Research Article

Physicomechanical Assessments and Heavy Metals’ Leaching Potential of Modified Asphalt Binders Incorporating Crumb Rubber and Tin Slag Powders

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Industrial solid waste has been widely used as an alternative additive for bituminous material modification. This study aims to evaluate the basic properties and quantify the leaching potential of modified asphalt binders incorporating crumb rubber powder (CRP) from waste tires and tin slag (TS) for a local smelting company. Three percentages of CRP and TS, at 5, 10, and 15%, were considered. The conventional asphalt binder (PEN 60/70), CRP, and TS-based modified asphalt binders were analyzed for toxicity, softening point, penetration value, elastic recovery, torsional recovery (TR), and coatability index. The findings indicated that the addition of the waste materials led to no significant heavy metal content in the asphalt binder mix. Moreover, the basic and physical properties of the asphalt binders were also improved by 5, 10, and 15% of the waste, respectively. However, TS waste exhibited limited effects on all the parameters and had a 5% optimum dosage. The modified binders’ results showed that the CRP modified asphalt binders had fewer heavy metals and responded more to elastic recovery and coatability.

1. Introduction

In Malaysia, the escalated usage of vehicles on roads generates a huge amount of waste tires at the end of their life cycle [1]. Up to mid-2017, there were 28,181,203 units of vehicles registered, as reported by the Malaysia Automotive Association (MAA) [2]. As a developing country, the huge increase in the generation of scrap tires is alarming. The disposal of waste tires poses a major environmental problem, as they have a long lifespan and possess nonbiodegradable properties. Disposal of waste tires is a challenging task as it will lead to scarcity of landfills capacity due to its large quantity [2, 3]. This issue can be overcome by recycling scrap tires to protect the environment from pollution [4, 5]. Since the last few decades, recycled waste tires are being utilized as a modifier in asphalt paving mixtures, additives in Portland cement concrete, and lightweight fillers. In addition, the tires can also serve as the crash barrier, a bumper, and an artificial reef [3, 6, 7]. The utilization of waste tires is effective in overcoming the issue associated with solid scrap tire disposal, and the recycled tires such as crumb rubber can act as a good modifier for enhancing the properties and performance of asphaltic concrete [2, 8, 9]. The utilization of polymer-modified bitumen is a cost-effective and efficient alternative to improve the performance of asphalt pavements [10, 11]. Vehicle tire shreds are usually found in the range of 460 mm to 25 mm, and thus, the small sizes of shred and chip
eased the production of ground crumb rubber [12]. The wire and other metal contaminants are removed [12–14]. The applications of crumb rubber in asphalt paving mixtures are known as rubber asphalt in the USA. It consists of asphalt cement, reclaimed tire rubber, and additives. According to the reports, approximately 15% of the rubber components are integrated into the rubber asphalt blend. During the blending process, grounded rubber particles were mixed with hot asphalt cement, resulting in swelling of the rubber particles [15]. The particles size of CRP influenced the physical properties of modified binders. Studies reported that the particle size of crumb rubber, which is subjected to high temperature, was an influential factor in viscoelastic properties [16, 17].

On the other hand, tin slag is formed through the smelting process of tin. Recently, a company from Penang managed to produce 27,172 tonnes of tin metal, thus making Penang the largest tin producer in Malaysia. Malaysia is known as the third-largest tin metal supplier globally, leading in the production of tin metal and tin-based products, as well as custom tin smelting [18]. Cassiterite is reduced to form tin metal with carbon at a very high temperature (1200°C to 1300°C). Currently, the lack of commercial application of tin slag and its unsuitability for disposal in landfills has resulted in the accumulation of a large quantity of waste that poses a disposal concern for smelting plant companies. The TS generally consists of SiO₂, Al₂O₃, CaO, Fe₂O₃, and TiO₂. The elements such as Pb, Cr, and Mn in TS tend to be soluble in an acid environment [19]. With stringent environmental restrictions by the government and local authorities, treatment, and disposal issues for scheduled waste are getting more attention from manufacturers or industry authorities. Along with this, an alternative approach such as reusing or recycling industrial waste or by-products has been considered. The outcome of previous research shows that those products are feasible to be used in road pavement construction as binder modifiers with and without additives [20–24].

