UDC 625
DOI: 10.15587/1729-4061.2023.289054

COMPARISON OF THE MOISTURE RESISTANCE OF A STEEL-SLAG STONE MASTIC ASPHALT MIXTURE MODIFIED WITH CA(OH)$_2$

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Stone mastic asphalt is a type of hot mix asphalt that requires much coarse aggregate, so substitution waste aggregate, such as steel slag, will be an economic reason. The problem is that there are still many things that have not been consistent in various studies related to the moisture resistance of steel slag.

The study aimed to compare the effect of Ca(OH)$_2$ on the moisture resistance of the steel-slag stone mastic asphalt mixture and to determine the optimal Ca(OH)$_2$ dosage for improving the mixture resistance. This study employs basalt aggregate, steel slag from Krakatau Steel Company, 60/70 penetration asphalt, a stabilizing substance made of bamboo fiber, and Ca(OH)$_2$.

The Texas boiling and the static immersed methods are used to test the adhesion on a loose mixture. The retained Marshall stability and indirect tensile strength are used to test the adhesion on the compacted mix.

Testing result of Krakatau steel slag shows that steel slag has a much higher Fe$_2$O$_3$ content than steel slag in general and has low water absorption; a poor affinity for asphalt results from this. The result of the Texas boiling method showed a decrease in the percentage adhesion value between steel slag and asphalt compared to natural basalt aggregates and asphalt. Marshall Stability Ratio and Tensile Strength Ratio increased after mixing the asphalt with Ca(OH)$_2$. Marshall test results show decreased stability in mixtures with steel slag substitution. Adding Ca(OH)$_2$ increased stability and resistance to moisture significantly. This indicated that Ca(OH)$_2$ enhances moisture resistance on stone mastic asphalt with modified steel slag. Stability, Marshall stability ratio, indirect tensile strength ratio, particle loss, and Texas boiling test significantly improved with adding Ca(OH)$_2$

Keywords: steel slag, stone mastic asphalt, Ca(OH)$_2$, moisture resistance, Marshall stability

Received date 02.10.2023
Accepted date 09.12.2023
Published date 22.12.2023

How to Cite: *Irawati, Djakfar, L., Arifin, M. Z. (2023). Comparison of the moisture resistance of a steel-slag stone mastic asphalt mixture modified with Ca(OH)$_2$. Eastern-European Journal of Enterprise Technologies, 6 (6 (126)), 62–70. doi: https://doi.org/10.15587/1729-4061.2023.289054*

1. Introduction

Stone mastic asphalt (SMA) pavement type with steel slag aggregate substitution promises a mixture with better stability and durability than conventional SMA. The use of steel slag in the Hot Mix Asphalt (HMA) mixture has been widely pursued for waste utilization and sustainable road construction [1]. However, there are still many things that have not been solved in previous research. Several studies reported that the substitution of steel slag as a substitute for aggregate increases moisture resistance [2, 3]. However, it was found in various experiments that the substitution of steel slag tends to reduce moisture resistance. Moisture resistance is an essential variable in the assessment of pavement performance. The use of aggregate waste for economic purposes and saving the environment becomes ineffective if it turns out that the modified mixture is not durable. Therefore, studies devoted to moisture resistance on stone mastic asphalt modified with steel slag are scientifically relevant.

2. Literature Review and Problem Statement

Stone mastic Asphalt with steel slag is a complex composite blend of HMA. The proportions selected must be such that they provide optimal stability, flow, and volumetric to produce a durable mixture. Stone Mastic Asphalt (SMA) is made from mortar (a mix of bitumen, filler, and stabilization material) and gap-graded aggregate. This asphalt pavement's fundamental idea is in the stone-on-stone contact structure [4]. The coarse aggregate structure is owned to form a skeleton that can withstand high loads. In addition, using SMA provides the advantages of low permeability, silencing on pavement, and high resistance to cracking and rutting. The ability possessed by SMA is relevant for use in Indonesia, with roadways typically sustaining premature damage due to overloaded traffic loads.

On the other hand, steel slag from several studies shows that the material is feasible as a substitute for aggregate. Steel slag as aggregate has good mechanical properties and a rich morphological surface [5]. The distinctive properties of steel slag aggregate are its rough texture and angular surface, which improve stability and slip resistance in asphalt concrete mixture [6]. In addition, steel slag shows good friction resistance on the Polish resistance test, which means that the surface of the pavement layer is resistant to friction [7]. Steel slag in asphalt concrete mix improves Marshall stability, Indirect Tensile Strength, raveling, and rutting resistance. This is also proven in field studies where the friction resistance of a mixture of asphalt concrete with steel slag is better than conventional asphalt concrete [6]. However, each steel slag from a different furnace has different physical and chemical properties that affect the mechanical properties of the asphalt concrete mixture. As a result, some research findings are different.

