

Article

A Performance-Based Design Framework for Enhanced Asphalt Concrete in the Caribbean Region

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Abstract: The majority of recent research in has been focused on the introduction, development, and evaluation of performance-based specifications for the design of asphalt concrete mixtures. In the Caribbean, most laboratories only use the Volumetric Marshall Mix design methodology. Road designers, engineers, consultants, and contractors have all highlighted the many shortcomings and inadequacies of the volumetric design mix selection process. The consensus is that there is a need to a develop process that addresses the service's performance and common distress on asphalt pavements through performance-based mix design. Performance-Based Mix Design (PBMD) has been used as a practical alternative to the volumetric mix design technique in evaluating pavement distresses by incorporating performance testing in conjunction with volumetric parameters into the mix design process. This study describes the findings of our comprehensive laboratory research, which was conducted to facilitate the development of a Performance-Based Mix Design framework for asphalt concrete mixtures. The research methodology involved the collection and integration of qualitative and quantitative data through case studies and experimental work. Two control and two PBMD mixtures were designed to evaluate both the volumetric and performance properties that address distresses of permanent deformation (rutting), fatigue cracking, stiffness, and moisture susceptibility. The PBMD framework led to the development of performance test criteria for permanent deformation, stiffness modulus, fatigue cracking, and an acceptable tensile strength ratio. The development and implementation of the PMBD framework for the Caribbean region could exemplify a significant step towards achieving sustainable asphalt pavements in the region. The framework, which incorporates best-practice solutions, is anticipated to increase awareness about the variables that affect the performance of asphalt mixtures.

Keywords: asphalt mix design; asphalt evaluation; performance-based mix design; road pavements; volumetric-based mix design



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1. Introduction

The degradation of road pavement structures during the design life is primarily due to quality control in the construction process, increasing impacts of traffic loads, and climate-related and environmental factors [1]. As a result, these variables deteriorate the performance of the structure and, by extension, the asphalt surface layer over time. Asphalt mixture design incorporates numerous factors that influence the performance of the resultant mixes, including mineral aggregates, asphalt binder content, and air content [2]. Therefore, a great deal of care must be taken in the preparation and selection of the mixtures. The Marshall mix design process is used locally and categorized as a Volumetric-based Mixture Design methodology. The Marshall methodology poses significant benefits in the

affordability and portability of equipment and facilitates a shorter testing period; however, it does have a few limitations. The impact compaction employed neglects to replicate mixture densification as it occurs in real pavement structures, thus posing challenges for those attempting to provide an accurate estimation of the specified mixture's rutting resistance [3]. Varma et al. [3] state that the measured sample peak load signifies the asphalt mix stability, while the flow denotes asphalt mix resistance to plastic deformation; nonetheless, both factors are unreliable in demonstrating the rutting performance. Further, the Marshall test does not directly account for permanent deformation, rutting fatigue, and cracking behaviors [4].

Due to the shortcomings and inadequacies of the volumetric design mix selection process, as identified by Buchanan [5], several research studies [6–10] have attempted to address the common distress on asphalt pavements through the use of a performance-based mix design. Performance-based Mix Design (PBMD), commonly referred to as Balanced Mix Design (BMD), integrates mechanical testing to determine the resistance level of asphalt mixtures to recurrent road distresses. Al-Khayat et al. [11] state that the BMD approach incorporates performance testing into the volumetric mix design parameters and is considered an extension of the volumetric mix design. A lot of research has been conducted to compare the volumetric properties of the mix to their engineering properties and performance [12–17]. One of Al-Khayat et al.'s most interesting findings is that both the prediction and performance in asphaltic pavement distress, including fatigue, cracking damage, and permanent deformation, are directly linked to changes in the mixture ingredients and content based on outputs of the volumetric checks.

Currently, there are three well-known implemented approaches to BMD: volumetric design with performance verification, performance-modified volumetric design, and performance design [18]. Each is progressively more reliant on mixture performance tests, and all of them were identified by the aforementioned research groups. Notably, the incorporation of the Marshall Mix Design approach in Performance-based Mix Design is a Volumetric Design with Performance Verification and entails the determination of the optimum binder content (OBC) that fulfills the volumetric criterion. In addition, the asphaltic mixture produced is verified against rutting and cracking criteria to determine the necessity for adjustments in the mixture. The Performance-based Mix Design allows for the optimization of Asphalt Mixtures and can be assimilated into the Marshall Mix Design Method and parameters.