However, incorporating various industrial wastes into asphalt binders has compelled me to conduct related studies to ascertain that the heavy metals are present in the CRP and TS modified binders. The studies are to ensure its environmental sustainability through the use of asphalt pavement technology. This study is also partially intended to examine the basic and physical characteristics of CRP and TS modified binders. Therefore, this study mainly aims to evaluate the possibility of adding different industrial wastes (CRP and TS) as additives to bituminous materials.

### 2. Materials and Methods

#### 2.1. Materials

The physical properties of conventional asphalt binder (PEN 60/70) used for the sample preparation in this study are shown in Table 1. The dosages of industrial waste that are used to modify asphalt binders, namely, crumb rubber powder (CRP) and tin slag (TS), are provided in Table 2. The CRP and TS industrial waste adopted were supplied by Malaysia’s Pan Century Oleochemicals Sdn Bhd. and Penang’s Malaysia Smelting Corporation Berhad (MSC). The physical appearance of the CRP is shown in Figure 1(a). The CRP is a processed waste tire, in which the size of the tire is reduced by grounding it into smaller particles. The distribution of particle size for both the CRP and TS is shown in Figure 2. TS was initially dried in an oven at 105 ± 5°C for 24 hours and then grounded for 8 hours to obtain finer particles using a laboratory scale ball mill. The tin slag went through a 75 μm sieve to remove coarser particles, as shown in Figure 1(b). The tin slag chemical composition is shown in Table 3 [25]. All samples were prepared using a liquid antistripping agent at 0.1% Silane additive based on the binder weight.

#### 2.2. Preparation of Samples

##### 2.2.1. Preparation of the Sample for Toxicity Characteristic Leaching Procedure (TCLP) Test

Initially, the asphalt binder in galvanized iron containers was preheated at 160°C for 1 hour. Besides that, modified binders with different dosages (5%, 10%, and 15%) of CRP and TS were also prepared to compare the impact of various dosages on the quantity of detected heavy metals. Before testing, the preheated modified binder in each galvanized iron container was manually stirred for 1 minute to improve its consistency. Then, the sample was poured into a container and cooled to room temperature for 1 hour prior to the test. The toxicity of the conventional and modified asphalt binders was tested according to US EPA Method 1311, Toxicity Characteristic Leaching Procedure (TCLP) [26] by using the water from the purification system (Figure 3(a)) and an automatic rotary agitator as shown in Figure 3(b).

##### 2.2.2. Preparation of the Sample for the Physical Property Tests

The TS and CRP modified binders were prepared using three dosages at 5%, 10%, and 15% by weight of asphalt binder. The incorporation of waste materials (TS that was passing 75 μm or CRP passing 1 mm) was incorporated in

### Table 1: The bitumen properties.

| Physical properties | Results |
|---------------------|---------|
| Torsional recovery  | 0.5%    |
| Softening point     | 50°C    |
| Elastic recovery    | 83%     |
| Penetration         | 65 dmm  |
| Flash point         | 273°C   |

### Table 2: Percentages of additives used.

| Types of additives | Designation | Dosages (%) | Sample designation |
|--------------------|-------------|-------------|--------------------|
| Crumb rubber powder| CRP         | 5           | 5% CRP             |
|                    |             | 10          | 10% CRP            |
|                    |             | 15          | 15% CRP            |
| Tin slag           | TS          | 5           | 5% TS              |
|                    |             | 10          | 10% TS             |
|                    |             | 15          | 15% TS             |

#### Table 2: Percentages of additives used.
Firstly, the conventional asphalt binder was preheated at a temperature of 160 °C before blending. After that, the waste materials were incorporated into the binder for 30 minutes at a temperature of 160 °C in a high-shear mixer. The waste materials were added gently into the binder to avoid clumping to produce a homogenous mixture.

**Figure 1**: Physical appearance of industrial waste powders. (a) Crumb rubber powder. (b) Tin slag.

![Physical appearance of industrial waste powders](image1)

**Figure 2**: Particle size distribution of crumb rubber powder (CRP) and tin slag (TS).

![Particle size distribution](image2)

**Table 3**: Chemical composition of tin slag.

|                  | CaO (%) | SiO₂ (%) | Al₂O₃ (%) | MgO (%) | FeO/Fe₂O₃ (%) | WO (%) | As (%) | Pb (%) | Cd (%) | TiO₂ (%) | Sn (%) | Zn (%) |
|------------------|---------|----------|-----------|---------|---------------|--------|--------|--------|--------|----------|--------|--------|
|                  | 16–20   | 28–32    | 10–13     | 2–4     | 13–18         | 20     | <0.01  | <0.01  | <0.0001| 4–6      | <0.3   | <0.14  |

**Figure 3**: TCLP test assembly. (a) Water purification machine. (b) Automatic rotary agitator.

![TCLP test assembly](image3)
modified binder. The mixing speed of the high-shear mixer to blend the waste material and binder was set at 1000 rpm.

