

Evaluation on Mechanical Deterioration of the Asphalt Mixtures Containing Waste Materials When Exposed to Corrosion Solutions

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Abstract

This research investigates the effect of corrosion solutions on the mechanical properties of asphalt concrete mixtures. A control asphalt mixture (CM) and five polymer-modified (PM) or filler-modified (FM) mixtures containing waste materials are prepared, namely PM high-density polyethylene plastic (PM-PL), PM crumb rubber (PM-CR), FM Para wood ash (FM-PA), FM palm empty fruit bunch ash (FM-EA), and FM rice husk ash (FM-RA). The experiment is conducted by immersing the mixture specimens in four types of water solutions (i.e., distilled water, alkaline solution, sulfate solution, and acid solution), followed by the splitting tests. Finally, the corrosion resistance factor (f_c) is computed to assess the corrosive effect of the corrosion solutions. The results show that the degree of reduction in tensile strength mainly depends on the type of corrosion solutions, type of mixtures, and immersion time. FM-EA provides better resistance under the alkaline and acid solutions, while PM-PL exhibits the greatest f_c under the sulfate solution. Among all the mixtures, PM-PL shows the greatest ability in withstanding the corrosion solutions.

Keywords: asphalt, waste material, mechanical deterioration, tensile strength, corrosion resistance

1. Introduction

Growing awareness has become the driving trend toward the use of recycled solid waste (RSW) materials in pavement construction, which typically requires a high volume of virgin materials. The use of RSW materials in highway pavement has the potential to achieve remarkable environmental and economic benefits, and yield satisfactory engineering performance, including durability of the pavement [1]. Attaelmanan et al. [2] concluded that the hot mix asphalt (HMA) containing waste plastics showed relatively better resistance against moisture damage and was much more economical. Choudhary et al. [3] studied the characterization of seven waste materials as fillers in the HMA mixtures, and found that all the waste-modified mixtures yielded an acceptable tensile strength which signified the resistance to cracking. Since the conventional HMA mixtures contain aggregates, asphalt binders, and/or filler materials, some RSW materials can be used in place of these materials. These RSW materials have been categorized as pavement by-products (e.g., recycled asphalt pavement, recycled concrete pavement, etc.), industrial by-products (e.g., steel slag, bottom ashes, fly ashes, waste plastics, waste tires, and waste glass), and construction and demolition by-products [4].

Asphalt mixture durability refers to the ability of asphalt concrete to maintain structural integrity throughout its expected service life [5]. The moisture in the environment is a factor which influences the durability of asphalt concrete pavement. Generally, the enhancement of asphalt mixtures may be conducted by using modified mixtures: binder-modified and filler-modified (FM) mixtures. Polymer-modified (PM) asphalt is commonly used to improve the asphalt mixture performance.

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As found in literature, stiffness can be increased by adding polymer of about 3-5% by weight of bitumen under the wet mixing method, and the mixture with polymer can provide better resistance against permanent deformation compared to the conventional mixtures [2, 6-9]. The materials such as stone dust, cement, hydrated lime, and fly ashes are frequently used as mineral fillers of 2-10% by weight of aggregates to improve the durability and the performance of the mixtures [3, 10-11]. Nevertheless, the asphalt concrete pavement can be eroded under the harsh environment, such as acid rain and tides, causing the asphalt paving deterioration and reducing the service life of asphalt [12]. Thus, understanding the effect of different water solutions on the asphalt mixture performance is very important.

This study aims to evaluate and compare the corrosion solution effect on the asphalt concrete mixtures containing waste materials with that on the conventional HMA mixture. The waste plastics including high-density polyethylene plastic (PL) and crumb rubber (CR) are selected as part of the polymer waste, while the biomass fly ashes including Para wood ash (PA), palm empty fruit bunch ash (EA), and rice husk ash (RA) are considered. Four different water solutions, including distilled water, an alkaline solution, a sulfate solution, and an acid solution, are used in the immersion test on the unmodified and modified mixtures.

