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Climate- Responsive Asphalt Pavement Design: Comparative Performance of Superpave and Marshall Mix Methods

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Abstract: This work compares the performance of Marshall and Superpave asphalt mix designs over many climatic zones with an eye toward rutting resistance, moisture sensitivity, and fatigue life. Designed under the Strategic Highway Research Program, Superpave uses performance-graded binders and optimal compaction techniques to be ideal for high temperatures, heavy traffic, and extreme climates, including tropical heat, freeze-thaw cycles, and arid conditions. Often used in moderate temperatures with less traffic, the Marshall technique is simpler and less expensive. Superpave routinely beats Marshall by 5–14% in rutting and cracking resistance across all regions achieves 90–100% resistance in freezing areas (Kazakhstan, Canada, China), compared with 60–70% in temperate regions (Jordan, Iraq, Alabama), and up to 94% in tropical and arid zones. Both methods perform similarly in moderate temperatures; Superpave has a slight edge. The study also underlines how adding recycled materials and additives can increase the sustainability and durability of both designs, so validating Marshall's relevance for low-cost projects and Superpave's excellence in demanding environments. Climate-responsive and performance-based strategies of mix design ensure resilient infrastructure with sustainable development within the transport sector.

Keywords: *Superpave; Marshall Mix Design; Rutting Resistance; Cracking Resistance; Asphalt Pavements; Climate Responsive*

1. Introduction

Different techniques of mix design affect asphalt pavements' performance in several ways. Particularly when using reclaimed asphalt pavement, superpave mix design has been shown to be able to create longer-lasting pavements with enhanced performance qualities [1]. Superpave was developed under the Strategic Highway Research Program (SHRP) to overcome some deficiencies in the older methods by considering factors such as traffic loads and variations in climate, and is thus particularly suitable for areas with extreme temperatures [2]. The Marshall method is relatively easier to run and of less complexity than other methods; it has a very wide application, especially under moderate climate zones [3, 4]. As for the asphalt pavements, the two major kinds of distress modes involve rutting and surface cracking-the two being related to service life and durability. Given that traffic loads in repetitions have usually been the natural cause of rutting, high temperatures occur to enhance this further [5, 6], The incidence of all kinds of cracks, such as fatigue and thermal cracking incidents, tends to be a bit greater in cold zones that experience freeze-thaw action [7, 8]. Superpave has also had success with its performance-graded binders and advanced compaction techniques, which have shown advantages in extreme climates; research from Kazakhstan and Iraq shows superior moisture and rutting resistance of Superpave [2, 9].

The Marshall method continues to be popular in states with moderate climates where the performance benefits of Superpave are not as critical and ease of implementation is emphasized [10- 12]. For example, studies from Libya have shown that, although the performance of the Marshall mixes was satisfactory in hot climatic conditions, they are inferior to Superpave regarding rutting resistance [13, 14]. Various comparative studies pointed out the superior performance of Superpave under heavy traffic and harsh climatic conditions. The study found that the Superpave mixes are more resistant to rutting because of enhanced compaction [15]. Various studies, like those conducted by go on to indicate that various modifications, such as lime and fibers, may enhance the performance of Marshall's, though they often still fall short of results obtained using Superpave [16]. Another point of attention in the greening of both Superpave and Marshall mixes is the application of recycled materials and advanced additives. For instance, research [17] showed that recycled materials in Superpave mixes improve performance and are cost-effective. The increasingly erratic climate patterns and the recent call for sustainable infrastructure, therefore, underline the need to select mix designs suitable for regional conditions. Only then can any road infrastructure be durable and cost-effective, taking the aforementioned into consideration [18, 19]. This research has been set forth with the goal of evaluating the Superpave and Marshall mix design methods in the framework of the climate-resilient asphalt pavement. Influence factors affecting pavement performance, such as geographic and climatic conditions, traffic loads, mix design parameters, and performance criteria such as rutting, fatigue, and moisture resistance, are studied. Also, the study emphasis on new developments and innovations in the pavement design field, aiming at improving climate adaptability, thus giving a complete knowledge of the performance of each design method under varying environmental and operational conditions. The evaluation uniquely focuses on attempting to fit climate response into asphalt pavement design when comparing Superpave and Marshall methods. While both designs are very well studied on their own, the performance is hardly ever analyzed from the perspective of climate adaptation. This paper fills that gap, providing a new facet in sustainable pavement engineering under changing environmental conditions.

2. Literature Review

Mix design methods greatly govern the performance of asphalt pavements, with Superpave and Marshall being the two most widely adopted globally. The Superpave is a design methodology developed to enhance the durability of a wide range of climatic and heavy traffic load conditions given to pavements [1, 3]. Several research works [2, 7] have pointed out that it results in reduced temperature cracking and deformation, especially in cold climates such as those found in Kazakhstan and regions with freeze-thaw cycles. In the meantime, the Marshall method, due to its simplicity and ease of application, has found wider application, especially in regions with limited technical resources [3, 4, 19, 20, 21]. Study [13] underlines that, in the case of moderate to hot climates, where the concern for temperature extremes is lower, it is still relevant. High temperature and heavy traffic impose limitations as the Marshall mixes develop deficiencies such as a high tendency for rutting and cracking, which various studies from tropical and desert climates have recorded [5, 6]. It would appear that while the Marshall is quite effective under relatively good conditions, the performance is not as good in very harsh conditions.

Comparative studies mostly place Superpave ahead in rutting resistance, which occurs in high-temperature regions. Several studies, such as [5, 8], explained that the compaction technique and binder selection in the Superpave method can contribute to superior rutting resistance and, therefore, are ideal to be applied for hot climates. Regions that usually experience excessive heat, such as Iraq, also demonstrate that Superpave designs maintain structural integrity better compared to Marshall. Similarly, the results of research [2, 9] point out that Superpave binders resist moisture and crack prevention in cold climates much better. That also supports the fact mentioned above, showing the advantages of Superpave over Marshall under specific conditions.