3. Test Methods

3.1. Toxicity Characteristic Leaching Procedure (TCLP). The testing was initiated by preparing samples of bitumen, CRP, or TS mixed binder of about 100 g with each placing in a 2 L plastic bottle together with extractor fluid #1 used as leaching fluid. The buffer chosen for the extraction of fluid depends on the pH of the samples. The preparation of extraction fluid #1 was started by mixing glacial acetic acid (CH₃COOH) (5.7 mL) into 1 L Type II reagent water, followed by the addition of 1 N NaOH (64.3 mL), and diluted it to the volume of 2 L with final pH 4.93 ± 0.05. Type II reagent water was filtered by the New Human Power System water filter (Figure 3(a)). Referring to Figure 3(b), the plastic bottles were placed in an Automatic Rotary Agitator at 18 ± 2 h at room temperature. After agitation, the samples were filtrated with 0.7 µm glass microfiber filters. The filtered samples were collected and analyzed for 21 chemical elements. The concentrations (ppm) of chemical elements such as arsenic (As), beryllium (Be), calcium (Ca), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), lithium (Li), magnesium (Mg), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), strontium (Sr), thallium (Tl), thallium (TI), vanadium (V), and zinc (Zn) were determined by state-of-the-art equipment namely ICP-OES (Varian 715-ES ICP Optical Emission Spectrometer). The same approach was repeated for tin slag samples. Table 4 shows the United States Environmental Protection Agency (US EPA).

| Metals          | Regulatory level (ppm) |
|----------------|------------------------|
| Arsenic (As)   | 5.0                    |
| Barium (Ba)    | 100.0                  |
| Cadmium (Cd)   | 1.0                    |
| Chromium (Cr)  | 5.0                    |
| Lead (Pb)      | 5.0                    |
| Mercury (Hg)   | 0.2                    |
| Selenium (Se)  | 1.0                    |
| Silver (Ag)    | 5.0                    |

3.2. Basic Properties of Asphalt Binders. The asphalt binder basic tests were carried out using the penetration, softening point, elastic recovery, and torsional recovery tests. The penetration test was performed in accordance with ASTM D5 [28] to evaluate the differences in penetration grade and the consistency of asphalt binders. Likewise, the softening point test determined the temperature of the initial asphalt binder response as followed by the ASTM D36 procedure [29]. Moreover, the determination of temperature susceptibility of crumb rubber and tin slag modified asphalt binders was evaluated from the penetration index (PI), which was obtained from the penetration and softening point test. The calculation of penetration index is shown in Shell Bitumen Handbook as stated in the following equation:

\[
PI = \frac{1952 - 500 \log (\text{Pen}25) - 20 \times SP}{50 \log (\text{Pen}25) - SP - 120},
\]

where Pen₂₅ refers to the penetration at 25°C, and SP refers to the softening point temperature of modified asphalt binder.

The elastomeric characteristics of the asphalt binder and modified binders were ascertainment via elastic recovery and torsional recovery. The elastic recovery test was done by following AASHTO T51 and ASTM D6084 [30, 31]. This elastic testing was conducted at 25°C according to ASTM specification, in which the binder specimens were pulled apart in a ductimeter and held after reaching a specified elongation during the test. The specimens are then cut in the middle of the elongation, and the percent recovery of each specimen is determined [31].

The torsional recovery test is an inventive method in determining the elasticity in the asphalt binder. It was conducted following the ARRBAG: PT/T112 procedure [32] at 25°C. This test was performed by embedding a metal disc in a cup of asphalt, and the sample container was rotated at 180°. Then, the band was removed, and the specimen was left aside to recover for 30 seconds. The torsional recovery percentage (TR) was calculated by the following equation:

\[
TR = \frac{A}{180} \times 100,
\]

where A is recovered angle, in degrees.

3.3. Binder Coatability Test. The coatability of the asphalt mixtures was determined based on the aggregate absorption method in accordance with the AASHTO T 195 [33]. In this method, only coarse aggregate particles are considered. The short-term aged coated aggregate with a soaking time of 60 minutes was presumed that a completely coated aggregate would demonstrate high resistance towards the diffusion of water due to the presence of asphalt film that covered the aggregate surface. Otherwise, a coated aggregate could be prone to water absorption by allowing the water to diffuse into the partly coated aggregate [34–36].

