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# The Impact of Polylactic Acid on Sustainable Asphalt Mixture

**Naktal.Z. Hamed**
naktal.21enp62@student.uomosul.edu.iq

**A.I. Al-Hadidy**
alhadidy@uomosul.edu.iq

Civil Engineering Department, College of Engineering, University of Mosul, Mosul, Iraq

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***ABSTRACT***

*Recently, sulfur waste SW has been utilized as a potential calcium carbonate $CaCO_3$ mineral filler replacement. This study evaluated the effects of polylactic acid (PLA) polymer on asphalt mixtures containing $CaCO_3$ filler and asphalt mixtures containing SW as alternative fillers. A 40-50 mixture of paving-grade asphalt with a PLA ratio of 1.5% by weight of asphalt was blended. Performance tests, including Marshall stability (MS), Marshall quotient (MQ), indirect tensile strength (ITS), and deformation strength (SD) in the Kim test, were performed on asphalt mixtures. Test results showed that the (MS) and (MQ) mixtures containing filler SW increased by 1.4% and 23.1%, respectively, while the values of the (ITS) and (TSR) rates decreased (13.1% and 2.8%), respectively, and (SD) were very close. The modified asphalt mixtures were better than the unmodified mixtures in terms of MS, MQ, ITS, TSR, and SD. The values increased by 37%, 27.9%, 29.4%, 4.35%, and 7.18%, respectively, incomprison with the unmodified asphalt mixtures containing sulfur waste. Likewise, the values increased by 50.6%, 56.8%, 32.1%, 2.66%, and 6.11%, respectively, in comparison with the unmodified asphalt mixtures containing $CaCO_3$. Generally, the modified mixtures were better than the unmodified mixtures. Sulfur waste can be used as a sustainable mineral filler for paving applications without and with 1.5% PLA polymer, as it is low-cost and available.*

***Keywords:***
*Sulfur waste (SW), Mineral filler, PLA-modified asphalt, Calcium carbonate replacement.*


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*Email: alrafidain_engjournal3@uomosul.edu.iq*

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## 1. INTRODUCTION

Hot mix asphalt (HMA), still the most widely used material in this kind of construction, makes up more than 95% of road pavements. Its extensive use may be attributed to its advantages in terms of economics, structure, and usefulness. (HMA) is the outermost layer of a road that is subjected to all environmental and traffic stresses, necessitates the highest construction costs, and directly affects indirect costs and road safety [1]. Hot asphalt (HMA) mixtures are complex compounds made of asphalt, minerals, and air spaces [2]. The most common substance utilized in building projects for different kinds of pavements is asphalt binder. Aggregates and asphalt binder are the two primary ingredients of asphalt mixes. Course, fine, and filler aggregates make up more than 90% of the asphalt mixture in hot mix asphalt (HMA), with asphalt binder making up the remaining portion [3]. For asphalt pavement to be long-lasting, technologies that increase the material life cycle and reduce life cycle costs are required. Reducing waste production through reuse [4]. Professionals and academics have expressed concerns about the practicality of using traditional building materials to address ecological challenges in light of the global movement towards environmental sustainability. The substitution of waste materials for traditional fillers is gaining traction as a means of enhancing the sustainability of pavement construction [5]. Furthermore, using sulfur waste in asphalt concrete mixes rather than conventional fillers is an innovative strategy that promotes economy, sustainability, and reduction in the quantity of waste disposed in landfills [6]. In a study conducted by H. T. Mahmood et al. [7], many experiments were performed on unmodified hot asphalt mixes and warm mixtures (added with zeolite), both of which contained two types of fillers (calcium carbonate and sulfur waste filler). The testing included Marshall characteristics (Marshall stability, Marshall quotient, and indirect tensile strength) that improved when the calcium carbonate filler was replaced with a sulfur residue filler in both hot and warm mixes. The TSR value reduced marginally when sulfur waste was used in hot mixes; however, warm mixtures saw a significant rise in the TSR value when sulfur waste was used as a filler. In a study conducted by S. K. Rasheed and A. Al-Hadidy [8], it was determined that using SW as a mineral filler in environmentally friendly pavement construction was feasible. In order to evaluate three different sulfur waste asphalt concrete (SWA) combinations with a reference calcium carbonate asphalt concrete mixture, asphalt binders with penetration grades ranging from 40 to 50 were used. While the standard AC mix had 5% $CaCO_3$ by total weight of aggregate, several SWA combinations were created with 4%, 5%, and 6% SW by weight of aggregate. Important characteristics for both AC and SWAC combinations were assessed, including tensile strength ratio, Marshall stability, and Marshall quotient. According to the study's findings, sulfur waste may be effectively added to asphalt concrete at weight-per-aggregate rates ranging from 4 to 5%. In a recent study, sulfur waste has been used as a partial substitute for asphalt [9]. In recent research, calcium carbonate, the conventional filler, has been replaced with another sort of sulfur waste known blowdown, which is accessible in great amounts in Iraq and is an inexpensive material that can be combined with hot asphalt mixes [10].Today, filler is just as important as bitumen and aggregates in the materials used to make pavements. Despite making up a very minor portion of the total weight, it has a significant impact on the running expenses of bituminous pavement. When filler is employed appropriately, the effectiveness of HMA combinations is improved and increased [11],[12]. Fillers must have certain physical and chemical qualities that allow the aggregates and asphalt binder to be compatible in order to provide excellent rheological behavior of the mixture at the various temperatures experienced over the life of the asphalt mixture layer [13],[14]. One of the primary causes of problems with HMA, such as fatigue cracking and moisture sensitivity, is the poor adhesion between the binder and particles in asphalt mixtures [15]. Different kinds of polymers are added to asphalt mixes as additives to increase the binders' and aggregates' adherence [16]. This enhances the dynamic modulus, rutting resistance, and fatigue life of asphalt mixes by making them harder and more flexible. These benefits are significant when compared with unmodified binders, particularly at high temperatures [17]. polylactic acid (PLA) is a thermoplastic polymer with a high modulus and strength that is insoluble in water made from yearly renewable resources like cornstarch or sugarcane [18]. Its chemical symbol is C2H4OHCOOH, and its melting temperature is 150–160 °C. Its density is 1210–1430 kg/m3, and its water absorption is 0.5–50% [19]. Petroleum-based plastics, which have a number of detrimental effects on the environment, including pollution, might be replaced with PLA, a possible plastic material. Polylactic acid (PLA) is biodegradable, easily obtainable, and environmentally benign. PLA is biocompatible and processable, and it resembles other common polymers both mechanically and physically. PLA will therefore be a long-lasting and reasonably priced product, in addition to shielding the environment from pollutants [20].

