IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Aggregate gradation effect on the mechanical properties of asphalt mixtures

To cite this article: Imad Dawood Sulaiman *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1296** 012001

Aggregate gradation effect on the mechanical properties of asphalt mixtures

Imad Dawood Sulaiman[1], Jasim M abed[2], Zaid Hazim Al-Saffar[3], Ramadhansyah Putra Jaya[4]

[1,2,3] Department of Building and Construction Technology Engineering, Engineering Technical College, Northern Technical University, 41002 Mosul, Iraq.
[4] Faculty of Civil Engineering Technology, University Malaysia Pahang Al Sultan Abdullah, 26300 Gambang, Pahang, Malaysia
*Corresponding author: emaddaood1993@gmail.com

Abstract. The issue of road deterioration in Mosul, Iraq, has become a matter of concern for local communities. The instability of road surfaces under the stress of vehicular traffic necessitates significant intervention to mitigate and manage this problem. This study has developed an asphalt mixture by following the Bailey method for aggregate gradation. The impact of aggregate gradation on the mechanical properties of the asphalt mixture was thoroughly analysed. Additionally, two separate mixtures were conducted using the conventional Marshall method to assess indirect tensile strength, Marshall properties, and susceptibility to moisture damage. The primary objective of this research is to design an aggregate structure that acts as a robust unit capable of withstanding heavy loads, repeated stresses, and high temperatures. The findings of the study indicate that the asphalt mixture created using the Bailey method exhibited superior stability with values of 13.6 kN, compared to the two traditional mixtures (11.8 kN, 9.2 kN), and. However, it is worth noting that the flow values also indicated a relative preference for the Bailey method, with values of and 3.1 mm, compared with 3.85 mm and 3.2 mm of the traditional mixtures. The results of Tensile strength ratio further corroborated the efficacy of Bailey's technique, with outcomes of 85.1 %, thus enhancing the applicability of this method. This observation is attributed to the concept of granular interlocking, which forms the foundation of the Bailey method.

Keywords: Asphalt mixture, Bailey method, Aggregate gradation, Marshall properties, traffic load

1. Introduction

A rutting issue has recently surfaced in the asphalt layers of Mosul, Iraq, particularly due to constant deformations caused by high temperatures. Thus, permanent deformation (rutting) in asphalt pavements remains a significant concern, indicating failure. Rutting has recently become the primary challenge for flexible pavement as vehicle tyre pressure has risen. The build-up of permanent deformation mainly contributes to deformed pavement surfaces in the pavement layers of partial or complete pavements. Moreover, pavement deterioration can induce rutting due to studded tires [1].

Rutting is a key concern owing to the plastic, non-linear, and viscous characteristics of asphalt mixtures frequently occurring in flexible pavements [2]. The surface depression caused by wheel tracks under high pavement temperatures and loaded situations is defined as rutting. This outcome typically occurs in slow-moving traffic places, particularly junctions and bus passages. Nevertheless, high-speed traffic can still demonstrate rutting issues [3]. The case is more severe in hotter climates as the rigidity of Hot Mix Asphalt (HMA) reduces when pavement temperature increases [4]. Interestingly, there is no significant rutting in the same asphalt pavement structure in intersection areas under fast-moving traffic. This observation implies a need for a modified asphalt mix at or near intersections to protect from slow or standing traffic loads without lasting deformation.

Ghuzlan's study [5] demonstrates that the utilisation of Bailey-type aggregate gradation typically results in favourable aggregate packing, leading to enhanced resistance against rutting. In comparison to Superpave mixes, Bailey mixes exhibit superior aggregate packing and overall mix properties. This distinction arises from the absence of a guideline mechanism to identify and optimise Superpave mixes.

Campen *et al* [6]. assessed 18 resurfacing projects in Omaha, Nebraska, and the study revealed rutting and shoving in areas where traffic was channelled, such as bus stops and intersections. Therefore, aggregate gradation was regarded as an influential parameter of asphalt mixture efficiency, particularly in rutting resistance. This study constructed the aggregate structure of asphalt mixes (various gradations) with the Bailey and traditional Marshall methods. Systematically, mixing aggregates with the Bailey method offered an excellent aggregate interlocking structure, producing solid aggregate skeletons to solve rutting issues and increase resilience [7]. In the early 1980s, the Bailey method was discovered by Robert D. Bailey, which was practical and applied effectively for producing and analysing hot asphalt mixtures in laboratories and fields [8]. The method also presented a construction plan for a durable solid aggregate skeleton, sufficient voids in the aggregates (minerals), and rut resistance.

In Marshall and Superpave approaches, the Bailey method is an excellent first step for producing mixes and planning revisions in the industries, which enhances the Voids in Mineral Aggregate VMA, general mix workability, and air voids. The solid aggregate skeleton of packed aggregates (coarse and fine) defines the Bailey method [9]. A robust aggregate structure is usually required since the compressive forces are efficiently sustained by the aggregate [10]. The Bailey method enables aggregate packing control and coarse aggregate interlock, determining the appropriate mixture characteristics [9]. Hence, manufacturing procedures can be modified to suit the quality standards (related industry) by understanding the aggregate gradation impacts on the asphalt mixture characteristics [8]. The gradation assessment in the Bailey method emphasises aggregate qualities, influencing the packing or fitting of aggregates in a limited volume or space. Since aggregates are one of the primary components of HMA, they are vital in asphalt mixture performance and constitute approximately 90 to 95% HMA by weight and 75 to 85% HMA by volume [11]. According to a study conducted by Elliot et al., the performance of the asphalt mixture experiences a notable impact when alterations are made in the aggregate's gradation, such as transitioning from a fine to a coarse gradation [11,12].

