The Use of Steel Slag as Substitution of Coarse Aggregate on Indirect Tensile Strength and Marshall Properties of AC-WC

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Abstract. High traffic levels on road can causing road damage, especially cases of permanent deformation and fatigue cracking. One solution is to utilize waste of material, such as steel slag as coarse aggregate and polymer modified asphalt as binding material. This paper explores experimental laboratory investigation on the use of steel slag on Marshall characteristics and indirect tensile strength of AC-WC mixture by using Starbit E-60 and Pen 60/70. Laboratory works begin with physical testing of material, then, finding the optimum bitumen content (OBC) for each type of the mixtures. Finally, Marshall Standard and indirect tensile strength (ITS) at OBC were conducted. Results shows that the use of steel slag for AC-WC mixture are proven to improve resistance to permanent deformation as well as fatigue cracking. Substitution of steel slag for coarse aggregates were able to increase Marshall stability, Marshall Quotient and indirect tensile strength (ITS) of the mixtures, however, it slightly decreases the volumetric performance of mixture, such as voids in total mixes become higher and voids filled with asphalt as well as voids in mineral aggregates tend to decrease.

1. Introduction

Roads are one of the most important land transportation facilities and as one of the important components supporting the economic growth of a country, with the importance role, it is necessary to improve the quality of the road in terms of its structure to provide maximum service. One type of pavement commonly used in Indonesia is the Asphalt Concrete-Wearing Course (AC-WC). Due to the high demand for steel as a material in construction projects, high levels of steel were produced, followed by an increasing amount of waste in the form of slag from the rest of the steel smelting. This situation encourages the need to conduct research using steel slag as a coarse aggregate material for road pavement, in an effort to reduce the steel waste.

Steel slag is a waste material obtained from the smelting of steel processing plants in the blast furnace slag process. In Indonesia, the increasingly rapid development of the steel industry has resulted in the creation of 800 thousand tons/year of steel slag, which causes problems on the part of steel producers, because of an obligation to process steel slag, while according to Indonesian Government regulation (PP 18, 1999), steel slag is hazardous waste from specific sources. According to Behnood and Ameri (2012) [2], the use of steel slag as the coarse portion of aggregates can enhance Marshall stability, resilient modulus, tensile strength, resistance to moisture damage and resistance to the permanent deformation of Split Mastic Asphalt (SMA) mixtures. The use of steel slag is also proven to improve fatigue behaviour of bituminous mixtures made with reclaimed asphalt pavement (Passeto and Baldo, 2012) [12]. Kok and Koluglu (2008) [7] studied indirect tensile strength (ITS) and creep modulus of hot mix asphalt and explained that the oxygen content in steel slag can cause an increase in the stiffness of the mixture, the
greater the addition of steel slag, the higher the stiffness of the mixture. Similarly, investigation on
the effect of recycled concrete aggregate and steel slag on the dynamic properties of asphalt mixtures has
been published by Arabani dan Azarhoosh (2012) [1]. Oluwasola et al (2016) [10] publish their reseach
of dense-graded and gap-graded asphalt mix incorporating Electric Arc Furnace (EAF) steel slag and
copper mine tailings (CMT), and they concluded that mixes containing EAF steel slag and CMT
performed better in rutting and were less susceptible to permanent deformation compared to control mix.
Furthermore, Passeto et al (2017) [11] also explored the use of steel slag as a substitute aggregate in
road pavements and resumed that steel slag resulted in increased resistance to rutting and permanent
deforation, but decreased resistance to fatigue cracking. Another laboratory experiment on the use of
steel slag in Split Mastic Asphalt mixtures (SMA) has been carried out by Chen and Wei (2016) [3],
who deduced that the use of steel slag improves the interlocking mechanism because the steel slag
material has a coarse texture, increases tensile strength, and increases resistance to rutting compared to
composites. using natural aggregates. Almost lately, study conducted by Liu et al (2019) [8] concluded
that the surface condition of the aggregate derived from coarse steel slag has a high stability value and
a low expansion rate. This has a risk of easy cracking of the asphalt mixture due to high stability but
low expansion. Another effort to reduce this problem is to use a polymer modified asphalt, such as
Starbit E-60.

