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Effect of copper slag addition on mechanical behavior of asphalt mixes containing reclaimed asphalt pavement

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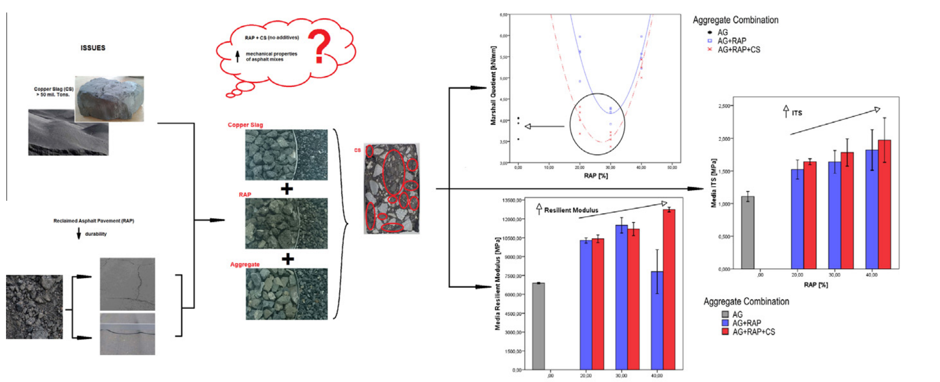
HIGHLIGHTS

- Marshall and ITS tests reveal the optimal percentage of copper slag to be used.
- The use of copper slag reduces asphalt mix rigidity with RAP.
- Asphalt mix with copper slag perform better at low rather than high temperatures.
- A stiffening effect of fine material appears when copper slag exceeds 15% addition.

GRAPHICAL ABSTRACT



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ABSTRACT

Annually, copper production and refining processes of generate large volumes of copper slag, and the disposal of this waste remains a major economic and environmental problem. This annual production causes an increase in the number and volume of landfills, as well as the quantity of slag that backs up landfills, it also produces leachates which contain metals such as Cu, Pb, Hg and SO_2. In this research, friction and cohesive qualities of copper slag are exploited, in order to incorporate this slag as aggregate in asphalt mixes containing Reclaimed Asphalt Pavement (RAP). Results demonstrate that the use of copper slag in an addition percentage of 35% is favorable, because flow values increase and stability values decrease. The Marshall Quotient is reduced up to 27%, improving the performance of mixes with RAP and obtaining behavior similar to a traditional mixture. This improvement is also reflected in an 8% increase in the indirect tensile strength, which stands the use of copper slag as a solution in RAP applications with more demanding tensile and fatigue requirements.

1. Introduction

Recovery and reuse of wastes and byproducts from industrial activities and construction sector has become very important in recent decades in reducing the use of raw materials for road construction. The use of crumb rubber [1], recycled concrete [2] or granite countertops manufacture wastes [3,4] have provided good results in hot mix asphalt, sometimes improving the results of a conventional mixture, and other limiting its use to low-traffic roads. However, the best results are generated with byproducts such as steel and thermal power plant slags [5], being able to replace the natural aggregates without reducing its mechanical properties and durability.

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Based on these experiences, copper slag is expected to have similar results. Copper slag (CS) is a byproduct of copper smelting, and from the beginning it has been classified as industrial waste, being placed around the smelting plants. About 2.2 tons of CS are produced for every ton of copper, which has led to large accumulations in Chile exceeding 50 million tons [6]. CS is considered an environmental liability, heavy metals included in the CS can generate leaching problems due to the high toxicity of metals such as Cu, Pb, Hg and SO_2, especially present in smaller size particles [7]. As an application to tackle the CS problem, this material has been used in the construction field, exploiting the properties of wear resistance, angularity, density and high hydrophilic property. CS in this regard is used as feedstock in the manufacture of tiles, bricks, concrete [8–12] and as a replacement for Portland cement [9,11–13].

When CS is used as an aggregate replacement in an asphalt mixture, the leaching that copper slag could generate is controlled, as each of the slag particles is coated by asphalt binder and sealed of all voids. Some projects with copper slag as a fine aggregate replacement in the manufacture of asphalt pavements have been developed, with successful results for additions ranging from 5% to 30%. However there is some inconsistency in the results of stability, as some research shows that addition of the slag increases stability [8,9], while in another study, stability was decreased [14]. This inconsistency can be attributed to temperature differences of the tests, as well as the size and percentage of the CS used.

