# Investigation of Rutting Performance of WMA Mixtures Containing Copper Slag

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**Abstract:**
Copper slag (CS) is an abrasive blasting grit made of granulated slag from metal smelting processes. As copper slags are known to be waste material and cause a lot of environmental problems, it would be a good idea to use them in different sections of industry such as pavement construction. On the other hand, in order to save energy and reduce the amount of pollutants released during the construction of asphalt pavements, the technology of Warm Mix Asphalt (WMA) is developing considerably. A very high amount of copper slag is produced in south of Iran where the weather is considered to be hot and rutting is the most important distress of asphalt concretes. This paper presents the influence of utilization of copper slag as fine material on the rutting performance of warm mixed asphalt. A laboratory study has been conducted on five asphalt mixtures with various CS contents, namely; 0%, 10%, 20%, 30% and 40% by weight of total aggregates. The amount of optimum bitumen and the value of Marshall Stability (MS) were determined with MS test for the samples. Then creep test and wheel track tests were conducted on the produced samples. The results indicated that the use of 20% CS in WMA enhances the marshal stability and rutting performance of WMA mixtures. However, the resistance of mixtures against rutting falls substantially by adding more than 20% CS.

**Keywords:** Copper slag, warm mix asphalt, by-products in asphalt mixtures, moisture sensitivity, creep test

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## 1. Introduction

In the last few decades, a lot of problems have occurred to the environment due to a large amount of waste materials produced by industrial sector. Many companies produce waste materials and by-products in addition to their main product such as acids, alkaline, oils, scrap metal, slag, fly ash, scrap rubber, stone pieces, powders, etc [Fadhil et al. 2013]. Therefore, the main goal of environmental protection agencies and governments is to find a safe way to dispose these by-products [Al-Jabri et al. 2006]. On the other hand, the amount of material which is at disposal for constructing roads and buildings are limited and the contractors must pay transportation costs to fetch qualified materials from quarries for their projects. Hence, industrial waste materials can be used as a secondary resource to satisfy the need for natural stone materials, which is needed for construction, reconstruction, and repairs of road pavements [Ameri , Hesami and Goli. 2013, Celauro, Bernardo and Gabriele, 2010]. Reusing waste materials in road construction not only saves energy and natural resources, but also reduces their impact and preserves the quality of environment [Chandra et al. 2002, Pasetto and Baldo, 2012a]. A large fraction of secondary and waste materials such as waste glass, steel slag, tire and plastics might have the potential to be used in road or building construction projects [Huang, Bird and Heidrich, 2007]. In addition to ingredients (bitumen and aggregates), the heat resources are required to process the paving materials, which has economic costs and adverse environmental effects [Chiu et al. 2008]. Drying and heating aggregates result in wasting a huge amount of energy and emitting gaseous pollutants. Therefore, scientists have developed a number of new technologies for asphalt pavement materials to reduce the mixing and compacting temperature such as warm and cold mix asphalts. These technologies need less energy and heating to produce asphalt mixtures and does not have many adverse effects on asphalt properties [Ameri et al., 2013]. In addition to what mentioned above, warm mix asphalt has some other advantages such as Paving benefits (Improved workability and compaction efficiency, provision of longer haul distances, and quicker turnover to traffic due to shorter cooling time), and Production benefits (Increased Recycled Asphalt Pavement (RAP) content and location of plant site in urban areas) [Ameri , Hesami and Goli. 2013]. Ideally, the performance of WMA should be at least the same as that of HMA, both structurally and functionally. In order to satisfy coating and workability requirements, WMA technologies need a reduction in the viscosity of the asphalt binder through the addition of organic or mineral additives, chemical emulsification