In addition to the advantages of steel slag as a substitute for natural aggregate in HMA, moisture resistance in asphalt concrete mixtures with steel slag substitution is reported inconsistently. Some studies reported that Indirect Tensile Strength (ITS) decreased with the addition of the proportion of steel slag substitution [1, 8]. The studies [1, 8] compared asphalt concrete (AC-13) with steel slag substitution in several grades, the results showed Tensile Strength Ratio (TSR) of each sample decreased gradually with the increase of steel slag content. It is concluded in the paper that steel slag is not good for water stability. However, there were unresolved issues related to moisture resistance stone mastic (SMA) asphalt with another type of steel slag.

The fact shows that in determining the SMA proportion, a review must still be made of the physical and chemical properties of the type of steel slag used. This study evaluates the characteristics of steel slag from Krakatau Steel Indonesia company. Further evaluation was carried out on proportion, stability, and moisture resistance. Testing of adhesion ability on the loose mixture with the Texas boiling test and Static immersion test and testing of adhesion ability on the compacted mix with Marshall stability immersed Marshal, and indirect tensile strength will answer questions regarding the moisture resistance of unmodified and modified SMA.

Moisture resistance is the resistance of asphalt concrete in the face of moisture damage. Moisture damage is the deterioration of complex pavement quality, a combination of physical, chemical, thermodynamic, and mechanical processes [9]. Moisture damage is the primary cause of damage in flexible pavement structures, particularly in nations with tropical climates like Indonesia. The key to durability in flexible pavements is their resistance, especially to moisture.

$Ca(OH)_2$ is a material that can increase moisture resistance in an asphalt concrete mixture. Adding $Ca(OH)_2$ to the asphalt concrete mix can improve physical and mechanical properties [10] The addition of $Ca(OH)_2$ to the asphalt concrete mixture will increase stability to some extent. The addition of $Ca(OH)_2$ will also increase the stiffness of the mixture. Increasing the binder content improves resistance to moisture-induced damage.

Previous research on wearing course layers showed that adding $Ca(OH)_2$ positively contributes to increasing moisture resistance, with levels up to 2.5 % of aggregate weight [11]. This article reports that adding $Ca(OH)_2$ increases stability, affinity, and moisture resistance. Although the study did not use the same mixture, $Ca(OH)_2$ can increase stiffness in asphalt mastic at the binder scale, resulting in improved moisture resistance. As a result, adding $Ca(OH)_2$ to SSAM will result in the same behavior.

Therefore, in this research, $Ca(OH)_2$ is used as an additive to different mixes i.e. SMA with steel slag substitution. Comparing the value of stability, Marshall stability ratio, tensile strength ratio, and particle loss between unmodified SMA modified SMA with steel slag, and modified SMA with steel slag and $Ca(OH)_2$ will answer questions about the optimum proposition of the mixture.

3. The aim and objectives of the study

The study aims to evaluate the use of steel slag substitution in SMA mixtures added with $Ca(OH)_2$ and how it impacts the mechanical performance of the mix. A combination of SMA, SS, and $Ca(OH)_2$ is expected to perform better in stability and moisture resistance than conventional SMA.

To achieve this aim, the following objectives are accomplished:

– investigating the physical and chemical characteristics of aggregates, steel slags, and all materials used in mixtures;

– investigating loose mixture adhesion and compare between unmodified and modified SMA, with static immersion and the Texas boiling testing;

– investigating compacted mixture adhesion with immerse Marshall and indirect tensile strength testing;

– investigating stability to compare and analyze the strength of modified and unmodified SMA compacting mixture, with Marshall-stability testing;

– investigating particle loss of compacted mixture to analyze the damage potential of modified and unmodified SMA, with Cantabro method.

4. Materials and Method

4. 1. Objects and hypothesis of studied

This research is investigating the modification of stone mastic asphalt, which is compared to unmodified stone mastic asphalt.

The research hypothesis is that steel slag as a substitute for SMA has a negative impact on moisture resistance, so it requires additional material to improve. To evaluate this, the loose mixture is tested and its adhesion, the loose mixture investigated is:

– aggregate and asphalt;

– steel slag and asphalt;

– steel slag, asphalt and $Ca(OH)_2$.

It also evaluates the compacted mixture of test specimens made from:

– SMA original without modification;

– steel slag is used to replace aggregate in Steel Slag Asphalt Mixtures (SSAM);

– SSAM adding with $Ca(OH)_2$ as much 1 %;

– SSAM adding with $Ca(OH)_2$ as much 2 %;

– SSAM adding with $Ca(OH)_2$ as much 3 %;

– SSAM adding with $Ca(OH)_2$ as much 4 %.