Standards for asphalt mix design are continuously being developed, updated, and implemented. They aim to harmonize the design, testing, and in situ performance of asphaltic mixtures. Generally, mix design methodologies standards should include the empirical mix design approach and, on the other hand, the fundamental, performance-based approach. Although both approaches aim to realize well-performing, structurally optimized pavements, an important advantage of the performance-based approach is the fact that it is based on the laboratory assessment of physically sound material parameters. These key performance parameters of HMA include material stiffness, fatigue resistance under repeated load cycles, resistance to cracking at low temperatures, and resistance to rutting due to thermal deformation. These material parameters can be used for specifying the mix properties within an advanced type testing procedure required to meet customized quality standards for materials defined in tender documents as well as for mix design [19].

A significant underlying issue in the current mix design methodology utilized by the construction sector of most Caribbean countries is that it only includes volumetric criteria but excludes the performance review of the selected mixture. Hence, due to the shortcomings of the volumetric design mix approach, it is beneficial to include the Performance-Based Mix Design within the overall design selection process, thus improving the performance of asphalt mixtures and accommodating stresses, strains, and incremental damages as a result of pavement distress failures that frequently occur in the Small Island Developing States (SIDS) of the Caribbean.

The aim of the present study was to develop and propose a systematic framework for adopting and implementing the PBMD process in the design of Caribbean asphalt mixtures. The general objectives of the study were as follows: (1) To critically examine the application of a Performance-Based Mix Design approach and frameworks with similar local climatic conditions through case studies and laboratory experiments and (2) to formulate an assessment criterion for a standard Performance-Based Mix Design Framework in the Caribbean region. The proposed performance criteria and specifications were developed for the evaluation of specified pavement distresses under laboratory experimental conditions; therefore, no field correlation was established. Additionally, the Performance-Based Mix Design Framework developed within this study is solely limited to Hot Mix Asphalt (HMA) mixtures.

2. Methodology

2.1. Case Studies

A desktop study was undertaken as an essential component of deriving secondary data on the implementation of PBMD in climate conditions similar to that of the Caribbean region. Case studies of various USA states [20–25] were reviewed. The states of Oregon, Nevada, and Missouri were selected due to their temperate conditions and utilization of the Volumetric Design with a Performance Verification approach. The literature pertaining to these states in the three prominent areas was reviewed as a baseline for obtaining background information and supporting evidence in the practical application of PBMD in asphalt testing and mixture development. The asphalt mixture design criteria for a few other islands in the Caribbean region were investigated. Case studies are comprehensive investigations of subjects, groups, and or phenomena that allow researchers to obtain a clearer understanding of the research problem and knowledge gaps. The case studies were mainly derived from reports, which were carefully chosen using primarily two fundamental criteria: the application of PBMD and temperate conditions similar to many countries in the Caribbean region. The case study information was divided into four (4) categories: the mixture properties, performance testing, performance-based specifications, and results of practical implementation of PBMD. Table 1 highlights the summary of the data obtained from the relevant case studies. It indicates the existing mix design specifications that are used for the acceptance and rejection of asphaltic mixtures at various locations.

Table 1. Summary of HMA mixture performance threshold.

Property	Oregon	Nevada	Missouri	Trinidad	Jamaica	St. Lucia	Test Method
Marshal Stability—kN	-	>8	-	>8	>8	>8	ASTM D6927
Marshall Flow (mm)	-	2–5	-	2–4	2–4	2–3.5	ASTM D6927
Tensile Strength Ratio	-	>0.7	-	>0.7	-	-	
Flexibility Index	6–8	-	-	-	-	-	
HWTT Rutting—mm	2.5–3	<12.5	<12.5	-	-	-	AASHTO T 324
Flow Number	500–1000	-	-	-	-	-	AASHTO T 378
Ideal CT	-	>54	-	-	-	-	ASTM D8225
Fracture Energy—J/m ²	-	-	>200	-	-	-	
IFIT	-	-	0.8–2.5	-	-	-	AASHTO T 393
Compaction Method	gyratory	gyratory	gyratory	Marshall	Marshall	Marshall	

2.2. Materials and Laboratory Experimental Framework

This research study included the designs of two control dense-graded hot mix asphalt (CTRL mix) used in the surface layer of the pavement structure. The Marshall Mix Design was employed and was based on volumetric criteria stipulated by the T&T Central Tenders Board Standards Specifications for asphaltic mixtures [26] (Table 2). The aggregates used were sourced from the National Quarry Company Limited (NQCL) and Ready-mix Limited. The binders used in the study were the modified polymer binder (60/75) and Trinidad Lake Asphalt (TLA) binder (60/70 and 40/55). Table 3 presents the properties of the binders.

Table 2. HMA volumetric criteria based on Marshall method.