or foaming using water. These processes allow for producing asphalt-aggregate mixtures at temperatures 17–55 lower than those in the production of traditional HMA [Hesami et al. 2013]. For this purpose, many binder additives have been introduced in order to compensate for less heating, such as Sasobit and Synthetic Zeolite [Jamshidi, Hamzah and You, 2013, Vaiana, Iuele and Gallelli, 2013, Menapace et al. 2014]. Sasobit is one of the best additives for producing warm mixed asphalt that not only reduces the viscosity of bitumen, but also increases the value of softening point, complex modulus, anti-rutting factor and reduces the value of the penetration and the phase angle; when the temperature is higher than 110 [Yi-qiu et al., 2012]. Copper slag is a by-product obtained during the matte smelting and refining of copper [Khanzadi and Behnood, 2009]. Copper slag contains materials such as iron, aluminum, calcium oxide, silica and others and was preliminary used to separate the metal and nonmetal constituents contained in the bulk ore [Hassan and Al-Jabri, 2010]. Producing every ton of copper generates approximately 2.2–3 tons of copper slag as by-product material. A substantial amount of copper slag is produced in the world each year. In the United States, the amount of copper sag produced is about four million tons, and in Japan, it is about two million tons per year. The production of approximately 360,000 and 244,000 tons of copper slag is reported in Iran and Brazil, respectively [Khanzadi and Behnood, 2009]. There are 3 alternatives to manage Copper slags.1- copper slag can be reused as raw material to recover copper and other metals. 2- Copper slag can be used as abrasive tools, roofing granules, cutting tools, abrasive, tiles, glass, road-base construction, railroad ballast, asphalt pavements and cement and concrete industries and 3- they can be dumped as disposal material in stockpiles near the company which produces them. However, the third alternative is not correct from environmental point of view [Khanzadi and Behnood, 2009] and one of the options is to utilize copper slag in road construction. Some researchers have investigated the possibility of effective utilization and also the application of copper slag in road construction as a novel aggregate. In 2013, Kumar investigated the Properties of pavement quality concrete and dry lean concrete containing copper slag as fine aggregate. Pavement quality concrete mixtures were prepared by replacing different percentages of copper slag in control mix. Workability and bleeding of green concrete, compressive strength, flexural strength at 7 and 28 days, drying shrinkage and abrasion resistance were measured for all mixtures. It was shown that using up to 40% of copper slag in lean concrete mixtures and pavement quality concrete does not have any negative impact on its properties [Kumar, 2013]. In 2007, Havanagi and his associates investigated the usage of CS and fly ash as aggregate in pavement layers such as base and sub-base. 25 to 75 percent of aggregates were replaced by copper slag and fly ash. They illustrated that using a combination of copper slag and fly ash as aggregate in pavement layers is practicable [Havanagi et al., 2007]. Al-Jabri et al investigated the use of copper slag as fine material in hot mix asphalt in 2010. Limestone aggregates were replaced by 0 to 40 percent of copper. Functional tests were performed on specimens to determine their dynamic modulus, compressive strength and resistance to moisture damage. The Marshall stability and dynamic modulus results indicated that the compressive strength declined by increasing the amount of copper slag in mixtures. However, master curves and shift factors, essential input parameters for Mechanistic-Empirical Pavement Design Guide (ME-PDG), were enhanced by replacing copper slag in mixes. Although adding copper slag had negative effect on indirect tensile strength of mixtures, the tensile strength rate (TSR) value emproved by replacing CS in the mixtures [Hassan and Al-Jabri, 2010]. In this research, the usability of copper slag in warm mixed asphalt concrete was investigated in order to bear the stresses occurring due to traffic loading. For this aim, five different asphalt mixtures were produced using CS in different proportions (10%, 20%, 30% and 40%) in order to conduct laboratory research. Mechanical testing used includes; Marshall properties, dynamic creep and wheel track tests.