4. 2. Materials

The mixture-forming materials used in this study are:

a) natural basalt aggregate meets Indonesia Highway Ministry 2018 specifications for fine SMA, as shown in Table 1. The aggregate comes from Pasuruan, East Java, Indonesia. Aggregate properties-are presented in Table 2;

b) steel slag used is from Krakatau Steel Indonesia company (Fig. 1, *a*). Steel slag is a substitute material for as much as 60 % of the aggregate weight in size 4.75–9.5 mm. The steel slag was crushed to fit the required size, as seen in Fig. 1, *b, c*. Steel slag properties can be seen in Table 1. Steel slag substitution cannot be done 100 %, and excessive substitution causes excessive heating of the entire mixture during production. In this case, the recommended proportion is 60 % of the total aggregate size of 4.75–9.5 mm [12, 13];

c) asphalt used is 60/70 penetration asphalt; the characteristics of asphalt are shown in Table 3;

d) bamboo fiber stabilizes Stone Mastic Asphalt to prevent the drain-down weight of the mixture (Fig. 2). The properties and sizes of bamboo fibers used are shown in Table 4;

e) $Ca(OH)_2$ is added to improve aggregate and bitumen adhesion, moisture resistance, and mixture stability (Fig. 3).

The proportion of aggregate used to make Stone Mastic Asphalt is coarse aggregate=51 %, medium aggregate=31 %, fine aggregate=10 %, and filler=8 %. Mixing these proportions follows the specification of fine SMA followed by Indonesia Highway Ministry 2018. The distribution of aggregate sizes used in this study can be seen in Table 2.

Stone Mastic Asphalt additives for stabilization use bamboo fiber by 0.3 % with a length of 6.5 mm and filtered with sieves sizes 20, 40, and 140. Details on the bamboo fiber properties are shown in Table 4.

Fig. 2. Bamboo fiber

Table 1

Particle size distribution

ASTM (mm)	19	12,5	9,5	4,75	2,36	1,18	0,6	0,3	0,15	0,075
% passing	100	98.79	70.76	29.11	19.41	14.94	12.79	11.72	10.69	9.95

Table 2

Aggregate properties

Properties	Coarse aggregate	Medium aggregate	Fine aggregate	Filler	Steel slag
Apparent specific gravity	2.890	2.889	2.708	2.750	3.846
Bulk specific gravity	2.722	2.703	2.587	2.676	3.748
Water absorption %	2.137	2.394	1.725	1.011	0.68
LA abrasion %	17.44	–	–	–	15.88

Table 4

Bamboo fiber properties

Properties	Value
Sieve retains (0.841 mm)	15 %
Sieve retains (0.420 mm)	45 %
Sieve retains (0.105 mm)	10 %
Sieve passing (0.105 mm)	30 %
Average fiber length (mm)	6.5
Specific gravity	0.6
Moisture content	3 %
pH	7.19

a *b* *c*

Fig. 1. Steel slag Krakatau steel company: *a* – bulk steel slag; *b* – steel slag 9.5 mm; *c* – steel slag 4.75 mm

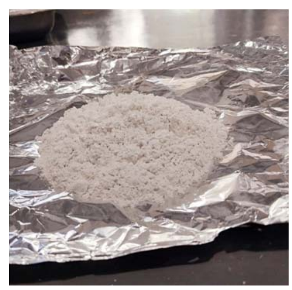

Fig. 3. $Ca(OH)_2$

Table 3

Asphalt Properties

Properties	Value
Penetration 25 °C (0.1 mm)	64
The softening point, °C	50
Ductility at 25 °C, cm	150

Table 5

$Ca(OH)_2$ properties

Properties	Value
Sieve pass (mm)	0.063
Sieve retains (mm)	0.045
Specific gravity	2.24
Purity	95 %

Fig. 3 shows the additive material $Ca(OH)_2$ used in research. The characteristics of $Ca(OH)_2$ additives are described in Table 5, with a purity level of 95 % and other impurities as much as a maximum of 5 %.

At the initial stage, the material mentioned above is made in a loose mixture to be tested for adhesion ability. At the final stage, all materials are made mixed design according to the specifications of thin SMA mixtures and compacted for mechanical and adhesion testing.

4. 3. Experiment setup and method

Fig. 4 describes how the research process started until completion. Start with investigating the material's mechanical, physical, and chemical, comparing loose mixture between modified and unmodified SMA. Comparison of stability and indirect tensile strength on compacted mixture between unmodified, and modified SMA.

Adhesion of aggregates and asphalt is based on the theory of adhesion and cohesion developed in a study [14] which consists of 4 fundamental theories, namely the theory of mechanics, electrostatic, chemical bounding, thermodynamic, and Bikermen adding the theory of weak boundary layer [15]. This is covered in [16]. It is believed that the chemical composition of the aggregate affects the adhesion force between the aggregate and the bitumen [17], and influences the aggregate's physical and mechanical characteristics. Therefore, this study examined the chemical content of natural basalt and steel slag aggregates used in the mixture.

