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EFFECT OF RECYCLED ASPHALT (RAP) AND COPPER SLAG (CS) AS PARTIAL SUBSTITUTION OF NATURAL AGGREGATE IN ASPHALT MIXTURES

Jelena Đorđević[1a], Jelena Stefanović[1b], Sandra Guševac[1c], Nevena Marković[1d], Zoran Avramović[1e], Nikola Jovanović[1f], Nikola Lekić[1g]

[1] Mining and Metallurgy Institute Bor, Alberta Ajnštajna 1, 19210 Bor, Serbia
[1a] jelena.djordjevic@irmbor.co.rs, 0000-0001-5406-0074
[1b] jelena.stankovic@irmbor.co.rs, 0000-0001-6418-1814
[1c] filipovic@irmbor.co.rs, 0000-0002-6776-9899
[1d] nevena.markovic@irmbor.co.rs, 0009-0005-1278-8805
[1e] zoran.avramovic@irmbor.co.rs, 0009-0006-7585-976X
[1f] nikola.jovanovic@irmbor.co.rs, 0009-0008-0982-2576
[1g] nikola.lekic@irmbor.co.rs, 0009-0005-9399-9849

Abstract
The expansion of the road network requires the use of a large amount of natural resources. On the other hand, industrial development leads to the creation and deposition of a large amount of industrial waste. Large amounts of this waste accumulate in landfills close to the production process and represent a major environmental and economic problem, which can be solved by reusing industrial waste in the construction sector. Many researchers dealt with the topic of using copper slag as a partial replacement of natural aggregate in asphalt mixtures and as a result obtained favorable physical and mechanical characteristics of asphalt mixtures. One of the negative impacts of this alternative material is the high porosity of the slag, which required a higher amount of bitumen in the asphalt mixtures. However, this problem is solved by adding recycled asphalt (RAP-Recycled asphalt pavement) in the mixes.

***Keywords**: copper slag, recycled asphalt, asphalt mixture, environmental protection*

1. INTRODUCTION

Every year, more than 1.6 billion tons of asphalt are produced in the world [1], and there is information that between 260 and 300 million tons are produced in Europe [2]. According to the data of the Republic Institute of Statistics [3], in recent years, production in Serbia was about 2.4 million tons of asphalt, with the exception of 2020, when production was slightly lower due to the COVID-19 pandemic.

For the construction and maintenance of roads, solutions aimed at reducing the negative impact on the environment in terms of greenhouse gas emissions and energy consumption, as well as the preservation of natural resources through the maximum use of recycled and alternative materials with the condition of maintaining the durability and satisfactory characteristics of the facilities during exploitation, are increasingly being applied. In this sense, copper slag, as well as scraped asphalt in asphalt mixes, is particularly important.

Copper slag is a by-product of copper smelting. This material has a high content of copper and precious metals, but is traditionally classified as waste that is disposed of in landfills near the production process.

The annual average of copper production in the world in the last 10 years is close to 19 million tons of copper, where from each ton of copper between 2 and 2.5 tons of copper slag is generated, which represents a significant amount of material in landfills. [4] The International Copper Study Group [5] has published statistical data on copper production in the period between 1900 and 2023, where one can see the successive growth of production both on a global level and on individual continents. Since 1960, when world production was less than 500,000 tons of copper, world

production in copper mines has grown by 3.14% peryear and will reach 22.4 million tons in 2023. [5]

Copper production capacity is estimated to reach 32.4 million tons by 2028. [5], which indicates the need to dispose of copper slag as waste generated in the copper production process and the possibility of using this alternative material for industrial purposes as a partial or complete replacement of natural raw materials. This would solve the problem of depositing copper slag, and on the other hand, it would save natural resources.

An alternative material successfully used in many countries for road construction is scraped asphalt (RAP). The use of this material affects the lower consumption of natural resources, the reduction of asphalt mixture production costs, as well as the reduction of negative impacts on the environment.

2. USE OF RECYCLED ASPHALT (RAP) AND COPPER SLAG (CS) AS PARTIAL REPLACEMENT OF NATURAL AGGREGATE IN ASPHALT MIXTURES

RAP is very successfully used in asphalt mixtures, and the amount of use is affected by the binder, which is an integral part of this material and which has lost its initial rheological characteristics. Studies of asphalt mixtures with high RAP content have shown changes in the physical behavior of the mixture, which affects durability. The percentage content of RAP in the mixtures between 40-60% affects the increase of stiffness and strength in indirect tension from 60% to 70%, while the Marshall flow decreases from 20% to 50%. Changes in these characteristics of asphalt mixtures affect the improvement of pavement resistance to rutting, but also the greater susceptibility to the formation of cracks due to fatigue and thermal effects. [4] The use of RAP in asphalt mixtures with copper slag can have a beneficial effect and reduce the negative impact of slag in terms of the need for a larger amount of bitumen, which is a consequence of the higher porosity of the slag. Adding RAP can replace bitumen, which additionally requires slag.

In order to solve the negative effects of RAP in asphalt mixtures, it is necessary to use a softer binder and/or add bitumen rejuvenation additives to the mixtures, in order to reactivate the aged binder in the RAP. In this way, the increase in stiffness and strength during indirect tensioning would be limited.

A.C. Raposeiras and other authors [4] investigated the physico-chemical and mechanical characteristics of asphalt mixtures with RAP and replacement of natural aggregate with copper slag.

The research work of this group of authors [4] was related to the examination of Marshall stiffness, indirect tensile strength and stiffness modulus of asphalt mixtures with different contents of copper slag, RAP and natural aggregate (table 1), in order to determine the mechanical characteristics of the mixtures.