The use of modified asphalt to improve pavement performance including resistance to fatigue
 cracking has been done by many previous researchers. Wang et al (2018) [16] stated that the use of
polymers for ordinary conventional asphalt modification can increase the stiffness of asphalt and
mixtures, thus causing the mixture to be more resistant to deformation and high temperatures. Previously,
Zhi et al (2012) [18] have also published that asphalt with the addition of polymer produces a stiffer
pavement and is more recommended for roads with high traffic and is more resistant to cracking.
Yhudianto et al (2017) [17].

Evaluate the use of Starbit E-60 regarding the effect of filling the cavity against infiltration velocity,
permeabilityof Porus asphalt mixture. Almost just recently, Subarkah et al (2020) [15] investigated the
use of Starbit E-60 and Pen 60/70 on AC-BC incorporating zeolite, and resulted that the mixture using
Starbit E-60 produce a higher permanent deformation and indirect tensile strength (ITS) as well as
resistance to disintegration of mixes than those of mixes with Pen 60/70. Maenkar et al (2020) [8] also
study the use of Starbit E 60 and Pen 60/70 on Marshall properties and resilient modulus of thin layer
mixture, and they demonstrated that mixes with Starbit E-60 were more resistant to temperature changes,
and having a higher modulus of resilience, however, they have a lower stability than the mixtures with
Pen 60/70.

According to the previous discussion, investigation on the use of steel slag incorporating Starbit E-
60 and Pen 60/70 in AC-WC are still very limited, therefore, this paper presents an evaluation of indirect
tensile strength (ITS) and Marshall performance of AC-WC containing Starbit E-60 and Pen 60 70 based
on Marshall standard (Bina Marga, 2018).

2. Materials and Method

Steel slags used were obtained from the smelting results at the PT Gunung Raja Paksi steel factory.
Chemical compositions of steel slag are presented in Table 1, while the photograph of steel slag can be
seen in Figure 1.

Table 1. Chemical Composition of Steel Slag

| No | Chemical Component | Percentage (%) |
|----|--------------------|----------------|
| 1  | Ca                 | 29.245         |
| 2  | MgO                | 28.290         |
| 3  | FeO                | 22.945         |
| 4  | SiO2               | 12.750         |
| 5  | Al2O3              | 5.875          |
Aggregate used were andesite aggregates from Clereng quarry, Yogyakarta, Starbit E-60 is a commercial product of PT Bintang Jaya, while Pen 60/70 were made by PT Pertamina. Gradation used is based on Bina Marga (2018) standard. In this study there was a slight change in the gradation design due to the substitution of Andesite coarse aggregate with steel slag, the substitution was carried out using calculations based on the ratio of specific gravity, substitution was carried out with variations of 0%, 25% and 50%. Figure 2 shows the design gradation of AC-WC mixture.

![Photograph of Steel Slag](image1)

**Figure 1. Photograph of Steel Slag**

![Design of Gradation](image2)

**Figure 2. Design of Gradation**

Based on the design gradation, specimens then were made for finding optimal bitumen content (OBC) by using percentage of asphalt content of 5%, 5.5%, 6%, 6.5%, and 7% of the total weight of the mixture. The optimum asphalt content is asphalt content, where all performance measured from several Marshall parameters reach their optimum performance. OBC needs to be obtained for each variation of steel slag substitution. There were three types of variations, namely the substitution variation of 0%, 25% and 50%. Following this, the Indirect Tensile Strength (ITS) and Marshall tests at OBC were conducted, to determine the performance of the asphalt mixture. The Marshall Test parameters include stability, flow, MQ (Marshall Quotient), VITM (Void in the Total Mix), VFWA (Void Filler with Asphalt), VMA (Void in Mineral Aggregate), and density.
Indirect Tensile Strength (ITS) is a test of the ability of asphalt concrete to withstand tensile loads. This test is carried out on a cylindrical test object. The loading is carried out parallel to the vertical diameter of the specimen to the point of damage, which is indicated by the occurrence of cracks in the vertical direction of the test object. This damage marks the maximum load that the mixture can withstand which indicates the tensile strength of the mixture.

