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Investigating the Effect of Experimental Factors on the Performance of Warm Mix Asphalt with Wax Additive using Application of the Taguchi Method

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ABSTRACT

The objective of this study was to assess the impact of experimental factors on the volumetric properties and performance of warm mix asphalt (WMA) with RH-WMA using the Taguchi method. The gradations of the mixtures were based on AC 14, as specified by the Public Works Department of Malaysia. An L16 orthogonal array was employed to design the mixtures, considering three factors: compaction temperatures ranging from 95 to 140°C, RH-WMA contents ranging from 1% to 4%, and asphalt contents ranging from 3.5% to 6.5%. Sixteen mixtures were prepared according to the L16 array. The study focused on investigating several volumetric properties, including bulk-specific gravity, air voids, voids filled with asphalt, and voids in mineral aggregates. Additionally, the strength behavior of the samples was analyzed using the Taguchi method. The resilient modulus and performance of the mixtures were also evaluated. The results of the study indicate that a high RH-WMA content led to a slight decrease in the strength of the asphalt mixture and air voids. However, it increased the voids filled with asphalt (VFA) and resulted in softening of the asphalt mixtures.

دراسة تأثير العوامل التجريبية على أداء الخلطة الاسفلتية الدافئة مع المضافات الشمعية باستخدام تطبيق طريقة تاقوتشي

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الكلمات المفتاحية:
خلطات الإسفلت الدافئة
RH-WMA
الخواص الحجمية.
معامل المرونة
طريقة تاغوشي

الملخص

الهدف من هذه الدراسة هو تقييم تأثير العوامل التجريبية على الخواص الحجمية وأداء الخلطة الإسفلتية الدافئة (WMA) مع RH-WMA من خلال طريقة تاقوتشي. وتم استخدام التدرج AC 14 استنادًا إلى إدارة الأشغال العامة في ماليزيا لأعمال الطرق (JKR / SPJ / 2008-S4) وتم تصميم الخلطات الأسفلتية في مصفوفة متعامدة L16 مع ثلاثة عوامل متغيرة وهي درجات حرارة الدمك (95-140 درجة مئوية) ومحتوى المادة المضافة RH-WMA (1%-4%) ومحتوى الأسفلت (3.5%-6.5%). وتم تحضير ستة عشر خلطة بواسطة مصفوفة L16 المقترحة بالطريقة. في هذه الدراسة تم اختبار الخصائص الحجمية مثل الكثافة والفراغات الهوائية والفراغات المملوءة بالإسفلت والفراغات في الركام المعدني وتم تحليل سلوك القوة للعينات باستخدام طريقة Taguchi. أيضًا تم تقييم معامل المرونة وأداء الخلطات. تشير النتائج إلى أن المحتوى العالي من RH-WMA أدى إلى انخفاض طفيف في قوة الخلطة الإسفلتية والفراغات الهوائية ولكن زاد محتوى VFA و RH-WMA مما تسبب في تليين الخلطات الإسفلتية.

Introduction

Warm mix asphalt (WMA) is an asphalt paving material that is produced and compacted at lower temperatures compared to traditional hot mix asphalt (HMA). This temperature reduction is achieved by incorporating

additives into the asphalt mixture [1–8].
The primary purpose of WMA production is to reduce the energy consumption, environmental impact, and cost associated with the preparation and application of asphalt materials [9].
The study aims to evaluate the effect of experimental factors on the volumetric properties and performance of WMA with a specific wax additive called RH-WMA. The Taguchi method, a statistical technique for experimental design and optimization, is employed in this study. The three factors considered are compaction temperatures (ranging from 95 to 140 °C), RH-WMA contents (ranging from 1% to 4%), and asphalt contents (ranging from 3.5% to 6.5%). Sixteen mixtures are

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prepared according to the L16 array proposed by the Taguchi method. The study aims to investigate the impact of three experimental factors: RH-WMA contents, asphalt contents, and compaction temperatures, on the strength and volumetric properties of warm mix asphalt (WMA). By utilizing the Taguchi method, the study can analyze the interaction effects of these factors and gain a better understanding of how they collectively influence the properties of WMA.