This study is organized into five sections. The introduction is presented in section 1, and the literature review corresponding to the corrosion resistance of asphalt concrete is described in section 2. The materials and the testing program used in this study are explained in section 3. Section 4 provides the experimental results and discussion, showing the performance of various asphalt mixtures against the effect of the corrosion solutions. Finally, the finding of this research is summarized in section 5.

2. Literature Review

Existing studies showed that the moisture susceptibility and corrosion resistance ability of an asphalt mixture depended on its mixture design and the material's composition. Sengoz and Agar [13] investigated five HMA mixtures with different asphalt film thicknesses and tensile strength ratio (TSR). The results indicated that TSR increased with the increasing thickness of the asphalt film, and the authors concluded that the optimal asphalt film's thickness ranged between 9.5 and 10.5 μm . Meanwhile, Zhou et al. [14] found that 6 μm asphalt film thickness yielded the maximum tensile strength for the mixtures. Almeida et al. [15] investigated the moisture damage and aging effect of the nanoclay-modified asphalt mixture containing waste plastics. They discovered that the mixtures had slightly higher indirect tensile strength (ITS) values, were less susceptible to moisture, and had an improved aging resistance.

Chen et al. [16] investigated the corrosion resistance of the styrene-butadiene-styrene (SBS)-modified asphalt mixtures in acid, alkaline, and sulfate solutions. The result under the freeze-thaw environment indicated that the corrosion factor value of the mixtures decreased with increasing corrosion time. The authors explained the damage to the aggregates, asphalt cement, and surface tension of the asphalt mixtures due to the corrosion effects of acid, alkaline, and sulfate solution reactions, respectively. Xiong et al. [17] have proposed a predictive model to find the correlation between the air void (AV) volume and tensile strength of the SBS-modified asphalt mixtures exposed to the sulfate environment and dry-wet cycle erosion. The results revealed that the internal cracks in the asphalt mixtures caused repeated expansion pressure under the combined action of sulfate erosion and dry-wet cycles.

The corrosion resistance of fuel oil toward unmodified and modified asphalt mixtures was investigated by Li et al. [18]. The authors observed that as the time of oil immersion increased, the mechanical performance of the asphalt mixtures degraded gradually, and the oil corrosion damage accelerated continuously. Additionally, the asphalt mixtures incorporating anti-fuel oil corrosion additives can successfully prevent aromatic compounds from corroding in the presence of oil. Further, it was discovered that the SBS-modified asphalt mixtures did not retain high performance for an extended time following oil corrosion. Zhang et al. [19] investigated the corrosion mechanism of the asphalt mixtures in salty and humid environments, and

found that the action of chloride ions reduced the adhesion between asphalt and aggregate, resulting in the deterioration of the bitumen's flexibility and deformability. They also recommended a mixture with a basalt fiber anti-stripping agent, which improved the performance of the asphalt mixtures in coastal areas.

Feng et al. [20] conducted a long-term investigation on the effect of acidic water erosion on the tensile strength of asphalt mixtures. They stated that while the strength ratio decreased by approximately 40% during the first 9 months in acidic water, it remained nearly constant thereafter. Zou et al. [21] assessed the microstructure and chemical composition including constituents of the asphalt mixtures under exposure to the corrosion solution. Through interaction, the solute could expedite the erosion of asphalt, with the degree of interaction increasing in the order $\text{Na}_2\text{SO}_4 < \text{NaCl} < \text{acid} < \text{alkaline}$.

However, the literature above mainly focused on the corrosive effect of only one type of asphalt mixtures. A limited number of researchers evaluated the strength reduction and moisture damage of various asphalt mixtures under different corrosion solutions. The question now is, if these RSW materials had been recycled in the HMA mixtures, what would be the effect of moisture damage on the durability performance of the asphalt mixtures, and what kind of waste materials are suitable for use in the mix to gain maximum advantage. The answers to these questions are the primary goal of this research.

