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"Volumetric design of bituminous mixtures – Portuguese experience"

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VOLUMETRIC DESIGN OF BITUMINOUS MIXTURES – PORTUGUESE EXPERIENCE

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ABSTRACT

In Portugal the Marshall method is used for bituminous mixtures design. However, methods based on empirical tests, such as the Marshall method or the Hveem method, are known to have major drawbacks. It is expected that the volumetric design of bituminous mixtures will replace these methods.

In the volumetric design of bituminous mixtures specimens are prepared using the gyratory compactor and their volumetric proprieties are used to determine the optimum binder content. This volumetric design is the core of the first stage, and many times the only stage, of bituminous mixture design in the USA and Australia, for instance. The definition of design values that can simulate the field behavior of the bituminous mixtures is important. However the definition of the design values has to take in account the bituminous mixtures proprieties, traffic levels, temperatures and the existing experience with the behavior of the bituminous mixtures.

In this work a study was carry on the application of gyratory compactor to common Portuguese bituminous mixtures taking in account the experience of other countries, the current practice and the capability to use this equipment as a base for volumetric design. The limit values for the volumetric design parameters such as the volume of voids or the VMA are also analyzed. New possible improvements in the known design procedures are discussed. Direction lines are draw regarding the application of volumetric design to the bituminous mixtures used in Portugal.

INTRODUCTION

As a result of the drawbacks of the bituminous mixtures design methods based on empirical tests the Strategic Highway Research Program (SHRP) has developed the Superpave system (FHWA, 1995). The Superpave system is composed of a performance-graded asphalt binder specification, aggregate criteria and a mixture design process. This work will address mainly the mixture design process. The design process consists mainly on selecting the bitumen content. The optimum bitumen content is selected on the basis of the volumetric proprieties of the mixtures evaluated in specimens compacted using a gyratory compactor.
The mixture design process has been arranged in three levels. The first level refers to the volumetric design of the bituminous mixtures using the gyratory compactor. The second level is mainly focus on the mechanical properties of the mixtures such as the dynamic modulus or creep resistance. The third level is concerned with the evaluation of the rutting and fatigue resistance of the mixtures.

The adoption of the volumetric design of bituminous mixtures based on the Superpave guidelines is not inexpensive. A broad range of testing equipment must be purchased to execute all the tests. The cost of the mixture's design is to a large extent higher using the Superpave guidelines than using the traditional Marshall method. An effort must be made for the cost and resources used in the design be balanced with the benefits of achieving a better mixture. The benefits must take into account the circumstances in which the mixture will be used and the consequences that will derive from an earlier failure of the mixture.

To address this problem the three levels of the design take into account the conditions in which the mixture will be used. For mixtures used in lower traffic roads only Level 1 is proposed to be performed. For mixtures used in medium to heavy traffics Level 1 and Level 2 are indicated. Only for roads with very heavy traffic the design of the mixture should be made using the three levels of the design.

The core of the design is Level 1 it is on this stage that the mixture composition is defined. Level’s 2 and 3 include performance tests, these tests can characterize the mixtures fatigue life or rutting resistance. These test are used mostly to assure the quality of the mixture, however they are the more expensive to perform. Therefore it is desirable that the mixture established in Level 1 will surpass Level 2 and Level 3. Furthermore, only for medium or heavy traffic roads Level 2 and 3 are performed. This means that an important amount of mixtures placed will be designed only by performing Level 1, or in other words, mixtures will be designed using only their volumetric properties. The design methods commonly include some refusal conditions in the volumetric design. These conditions try to avoid the selection of mixtures in Level 1 that would not be rut resistant. The refusal condition is set as a minimum air void content that could be reached, if the mixture has a lower void content after the defined compaction level the mixture should be rejected.

It was expected that Level 1 would be used in low traffic roads with less than 1 million ESALs, Level 2 would be used in roads with traffic 1 and 10 millions ESALs and Level 3 in roads with more than 10 million ESALs (Cominsky et al, 1994). However, in the USA where all developments are reached, the performance tests to be used and their specifications have not been yet defined and therefore only Level 1 has been currently implemented at several DoTs and it has been used, at least as an indication, for all traffic levels.