The Taguchi method allows for the systematic design of experiments and the optimization of parameters. It helps in identifying the optimal combination of factor levels that will result in the desired performance or quality characteristics of WMA. Additionally, the Taguchi method can also assess the sensitivity of the WMA properties to variations or noise factors, enabling researchers to develop robust and reliable mix designs. By employing the Taguchi method in this study, the researchers will be able to evaluate how changes in RH-WMA contents, asphalt contents, and compaction temperatures affect the strength and volumetric properties of WMA. This analysis will provide valuable insights into the combined influence of these factors and aid in optimizing the mixture design to achieve the desired properties for WMA production.

In environmental science response surface method (RSM) has been applied to optimize pollutant removal processes, such as wastewater treatment or air pollution control. In concrete technology, RSM has been used to optimize the mix design parameters, such as water-cement ratio and aggregate proportions, to achieve desired strength and durability properties. In material science, RSM has been employed to optimize the processing parameters for various materials, such as ceramics or polymers, to improve their mechanical or thermal properties. In mechanical engineering, RSM has been utilized to optimize the manufacturing processes and design parameters of components or systems.

Overall, RSM is a versatile and powerful statistical technique that allows researchers and engineers to understand and optimize complex systems by exploring the relationships between input variables and the response of interest. Its widespread application across different disciplines highlights its effectiveness in solving various scientific and engineering problems.

In asphalt research, Hamzah et al. [10] Using the response surface method (RSM), researchers have applied this statistical technique to determine the optimum binder content of warm mix asphalt (WMA) incorporating Rediset. Rediset is an additive commonly used in WMA production to improve workability and reduce mixing and compaction temperatures.

Khodai et al. [11] employed the response surface method (RSM) to assess the effects of aggregate gradation and lime content on the tensile strength ratio and indirect tensile strength (ITS) of dry and saturated hot mix asphalt.

Taguchi method

The Taguchi method is a statistical method developed by Genichi Taguchi is a Japanese engineer who made significant contributions to the field of quality engineering. He developed the Taguchi methods, which are a set of techniques and principles aimed at improving the quality of manufactured goods while reducing variation and costs.

The Taguchi method focuses on understanding and optimizing the performance of systems, products, or processes by considering the effects of various factors and their interactions. It involves three main steps: system design, parameter design, and tolerance design.

In system design, the objective is to identify the key factors that have the most significant impact on the performance of the system. These factors are often referred to as design parameters or control factors.

In parameter design, the goal is to determine the optimal levels of the design parameters that will lead to the desired performance or quality characteristics. The Taguchi method utilizes orthogonal arrays, which are structured matrices, to efficiently conduct a series of experiments with a minimum number of trials.

The Taguchi method emphasizes the concept of "quality loss function," which quantifies the deviation from the target value and the associated costs. By minimizing the quality loss function, the Taguchi method aims to achieve robust and reliable designs that are less sensitive to variations and produce higher-quality products.

Overall, the Taguchi method is a systematic and practical approach to improving the quality and performance of products and processes. It has been widely applied in various industries, including manufacturing, engineering, and quality management, to optimize designs, reduce costs, and enhance customer satisfaction [12]. Ahmet Tortum et al. [13] used this method to determine optimum conditions for tire rubbers in asphalt concrete with the Marshall test. Imane Harizi et al. [14] utilized the Taguchi method to evaluate the stiffness modulus of a modified bituminous concrete with PR PLAST Sahara. In concrete technology, Erdogan Ozbay et al. [15] used the Taguchi method to investigate mixed proportions of high-strength self-compacting concrete. M.J.A. Mijarsh et al. [12] utilized the Taguchi method to investigate the main parameters that affect compressive strength. Abolghasem Yazdani [16] also used this method for the optimization of asphalt binders modified with PP/SBS/nanoclay nanocomposite. Lin, JL. et al.

[17] employed the method with fuzzy logic to optimize the electrical discharge machining process with multiple performance characteristics. In this paper, we used the L16 OA for the three controlling factors to obtain more reliable data.

Materials and experimental procedures

The materials and experimental procedures used in this study are as follows:

① Granite Aggregate: The study utilized granite aggregate supplied by Kuad Sdn. Bhd. This aggregate met the local standard specifications [24] for use in the AC 14 mix.

② Pavement Modifiers (PMD): PMD, a grayish-black powder mineral filler, was used as an anti-stripping agent in the mixtures.

③ Asphalt Binders: The study utilized asphalt binders with properties similar to those used by Aburawi [11]. The specific properties and grades of the binders were not mentioned.

