

Evaluation of Marshall stiffness, indirect tensile stress and resilient modulus in asphalt mixes with reclaimed asphalt pavement and copper slag

Evaluación de rigidez Marshall, tracción indirecta y módulo resiliente en mezclas asfálticas con RAP y escoria de cobre

A. Raposeiras ^{1*}, D. Movilla *, A. Vargas **, R. Bilbao *, C. Cifuentes *

* Universidad Austral de Chile, Valdivia. CHILE

** BITUMIX Austral, Puerto Montt. CHILE

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Abstract

Asphalt mixes with Reclaimed Asphalt Pavement (RAP) offer many advantages when reusing this material. But without the adequate treatment, these mixtures present durability problems due to the material's loss of properties over time. The use of copper slag can reduce these problems through its physical-chemical properties, such as highly angular characteristics, lime content in its composition and low silica content, while contributing with friction and strong adhesive characteristics. On the other hand, the amount of copper slag stockpiles and their associated lixiviation are also reduced. This work presents the results obtained in asphalt mixes with RAP percentages from 0 to 40%, combined with copper slag percentages ranging from 0 to 35%. Sixteen (16) combinations of materials were used to prepare Marshall specimens in order to carry out stability and flow tests, indirect tensile strength tests and resilient modulus by diametral compression. The use of copper slag improves the performance of asphalt mixes with RAP. With 15% copper slag amounts by mass, the stability and flow values are stabilized, thereby improving the Marshall stiffness index. The values for indirect tensile strength and resilient modulus with RAP percentages over 20% are also improved, especially in mixtures with high RAP percentage (40%). These results favor the use of RAP in applications that require more demanding parameters.

Keywords: Copper slag (CS), reclaimed asphalt pavement (RAP), copper smelting, asphalt mix, durability

Resumen

Las mezclas asfálticas con RAP (pavimento asfáltico reciclado) tienen muchas ventajas relacionadas a la reutilización de este material. Pero sin el adecuado tratamiento, estas mezclas tienen asociados problemas de durabilidad debido a la pérdida de propiedades que sufre este material con el paso del tiempo. La utilización de escorias de cobre puede ayudar a solventar parte de estos problemas gracias sus propiedades físicas-químicas, como la elevada angulosidad, el contenido de cal en su composición y su bajo contenido en sílice, aportando fricción y adhesividad elevada. A su vez, también se reduce el volumen de escorias de cobre acopiadas y la lixiviación asociada a éstas. Este trabajo muestra los resultados obtenidos en mezclas asfálticas con porcentajes de RAP de 0 a 40% combinados con porcentajes de escoria de cobre del 0 al 35%. Se realizaron 16 combinaciones de materiales con las que se elaboraron probetas Marshall para su análisis mediante ensayos de estabilidad y fluencia, tracción indirecta y módulo resiliente por compresión diametral. La utilización de escorias de cobre provoca una mejora en el comportamiento de mezclas asfálticas con RAP. Con cantidades de escorias de cobre del 15% en volumen, los valores de estabilidad y fluencia se estabilizan, mejorando el índice de rigidez Marshall. También se mejoran los valores de tracción indirecta y módulo resiliente para porcentajes de RAP mayores al 20%, especialmente en mezclas con porcentajes altos de RAP (40%). Estos resultados ayudan a potenciar la utilización de RAP en aplicaciones que requieran parámetros más exigentes.

Palabras clave: Escoria de cobre (EC), pavimento asfáltico reciclado (RAP), fundición de cobre, mezcla asfáltica, durabilidad

1. Introduction

Copper slag (CS) is a byproduct of copper smelting, which has been traditionally classified as a waste, thus creating stockpiles located near the smelting plants. Two to 2.5 tons of copper slag are generated per each ton of blister copper that is produced; therefore, it is estimated that, only in Chile, the total accumulation amounts to approximately 50 million ton (Sepúlveda, 2006; Sánchez et al., 2004). Copper slag is composed of heavy metals such as copper, lead, mercury, or sulfur dioxide, which are particularly present in the slag's finest materials, thus generating lixiviation problems associated to the toxicity of these metals. Copper slag has been used in a wide range of processes, for example, in the treatment of waters contaminated with phenol or in the construction industry due to its wear resistance, angular characteristics, high density and low water absorption, hereby

neutralizing the toxicity of the heavy metals. Likewise, it has been used as raw material in the manufacture of tiles, bricks, concrete (Goria and Jana, 2003; Havanagi et al., 2009; Nazer et al., 2010) and as a substitute of Portland cement (Sepúlveda, 2006; Havanagi et al., 2009).