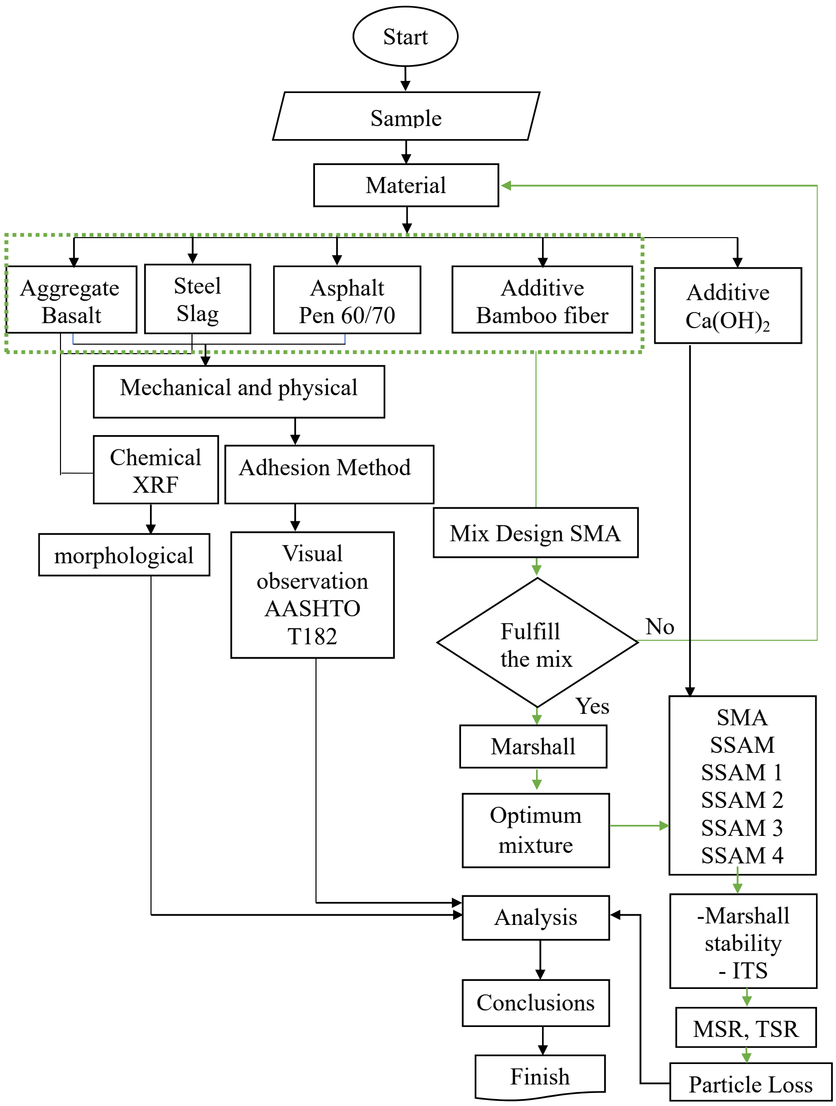

Fig. 4. Flowchart of the experiment

Physical properties investigation is carried out on aggregate and steel slag, following the Indonesia standard SNI 03-1969-1990. The X-ray fluorescence (XRF) technique using a PANalytical spectrometer, Manipal type 4, to investigate the chemical composition of steel slag.

Loose mixture adhesion testing of natural aggregates and asphalt, as well as steel slag and asphalt aggregates, was carried out using two methods, namely Texas Boiling Test (ASTM D3625) and Static Immersion test, which refers to AASHTO T182, against loose mixtures. This stickiness testing also indicates the mixture's resistance to moisture.

Texas Boiling test procedure is performed by putting a loose mixture of aggregate and asphalt in boiling water at 100 °C for 10 minutes. Next, the mixture is cooled, the water and exfoliated parts are removed, and the mixture is drained and allowed to dry; furthermore, visual observations of the retained asphalt to the aggregate. In the Static Immersion test, according to AASHTO T182, mix 100 grams of aggregate and 5.5 grams of asphalt, then put in the oven for 2 hours, then immersed in water for 16–18 hours. Then, visual observation and assessment are carried out on the specimen.

The observation for three mixed combinations was compared and evaluated. The mixture combination is natural aggregate and asphalt, steel slag and asphalt, steel slag and asphalt added with $Ca(OH)_2$.

Compacted mixture adhesion testing to analyze the adhesion ability of the mixture under the compacted condition with immerse Marshall testing and indirect tensile strength. Specimen preparation for compacted mixture is done with a fabricated Stone Mastic Asphalt mixture weighing 1200 grams on a 4-inch cylindrical mold. Stone Mastic Asphalt mixture is made to obtain optimum asphalt content (OAC) values with maximum stability.

Stability and flow measurements using the Marshall test (ASTM D-6927) were carried out on SMA specimens with unmodified basalt aggregate (SMA) and SMA steel slag substitution (SSAM) and with modifications $Ca(OH)_2$ (SSAM1, SSAM2, SSAM3, SSAM4).

The resistance of the mixture to water is related to the durability of the pavement, and its effect on the addition of steel slag and $Ca(OH)_2$ was studied. For compacted mixtures, moisture susceptibility can be measured using the Marshall Stability Ratio (MSR), also called retained Marshall stability. MSR is the ratio between conditioned Marshall and unconditional stability values. Immerse Marshall testing follows the LS 283 Ministry Ontario standard method.