The implementation of this design methodology represents a step forward from the current procedures. In Portugal the Marshall method has been used for many decades and there is a huge experience with it, but there are also some significant limitations that have restricted its use in practice. With the introduction of new types of mixtures and higher performance requirements the limitations of the Marshall method will become more evident.

In this work the Marshall method and the volumetric design method are analyzed and their application to Portuguese conditions evaluated. The implementation in practice and the advantages of the volumetric design method are also discussed.
VOLUMETRIC DESIGN METHOD USING THE GYRATORY COMPACTOR

In the volumetric design method of bituminous mixtures for a given gradation a series of trial mixtures with different binder contents are manufactured. The mixtures are compacted in a gyratory compactor under specified conditions. The analysis of the density of the specimens permits a compaction curve to be drawn. The selected binder content will be the one that has a target air voids for the compaction level defined.

The specimens are compacted in a gyratory compactor using a specific compaction effort. The compaction effort is measured by the number of gyrations, the angle and the compaction pressure. The angle used in the Superpave design method is 1.25°, higher angles produced high rates of compaction which makes difficult to determine the compaction curves. Lower angles tend to produce insufficient compaction. The compaction pressure is 600 kPa. The specimens are cylindrical with 150 mm of diameter and 115 mm in height. The sample is subjected to the compaction load and is inclined 1.25 degrees rotating at 30 revolutions per minute. This is thought to reflect the compaction and particle orientation achieved in the field.

There are three different gyration numbers. \( N_{\text{initial}} \) is the number of gyrations that simulates the construction compaction. If the void content after \( N_{\text{initial}} \) is too low the mixture has compacted too quickly and as a result the mixture may be unstable when subjected to traffic. \( N_{\text{design}} \) is the number of gyrations that produces the compaction that is expected in field after the traffic expected through the design life. At \( N_{\text{design}} \) the void content of the mixture should be of 4%, which is the desirable void content after construction and trafficking. The mixture selection is made to accomplish this condition. \( N_{\text{max}} \) is the number of gyration that produces a compaction that should never be exceeded in the field. If the void content after \( N_{\text{max}} \) is bellow 2% then the mixture is likely to have rutting problems. The optimum binder content is established for mixtures compacted to \( N_{\text{design}} \). The original levels were based on temperature and traffic resulting in 28 levels for \( N_{\text{design}} \). These levels were revised and reduced to four levels which differ only with the expected traffic (NCHRP, 2001). These levels are presented in Table 1.

<table>
<thead>
<tr>
<th>20-yr Traffic Loading (in millions of ESALs)</th>
<th>Number of Gyrations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N_{\text{initial}} )</td>
</tr>
<tr>
<td>&lt; 0.3</td>
<td>6</td>
</tr>
<tr>
<td>0.3 to &lt; 3</td>
<td>7</td>
</tr>
<tr>
<td>3 to &lt; 30</td>
<td>8</td>
</tr>
<tr>
<td>≥30</td>
<td>9</td>
</tr>
</tbody>
</table>

Threshold values for volumetric properties such as VMA and VFA for 4% voids are also defined. While the VMA values differ with the type of mixture, VFA limits differ with the number of predicted ESALs. These requirements are presented in Table 2.
Table 2 - Volumetric requirements for Superpave mixtures (NCHRP, 2001).