Steel slag has been more frequently used than copper slag in the construction of flexible pavements, and it has yielded satisfactory results in its usage both in granular layers and asphalt layers. Due to the generation processes of copper and steel slags, similar mechanical properties are obtained for both materials; therefore, their performance in asphalt mixes is found to be similar. Some researchers have used copper slag as substitute of fine aggregates in the manufacture of asphalt mixes, presenting good results with 5% to 30% slag additions. However, certain researches show a wider range of variations among the stability results of these mixtures, since in some of them this property increases when adding the slag

¹ Corresponding author:

Universidad Austral de Chile, Instituto de Obras Civiles, Facultad de Ciencias de la Ingeniería, Valdivia, Chile.
E-mail: aitor.raposeiras@uach.cl



(Goria and Jana, 2003; Havanagi et al., 2009), while in others it decreases (Hossam and Khalifa, 2010).

On the other hand, the use of reclaimed asphalt pavement (RAP) in the production of new materials has economic advantages, besides reducing the environmental impact related to its accumulation and the use of other virgin raw materials; thus, it is currently a widely used alternative. The inclusion of RAP as an aggregate in asphalt mixes reduces the use of new raw materials (aggregates and asphalt cement) by recycling crushed stones and bitumen contained in the RAP, thus preventing this material from being deposited in the dumps (Querol and del Pozo, 2011).

There are previous studies dealing with the incorporation of RAP in the manufacture of both concrete and asphalt mixes. The results show that it cannot be used as a substitute of aggregates in concrete with structural purposes; nevertheless, asphalt mixes show results that are comparable to conventional mixes, provided that the used RAP percentage is lower than 20%, reducing in turn the mixture's permeability. If higher RAP amounts are included, the physical performance of the asphalt mix is modified, reducing the durability and final strength. (Avilés, 2002; Al-Qadi et al., 2012; Valdés et al., 2011; Peña et al., 2011). Al-Qadi et al. (2012), observed that the stiffness and indirect tensile strength increases when adding between 40 and 60% RAP, thereby increasing the values for stiffness and indirect tensile strength in these tests by 60 and 70%. Furthermore, the flow capacity of the mixes decreases between 20 and 50% as the RAP content increases, which generates less rutting failures but causes fatigue cracking at an earlier stage (Al-Qadi et al., 2012; Valdés et al., 2011; Peña et al., 2011).

These problems have been solved by using lower penetration bitumen or by incorporating rejuvenating additives of asphalt binder into the mixes, with the purpose of recuperating part of the binder's original rheological characteristics (Querol and del Pozo, 2011; Avilés, 2002; Al-Qadi et al., 2012; Peña et al., 2011). With 50% RAP incorporations, this has caused stiffness and indirect tensile strength to increase by 25 and 5% respectively, maintaining flow values similar to those of a traditional mix (Peña et al., 2011).

Despite the existing solutions for RAP incorporation in asphalt mixes, these are usually used in the pavement's lower layers, avoiding its usage as surface course (Avilés, 2002). This study proposes to make the most of the natural

advantages of the copper slag mentioned above, in order to improve the performance of asphalt mixes with high contents of RAP. This solution allows improving the performance of the mixes with RAP thanks to the friction and cohesive properties of the CS, which are provided by the angular characteristic of its particles and the lime content. On the other hand, it allows a safe use of the CS, since it neutralizes the toxicity of heavy metals through the particles asphalt film coating (Goria y Jana, 2003; Reyes y Rincón, 2013).

2. Methodology

2.1 Materials and types of asphalt mix

Since different densities were obtained for each material, aggregates of different asphalt mixes were proportioned by mass. Therefore, 16 percentage combinations were made by mass of aggregate (AG), CS and RAP in the mixes (Table 1), while the incorporation of asphalt cement (AC) was done in relation to the weight, as specified in the AASHTO T 245, including the binder contained in the RAP within this amount, which reduces the quantity of new binder to be added.

The incorporation percentage corresponds to 100% of the aggregates, but not to 100% of the specimen's volume, since the latter will depend on the AC percentage to be added to the mix.

AC should be added to the materials mentioned above, and incorporated in its optimal measure according to the procedures described later on. The procedure stipulated in the AASHTO T 245 was used to add the AC to the mix, where the manufacturing process for a Marshall specimen is indicated.

For manufacturing the asphalt mix, a semi-dense grading of type IV-A-12 was used, according to the Chilean Highway Manual Vol. 5 (Ministerio de Obras Públicas, 2012). This grading was selected because it is one of the most frequently used both in the wearing course and binder course. In order to make the most of the recuperated amount of byproducts (CS and RAP), a sieve analysis was made to these byproducts and then added to the mix, according to the percentage obtained for each sieve (Figure 1), and aggregates were then added to adjust the final grading to the center of the sieving range of the semi-dense mix.