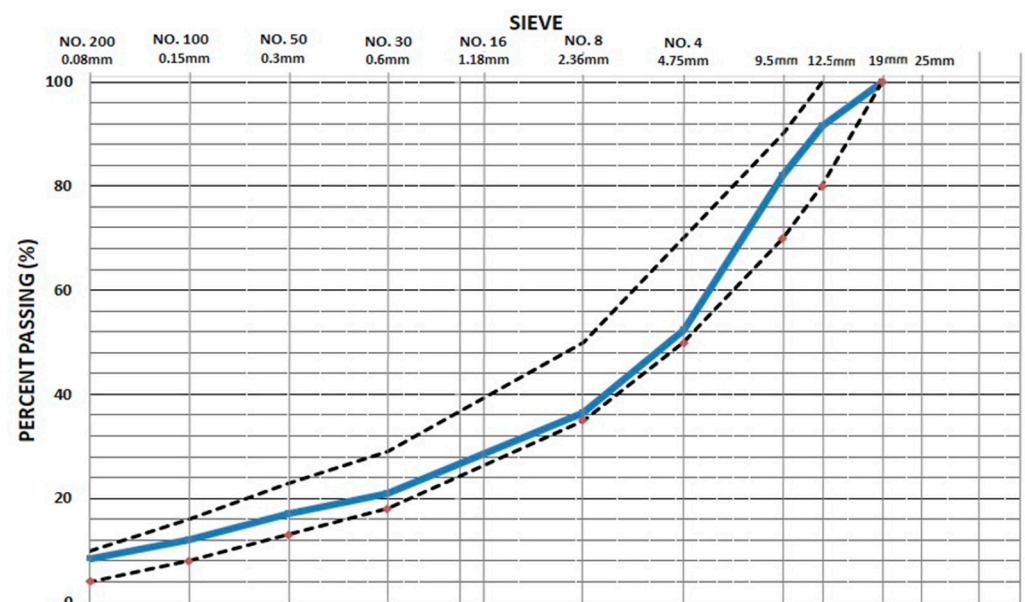
Property	Trinidad	Asphalt Institute	St. Lucia	Jamaica
Optimum binder content (OBC), %	4–7	4–7	4.5–7	4–7
Marshall stability, kN	>8	>8	>8	>8
Marshall flow (mm)	2–4	2–3.5	2–3.5	2–4
Air voids content, %	3–5	3–5	3–5	3–5
Voids in mineral aggregate (VMA), min%	>15	>13	>14	>14
Voids filled with asphalt (VFA), %	70–80	65–75	65–75	75–85
Dust/asphalt ratio	0.6–1.3	-	1.5–1	-
No. of blows per specimen face	75	75	75	75

Table 3. Characteristics of the study binders.

Property	60/75 Pure TLA	40/55 Pure TLA	60/70 Polymer Modified
Specific gravity @ 25 °C (g/cm ³)	1.022	1.2	1.1
Penetration @ 25 °C (mm)	7.2	5.1	6.7
Flash point °C	135	150	165
Kinematic Viscosity @ 135 °C (Pa.s)	414	677	409

The asphalt mix design was completed following the procedures given in the Asphalt Institute MS-2 Asphalt Mix Design Methods [27]. Mixture samples were batched at binder contents of 4.0%, 4.5%, 5.0%, 5.5%, and 6.0% of the total weight of the mix and compacted using the Marshall Mix Design Method as outlined in the standards. The mixing (min. 140 °C) and compaction (min. 135 °C) temperatures were developed from viscosity testing that was performed on each binder type and determined in accordance with the Asphalt Institute’s standards [20]. With regards to aging, a minimum of 2 h of aging was allowed for all samples after mixing. The aggregate blend used for both the control mixture and the improved PBMD mixture is shown in Figure 1. All study mixtures had the same aggregate size/gradation, only differing in terms of the binder type used. The Marshall mixture design method was used to obtain the optimum binder content (OBC) of the control mixtures, and these values were as follows:

- CONTROL MIX 1: Utilized 4.1% TLA Blend 60/75 bitumen
- CONTROL MIX 2: Utilized 4.7% TLA Blend 60/70 modified bitumen

**Figure 1.** Gradation blend curve for study asphalt mixtures.

Both the CTRL and PBMD specimens were prepared using a gyratory compactor and then they were subjected to volumetric (as shown in Table 1) and performance tests, including a Repeated Load Axial Test (RLAT), Indirect Tensile Stiffness Modulus Test (ITSM), Indirect Tensile Fatigue Test (ITFT), and Tensile Strength Ratio Test (TSR).