This study determined the coatability of asphalt base binder and modified asphalt mixtures by the following procedures. Firstly, the 20 mm coarse aggregate was wet-sieved in order to remove the excessive fine particles. Then, the coarse aggregate was dried in an oven at a temperature of 105 ± 5°C for 24 ± 0.5 hours. Oven-dried coarse aggregate was sieved, and the portion retained on the 10 mm sieve size was used to prepare the sample. A 2,000 g batch sample consisted of 26% of aggregate between 20 mm and 14 mm, and 74% of aggregate with sizes ranging from 14 mm to 10 mm was prepared. Six individual batches were formed from coarse aggregate gradations following Marshall mix design, with three batches sample of 2,000 g subjected to preheating at a mixing temperature of 160°C for four hours, and the others were stored at the room temperature. The considerations have taken to their rheological behavior at mixing, and construction temperature, the base asphalt.
binder, and modified asphalt binder were subjected to a high
temperature of 163°C for at least 85 minutes to simulate the
short-term aging process artificially. The aging process was
conducted in accordance with ASTM D 2872 [37].
Mix design and the surface area distribution of the coarse
aggregate fraction determined the required amount of
binder. Equations (3) to (6) were used to compute the binder
content and the output parameters such as absorption of loss
mixture aggregate, absorption of aggregate, and coating
index of each mixture. The input parameters used for the
sample preparation are presented in Table 5. The amount of
 binder of 41.25 g was mixed with the 2,000 g of coarse ag-
gregate fraction batch. The optimum binder content (OBC)
of Pb was obtained from the Marshall mix design. The as-
phalt binders were subjected to heating for two hours. Then,
the loose mixture was placed into a bucket mixer for 60
seconds before being transferred into a tray and heated in the
oven for the next two hours. These allow for binder ab-
sorption and induce the short-term aging process during
production simultaneously. Moreover, the loose mixture
was cooled at room temperature overnight. Both aggregates
and loose mixture were exposed to water for 60 minutes.
Then, a dry towel was used to remove the excess water until
the saturated surface dried (SSD) condition was achieved.
The masses obtained for aggregate and loose mixture in SSD
condition were recorded as $W_{agg-SSD}$ and $W_{loose-SSD}$
respectively.

Binder content, $W_b = W_{agg} \times \frac{P_b}{100} + \frac{SA_{coarse}}{SST} \times \frac{1}{P_{f-coarse}}$, (3)

Abs% loose = $\frac{W_{loose-SSD} - (W_{agg} + W_b)}{W_{agg} + W_b} \times 100$, (4)

Abs% agg = $\frac{W_{agg-SSD} - W_{agg}}{W_{agg}} \times 100$, (5)

coating index = $\frac{Abs\%_{agg}}{Abs\%_{loose}} \times 100$. (6)

The surface area of mix design combined with aggregates
is calculated by adopting methods from previous studies and
past laboratory work experiences regarding aggregate gra-
dation [38]. The calculation for surface area determination is
shown in Table 6.

4. Results and Discussion

4.1. Effect of Crumb Rubber and Tin Slag on the Leaching
Potential. The current study investigates the potential
leaching of heavy metals from crumb rubber, tin slag, and
conventional asphalt binder through TCLP experiments.
The collected leachates of the samples were analyzed for the
heavy metals by Inductively Coupled Plasma Optical
Emission Spectrometry (ICP-OES). The initial TCLP test
was performed on raw material, namely, crumb rubber
powder, tin slag, and unmodified asphalt binder. Next, the
TCLP test was performed on crumb rubber powder and tin
slag incorporated asphalt mixture. The TCLP test was
conducted at two different stages to deliver a thorough
correlation between the leaching of raw materials and the
incorporation of raw material into asphalt mixtures. Along
with this, the research findings indicated the effect of asphalt
binder in reducing the leaching of heavy metals from the raw
materials. Furthermore, the findings of TCLP analysis for
crumb rubber powder, tin slag, and asphalt binder can be
used to portray the mobility of heavy metals and replicate the
leaching situation, as heavy metals elements were leached by
acid rain.