Table 1. Proportioning by mass of aggregate in the mix

Group	Typology, Aggregate Combination (%AG - %RAP - %CS)			
	I	II	III	IV
A	100-0-0	85-0-15	75-0-25	65-0-35
B	80-20-0	65-20-15	55-20-25	45-20-35
C	70-30-0	55-30-15	45-30-25	35-30-35
D	60-40-0	45-40-15	35-40-25	25-40-35

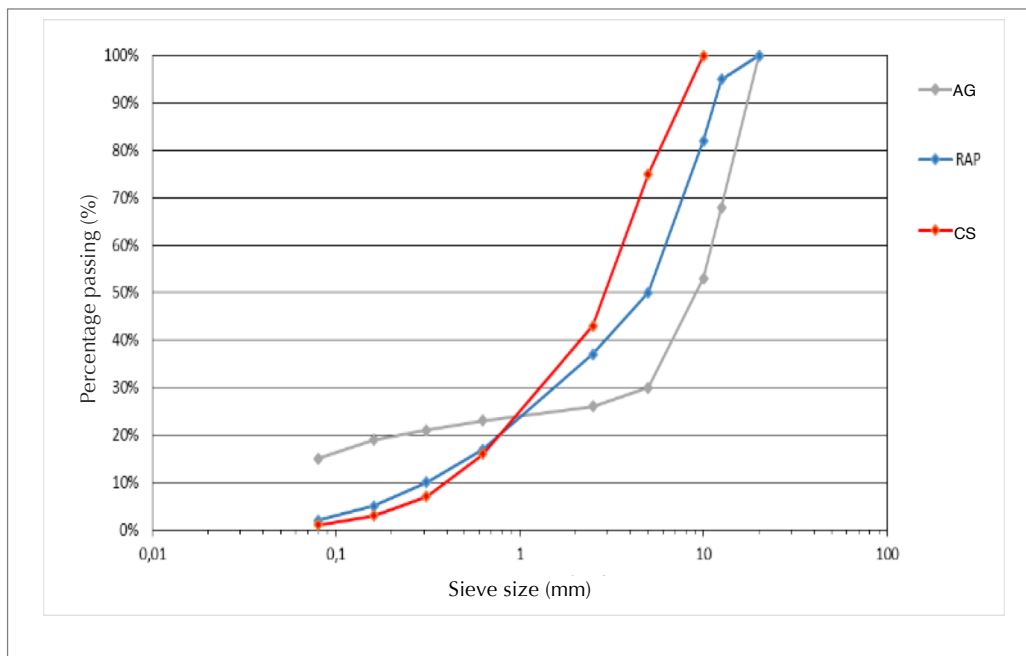


Figure 1. Materials grading

Several typologies can be differentiated among the mixes evaluated in this research, according to the type of aggregates used. The first one is composed of three types of aggregates (AG, RAP and CS). The second typology is composed of two types of aggregates (AG and RAP). A further typology includes AG and CS. And the last typology corresponds to the standard mix, which includes only AG. The first three typologies allowed evaluating the influence of CS on the mixtures with and without RAP, while the third typology allowed comparing the other typologies with a conventional mix.

A sample of some of these typologies can be appreciated in Figure 2, where the type of aggregate is illustrated, highlighting the CS share (greyish zones marked in red), which stands out for its darker color, compared with the rest of the stony aggregates. There are no major differences between the other two typologies of the picture, except that those containing RAP show small particles of fine material, which stayed together during the mixing process and did not mix with the new asphalt cement, thereby causing a certain segregation.

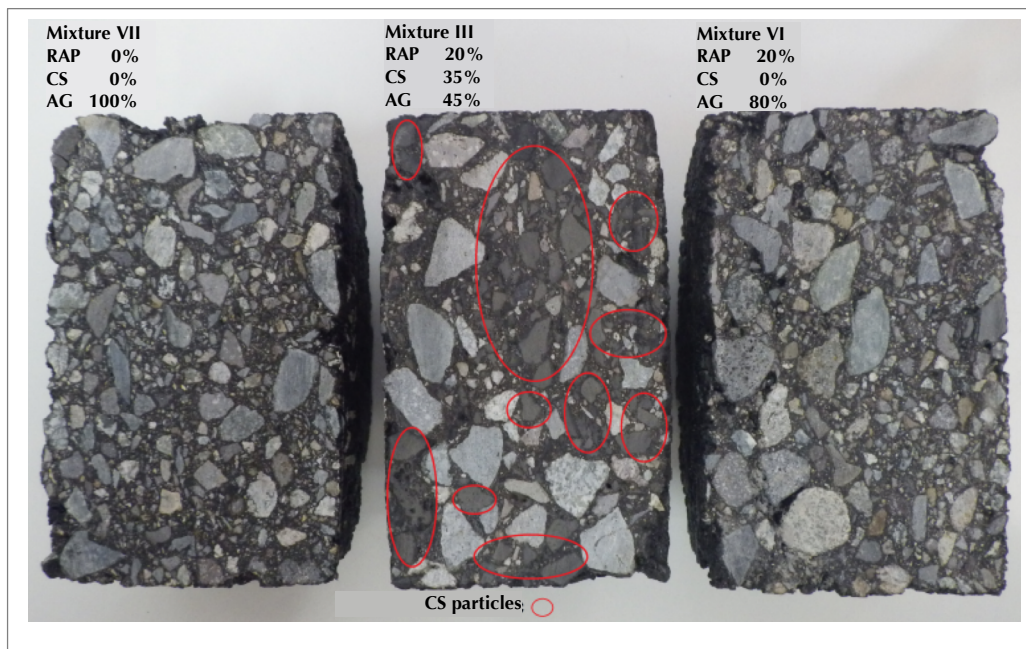


Figure 2. Test specimens with different mix typologies



2.2 Manufacturing, analysis and test processes

The standards AASHTO T 84 and AASHTO T 85 were used for the physical characterization of the aggregates and bitumen, and to determine the density and absorption of the fine and coarse aggregates respectively. The AASHTO T 96-99 was used to evaluate the wear; and the particles' cubicity was determined through the AASHTO M 283 procedure. The bitumen density was obtained with the AASHTO T 229-97 procedure.