Additives

RH-WMA, an organic additive, is commonly used in asphalt mixtures. The technology incorporating organic additives involves the addition of waxes to the mixture. As the temperature rises above the melting point of the waxes, a decrease in viscosity is typically observed [19–23]. The typical amount of wax added is in the range of 2% to 4% of the total mass [2, 24]. Fig. 1 illustrates the appearance of RH-WMA, which is characterized by small white particles.

Fig. 1: RH-WMA as Additive for WMA

The preparation of the samples involved the following steps:

① Blending RH-WMA with Asphalt Binder: The predetermined amounts of RH-WMA were blended with the asphalt binder using a propeller mixer at a temperature of 145 °C for a duration of 30 minutes.

② Mixture Preparation: Mixtures were prepared for each set of mixing temperatures, RH-WMA contents, and asphalt contents. The mixing temperature was set 5°C higher than the compaction temperature.

③ Short-Term Aging: The loose mixtures were subjected to short-term aging for 2 hours at the anticipated compacted temperature.

④ Compaction: The mixtures were compacted at the compaction temperature using a Superpave gyratory compactor. The compaction process involved a compactor speed of 30 rpm and a compaction angle of 1.25° for 100 gyrations. Additionally, conventional HMA samples were also compacted at 150 °C, and their responses were recorded for comparison purposes.

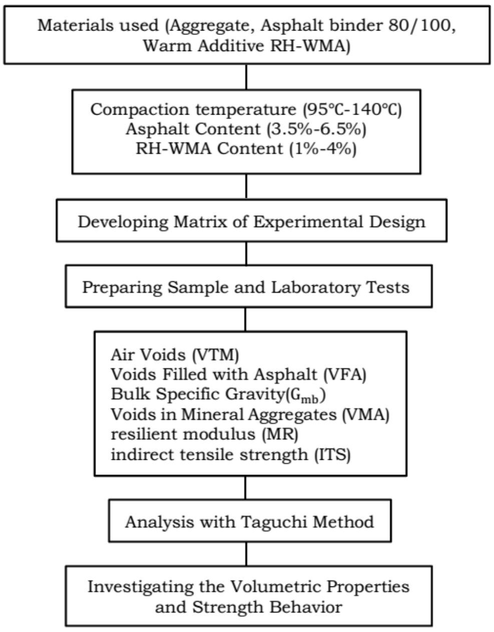

Fig. 2: Study process

The Taguchi method was employed for statistical analysis of the responses. The statistical analyses were conducted using Design-Expert software (version 6.0.6). The significance of the model and factors was determined for each response, and the necessary graphs were generated. Subsequently, the optimum binder content (OBC) was determined using the predicted response from each model. The study process is illustrated in Fig. 2.

Design of the mixtures

The mixtures in this study were designed using the Taguchi method to determine the optimal combination of parameters for achieving desired mechanical properties. The study focused on three main factors: compaction temperatures (A), asphalt contents (B), and RH-WMA contents (C). Each factor was evaluated at four levels, as shown in Table 1.

Table 1: Introduced levels for each factor in the Taguchi experimental design.

Factor	Unit	Level 1	Level 2	Level 3	Level 4
A: Compaction Temperature	℃	140	125	110	95
B: Asphalt Content	%	3.5	4.5	5.5	6.5
C: RH-WMA Content	%	1	2	3	4

To conduct the experiments, the Taguchi method recommended an L16 array design, which allowed for the evaluation of the three factors at the four levels. The specific design configuration is presented in Table 2.

Table 3 provides details of the values and trial mixture proportions used in the series of 16 mixtures. These mixtures were prepared and tested to assess their strength behavior values.

To evaluate the strength behavior of the trial mixtures, a response index was calculated for each factor based on the S/N (signal-to-noise) principles. The S/N ratio represents the quality of the response, with a higher S/N indicating a better response index. By analyzing the response indexes, the study aimed to determine the effects of the compaction temperatures, asphalt contents, and RH-WMA contents on the mechanical properties of the mixtures and identify the optimal combination of parameters that would result in the desired mechanical performance.

Overall, the Taguchi method was employed to systematically evaluate the effects of the factors and their levels on the mixture properties, allowing for the determination of an optimum mixture design based on the calculated response indexes.

Table 2: Taguchi method of orthogonal arrays [L16 (4*5)] of the experimental design.