<table>
<thead>
<tr>
<th>20-yr Traffic Loading (in millions of ESALs)</th>
<th>Required Density (as a % of theoretical max. spec. gravity)</th>
<th>Voids in Mineral Aggregate (minimum, %)</th>
<th>Voids Filled With Asphalt (%)</th>
<th>Dust to Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N_{\text{initial}} )</td>
<td>( N_{\text{design}} )</td>
<td>( N_{\text{max}} )</td>
<td>Max. Agg. Size (mm)</td>
</tr>
<tr>
<td>(&lt; 0.3)</td>
<td>( \leq 91.5)</td>
<td>( \leq 90.5)</td>
<td>( \leq 98.0)</td>
<td>11.0</td>
</tr>
<tr>
<td>(0.3 \text{ to } &lt; 3)</td>
<td>( \leq 96.0)</td>
<td>( \leq 98.0)</td>
<td>( \leq 98.0)</td>
<td>11.0</td>
</tr>
<tr>
<td>(3 \text{ to } &lt; 30)</td>
<td>( \leq 96.0)</td>
<td>( \leq 98.0)</td>
<td>( \leq 98.0)</td>
<td>11.0</td>
</tr>
<tr>
<td>(\geq 30)</td>
<td>( \leq 89.0)</td>
<td>( \leq 98.0)</td>
<td>( \leq 98.0)</td>
<td>11.0</td>
</tr>
<tr>
<td>(&lt; 0.3)</td>
<td>( \leq 89.0)</td>
<td>( \leq 98.0)</td>
<td>( \leq 98.0)</td>
<td>11.0</td>
</tr>
</tbody>
</table>

On Level 1 of the volumetric design method the mixtures are not subjected to any mechanical test. In this case the volumetric design method addresses permanent deformation and fatigue by specifying asphalt binder properties, aggregate properties (such as angularity), and gyratory compactor requirements. However, the volumetric proprieties of the mixtures may not be enough to ensure the quality of the mixture obtained.

The adoption of the Superpave volumetric mixture design requires the purchase of new test equipments and the training of the staff in its use. However, more proprieties from the components and the mixtures are studied. Primarily more performance-related proprieties are characterized. A survey made on highway administrations that have adopted the Superpave design method show that most of them did not notice performance changes in the pavements (TRB, 2005). From those who have seen benefits in performance better rutting performance was the most reported. This survey was not based on performance studies but on the perception of the highway administrations from the experience with the use of the Superpave method. Even if performance improvements are not visible instantaneously the conviction of the highway administrations is that the benefits with extended service life of the pavements obtained are clearly superior to the costs involved in the adoption of the volumetric design method.

PORTUGUESE EXPERIENCE IN MIXTURE DESIGN

In Portugal the Marshall Method is used to design bituminous mixtures. This method uses an empirical test – the Marshall Test – to achieve the optimum binder content. The compaction of the specimens is made by impact compaction. This method of compaction can achieve void contents similar to those obtained in the field. However the mixtures don’t resemble those obtained in the field, particularly the particle orientation.

The Marshall is performed in cylindrical specimens with 101.6 mm in diameter and 63.5 mm in height. Therefore only mixtures with a maximum aggregate size of 25.4 mm or less can be tested. This has been an important limitation since there are mixtures used in Portugal with 37.5 mm of maximum aggregate size. The volumetric design of the mixtures using the gyratory compactor is more versatile, thus a wider range of bituminous mixtures can be tested.

In this design method a mechanical test is performed in the mixtures. However the Marshall test is an empirical test that can not replicate the field loading conditions. To predict permanent deformation the Marshall stability-flow ratio could be used, but the limitations of the test have showed that for
medium or high trafficked roads performance tests such as the Wheel-Tracking test have to be performed (Gardete and Picado-Santos, 2006). These tests are not included in the specifications so the Portuguese design method to ensure permanent deformation resistance of the mixtures defines requirements for aggregates and bitumen.

The bitumen requirements are simple since Portugal is a small country and generally only two grades of bitumen are used for bituminous mixtures production. The penetration grade used depends on the traffic and the temperatures in the hot season (JAE, 1995).

For aggregates the requirements are very comprehensive. The gradation, angularity, percentage of flat and elongated particles, Los Angeles Abrasion, and other requirements are established for aggregates for the production of bituminous mixtures. Some requirements are also made for the bituminous mixtures when submitted to the Marshall test. These requirements are Marshall Stability, Marshall Flow and loss of Marshall Stability. There are also requirements for volumetric proprieties of the mixtures. These requirements include void content, VMA (Voids in the Mineral Aggregate) and dust-to-binder ratio.