3. Result and Discussion

3.1. Physical Properties of Materials

Laboratory results of physical properties of bitumen and steel slag materials are presented in Table 2 and Table 3. Table 2 shows that Starbit E-60 have a significantly lower penetration, flash point, and fire point, but higher softening point, compared to Pen 60/70. These results indicate that Starbit E-60 is harder and less susceptible to temperature changes, compare to Pen 60/70. Meanwhile, as can be seen in Table 3, steel slag aggregates have a significantly higher specific gravity, water absorption, and abrasion compared to Clereng aggregates. Based on data analysis of all Marshall properties, mention before, OMC for each of types of variation were obtained (Table 4).

| Parameters                | Starbit E-60 | Pen 60/70 |
|---------------------------|--------------|-----------|
| Specific gravity          | ≥ 1.0        | ≥ 1.0     |
| Penetration (0,1 mm)      | 50-80        | 60-70     |
| Ductility (cm)            | ≥ 50         | ≥ 100     |
| Flash Point (°C)          | ≥ 232        | ≥ 232     |
| Fire Point (°C)           | ≥ 232        | ≥ 232     |
| Softening Point (°C)      | ≥ 60         | ≥ 48      |
| TCE Solubility (%)        | ≥ 99         | ≥ 99      |

| Type                      | Fine Aggregate | Coarse Aggregate |
|---------------------------|----------------|------------------|
| Specific gravity          | ≥ 2.5          | ≥ 2.5            |
| Water absorption/porosity (%) | ≤ 3            | ≤ 3              |
| Adhesion of aggregates-asphalt (%) | -              | ≥ 95            |
| Abrasion (%)              | -              | ≥ 40             |
| Sand Equivalent           | ≥ 55           | 91.99            |

| Percentage of steel slag (%) | Pen 60/70 | Starbit E-60 |
|------------------------------|-----------|--------------|
| 0                            | 6.15      | 6.15         |
| 25                           | 6.20      | 6.25         |
| 50                           | 6.35      | 6.4          |
From Table 4, it can be explained that as the percentage of steel slag substitution increases, the optimum asphalt content increases because of the aggregate steel slag has more cavities than andesite aggregates, so it requires more asphalt to penetrate to fill the void in aggregates particles.

3.2. Performance of AC-WC at Optimum Bitumen Content

In Marshall method, stability and flow are importance performance of the mixture. Figure 3 and Figure 4 present stability and flow of the mixture at OAC.

Figure 3 shows that stability of the both mixes tend to significantly increase along with the addition of steel slag aggregate proportion. The substitution of 50% steel slag resulted in a 25.7% increase in stability of the mixture with Starbit, and 15.2% on mix with Pen 60/70. Steel slag aggregate which has a fairly hard texture is a factor that affects the increase in the stability. The harder texture of steel slag is evidenced by material abrasion test with a result of 7.04%, lower than the abrasion of Clereng andesite aggregate, which is 13.04%. This shows that steel slag is more resistant to abrasion than Clereng andesite stone. This is in accordance with Hainin et al (2015) [6] which states that the greater the addition of steel slag, the higher the stability of the mixture, due to its interlocking properties and greater hardness of steel slag, resulting in increased resistance to deformation of the mixture. This result is also in regards with previous researchers (Liu et al, 2019; Passeto et al, 2017; Chen and Wei, 2016; Oluwasola et al, 2016; and Behnood and Ameri, 2012). It is also shown that mixes with Starbit E-60 generate a higher mixture stability than those with Pen 60/70. This is due to the higher hardness of the Starbit E-60, compared to the 60/70 Pen, resulting in greater mixture stability. This result is regards with Subarkah et al (2020) [15], however this result is in contrast with Maenkar et al (2020) [8], who investigate Starbit E-60 polymer modified asphalt for thin layer mixture.