Another study by Kandhal *et al*[14] investigated the asphalt content measurements and their corresponding aggregate gradation impacts. The study discovered that asphalt cement, incorporating 547 binders and 147 coarse mix specimens, was obtained using the "Standard Test Methods for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures". This procedure was outlined in ASTM D2172. The study then investigated the correlation of different sieve sizes (pavement layer density) with asphalt cement content. Thus, the percentage flowing through the sieves (2.36 and 4.75 mm) for binder course mixtures was correlated with the calculated asphalt cement content. Projected gradation shift formulas were also constructed in adjusting the estimated asphalt cement content for the study (12.5 mm sieve mix formula to 2.36 or 4.75 mm sieve) [15].

A study by Krutz *et al*[14] assessed the aggregate gradation influence on the HMA mixes (permanent deformation), in which four distinct gradations, two aggregate sources, and two asphalt cement (AC20 asphalt binder) were utilised. For two of the gradations passing through sieve No. 4, the study presented extremely fine and coarse values of 60 and 40%, respectively. Meanwhile, 52 and 54% were recorded for the corresponding middle gradations passing sieve No. 4. Based on the Hveem mixture approach, the constructed asphalt mixtures evaluated all the mixes using triaxial load test repetitions. The study revealed that the most efficient aggregate gradations were based on the aggregate type and source. Alternatively, coarse aggregate gradations produced the lowest aggregate performance [16].

Certain researchers have chosen to employ Bailey's method with the use of specific types of aggregates. For instance, Swathi [17] observed that Steel Slag Aggregate (SSA) exhibited superior physical characteristics in comparison to Natural Aggregate (NA). Some of these attributes, such as impact resistance and abrasion resistance, can be attributed to the higher concentration of iron oxides in SSA. Additionally, properties like angularity are linked to the predominantly cubical shape of SSA. However, it is worth noting that the properties that significantly impact the design of asphalt mixes involving SSA are primarily related to its high-water content.

Thompson investigated a similar strategy for dense-graded mixes utilising aggregate sources in Oregon. In contrast to the typical *S*-shaped gradation curve, the design strategy in this study incorporated the bulk density of the aggregate, which produced fine mixtures. Although the Bailey method parameters were valuable for managing gradation, the study did not provide quantitative relationships with VMA and other volumetric factors. From the various mixes, the study determined that fine aggregate blends were crucial in enhancing the rutting performance of mixes [18]. Similarly, Daniel and Rivera analysed six typical New Hampshire mixtures, and the rutting performance evaluation of traditional and Bailey-based mixes was conducted. The study suggested that the Bailey method should be utilised as an evaluation and guidance tool during the mix design process [19]. The core objective of the Bailey method is to achieve a precise balance between the stiffness and flexibility of the asphalt mixture. This balance is essential because it enables the mixture to withstand the stresses and strains imposed by heavy traffic loads, while simultaneously preventing rutting. By employing the Bailey method, the goal is to determine the optimal quantity of bitumen and aggregate gradation necessary to create a blend with the ideal ratio of stiffness to flexibility.

Since few studies were conducted on the Bailey method, this study aimed to examine the granular aggregate gradient effect and its impact on the Marshall stability, void ratio, density, flow, stiffness, indirect tensile strength (ITS), and tensile strength ratio (TSR). The outcome was compared to two mixture types using the conventional Marshall method. Addressing the issue of rutting in the streets of Mosul holds significant importance due to its wide-ranging impacts. This issue can also contribute to environmental matters by reducing the need for frequent bitumen application. Moreover, the substantial expenses associated with road removal and repaving significantly influence the local economy. This study aims to offer solutions to the challenges posed by pavement failures under repeated loads. The objectives of this investigation are as follows: (1) To assess the influence of different aggregate gradations on the Marshall properties of HMA, (2) To examine how aggregate gradation impacts the process of ITS & water damage in HMA, and (3) To analyse how varying design elements of mixture gradations are affected by binder content.

2. Materials and Methods

2.1. Materials

A bitumen with a penetration grade between 40 to 50 (mainly utilised in Iraq) was applied in the experimental design of this study. The characteristics of the chosen materials were assessed with conventional testing and compared to the SCRB (R/9) [20]. Subsequently, the bitumen was obtained from the Al-Qayyarah refinery, approximately 55 km south of Mosul. **Table 1** lists the bitumen properties utilised in the experiment. In a dense-graded mix design, the necessary data for the Bailey method was the sieve size distribution alongside coarse and fine aggregate values (unit weight).

Table 1. Summary of the bitumen properties

Test	**ASTM Designation**	**Test Data**	**SRCB Specification**
Penetration (100g, 25c, 5sec)	D-5	42	40–50
Ductility	D-133	122	> 100
Flash point	D-92	240	232
Softening point	D-36	52	-
Specific gravity	D-70	1.03	> 99

The Rodded Unit Weight (RUW) and Loose Unit Weight (LUW) were measured using the Bailey method. Only RUW was used for the fine aggregate using the AASHTO T-19 procedure, while RUW and LUW were applied for the coarse aggregate. **Tables 2** and **3** tabulates the LUW, RUW, and the typical aggregate parameters obtained from the Al-Khazir district in Ninawa, Iraq.