Trial	Factor A	Factor B	Factor C
T1	3	2	4
T2	1	3	3
T3	1	1	1
T4	2	3	4
T5	4	2	3
T6	4	3	2
T7	1	2	2
T8	1	4	4
T9	2	1	2
T10	3	1	3
T11	4	4	1
T12	2	2	1
T13	2	4	3
T14	3	3	1
T15	4	1	4
T16	3	4	2

The responses (dependent variables) in this study were selected as volumetric measurements, which were defined according to the Malaysian road work specifications for the design of dense mixtures [25]. Table 4 provides a list of these variables along with their acceptable ranges. The values presented in Table 4 serve as the fundamental criteria for evaluating the volumetric properties and performance of Warm Mix Asphalt (WMA) based on Malaysian specifications [25].

Table 3: Mix proportions used for Taguchi optimization.

Mix	Weight of Binder (g)	Compaction Temperature (℃)	Asphalt Content (%)	RH-WMA Content (%)
T1	51.8	110	4.5	4
T2	64.0	140	5.5	3
T3	39.9	140	3.5	1
T4	64.0	125	5.5	4
T5	51.8	95	4.5	3
T6	64.0	95	5.5	2
T7	51.8	140	4.5	2
T8	76.5	140	6.5	4
T9	39.9	125	3.5	2
T10	39.9	110	3.5	3
T11	76.5	95	6.5	1
T12	51.8	125	4.5	1
T13	76.5	125	6.5	3
T14	64.0	110	5.5	1
T15	39.9	95	3.5	4
T16	76.5	110	6.5	2

Table 4: Responses and their acceptable range based on the Malaysian specifications [25].

Responses	Acceptable range	Parameters for determining the OBC*
Volumetric response		
Air voids in mix	3.0–5.0%	Air voids = 4%
G_{mb}**	-	Peak point
VFA***	70–80%	VFA = 75%

* The average value of this column is used for determining the OBC.
** Bulk specific gravity.
*** Voids in aggregate filled with asphalt binder.

Resilient modulus (M_R) and ITS are important characteristics in the structural design and response of asphalt pavements under loading. High asphalt mixture M_R can enhance the pavement structure's load-bearing capacity.

Another procedure is the inclusion of M_R and ITS, which are considered important parameters in the load-bearing performance of pavements.

The volumetric measurements were selected as the responses (dependent variable). These variables were defined based on the Malaysian road work specifications for the design of dense mixtures [25]. Table 4 lists these variables and their acceptable ranges. Strength response uses M_R (peak point). The values presented in Table 4 and the peak point for M_R are considered the basic criteria to determine OBC.

Results and discussion

Table 5 shows the results of the volumetric properties and strength behavior conducted on the 16 trial mixtures prepared as suggested by the Taguchi method.

Based on the results, the evaluation of volumetric properties (response index) for each factor was calculated by averaging the air voids (VTM), voids filled with asphalt (VFA), bulk specific gravity (G_{mb}), voids in mineral aggregate (VMA), M_R, and ITS for each trial mixture containing a particular factor.

Table 5: Changes of volumetric properties and strength behavior of trial mixes.

Trial Mix	Combination	Volumetric Properties				Strength Behavior		
		Response 1	Response 2	Response 3	Response 4	Response 5	Response 6	Response 7
		G_{mb} (g/cm3)	VTM (%)	VMA (%)	VFA (%)	M_R (MPa)	ITS (MPa)	Flow (mm)
T1	A3B2C4	2.348	2.6	13.0	80	3094	2286.1	1.59
T2	A1B3C3	2.243	8.2	15.2	46	3595	1431.4	1.45
T3	A1B1C1	2.308	5.9	13.6	57	3328	2694.0	1.55
T4	A2B3C4	2.325	8.9	14.8	40	2040	1768.3	1.77
T5	A4B2C3	2.327	7.2	13.8	47	2276	1894.5	1.57
T6	A4B3C2	2.245	8.8	15.1	41	2282	1429.8	1.62
T7	A1B2C2	2.294	6.7	14.1	53	3991	2086.6	1.70
T8	A1B4C4	2.308	2.7	15.4	82	1480	1663.8	2.22
T9	A2B1C2	2.232	8.4	16.4	49	2004	1698.8	1.62
T10	A3B1C3	2.177	12.4	17.6	30	1848	2449.3	1.90
T11	A4B4C1	2.323	6.2	14.0	56	3169	1368.6	1.30
T12	A2B2C1	2.312	5.0	15.3	67	1498	1400.2	2.39
T13	A2B4C3	2.255	7.8	15.6	50	1843	1373.6	1.75
T14	A3B3C1	2.304	5.7	14.7	61	1896	1596.0	2.14
T15	A4B1C4	2.290	8.1	16.1	49	2400	1921.1	1.70
T16	A3B4C2	2.204	10.9	16.6	35	1105	831.9	1.85