2.3. Mix Performance Test Criteria and Description

As highlighted in Table 1, the Caribbean has no performance test beyond that of the volumetric specifications used in the selection of bituminous mixtures. Therefore, because of this limitation, the study proposed an appropriate mixture performance test criterion for T&T, which was established by reviewing multiple publications in the literature and International/local testing standards (Table 4). Publications in the literature [27–31] provided the rationale behind the development of various failure criteria and the purpose of setting suitable threshold values. Additionally, International/Local testing standards helped specify the pass/fail criteria associated with the performance test utilized.

Table 4. Proposed mix design performance threshold.

Test	Test Temperature (°C)	Loading Cycles	Selection Criteria
Repeated Load Axial test (RLAT)—% strain (deformation/rutting)	60	3600 s	<5 (Good) >5 (Fail)
Indirect Tensile Stiffness Modulus Test (ITSM)—MPa	25	NA	>3000 (Good) <1500 (Fail)
Indirect Tensile Fatigue Test (ITFT)—% strain (cracking)	25	NA	<2 (Good) >2 (Fail)
Tensile Strength Ratio test (TSR)	25	NA	>0.70 (Good) <0.70 (Fail)

The control mixtures (CTRL) were subjected to both volumetric and performance tests. Subsequently, the results were reviewed, leading to the development of the PBMD mixture, which was significantly modified based on the outcomes of the performance test. To improve rutting, we upgraded to a stiffer binder (40/55 penetration), and for cracking, we increased the binder content by +1%. These modifications were made based on experience, previous in-house mixture designs, and studies with the binder types, as well as information found in the literature regarding techniques to improve rutting and cracking resistance of asphalt concrete. The modified mixtures and properties were as follows:

- PBMD MIX 1: Utilized 5.1% TLA Blend 60/75 bitumen (+1% of control mix 1%)
- PBMD MIX 2: Utilized 5.7% TLA Blend 40/55 bitumen

The performance tests used in the study can be summarized as follows:

- Indirect Tensile Fatigue Test (ITFT)—The EN 12697-24 test is commonly used to as a quick decision-making tool in the design of asphalt mixes. The method consists of characterizing asphalt mix fatigue behavior under repeated loads with constant stress using indirect tensile (ITT). Diametral compression force is applied to a cylindrical specimen followed by rest time, with the test being down at ambient to low temperatures.
- Repeated Load Axial Test (RLAT)—The EN 12697-25, which is sometimes referred to as the Flow Number procedure, uses a cylindrical specimen with a diameter of 100 mm or 150 mm and a thickness preferably between 40 mm and 100 mm. A repeated load is applied axially, while the vertical deformation of the specimen is measured by two LVDTs. The pulsating load consists of a square waveform with a frequency of 0.5 Hz, which simulates the slow-moving traffic that leads to the majority of deformation visible on real roads. The input parameters for testing are temperature, specimen thickness and diameter, and stress and number of load pulses, including

those for the conditioning stage. The standard test uses a vertical stress of 100–250 kPa at a temperature of 60 °C up to 3600 pulses. During testing, if the specimen deforms more than 10 mm before reaching the specified number of pulses, the test is then terminated. The test output consists of vertical deformations of the specimen plotted against a number of load cycles. The lower the axial permanent percent strain, the more resistance the sample has to rutting/deformation.

- (c) Indirect Tensile Stiffness Modulus (ITSM)—The stiffness of bituminous material can be measured quickly and easily using the EN 12697-26 non-destructive method. This testing method uses cylindrical specimens that may be prepared in the laboratory or sampled from the field. The load is applied in the vertical plane while the strain/deformation is measured in the horizontal plane. When applying the load in the vertical plane, the horizontal plane experiences extension (indirectly, tension), which is where the test's name is derived from. The average resilient stiffness modulus of the sample is calculated. Samples with stiffness modulus values above 3000 MPa are considered to have adequate resistance to rutting and cracking.
- (d) Tensile Strength Ratio (TSR)—This is a moisture susceptibility test that uses the ratio of the indirect tensile strength of wet conditioned specimens to that of dry specimens.

3. Results and Discussion

3.1. Volumetric and Performance Check

As shown in Figure 1, the study developed Section 1 of the framework (volumetric check). This section evaluates the mixture based on volumetric properties set in the CTB specifications. Section 1 of the framework is designed using optimum binder content plotted against the mixture's volumetric properties. Both the acceptance or rejection of mixture in both frameworks are based on the following classifications: Good—meets both volumetric/performance requirements; Poor—meets only one volumetric/performance requirement; and Fail—meets none of the volumetric/performance requirements. The ranges of these indicators were developed from the values previously highlighted in Tables 2 and 3.

The study CTRL samples, indicated in black (triangle) and yellow (circle), were evaluated using Section 1 of the framework, as previously described. As shown in Figure 2, CTRL mixtures were classified as POOR under the current local mix selection criteria. However, the local road agency would relax one of the volumetric properties on a case-by-case basis, which could result in mixes being classified as acceptable, as in the case of CTRL Mix 1.