## 2. Material and Methods

The main procedure of this study was divided into two steps. At first Marshall test were conducted for different percentages of copper slag in order to find the optimum bitumen content (OBC). According to ASTM D1559, the OBC were chosen based upon the maximum specific gravity, maximum marshal stability and 4% air void. After that, indirect tensile strength (ITS), resilient modulus and dynamic creep tests were conducted to obtain more information about warm mix asphalts containing copper slag as fine aggregate.

### 2.1 Basic Materials

#### 2.1.1 Aggregates

Crushed limestone was provided from quarries around Tello (located in north east of Tehran) which are mainly used for highway construction. In order to find out the properties of limestone aggregates, specific gravity (ASTM C127-07, ASTM C128-12), Los Angeles abrasion resistance test (ASTM C131-06) and water absorption test (ASTM C127-12) were conducted on limestone aggregates. The copper slag used in this study was obtained from Sarcheshmeh Copper Plant (located in Kerman, Iran). The physical properties of copper slag and limestone aggregates (LA) are shown in Table 1.

**Table 1. Physical properties of CS and LA aggregates**

| Physical properties | CS | LA |
|---|---|---|
| Specific gravity (fine agg.) | 3.57 | 2.61 |
| Water absorption | 1.3 | 0.7 |
| Specific gravity (coarse agg.) | - | 2.63 |
| Los Angeles abrasion (%) | 16.7 | 23.5 |
| Loose uncompacted void (%) | 58.31 | 45.63 |
| Coarse aggregate fracture (%) | 100 | 100 |

Aggregate grading curves for asphalt mixtures were obtained from Iran Highway Asphaltic Pavements Code. No.234 which is about AC for binder layer. The midline gradation of the aggregate used in the mix design is shown in Figure 1. It should be noted that this gradation is used for all of the mixtures, and Copper slag was used to replace the 0.75–4.75 mm size aggregate with percentages of 10, 20, 30, and 40%, by weight of total aggregates.

Aggregate angularity, which is influenced by the degree of roughness and sharp angles of the aggregate particles, was also investigated. To do so, fine aggregate angularity (FAA) of copper slag and lime stone aggregates are estimated by measuring the void content of loosely compacted fine aggregate samples in accordance with AASHTO T 304. The fracture percentage of coarse aggregates was also determined based on AASHTO T 335. The results are indicated in Table 1.

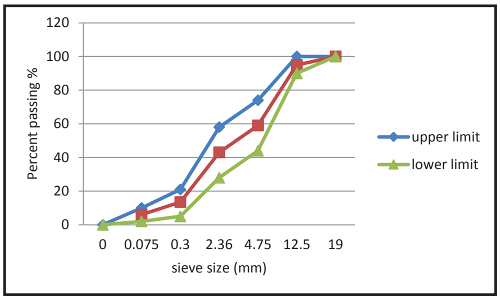


**Figure 1. Gradation of designed aggregates**

### 2.1.2 Bitumen

In this study standard AC 60/70 penetration bitumen was used for the laboratory production of specimens, the properties of the bitumen are presented in Table 2.

**Table 2. Properties of asphalt binder**

| test | Standard test | result |
|---|---|---|
| Viscosity Test at 135°C (cSt) | ASTM D2170 | 354 |
| Penetration Test (0.1 mm) | ASTM D5 | 61 |
| Ductility Test (cm) | ASTM D113 | 100 |
| Softening point (°C) | ASTM D36 | 48 |
| Flash point (°C) | ASTM D92 | 310 |
| Specific Gravity | ASTM D70 | 1.02 |

### 2.1.3 Binder Additive

Sasobit was taken as binder additive. Sasobit is a long chain aliphatic hydrocarbon (chain lengths of 40–115 carbon atoms) obtained from coal gasification using the Fischer–Tropsch process. The melting point of Sasobit is around 85–115º. Sasobit dissolves in binder homogeneously on stirring and reduces the binder's viscosity. Based on the available literature, dosage rates for organic additive ranged from 1.0% to 4.0% by weight of the bitumen [Yi-qiu et al., 2012]. Sasobit either can be blended with hot asphalt binder (no high-shear mixing required) or it can be blown directly in to the mixing chamber [Jamshidi et al., 2013]. Therefore, in this study 2% Sasobit were added to bitumen at the temperature of 120 and blended for 5 minutes.

### 2.2 Sample Preparation

75 specimens containing 0%, 10%, 20%, 30% and 40% CS were prepared for Marshall tests. For all of the five mix types, bitumen was added as 4%, 4.5%, 5%, 5.5%, 6% and 6.5% in order to find out the optimum bitumen content. For each percentage of bitumen, Marshall Specimens were made and tested according to ASTM D1559. The aggregates were heated to 135 for 24 hours and heated bitumen containing sasobit were added and mixed for up to 5 minutes. For compacting Marshall specimens, Marshall compacting machine were used for 75 cycles for each side of specimens in accordance with ASTM D1559. After the OBC had been found for each mixture, 30 specimens were prepared by Superpave Gyratory Compactor (SGC) in order to take creep and wheel track tests. The SGC uses a specially designed mold, which is rotated through 1.25 angle, to hold the loose asphalt mixture. This mold is rotated through a 1.25 angle by a jig. While the mold is being rotated at 30 gyrations/min, a 600kPa static load is placed on the specimen through the use of a ram. The SGC was adjusted to compact the mixtures until the air void of 4%. The mixing temperature was 135º, and the OBC of each mixture was used to prepare its corresponding specimen. All of the specimens compacted by Marshall hammer and gyratory compactor were produced in cylindrical molds that also had a diameter of 102 mm. The weight of total aggregates in specimens was 1200 g. The laboratory mixing temperature was 135 and the compaction temperature was 110.