In order to be able to compare different combinations of materials, the grading proportions were maintained. Both for RAP and CS, the original proportions of each material in its different sieves were used, while AG amounts were added in the proportions needed for each sieve, so that the final grading of the mix of the three materials could be adjusted to the center of the sieving range of the design grading band (type IV-A-12). Regarding the different combinations, the proportioning of materials was made by mass, due to the existing volume difference among the materials.

The Marshall design methodology, described in AASHTO T 245, was used for the manufacture of test specimens, considering also that the working temperature of RAP can be lower due to the bitumen already present in this material. In order to make the mixtures, the RAP was prepared separately from the rest of the materials to prevent overaging of the binder included in the RAP. Thus, the RAP was subjected to temperatures of 80, 90 and 100°C for the incorporations of 20, 30 and 40% RAP respectively, as in previous experiences when working with RAP in hot mixes, where the barrier of 100°C is established to avoid the accelerated loss of properties of the already aged binder (Alarcón, 2003). The RAP's warming temperature intervals are established according to the included percentage, so as to prevent a fast cooling of the mix during compacting due to this material's lower temperature. The other aggregates (AG and CS) were prepared at temperatures higher than the traditional ones, between 175 and 195°C, in order to reach a mixing and compacting temperature of 155°C, thus compensating the temperature decrease when the AG and CS are mixed with the RAP.

Mixing was done manually and compacting was done with a Marshall mechanical hammer, with 75 strokes per each face to achieve the optimal density percentage in the mix, as indicated in the standard for this type of mixes.

With the aim of establishing the optimal binder percentage, specimens with four addition percentages were made (4.5; 5.0; 5.5; 6.0), three identical specimens for each one, according to the Marshall procedure specified in the AASHTO T 245. The binder contribution in the RAP was included in each percentage, which was obtained through the ignition oven for different fractions of used RAP. Once the

optimal binder percentage was determined, eight specimens needed for each combination and the mechanical tests were manufactured according to the Marshall Method: four for the Marshall stability and flow tests and four for the resilient modulus by diametral compression and indirect tensile strength tests.

The Marshall stability and flow tests was carried out with the Marshall press at a deformation speed of 50 mm/min, according to the AASHTO T 245. In the indirect tensile strength test, the AASHTO T 283 was used, applying the compression at a deformation speed of 0.85 ± 0.02 mm/s; so, in this test, the Marshall press was also used with the adequate clamp to achieve the diametral compression.

The specimens for the Marshall test were immersed in a water bath at 60°C for 50 minutes, while the specimens for the indirect tensile strength test were kept at 25°C during 6 hours previous to the test. The specimens for the resilient modulus test were kept 24 hours at 15°C, according to the AASHTO T 294-921.

3. Results

The values for the physical characterization of the AG and RAP were within the usual range, with densities between 2.6 and 2.8 g/cm³, both for fine and coarse materials, water absorption was between 1.00 and 1.25% and wear was close to 15.5%. The CS presented densities values between 3.6 and 3.8 g/cm³, which are higher than those obtained for the other materials, due to the high iron oxide content. It also presented lower water absorption due to its crystalline structure, which reduces its porosity, and greater wear compared with the rest of the aggregates, because of the high proportion of edges, which also reflects the fact that 100% of the particles were grinded. Values comply with the specifications required for its usage as aggregates in asphalt mixtures, according to the Chilean Highway Manual, Volume 5 (Ministerio de Obras Públicas, 2012).

Afterwards, the optimal binder percentage was determined for the 16 combinations, therefore considering the amount of binder included in the RAP (Table 2). The Marshall design was followed and the density, stability and void content values were analyzed (Figures 3 and 4).

The CS incorporation increases the densities as the proportion of CS grows. This increase ranges from 3% to 16% compared with the specimens without CS.

The stability results show that the slag generates ranges of stability values that are less dispersed than in the mixes without this addition; this property is solely ascribable to the CS, which helps generating more stable mixes that are closer to a conventional mix (Figure 3).