Improvement to increase the performance of the mix was made by incorporating different types of additives, like lime, fiber, steel slag, crumb rubber, and polymers [6, 10, 11, 21, 22]. These modified Marshall mixes were able to increase rutting and cracking resistance of these mixes but were not equal to Superpave. Use of recyclables has also been explored in the cases of both Superpave and Marshall mixes.

Studies [14, 18] showed that recycling in asphalt enhances sustainability and maintainability, especially with Superpave. However, the introduction of recycled material in usual Marshall mixes generally adds another degree of complexity and expenditure and may render the long-preferred technique less attractive given its relative simplicity [21].

Besides, while extremely superior in performance, there is still limited use due to the special equipment and training required for Superpave in developing regions. Work by [16] points out that although Superpave offers some long-term benefits related to less maintenance cost and prolonged pavement life, the high initial cost of investment often acts as a deterrent, especially for regions with tight infrastructure budgets. Furthermore, mix design adaptability to changing climatic conditions is of more essence nowadays. Studies [2, 17] emphasized that there is a dire need for flexible design strategies that would resist the shifting weather pattern-in most cases, Superpave is better positioned for these challenges. But more research is needed to keep both methods viable with changing climate conditions.

3. Methodology

3.1 Research Design

The methodology systematically evaluates a wide range of existing research on Superpave and Marshall Mix Designs in respect to the susceptibility to rutting and/or cracking over several climate regions. In order to ensure this study effectively delivers applicable results, the findings from twenty-seven judiciously selected research studies are systematically analyzed since those make direct comparisons between the two mix designs under different environments. These studies, in fact, represent a very broad array of geographic locations, traffic conditions, and mix modifications; as such, they are ideal for gaining an understanding of the broader implications of climate and mix design on the long-term performance of asphalt. The review will be based on a structured approach toward data collection, analysis, and synthesis of conclusions to clearly present how each mix design performs across diverse climate regions.

3.2 Data Collection

3.2.1 Selection of Studies

As regards to the review study, the selection of studies has selected, in total, 27, in relevance with comparing the Superpave to the Marshall Mix Design in terms of performances due to rutting and/or cracking at variable climates and traffic load and regions where these types of mixtures, such as Superpave or Marshall, take place.

3.2.2 Techniques Used

A summary of key tests used across the studies is given below;

1. Creep tests, Air void analysis, Wheel tracking: These tests have been used for the assessment of permanent deformation and resistance to rutting by simulating load stresses and checking the air voids in the asphalt mix.
2. Wheel tracking, ITS tests, Volumetric analysis: These techniques focus on assessing resistance to rutting or moisture susceptibility by measurement, amongst others, of its tensile strength, volume properties, and wheel tracking permanent deformation under imposed stress.
3. Mechanistic-Empirical Pavement Design Guide (MEPDG) Calibration, Trench Investigations, and Temperature Monitoring: The work has involved the calibration of MEPDG for local conditions and field investigations into the assessment of rutting in freeze-thaw conditions.
4. Field Observations, Density Analysis, Deformation Measurements: These techniques are usually conducted in the field to monitor and analyze the rutting and cracking behaviors of asphalt under heavy loads.

5. Dynamic Modulus (|E|), Hamburg Wheel Tracking Test: These two tests in combination characterize properties of the binder and resistance to rutting of asphalt mixes, while assessing the stiffness and deformation under load.

These tests and techniques will provide full-scale testing of both Superpave and Marshall Mix Designs for resistance to rutting, cracking, and moisture in different climates.

3.2.3 Analyzing the Parameters

The parameters extracted from every study have been categorized into five main groups, illustrated in Figure 1. The principal parameters extracted include geographical and climatic context parameters, which distinguish different climate conditions in which the study might have been carried out, such as tropical, arid, or freeze-thaw zones etc. These factors play an important role in assessing the pavement's performance against various weather extremes. Traffic conditions are defined in terms of the nature of traffic and its volume, which increases the pavement's susceptibility to rutting and cracking, apart from general heavy truck traffic. The mix design parameters are also examined in the studies; they represent the parameters of the Superpave and Marshall mix designs employed and include details regarding PG binder type, aggregate gradation, compaction method, and any modifications made, such as additives or recycled materials. The Performance Graded (PG) Binders represent an asphalt binder classification system developed in conjunction with the SHRP under the Superpave concept. It is graded on a performance basis in a specific temperature range and is therefore more dependable as a predictor of how the binder would perform under different climatic and traffic conditions. Other important performance metrics include the results concerning each mix's susceptibility to rutting and cracking, as tested in the laboratory through creep, wheel tracking, and dynamic modulus tests, coupled with field observations.

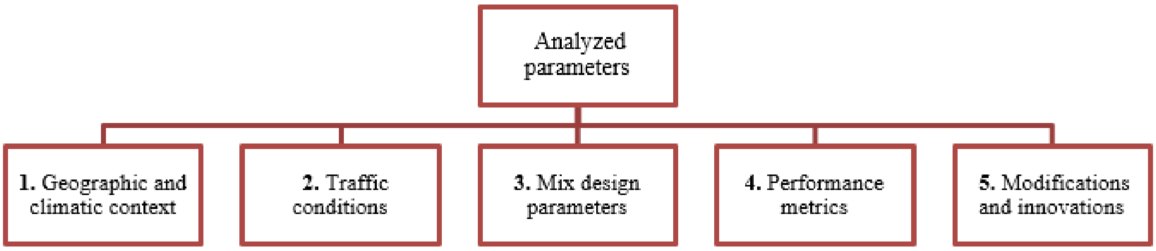

Figure 1: Key parameters and innovations in pavement mix design studies

4. Results and Analysis

4.1 Techniques and Measured Parameters

A summary of techniques, tests used, and the parameters measured for the 27 studies related to Superpave and Marshall mix designs, together with references of the studies, are presented in Table 1. In this case, different methodologies have been used to evaluate the performance of asphalt mixes under diverse conditions. The utilization of creep tests, wheel tracking, and air void analysis techniques is quite common to understand the rutting resistance and permanent deformation of the asphalt mixtures. These methods assist one in determining how well the mixtures could resist stress for a long period of time, especially at heavy loads or fluctuating temperatures.