Indirect tensile strength (ITS) testing according to ASTM D4867 standard. Putting concrete asphalt into the ring and applying constant pressure with an average strain of 50 mm/min until it reaches maximum load P, and is carried out until failure. Tensile strength Ratio (TSR) MSR is the ratio between conditioned and unconditional ITS values. Conditioning TSR testing follows the LS 283 Ministry Ontario standard method.

The Cantabro test method carried out particle loss testing following Text-245-F, 2014; Texas Department of Transportation. Particle loss testing is a technique for determining the raveling damage potential of modified and unmodified SMA mixtures. The test procedure follows: the compacted asphalt concrete mixture specimen was rotated inside the Los Angeles engine at 30–33 rpm for 300 revolutions without inserting steel balls. Then, let's calculate the percentage of weight left behind compared to the initial weight.

5. Result of moisture resistance of stone mastic asphalt mixture with steel slag and $Ca(OH)_2$

5. 1. Physic, and chemical properties

The results of steel slag properties show a high bulk specific gravity of 3.748 and a low absorption ability of 0.68 (Table 1). This condition is thought to be one of the reasons for the low adhesion of asphalt and steel slag. In addition, testing of the chemical element content shows that Krakatau Steel slag has a very high Fe_2O_3 content of 57.17 % (Table 6) compared to other general compositions of steel slag. This condition affects the physical appearance, as seen in Fig. 2, *a*. Compared to basalt aggregates, steel slag aggregates have a much lower chemical composition of SiO_2. SiO_2 can adversely affect the mixture because it will weaken the adhesion to the binder [18]. So, the presence of SiO_2 in steel slag is not the reason for the decreased adhesion ability of the mixture.

Table 6

X-ray fluorescence test (XRF)

No	Oxide content	Aggregate Basalt	Steel slag Krakatau steel	General composition of steel slag
	%	%	%	%
1	Al_2O_3	12	2.60	1.2–1.7
2	SiO_2	40.1	9.20	7.5–15
3	CaO	1.6	25.70	47–55
4	MnO	0.41	2.60	3.5–5.3
5	Fe_2O_3	28.3	57.17	20–26
6	Others	2.387	2.46	–

Data on the general composition of steel slag were obtained from the research of Tam Minh Phan [18]. In the statement, it is shown that Fe_2O_3 only ranges from 20–36 %.

5. 2. Determination of affinity between aggregate, steel slag and asphalt

This test assesses the affinity loose mixture between aggregate and asphalt, steel slag and asphalt, and steel slag, asphalt, plus $Ca(OH)_2$. The three types of samples were tested using static immersion and the Texas boiling test. According to test results on aggregate adhesion with asphalt, adhesion between natural aggregate and asphalt, as well as adhesion between steel slag aggregate and asphalt, they compared favorably to bonding between aggregate and asphalt mixed with $Ca(OH)_2$ at 100 % when tested using the static immersion method.

Testing using the Texas Boiling test method encountered different things. There was a decrease in the percentage of adhesion of asphalt with aggregate steel slag to 70 % and an increase in the adhesion of asphalt with aggregate steel slag plus $Ca(OH)_2$ by 90 %. Fig. 5 describes adhesion testing results between aggregate and asphalt, steel slag and asphalt, and steel slag with asphalt plus $Ca(OH)_2$ in Static Immersion and Texas boiling test.

Fig. 5 shows that natural aggregates and steel slag have more than 90 % adhesion ability in the static immersion test method. This condition indicates that the mixture is feasible to be used as a material in making an asphalt hot mix where the requirements given are >95 %. The Texas Boiling test in Fig. 6 shows that the value is above 80 for natural aggregates and steel slag plus $Ca(OH)_2$ but below 80 for steel slag. Based on preliminary testing, it is concluded that retained less than 80 of the asphalt on the aggregate needs susceptibility moisture treatment.

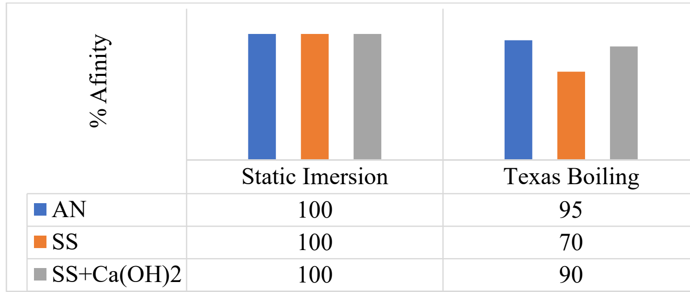

Fig. 5. Adhesion with asphalt

5. 3. Marshall stability and Marshall stability ratio

Marshall stability, immersion Marshall, and indirect tensile strength tested the compacted mixtures' strength and adhesion ability. Aggregates with selected distribution are added bamboo fiber stabilization materials 0.3 % with optimum asphalt forecasting content value of 6 %. The variation in tried asphalt content is estimated at 5 %, 5.5 %, 6 %, 6.5 %, and 7 %.

The optimum asphalt content was determined by the Marshall method (ASTM D-6927). The test result of the optimum asphalt content (OAC) value estimated at 6.5 % was chosen as a control test specimen, compared to the modified SMA. Visualization of modified test specimens can be seen in Fig. 6.