ADEQUATION OF PORTUGUESE SPECIFICATIONS TO THE VOLUMETRIC DESIGN METHOD

In the USA the development of the Superpave design method has started 20 years ago. During this time the laboratories have been upgrading their methods and equipments. The adoption of such a comprehensive method of design in a short period of time is a very difficult task. The research and findings that have occurred can help to shorten the adoption period. However, the bituminous mixtures design methods must take in account the experience and practice of each country. The adoption of the different Superpave specifications in Portugal is discussed regarding the current state of the Superpave project and the Portuguese current practice.

In Portuguese current practice the bitumen characterization is made with Penetration at 25°C and Softening Point. Therefore, the Superpave bitumen performance grade specification has a range of tests that are not in commonly used in Portugal and that most laboratories do not have the needed equipment. In the performance grade classification of bitumens their behavior to high and low temperatures is characterize. Portugal has severe summers and the high temperature behavior of the bitumen is very important. However, low temperature behavior is not much important when compared to other countries and in practice there are no records of failures associated with low temperatures. The use of a great number of performance grade bitumens would probably be difficult and inefficient in a small market like the Portuguese. Only two penetration grade bitumens are commonly used for HMA production, the 35/50 and the 50/70. The adoption of the Superpave binder specifications without modifications does not seem feasible in a near future in Portugal.

The aggregate criteria in Superpave mix design were made for the type of mixtures used in USA. In Portugal the local Highway Administration has aggregate criteria for the mixtures commonly used. The aggregate criteria are very comprehensive and include proprieties such as Gradation, Flat/Elongated Particles, Sand Equivalent, Methylene Blue Adsorption value, Los Angeles Abrasion Test, Coarse Aggregate Angularity and Absorption. It is expected the adoption of the micro-deval test in aggregate characterization in a near future.
The definition of different values for these properties is the basis of the mixture that will be obtained. Therefore, the use of the Superpave criteria will lead to the certain kind of mixtures, commonly referred as Superpave SMA Mixtures. That would imply an important change in current practice since some of mixtures used in Portugal differ from Superpave mixtures. The adjustment of the mixture design to the existent aggregate criteria seems more adequate than the adoption of new type of mixtures from which there is no local experience with its use.

The introduction of the volumetric bituminous mixture design using the gyratory compactor can be done without adopting the bitumen specifications and aggregate criteria. The Marshall method has limitations that can not be surmounted because of its empirical nature. The use of the volumetric design is a step forward in bituminous mixture design.

The adopted design method will be more quickly accepted and applied if it appears has an evolution of the procedures currently used and not something entirely new and a cut with the actual practice. Therefore, the principles of the volumetric design method used in the Superpave program and in Portuguese practice where merged and a proposal is made for the principles that should be adopted in Portugal.

The Portuguese practice with the Marshall method is to use 0.5% increments and a set of 5 test series each one with 3 replicate specimens. It is desirable that at least two mixtures have bitumen content bellow the optimum and at least two mixtures have bitumen content above the optimum. From experience and highway administration publications the range of bitumen contents to be tested can be defined. Similar procedures can be used with the volumetric design method. The use of similar procedures makes the transition process between different methodologies easier.

In Table 3 the traffic levels used in Portugal are showed. The threshold values for the volumetric properties of the most common mixtures are also presented.

Table 3 – Volumetric properties of typical Portuguese bituminous mixtures (JAE, 1998).

<table>
<thead>
<tr>
<th>Level</th>
<th>20-yr Traffic Loading (in millions of ESALS)</th>
<th>Voids in Mineral Aggregate (minimum, %)</th>
<th>Dust to Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Type of Mixture/Max. Agg. Size (mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MB/37,5</td>
<td>MB/25,0</td>
</tr>
<tr>
<td>T0</td>
<td>&gt; 100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>70 to 100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>40 to 70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>20 to 40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>8 to 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>2 to 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>&lt; 2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) – The design of this mixture is not made with the Marshall Method and there is no minimum value for VMA defined, but a minimum value of 12% or 13% should be expected.