A lot of focus on these studies could be seen with respect to the evaluation of moisture susceptibility and resistance against freeze-thaw cycles, as observed from some references where tests such as Indirect Tensile Strength (ITS) and Mechanistic-Empirical Pavement Design Guide (MEPDG) calibration are applied. Tests can then be used to predict performance in climates where moisture and freeze-thaw conditions may accelerate damage. The capability of such prediction is important to maintain pavement quality in cold or wet regions. However, fewer studies have been conducted to investigate long-term durability in hot arid conditions, which may require further research. Of course, the other common analysis in this case is field observations with laboratory dynamic modulus tests that give evidence in both in-situ and controlled conditions. A combination of data obtained from the field and a laboratory analysis makes the mixture performance clear under traffic loading conditions, for example, density and deformation assessments. Such information is useful for verification of laboratory predictions and calibration of pavement design models such as MEPDG.

Table 1: Techniques and measured parameters in the studies

No.	Techniques/Tests Used	Measured Parameters	Study References
1	ITS tests, Volumetric analysis, Wheel tracking	Rutting resistance, Moisture susceptibility	[2]
2	Field performance evaluation, Air voids measurement, Rutting and cracking assessment	Rutting, Cracking, Air voids, Durability	[3]
3	Rutting tests, Aggregate gradation analysis, Superpave Gyratory Compactor (SGC), Marshall Compactor	Rutting resistance, Aggregate gradation, Permanent deformation	[4]
4	Creep tests, Air void analysis, Wheel tracking	Rutting resistance, Permanent deformation	[5]
5	Field observations, Density analysis, Deformation analysis	Rutting, Cracking under heavy loads	[6]
6	MEPDG calibration, Trench investigations, Temperature calibration	Freeze-thaw performance, Rutting prediction	[7]
7	Dynamic Modulus (|E*|), Hamburg Wheel Tracking (HWT)	Rutting resistance, Binder properties	[8]
8	Volumetric analysis, Resilient modulus testing, and Moisture sensitivity testing	Density, Voids in Mineral Aggregate (VMA), and Moisture durability	[15]
9	Accelerated loading tests, Stress response measurement, and Rutting analysis	Stress response, Rutting depth, Load-induced deformation	[17]
10	Marshall Stability test, Fatigue resistance, Volumetric analysis	Rutting, Cracking, Fatigue resistance	[23]
11	Marshall Stability, Rheological tests, Wheel tracking	Rutting resistance with additives	[24]
12	ITS tests, Moisture resistance, High-temperature tests	Recycled material performance, Rutting	[25]
13	Resilient Modulus (Mr), Permanent deformation tests, ITS tests	Rutting resistance, Aggregate gradation	[26]
14	Hamburg Wheel Tracking (HWT), Logistic regression	Rutting prediction, Model-based performance	[27]
15	Anti-rutting and anti-cracking balance method, Mechanical performance tests, Laboratory fatigue tests	Anti-rutting performance, Anti-cracking performance, Fatigue resistance	[28]
16	Superpave mixture analysis, Pavement performance evaluation, Field performance tests at airport pavements	Rutting resistance, Pavement durability, and Field performance under heavy traffic	[29]
17	Theoretical analysis of different mix designs, Comparative review of methods for developing countries, Simulation of traffic loading	Applicability of mix design methods for developing countries, Durability,	[30]

		Performance under various traffic loads	
18	Suitability assessment, Laboratory mechanical tests, Performance grading, Field evaluation of Superpave and Marshall mixes	Rutting resistance, Cracking resistance, Overall performance under different climatic conditions	[31]
19	Dynamic modulus test, Resilient modulus test, Simple Performance Test (SPT)	Rutting resistance, Resilient modulus, Permanent deformation	[32]
20	Marshall Stability, Indirect Tensile Strength, Fatigue Life, Resilient Modulus	Stability, Indirect tensile strength, Fatigue resistance, Resilient modulus	[33]
21	Gyratory compaction, Air voids measurement, Moisture susceptibility tests	Air voids, Moisture resistance, Rutting potential	[34]
22	Static bending and flexural fatigue tests, Rutting tests, Raveling tests	Flexural strength, Rutting resistance, Raveling susceptibility	[35]
23	Superpave repetitive simple shear test (RSST-CH), Four-point bending beam test	Rutting depth, Fatigue performance, Shear strength	[36]
24	Rutting tests, Moisture susceptibility tests, Dynamic modulus tests	Rutting resistance, Moisture damage, Stiffness	[37]
25	Dynamic modulus test, Indirect tensile creep compliance test, Triaxial shear strength test	Fracture energy, Fatigue resistance, Rutting resistance	[38]
26	Superpave Asphalt Concrete Mix Design, Performance testing under local climatic and traffic conditions, Volumetric analysis of asphalt mixes	Rutting resistance and moisture susceptibility, Air voids, Stability and flow	[39]
27	Superpave Grading and Performance Grading (PG) evaluation, Indirect Tensile Strength (ITS) test, Dynamic modulus test	Rutting potential through Wheel Tracking test, Tensile strength ratio (TSR) for moisture susceptibility, Stiffness and viscoelastic properties	[40]

4.2 Geographic and Traffic Conditions

The countries shown in Figure 2, have different climatic conditions selected for this study, which in turn affect their various environmental and infrastructural requirements. Iraq is a very hot and arid country; the temperature during summer is extremely high, while the rainfall is scant. Kazakhstan has extremely cold winters with moderate summers, hence a huge variation in seasonal temperature. Canada, especially Ontario, experiences cold winters with freeze-thaw cycles. The USA has a huge variation in climate, from the cold of Alaska to the subtropical warmth of Alabama, known for its hot and humid summers and mild winters.