Section 2 of the framework, as shown in Figure 3, is a performance-based check that supports the proposed methodology for selecting T&T asphalt mixtures. The section is based on the cracking, rutting, stiffness, and moisture damage properties of the asphaltic concrete mixes. The performance test for both control mixtures failed. As a result, the modified mixtures, in this case, the PBMD mixtures (blue diamond & orange square), are manufactured and subjected to volumetric and performance testing. The performance requirements were met by PBMD Mix 2, which was modified with a stiffer binder. The mixtures can be modified by relaxing volumetric properties, adjusting the mix gradation, or replacing the aggregate and/or binder type.

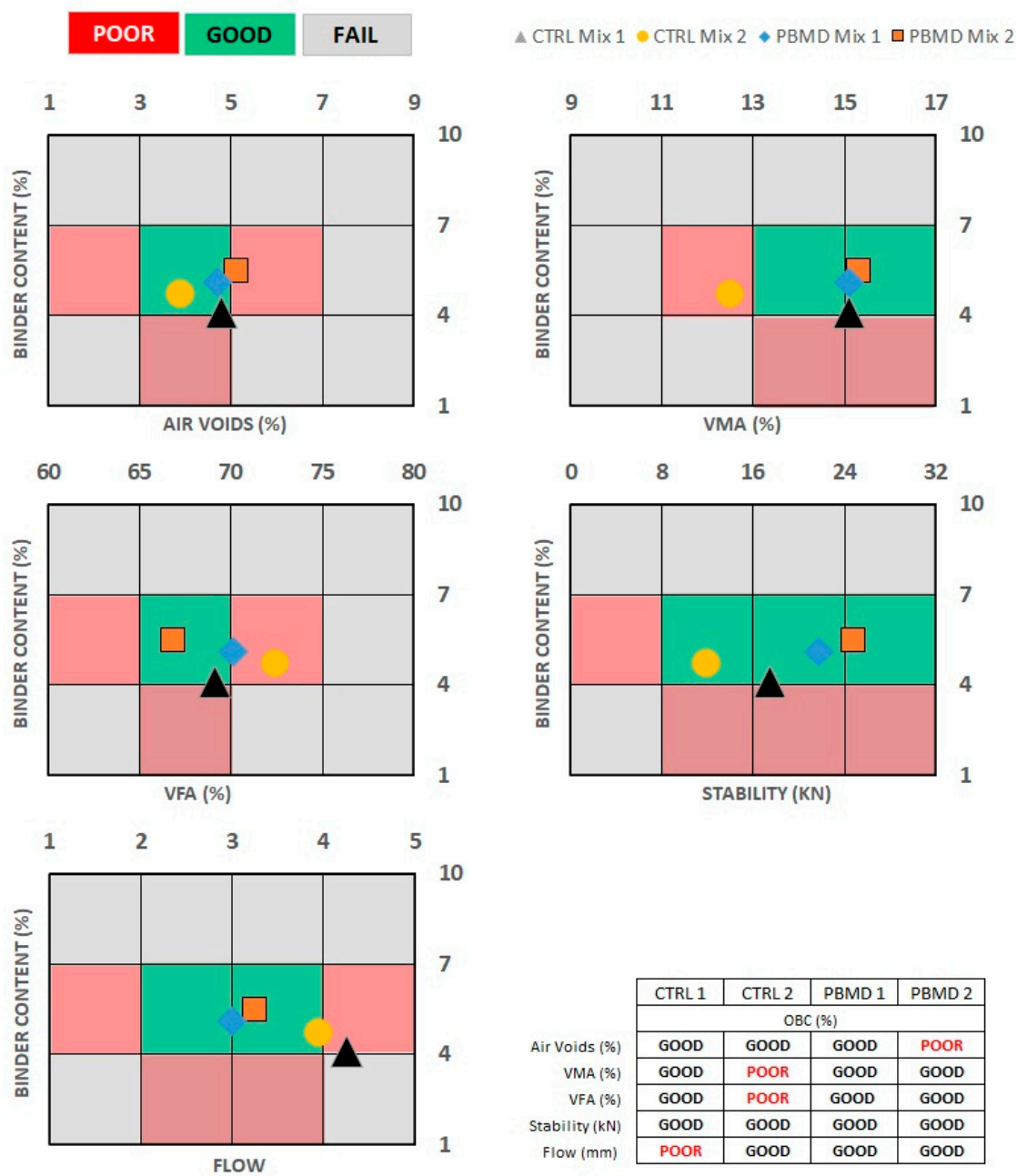


Figure 2. Section 1 of the mixture selection framework—volumetric properties.