Voids Filled with Asphalt (VFA) is not a parameter that has been used in the Portuguese specifications, but analyzing the properties of the mixtures presented in Table 3 the value of VFA should be in the range of 65% to 80%. The use of VFA limits is to assure that the bitumen content is
not too low or too high. However, this can be assured using other volumetric properties. The use of a target design void content and minimum values for VMA controls the use of low bitumen contents. Establishing maximum VMA requirements will avoid the use of high bitumen content that would decrease the rutting resistance of the mixtures. With the use of minimum and maximum VMA requirements there is unnecessary to use VFA to control bitumen content (TRB, 2006). The maximum VMA values are usually set approximately 2% above the minimum values.

The optimum bitumen content obtained by both methods is generally not equal. Some authors indicate that lower optimum bitumen content is obtained with the gyratory compactor (Neubauer and Partl, 2004). This is in part because the \( N_{\text{design}} \) levels imply high compaction effort. This has lead to mixtures that have a good permanent deformation resistance but do not have adequate fatigue resistance.

The rutting resistance has been the main concern for the volumetric design. The definition of high \( N_{\text{design}} \) levels lead to lower binder contents and consequently to better rutting resistance but also to lower fatigue resistance. To avoid this effect \( N_{\text{design}} \) levels could be decreased. The objective is to have \( N_{\text{design}} \) levels that lead to mixtures with a more balanced permanent deformation and fatigue performance. If \( N_{\text{design}} \) is increased the optimum binder content obtained is lower and the mixture will have higher permanent deformation resistance but lower fatigue resistance. If \( N_{\text{design}} \) is decreased the optimum binder content obtained is higher and the mixture will have lower permanent deformation resistance but higher fatigue resistance. Some authors recommend that to reach a better balance between permanent deformation resistance and fatigue resistance the \( N_{\text{design}} \) should be in the range of 75 to 85 gyrations (Prozzi and Aguiar, 2007).

Studies referred that the numbers of gyrations for design from Table 1 defined for traffics greater than 0.3 million ESALs are higher than needed to reached the density occurred in the field. The field densities in the evaluated pavements and test sections were approximately 1.5% less than the densities in the laboratory-compacted samples using \( N_{\text{design}} \) from Table 1 (NCHRP, 2007).

The external angle of gyration is not adequate to define the compaction effort and it should be adopted the dynamic internal angle (DIA). Differences in densities were observed between different compactors. This was due to deficient control of compaction when the external angle was used. For different manufactures for the same external angle differences were found in the internal angle. Therefore the DIA is more adequate to control the compaction effort than the external angle. For the most common equipments an external angle of 1.25 degrees corresponded to an average DIA of 1.16 degrees (Prowell et al, 2003 and Al-Khaateeb et al, 2002). From these findings the \( N_{\text{design}} \) levels were reduced. For a DIA of 1.16 the recommended \( N_{\text{design}} \) levels are presented on Table 4.

The decrease in the \( N_{\text{design}} \) level might not lead to higher bitumen content if contractors modify the gradation to keep the bitumen content low. Gradation, VMA and void content limits must be defined assure that the bitumen contents are in fact increased. An increment in the minimum VMA value is recommended to assure an increase in the optimum bitumen content (NCHRP, 2006). Some DOTs in the USA to increase optimum bitumen content have reduced the number of gyrations for \( N_{\text{design}} \) increased the VFA limits, increased VMA lower limits or have set a lower design void content.
Table 4 - Proposed N_{design} levels for an SGC DIA of 1.16 degrees (NCHRP, 2007).