China is subjected to a wide scope of climatic conditions, where northern areas receive frigid winters and tropical conditions lead to southern areas. Pakistan comprises arid deserts; hence, it has extreme heat during summer and a monsoon season. Japan has a temperate climate, in which both winters are severe and the summers are mostly hot and humid. Zambia has clearly marked wet and dry seasons for its tropical climate. Southeast Asia-Nation member Malaysia is characterized by a tropical climate with high humidity practically throughout the whole year and quite a plentiful rainfall. Jordan is a country in southwest Asia, basically having an arid desert climate. Its winters are usually mild. In contrast, Malaysia, a country situated in Southeast Asia, has high temperatures and frequent rainfall due to its equatorial region features.

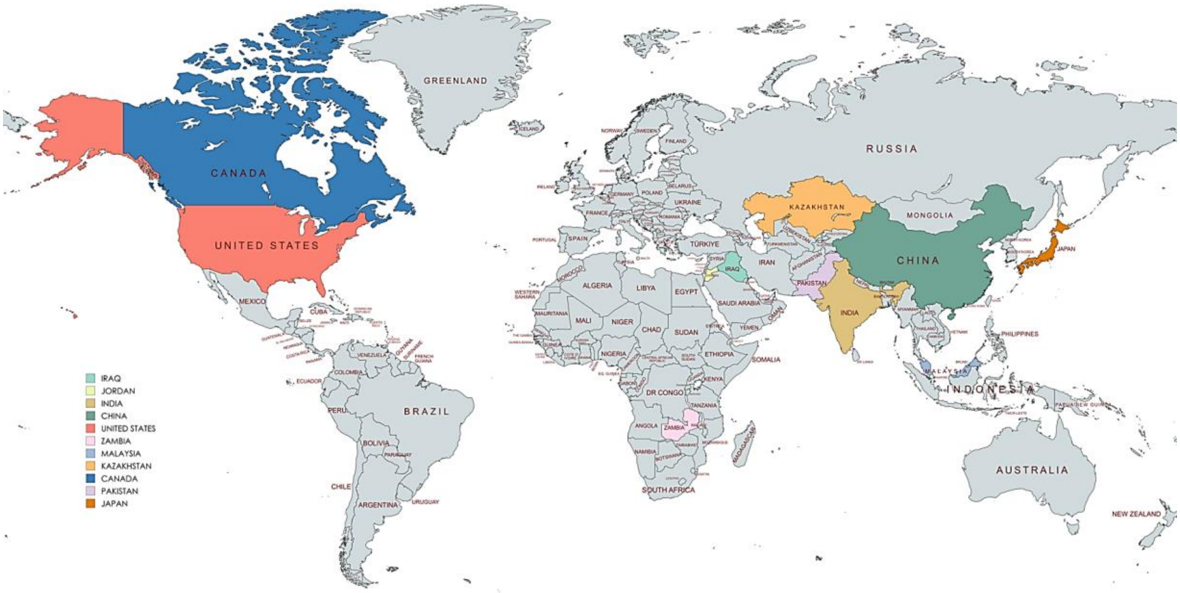

Figure 2: Diverse climate conditions across selected countries in the study

Table 2 presents some deep analyses from different studies examining the performance of Superpave and Marshall mix design performances across various geographic and climatic contexts. Each study examines some unique combination of climate and traffic conditions, which vary greatly and affect asphalt pavements differently in performance. For instance, the research studies carried out in areas like Iraq express the impact of hot and arid climatic conditions, which may accelerate aging as well as deformation in asphalt with increased temperature. Most of the studies consider heavy traffic flow conditions comprising slow-moving trucks, adding to the stress as well as rutting in the pavement.

On the other hand, the effects of freeze-thaw cycles are the main concern in the studies done in countries like Kazakhstan and Ontario. A number of challenges are present, including higher chances of cracking and moisture damage. Most studies done within these regions assess the performance of asphaltic concrete pavements under cyclic freeze and thaw conditions and moderate to heavy traffic damage. This emphasis on local circumstances indicates the requirement for asphalt mixes that have sufficient resistance to the effects of thermal changes and frost heave, and thermal cracking.

In such hot and wet tropical climates, the priority is around susceptibility to moisture, and the damage caused by heavy trucks traveling at low speeds on steep gradients. It makes the rutting and damage by water more pronounced; hence, moisture resistance is an important design parameter for choosing the mixtures for asphalt construction. Regional studies typically categorized these pavements as high-stress pavements, so the study results emphasized the need for both rutting and moisture damage resistance in pavement designs.

In general, the data in Table 2 suggest the need for the formulation of different kinds of asphalt mix designs tailored to specific climatic and traffic conditions. The solution is to adopt different pavement design methodologies that are relative to each region's unique environmental and load conditions. Severe weather, such as hot or cold climates, requires the use of specialized testing and material alterations as a way to strengthen the lifespan of the pavement. Table 2 also outlines research needs, such as effects of climate changes on the traditionally cold or hot regions, which are necessary in the future pavement design to guaranty the durability and safety.