Table 2. Summary of the coarse and fine aggregate properties

Property	**Test Data**	**ASTM Designation**
Coarse Aggregate		
Bulk specific gravity	2.63	C-127
Apparent specific gravity	2.71	C-127
Water absorption	0.37	C-127
Loose unit weight	1647	T-19

Rodded unit weight	1790	T-19
Fine Aggregate		
Bulk specific gravity	2.58	C-128
Apparent specific gravity	2.67	C-128
Water absorption	1.51	C-128
Loose unit weight	1950	T-19
Rodded unit weight	2070	T-19

Table 3. Summary of the physical characteristics of the aggregate

Characteristic	Test Result	Specification Limits
Sand equivalent	80.5	> 45
Plasticity index	0	< 4
VMA	16	> 12
Percentage of harmful substance	1.0%	< 3%
Elongation	4	< 10
Percentage of mechanical wear	18	< 35
Percentage of chemical wear	1.64	< 12
Asphalt coverage	97	> 95%

2.2. Sample Preparation

The Marshall method was employed to prepare the specimens in all mixes. Subsequently, the stability, flow, and volumetric parameters were examined with the Marshall method to evaluate the mix quality and calculate the optimised bitumen. These parameters were obtained from compacted specimens acquired from utilising a Marshall compactor. This study also selected two different gradation types designed by the Marshall method and one created by the Bailey method. The study utilised Asphalt Concrete (AC) Grades 1 and 2 (represent traditional mixtures used in Mosul city), and Grade 3 (using Bailey gradation method), adhering to the criteria outlined in the Iraqi standard SCRB/R9. The percentage differences in aggregate gradation for each of the three mixtures employed in the research are presented in Table 4 and Figure 1. To conform to the relevant standards, it is imperative that the proportions of coarse aggregate, fine aggregate, and filler material meet the specified requirements. The prescribed quantity of the mixture was employed to create compacted bituminous specimens with an approximate thickness of 63.5 mm. Achieving this thickness necessitates the use of 1200 grams of aggregate and filler. The compaction mould assembly and rammer are thoroughly cleaned and pre-heated to a temperature ranging from 100°C to 145°C, while the aggregates are heated to temperatures of 175°C to 190°C. Subsequently, the required amount of initial trial bitumen is added to the heated aggregate and thoroughly mixed after the bitumen attains a temperature within the range of 155°C to 163°C. The resulting mixture is poured into a mould and compacted with the stipulated number of blows. After a brief period, a sample extractor is employed to remove the sample from the mould. Figure 2, displayed below, illustrates the methodology employed in the study to attain an asphalt mixture that aligns with the objectives of meeting the requirements of Marshall's standard tests while also achieving favourable outcomes in terms of moisture damage resistance.

Table 4. Summary of the mixture gradations

Sieve Size(mm)	**AC Grade 1**	**AC Grade 2**	**AC Grade 3**
Types of mixtures	Traditional mixtures		Bailey method
19	96	94	92
12.5	84	78	79
9.5	76	69	70
4.75	55	50	50
2.36	34	29	36
0.3	15	9	15
0.075	5.6	6.9	6
%Bitumen	4.85	4.63	4.45

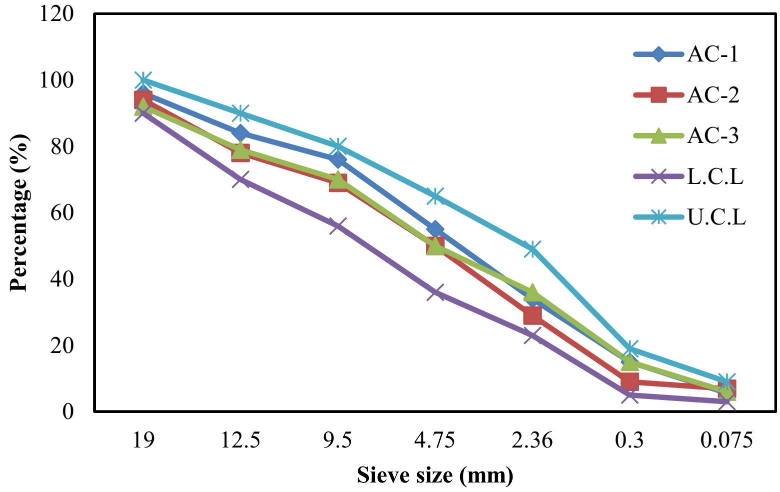

Figure 1. Obtained aggregate gradation for all mixtures.