The unmodified asphalt binder was tested as a control
sample. The filtered samples or leachate solution was ana-
lyzed for the chemical elements using optical emission
spectroscopy (ICP VARIAN 715-OES). The results from the
leachate solution of the unmodified asphalt binder analysis
implied that the chemical elements such as Arsenic (As),
Beryllium (Be), Cadmium (Cd), Cobalt (Co), Copper (Cu),
Lithium (Li), Lead (Pb), Strontium (Sr), and Thallium (Tl)
were not detected. However, Ca, Cr, Fe, Mg, Mn, Mo, Ni, Sb,
Se, Ti, V, and Zn were detected via the conducted tests. The
experimental results of the TCLP for these materials in
Table 7 were expressed in part per million (ppm). Zinc was
detected with the highest concentration recorded as 62 ppm
in crumb rubber powder, but it is still considered within the
safe level compared to its maximum allowable limit of
250 ppm in Table 4. Chromium and selenium, which are
more hazardous, were obtained at a concentration of
0.007 ppm and 0.235 ppm, respectively, for crumb rubber
powder, while they were 0.003 ppm and 0.078 ppm for tin
slag. Chromium was not detected in asphalt binder samples,
yet selenium was detected at 0.134 ppm. Nevertheless, it is
very much lower than the regulatory level according to the
metals hazardous waste parameters by US EPA regulatory in
Table 4 [27].

Meanwhile, the results in Table 8 show the detected
metal elements concentrations for the samples of asphalt
binder with the incorporation of crumb rubber powder at
different concentrations. Generally, the trend of the ex-
perimental results showed that the increasing amount of
crumb rubber powder caused a hike in certain heavy metal
elements. A higher amount of heavy metals contamination
for Ca, Fe, Mg, and Ti was detected in the filtered leachate
solution for a higher portion of crumb rubber powder. This
proved that incorporating asphalt binder mixed with crumb
rubber powder does not facilitate or has no effect in reducing
these heavy metal elements in the leaching process, which
primarily comes from crumb rubber powder. In the case of
selenium, it was found to be eliminated in bitumen mixed
for 5%, 10%, and 15% added crumb rubber, but vanadium
was slightly increased at 15% added crumb rubber in
comparison to 5% and 10%. There was a fluctuation for Mo,
Sb, and Zn, which could be occurred due to many factors
such as the varying portion of chemical elements in the
crumb rubber added into the specimens.

The metals considered as hazardous such as As, Cd, Cr,
and Pb were evaluated to be below detectable limits, except
Se that was obtained at 0.171 ppm but below 1 ppm limit.
Other metals obtained below detectable limits consisted of Be, Co, Cu, Li, Mn, Ni, Sr, and Tl. The analysis was obtained in a minimum of Ca, Fe, Mg, Mo, Sb, Se, Ti, V, and Zn. The results showed that not only bitumen mixed sources of toxicity from crumb rubber were emanated but the bitumen itself also contributed to some of these toxic contaminants. Table 9 shows the metal elements concentrations on bitumen added tin slag mixed leachate solutions. The experimental results show that a bigger portion of tin slag causes higher Ca, Fe, Mg, Se, and Ti contamination in the leachate solutions. Meanwhile, for Mo, Sb, V, and Zn, the fluctuations might be similar to what was mentioned earlier.

Table 5: The amount of materials required for the sample preparation.

| Parameters                                      | Values       |
|------------------------------------------------|--------------|
| The optimum of binder content, Pb              | 5.0%         |
| Coarse aggregate, W_{agg}                      | 2.000 g      |
| The surface area of the combined aggregate, S_{coarse} | 0.41 m²/kg  |
| The total surface area of mix design combined aggregate, S_{T} | 5.507 m²/kg |
| Percentages of coarse aggregate retained on a 10 mm sieve, P_{coarse} | 19%         |

Table 6: The determination of surface area.

| Sieve size (mm) | Percent passing (%) | Surface area factor (m²/kg) | Surface area (m²/kg) |
|-----------------|---------------------|-----------------------------|----------------------|
| 20              | 100                 | —                           | 0.41                 |
| 14              | 95                  | —                           | 0.229                |
| 10              | 81                  | —                           | —                    |
| 5               | 56                  | 0.41                        | 0.229                |
| 3.35            | 47                  | 0.82                        | 0.3854               |
| 1.18            | 26                  | 1.64                        | 0.4264               |
| 0.425           | 18                  | 4.78                        | 0.8604               |
| 0.15            | 10                  | 12.29                       | 1.229                |
| 0.075           | 6                   | 32.77                       | 1.9662               |