Table 2: Review of geographic and traffic conditions in the studies

No.	Geographic and Climatic Context	Traffic Conditions	Study References
1	Kazakhstan- Extreme cold and moderate climates	Moderate traffic, local conditions	[2]
2	Alabama, USA - Hot, humid climate	Moderate to heavy traffic, including high-load roads	[3]
3	Middle East (Iraq)- Hot and arid climate, high temperatures	Heavy traffic with slow-moving trucks, a high-temperature environment	[4]
4	Iraq- Hot and arid climate, high temperatures	Heavy traffic loads, slow-moving trucks	[5]
5	Tropical climate, high temperatures, heavy precipitation	Heavy trucks with slow speeds due to steep gradients	[6]
6	Ontario, Canada- Freeze-thaw cycles, cold climate	Heavy traffic, high volume, slow-moving loads	[7]
7	USA- Varies, climates with temperature extremes	Mixed traffic, both high and moderate volumes	[8]
8	Minnesota, USA - Cold climate with local government focus	Local roads with moderate traffic	[15]
9	China - Effects of accelerated loading in varied climates	Simulated high-load conditions under accelerated loading	[17]
10	Moderate climates in the Middle East	Moderate to heavy traffic conditions	[23]
11	Iraq- Hot climate, extreme temperatures	Heavy traffic, high-volume highways	[24]
12	China- High temperature regions, focus on recycling	Varied traffic volumes, with a recycling focus	[25]
13	Pakistan- High temperatures, moderate climate	Moderate traffic, lab simulations	[26]
14	USA- Warm climates, focus on temperature effects	Heavy traffic conditions, highway focus	[27]
15	China- Mix design targeted for tropical and temperate regions	Moderate to heavy traffic conditions in tropical and temperate climates	[28]
16	Tokyo, Japan- Cold and temperate climates, international airport	High traffic volume, heavy aircraft loads, and high durability requirements	[29]
17	Zambia- Tropical and semi-arid climates	Moderate to heavy traffic, focus on mix designs for developing countries	[30]
18	Southeast Asia- Tropical climate, high moisture levels	Heavy traffic with high moisture and humidity, typical of tropical climates	[31]
19	Tropical climates - Focus on Malaysia and Southeast Asia	Heavy traffic in urban and suburban regions	[32]
20	Jordan - Arid to semi-arid climate	High-load roads with significant traffic in arid regions	[33]
21	USA - Various regions with focus on warm climates	Moderate traffic with a focus on simulating various load conditions	[34]
22	Japan - Airfield conditions with variable climate	Airfield traffic with high wheel loads	[35]

23	USA - Different regions, with focus on rubberized mixtures under varying conditions	Varied traffic conditions, with a focus on heavy trucks	[36]
24	Malaysia - Tropical climate	Urban roads with heavy traffic	[37]
25	China - Testing under varied climate conditions	Laboratory simulations of varied traffic conditions	[38]
26	Jordan - Hot, arid climate with high temperatures,	Heavy traffic loads, increased risk of rutting and deformation.	[39]
27	India- climate varies significantly across different regions, it focuses on areas experiencing high temperatures	High and moderate traffic volumes, impact of heavy traffic on pavement deformation	[40]

4.3 Results of Mix Design, Performance Metrics, and Innovations in the Studies

4.3.1 Mix Design

As can be seen from Table 3, each of the studies targets parameters regarding binder type and aggregate composition as factors to measure performance. For example, study [5] develops the performance comparison of super-pave and Marshall mixes with a 40-50 grade binder; for example, the results showing the addition of lime increase the resistance of super-pave to deformation are shown. A related research [2] considers the PG 70 binder applied to granite aggregates. It is designed to resist permanent deformation up to 70°C (158°F) in hot weather. In which discussion has been made on the relative benefits derived from Superpave design over that of Marshall against extreme climate conditions? PG binder grades are used to classify asphalt binders based on their ability to perform under specific temperature conditions. Each such research helps the professionals understand what importance that could logically be granted to binder-grade or the types of selection-related matters under local demands and application prospects.

4.3.2 Performance Metrics

Performance metrics of the Superpave designs from both studies demonstrate that their resistance to rutting and moisture damage is generally better than that observed for Marshall mixtures. For instance, Superpave mixes were found to perform well in terms of rutting and moisture susceptibility [5], especially in cold regions. It is also known that Superpave mixes generally showed much better performance (specimens exposed to free-thaw) than what would have been expected for typical Marshall designs in Ontario [7]. On the other hand, studies like [6] show that Marshall mixes are not ideal for use as rutting is more pronounced under high pressures and slower traffic speeds, particularly in tropical regions.

4.3.3 Modifications and Innovations

The changes or advancements studied in these papers are directed to improve both Superpave and Marshall mixes. Another research by [5] also confirmed that the addition of lime into Superpave mixes leads to strain reduction and provides better resistance against deformation. Another work [7], concentrates in the local calibration of binder grades for better performance to regional climatic conditions and hence a more accurate prediction into MEPDG type models Further, the recent study [8] of creating statistical models for prediction of rutting performance provides a rigorous data based tool to optimize mix design parameters. The changes show the tireless work to further optimize asphalt mix designs for longer-lasting and maximized performance under different environmental and traffic conditions.