## 2. STUDY OBJECTIVE

This study's primary goal was to compare the mechanical performance of unmodified and modified asphalt mixtures with PLA. The asphalt mixtures contained two different types of fillers: calcium carbonate and sulfur waste. To achieve this, a number of laboratory tests were conducted, including performance tests, including Marshall stability tests, Marshall quotient tests, and tests of the mixture's indirect modulus tensile strength at 25 °C and 60 °C, as well as the tensile strength ratio, crack tolerance index (CTindex), and KIM deformation strength test at 60 °C.

## 3. MATERIALS

### 3.1 Aggregate

As seen in Table 1, the material utilized in this study is river sand and crushed gravel from Khasir Quarry. In northern Iraq, road building projects often employ these kinds of materials. In this investigation, a high-density asphalt mixture (D4) that complied with ASTM D3515 criteria was employed [21]. Figure 1 shows specifics on the aggregate gradation, which is included within the specification limitations' median range.

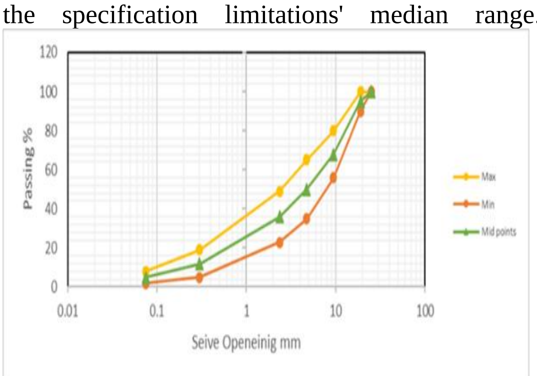



Figure 1: The aggregate gradation, falling within the median range of specification limit

Table 1: Aggregate characteristics, both fine and coarse

| Property | Coarse aggregates | Fine aggregates | Specification ASTM |
|---|---|---|---|
| Toughness | 19.61% | - | C131[22] |
| Angularity | 96.21% | 44.71% | D5821 [23]&[24] C1252 |
| Soundness $Na_2SO_4$ | 0.95% | 0.721% | C88[25] |
| Water absorption | 0.98% | 1.432% | C127[26] & C128[27] |
| Bulk specific gravity | 2.73 | 2.65 | C127[26]& C128[27] |
| Apparent specific gravity | 2.77 | 2.72 | C127[26]& C128[27] |

### 3.2 Asphalt Binder

Asphalt cement (AC) with a penetration grade of 40–50 (P40) was provided by Dora Refinery for this study. This type of asphalt is used to build the bulk of the country's highways [6]. Table 2 shows the rheological properties of PLAMA and P40.

To make a homogenous binder, PLA was combined with P40 asphalt at a rate of 1.5%. As seen in Figure 2, the polymer strands were crushed in a food mill to lower molecular weights and enable a consistent mixing procedure in order to produce PLA-modified asphalt (PLAMA).
The following procedure was followed to mix the modified asphalt cement samples:

1. The asphalt cement was heated in the kiln to a temperature of no less than 160 °C Celsius.
2. The stainless steel mixing bowl is kept in the oven at a temperature of no less than 160 °C.
3. To determine the appropriate ratio of additive to asphalt, we first weighed the required amount of asphalt in the beaker and then the required amount of additive.
4. Asphalt mixtures were made using 1.5% PLA according to the total weight of asphalt.
5. The beaker was placed on a hot plate with a minimum mixing temperature of 160 °C for a minimum of two hours. Next, the laboratory mixer's impeller was placed about 1.5 cm above the beaker's bottom.
6. Lightly agitate the beaker and gradually pour the prepared quantity of additive into it after turning on the blender. For 1.5 hours, the mixer speed was increased to 680 rpm in order to produce a homogenous asphalt binder [28].

(a) (b)

Figure 2: PLA mixing process (a) -PLA filaments during grinding, (b) -Mixing PLA and AC with a shear mixer.

Table 2: The rheological properties for P40 and

| Property | Test method | P40 | NCCL limits [29] | 1.5% PLA |
|---|---|---|---|---|
| Penetration at 25°C (0.1mm) | ASTM D5 [30] | 40 | 40-50 | 32 |
| Softening point (°C) | ASTM D36 [31] | 51 | 51-62 | 52 |
| Ductility at 25°C (cm) | ASTM D113 [32] | >100 | 100 min. | >100 |
| Elastic recovery @ 25°C (%) | ASTM D6084[33] | 35 | 75 min | 15 |
| Homogeneity (%Passing) | ASTM D6230 [34] | - | - | Passed |

PLAMA

### 3.3 Mineral fillers

#### 3.3.1 Mineral fillers ($CaCO_3$)

The Ashur Hot Mix Asphalt Factory in Mosul provided the ($CaCO_3$), which was used as a filler.