As plotted in Figure 4, flow of both types of mixes are rising along with the increasing in the percentage of substitution of steel slag. This means that the deflection of those mixtures greater, indicates that they become more flexible with the increasing percentage of steel slag substitution. This is due to the increase in asphalt content along with the addition of the percentage of steel slag substitution in all types of the mixtures. There were no differences of flow value in all percentages of slag steel, between the mixtures using Starbit E-60 and Pen 60/70. Rindu et al (2019) also stated that with the increasing of steel slag substitution, the flow of the mixture will increase.

Figure 5 depicted the curves of relationship between percentage of steel slag with Marshall Quotient (MQ), while Figure 6 with voids in mineral aggregates (VMA). As can be seen in Figure 5, MQ of both types of mixes are going up with the increasing number of substitutions of steel slag. This is because of the use of steel slag increase the stability of mixture significantly, but only slightly mount flow of mixes. This result is in accordance with the research of Bethary et al (2019), which stated that the MQ value of mixture increased with the increase in the percentage of steel slag substitution, causing the
mixture to become stiffer. It is also shown from the curve that mixes with Starbit E-60 produce a higher MQ than those with Pen 60/70. MQ of the mixture using Starbit increased more sharply by 17.8%, while those with Pen 60/70 only increase by 13.5% at 50% steel slag substitution. This is because of the higher hardness of the Starbit E-60, compared to the 60/70 Pen, resulting in greater stiffness of the mixture.

**Figure 5.** The Relationship between Steel Slag Substitution and MQ of AC-WC

**Figure 6.** The Relationship between Steel Slag Substitution and VMA of AC-WC

As shown in Figure 6, both two curves of VMA decline with the increasing of percentage of steel slag substitution. There are no differences of VMA between mixes with different bitumen types. This is because of steel slag stones tend to have higher pores compared to Clereng andesite stone (Tables 3), so that a more amount of bitumen penetrates inside to the steel slag cavity, resulting less amount of bitumen cover the surface of steel slag and fill in the void of the mixture, therefore, the percentage of pores between aggregates tends to be lower in mixtures using higher percentage of steel slag stone. This result is in line with Gowtham and Ganesh (2018) and Rindu (2019), they resumed that the higher the percentage of steel slag substitution, the lower the VMA value of the mixture.

**Figure 7 and Figure 8** represent the graphs of voids in total mix (VITM) and void filled with asphalt (VFWA) of the mixes on various of steel slag percentage and different bitumen types.

**Figure 7.** The Relationship between Steel Slag Substitution and VITM of AC-WC

**Figure 8.** The Relationship between Steel Slag Substitution and VFWA of AC-WC
Based on Figure 7 it shown that VITM of mixture terrace along with the rise of steel slag proportion. This is because of steel slag stone are more porous than that of Clereng andesit aggregate (Table 3), so that a more amount of bitumen absorbed in steel slag cavity, resulting less amount of bitumen cover the surface of aggregates and fill in the void of the mixture, therefore, the percentage of pores in the mixture tends to decrease along with the higher percentage of steel slag stone. Moreover, the surface texture of steel slag aggregates tend to be more rough and angular than Clereng andesit stones, resulting a larger voids in mixture will generate at higher amount of steel slag substitution. This is in line with many previous publication (Rindu, 2019; Gowtham and Ganesh, 2018; and Arbani and Azarhoosh, 2012). They also concluded that the addition of steel slag produced an increase in the VITM of mixes value, caused by the porosity and angularity of steel slag. In terms of bitumen types, the figure also shown that mixes with Starbit E-60 generates a higher VITM than those with Pen 60/70. This is due to the higher penetration grade and viscosity, as well as lower temperature susceptibility of Starbit E-60, compared to Pen 60/70 (Tables 2), so that at the same temperature Starbit is harder to fill the pore of the mixture, resulting in greater VITM. This result is in regards with research conducted by Maenkar et al (2020).

