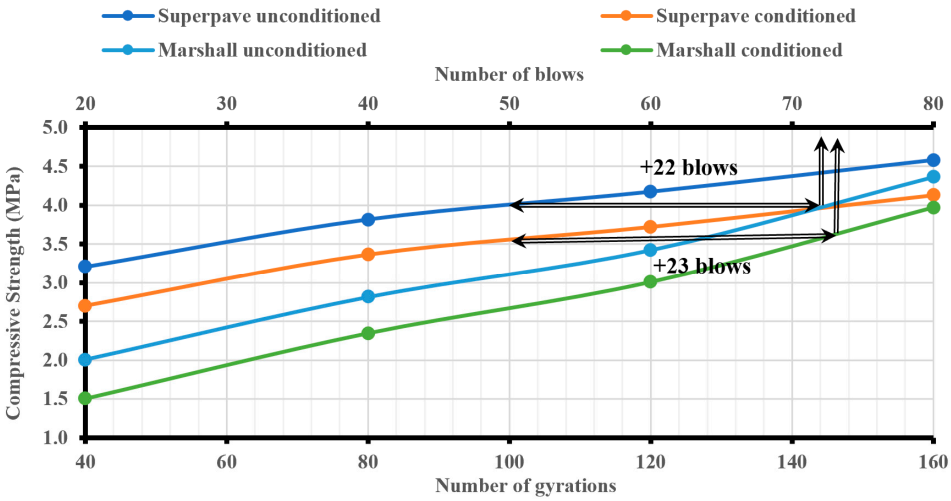


(a) compressive strength versus number of blows and gyrations Source B

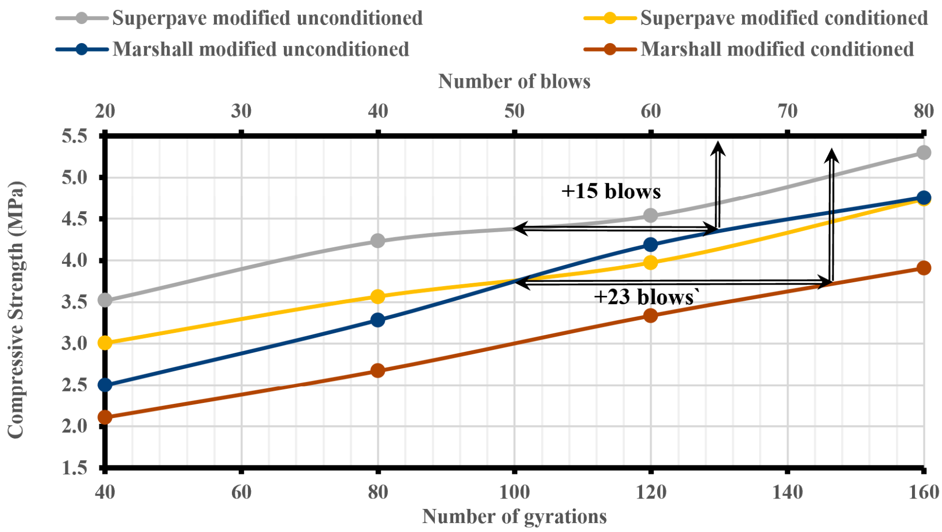


(b) compressive strength versus number of blows and gyrations Source B

Figure 10. Effect of CR on compressive strength for source B.



(a) compressive strength versus number of blows and gyrations Source C



(b) compressive strength versus number of blows and gyrations Source C

Figure 11. Effect of CR on compressive strength for source C.

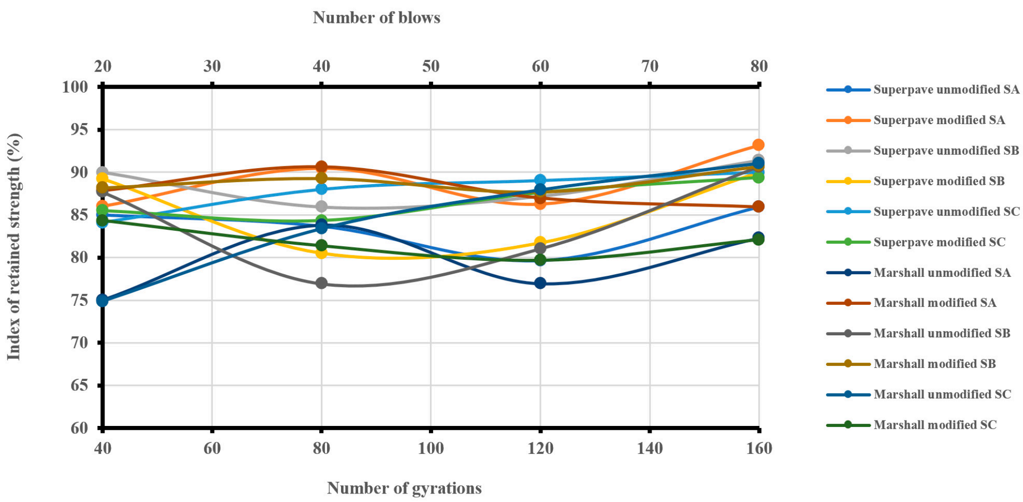


Figure 12. Index of retained strength at various numbers of blows and gyrations. Note: SA, SB, and SC indicate source A, source B, and source C.