### 3.3.2 Sulfur Waste

Sulfur waste (SW) was also used instead of the typical mineral filler ($CaCO_3$) in this study. The Mishraq sulfur plant in Nineveh, northern Iraq, was a source of solid waste. It was collected there as waste from processes involving the manufacture of sulfur. The physical and chemical properties of fillers are listed in Table 3. Figure 3 shows the many types of fillers.

(a) (b)

Figure 3: (a- $CaCO_3$ & b- Sulfur waste)

Table 3: Physicochemical Properties Fillers ($CaCO_3$ and SW)

| CaCO3 | | Sulfur waste | |
|---|---|---|---|
| Element | Weight % [35] | Element | Weight % [9] |
| ($SiO_2$) | 2.7 | Total sulfur | 92.3 |
| ($Al_2 O_3$) | 0.35 | Combined sulfur with carbon | 13.28 |
| ($Fe_2 O_3$) | 0.94 | Free sulfur | 79 |
| (Cao) | 50.7 | Total carbon | 7.64 |
| (MgO) | 0.65 | Bitumen | 0.029 |
| ($Na_2 O$) | 0.02 | Ash as a pentonite | 0.069 |
| Sulfur Trioxide ($SO_3$) | 0.75 | Carbonized materials | 20.98 |
| Specific Gravity | 2.7 | Specific gravity | 2.20 |
| Gradation for Two Types of Filler | | | |
| Sieve Opening (mm) | Passing % | [36] | |
| 0.6 | 100 | 100 | |
| 0.3 | 100 | 95 – 100 | |
| 0.075 | 100 | 70 – 100 | |

## 4. EXPERIMENTAL WORKS

### 4.1 Mixture design

The Marshall method was used to estimate the optimal asphalt content (OAC) for each type of binder and to construct asphalt mixtures according to ASTM D6927-1 [37]. Asphalt samples were manufactured using five different percentages of bitumen: 4%, 4.5%, 5%, 5.5%, and 6% by weight of the mixture.

Using a typical Marshall template, three cylindrical samples were made for each bitumen concentration. After being pounded 75 times on each side, the samples were left to cool for a day. Prior to testing, the samples were submerged for thirty to forty minutes in a water bath at 60 °C. An automated Marshall tester was then used to accomplish lateral compression until the maximum load was reached, at a loading rate of 50.8 mm/min. For every modified asphalt mixture (PLAMA) that contained carbonate filler and every unmodified hot mix asphalt (HMA), an assessment was carried out that included flow (mm), air spaces (%), stability (kN), and aggregate voids (%). $CaCO_3$, or calcium. According to NCCL limits (4%-6%) , the OBC for virgin binder and PLAMA binder were 5% (by total weight of mixtures) [29]. This research resulted in four different types of asphalt mixtures, two of them were unmodified and contained P40 asphalt, and the other two types of fillers were used at a ratio of 5% of the weight of the total aggregate (calcium carbonate and sulfur waste). The other contains a modified asphalt binder at a rate of 1.5% (PLA) by weight of the total asphalt using the two types of fillers above. Numerous techniques have been used to assess the mechanical qualities of asphalt mixes, including Marshall properties and indirect tensile strength assessments. A measure of durability, particularly in relation to moisture damage, was the tensile strength ratio. KIM tests were also used to assess persistent deformation.

### 4.2 Tests for Marshall Stability and Flow

As a typical practice, the Marshall mix design (ASTM D 6927) approach is used to optimize mixes for asphalt concrete [37]. Furol Viscosity (FV) was used to determine the mixing and compaction temperatures for both PLAMA and unmodified asphalt mixes at various temperatures. The Seybold-Furol viscosities at these temperatures are, respectively, 85 and 140 s, citing the Asphalt Institute handbook [38],[39] . It should be noted that the 1.5% PLA addition rates were chosen as a result of the trials carried out to produce a homogenous binder, and they were subsequently added to the optimal asphalt content

(OAC). The compatibility of PLA with asphalt was demonstrated using the ASTM D6230 test [34]. How this test process is conducted will depend on whether the polymer and asphalt binder can work together to produce a homogenous slurry that can pass the ASTM 100 sieve. The combined sample was passed through an ASTM 100 sieve after being heated to 165 °C for ten minutes. At the end, it was found that more than 95% of combinations passed through, indicating compatibility with PLA asphalt binder. The FV of P40, or the mixing and compaction temperatures of the hot-mix asphalt, increases with the addition of PLA, asillustrated in Figure 4.

Marshall tests were performed, in compliance with ASTM D6927-15 [37], on samples of HMA and PLAMA mixes with regular fillers as well as samples containing sulfur waste after they were submerged in a water bath at 60 °C for 30 to 40 minutes. The samples were run into a Marshall test machine at a rate of 50.8 mm per minute until failure after their surface had dried. Figure 5 illustrates the Marshall testing for samples of asphalt. The maximum load value (kN) at which a sample fails is known as Marshall stability. The entire amount of deformation measured at maximum load is known as the Marshall flow (mm). The Marshall quotient, which is equal (stability/flow) has also been used to evaluate the hardness of mixtures.