Fig. 6. Stone mastic asphalt modified steel slag and $Ca(OH)_2$

Marshall stability tests are performed to investigate the strength of mixtures and compare them with several combinations. The result of Marshall stability testing on various original SMA and modified SMA is shown in Fig. 7 stability value. The stability SMA standard is up to 600 kg. The results show that the stability of all types of mixtures has exceeded the standard value. However, with the addition of $Ca(OH)_2$, there was a consistent and significant increase in the stability value.

Steel slag from Krakatau Steel Company substitution based on testing with the Marshall method causes a decrease in stability by 6.5 %, from 877 kg to 820 kg. This is due to the affinity of steel slag with asphalt, which is lower than that of aggregate basalt with asphalt. The mixture's stability increases significantly after adding $Ca(OH)_2$, from 820 kg to 916 kg, even exceeding the combination without modification (SMA).In the Marshall test, the substitution of steel slag, which has properties as a heat conductor, causes asphalt to soften, and stability decreases compared to the same test on SMA with natural aggregate.

Fig. 8 shows the result of immerse Marshall testing, comparing conditional and unconditional treatment. MSR has a pattern of decrease in the SSAM mixture type, which significantly increases with the addition of $Ca(OH)_2$. In the LS 283 method, there is a difference in treatment between the Marshall test and the MSR test. In immerse Marshall testing, there is an interval of 1 hour for cooling the sample before Marshall testing. At intervals, the specimen hardens, and the test results show different reactions compared with the Marshall test.

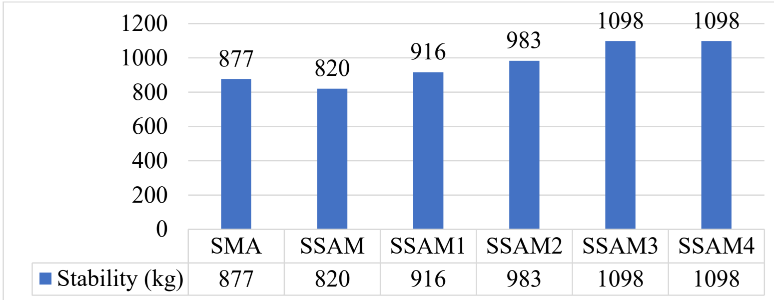

Fig. 7. Marshall stability

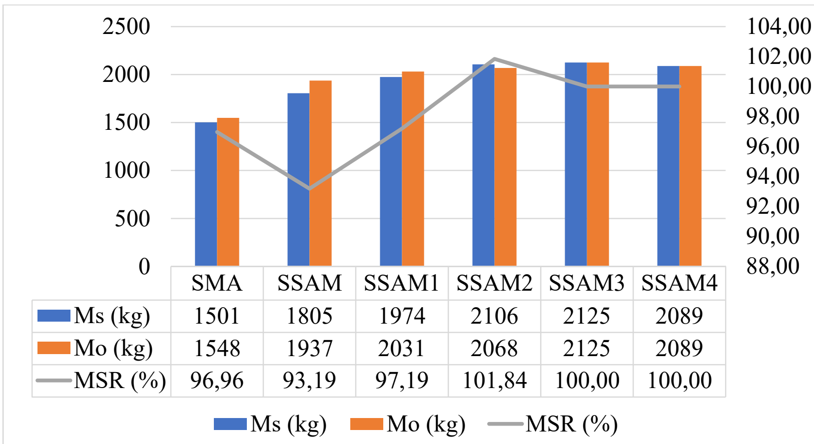

Fig. 8. Marshall Stability Ratio (MSR)

The standard MSR value for SMA is at least 90 %. All SMA mixtures have more than 90 % MSR value, above the standard MSR. That means the mix of unmodified and modified SMA is generally not moisture-sensitive. However, in SMA with steel slag substitution, there is a decrease in MSR value, and with the addition of Ca $(OH)_2$, there is an increase in MSR value.

5. 4. Indirect tensile strength and indirect tensile strength ratio

The indirect tensile strength (ITS) testing results on unconditional and conditional can be seen in Fig. 9. The result shows that the ITS and TSR values pattern increased with additive $Ca(OH)_2$. SMA's standard TSR value is at least 80 %. All TSR results show that it is valued higher.

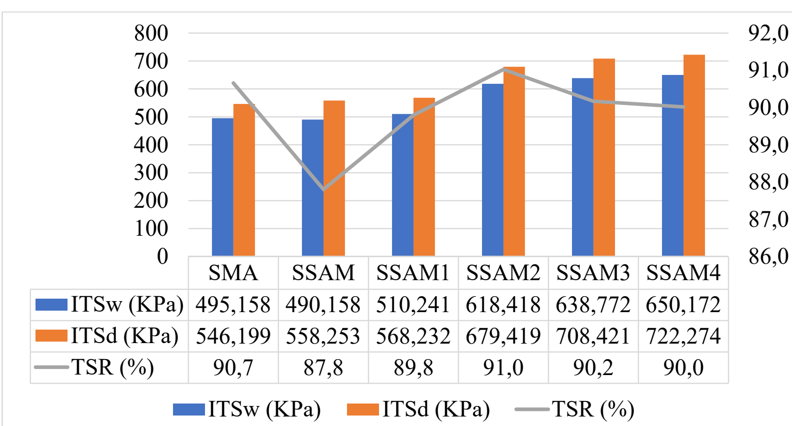

Fig. 9. Indirect tensile strength

The ITS value shows an increased pattern in both wet and dry conditions. The tensile strength ratio value shows the same pattern as MSR, where the peak is reached in SSAM with a modified $Ca(OH)_2$ of 2 %.