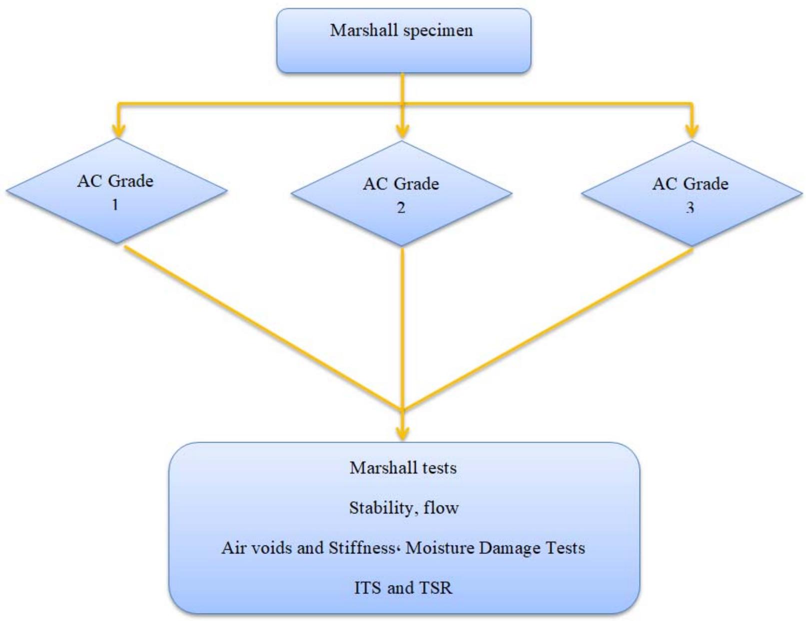

Figure 2. Flowchart of this study

2.3. Determining the Optimal Asphalt Content (OAC)

Based on the works of the Asphalt Institute, cylindrical specimens of a total aggregate mass of 1.2 kg and specific specifications (100 mm diameter and 62.5 mm height) were employed for determining the Optimal Asphalt Content (OAC) [21]. Before combining, the bitumen and aggregate were placed in an oven at mixing temperature and blended in a mechanical mixer. Each gradation produced three specimens, which were compressed using bitumen content from 4 to 6% to determine the OAC. The OAC was measured to be 4.0% of air voids, which was necessary to confirm other combination parameters in adhering to the specifications. It is essential to emphasize that determining the bitumen content is typically carried out through a combination of laboratory testing, mix design procedures, and field trials. The selection process should take into account local specifications, guidelines, and expert judgment to ensure the optimal performance of the asphalt mixture.

Several factors influence the ratio of bitumen in the mixture, including aggregate gradation, the percentage of air voids, the desired resistance to rutting, improved durability, and the prevailing weather conditions, which all play a significant role in determining the quality and quantity of bitumen used in the asphalt mixture.

The relationship between aggregate gradation and the bitumen ratio is a pivotal consideration in the design and production of asphalt mixtures. Aggregate gradation pertains to the distribution of particle sizes within a given aggregate blend, whereas the bitumen ratio signifies the proportion of bitumen in relation to the total mixture weight. The bitumen ratio directly influences the amount of bitumen available to coat and bind the aggregate particles in the mixture. Bitumen, in turn, provides the necessary cohesion and adhesion to the aggregate, resulting in a durable and flexible asphalt matrix. This ratio further impacts the workability and compactability of the mixture during construction and has long-term implications for pavement performance.

2.4. Laboratory Tests

2.4.1. Marshall and Flow Tests

The specimen testing temperature was achieved in a water bath for 20 to 40 mins. Subsequently, the inner surfaces of the test heads and guiding rods were meticulously washed. The guide rod was greased to ensure the upper test head could move easily, while the water bath specimen was positioned in the lower section of the breaking head. The upper section of the breaking head was then positioned on the specimen, and the entire setup was set on the experimental apparatus. When the load was applied, the flowmeter was transferred over the guide rods while the sleeve was solidly pushed on the upper section of the breaking head. The flow metre was set to zero before initialising the test. The specimen was then loaded (50 mm per min rate) and stopped at maximum load, where the load began to reduce. The maximum load was obtained as soon as it became lower, with the flowmeter above the guide rod pulled out from its position. Lastly, the flow rate was measured and recorded while the duration between the water bath specimen removal and maximum load calculation was ensured to be below 30 s [22].

2.4.2. Moisture Damage Tests

The moisture damage's effect on asphalt mixtures was conducted in accordance with ASTM D4867 [21]. Each type of mixture was represented by six samples, which were compacted to achieve an air void content of 7% ± 0.5% (as shown in Table 5). Subsequently, the samples were divided into two sets: one set remained in a dry condition, while the other set was gently saturated with distilled water within a vacuum vessel for a specified duration at 25°C and 70 kPa. The level of saturation was determined as a percentage by dividing the volume of water absorbed by the void volume. It is important to note that ASTM standards stipulate a required saturation level ranging from 55% to 80%. For the wet subgroup, the samples were subjected to a water bath at 60°C for 24 hours, followed by another bath at 25°C for one hour. Subsequently, the dry subset was tested for tensile splitting while submerged in a water bath for 20 minutes at 25 degrees Celsius, with a loading rate of 50.8 mm per minute. From Equation 1, the maximum load at failure determined the ITS of the mixes. Thus, the wet specimen tensile strength to dry specimen tensile strength (TSR) ratio is obtained by testing the moisture sensitivity of asphalt mixtures as follows [23]:

$$ITS = 2000P/\pi dh \quad (1)$$

where ITS represents the indirect tensile strength (kPa), P represents the maximum load (N), h represents the specimen height (mm), d represents the specimen diameter (mm), and π represents a value of 3.14.