G_{mb}= Bulk Specific Gravity   VTM = Percent Voids Total Mix   VMA= Void in the Mineral Aggregate

VFA= Percent Voids Filled with Asphalt M_R= Resilient Modulus

Analysis of volumetric properties

The G_{mb}, VTM, and VFA with asphalt binder are volumetric properties that play a crucial role in determining the OBC [25]. These parameters are also utilized in various other mixed design methods.

To assess the volumetric properties of all samples, the Taguchi method was employed. The analysis resulted in quadratic models, as depicted in Table 5, which accurately represent the volumetric behaviors.

Effect of factors on bulk specific gravity (G_{mb})

Figure 3 demonstrates the impact of different factors on G_{mb}. It is observed that G_{mb} rises as the temperature compaction (factor A) increases. This can be attributed to the decrease in viscosity, which aids in the consolidation and compaction of granular aggregates, resulting in an increase in the G_{mb} value of the asphalt mixture.

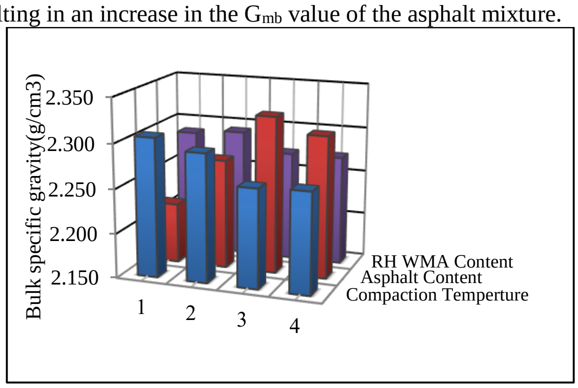

Fig. 3. Effect of (a) compaction temperature, (b) asphalt content, and (c) RH-WMA content on bulk specific gravity

Furthermore, G_{mb} increases with an increase in asphalt content (factor B) up to a maximum value at level 3, where the asphalt content reaches 5.5%. On the other hand, the G_{mb} decreases as the RH-WMA content (factor C) increases.

Effect of factors on air voids (VTM)

Fig. 4 shows the effect of factors (A, B, and C) on air voids (VTM). The figure shows the relationship between compaction temperature (factor A) and the percentage of air voids of the asphalt mixture. The percentage of air voids was noted to decrease with increasing compaction temperature (factor A) and asphalt content (factor B).

The decline in the percentage of air voids is caused by the increase in compaction temperature. The increase in compaction temperature results in less viscosity and increased susceptibility of bitumen coating to aggregate, rendering easy operability. Then coating aggregate can have compacted and movement interlaced become something easy and easy are approximately each other, which reduces the percentage of air voids. The plots of air void content against asphalt content show a gentle downward curve, whose gradient diminishes with increasing asphalt content (factor B), while the air voids increase with increasing RH-WMA content (factor C).

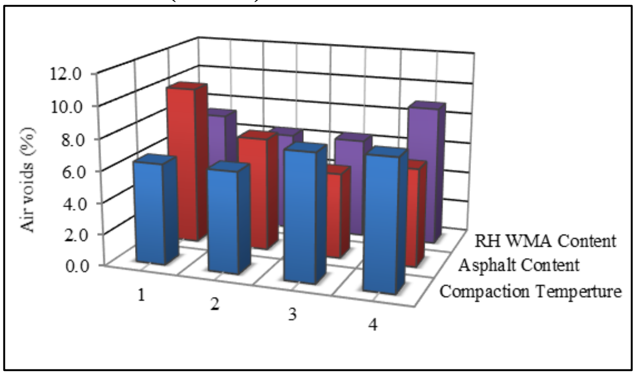

Fig. 4. Effect of (a) compaction temperature, (B) asphalt content, and (C) RH-WMA content on air voids

Effect of Factors on VFA

Fig. 5 shows the relationship between compaction temperature (factor A) and voids filled with asphalt for the asphalt mixture. The shape illustrates that the percentage of voids filled with bitumen increased with increasing compaction temperature (Factor A), which is due to the same reasons mentioned in the relationship between the air voids percentage and change in compaction temperature. VFA increased with increasing asphalt content (Factor B). Factor C VTM increased with the increase in factor RH-WMA content.