<table>
<thead>
<tr>
<th>20-yr Traffic Loading (in millions of ESALs)</th>
<th>2-yr Traffic Loading (in millions of ESALs)</th>
<th>N_{design} for binders &lt; PG 76-XX</th>
<th>N_{design} for binders ≥ 76-XX or mixtures &gt; 100 mm from surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.3</td>
<td>&lt; 0.03</td>
<td>50</td>
<td>NA</td>
</tr>
<tr>
<td>0.3 to &lt; 3</td>
<td>0.03 to &lt; 0.23</td>
<td>65</td>
<td>50</td>
</tr>
<tr>
<td>3 to &lt; 10</td>
<td>0.23 to &lt; 0.925</td>
<td>80</td>
<td>65</td>
</tr>
<tr>
<td>10 to &lt; 30</td>
<td>0.925 to &lt; 2.5</td>
<td>80</td>
<td>65</td>
</tr>
<tr>
<td>≥ 30</td>
<td>≥ 2.5</td>
<td>100</td>
<td>80</td>
</tr>
</tbody>
</table>

The number of N_{design} gyrations must be studied with attention. The mixtures commonly used in Portugal have showed good resistance in the field. Therefore trials must be made with the N_{design} from Superpave and with the number of gyrations that would lead to optimum bitumen content close to the used in practice. These trials must be submitted to performance prediction tests. Then the number of gyrations for N_{design} can be defined so the mixtures obtained can assure good performance both for permanent deformation and fatigue resistance. This is crucial to assure that the mixtures design with the volumetric method will have a good behavior. If the mixtures that are designed in Level 1 have good performance then they will probably be surpass Level 2 and Level 3 making the design process faster and cheaper.

Studies point that densities at N_{initial} and N_{maximum} are not performance-related to rutting resistance. It has been observed that several mixtures that failed in those requirements performed well in the field with very good rut resistance. The use of maximum densities at N_{initial} and N_{maximum} as refusal conditions is not recommended (NCHRP, 2007).

The binder specification, aggregate criteria and volumetric requirements are not enough to assure good performance of the mixtures in heavy trafficked roads. The implementation of Level 2 and Level 3 of the design process with performance tests is crucial. The new European Standards include performance tests that can be used for Level 2 and Level 3 of the mixture design. In Portugal wheel-tracking tests and four point bending beam test should be adopted as performance tests for permanent deformation and fatigue characterization (Gardete and Picado-Santos, 2006; Antunes and Freire, 2006).

RECOMMENDATIONS

The full implementation of the Superpave design method, with binder specification, aggregate criteria and mixture design is not inexpensive. The immediate adoption of the full method in Portugal is not feasible, mainly from the assortment of tests used. The adoption of new design methods also has to take in account local experience and conditions and, of course, directives from European Community (EC).

The performance grade binder must be adjusted for Portuguese conditions. The use of the low temperature performance grade has no importance in Portugal. New tests are required for the characterization of bitumens that are not in current in Portuguese practice.
For now the Portuguese Highway Administration has aggregate criteria that are comprehensive. In a very near future when this type of criteria moved to an EC directive, basically a small amount of changes will be introduced. It can be said that these aggregate criteria can be used with the described volumetric mixture design without significant modifications.

The compaction effort, \( N_{\text{design}} \), and volumetric requirements must be studied for the bituminous mixtures used in Portugal. The design of bituminous mixtures with better performance is dependent on the values defined for those parameters. The volumetric mixture design method can consequently produce better performing mixtures when compared to the Marshall method.

The use of requirements for VFA is not necessary. However, it should be established minimum and maximum limit values for VMA. A design target void of 4% can be adopted.

The use of maximum densities at \( N_{\text{initial}} \) and at \( N_{\text{maximum}} \) as refusal conditions is not recommended. The compaction angle should be defined using the dynamic internal angle and not the external angle. A value of the dynamic internal angle of 1.16 degrees should be adopted.

Effort must be made to implement design Level 2 and Level 3. The use of performance test to assure the performance of bituminous mixtures in heavy trafficked roads is necessary. The Levels of traffic, tests procedures and threshold values for Level 2 and Level 3 must be defined. Nevertheless, these types of procedures will be on Portuguese practice in the next year following the EC orientation related to the validation of the mixtures design.

REFERENCES