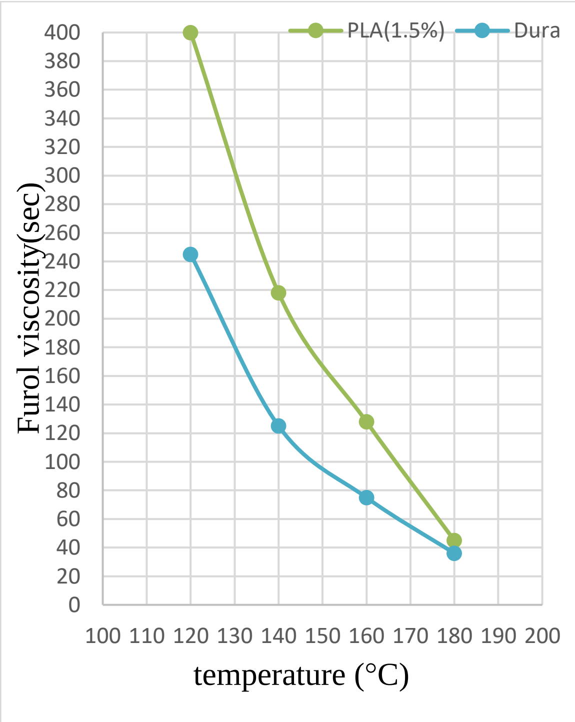



Figure 4: Furol viscosity

(a) (b)

Figure 5: Marshall Testing for Asphalt Samples (a- the machine, b- tested specimens).

### 4.3 Tensile and moisture damage characteristics

The indirect tensile strength (ITS) test, which was conducted in accordance with ASTM D6931 [40], was used to assess the tensile properties and moisture susceptibility of asphalt mixtures. The procedure outlined in the Marshall method was the same for preparing specimens for the ITS test. The specimens that were produced had a diameter of 101.6 and an air void content of 7.0 ± 1%. The specimens were allowed to cool for a day at room temperature after the compaction process. Subsequently, three samples from every combination group were submerged for 120 minutes at 25 °C in a water bath. The Marshall compression machine (Figure 6) was then used to test each sample's ITS at a load rate of 50.8 mm/min until the maximum load was recorded. To get the ITS values for the specimens, the following equation (1) was used:

$$ITS = \frac{2P}{\pi d t} \quad \text{……..(1)}$$

The 'P' in this equation stands for the ultimate load in Newtons (N), the 't' for thickness in millimeters (mm), and the 'd' for diameter in millimeters (mm). The 'ITS' in this equation is measured in megapascals (MPa). The tensile strength ratio (TSR) test, however, is one of the most crucial techniques for determining the extent of moisture damage to asphalt pavements. The results of this test meet the requirements of the ASTM D4867/D4867M [41] standard, which specifies that an air void volume of 7 ± 1% is the best testing condition. Three Marshall samples from each mixing group are submerged in water maintained at 60 °C for a whole day in order to conduct the TSR test. After that, they spend two hours in a water bath at 25 °C, and an ITS test is carried out. The tensile strength of these conditioned samples is then contrasted with that of unconditioned samples from the same mix. The indirect tensile strength (ITS) can be calculated to enable this comparison. The unconditional (U) tensile strength is provided at 25°C, while the conditional (C) tensile strength is provided at 60°C. After that, the final TSR% is calculated using Equation (2):

$$TSR\ (\%) = \left(\frac{ITS_C}{ITS_U}\right) 100 \qquad …….(2)$$

Here, "ITSC" denotes the conditional indirect tensile strength in megapascals (MPa), "ITSU" denotes the unconditional indirect tensile strength in MPa, and "TSR" denotes the percentage (%) of tensile strength.

(a) (b)

Figure 6: Indirect Tensile Strength (a- the machine, b- tested specimens).

### 4.4 Indirect Tension asphalt cracking test (IDEAL-CT) at intermediate temperatures

The cracking resistance of both unmodified and PLA-modified asphalt mixtures was evaluated using the IDEAL-CT test. In compliance with ASTM D8225 [42], the test was carried out at intermediate temperatures, namely 25 °C for the binders used in this work. The specimens were crushed by a continuous displacement force applied at a speed of 50 mm/min. For every group, an air-void percentage objective of 7±0.5% was set. Several crushing performance metrics may be computed using this test by looking at the load versus displacement curve that is noted. the crack tolerance index $CT_{index}$. Higher ITS and $CT_{index}$ values imply greater resistance to fatigue cracking. The $CT_{index}$ is a performance indicator statistic that's used to evaluate how resistant the mixture is to cracking. It is calculated using the parameters of the load-displacement curve as shown in Figure 7 [43], and the outcome is given by using Eq. (3):

$$CTindex\ = \frac{t}{62} \times \frac{l75}{D} \times \frac{Gf}{|m75|} \times 10^6 \qquad ….. (3)$$

Whereas CT is an indicator of fracture tolerance, Gf is failure energy (joules/m$^2$). The absolute value (N/m) of the post-peak slope is $|m_{75}|$. The displacement (mm) at 75% of the post-peak load is denoted by L75.D is the diameter of the specimen (mm), and t is the thickness of the specimen (mm).

Equation (4) may be used to compute Gf by dividing the work of failure, or the area under load versus the mean displacement curve, by the cross-sectional area of the specimen.

$$Gf\ = \frac{\mathrm{wf}}{\mathrm{D}\times\mathrm{t}} \times 10^6 \qquad …….(4)$$

where Wf = work of failure (joules), D = specimen diameter (mm), t = specimen thickness (mm), and Gf = fracture energy (joules/m$^2$).