On the other hand, the use of reclaimed asphalt pavement (RAP) in developing new materials is a technique increasingly relevant due to the economic advantages and environmental impact reduction [15,16].

Some researches have been conducted with high additions of RAP in asphalt mixes, and the results show a change in the physical behavior of the mixes, affecting both durability and structural performance [17–21]. Additions between 40 and 60% of RAP increased stiffness and indirect tensile strength from 60 to 70%, and the Marshall flow of mixes was reduced between 20 and 50% as the content of the RAP increases. All these changes generate pavements that are more resistant to rutting, but susceptible to the generation of fatigue cracking when no additives or modified binder are used [18–21].

To solve these inconveniences, softer penetration binder has been used and/or asphalt binder rejuvenating additives have been incorporated to the mixes, so that the initial rheological characteristics of binder can be partially recovered [15,17,18,21]. Such solutions have achieved a stiffness increase of 25%, but tensile strength values increased 5% when incorporating up to 50% of RAP, also achieving Marshall flow values equivalent to those of a traditional mixture [21].

The behavior of mixes including high RAP content can be improved through friction and cohesive properties of the copper slag provided by the angularity of their particles and their calcium content. Also, it allows for a safe use of these slags since the toxicity of heavy metals is neutralized with the asphalt film which covers them, being safe for the environment [8,22].

Table 1
Copper slag, RAP and aggregate combinations.

Combination	Volume dosage [%]		
	AG	RAP	CS
I	45	40	15
II	45	30	25
III	45	20	35
IV	60	40	–
V	70	30	–
VI	80	20	–
VII	100	–	–

2. Methodology

This study was conducted by fabricating 140 samples of 101.6 mm diameter and 63 mm nominal height, in seven different types of asphalt mixes with different percentages of copper slag (CS) and RAP (Table 1). Each type of mixture was evaluated by eight equal samples with optimal binder percentage.

2.1. Materials

The materials used in this research were: aggregate extracted from quarry (AG), reclaimed asphalt pavement (RAP), copper slag dump (CS) and AC-30 asphalt cement (AC-30) according to the classification of ASTM D3381/D3381M [23]. An IV-A-12 semi-dense mixture gradation curve (Fig. 1) has been used for the development of the samples [24].

AG and RAP were included in all sieve sizes of the gradation curve, while CS was only included in sieves between No. 4 to No. 100 as appropriate, incorporating the highest percentage of this material as aggregates with a particle size larger than 2.5 mm. This distribution maintains the common size and percentage of RAP in the asphalt mixture, substituting certain percentage of AG for CS.

Volume dosing of the aggregates for the different asphalt mixes was carried out, while the incorporation of AC-30 was performed by weight [25]. This binder dosage considered the percentage of binder included in RAP, in order to not exceed optimal binder dosage for the mixes.

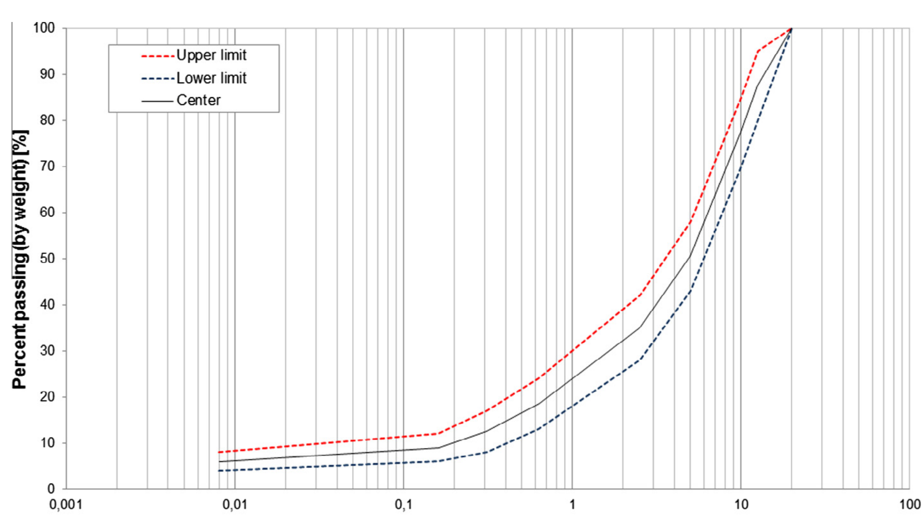

Fig. 1. IV-A-12 gradation curve.