Table 5. Selected mixture summary of the air void percentages

Mixture Type	**Original Samples Air Voids (%)**	
	ITS Samples @ 25°c	**ITS Samples @ 60°c**
AC-1	6.7	7.0

	6.6	7.1
	6.9	6.7
	7.1	7.3
AC-2	6.9	6.9
	6.8	7.0
	7.0	7.2
AC-3	6.8	6.9
	7.1	6.9

3. Result and Discussion

3.1. Marshall Properties

3.1.1. Marshall Stability

The Marshall stability demonstrates the ability of the asphalt mixture to resist permanent deformation. Therefore, a larger Marshall stability amount suggests an increase in Marshall stiffness. This study suggested that the Bailey method increased the Marshall stability. When the Bailey method was used instead of the standard method, the Marshall stability was raised by 13.2 and 32.3% for Grades 1 and 2, respectively. The mixture with the highest gradation band (AC-3) produced the greatest stability, while the lowest (AC-2) generated the least. A stiffer mixture was created from a higher stability value divided by a lower flow value. These results were due to the Bailey method precisely determining the quantity of each gradient. Conversely, the Marshall method relied on a trial-and-error approach. Since the mixture transformed into a solid mass owing to the granular interlock (accounted in advance from the Bailey technique), the stability strength of the Grade 3 mixture increased. **Figure 3** illustrates the distinction between all gradations.

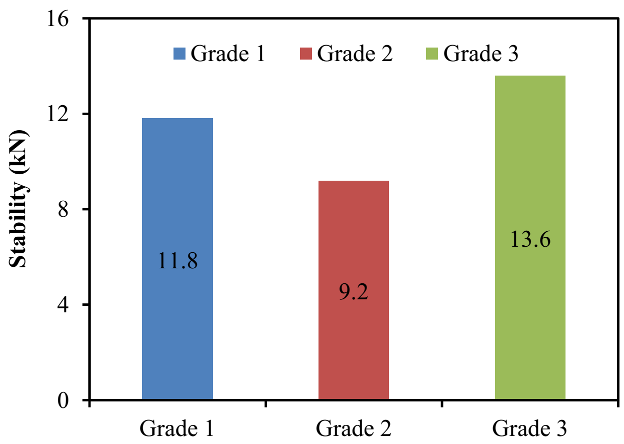

Figure 3. The relationship between aggregate structure constructed with varying gradations and stability.

3.1.2. Marshall Flow

Generally, high flow values demonstrate a higher plastic mix vulnerability to permanent deformation owing to traffic loads. Alternatively, small flow values suggest a mixture with greater-than-normal voids and inadequate bitumen for sturdiness, which promotes early cracking over the lifespan of the pavement due to mixture brittleness. **Figure 4** presents the aggregate gradation impact on Marshall flow. When the traditional method was utilised instead of the Bailey method, the Marshall flow increased by 24.13 and 3.2%. Thus, the stability-to-flow ratio measured the stiffness of the mixture, corresponding to tyre pressure. Lee *et al*. noted that for the 100 psi tyre pressure design, a minimum value of 2.1 kN/mm (120 lb/.01") for the Marshall stiffness was vital to avoid irreversible deformation of the mixture under extreme stress [24]. In **Figure 5**, the Marshall stiffness for all gradations is much higher than the minimum value of 2.1 kN/mm.

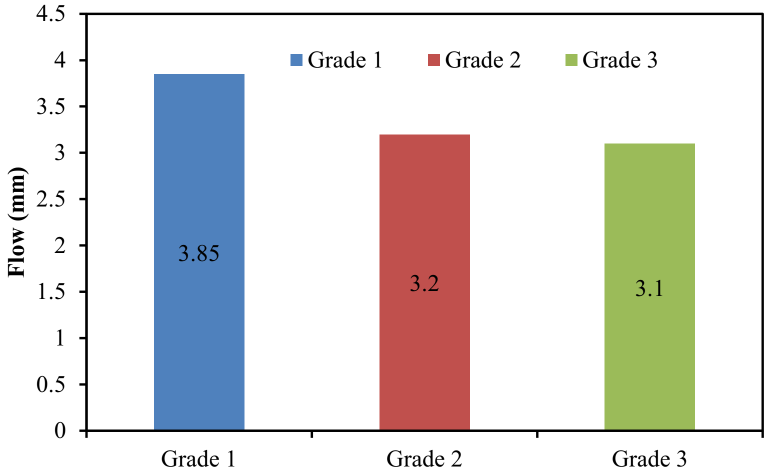

Figure 4. The relationship between flow and aggregate structure formed with varying gradations.

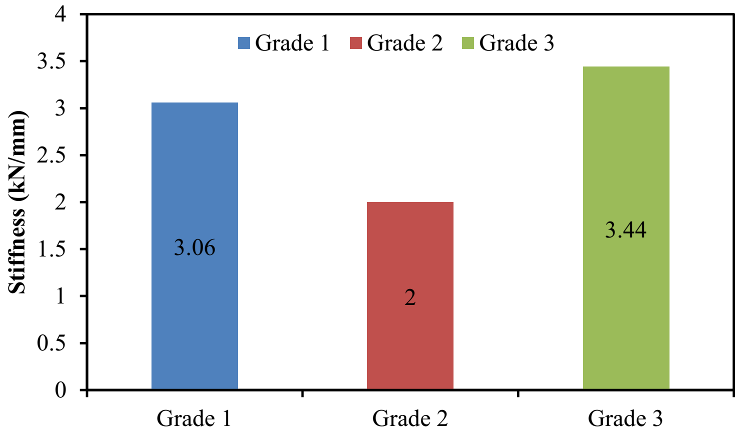

Figure 5. The relationship between flow and aggregate structure created with varying gradations.