3. Materials and Method

3.1. Materials

The HMA materials used in this study comprise aggregates, mineral fillers, and asphalt cement. The waste materials are used as both asphalt-modified and FM materials in the HMA materials. The properties of all these materials are tested according to the Thailand Department of Highway (DOH) specification for the wearing course surface, which is designed for heavy traffic.

3.1.1. Aggregates

Based on the DOH specification, four different sizes of crushed limestone (Fig. 1(a)) are obtained from the local quarry: one size for fine aggregates (stone dust) and three sizes for coarse aggregates (9.5 mm, 12.5 mm, and 19 mm). The physical properties of the aggregates used for the mixtures are given in Table 1.

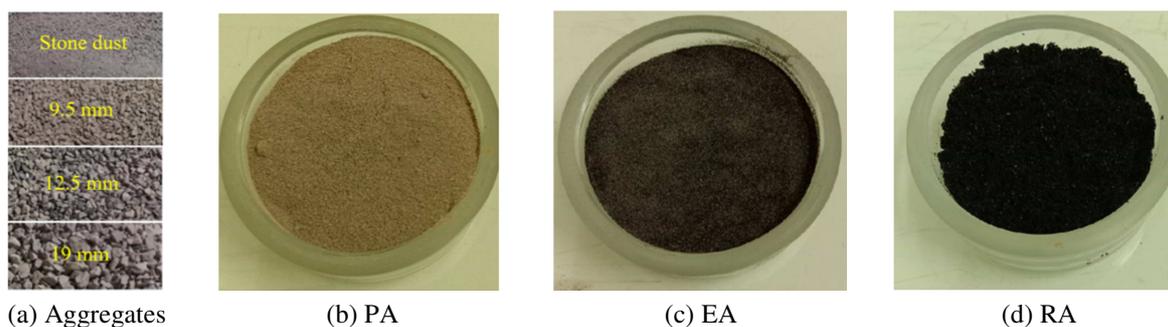


Fig. 1 Aggregates and waste mineral fillers

Table 1 Characterization of coarse and fine aggregates

Properties	ASTM/BS standard	Bin 1 stone dust	Bin 2 9.50 mm	Bin 3 12.5 mm	Bin 4 19.0 mm	DOH specification
Bulk specific gravity	C127/C128	2.685	2.707	2.687	2.637	-
Water absorption, %	C127/C128	0.30	0.33	0.29	0.14	-
L.A. abrasion, %	C131/C535	-	21.60	24.63	29.33	< 40
Sand equivalent, %	D2419	67	-	-	-	> 50
Soundness, %	C88	1.0	1.14	1.10	0.70	< 9
Flakiness index, %	BS812	-	20	16	15	< 30
Elongation index, %	BS812	-	12	18	20	< 30

3.1.2. Mineral fillers

Three types of mineral fillers (Figs. 1(b)-(d)), i.e., PA, EA, RA, are obtained from biomass ashes. PA is a by-product of the biomass (particleboard industry) combustion plant situated in the Songkhla province. EA is collected from a local oil palm plant, and RA is taken from a local rice processing mill. The sieve analysis confirms that the particle size meets the DOH specification (Table 2), and only filler fractions which pass the 75 μm sieve are used [3]. The results of the specific gravity test of PA, EA, and RA are 2.44, 2.13, and 2.01, respectively. The particle's shape, size, and morphology of the fillers are also examined using the scanning electron microscopy (SEM), as shown in Fig. 2. As seen, PA and EA have a sub-round to round shape. On the contrary, an angular grain shape with the presence of sharp edges is found in RA.

Table 3 shows the chemical composition of the three mineral fillers obtained from the X-ray fluorescence spectrometry analysis. As shown in Table 3, PA is composed of 33.43% calcium oxide (CaO). The remaining three main compounds are silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and ferric oxide (Fe_2O_3), at 17.4%, 2.84%, and 2.41%, respectively. RA has a dominant SiO_2 content of 80.27% and a low CaO content of 0.90%. For EA, the total amount of SiO_2 , Al_2O_3 , and Fe_2O_3 is 54.69%, and the CaO content is 13.36%. The loss on ignition (LOI) of PA, RA, and EA is 5.36%, 13.55%, and 12.79%, respectively. The quantity of PA, EA, and RA is set as 3% by the weight of the aggregates [22].