Marshall stability results for all mix combinations showed that for mixes containing only natural aggregate and RAP, Marshall stability values increased from 40% to 80% with increasing RAP content in the mixes. However, when adding CS, variable results were obtained for Marshall stability. In mixtures without RAP, CS affects the increase of the resistance of the mixture, which is a consequence of the greater stiffness of the mixture, the shape of the grains of CS and good adhesion with the binder. In mixes containing both alternative materials, RAP and CS, there is a compensating increase in stability. If the asphalt mixture contains 20% RAP, the highest values of Marshall stability were obtained with the addition of 15% CS in the mixture, and if the content of copper slag increases to 35%, the stability of the mentioned mixture is close to the stability of the conventional mixture. For a RAP percentage of 30% in asphalt mixtures, 25% copper slag is required to achieve stability similar to conventional mixtures. Based on the mentioned test results, it can be concluded that in asphalt mixtures CS controls the Marshall stability, and with the

addition of RAP the growth of stability can be controlled and lead to similar values that occur in conventional mixtures. As an explanation of these results, the fact that CS is affected by the aged binder from RAP, which is not adequately activated, and thus the workability of that binder is poor and the coating of CS grains is irregular, which affects the reduction of the resistance of the mixture. [4]

Table 1. Percentage participation of alternative materials in asphalt mixtures for mechanical analysis

Percentage content of material			
Asphalt mixture	**RAP (%)**	**Copper slag (%)**	**Natural aggregate (%)**
M1	-	-	100
M2	20	25	55
M3	30	15	55
M4	40	35	25
M5	20	15	65
M6	30	35	35
M7	40	25	35
M8	-	15	85
M9	-	25	75
M10	-	35	65
M11	40	15	45
M12	30	25	45
M13	20	35	45
M14	40	-	60
M15	30	-	70
M16	20	-	80

Flow results also vary depending on the ratio of participation of alternative materials in asphalt mixtures. Mixtures containing RAP without the participation of copper slag record an increase in deformations proportional to the increase in the participation of RAP in the mixtures. Also, mixtures containing only CS from alternative materials have an increase in Marshall flow, which the authors explain by the fact that copper slag has hydrophobic properties and as such does not absorb the binder as a natural aggregate, but the binder only sticks to the surface of the slag grains, which causes deformation of the binder before the mixture cracks. Combining RAP and CS stabilizes deformations, i.e. flow in the mixture. A content of 20% of RAP requires the participation of 35% of CS to obtain yield values similar to those of the conventional mixture, while a content of 40% of RAP in the mixture requires 15% of CS to stabilize deformations. The increase in deformation occurs due to the decrease in the amount of binder needed to bind the aggregates in the mixture, which leads to greater freedom of movement of the aggregate grains. CS affects the reduction of deformations due to the shape of the grains, which enables a good packing of the aggregates.

The results of indirect tensile strength and stiffness modulus in asphalt mixtures with RAP and CS change according to the same principle as stability and Marshall flow parameters. The presence of RAP in the mixtures increases the indirect tensile strength, while the addition of CS controls the large growth of this parameter.

Mohi ud din, Ishfaq and Mir, Mohammad studied the behavior of hot process asphalt mixtures with recycled asphalt and copper slag as partial replacement of natural materials. [6]

The authors had interesting observations related to surface permanent deformation - ruts. The most common causes of rutting are: low content of air-filled voids, high amount of binder in asphalt mixtures, excess sand or mineral filler and rounded aggregate grains. Analyzing mixtures with RAP and CS, the authors stated that asphalt mixtures containing RAP in percentages between 40% and 60% have increased stiffness and reduced Marshall flow. These mixes have shown favorable

results in terms of resistance to permanent deformation, but are prone to fatigue and thermal cracking. This problem was solved by adding rejuvenators to the mixtures, which improved the rheological properties of the bitumen to some extent. Mixes with 50% RAP and 20% CS showed a 25% increase in stiffness and reached Marshall yield values close to those of the conventional mix. These results can be explained by the angular shape of the CS grains, which leads to an increase in internal friction, which further results in a higher resistance to rutting. [6]

The resistance of asphalt mixtures to the action of water is an important characteristic for the durability of pavements. The sensitivity of asphalt mixtures to the action of water is a complex phenomenon and serious experimental work is necessary to understand the behavior of CS under the action of water. However, the test results of many researchers show that asphalt mixtures containing CS have a higher resistance to the harmful effects of water, which is a consequence of the good adhesion of CS grains with bitumen. Although CS is more hydrophilic than limestone aggregates, the strong bond formed between CS and bitumen prevents water from reaching its surface. On the other hand, limestone aggregate containing a higher ratio of CaO/SiO_2 has a strong bond with the asphalt binder, but this same ratio of chemical compounds contributes to the leaching of the binder from the aggregate grains, which again leads to the conclusion that CS as an aggregate has a better resistance to the action of water. [6]

Good adhesion of CS grains and bitumen was achieved due to the rough surface texture of the slag grains, a large number of pores, cavities and unevenness. On the other hand, good adhesion requires a larger amount of bitumen, which the RAP content can replace if the rheological properties of the aged binder are activated with additives.

3. CONCLUSION

Tests of asphalt mixtures containing RAP and CS as a partial replacement of natural aggregates showed better results than conventional mixtures, if the appropriate measure of the content of these alternative materials was determined.

The general conclusion is that based on the available data from various research works in the world, RAP and CS can be used in road construction, as a partial replacement of natural aggregates. As there are landfills with a large amount of CS in our country, it should be investigated whether this alternative material in combination with RAP can be used in the construction industry in our country, which has already been investigated to a certain extent.

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