3.1.3 Air Voids

Air voids in the mixture are essential criteria as it enables the qualities while predicting the mixture efficiency throughout the lifespan of the pavement. Additionally, the air void percentage is correlated with asphalt mixture durability. Air void proportions of approximately 4% are sufficient to prevent flushing or bleeding, thus diminishing the skid resistance of the pavement and raising its susceptibility to fatigue. **Figure 6** reveals the influence of aggregate gradation on total mix percent voids. Compared to Grade 2, the results demonstrated that the air void was lower with the Bailey method. According to the Bailey method, the coarse aggregate generated voids when packed in a container. Meanwhile, the fine aggregate filled these voids while creating air voids within the specification limits.

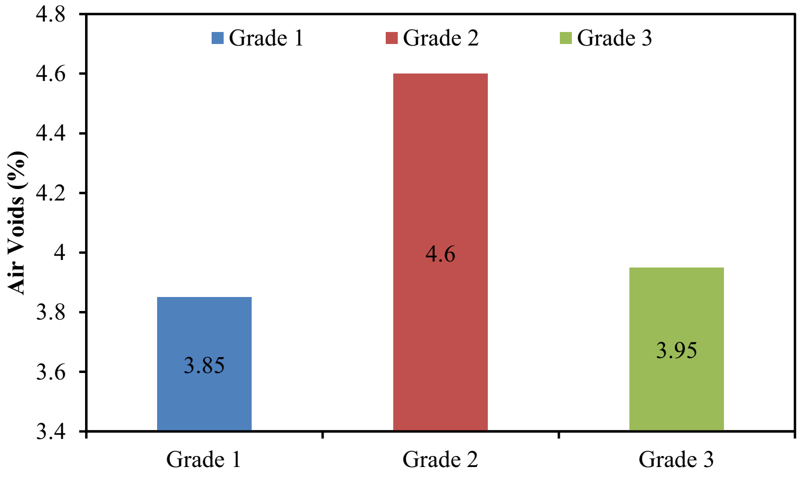

Figure 6. The relationship between air voids and aggregate structure with varying gradations

3.2. Moisture Damage

Moisture damage can negatively influence the longevity and strength of asphalt mixtures [25]. Therefore, the ITS test is frequently utilised to evaluate the moisture susceptibility of asphalt mixtures. Larger ITS and TSR values often suggest a mixture can function well and withstand moisture degradation [26]. **Figures 7** and **8** exhibit the conditioned and unconditioned ITS values obtained from the data, respectively. The AC-3 mixture indicated greater ITS values than the AC-1 and AC-2 mixtures. Hence, the Bailey method dominated the ITS values, which appeared more robust and rigid than the Marshall method. Likewise, the ITS values (traditional mixtures) were lower for conditioned specimens (60°C) than unconditioned specimens (25°C). As predicted, the outcome accounted for cohesion loss in the mixtures. Consequently, AC-1 specimens exhibited the highest TSR values, whereas AC-2 specimens produced the lowest.

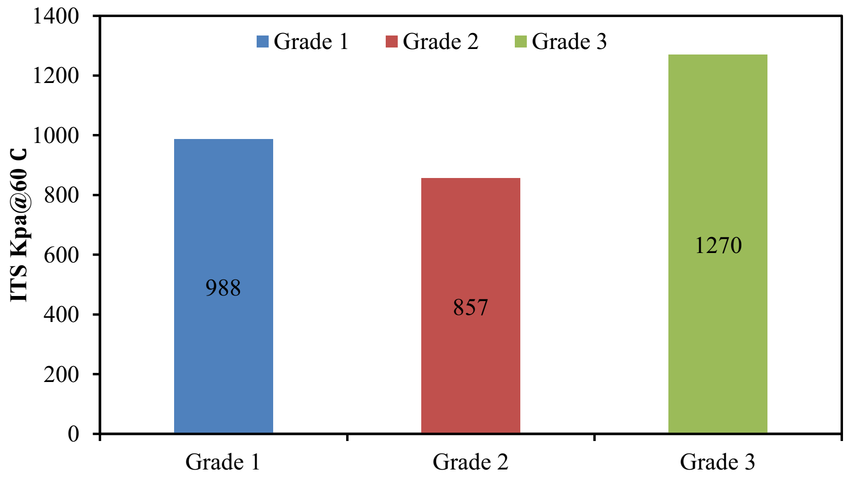

Figure 7. The relationship between ITS at 60°C and aggregate structure created with various gradations.