## 2.3. Testing Program

### 2.3.1 Marshall Testing

The Marshall stability test is used in highway engineering for both mix design and evaluation. Although Marshall method is essentially empirical, it is useful in comparing mixtures under specific conditions [Ahmed et al., 2006, Pasetto and Baldo, 2012b, Asi, 2006]. Marshall stability and flow test was carried out on specimens with various bitumen contents and the optimum bitumen content was obtained according to ASTM D1559. Three specimens from each mixture were placed in a 60 water bath for 30-40 minutes, after submerging the specimens for the required amount of time, the specimens were immediately subjected under a loading rate of 51 mm per minute until occurrence of failure. The Bulk specific gravities and air void contents of specimens were measured in accordance with ASTM D2726.

### 2.3.2 Dynamic Creep Test

Rutting which is defined as the progressive accumulation of the permanent deformation in asphalt layers is one of the major distresses in asphalt pavements [Li et al., 2014, Pasetto and Baldo, 2014a, Pasetto and Baldo, 2014b, Abo-Qudais and Al-Shweily, 2007]. In order to measure the resistance of asphalt mixtures to permanent deformation, dynamic creep test is thought to be one of the best methods [Khodaii and Mehrara, 2009]. In this study creep and permanent deformation tests were conducted in accordance with Australian AS289-12-1, so that the specimens are subjected under a repeated pulse uniaxial stress and the deformation in the same direction of loading is measured by linear variable differential transducers (LVDT). As the rutting occurs mostly in high temperatures and under heavy loads [Qi-sen et al., 2009], the creep test was conducted at 50 in order to simulate the worst environmental condition. At first, 3 specimens from each type of mixtures were placed in an environmental chamber at 50 for 5 hours. The Universal Testing Machine (UTM-5P) was used for this purpose. Then a stress of 450 kPa was applied as deviator stress with 0.5 s loading and 1.5 s rest time for each loading pulse cycle, and the axial deformation was measured using LVDT. Flow number, which is defined as the number of cycle in which permanent strain in the specimen dramatically increases, was chosen as a criterion to compare the mixtures resistance to permanent deformation. As shown in Figure 2 the typical results between the measured permanent strain and load cycle can be divided into three major zones. In the primary phase, the strain rate decreases; and in the secondary phase the strain rate is constant; and in the tertiary phase the permanent strain rate dramatically increases which occurs at high stress levels. The flow number is defined as the postulated cycle when tertiary flow starts in the mixture [Witczak, 2007]. The flow number can be correlated with rutting potential.

