Revista Ingeniería de Obras Civiles - RIOC - Volumen 2/2012
ISSN 0719-0514

Bailey method design for a dense asphalt concrete and its influence on permanent plastic deformations resistance

Diseño de un concreto asfáltico denso por el método Bailey y su impacto en la resistencia a las deformaciones plásticas permanentes

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ABSTRACT

Historically, asphalt mixes have been designed considering the professional experience and proper values of volumetric parameters, such as continuously graded aggregate (gradation curve does not have any abrupt slope change), and respecting the technical specifications limits that are related. Taking that into account the asphalt binder rheological behavior is analyzed as well as the designed mix mechanical response to modeled static and/or dynamic loads that try to simulate the field conditions.

However, it has been proved that not always these initial design criteria consider all the variables that condition the granular stability of the system.

The present work develops the method proposed by Robert Bailey, from the Illinois Department of Transportation, applied to a dense asphalt mix NMPS 20 mm (HMA - D20). The method proposes to optimize the aggregate skeleton to achieve a lower rate of permanent deformations of the mixtures in service. This optimization is done considering the relation between gradation and voids changes in the mix properties. To that end Control sieves are defined, these allow a more accurate aggregate blend evaluation.

In order to show how these considerations modify the dense asphalt mix properties a comparison was done between one conventionally designed mix and one designed with the Bailey method (in both cases the optimum binder content was determined by the Marshall method). These mixes were submitted to dynamic loads at 60 °C with the Wheel Tracking Test, evaluating rut resistance in each case.

ARTICLE INFO

Article history:
Received 18-07-2012
Accepted 26-10-2012
Available 20-12-2012

Asphalt mix
Bailey method
Rut resistance

RESUMEN

Históricamente las mezclas asfálticas se han diseñado considerando en este proceso la experiencia del profesional y manteniendo criterios volumétricos, tales como concavidad y continuidad de la curva granular y respetando los límites de las especificaciones técnicas que se constituyen en la franja de trabajo. A partir de allí se analiza normalmente el comportamiento reológico del ligante asfáltico y la respuesta mecánica del diseño frente a cargas estáticas y/o dinámicas de modelos que tratan de simular las condiciones de servicio.
Sin embargo se ha probado que no siempre estos criterios iniciales de diseño consideran todas las variables que condicionan la estabilidad granular del sistema.
El presente trabajo desarrolla el método propuesto por Robert Bailey, del Departamento de Transporte de Illinois, aplicado al diseño de una mezcla asfáltica densa de TMN de árido 20 mm (CAC - D20). El método propone optimizar la estructura granular de los áridos logrando así una disminución de las deformaciones plásticas permanentes de las mezclas en servicio. Esta optimización se logra teniendo en cuenta la relación granulométrica con los vacíos que produce la mezcla. Para ello se definen diferentes tamices de control que permiten la evaluación de la mezcla de agregados con mayor precisión.
A efectos de probar la incidencia de estas consideraciones de diseño, en el comportamiento de la mezcla asfáltica densa, se establece una comparación de desempeño entre la mezcla diseñada convencionalmente y la propuesta por la metodología descripta (en ambos casos el porcentaje óptimo de ligante, se determinó mediante la metodología Marshall), frente a la aplicación de cargas dinámicas a 60 °C mediante el ensayo de Wheel Tracking Test, el cual pondrá de manifiesto la resistencia al ahuellamiento en cada caso.

INFORMACIÓN DEL ARTICULO

Historial del artículo:
Recibido 18-07-2012
Aceptado 26-10-2012
Publicado 20-12-2012

Palabras Claves:
Mezcla Asfáltica
Método Bailey
Ahuellamiento

1. Initial considerations

One of the reasons for failures in flexible pavements is the instability of the upper layer, called surface course, in front of the action of the heavy low-frequency loads and high temperatures.
As an unwanted effect rutting appears in the tyre-pavement contact zone generating an insecurity area for driving, water accumulation and risk in the braking conditions [1].
This kind of failure on the pavement responds to several factors. Among them it can be mentioned the type of asphalt binder selected. In this case it is important to select the asphalt binder considering the relation between the complex shear modulus (G*) and the phase angle (δ) that is the lag between the asphalt binder response and the resulting shear strain when torque is applied using a Dynamic Shear Rheometer (DSR). The SUPERPAVE methodology, developed in the United States, sets extreme values for the quotient between these two variables considering virgin and aged asphalt binder samples in order to , if these values are accomplished, eliminate the rutting risk condition in asphalt mixes due to the load and temperature values mentioned before.
As a consequence of this, higher viscosity asphalt binders can be selected, or the usage of polymer modified asphalts can be considered. After the asphalt binder selection, under the mentioned conditions, is left to consider the other variables that influence the rutting resistance of an asphalt mix. In that sense it should not be left behind the fact that an asphalt mix is composed of aggregates that constitute more than 90% of the mix in volume, and therefore they are a fundamental point when considering the final performance.
Precisely in this work the following characteristics related to the aggregates will be considered [2]:

- Aggregate type: mineralogical origin.