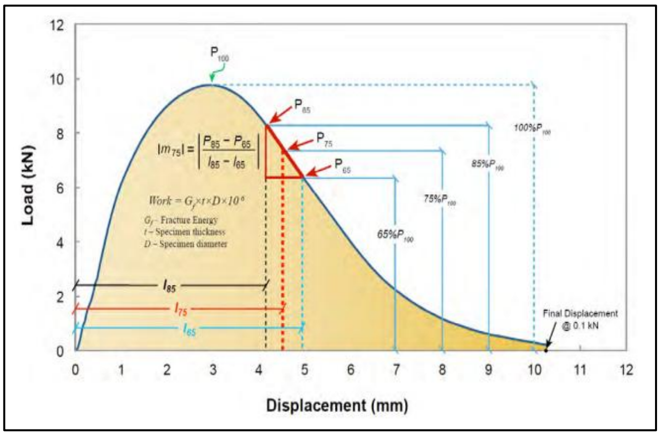



Figure 7. Curve of recorded load (P) and load-line displacement. ASTM D8225 [42]

### 4.5 Kim test (Deformation strength)

Asphalt mixes' deformation strength (SD) is assessed using the Kim test. It has been shown that the results of tests linked to ruts, including wheel tracking for mixes with dense grades, agree rather well (R2 > 0.9) with the SD found by the relatively easy and fast Kim test. Consequently, the SD was approved as a standard specification for asphalt mixture design by the Korean Ministry of Land, Transport, and Maritime Affairs. [44]. preparing the specimen in a manner similar to the Marshall approach [45], subsequently, a loading head with a diameter of 30 mm and a circular edge radius of 7.5 mm is positioned at the top center of the specimen, and a static load is delivered at a rate of 50.8 mm/min. This is the methodology used for the Kim test. As shown in Figure 8, the specimen is placed on the loading frame after being submerged in water at 60 °C for 30 minutes. The SD was calculated using Equation (5).

$$SD\ = \frac{4P}{\pi\left[D-2\left(r-\sqrt{2ry-y^2}\right)\right]^2} \qquad ……. (5)$$

"D" denotes the loading head diameter (mm), "r" the radius of curvature at the loading head's bottom (mm), "P" denotes the maximum load (N), "y" denotes the deformation (mm), and

"SD" is the deformation strength in megapascals (MPa).

(a) (b)

Figure 8: Kim test (a-the device, b- tested specimens)

## 5. RESULTS AND DISCUSSIONS

The statistical analysis, which comprised Fisher's least significant difference (LSD) comparison and analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$, was carried out using Minitab software. Following the LSD computation, pairwise comparisons of all sample means were performed. If the sample mean difference was more than or equal to the LSD, the samples were considered statistically different, as shown in Table 4; groups whose letters differed were considered to be significantly different. Keep in mind that the letter "A" represents the highest values, and the letters that follow it represent lesser values.

### 5.1 Marshall test characteristics

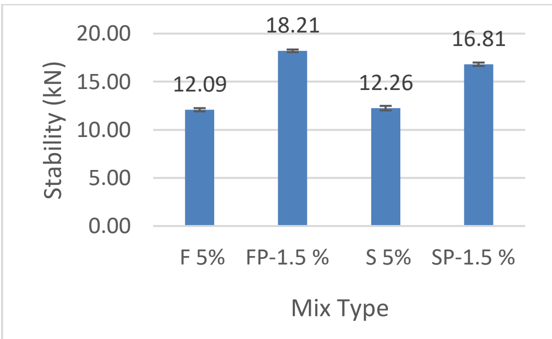
Marshall stability results using the LSD test, as shown in Table 4, show that there are differences between the different asphalt mixtures examined. In comparison to mixtures using unmodified calcium carbonate filler F, the inclusion of unmodified sulfur waste filler S improved the stability of A40 mixtures by 1.4%. Also, the modified mixtures (SP1.5%) showed higher stability than the unmodified mixtures by 37.1%. Likewise, for the modified mixtures of FP1.5%, stability values increased by 50.6% compared to the unmodified F mixtures. As shown in Figure 9a.

Overall, adding waste sulfur to both A40 and PLAMA mixtures improves Marshall stability. According to Marshall flow values (Figure 9b), for the A40 mixtures, the unmodified S mixtures had lower flow values than the unmodified F mixtures, with a decrease of 17.72%. This could be explained by the free sulfur in the sulfur waste causing the crystallization and organization of the asphalt mixtures' structure, which enhances the mixtures' stability, hardness, and corrosion resistance [46]. As for the modified mixture, SP1.5%, the flow value increased by 9.32%. The modified mixtures FP (1.5%) had lower flow values than the unmodified mixtures F, with a decrease of 3.17%.

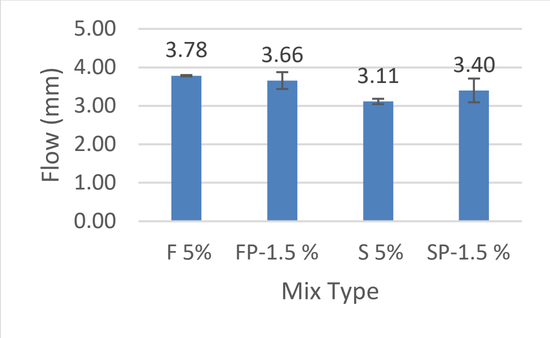
The stiffness was calculated using the Marshall quotient (MQ), which is equal to stability/flow. Harder mixtures, indicated by higher Marshall quotient values, indicate greater resistance to rutting [47]. According to the MQ results (Figure 9c), there is an improvement of 23.1% when comparing the unmodified S mixtures with the unmodified mixtures F. Likewise, the MQ values of the SP 1.5% modified mixtures were found to be higher than those of the unmodified S mixture, with an increase of 27.9%. MQ values were significantly larger in the modified mixtures of FP1.5% than in the original F mixture, with an increase of 56.8%.