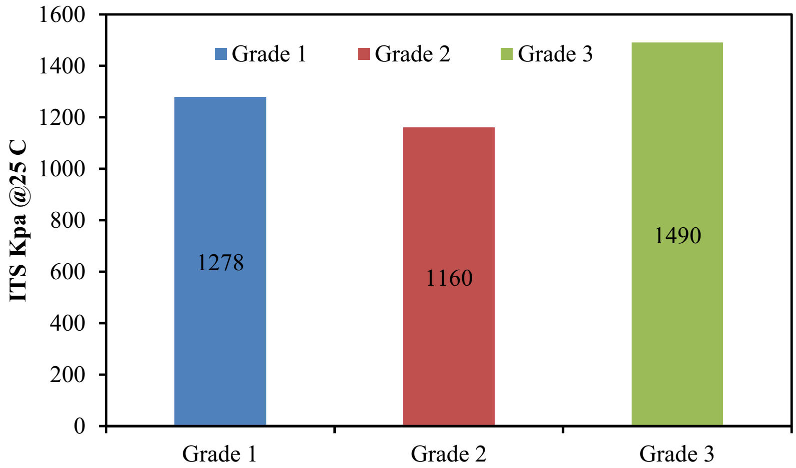

Figure 8. The relationship between ITS at 25°C and aggregate structure created with various gradations

The TSR values (criteria for moisture susceptibility) are demonstrated in **Figure 9**. Higher TSR values indicated greater asphalt mixture resistance to moisture degradation. The AC-3 exceeded the AASHTO TSR minimum level (> 80%). On the contrary, the AC-2 attained the lowest TSR value of all mixtures. This outcome indicated that the Bailey method increased the susceptibility of the mixture to moisture owing to the strong bonding between aggregate particles in the traditional Marshall method. In the Bailey method, the susceptibility of the mixture to damage decreased due to its low stability, resulting in decreased TSR value. It's worth mentioning that all samples were tested under identical circumstances, no outside factor could have influenced the test outcomes.

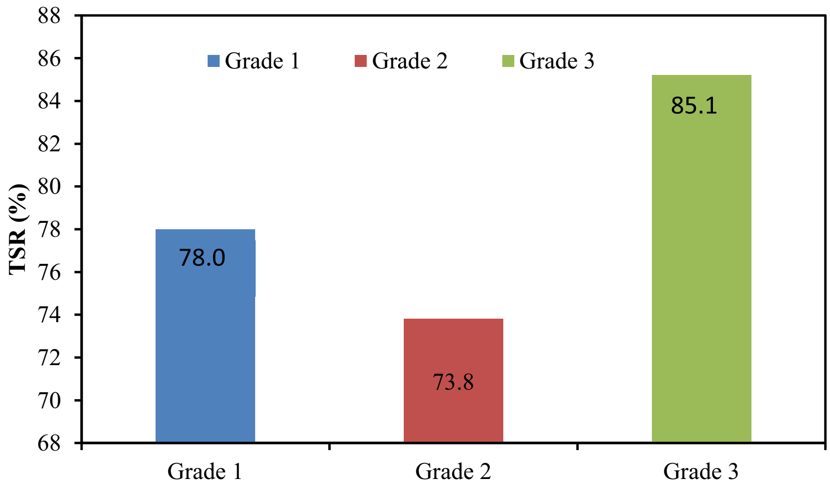

Figure 9. The relationship between TSR and aggregate structure created with various gradations.

4. Conclusions

This study successfully examined the gradation impact on the performance of asphalt mixers. In conclusion, several key points are successfully confirmed below:

1. The measured aggregate gradation of the Bailey method nearly matched the middle limits of the Iraqi standards.
1. The Marshall stability in the Bailey method was always greater than that of the traditional methods, as the asphalt mixture formed a cohesive unit owing to the uniform gradation.
2. The Bailey method for calculating each volumetric ratio of the gradient was based not on trial and error but on real foundations and formulae.
3. The principle of the bailey method depended on the interlocking of the aggregate granules in ensuring the mixture could work as a single mass, which meant the fine aggregate amounts that filled the voids between the coarse aggregate granules could be calculated, with a ratio of voids conforming to the specifications.
4. The indirect tensile strength value increased by 6 to 8% compared to the traditional methods, while the TSR value increased up to 85.1%
5. The Bailey method offers economic advantages and is applicable worldwide, particularly when aggregate gradation design is integrated with electronic computing, expediting the design process and minimising errors.
6. For future studies, it is necessary to conduct specialized tests for rutting, such as the creep test and the wheel tracking test.

Acknowledgments
The authors express their gratitude to the Northern Technical University (NTU), Ministry of Higher Education - Iraq for supporting this work.