- Crushing process: If the aggregate is natural or crushed, and in the last case which were the crushing process used.
- Accelerated polished stone coefficient.
- Los Ángeles abrasion coefficient.
- Shape indicators: flakiness, elongation, cubicity.
- Texture
- Gradation and NMPS/ layer thickness relation.
- Relation between the different aggregate fractions: granular stabilization.

To consider these variables gradation curves have been established according to the current specifications and criteria, usually called restriction zones. These values will be considered as limitations given that are currently used worldwide, not just Latin America but the European Union and the United States as well.

2. Robert D. Bailey study of the Illinois Department of Transportation of the United States.

The methodology for aggregate blend design, developed by Bailey, to reduce the permanent plastic deformations is a customary topic worldwide and therefore the related experiences are new in this field. The present work pretends to compare the behavior using the usual methodology in one case and using the Bailey methodology in the other case, fulfilling in both cases the Asphalt Permanent Commission General Technical Specifications (APCGTS) for a HMA – 20, which are used in Argentina and in other countries.
In this case the main intention is to optimize the aggregate granular structure throughout an optimum interlocking and a higher contact between the aggregates varying the voids in the mixture [3].
The Bailey method proposes to improve the granular structure achieving a better aggregate interlocking in order to improve its performance in front of permanent plastic deformations and it can be use with any method of mix design (Superpave, Marshall, Hveem, etc.).
The following tests must be done for the application of the method, they are normally carried out in control and design laboratories but in some cases they must be considered as priority given not to do so invalidate the methodology [3]:

- Loose Unit Weight of an aggregate
- Rodded Unit Weight of Fine and Coarse Aggregate
- Density of the coarse aggregate, the fine aggregate and the filler
- Gradation of the coarse aggregate, the fine aggregate and the filler

First of all it is necessary to choose a certain percentage of the **loose unit weight of the coarse aggregate considering it must be lower than 90%** for dense mixes. Adopting this value and taking into account the aggregate density the percentage of the voids generated by the coarse aggregate is calculated.
It is considered that the fine aggregate must fill the voids created under that condition.
On the other side the definition of coarse and fine aggregate, according to the method, is not the conventional one where the break point sieve is the 4.75mm IRAM sieve but the coarse aggregates are considered as the particles than when place in a certain volume create voids, which may be fill with smaller particles being these last ones the fine aggregate. From this definition it can be seen that more than one control sieve is needed for the aggregate division, so from the coarse aggregate gradation the following IRAM (Instituto de Normalización Argentino) or ASTM sieves are calculated:

Primary Control Sieve: 22 % of the nominal maximum particle size

PCS = NMPS*0.22 Formula N°1

The Nominal Maximum Particle Size, NMPS, is defined as one sieve larger than the first sieve that retains more than 10%. In this case as the NMPS is of 19mm, the PCS is of 4.75mm. Assuming that such size can be considered as the N°4 sieve from ASTM, the 4.75mm divide coarse from fine aggregate. From that value the aggregate percentage is revised according to the amount of fine aggregate the coarse aggregate contain and vice versa.
Then the percentage of the N°200 sieve must be corrected according to the filler incorporated, if necessary.
Once the final percentage is obtained the left control sieves are calculated.
The next one is the called **Half Sieve, HS:**

HS = NMPS * 0.5 Formula N°2

In this case the HS is of 9,5mm that is the same as the 3/8" ASTM sieve.
Then the Secondary Control Sieve is calculated as follows:

SCS = PCS * 0.22 Formula N°3

In this case 1,18mm is the same as the N°16 ASTM sieve.
At last the **Tertiary Control Sieve** is calculated as follows:

TCS = SCS * 0.22 Formula N°4

In this case the obtained value is 0.30mm the same as the N°50 ASTM sieve.