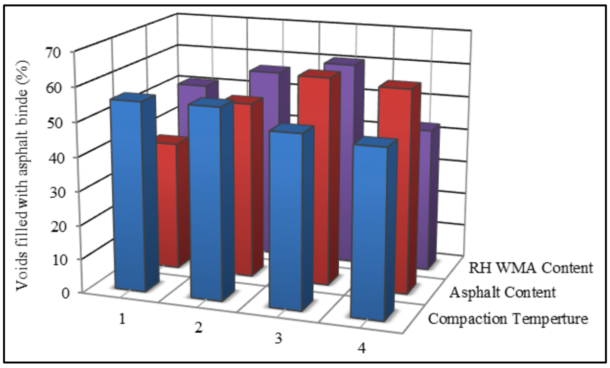

Fig. 5. Effect of (a) compaction temperature, (B) asphalt content, and (C) RH-WMA content on voids filled with asphalt

Effect of Factors on M_R and ITS

Fig. 6 and Fig. 7 show the relationship between the effects of compaction temperature (factor A). The figures of the values of M_R and ITS test are noted to increase with increasing compaction temperature.

The increase in the values of M_R and ITS test with increasing compaction temperature was due to the increase in the intensity of adhesion between the aggregate as a result of the low viscosity of bitumen, thereby allowing an easy mixture and overlapping of granular aggregates during compaction. Notably, the values of M_R and ITS test dramatically increased in the blood temperature of 125°C compared with the compaction temperature of 95°C.

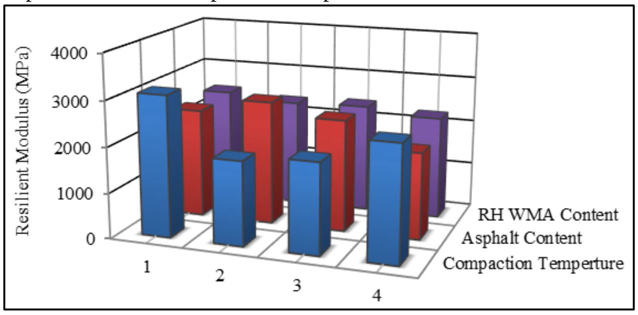

Fig. 6. Effect of (a) compaction temperature, (B) asphalt content, and (C) RH-WMA content on resilient modulus

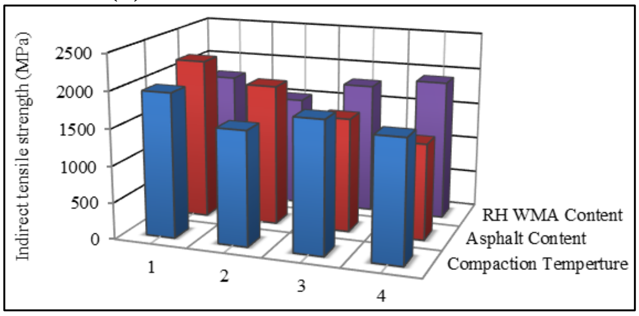

Fig. 7. Effect of (a) compaction temperature, (B) asphalt content, and (C) RH-WMA content on indirect tensile strength

Conclusion

This study demonstrates that the Taguchi method can effectively analyze the impact of experimental factors on the volumetric properties and strength behavior of Warm Mix Asphalt (WMA). The study yielded the following findings:

- Simultaneous statistical analysis of strength and volumetric properties of WMA mixtures is possible.
- WMA mixtures compacted at lower temperatures require a lower optimum binder content to meet mix design criteria. However, these mixtures exhibited lower stability and quotient compared to mixtures fabricated at higher temperatures. The optimum binder content (OBC) of WMA was slightly lower than that of Hot Mix Asphalt (HMA) without the warm additive RH-WMA.
- Increasing the values of bulk-specific gravity and Indirect Tensile Strength (ITS) led to higher compaction temperatures, while reducing the percentage of air voids and voids filled with bitumen resulted in higher compaction temperature ratios for achieving the optimum asphalt mixture.
- A higher content of RH-WMA slightly decreased the strength of the asphalt mixture and reduced air voids, but increased the Voids Filled with Asphalt (VFA). This indicates that a higher RH-WMA content leads to a softening effect in asphalt mixtures.

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