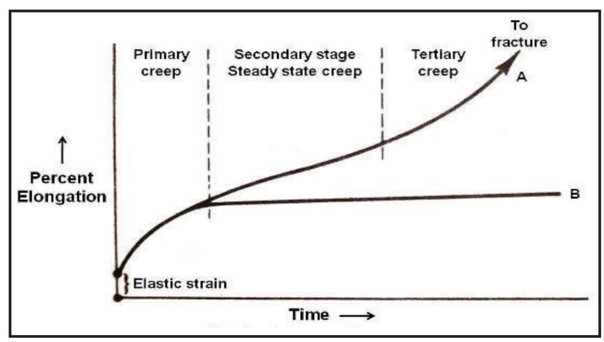


**Figure 2. Typical creep test curve [Witczak, 2007]**

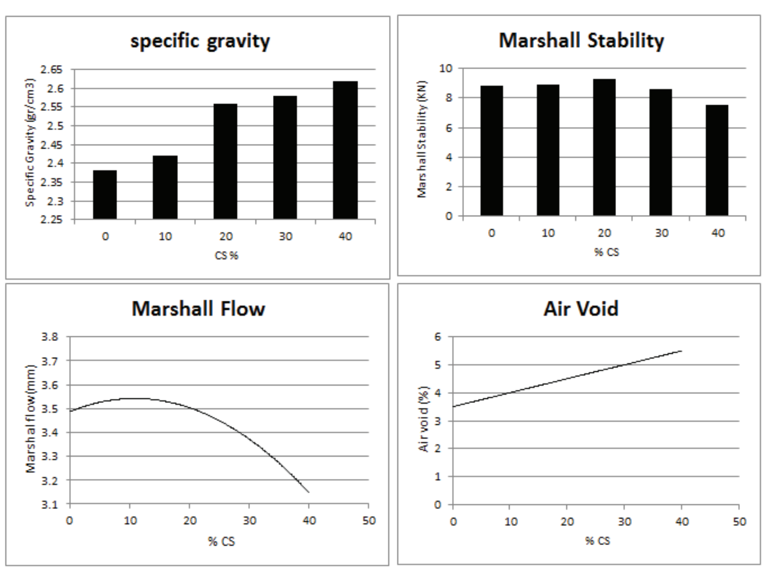


**Figure 3. Marshall tests results**

### 2.3.3 Wheel Track Test

Laboratory wheel-tracking device was used to run simulative tests that measure asphalt qualities by rolling a small loaded wheel device repeatedly across a prepared WMA specimen. Performance of the test specimen is then correlated to actual in-service pavement performance. Laboratory wheel-tracking devices can be used to make rutting predictions. In this study, the Georgia wheel tracker was used to determine the rutting resistance of mixtures. So that after conditioning the specimens at 50  for 5 hours, the specimens were placed under the wheel load of 350 N for 8000 times and then the maximum rutting depth was measured using a digital caliper.

## 3. Results and Discussion

### 3.1 Marshall Stability and Flow

The Marshall test results of each type of mixtures are presented in Table 3 and Figureureure 3.

**Table 3. Marshall tests results**

| CS content (LA % / CS %) | | | | | |
|---|---|---|---|---|---|
| Mixture type | 100/0 | 90/10 | 80/20 | 70/30 | 60/40 |
| O.B.C % | 5.2 | 5.6 | 5.5 | 5.6 | 5.8 |
| Marshall stability (KN) | 8.8 | 9.3 | 9.8 | 8.6 | 7.5 |
| Marshal Flow (mm) | 3.5 | 3.45 | 3.5 | 3.2 | 3.2 |
| Bulk specific gravity | 2.38 | 2.42 | 2.51 | 2.56 | 2.62 |
| Air void % | 3.8 | 4 | 3.5 | 3.8 | 4.2 |
| VMA % | 14.2 | 14.4 | 15.2 | 15.1 | 14.6 |
| MQ (KN/mm) | 2.51 | 2.69 | 2.8 | 2.68 | 2.34 |

It should be noted that the results are average of 3 specimens. As it's shown in table 3, The O.B.C obtained from maximum Marshall stability, maximum specific density and 4% air void, increases slightly by increasing the content of CS in mixtures. The Marshall stability, which is a criterion for resistance to shoving and rutting under traffic [Ameri and Behnood, 2012], increases by adding CS in mixtures up to 20% and then it declines, however, the marshal stability content related to 30% CS still is in allowable range in accordance with ASTM D1559. The increase of Marshall stability is due to the high angularity and friction angle (up to 53) of copper slag aggregates which lead to excellent stability and load bearing capacity [Gorai, Jana and Premchand, 2003]. The decrease of Marshall stability, which occurs by adding more than 20 percent of CS, would be probably because of the coarse aggregate segregation which occurs due to the high bulk specific gravity and low volume of fine CS aggregates which results in less volume of fine aggregates in the mixture and less interlock between aggregates. Based on several articles, the commonly accepted qualitative definition of aggregate segregation is "the non-uniform distribution of coarse and fine aggregate components within the asphalt mixture" [Williams, Duncan and White, 1996b, Khedaywi and White, 1996, Kennedy, Mcgennis and Holmgreen, 1987]. There are two basic types of aggregate segregation; coarse segregation and fine segregation [Williams , Duncan and White, 1996a, Williams , Duncan and White, 1996a 1996b]. Coarse segregation occurs when gradation is shifted to include too much coarse aggregate and not enough fine aggregate. Asphalt concretes containing CS as fine aggregate are prone to coarse segregation because of the high specific gravity and low volume of CS aggregates which lowers the volume of fine aggregates and subsequently leads to less interlock [Hassan and Al-Jabri, 2010]. The solution can be replacing CS aggregates by volume. For this purpose, it is suggested to find the volume of aggregates using the specific gravity and weight. Then try replacing natural aggregates with CS by volume. As it was expected because of the high bulk specific gravity of CS, adding CS leads to increase in specific gravity of mixtures. Voids in the Mineral Aggregates or VMA, which is the intergranular space occupied by asphalt and air in a compacted asphalt mixture, increases by replacing CS up to 20% and then it falls slightly. The Marshall flow decreases by increasing the amount of CS in the mixtures. The Marshall Quotient (MQ) which is the ratio of the Marshall stability to the Marshall flow is also used to indicate the mixtures stiffness. The higher MQ, the stiffer mixture is [Lavin, 2003]. As represented in Table 3, the MQ increases by adding up to 20 % CS in the mixtures.