These sieves allows to divide the final aggregate blend in different portions for a better study, generating control points that are wider than the ones considered in a conventional curve[3]. In a detail of this analysis it can be said that the combined blend is broken down into three distinct portions, and each portion is evaluated individually: the coarse portion of the combined blend is from the largest particle to the PCS and the fine portion is broken down and evaluated as two portions with the SCS and the TCS.
Three different portions are defined:

- Coarse Aggregate
- Coarse Portion of Fine Aggregate
- Fine Portion of Fine Aggregate

Coarse Aggregate (CA)
The CA Ratio is used to evaluate packing of the coarse portion of the aggregate gradation and therefore to analyze the resulting void structure.
For its calculation the PCS and the HS are used:

$$\text{CA Ratio} = \frac{(100\%\ \text{Passing HS}) - (\%\ \text{Passing PCS})}{(100\% - 100\%\ \text{PHS})} \qquad \text{Formula N°5}$$

Particles smaller than the half sieve are called "interceptors." These are too large to fit in the voids created by the larger coarse aggregate particles and hence spread them apart. The balance of these particles can be used to adjust the mixture's volumetric properties. When the CA Ratio decreases compaction of the fine aggregate fraction increases because there are fewer interceptors to limit compaction of the larger coarse aggregate particles; besides the blend could be prone to segregation. As the CA Ratio increases towards 1.0, VMA will increase. However, as this value approaches 1.0, the coarse aggregate fraction becomes unbalanced because the interceptor size aggregates are attempting to control the coarse aggregate skeleton. Finally, as the CA Ratio exceeds a value of 1.0, the interceptor-sized particles begin to dominate the formation of the coarse aggregate skeleton. The coarse portion of the coarse aggregate is then considered "plugger," as these aggregates do not control the aggregate skeleton, but rather float in a matrix of finer coarse aggregate particles.
The CA has a meaningful effect on the mix volumetric properties as the CA portion increases the VMA increases as well.
Besides it can indicate construction problems, given that if the CA portion decreases the blend has a greater tendency to segregate.

Coarse Portion of Fine Aggregate (FA_c)
All of the fine aggregate (i.e., below the PCS) can be viewed as a blend by itself that contains a coarse and a fine portion. The coarse portion of the fine aggregate creates voids that will be filled with the fine portion of the fine aggregate. The FA_c is calculated using the PCS and the SCS as follows:

$$FA_c = \frac{(\%\ \text{Passing SCS})}{(\%\ \text{passing PCS})} \qquad \text{Formula N°6}$$

It is desirable to have this ratio less than 0.50, as higher values generally indicate an excessive amount of the fine portion of the fine aggregate is included in the mixture.

Fine Portion of Fine Aggregate (FA_f)
The fine portion of the fine aggregate fills the voids created by the coarse portion of the fine aggregate.

$$FA_f = \frac{(\%\ \text{Passing TCS})}{(\%\ \text{passing SCS})} \qquad \text{Formula N°7}$$

The FA_f should be lower than 0.50. The FA_c and the FA_f have similar effect on the blend given that the VMA will increase with a decrease in this ratio.
Since there are not experimentations in the matter the range of proportions can be broaden if the designer obtains acceptable mixes.
In this experience the operations are shown in a excel calculation sheet.

3. Experimental development

The designed asphalt mix will constitute a road surface of a road with heavy traffic with a AADT of 2000 vehicles per day, being 70% heavy vehicles. It will be a hot dense mix consisting of 2 inches with a 20mm NMPS, designated as HMA – D20. The materials will be constituted by aggregates from a quarry of Tandil, Province of Buenos Aires, of granitic origin, crushed, and commercially designated as 6:20 coarse aggregate. On the other hand, the fine portion is constituted by a triturated sand of the same origin that the coarse aggregate, commercially designed as 0:6 sand.

The hydrated lime has been selected as filler, considering filler as the particles that pass the 175um ASTM sieve.

The asphalt cement used is classified as AC-30 according to the viscosity values and accomplishing 1,3KPa for G*/sen δ for the virgin binder and 2,5 KPa for the aged binder. This asphalt is provided by an YPF refinery of the city of La Plata. In this way it is warranted a good performance of the asphalt binder in 60°C work conditions and low frequency traffic, considered in this case as 26.5 cycles per minute, which are compatible with the Wheel Tracking Test that was used to evaluate the design process.

Considering the current specifications in Argentina, which are similar to the specifications in the region, the aggregates were characterized (part 3.1) and then the corresponding gradation curve was designed using the conventional method (part 3.3), this asphalt mix was called **CM**.