Table 2. Optimal binder percentage by combinations

Group	Optimal Binder Percentage			
	I	II	III	IV
A	4.9	5.3	5.6	4.9
B	4.9	4.9	5.2	4.7
C	5.1	4.9	5.0	4.5
D	5.1	4.8	5.2	4.9

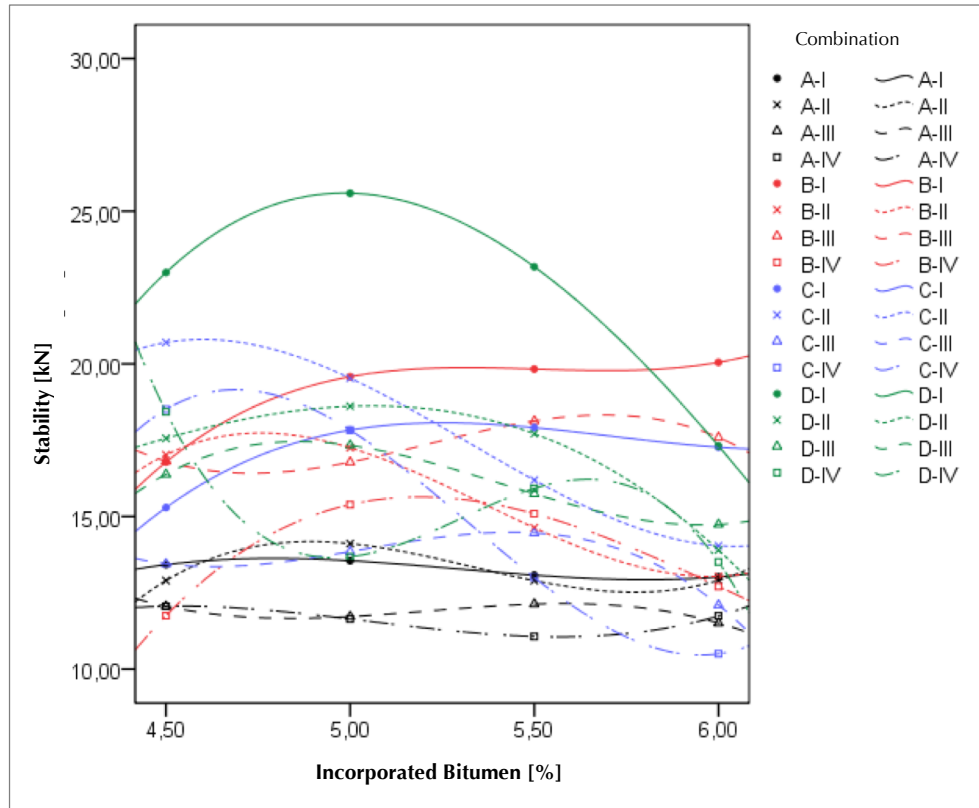


Figura 3. Stability vs. bitumen percentage

Regarding the void percentages (Figure 4), when comparing the mixes with RAP, it was possible to establish that in the specimens with added CS, lower void percentages were obtained in the mixes; which decreased more drastically with binder additions higher than 5%. It was observed that, in order to get a 5% void percentage, lower binder quantities were needed, partly due to the shape of the particles. Differences range from 25 to 40%, still under the reference values of the traditional mix. However, with a lower RAP content and a higher CS share, these differences reached only 9%, but still under the values of a traditional mix. These results keep the mixes with CS within the limit of the specifications regarding the minimum content of voids needed to be part of an asphalt mix.

Once the optimal bitumen percentage was determined, test specimens for the mechanical tests were manufactured. The Marshall stability and flow tests (Figures 5 and 6) and the Marshall stiffness index (Figure 7) show several trends. First, the CS incorporation reduces the stability values in the presence of high RAP percentages. This decrease varies between 15 and 35%. This performance becomes more evident when CS quantities are lower.

If the RAP percentages are lower (between 0 and 30%), the CS addition slightly increases the stability values, reaching around 15%, which are more evident in low CS amounts (Figure 5). Results show that any CS addition achieves values higher than 11.90 kN, obtained for the standard mix (0% RAP – 0% CS), and that the values for mixes with RAP are closer to the results of the standard mix.



These decreases are due to the low friction from the faces of the CS particles, which has a greater influence than the angular shape of the particles when exceeding 30°C. At this moment, the viscosity of the binder changes, showing a more

elastic performance. The presence of lime has also a certain influence on the CS fine material, increasing the adhesive bonding and reducing the stability loss in the mixes.