In harmony with the VITM phenomenon discussed above, as can be seen in Figure 8, VFWA of mixture fall along with the incline with the number of steel slag substitution. The higher the percentage of steel slag substitution, the lower the VFWA of mixture will produce. This is due to the less asphalt fill the mixture cavity, because of a more amount of bitumen tends to be absorbed into pore of the steel slag stone, so that only less amount of bitumen covers the aggregates and fill the voids of mixture, therefore, the VFWA of mixture will decrease. This result is convenient with the research of Rindu (2019), Gowtham and Ganesh (2018), and Rindu, 2019; and Arbani and Azarhoosh (2012), which sum up their study that the higher the percentage of steel slag substitution the increase in the number of pores in the mixture (VITM) and decreases the number of pores filled with asphalt (VFWA). In regards, with VITM phenomenon mention earlier, mixes with Starbit E-60 produce a lower VFWA of mixture, than those with Pen 60/70. This is due to the higher penetration grade and viscosity, as well as lower temperature susceptibility of Starbit E-60, compared to Pen 60/70 (Tables 2), so that at the same temperature Starbit E-60 is harder to fill the pore of the mixture, resulting in lower VITM. This also is in line with Maenkar et al (2020).

Figure 9 and Figure 10 present the curves of density and indirect tensile strength (ITS) of the mixes on various of steel slag substitution and different bitumen types.

![Figure 9](image1.png)  
**Figure 9.** The Relationship between Steel Slag Substitution and Density of AC-WC

![Figure 10](image2.png)  
**Figure 10.** The Relationship between Steel Slag Substitution and ITS of AC-WC

As plotted in Figure 9, density of both types of mixtures are slightly incline with the addition of steel slag substitution. The increase of mixes density influenced by the higher specific gravity of the steel slag so that the more amount of steel slag, the mixture becomes heavier and denser. This is in line with Behnood and Ameri (2012), who stated that the increase in density is caused by the higher density of...
steel slag and easier for bitumen to stick, so that the mixture becomes denser. It also shown from the graph, that there are no differences in mixes density due to bitumen types used. This is in accordance with Subarkah et al. (2020) and Maenkar et al. (2020).

Figure 9 exhibits that for both of mixes, indirect tensile strength (ITS) rise along with the increase of steel slag substitution. This is due to the surface roughness and angularity of steel slags than Clereng andesite stone, so that they have better interlocking and interparticle friction and contributes to increased resistance to tensile. Moreover, steel slag has a significantly higher specific gravity than Clereng andesite stone (Tables 3), so that the mixture becomes denser and also has a more resistance to displacement. This is in accordance with the study of Passeto and Baldo (2012) which stated that the mixture using steel slag increased ITS value of mixes. Subarkah et (2020) also also explained that mixtures with Starbit E-60 binder have a higher ITS value because of Starbit E-60 is more ductile than Pen 60/70. These results are also in accordance with Behnood and Ameri (2012) and Kok and Koluglu (2008). They resumed that the use of steel slag as the coarse portion of aggregates can enhance tensile strength hot mix asphalt.

4. Conclusion
According to the discussion above it can be resumed that the use of steel slag as a substitute for coarse aggregate in the AC-WC mixture are proven to improve stability, Marshall Quotient and indirect tensile strength of the mixtures, however, it slightly decreases the volumetric performance of mixture, such as voids in total mixes become higher and voids filled with asphalt as well as voids in mineral aggregates tend to decrease. With the increasing of Marshall stability indicates that mixes having a more resistance to permanent deformation, while improving in ITS means that mixes are more resist to fatigue cracking.

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