References

[1] H. M. Mahan, "Behavior of Permanent Deformation in Asphalt Concrete Pavements Under Temperature Variation," *J. Eng. Sci.*, vol. 6, no. 1, 2013.
[2] T. D. White, *Contributions of pavement structural layers to rutting of hot mix asphalt pavements*, vol. 468. Transportation Research Board, 2002.
[3] P. Chaturabong and H. U. Bahia, "Mechanisms of asphalt mixture rutting in the dry Hamburg Wheel Tracking test and the potential to be alternative test in measuring rutting resistance," *Constr. Build. Mater.*, vol. 146, pp. 175–182, 2017.
[4] E. R. B. Prithvi S.Kandhal,Rajib B.Mallick, "Hot Mix Asphalt for Intersections in Hot Climates," *NCAT Rep. 98-06*, no. March, 1998.
[5] K. A. Ghuzlan, A.-M. Bara'W, and A. S. Al-Momani, "Rutting performance of asphalt mixtures with gradations designed using Bailey and conventional Superpave methods," *Constr. Build. Mater.*, vol. 261, p. 119941, 2020.
[6] W. H. Campen, J. R. Smith, L. G. Erickson, and L. R. Mertz, "The Effects of Traffic on the Density of Bituminous Paving Mixtures," in *Proc. AAPT*, 1961.
[7] A. H. Abedali and Y. M. Jebur, "Reduced Permanent Deformation of Asphalt Pavement by Enhancing Aggregate Gradation," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 671, no. 1, 2020, doi: 10.1088/1757-899X/671/1/012082.
[8] V. Aurilio, W. J. Pine, and P. Lum, "The Bailey Method Achieving Volumetrics and HMA Compactability," *Fiftieth Annu. Conf. Can. Tech. Asph. Assoc.*, pp. 159–183, 2005, [Online]. Available: http://aicms.memexonline.com/dotAsset/89f728e5-6dbb-4d8b-b723-b3f36ecca7d1.pdf
[9] J. S. Daniel and F. Rivera, "Application of the Bailey Method To New Hampshire Asphalt," *Impact Asph. Thick. Pavement Qual.*, vol. 39, no. 2, pp. 611–627, 2019.
[10] W. R. Vavrik, W. J. Pine, G. Huber, S. H. Carpenter, and R. Bailey, "The Bailey method of gradation evaluation: The influence of aggregate gradation and packing characteristics on voids in the mineral aggregate," *Asph. Paving Technol. Assoc. Asph. Paving Technol. Tech. Sess.*, vol. 70, no. August, pp. 132–175, 2002.
[11] F. L. Roberts, P. S. Kandhal, E. R. Brown, D.-Y. Lee, and T. W. Kennedy, "Hot mix asphalt materials, mixture design and construction," 1991.
[12] R. P. Elliott, M. C. Ford Jr, M. Ghanim, and Y. F. Tu, "Effect of aggregate gradation variation on asphalt concrete mix properties," *Transp. Res. Rec.*, no. 1317, 1991.
[13] E. Sangsefidi, H. Ziari, and M. Sangsefidi, "The effect of aggregate gradation limits consideration on performance properties and mixture design parameters of hot mix asphalt," *KSCE J. Civ. Eng.*, vol. 20,

no. 1, pp. 385–392, 2016, doi: 10.1007/s12205-015-0265-8.
[14] P. S. Kandhal and S. A. Cross, "Effect of aggregate gradation on measured asphalt content," *Transp. Res. Rec.*, no. 1417, pp. 21–28, 1993.
[15] P. S. Kandhal and R. B. Mallick, "Effect of mix gradation on rutting potential of dense-graded asphalt mixtures," *Transp. Res. Rec.*, vol. 1767, no. 1, pp. 146–151, 2001.
[16] N. C. Krutz and P. E. Sebaaly, "The effects of aggregate gradation on permanent deformation of asphalt concrete," *J. Assoc. Asph. Paving Technol.*, vol. 62, 1993.
[17] M. Swathi, T. Andiyappan, G. Guduru, M. A. Reddy, and K. K. Kuna, "Design of asphalt mixes with steel slag aggregates using the Bailey method of gradation selection," *Constr. Build. Mater.*, vol. 279, p. 122426, 2021.
[18] G. Thompson, "Investigation of the Bailey Method for the design and analysis of dense-graded MHAC using Oregon aggregates.," Oregon. Dept. of Transportation. Research Unit, 2007.
[19] G. Thompson, "Investigation of the Bailey Method for the Design and Analysis of Dense- Graded HMAC Using Oregon Aggregates," no. September, 2006.
[20] SCRB/R9, "General Specification for Roads and Bridges, Section R/9, Hot-Mix Asphalt Concrete Pavement, Revised Edition," *State Corp. Roads Bridg. Minist. Hous. Constr. Repub. Iraq*, 2003.
[21] MS2, *MS-2 Asphalt Mix Design Methods (7th Edition)*. 2015.
[22] S. A. R. Shah *et al.*, "Marshall stability and flow analysis of asphalt concrete under progressive temperature conditions: An application of advance decision-making approach," *Constr. Build. Mater.*, vol. 262, p. 120756, 2020.
[23] C. Paper, "Moisture damage evaluation of asphalt mixtures using AASHTO T283 and DC (T) Fracture Test Moisture Damage Evaluation of Asphalt Mixtures using AASHTO T283," no. January 2006, 2016.
[24] M. A. Sobhan, S. A. Mofiz, and H. M. Rasel, "Effect of gradation and compactive effort on the properties of bituminous mixes with waste concrete aggregates," *Int. J. Civ. Environ. Eng.*, vol. 11, no. 4, pp. 18–21, 2011.
[25] Z. H. Al-saffar *et al.*, "The Use of Vacuum Residue as a Potential Rejuvenator in Reclaimed Asphalt Pavement : Physical , Rheological , and Mechanical Traits Analysis," 2023.
[26] F. Xiao and S. N. Amirkhanian, "Laboratory investigation of moisture damage in rubberised asphalt mixtures containing reclaimed asphalt pavement," *Int. J. Pavement Eng.*, vol. 10, no. 5, pp. 319–328, 2009.