The air-void ratio of the unamended mixtures S decreased slightly by 0.5% compared to the unamended mixtures F. Also, the mixtures amended with SP1.5% and the unamended mixture S had almost identical air-void ratio values. The modified mixtures FP1.5% showed a 17.5% reduction in air void ratios compared to the unmodified mixtures F, as shown in Figure 9d.

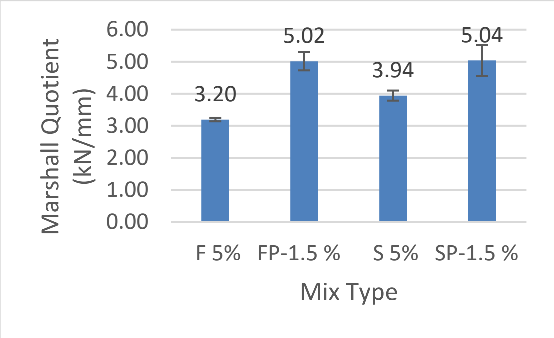
In general, the behavior of the Marshall properties results for unmodified asphalt mixtures containing calcium carbonate fillers and sulfur residue fillers was identical to the behavior of the results of a recent study conducted by H. T. Mahmood et al.[7]. The reported improvement of the modified asphalt mixtures compared to the unmodified asphalt mixtures, may due to the improvement of the properties of the binder when adding PLA [48] .



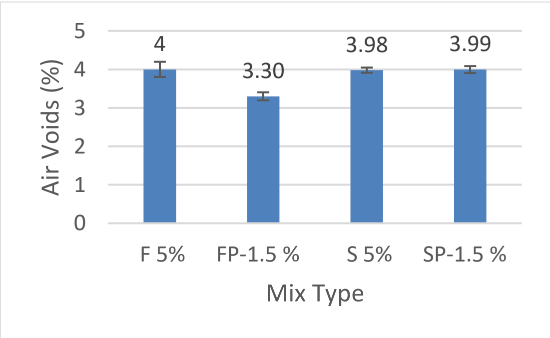

(a)




(b)




(c)




(d)

Figure 9: Marshall test results (a- stability, b - flow, c- Marshall quotient, d- air voids)

### 5.2 Deformation Strength (Kim test)

Based on the LSD test results in Table 4 for the A40 mixture, Figure 10 displays the SD results. Mixtures S display a similar SD value to mixtures F. the results were lower than those obtained in a recent study [49] ,where blowdown was used as a filler. The reason for this may be that blowdown contains more free sulfur than sulfur waste used and that adding material based on sulfur to asphalt mixtures increases the mixtures' stiffness, which increases their resistance to rutting [50], [51]. In addition, the SD value was improved by 7.18% for the modified mixtures SP 1.5% compared with mixtures S, and the modified mixtures FP 1.5% showed an improvement over mixture F of 6.11%. According to the standards provided by the Korean Ministry of Land, Infrastructure, and Transport, all SD values were higher than the minimum value of 3.20 MPa [52].

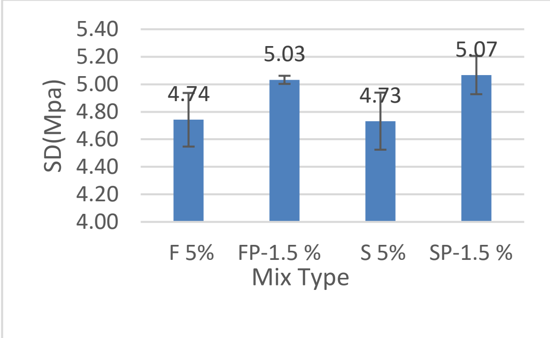
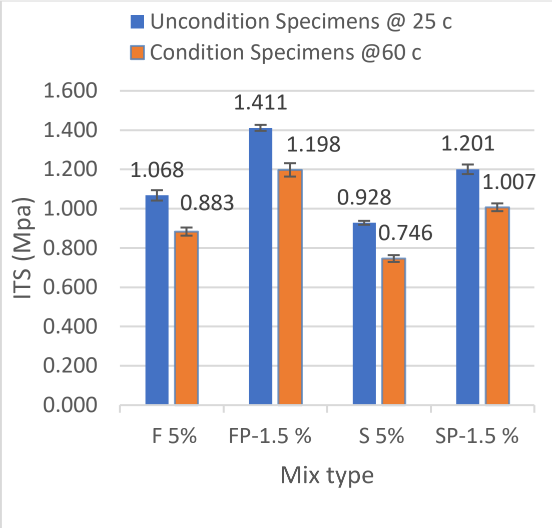