Table 5. Effect of CRM on the compressive strength.

Sources	Superpave Samples				Marshall Samples			
	Number of Gyrations	Compressive Strength (MPa)			Number of Blows	Compressive Strength (MPa)		
		Modified	Unmodified	Percentage Increase (%)		Modified	Unmodified	Percentage Increase (%)
Source A	40	2.55	2.04	25	20	2.23	1.81	23
	80	3.21	2.50	29	40	2.89	2.05	41
	120	4.08	2.75	48	60	3.13	2.35	33
	160	4.48	3.26	38	80	3.85	2.89	33
Source B	40	3.31	3.06	8	20	2.80	2.20	27
	80	3.92	3.62	8	40	3.37	2.74	23
	120	4.74	3.97	19	60	3.67	3.49	5
	160	5.10	4.74	8	80	3.88	3.55	9
Source C	40	3.52	3.21	10	20	2.50	2.01	24
	80	4.23	3.82	11	40	3.28	2.82	17
	120	4.54	4.18	9	60	4.19	3.42	22
	160	5.30	4.59	16	80	4.76	4.37	9

Consequently, if the percentage that the compressive strength increased was considered being due to the effect of CRM, it can be seen in Table 5 that the compressive strength values of the Superpave and Marshall samples increased by 48 and 41 percent for source A, 19 and 27 percent for source B, and 16 and 24 percent for source C. Therefore, adding CRM to HMA is essential to improve the compressive and tensile strengths of an asphalt mixture in order to reduce the possibility of pavement distress, such as permanent deformation. The mechanism of the improvements in the mechanical properties of asphalt mixtures is attributed to an increase in the elastic response of the viscoelastic part of the asphalt cement in the entire mixture. This helps in recovering after a load has been applied and specifically provides resistance to permanent deformation. The results of this study conform with the results of [70].

5. Conclusions

A comprehensive experimental study was conducted in order to evaluate the performance of compaction effort and to check the moisture sensitivity between the SGC and the MIH for the unmodified and modified mixtures with CRM using the Superpave and Marshall mix design methods. The conclusions can be concisely summarized as follows:

i. The percentage of the optimum asphalt content determined using the Superpave mix design was lower than that determined using the Marshall mix design for the three sources used in this study. This reveals that the Superpave mix design is more economical.

ii. In comparison to the Marshall mix design, the Superpave mix design provided the highest level of stability for all sources. However, at 9 percent CRM, both mix designs provided maximum stability. Therefore, 9 percent CR was selected as the OCRC in this study.

iii. Based on the various numbers of blows and gyrations, the Superpave mix design provided higher stability than the Marshall mix design for the three sources that were used and even for the modified mixtures at the OCRC.

iv. The Superpave mix design provided higher tensile and compressive strengths than the Marshall mix design for the unmodified and modified mixtures, whereas the modified mixtures provided greater tensile and compressive strengths than the unmodified mixtures.

v. Because of the excellent performance (stability, density, indirect tensile strength, and compressive strength) achieved by the SGC for the unmodified and modified mixtures at the OCRC, it was important to attain the same performance using the

MIH at N_{design}. The average numbers of extra blows (after 50 blows) required by the Marshall samples to obtain the same performance as with the Superpave samples, based on the three sources that were used, were approximately 21 extra blows for stability, 21 extra blows for density, 18 extra blows for tensile strength, and 24 extra blows for compressive strength.

vi. The superiority of the Superpave compaction method using the SGC over the MIH was due to the effect of kneading during compaction, which increased the shear strength of the mixture and improved the tensile and compressive strengths of the asphalt mixture.

vii. The Marshall samples failed to satisfy the 80 percent criteria of the IRS at four compaction levels from unmodified sources A, B, and C, while the Superpave samples satisfied these criteria for all compaction levels from all the sources that were used.

viii. In addition to increasing the compressive strength in the range from 16 to 48 percent, CRM also provided a higher IRS percentage than the unmodified mixtures. This allowed the mixtures to have more resistance to permanent deformation and moisture damage.

The main significant finding of this study was determining the possibility of using MIHs instead of SGCs in laboratories at an equivalent number of blows corresponding to the N_{design} number of gyrations. It is recommended to use asphalt pavement performance tests such as wheel tracking, the repeated load axial test, and the indirect tensile stiffness test using styrene butadiene styrene (SBS) in future studies.

Author Contributions: Conceptualization, A.F.T.; Methodology, A.F.T.; Software, D.B.Q.; Validation, A.F.T.; Formal analysis, A.F.T.; Investigation, D.B.Q.; Resources, D.B.Q.; Data curation, D.B.Q.; Writing—original draft, D.B.Q.; Writing—review & editing, A.F.T.; Visualization, D.B.Q.; Supervision, A.F.T.; Funding acquisition, D.B.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon request from the corresponding author.

Acknowledgments: The authors acknowledge the support provided by the Directorate of Weight Stations, Erbil; the Directorate of the Erbil Construction Laboratory; and the Department of Civil Engineering, College of Engineering, Salahaddin University-Erbil, Erbil, Kurdistan region, Iraq.

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

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