5. 5. Particle loss

Particle loss testing shows that the mixture's average particle loss is low because the SMA mixture has a high asphalt content compared to other hot mix mixtures. Fig. 10. shows that stone mastic asphalt without a mixture of steel slag and $Ca(OH)_2$ has the highest percentage of loose particles compared to the modified SMA. Substitution of some aggregates causes a significant decrease in particle loss. Particle Loss of conventional SMA 2.71 % decreased to 1.7 %, a decrease of 37.26 %. Adding $Ca(OH)_2$ to SSAM caused an increase in particle loss value to 2.46 % but still below SMA particle loss value without modification. Adding $Ca(OH)_2$ levels gradually decreases the particle loss value in the SSAM mixture.

This testing result explains that replacing aggregate with steel slag causes the mixture to become more compact, and addition with additive $Ca(OH)_2$ causes an increase in the number of particle losses but is still below the original SMA value. The addition of $Ca(OH)_2$ levels gradually decreases the value of particle loss.

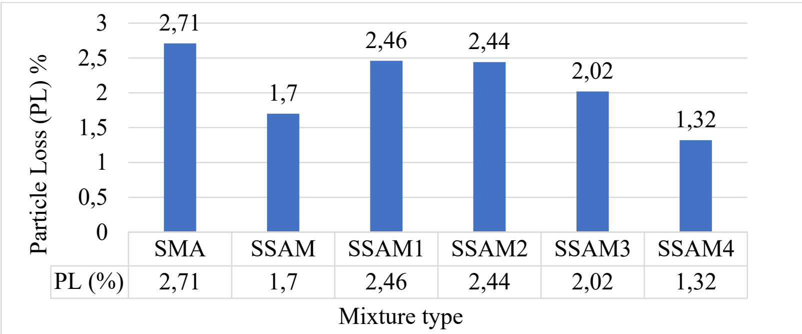

Fig. 10. Particle loss

6. Discussion of moisture resistance of stone mastic asphalt mixture with steel slag and $Ca(OH)_2$

According to previous studies, aggregate steel slag has a high angularity and porosity [18, 19]. However, this is not the case for the Krakatau Steel slag employed in this study. Compared to steel slag studied by previous researchers, the steel slag used in this research contains Fe_2O_3, which is much higher at 57.17 %, while the average in general Fe_2O_3 levels in steel slag range from 20–26 % [18]. This condition affects the physical characteristics so that steel slag aggregates are denser and have fewer pores than steel slags from other sources with grades lower than Fe_2O_3. This causes the water absorption of steel slag to be deficient at 0.68 % compared to basalt aggregate, where the water absorption ranges between 1.725 and 2.137 %. The Texas Boiling Test tests corroborate the assumption that the adhesion ability of steel slag to bitumen is lower than the natural basalt aggregate depicted in Fig. 5. Adding $Ca(OH)_2$ to the asphalt is mixed into the aggregate, increasing the adhesion between both. The adhesion of steel slag and asphalt, previously 70 %, increased to 90 %. Mixing $Ca(OH)_2$ into aggregate and asphalt must be preceded by mixing asphalt and $Ca(OH)_2$ and then mixing with the aggregate. If $Ca(OH)_2$ is directly mixed into steel slag aggregate and mixed with asphalt, it will cause different effects. The adhesion of the aggregate mixture of steel slag, $Ca(OH)_2$, and asphalt becomes very low. It can be understood that the presence of $Ca(OH)_2$ on the surface of the steel slag aggregate creates a weak boundary layer, where $Ca(OH)_2$ reacts like dust on the aggregate surface, weakening the adhesion force. This condition follows Bikermen's weak boundary layer [15].

The substitution of steel slag into SMA causes the mixture to be more compact. Fig. 6 illustrates this, which results in a greater specific gravity for steel slag. Compared to the original SMA, SSAM has the specimen's thickness reduced by an average of 1 centimeter and particle loss reduced by 37.3 % (Fig. 10). Unmodified modified SMA has much better compactness when compared to the same test on the other type of Hot Mix Asphalt conducted in the study [20].

Marshall's stability testing showed different results where the substitution of steel slag caused a decrease in the stability value by 6.5 %; the explanation can be seen in Fig. 7. This is possible because the substitution of steel slag, which is a conductor of heat and morphological properties of Krakatau steel slag with a slippery surface, low angularity, and small absorption power causes the adhesion bond between steel slag and asphalt to be down at hot temperatures, resulting in decreased stability.