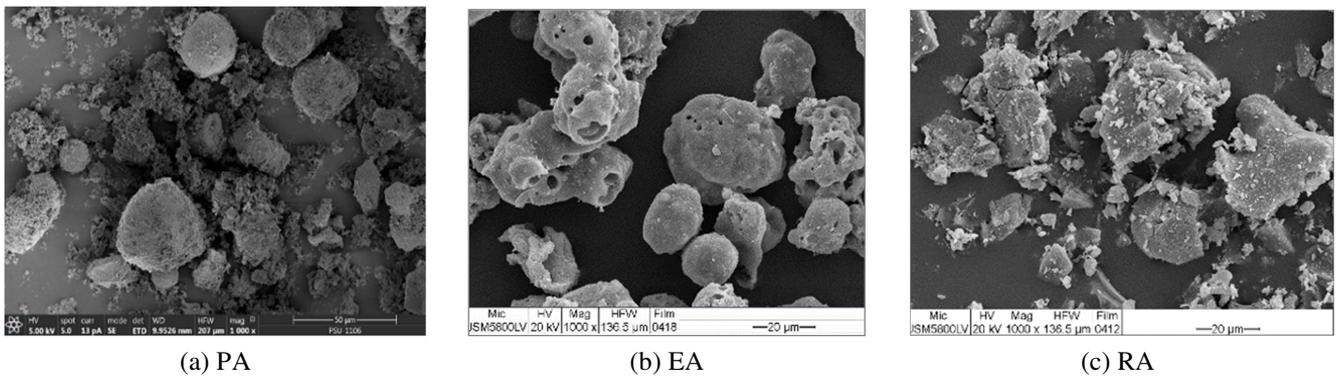


Fig. 2 SEM images of the mineral fillers with 1,000x magnification

Table 2 Gradation test result of mineral fillers

Sieve analysis (ASTM D546)	% Passing			DOH specification
	PA	RA	EA	
#30 (0.600 mm)	100	100	100	100
#50 (0.300 mm)	97.1	99.2	98.2	75-100
#200 (0.075 mm)	55.3	63.1	56.7	55-100

Table 3 Mineral composition of waste fillers obtained from X-ray fluorescence (XRF) test

Chemical composing (%)	PA	RA	EA
SiO_2	17.40	80.27	49.97
Al_2O_3	2.84	0.15	1.89
Fe_2O_3	2.41	0.16	2.83
CaO	33.43	0.90	13.36
MgO	2.85	0.61	3.53
NaCl	7.62	0.08	0.06
SO_3	6.41	0.18	1.23
P_2O_3	1.90	1.14	4.52
KCl	18.63	2.79	9.09
Other	1.15	0.15	0.73
Loss on ignition (LOI)	5.36	13.55	12.79

3.1.3. Asphalt materials

In this study, unmodified asphalt cement (AC 60/70) and two types of PM asphalt, namely plastic-modified asphalt (PMA) and crumb rubber-modified asphalt (CMA), are used as asphalt binder materials following the wet mixing process. PMA is prepared by blending shredded PL bags (Fig. 3(a)) and AC 60/70 at the temperature of 170°C. Similarly, CMA is obtained by blending CR and AC 60/70. A commercial passing sieve (30-mesh) of CR (Fig. 3(b)) is used in this study. The quantity of PL and CR is selected as 5% by the weight of asphalt cement. The details of the asphalt materials used are shown in Table 4. All asphalt materials are tested following ASTM standards by specific gravity, penetration, and softening point tests.