Total surface area of combination size aggregate 5.507

Table 7: Metal elements’ concentrations on bitumen, crumb rubber powder, and tin slag leachate solution.

| Metal elements   | Bitumen (ppm) | Crumb rubber (ppm) | Tin slag (ppm) |
|------------------|---------------|--------------------|----------------|
| Calcium (Ca)     | 0.538         | 26.050             | 19.341         |
| Chromium (Cr)    | —             | 0.007              | 0.003          |
| Iron (Fe)        | 0.034         | 2.275              | 5.921          |
| Magnesium (Mg)   | 0.116         | 1.020              | 3.369          |
| Manganese (Mn)   | —             | 0.035              | 0.466          |
| Molybdenum (Mo)  | 0.077         | 0.108              | 0.256          |
| Nickel (Ni)      | —             | 0.035              | 0.034          |
| Antimony (Sb)    | 0.074         | 0.045              | 0.051          |
| Selenium (Se)    | 0.134         | 0.235              | 0.78           |
| Titanium (Ti)    | 0.044         | 0.049              | 0.050          |
| Vanadium (V)     | 0.005         | 0.011              | 0.046          |
| Zinc (Zn)        | 0.152         | 61.8IACT5           | 0.495          |

Table 8: Metal elements’ concentrations on CRP-modified bitumen leachate solution.

| Metal elements   | Bit. +5% CRP (ppm) | Bit. +10% CRP (ppm) | Bit. +15% CRP (ppm) |
|------------------|--------------------|---------------------|--------------------|
| Calcium (Ca)     | 0.271              | 0.542               | 0.798              |
| Iron (Fe)        | 0.045              | 0.064               | 0.367              |
| Magnesium (Mg)   | 0.226              | 0.314               | 0.956              |
| Molybdenum (Mo)  | 0.064              | 0.062               | 0.062              |
| Antimony (Sb)    | 0.112              | —                   | 0.049              |
| Selenium (Se)    | —                  | —                   | —                  |
| Titanium (Ti)    | 0.046              | 0.047               | 0.093              |
| Vanadium (V)     | 0.004              | 0.004               | 0.006              |
| Zinc (Zn)        | 0.084              | 0.060               | 0.089              |
However, metal elements in bitumen added with tin slag mixed leachates solution are very low and below the regulatory level according to the metals hazardous waste parameters stated by US EPA, as shown in Table 4.

### 4.2. Basic and Physical Characterization of the Asphalt Binder

#### 4.2.1. Softening Point, Penetration, and Elastic Recovery

Results tabulated in Table 10 show that the asphalt binder’s basic and physical properties are incorporated with crumb rubber powder and tin slag. The properties of all asphalt binders were assessed through penetration tests by evaluating their consistency and softening point. These tests were assisted in identifying the maximum service temperature; meanwhile, an elastic recovery test was used to determine the rate of the elastic response of asphalt binders. Table 10 demonstrates a reduction in penetration, while the softening point value increased with the increasing content of additive. This trend was acceptable on the crumb rubber modified asphalt binder except for the tin slag modified asphalt binder. There were no changes in the penetration and softening point for the tin slag modified asphalt binder, regardless of their concentrations. Nonetheless, the penetration and softening point of tin slag modified asphalt binder exhibited lower than the control asphalt binder. The increase in softening point is essential as the asphalt binder will be less temperature susceptible in resisting permanent deformation. The higher softening point and lower penetration value are due to the stiffening effect of additives. In addition, the different tin slag dosages have resulted in similar results for both the softening point and penetration value due to insufficient elastic response and stiffening effect of tin slag. Bitumen with imbalanced chemical compound and molecular weight distribution has presented a low penetration ratio and penetration index (PI) values resulting in high-temperature susceptibility. The asphalt binder was enhanced by reducing the temperature susceptibility, which led to a higher penetration index. The asphalt binder was compared to the control asphalt binder as the crumb rubber content increased. Nevertheless, the tin slag modified asphalt binders are prone to temperature difference since the penetration index is much lower than the control asphalt binder due to the effects of softening point.