Table 3: Mix design, performance metrics, and innovations

No.	Mix Design Parameters	Performance Metrics	Modifications and Innovations	Study References
1	PG 70 binder, granite aggregate, Superpave, and Marshall	Superpave showed superior rutting and moisture resistance	None	[2]
2	Design levels, Air voids, Asphalt content	Rutting resistance, Durability, Cracking resistance	Adjustment of Design for traffic levels, Emphasis on field compaction	[3]
3	Superpave and Marshall methods; Aggregate gradation, binder content, voids in mix	Rutting resistance, permanent deformation, void content	No specific modifications, focus on traditional Superpave and Marshall methods	[4]
4	Marshall vs. Superpave, 40-50 grade binder, lime filler	Better rutting resistance in Superpave compared to Marshall	Lime added to reduce strain in Superpave mixes	[5]
5	Modified Marshall mix, low air voids, slow traffic design	Marshall is more prone to rutting in heavy traffic conditions	Binder modification for improved performance in tropical climates	[6]
6	Superpave and Marshall mixes, calibrated binder grades	Superpave outperformed Marshall in freeze-thaw environments	Local calibration of binder grades for better performance	[7]
7	Various binder grades, aggregate sources, and RAP content	Binder properties correlated with rutting resistance	Statistical model developed for predicting rutting	[8]
8	Volumetric mix design, Aggregate gradation, Binder selection	Moisture durability, Volumetric stability, Resilient modulus	Local adaptation of Superpave for Minnesota climate, Simplification of procedures	[15]
9	Binder type, Aggregate gradation, Load application conditions	Rutting depth, Stress response, Load deformation	Focus on accelerated testing, Evaluation of load-induced rutting effects	[17]
10	Traditional vs. Superpave, 40-50 grade binder	Superpave had better performance in terms of rutting	No modifications mentioned	[23]
11	Superpave, modified with carbon nanotubes	Significant improvement in rutting with carbon nanotube addition	Carbon nanotubes added to Superpave for improved rutting resistance	[24]
12	Recycled asphalt mixtures with high RAP content	Superpave mixes outperformed Marshall in rutting resistance	Recycled materials with Superpave and Marshall designs	[25]
13	Superpave, aggregate gradations, binder modification	Superpave mixes showed better modulus and rutting resistance	Restricted zone analysis for Superpave gradation improvements	[26]
14	Superpave, model-based binder optimization	Superpave predictive model provided improved rutting resistance	New mathematical model for predicting rutting performance	[27]
15	New method for balancing anti-rutting and anti-cracking properties; Binder	Rutting resistance, cracking resistance, fatigue performance	Introduction of a new balancing method for anti-rutting and anti-cracking properties	[28]

	stiffness, aggregate gradation			
16	Superpave mixtures for heavy load conditions; Optimized binder and aggregate selection for airport pavements	Rutting performance under aircraft loads, pavement durability, and moisture susceptibility	No modifications, focus on the field application of the standard Superpave for airport pavements	[29]
17	Comparative review of Marshall and Superpave methods; Focus on simple mix designs for developing countries	Applicability of designs for heavy traffic, durability under varying conditions	No modifications, comparative analysis of existing methods for applicability in developing countries	[30]
18	Evaluation of both Superpave and Marshall methods; Analysis of binder, aggregates, compaction techniques	Rutting and cracking resistance, overall performance in tropical climates	No specific modifications, suitability analysis of Superpave and Marshall designs	[31]
19	Asphalt binder content, Gradation, Dynamic modulus	Permanent deformation, Rutting, Resilient modulus	Use of dynamic modulus for characterization, Adaptation for tropical climates	[32]
20	Superpave and Marshall gradation, Asphalt content, Indirect tensile strength	Fatigue resistance, Resilient modulus, Rutting depth	Modification of Superpave design for local materials, Creation of temperature zoning map	[33]
21	Design levels, Air voids, Volumetric properties	Moisture susceptibility, Rutting, Volumetric stability	Introduction of Level I Superpave for specific traffic conditions	[34]
22	Superpave gradation, Binder content, Aggregate size	Rutting resistance, Raveling, Flexural strength	Application of Superpave to airfield designs, Adjustments for high wheel loads	[35]
23	Rubberized asphalt binder, Superpave and Marshall comparison	Rutting depth, Aging resistance, Fatigue life	Incorporation of rubberized asphalt, Superpave for improved aging resistance	[36]
24	Superpave and Marshall comparison, Binder content, Resilient modulus	Rutting resistance, Moisture damage, Stiffness	Comparison of performance across different climates, Emphasis on resilient modulus	[37]
25	Gradation through and below restriction zone, Asphalt content	Fracture energy, Fatigue life, Dynamic modulus	Evaluation of restricted and non-restricted gradation zones	[38]
26	Superpave mix design approach, aggregate gradation, binder selection, volumetric properties	Rutting resistance, Moisture susceptibility	Superpave design procedures to fit the local hot climate and heavy traffic conditions, binder selection and compaction methods.	[39]
27	Superpave Graded Bituminous Mix using PG criteria, Binder selection, dynamic modulus	Rutting potential, Moisture damage assessment, Dynamic modulus	Implementation of PG system, Enhanced testing methodologies, Emphasis on developing asphalt mixes	[40]

4.4 Rutting and Cracking Resistance Performance Ratings of Asphalt Mix

The performance ratings in Figures 3–5 were obtained by converting the measured or reported values of cracking resistance, rutting resistance, and moisture susceptibility into a 1–5 scale for an easy comparison. As for the rating criteria, anything equal to or above 90% performance was rated 5 (Excellent); 80–89% was rated 4 (Good); 70–79% was rated 3 (Moderate); 60–69% was rated 2 (Low); and anything under 60% was rated 1 (Poor).

Figure 3 provides a summary of the rutting and cracking resistance observed for Superpave and Marshall asphalt mixes in defined climates or regions based on the reported references. Superpave showed excellent cracking resistance in cold and arid/hot regions, while Marshall rated lower, especially in harsher climates. The Superpave specification used is known in the industry for ratings of residual rutting and cracking resistance of 4-5, respectively, and as such provides excellent performance data for freezing climates such as Kazakhstan, Canada, and China. This shows the system's ability to withstand freeze-thaw as well as thermal cracking that can be controlled by better selection of binder and compaction strategies. In temperate climates (e.g., Jordan, Iraq, and Alabama), performance becomes more moderate as the Marshall mixes show less rutting and cracking resistance due to compaction difficulties and moisture susceptibility. The Japanese study of airfields identifies Superpave high traffic loads as another benefit, which demonstrates its ability to meet the needs of a demanding environment. Overall, these findings confirm Superpave's superiority over traditional Marshall designs, especially in extreme climates, while emphasizing the importance of tailoring optimization efforts to suit less severe conditions.