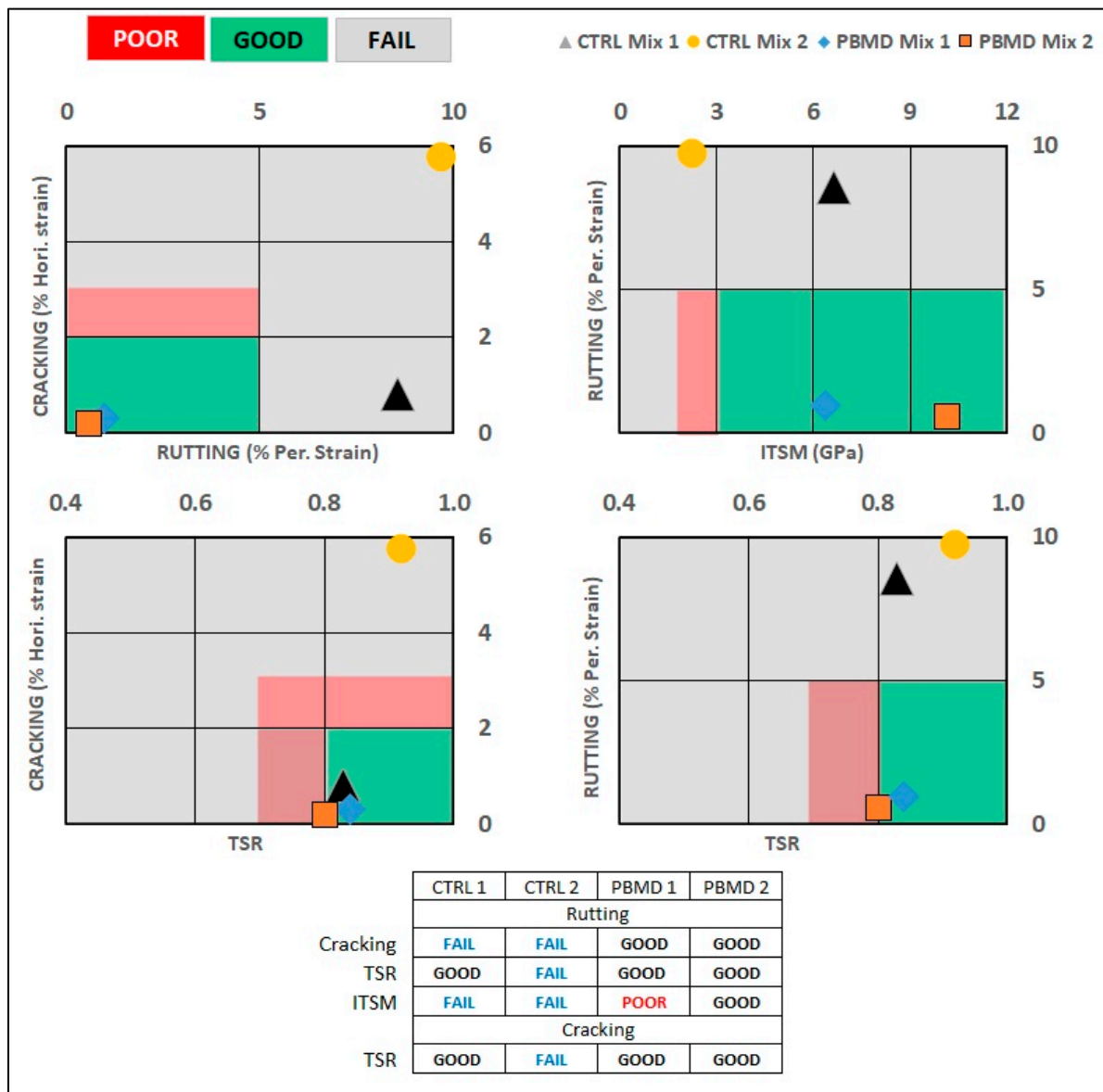


Figure 3. Section 2 of the mixture selection framework—performance-based properties.

3.2. Proposed PBMD Framework

The performance-based mix design framework for asphalt mixtures is depicted in Figure 4. Volumetric Design with Performance Verification is the framework that was created. The framework starts with the sourcing of aggregates and binders, which must meet the CTB Schedule 20 specification to be accepted. The gradation(s) of the mix design can be chosen based on the grading band limits. The standard asphalt mix design procedure (Marshall Mix Design) is then used to select the best binder content for the proposed mixture. This is followed by the creation of three samples that will be subjected to volumetric checks, as shown in Figure 1. If the mixture fails this check, the mixture can be redesigned by changing the gradation or the binder type. If the mixture is classified as POOR or GOOD, the mix selection process may be repeated. If a mixture is classified as POOR, the next stage will be rejected or accepted depending on which volumetric property the governing road agency has removed or relaxed to proceed to the performance stage. Locally, the only attributes that have been relaxed for Hot Mix Asphalt are the VMA and VFA properties (HMA). A VMA check is not required for Stone Matrix Asphalt (SMA).