Stability gradually increases with the addition of $Ca(OH)_2$. A significant increase in stability occurred in the provision of $Ca(OH)_2$ levels of 1 %, where stability increased by 11.7 % compared to SSAM, and the stability value achieved was 916 kg, exceeding the stability value of the original SMA with a value of 877 kg. SSAM1 stability compared to SMA increased by 11.7 %. Adding a 2 % increase in $Ca(OH)_2$ levels provides a 7.3 % increase in stability compared to lower $Ca(OH)_2$ use. Adding a 3 % increase in $Ca(OH)_2$ levels provides an 11.7 % increase in stability compared to more subordinate $Ca(OH)_2$ use. Furthermore, adding $Ca(OH)_2$ levels by 4 % provides no increase in stability compared to the administration of lower $Ca(OH)_2$ levels.

Marshall immersion testing showed that the average ratio between the stability of the mixture in the original and modified SMA conditions was high, indicating that residual strength after soaking was not significantly different from in dry conditions. All MSR results show that values up to 90 % mean all SMA types are not moisture-sensitive. Adding steel slag to the SMA mixture decreased the 3.74 % MSR value compared to the original SMA and increased after adding $Ca(OH)_2$. This means that the modification of steel slag causes a considerable difference in stability performance in conditional and unconditional treatment. $Ca(OH)_2$ treatment improved MSR performance above MSR SMA without modification (Fig. 8). Adding $Ca(OH)_2$ 1 % to SSAM resulted in a 3.96 % increase in MSR value. An average increase of 3.9 % with each addition of $Ca(OH)_2$ levels, rather than an increase in MSR value above 2 %, did not make a difference.

The same pattern is due to the result of Indirect tensile strength testing; all TSR values show decreases when steel slag substitution is carried out, and there is an increase in the addition of $Ca(OH)_2$. Adding $Ca(OH)_2$ to more than 2 % has no significant effect on TSR. The addition of steel slag and $Ca(OH)_2$ caused a significant decrease of a void in the mixture (VIM) value; in unmodified SMA, the VIM value of 7.72 in SSAM to 5.37 and SSAM1, SSAM2, SSAM3, and SSAM4 had values of 5.165, 3.98, 4.05 and 4.92. The standard limitation of SMA's VIM on by Indonesia Highway Ministry 2018 and Indonesian National Standard SNI 8129:2015 is about 4–5. Based on this study, 1 % to 2 % additives are recommended for a combination of stability, MSR, TSR, and VIM values matching the target specification.

The study's limitation is that the steel slag used comes from a single source (Krakatau Steel Indonesia co), and the percentage of substitution is 60 % of the aggregate weight at 4.75–9.5 mm. More research on the different types of steel slags is needed so that their effects on the mechanical properties of SMA mixtures can be directly compared, to determine the specifications and proportions of steel slags that can be used in practice.

7. Conclusions

1. The physical and chemical characteristics of steel slag play an essential role in the stability and moisture resistance

of the mixture. Krakatau steel slag has a very high reach 57.17 % Fe_2O_3 content. Substitution of steel slag in SMA mixture increases mixture compactness and decreases particle loss, a decrease of 37.26 %.

2. Adhesion testing on a loose mixture showed that steel slag has lower adhesion than aggregate basalt, a value of 70 %, and adhesion increases after the addition of $Ca(OH)_2$ to 90 %.

3. Adhesion testing on compacted SMA mixture with MSR values in steel-slag stone mastic asphalt modified $Ca(OH)_2$ mixtures were more than steel-slag stone mastic asphalt without $Ca(OH)_2$. The MSR value of SSMA decreases by 3.8 % of SMA and gradually increases after adding $Ca(OH)_2$. The Marshall stability value on the mixture of SSAM decreases by 6.5 % and increases significantly after adding $Ca(OH)_2$.

4. Indirect tensile strength value tends to increase. The tensile strength ratio (TSR) shows a decrease in SSAM by 3.2 % of the original SMA and gradually increases after adding $Ca(OH)_2$. However, the results of MSR and TSR showed that all SMA mixes are not moisture-sensitive.

5. Particle loss (PL) value shows that adding steel slag decreases by 37.27 % compared to unmodified SMA. Adding $Ca(OH)_2$ to the mix makes particle loss increase but still under the PL value of unmodified SMA.

Conflict of interest

The authors declare that they have no conflict of interest with this research, whether financial, personal, authorship, or otherwise, that could affect the study and its results presented in this paper.

Financing

This study was conducted under the research project "Doctoral Dissertation Research (Project No: 199/E5/PG.020.00. PL/2023)" (PDD) DRTPM DIKTI TA Research Program 2023 by LPPM Brawijaya University funded by the Ministries of Education, Culture, Research, and Technology Indonesia.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

The authors thank the research team members for their guidance and support throughout LPPM Brawijaya University and the Ministries of Education, Culture, Research, and Technology Indonesia.

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