In this work, being the objective to compare design criteria, the initial design applied was the estimation method considered as conventional (CM) and then the Bailey criteria was applied, the results obtained with the Bailey method were called B.

Based on the original gradation three new gradation curves were designed varying the “Chosen Unit Weight” (CUW) of the coarse aggregate, using 50%, 55% and 60% of the CUW and they were called **MB 50, MB 55, MB 60.**

Optimum asphalt content determination in a conventional mix **CM** was done by Marshall design methodology and it was kept constant for three mixes, **MB 50, MB 55, MB 60** (part 3.1.4)**.**

Rutting resistance assessment method was done with an European Community standard test: the Wheel Tracking Test (WTT) UNE 12697-22, Bituminous mixtures - Test Methods for hot mix Asphalt - Part 22 (part 3.2). [4]

3.1. Aggregate characterization

Table N°1 shows the obtained results in the aggregate characterization process. The reference standard is the IRAM. When VN appears it means the reference standard is from the Argentine National Road Department – Dirección Nacional de Vialidad de Argentina.

Table Nº 1. Aggregate characterization

HMA - D20 AGGREGATES			
Aggregate type	**6:20**	**0:6**	**Lime**
G_{bs} (Kg/m^3) (IRAM 1533)	**2.835**	**2.769**	**2.480**
UW_{Loose} (kg/m^3) (IRAM 1548)	**1647**	-	-
UW_{Rodded} (kg/m^3) (IRAM 1548)	**1771**	**1636**	-
Índices de Lajas (%) (IRAM 1687)	**20**	-	-
Flakiness index (%) (IRAM 1687)	**24**	-	-
Los Angeles abrasion test (%) (IRAM 1532)	**15**	-	-
Plasticity, fine fraction (VN - E2 - 65)	-	**No plastic**	-
Adhered dust (ml) (VN - E68 - 75)	**1.1**	-	-

3.2. Binder characterization

Table N°2 shows viscosity values of the used asphalt binder, according to IRAM 6835 [6], and mixing and compaction temperatures obtained through the viscosity profile. These temperatures express the value in °C in which aggregates and binder can be mixed and at which the asphalt cement has a viscosity of 1.8 to 2.8 Pa*sec.

Pfeifer penetration index express the relation between penetration and softening point recorded in the asphalt binder control.

The values of the ratio between the complex modulus and the phase angle express the aptitude or not of the asphalt to form a plastic deformation resistance mix. In this case, since the values are higher to 1 and 2,2 KPa, the standard parameters are achieved.

Table Nº 2. Binder characterization

VISCOSITY CLASSIFICATION (rotational viscosimeter)		
At 60 °C (dPa*seg)	**3070**	**AC - 30**
At 135 °C (mPa*seg)	**570**	
Compaction and mixing temperatures		
Compaction temperature (°C)		**150**
Mixing temperature (°C)		**160**
Pfeifer Index		
- 0,9		
G*/sen δ, DSR		
Virgin binder (KPa)		**1,3**
Aged binder (KPa)		**2,5**

3.3. Aggregate dosification using the two methodology

Table Nº 3 shows the limit curves for an asphalt concrete, normally called HMAC – D20

Table N°3 Limit curves

	% passing							
SIEVE (mm)	**25**	**19**	**9,5**	**4,75**	**2,36**	**0,60**	**0,30**	**,075**
UPPER LIMIT	**100**	**83**	**60**	**45**	**33**	**17**	**12**	**5**
LOWER LIMIT	**-**	**100**	**75**	**60**	**47**	**29**	**21**	**8**

Table N°4 shows the aggregate proportions considering the following criteria:

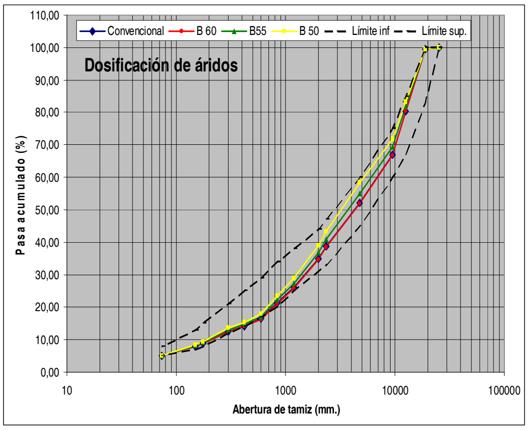
- Each aggregate contribution for the total aggregate curve corresponds to the conventional mix (CM).
- Using the control sieve methodology the Bailey curves were designed considering to obtain a copy of the conventional design curve so as to have a comparison parameter.
- Then the first curve was the **MB 60** (chosen unit weight 60% of the loose unit weight), this **MC and MB 60** curves match all sieves except in the higher sieve sizes where there is a little difference (+/- 0.2).
- The other Bailey curves were designed with 50% and 55%, and called MB 50 and MB 55, the choice of those unit weight is limited by the Asphalt Permanent Commission General Technical Specifications, used in Argentina, see Table N° 4.