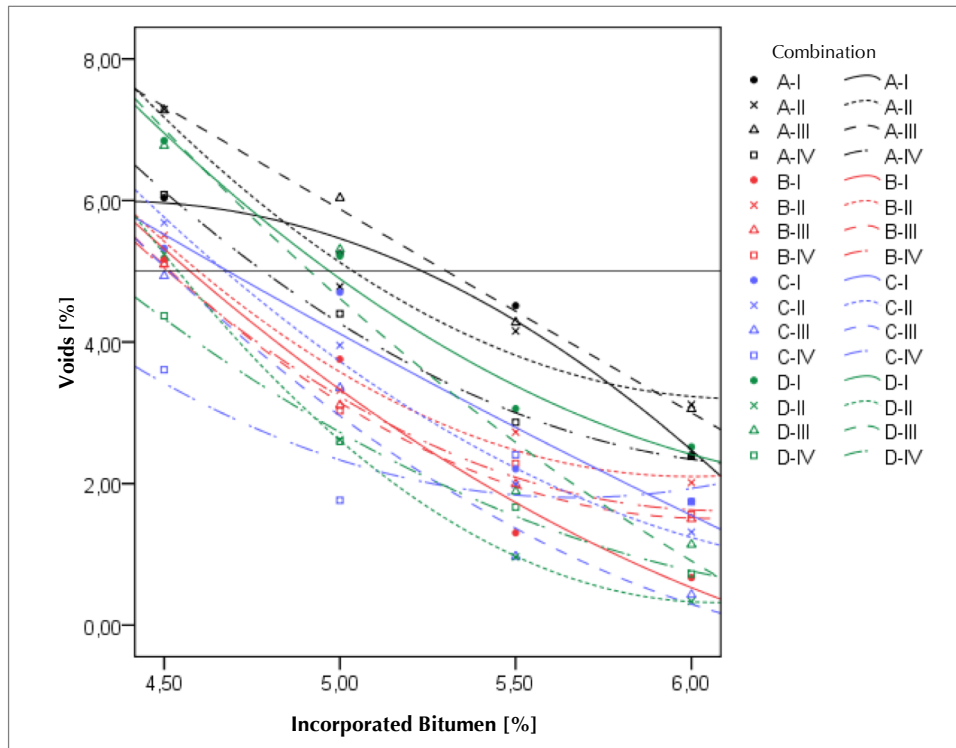


Figure 4. Percentage of voids in the mix vs. bitumen percentage

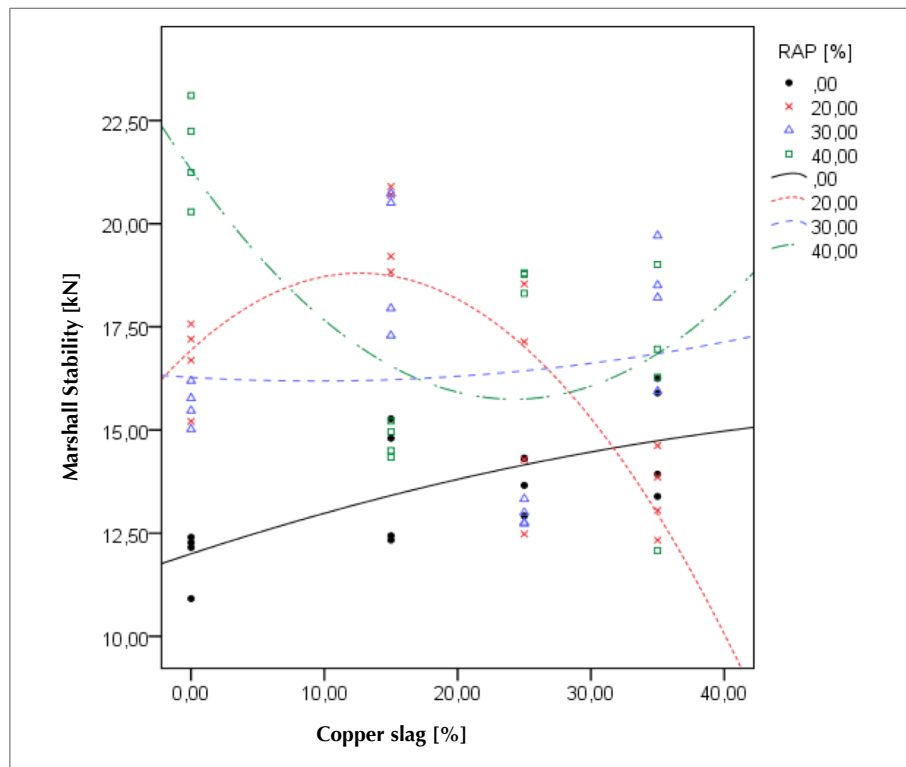


Figure 5. Stability vs. CS percentage

In turn, flow results show (Figure 6) that CS increases the values of this parameter, especially with lower RAP values (from 0 to 20%). The higher the amount of CS, the higher the flow values. For RAP values between 20 and 30%, the addition of 35% CS gets closer to the flow values obtained in the standard mix, around 3.0-3.5 mm, always within the specifications required for their use as wearing course. A good performance is also observed in mixes with 40% RAP and lowest CS addition (15%), since the flow is reduced and values are very close to those of the standard mix. These data show the bonding capacity of the lime content, which prevails in the CS fine particles and allow greater deformation before rupture occurs in excessively stiff mixes, and provide strength in mixes that are highly deformable.

In relation to the Marshall stiffness index (Figure 7), it was determined that the CS stands out for its adhesive property and friction capacity with the bitumen at maximum service temperatures, because it transforms the Marshall stiffness index of mixes with RAP into values very close to those obtained with the control mix, particularly when CS additions exceed 25%, generating difference ranges below 10%. It could also be observed that it enables the stabilization of the Marshall stiffness results at similar values, regardless of the RAP quantity, and approaches them to a traditional mix.