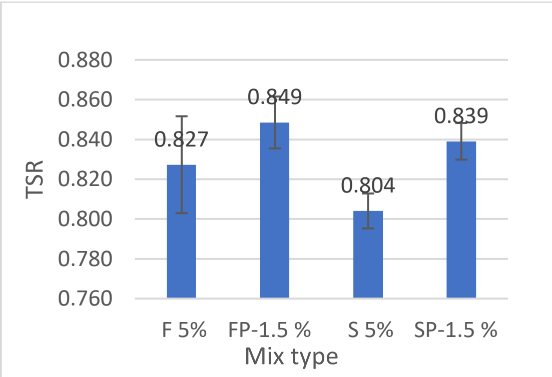

Figure 10: Kim test results

### 5.3 Tensile strength and moisture susceptibility tests

According to the results of the LSD test (Table 4) and the indirect tensile strength test (Figure 11a) of the unconditioned samples, mixture S has 13.1% lower ITS values than mixture F. When comparing the SP 1.5% modified mixture with the unmodified mixture S, the ITS value increased by 29.4%. The modified mixtures of FP1.5% also had a higher ITS value, 32.1% more than the unmodified mixture F. This indicates increased resistance to tensile stresses and can help prevent cracking. As for the TSR values shown in Figure 11b, they are within NCCL (2018) specifications. When adding sulfur waste filler, the TSR values decreased slightly by 2.8% compared to mixtures containing calcium carbonate. The TSR value of the modified mixture SP1.5% increased slightly by 4.35% compared to the mixture S. Likewise, the modified mixture FP1.5% had a slightly increased TSR value of 2.66%. compared to the unmodified mixture F. The use of sulfur waste as filler and its high sulfur content, which may cause poor bonding in asphalt mixtures, is the reason for the low TSR values. When exposed to water at a temperature of 60 °C for 24 hours [53], Figure 11b shows the TSR values. However, the effect of adding sulfur residue on the TSR value was limited, indicating that these modified mixtures still had sufficient resistance against moisture, and the TSR value was acceptable according to NCCL standards [29].

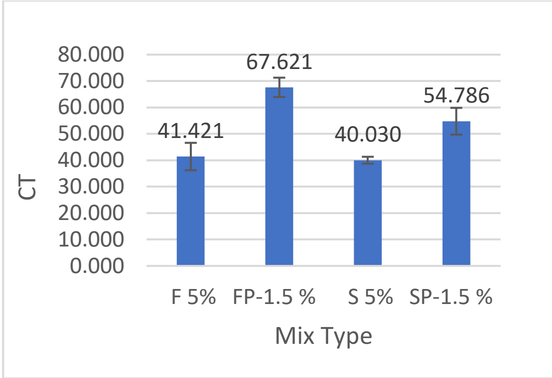



(a)

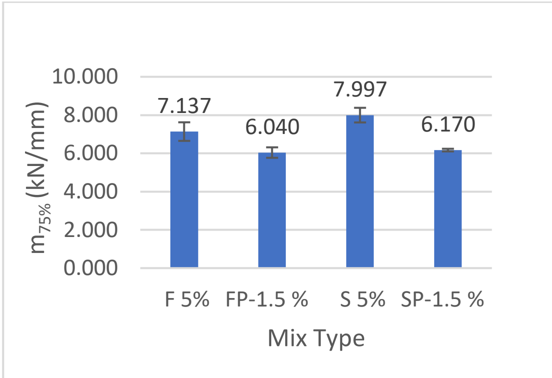



(b)

Figure 11: Tensile characteristics results (a- ITS, b – TSR)




(a)




(b)

Figure 12: Tensile characteristics results (a-Ct, b - $m_{75\%}$)

### 5.4 IDEAL-CT at intermediate temperatures

The $CT_{index}$ analysis approach was used in this study to evaluate the asphalt mixes' cracking propensity for the ITS test. Based on the load-displacement curve acquired from an ITS unconditioned test [54], Figure 12a shows that the $CT_{index}$ increased while $m_{75}$ dropped, as shown in Figure 12b [55]. According to the results of the LSD test (Table 4) and the crack tolerance index $CT_{index}$ test (Figure 12a) of the unconditioned samples, mixture S has 3.3% lower $CT_{index}$ values than mixture F. When comparing the SP 1.5% modified mixture with the unmodified mixture S, the $CT_{index}$ value increased by 36.8%. The modified mixtures of FP1.5% also had a higher $CT_{index}$ value, 63.2% than the unmodified mixtures of F. All of the mixes' meet the requirements of ASTM D 8225 [42].

Table 4: arranging data information using the LSD test.

| Test | F | FP 1.5% | S | SP 1.5% |
|---|---|---|---|---|
| Marshall stability | C | A | C | B |
| Marshall flow | A | AB | B | AB |
| Marshall quotient | B | A | B | A |
| Air voids | A | B | A | A |
| Indirect tensile strength, 25 °C | C | A | D | B |
| Tensile strength ratio | A | A | A | A |
| Deformation strength (Kim test) | A | A | A | A |
| CT (Cracking Tolerance Index) | BC | A | C | AB |

In a study conducted by N. Jailani et al. [56], in which different percentages (3%, 5%, 7%, and 9%) were mixed with asphalt (a penetration degree of 60–70), the study proved that PLA was chemically compatible with asphalt.

Generally, PLA-modified mixtures are much better than unmodified mixtures. This may be due to the interaction or compatibility between asphalt and PLA, which leads to the formation of copolymers that strengthen the asphalt binder during modification [57].

## 6. CONCLUSION

This study examined the use of unmodified and PLA-modified sulfur waste as a mineral filler in high-density asphalt mixtures, specifically when applied to the binder layer. The following preliminary conclusions were drawn after examining the parameters and performance test results:

• Both unmodified and PLA-modified asphalt mixtures meet ASTM and NCCL standards.

• The Marshall properties of unmodified asphalt mixtures using sulfur waste as mineral filler were somewhat higher than those of mixtures containing $CaCO_3$ filler, where the Marshall stability and Marshall quotient increased by 1.4% and 23%, respectively. The stability values were 12.26 kN and 12.09 kN. The Marshall quotient values were 3.94 kN/mm and 3.2 kN/mm, respectively.