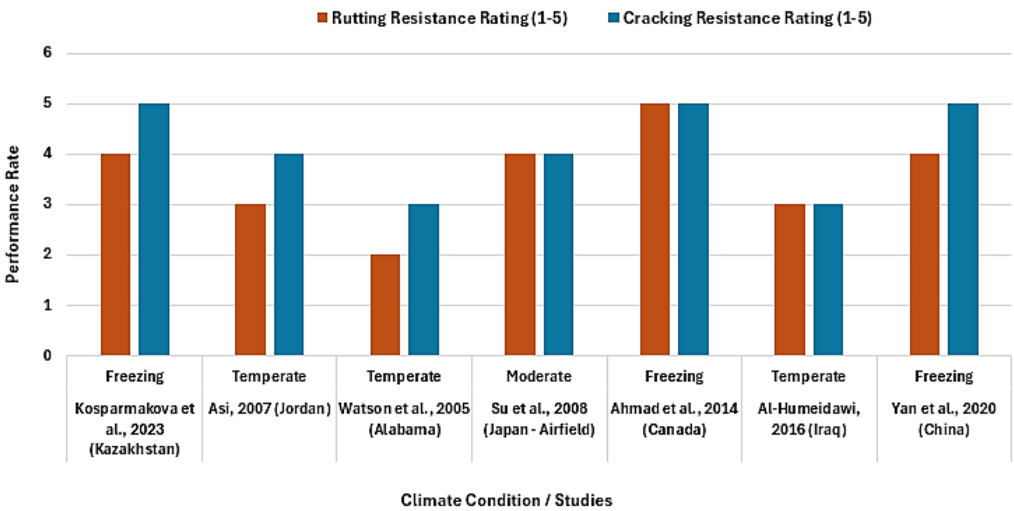

Figure 3: Rutting and cracking resistance in climate conditions in various studies

In regions with extreme temperatures, such as arid/hot and cold (freeze-thaw) climates, Superpave mix designs are consistently superior to Marshall mix types, as shown in Figures 4 and 5, by analyzing their rutting resistance. With its unique selection of binders and compaction methods, Superpave has an edge in this respect, whereas Marshall's rutting resistance system is only 60 and 75 percentages, respectively, with scores of 90 and 85 percentages. Superpave is better suited for environments with extreme temperature fluctuations or temperatures that require enhanced structural integrity to prevent deformation during repeated loads. However, in areas with moderate climates, the difference between Superpave and Marshall designs in terms of rutting and cracking resistance becomes less significant. The Marshall mix design exhibits similar performance, with a slightly better score in moderate climates (80 for the rutting resistance compared to Superpave's 75). Despite the effectiveness of Superpave in harsh environments, the Marshall method, which is less expensive and more straightforward than other methods, remains a practical solution for areas with severe temperature stresses.

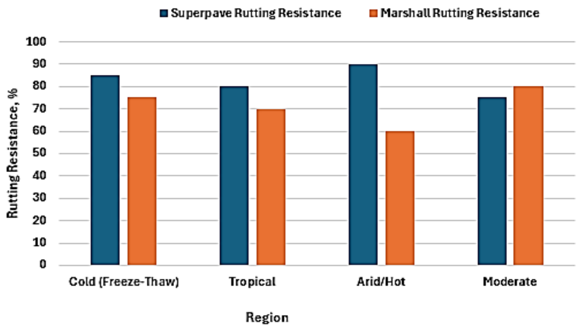

Figure 4: Superpave vs. Marshall Rutting Resistance in Various Climatic Regions

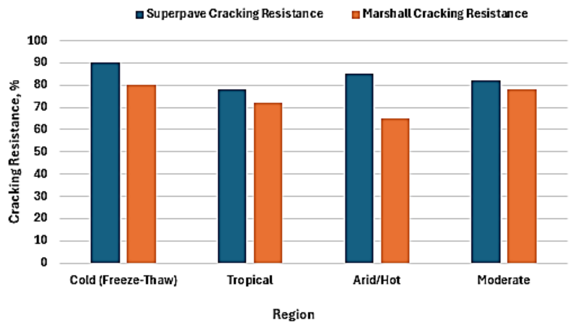

Figure 5: Superpave vs. Marshall Cracking Resistance in Various Climatic Regions

The gradual deformation of asphalt surfaces from repeated traffic loads that occurs in tropical areas is caused by high temperatures. High moisture levels in pavement layers caused by heavy rainfall and humidity can lead to stripping and weakening of the structure. Although Superpave mixes are more resistant to rutting, they can still be damaged by moisture without proper drainage. Conversely, moisture damage and rutting are more common in Marshall designs, which means that the product's lifespan is shorter without proper upkeep. The maintenance of performance requires frequent interventions, such as resurfacing and moisture control. Studies in Jordan and Iraq have shown some success with Superpave mixes, but they are not as effective without drainage, which is crucial to water conservation, enhancing durability [4, 20, 33]. Water infiltrates pavement layers during cold climates, where it expands and causes freeze-cracking. With an increase in temperature, the ice melts away, leaving the structure vulnerable to damage and potholes. In addition, the sudden thermal contraction due to temperature drops shrinks and cracks asphalt as a result, especially in pavements with poor flexibility. Superpave mixes are preferred due to the use of temperature-sensitive binders (e.g., PG-58-34, where the pavement could reach a temperature range of as high as 58°C in hot weather and as low as -34°C in cold weather). This prevents cracking and resists thermal contraction. Marshall designs are more likely to be exposed to freeze-thaw cycles and thermal stress, which lead to faster degradation and increased maintenance requirements. Proactive maintenance, such as crack sealing and snow removal, is essential for pavements to have a longer lifespan [2, 8, 9].