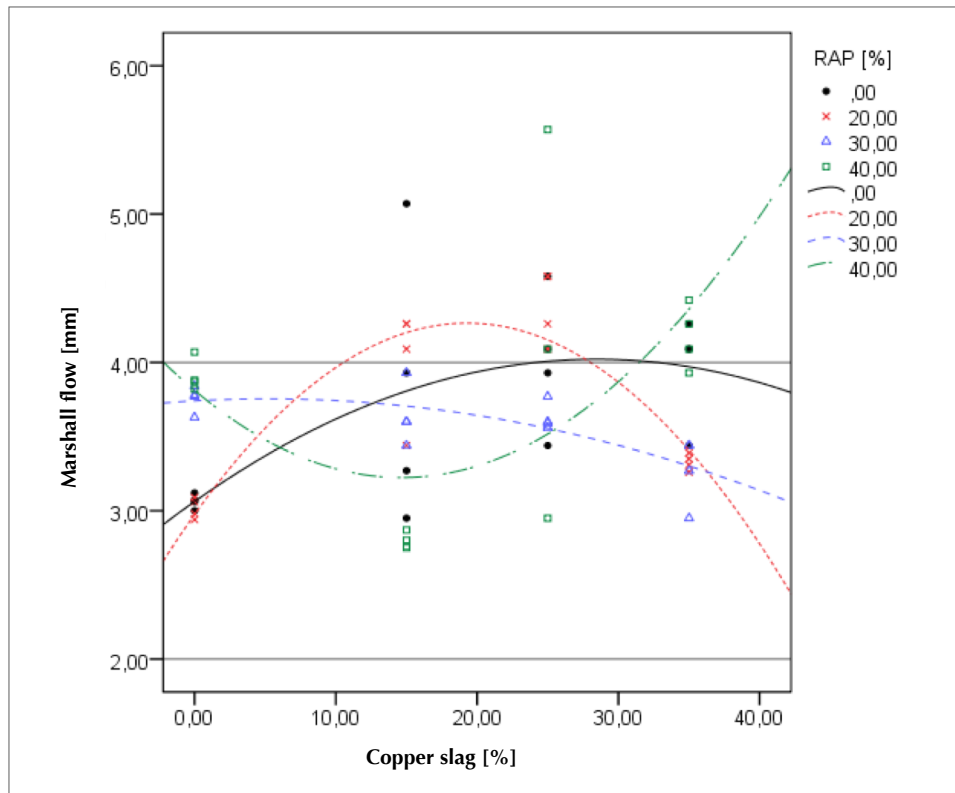


Figure 6. Flow vs. CS Percentage



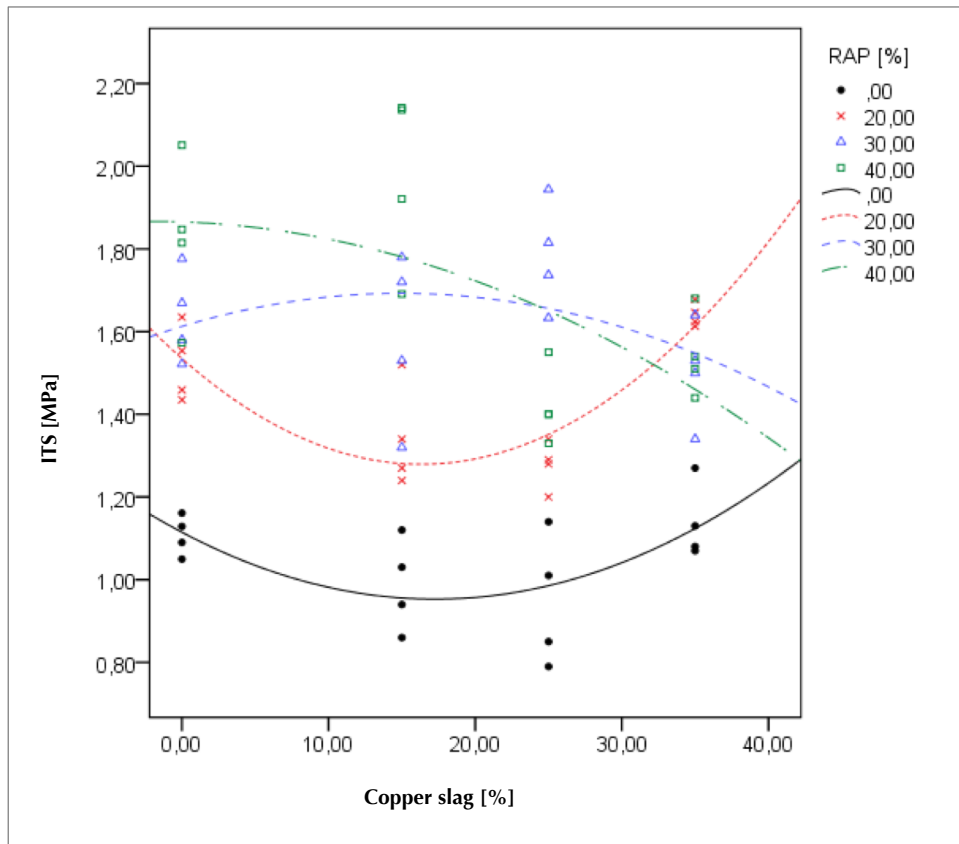


Figure 8. ITS vs. CS percentage

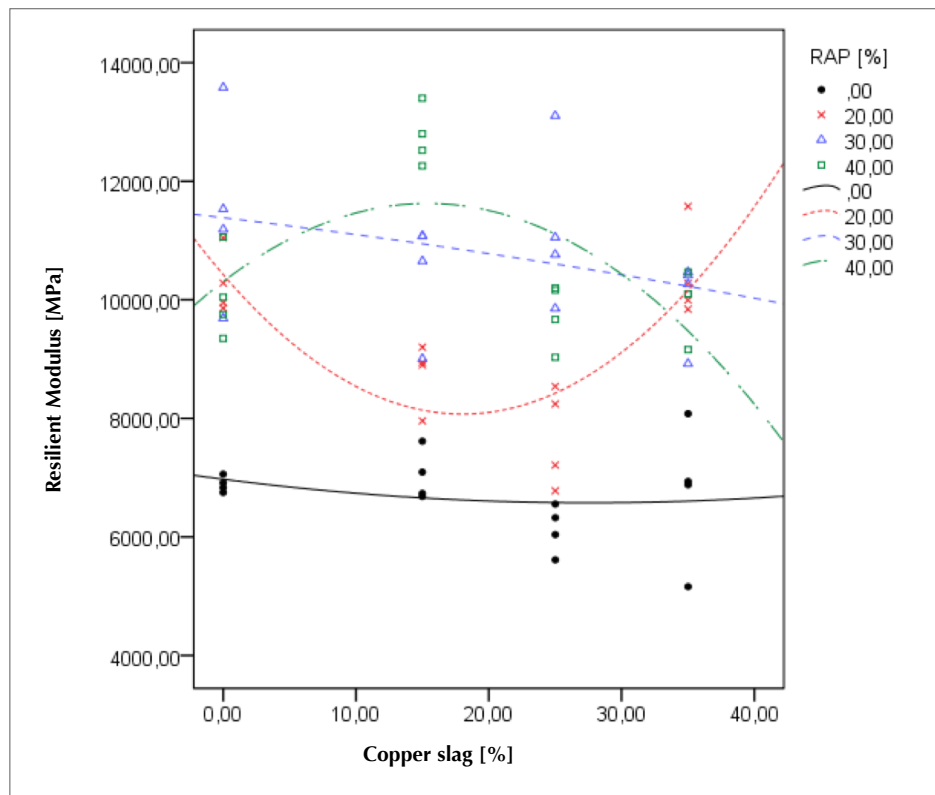


Figure 9. Resilient modulus vs. CS percentage



4. Conclusions

Several conclusions are derived from the effect caused by the CS addition in replacement of the AG aggregate in hot asphalt mixes containing RAP.

The presence of CS increases the density of the mixes around 16% due to the iron content included in its composition.

By incorporating CS, the stability of the mixes is reduced, which allows obtaining values close to those of the conventional mix. However, the indirect tensile strength was increased between 20 and 50%, depending on the combination of RAP and CS. This shows the influence of the test temperature on the performance of the CS with the asphalt cement, since both tests are made at different temperatures, where the stability test temperature is higher than that of the indirect tensile strength test.

At low temperatures, the mixes with CS make the most of the angular characteristic and cohesiveness of this material, thereby increasing the final strength. At high temperatures, these properties reduce their influence by stabilizing the strength loss through the bonding action provided by the lime component that is part of the CS fine material.

The CS addition has favorable effects on the flow of the mixes, which keeps the flow values within the limits allowed by the standard, and close to the traditional mix. With large RAP quantities, the optimal values are obtained for 15 and 25% CS, while with small RAP quantities, 35% RAP is recommended.

The incorporation of 15% CS in mixes with RAP amounts higher or equal to 30% improves the performance of these mixes, limiting the fluctuation in the values for stability, flow and stiffness.

The CS fine material, the binder and the test temperature are directly related, because at low temperatures the mastic stiffens, causing a loss of elasticity in the mixes. This effect is produced when the amount of CS+RAP exceeds 55%, emulating the performance of the mixes with RAP and without CS.

The CS improves the performance of asphalt mixes with RAP, considering that as the proportion of RAP increases, results improve by reducing the CS proportion, where the best results are obtained in combinations of 55% CS+RAP. Adding CS to the mixes with usual RAP percentages improves the flow and tensile strength performance of the mix with no need of including rejuvenating additives.

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