Table Nº 4. Aggregate dosification
Conventional "C" and Bailey "B"

Aggregate Fractions				
Aggregate fraction	**C**	**Bailey mixes**		
		B 60	**B 55**	**B 50**
6:20 (%)	**46.4**	**46.7**	**43.3**	**39.8**
0:6 (%)	**52.6**	**52.3**	**56.0**	**59.8**
Cal (%)	**1**	**1.0**	**0.7**	**0.4**

- For these steps a calculation sheet was made allowing to do the adjustment of the fine proportion and to obtain a break point in the control sieves. Because the length of these operations they cannot be included in this work, but with the bibliography and the Bailey method the same operations can be arrived at.

The limit curves according to the APCGTS, the **MC, MB50, MB55** and **MB60 curves,** can be seen in the following Graphic N°1[7].



Graphic N° 1. Resulting curves

4. Mechanical and volumetric assessment of the mixes

Once the optimum combination of the aggregate blend was achieved, the optimum binder content was determined.

First of all the optimum binder content of the conventional mix, called CM, was determined. Five different mixes with growing asphalt content were designed, modifying in a similar proportion the aggregates so as to keep constant the aggregate dosification curve. The optimum asphalt content adopted was 4.3%; the verification can be seen in Table N°5 and N°6.

MB 50, MB 55 and **MB 60** mixes were designed with the same asphalt content in order to have just the chosen unit weight as the only variable. This can be seen in Table N°7.

Another design considerations that must be addressed are: mineral filler weight versus asphalt weight; volumetric concentration (V_c) and critical filler concentration (CFC) , this can be seen in Table N°7.

The test for the Vc/CFC ratio was done fir the conventional mix given that corresponds to the higher filler proportion among the mixes.

Table Nº 5. Volumetric analysis of the Marshall method molded samples

Optimum asphalt content verification				
Parameters	CM	Bailey mixes		
		MB 60	MB 55	MB 50
D_{Rice} (g/cm^3)	2.552	2.573	2.567	2.543
$D_{Marshall}$(g/cm^3)	2.430	2.467	2.443	2.422
V (%)	4.7	4.1	4.4	4.8
VAM (%)	15	14.7	14.9	15.2
VFA (%)	69.7	72.2	70.5	68.5

Table Nº 6. Mechanical analysis of the mixes

Optimum asphalt content verification				
Parameters	MC	Bailey mixes		
		MB 60	MB55	MB 50
S (kg)	1099	1340	1241	1181
F (mm)	3.5	4.3	4.1	3.3
S/F (kg/cm)	3140	3116	3027	3597

Table Nº 7. Final mixes dosification considering the asphalt %

Composing fractions of each mix				
Fraction	MC	Bailey mixes		
		MB 60	MB 55	MB 50
6:20 (%)	**44.50**	**44.70**	**41.40**	**38.1**
0:6 (%)	**50.30**	**50.00**	**53.60**	**57.2**
Lime (%)	**1.00**	**1.00**	**0.7**	**0.4**
Asphalt (%)	**4.30**			
Filler (5%) /asphalt 0.8 < f/a < 1.3	1.1			
V_C	0.299	accomplished		
CFC	0.315			
CFC/V_C < 1	0.950			

In photograph N°1 it can be seen the different mixes elaboration in a heated bath.

Photograph N° 1. Asphalt mixes elaboration

5. Permanent plastic deformations assessment

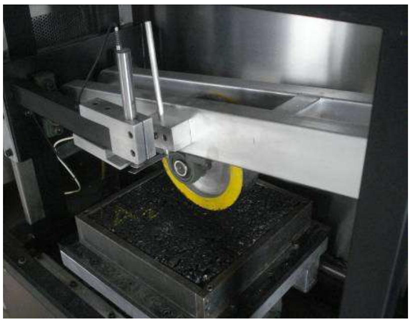
Permanent plastic deformations in an asphalt concrete layer are primarily caused by displacement with constant volume (plastic flow), a volumetric reduction of the asphalt mix composing materials or by shear stress deformations produced by the traffic loads. As told, this occurs for high surface road temperatures and low traffic frequency. In the model used in Argentina, based on the European standard - Test methods for hot mix asphalt - Part 22: Wheel tracking test- where the mix is submitted to 60°C and a load application frequency of 26.5 cycles per minute with 10,000 cycles in total. This represents the road behavior in front of high temperatures and dynamic loads. This test gives potential failure criteria when the proportional rut depth (PRD air) and the wheel tracking slope (WTS air) are high. This can be seen in Table N°8, the results are from the media from two samples according to mentioned standard.