Table 4: Comparison of pavement performance in tropical vs. cold climates

No.	Factor	Tropical Climate Pavements	Cold (Freeze-Thaw) Climate Pavements
1.	Temperature Range	High temperatures throughout the year	Wide temperature variations, including freezing
2.	Key Challenge	Rutting due to softened asphalt and heavy traffic	Cracking from freeze-thaw cycles and thermal contraction
3.	Moisture Susceptibility	High due to rainfall and humidity, prone to stripping	Moderate to high, with frost heave and cracking risk
4.	Performance of Superpave	Good rutting resistance but requires proper drainage	Excels in crack resistance and moisture control
5.	Performance of Marshall	Prone to rutting and moisture damage, reduced durability	Vulnerable to cracking, requires more maintenance
6.	Maintenance Requirements	Frequent resurfacing and drainage control	Crack sealing and snow removal

7.	Binder Selection	High-temperature-resistant binders (e.g., PG 70-10)	Low-temperature binders (e.g., PG 58-34)

4.5 Evaluation of Asphalt Pavements: Impact of Temperature, Moisture, and Fatigue

Table 5 summarizes the results of asphalt studies conducted in different regions, examining three critical performance parameters- temperature susceptibility, moisture damage, and fatigue life- based on their impact on asphalt performance. The use of PG binders in Superpave designs helps pavements to endure low temperatures in cold climates, such as Kazakhstan, Canada, and China, which makes them more resistant to freezing. The binder properties in these regions are designed to resist thermal contraction and cracking, providing optimal protection. Studies indicate that pavements in these areas are less susceptible to extreme cold weather, leading to improved durability. High temperatures in hot and temperate climates, such as Jordan, Iraq, and Alabama, make them moderately vulnerable to rutting [20]. The Iraq study demonstrates how extreme heat weakens the structure, softening asphalt. Some compaction-related problems are present in Alabama, which is a stark contrast to the challenges of temperate climates. Adjustments in mix design may be required based on the moderate rating in these studies. Moisture-Resistant Pavements (Canada, China) are resistant to moisture with binders of superior quality and proper compaction methods. These designs limit moisture infiltration and minimize the risk of stripping. Poor drainage in Iraq results, for example, in severe moisture damage (everything from stripping to deteriorating pavements). In Jordan, the pavement is susceptible to moisture levels, which must be adequately drained for proper operation. Although pavements are relatively effective, water damage must be mitigated by drainage systems. This demonstrates the necessity of structural maintenance in both cold and temperate environments. High fatigue life countries, such as Kazakhstan, Canada, and China, benefit from optimized mix designs that improve crack resistance and extend pavement life. This is particularly true for these areas where traffic loads are heavy. Superpave technology is responsible for ensuring optimal performance over time. Jordan and Iraq have a moderate fatigue of life, as they are exposed to moisture, traffic stress, and rutting. Heavy loads in hot climates cause pavement decomposition at a faster rate than in cooler climates.

Table 5: Evaluation of asphalt pavement performance parameters

No.	Temperature Susceptibility	Moisture Damage	Fatigue Life	Study References
1	Low with temperature-specific PG binders, good for cold regions	Resistant but drainage system needed	Long fatigue life under heavy traffic	[2]
2	Excellent, handles extreme freezing conditions well	Minimal moisture issues due to binder properties	Excellent crack resistance, long-lasting pavement	[9]
3	Low susceptibility, optimized for cold climates	Minimal moisture susceptibility	High fatigue life with optimized mix design	[8]
4	Moderate, affected by high temperatures	Moderate, stripping can occur without drainage	Moderate, affected by heavy traffic loads	[33]
5	High, prone to rutting in hot weather	High moisture damage without interventions	Moderate, influenced by rutting and traffic stress	[4]
6	Moderate, some issues related to compaction in temperate conditions	Moderate moisture issues but manageable	Moderate durability, needs compaction adjustments	[3]

5. Conclusion

This study emphasis the essence of selecting asphalt mix designs specifically prepared for the traffic and environmental conditions of various geographical regions. It reveals that in extremely cold areas such as Kazakhstan, Canada, and China, the Superpave mixes, particularly those with performance-graded binders, are capable of resisting rutting, cracking, moisture damage, and fatigue to a much higher degree. The main reason attributed to the better performance of the Superpave mix is to resist the freeze-thaw attack and control thermal cracking and moisture ingress through the use of optimized compaction methods and aggregate gradation, as well as binder selection. In contrast, Marshall mixtures are still suitable and cost-effective in areas with a temperate climate, such as Jordan, Iraq, and Alabama, where ease of application and financial considerations take precedence over any sort of performance that would be expected under extreme climatic conditions. Insistence is also laid upon selecting drainage and maintenance techniques, as issues like moisture susceptibility and poor compaction standards arise within these moderate climates. Moreover, both Superpave and Marshall can become more sustainable and durable with the addition of additives, recycling materials, and innovative binders, thus increasing fatigue life and contributing positively toward the environment. In truth, the ultimate contest between the design of asphalt mix and the traffic and climate peculiarities of each region dictates the long life and performance of pavement.

Author's Contribution

The author conceptualized and designed the review, conducted the literature search, analyzed and synthesized the findings, and wrote the manuscript. She also reviewed and revised it to ensure accuracy and coherence.

Conflict of Interest

None

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