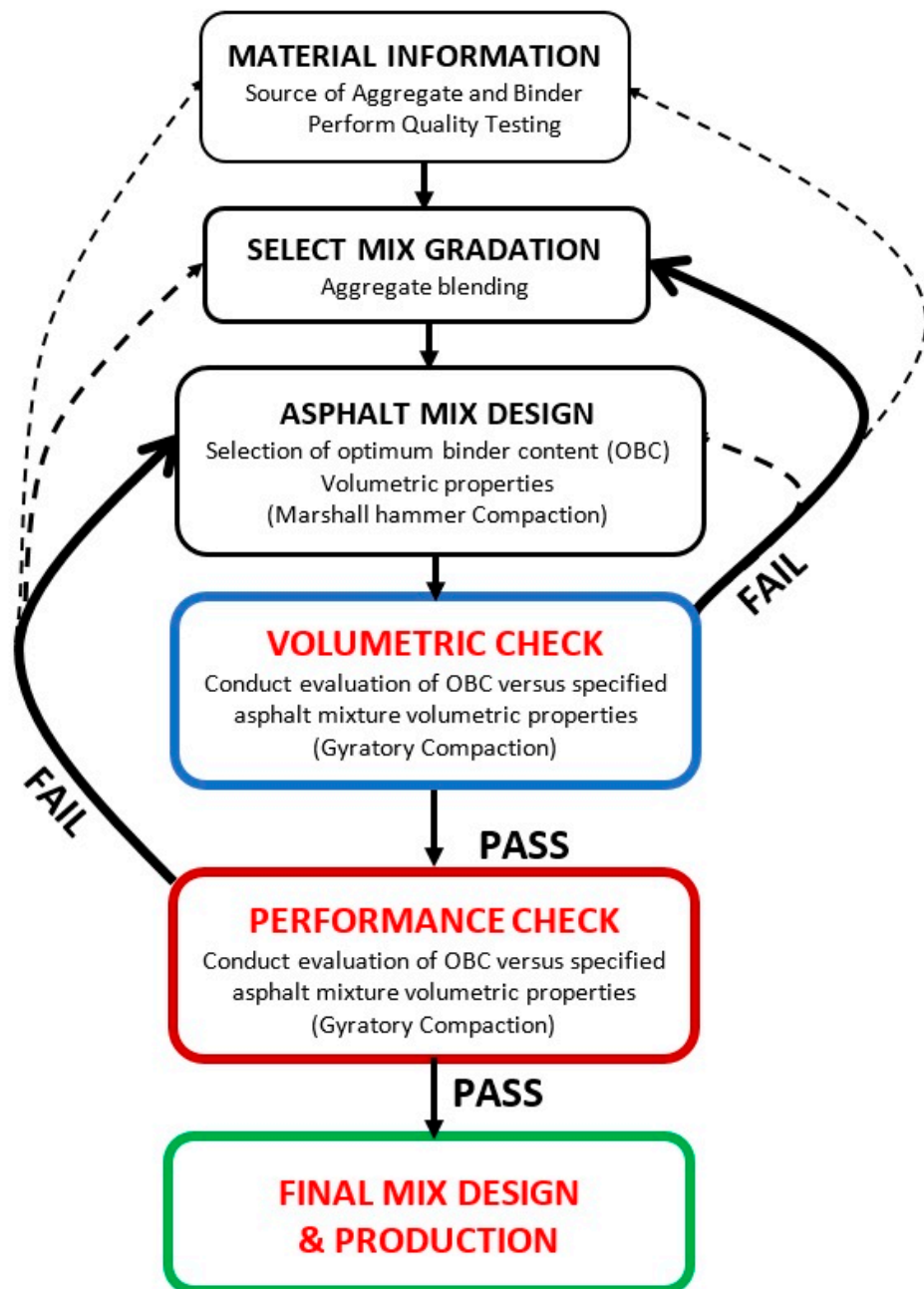


Figure 4. Proposed performance-based mix design framework.

In the next step, the sample undergoes a performance check, as previously indicated in Figure 3. If the sample is classified as GOOD, the mixture may be selected. However, if the mixture records a FAIL or POOR score on the performance check, then modification of the mixture is required from the design stage of the process. When the mixture has achieved a satisfactory result for both volumetric and performance-based evaluations, the asphalt mix can be approved, and production at asphalt plants commences.