The wheel tracking slope "WTS air" represents the evolution of rut depth in the contact zone, where a high value indicates deformation susceptibility; the proportional rut depth represents the rut depth based on the sample thickness. Both parameters are calculated from the table in Graphic N°2. It represents the deformation cycles; each point is a media between 25 points in the central 100mm of the wheel path with a 26.5 cycles per minute frequency. The test equipment can be seen in photograph N°2. The tested samples can be seen in photograph N°3. The Ic value represents the media compaction coefficient in each case [5].

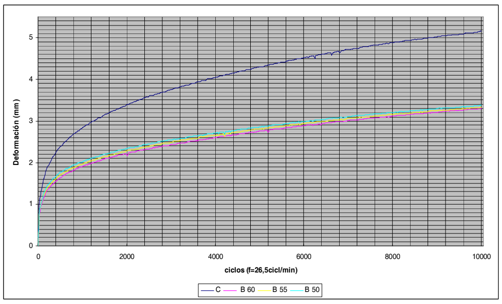
ISSN N° 0719-0514

Table Nº 8. WTT parameters

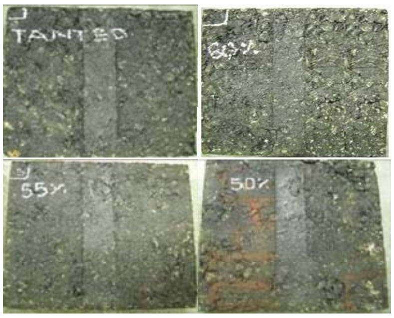
BS EN 12697-22, Bituminous mixtures - Test methods for hot mix asphalt - Part 22: Wheel tracking test.				
Sample Nº	Ic (%)	RD_{AIR} (mm)	PRD_{AIR} (%)	WTS_{AIR} (mm/10^3 cycles)
MC	98.6	5.2	10.3	0.170
MB 60	97.4	3.3	6.6	0.108
MB 55	97.3	3.3	6.7	0.104
MB 50	98.0	3.4	6.8	0.104



Photograph Nº 2. WTT equipment



Graphic Nº 2. WTT curves for each mix



Photograph Nº3. WTT samples for each tested mix

6. Result analysis

From the tests made the following analysis can be done:

- Granular curve elaboration considering sieve control can be adjusted without any previous experience regarding proportions.
- Comparing with an effective design that was done for approximation in the dense graded mixes, 60% of the unit weight seems to be the percentage that better adjust to the previous method curve.
- The better aggregate interlocking and higher contact between the particles proposed by the Bailey methodology can be seen in the volumetric parameters: D_{Rice}, V, $D_{Marshall}$, VAM and **MB 60** stability compared with **MC** keeping S/F relation constant.
- When the coarse aggregate chosen unit weight decreases (**60** %,**55** % and **50** %), and given that the asphalt content is the same, the aggregate interlocking increases because of the voids raise, stability parameter decrease, and Rice density and compacted density decrease.
- The **MB 60** mix rut depth **RD** (3,3 mm) was lower than the MC mix **RD** (5.2 mm) in a 35% approximately.
- The MB 60 Bailey method proportional rut depth was lower, in a 36%, than the MC conventional mix.
- The PRD and WTS results in the Bailey mixes (**MB 60, MB 55** y **MB 50**) did not represent significant differences among them.

7. Conclusions

* The Bailey method proved to be an adequate strategy for the granular design of asphalt mixes. In the special case of the dense mixes tested in this work a 60% of the loose unit weight seems to give granular stability, concavity and continuity to the curve and an optimum dosification according to the studied parameters.

- In the case of an inexperienced designer, the Bailey method presents a starting point for the first mix design.
- The control points become helpful tools to define the curve concavity according to the specifications range.
- The mechanical and volumetric values from the Marshall test are optimized with the chosen unit weight.
- The methodology has allowed to reduce the designed mix rut given the granular curve path.

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