The incorporation of crumb rubber powder has a significant influence on the behavior of modified asphalt binders. The crumb rubber powder-based modified asphalt binder shows a linear increase for all types of rubberized asphalt binder. Elastic recovery findings were comparable to rubberized bitumen ductility outcomes as it demonstrates the high elasticity of modified asphalt binder and its recovery after deformation, enhancing the resistance behavior towards permanent deformation. The outcome of the test presented that a lower percentage of recovery indicated a better recovery. The elastic recovery findings improved for all concentrations of crumb rubber powder from 92.3% for unmodified asphalt binder to 54%, 37%, and 32% for 5%, 10%, and 15% for crumb rubber powder modified asphalt binders, respectively. The crumb rubber powder has significantly improved the elastic recovery and indicated that the asphalt binder could recover after removing a certain amount of strain load. This is caused by the natural elastic behavior of the crumb rubber powder, which is also an elastomer. However, the tin slag modified asphalt binders do not portray any elastic recovery since the findings are comparably similar to the control sample. This is because tin slag does not possess an elastic behavior as it is not an elastomer. Conclusively, it inferred that the addition of crumb rubber powder significantly affected the basic properties of asphalt binder, while tin slag showed the opposite due to its inelastic behavior.

#### 4.2.2. Torsional Recovery (TR)

Results for torsional recovery of asphalt base binder modified with CRP and TS at 5%, 10%, and 15% dosages are presented in Tables 11 and 12, respectively. The incorporation of CRP and TS as additives in asphalt binder changes the recovery percentage at 5%, 10%, and 15% compared to the control binder. The torsional recovery percentage of the binder with the incorporation of CRP in Table 11 portrayed a significant improvement in the elasticity of the asphalt binder at all percentages. Moreover, the highest and the least percentage recovery difference observed compared to the conventional asphalt binder were 9% and 1.7%, respectively. The addition of TS in the asphalt binder, as shown in Table 12, showed a contrary pattern as compared to CRP. The torsional recovery differences of 5%, 10%, and 15% modified TS binders in the conventional asphalt binder have identical values with 0.5% due to their similar torsional recovery angle observed.
Conclusively, it deduced that the incorporation of CRP and TS, which was influencing the formation of crystalline network lattice in the binder structure, resulted in returning the pointer of the apparatus to its initial position due to controlled recovery force.

4.2.3. Coatability Index. The coatability results for the conventional asphalt mixture (HMA) and wastes modified asphalt mixtures of CRP and TS are shown in Table 13. Subsequently, the averaged absorption of the three trials with loose mixes and the bare aggregates was tested, and the coating indexes were computed. The conventional HMA findings are compared with wastes modified asphalt mixtures. The coatability testing for the mixtures was conducted by using three different dosages at 5%, 10%, and 15% (CRP and TS), respectively. The results of asphalt added with CRP and TS were different from those of the controlled sample. The coating index of the mixture with CRP showed better performance at 5% dosage; meanwhile, TS performed better at 10% dosage. Moreover, the absorption of the aggregate particles was decreased due to the improvement in coating index by the modified asphalts. However, a low marginal difference was observed between different percentages of TS. The mixtures containing 15% CRP and TS showed the highest absorption rate corresponding to the lowest coating index. This indicates that absorption and coatability rate was dependent on the dosages and chemical compositions of waste materials. Likewise, the CRP exhibits more elastic and bonding characteristics than the TS. The results show reasonable trends in the variable percentages of CRP and TS in asphalt mixture compared to HMA.

5. Conclusion

This current study demonstrated the effects of differences in percentages of CRP and TS on the leaching potential, basic, and physical properties, as well as the coatability of asphalt binder. The obtained findings concluded that the quantity of CRP and TS waste materials in bitumen impacts the metal concentration present in mixtures with leachate solutions. Moreover, the higher percentage portion of CRP and TS resulted in a higher increment of the metals content. The existence of metals in bitumen mix was a minor concern due to their low quantity and minimum toxicity. Therefore, this study portrayed that CRP and TS metals content presents an insignificant source of hazard towards the environment and groundwater.

Furthermore, the basic properties of CRP and TS modified binders significantly improved the physical properties (softening point, penetration, elastic recovery, and coatability) of the conventional asphalt binder and modified binder. The modified binders with CRP
demonstrated a better improvement compared to the base asphalt binder and TS.

Torsional recovery results with CRP incorporation showed an obvious improvement inelastic response of the asphalt binder at all percentages compared to the base asphalt binder and TS samples. In addition, the TS showed an identical elastic response across the percentages considered.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure
Any opinions, findings, and conclusions expressed in this manuscript are those of the authors and do not necessarily reflect the view of USM.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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