3.3. Comparative Analysis with Recent Literature

Zaumanis et al. [32] carried out research on the performance-based design of asphalt mixtures and reviewed the key parameters acting on them. They suggested that the performance-based design can increase cost effectiveness and improve the durability of the asphalt. In addition, they found that environmental impacts were reduced due to the use of this approach. Furthermore, they suggested including aging as a part of the mix

design procedure to yield better results. Zhang et al. [33] researched the performance-based design for hard asphalt mixtures. This was based on different compaction levels. They found that the hard asphalt mixtures perform well under lower temperatures and illustrate significant fatigue resistance. They concluded that even marginal hard asphalt performs better than traditional asphalt. This suggests the importance of looking at performance-based mix designs. Zhang et al. [34] tested the performance-based design of recycled hot-mix asphalt using compaction effort as a variable. They found the compaction effort significantly influences the properties of recycled hot-mix asphalt (thermal and fatigue). They did not require the high compaction effort compared to traditional asphalt. Thus, the cost-effectiveness is higher. Asphalt mixtures with Reclaimed Asphalt Pavement (RAP) were tested for performance-based mix designs in another research study by Sabouri [35]. Sabouri found interesting results from the addition of RAP into the mix design. As expected, increasing RAP content deteriorates fatigue and improves rutting. However, in conclusion, the cost-effectiveness is increased due to the mixture with RAP content. Norouzi et al. [36] conducted a performance-based design of asphalt pavements for reliability analysis. They proposed a new design that was based on performance concerning fatigue failure. In addition, a new limit state function for accumulative fatigue failure was presented in their research study. However, in this research study, the performance-based mix design approach was used as an alternative to the volumetric mix design technique. This study consisted of laboratory-based experimental work. A comprehensive analysis was carried out to assess the performance of permanent deformation (rutting), fatigue cracking, stiffness, and moisture susceptibility. Excellent results were achieved through the analysis, and this could lead to significant improvements in achieving sustainable asphalt pavements in the Caribbean region.

4. Conclusions

The primary focus of this research study was the development of a Performance-Based Mix Design Framework for Trinidad and Tobago. The PBMD approach and framework developed in this study considered the Volumetric Design with Performance Verification. The developed PBMD framework can be incorporated locally into the Marshall Mix Design with the performance test methods shown in this research as it has exhibited adherence to acceptable standards. The location-specific PBMD framework has led us to draw the following conclusions:

- (1) Volumetric Properties of mixture selection of the rejection process were categorized as 'GOOD' for achieving the established volumetric criteria, 'POOR' for demonstrating marginal results, and as a 'FAIL' if they did not satisfy the established criteria specified in both the CTB Schedule 20 Specifications and The Ministry of Works and Transport—Programme for Upgrading Roads Efficiency (MOW—PURE) Specifications and the Asphalt Institute MS-2 Asphalt Mix Design Methods. The control mixes were categorized into the FAIL or POOR groups for 50% of the volumetric criteria within the local specification. However, the PBMD mixtures were classified as POOR for less than 20% of the volumetric requirements.
- (2) Based on performance testing data, the selection process similarly factored in categorization (into GOOD, POOR, and FAIL groups). The control mix designed using the existing local specification failed some of the performance testing grouping used in the study. The control mixes were categorized as poor when examined against the PBMD grouping criteria (Rutting vs. TSR, Rutting vs. ITSM, and cracking vs. Rutting). However, although some of the PBMD mixtures were classified as poor under the volumetric requirements, all recorded a classification of GOOD for the performance evaluation.

Based on these results, PBMD mixtures can be considered the optimal mixture type, achieving the best volumetric- and performance-based results with regard to the PBMD framework designed in this study. As such, performance tests should be considered an integral part of the HMA mix design. Notably, it is impossible to change one parameter

without causing a change in others. These effects are predicted to influence other properties of the respective parameters (Air Voids, VFA, VMA, Density, Flow, and Stability). Our research contributes to the theory that an established PBMD framework can be implemented in an asphalt mix design for testing in the Caribbean region.

This project on the development of a PBMD framework for the Caribbean region exemplifies a significant step towards achieving sustainable asphalt pavements regionally. The Performance-Based Mix Design Framework, which incorporates best-practice solutions, is anticipated to increase awareness about the variables that affect the performance of asphalt mixtures. However, in response to further research on the Performance-Based Mix Design approach, further adjustments to the framework are anticipated. Additionally, further research is required to correlate the field testing applications of the developed Performance-Based Mix Design Framework for the Caribbean region.

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