• The unmodified mixtures containing sulfur residues witnessed a slight decrease in the ITS value at 25 °C and the TSR value compared to the unamended mixtures that used calcium carbonate filler, where the percentage of decrease reached 13.1% and 2.8%, respectively. However, they still meet NCCL standard restrictions. The ITS values for the mixtures containing sulfur waste filler and calcium carbonate filler were (0.982 and 1.068) Mpa, respectively, and the TSR values were (0.804 and 0.827), respectively.

• When sulfur waste is used as a filler, the deformation strength is almost identical to that of mixtures containing calcium carbonate. The deformation strengths were 4.73 MPa and 4.74 MPa, respectively.

• Compared to control mixtures (unmodified), the crushing tolerance index is greater for FP and SP mixtures. In addition, the FP mixture is superior to the SP mixture in terms of crack tolerance index ($CT_{index}$). This indicates that the FP mixture is more resistant to fatigue . Regarding the comparison between modified and unmodified asphalt mixtures:

• The mixtures modified in which sulfur waste was used as a filler were better than the unmodified mixtures, where the values of Marshall stability were 16.8 kN, Marshall quotient was 5.04 kN/mm, ITS was 1.201 MPa, TSR was 0.839, and SD was 5.07 MPa, with an increase of 37%, 27.9%, 29.4%, 4.35%, and 7.18%, respectively.

• Also, for the mixtures containing calcium carbonate as a filler, the modified mixtures were better than the unmodified mixtures, where the values of Marshall stability were 18.21 kN, Marshall quotient was 5.02 kN/mm, ITS was 1.411 MPa, TSR was 0.849, and SD was 5.03 MPa, with an increase of 50.6%, 56.8%, 32.1%, 2.66%, and 6.11%, respectively.

• PLA-modified mixtures are much better than unmodified mixtures. This may be due to the compatibility between asphalt and PLA, which leads to the formation of polymers that strengthen the asphalt binder upon modification.

• The modified asphalt mixtures using $CaCO_3$ filler were somewhat better than those in which sulfur waste filler was used.

• The use of 1.5% PLA by weight of total asphalt is considered an economical percentage compared to percentages of industrial polymers that reach 5% or more by weight of asphalt. On the other hand, using waste sulfur to replace calcium carbonate in asphalt mixtures saves money and space in landfill sites.

From the above, the use of asphalt mixtures modified with PLA that contain calcium carbonate filler and those that contain sulfur waste filler provides many benefits by improving Marshall properties and durability performance standards, in addition to increasing the mixture's resistance to cracks and wrinkles. On the other hand, the possibility of using sulfur waste provides a waste-free environment and saves the cost of disposing of this solid waste, which is difficult to dispose of easil.

Finally, the authors recommend further research on.

• Behavior of these two types of fillers during short- and long-term aging of modified and unmodified asphalt mixtures.

• Using different modification ratios of PLA and comparing them with the ratio used in this research, which is 1.5% by weight of asphalt.

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# تأثير حامض البوليلاكتيك اسد على استدامة الخلطة الإسفلتية

**نكتل زياد حامد**
naktal.21enp62@student.uomosul.edu.iq

**عبدالرحيم ابراهيم الحديدي**
alhadidy@uomosul.edu.iq

قسم الهندسة المدنية، كلية الهندسة، جامعة الموصل، الموصل، العراق

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***الملخص***

*في الآونة الأخيرة، تم استخدام نفايات الكبريت (SW) كبديل محتمل للحشو المعدني من كربونات الكالسيوم ($CaCO_3$). قامت هذه الدراسة بتقييم تأثير بوليمر حمض البوليلاكتيك (PLA) على المخاليط الإسفلتية المحتوية على حشو CaCO3 والمخاليط الإسفلتية المحتوية على مخلفات الكبريت كمواد مالئة بديلة. تم خلط خليط من الأسفلت بنسبة 40-50 مع نسبة PLA تبلغ 1.5% من وزن الأسفلت. تم إجراء اختبارات الأداء، بما في ذلك ثبات مارشال (MS)، وحاصل مارشال (MQ)، وقوة الشد غير المباشرة (ITS)، وقوة التشوه (SD) في اختبار كيم، على الخلطات الإسفلتية. أظهرت نتائج الاختبار أن (MS) و (MQ) للخلطات التي تحتوي على مخلفات الكبريت كمادة حشو زادت بنسبة 1.4% و 23.1% على التوالي، في حين انخفضت قيم معدلات (ITS) و (TSR) بنسبة (13.1% و 2.8%). )، على التوالي، و (SD) كانت قريبة جدا. وكانت الخلطات الاسفلتية المعدلة أفضل من الخلطات غير المعدلة من حيث MS، MQ، ITS، TSR، وSD. وارتفعت القيم بنسبة 37%، 27.9%، 29.4%، 4.35%، و7.18% على التوالي، عند مقارنة الخلطات الإسفلتية المعدلة وغير المعدلة المحتوية على مخلفات الكبريت. كما ارتفعت القيم بنسبة 50.6%، 56.8%، 32.1%، 2.66%، و6.11% على التوالي، عند مقارنة الخلطات الإسفلتية المعدلة وغير المعدلة المحتوية على كربونات الكالسيوم. وبشكل عام كانت المخاليط المعدلة أفضل من المخاليط غير المعدلة. يمكن استخدام نفايات الكبريت كحشو معدني مستدام لتطبيقات الرصف بدون أو باستخدام بوليمر PLA بنسبة 1.5%، حيث أنه منخفض التكلفة ومتوفر.*

***الكلمات الداله:***

*نفايات الكبريت (SW)، الحشو المعدني، الأسفلت المعدل بـ PLA، استبدال كربونات الكالسيوم.*