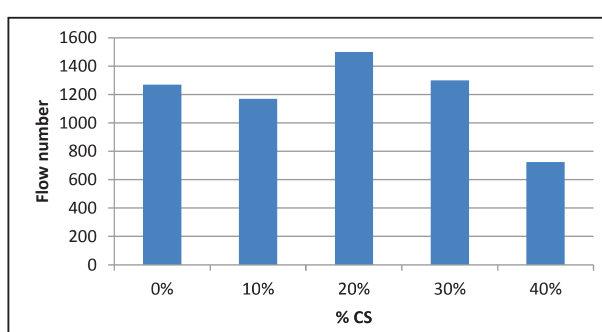


**Figure 4. dynamic creep test results**

### 3.2 Dynamic Creep

The dynamic creep test results are indicated in Figureureure 4. It can be seen that the results of dynamic creep test agree with Marshall stability results and the ability of asphalt mixtures to resist rutting and permanent deformation is enhanced by replacing up to 20% LA with CS. By replacing more than 20% of LA with CS the flow number decreases substantially.

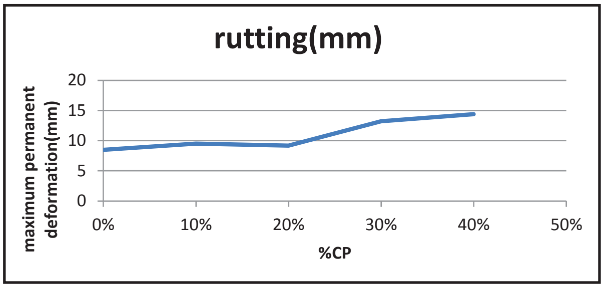


**Figure 5. Wheel Track test results**

Angular materials are desirable in paving mixtures because they tend to lock together and resist deformation after initial compaction, and shortage of fine aggregate angularity can lead to rutting, whereas rounded materials may lead to less interlock and subsequently cause rutting [Topal and Sengoz., 2005]. As indicated in Table 1, the FAA of copper slag aggregates are significantly higher than that of limestone aggregates which results in higher rutting resistance of mixtures containing CS aggregates. Hence, the increase of flow number when 20% of CS is replaced in the mixtures can be due to the high fine aggregate angularity of CS particles. However, as mentioned in section 3.1, if high percentage of fine CS aggregates is used in the mixtures, coarse aggregate segregation will occur which leads to decrease in the mixtures resistance against rutting.

The rutting resistance of mixtures is also affected by the bitumen content. Too much binder in the mixture can lubricate the aggregate particles, allowing them to shift more than they should [Williams, 2003]. As indicated in Table 3, the optimum bitumen content of miaxtures increases by increasing the amount of CS, and the CS particles tend to absorb more bitumen than limestone aggregates. Hence, the high bitumen content in the mixtures containing CS could be another factor that leads to decrease in rutting resistance when more than 20% of CS is replaced by limestone aggregates in the mixtures.

### 3.3 Wheel Track test

As it is shown in Figure 5, the rutting resistance of mixtures is enhanced slightly by adding up to 20% CS. However, by replacing more than 20% of CS as fine aggregate the resistance of mixtures against rutting decreases substantially. Two important factors affecting rutting in asphalt mixtures are aggregate interlock and bitumen stability. The less resistance of mixtures containing more than 20% of CS to permanent deformation is due to the less interlock between aggregates caused by coarse segregation. It can be avoided by replacing CS aggregates by volume. The higher amount of bitumen content in the mixtures containing copper slag can also exacerbate the effect of coarse segregation and make the mixtures less rutting resistant.

## 4. Conclusions

This study investigated the mechanical properties of WMA containing copper slag as fine aggregate. Lime stone fine aggregates were replaced with up to 40% of copper slag by weight of total aggregates, so that properties of 5 different mixtures were evaluated. According to test results, the conclusions are as follows:

- According to Marshall test results replacing up to 20% of CS by weight of total aggregates leads to an enhancement in Marshall stability and MQ. The Marshall flow also decreases by increasing the amount of copper slag in mixtures.
- Due to the high angularity and friction angle of CS aggregates, the resistance to permanent deformation of the mixtures containing up to 20% CS increases and then it falls substantially. Hence, using up to 20% of CS is recommended in asphalt pavements located in hot areas.
- Replacing more than 20% CS causes less interlock between aggregates. However, this problem can be avoided by replacing CS aggregates by volume. Therefore, it is strongly recommended for future researches to replace CS aggregates by volume of total aggregates.

## 5. Acknowledgements

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