(a) Shredded PL (waste plastic bags)



(b) CR (waste tires)

Fig. 3 Waste polymer used as PM asphalt

Table 4 Mixtures and waste materials used

Mixture group	Mixture name	Asphalt binder	Waste material content used
G1: control mixture (CM)	CM	AC 60/70	-
G2: PM mixture	PM-PL	PMA	PL @ 5% by wt. of AC
	PM-CR	CMA	CR @ 5% by wt. of AC
G3: FM mixture	FM-PA	AC 60/70	PA @ 3% by wt. of aggregate
	FM-RA	AC 60/70	RA @ 3% by wt. of aggregate
	FM-EA	AC 60/70	EA @ 3% by wt. of aggregate

Table 5 Rheological properties of asphalt binder materials

Properties	ASTM standard	Asphalt binder materials		
		AC 60/70	PMA	CMA
Specific gravity	D70	1.030	1.046	1.053
Penetration (0.1 mm)	D5	63	34	57
Softening point (°C)	D36	47	72	54
Penetration index, PI	-	-1.46	2.20	0.07

The test results for the rheological properties of these asphalt materials are shown in Table 5. As shown in Table 5, the specific gravity of both the PMA and CMA is higher than that of the unmodified asphalt AC 60/70. The penetration index (PI) can be calculated using the following equation [23]:

$$PI = \frac{1952 - 500 \log P - 20SP}{50 \log P - SP - 120} \quad (1)$$

where P and SP are the penetration at 25°C and the softening point values, respectively.

In general, asphalt binders containing a higher PI value are much more permanent in terms of deformation and temperature cracking. From the result of the PI value, it can be observed that both the PMA and CMA are less susceptible to temperature changes than the conventional AC 60/70. Asphalt mixtures with higher PI binder values are more resistant to permanent deformation and temperature cracking. At low temperatures, asphalt with a PI less than -2 becomes much more brittle. Asphalt with a PI greater than +2 has less temperature sensitivity, is less brittle at low temperatures, and has a significant time-dependent elastic property [23]. According to the PI values shown in Table 5, PMA and CMA are less susceptible to temperature changes than the conventional AC 60/70. This is due to the modified asphalt having higher P and lower SP values than the unmodified asphalt.

3.1.4. Corrosion solutions

The asphalt pavement in different locations may be exposed to different types of water solutions. Rainfall, tides, and sea fog can all bring soluble salt to a coastal environment, which may contain up to 10% sodium chloride or 5% sodium sulfate [14]. Acid rain with a pH as low as 3.5 has been measured, and rainfall in the 4.5-5.0 range is not uncommon in heavily industrialized or urban areas. While some saline-alkali areas have alkaline precipitation, alkaline precipitation raises the pH of rainwater to 8.5-10 [24]. According to previous research works, a wide range of pH values for water solutions have been studied, for instance, by Yang et al. [12], Chen et al. [16], and Feng et al. [20]. In their study, the investigation on the mechanical deterioration of the asphalt mixtures was conducted through immersion in four different water solutions, namely distilled water, an alkaline solution, a sulfate solution, and an acid solution. In this study, a pH meter is used to measure the pH value for all kinds of water solutions. The acidic solution (pH = 3.5) is prepared with nitric acid (HNO_3) and dissolved in distilled water [16]. The alkali solution (pH = 10) is prepared by dissolving solid sodium hydroxide (NaOH) [16]. The sulfate solution (pH = 8.5) is obtained by dissolving 5% of sodium sulfate (Na_2SO_4) in distilled water [14].

3.2. Specimen preparation and mixture design

Based on the DOH specification, this research prepares dense gradation asphalt concrete mixtures for the wearing course surface. A total of six mixtures are prepared according to ASTM D6926 and are summarized in Table 4 [25]. To evaluate the durability of the mixtures, the specimens are categorized into 3 groups, namely G1: control mixture (CM), G2: PM mixture, and G3: FM mixture. The particle size distribution of the aggregates of the selected gradation is shown in Fig. 4. For G1 and G2 (Fig. 4(a)), the mix proportion of aggregate size's Bin: 1:2:3:4 is 50:22:16:12. For G3 (Fig. 4(b)), the replacement of 3% by weight of aggregates for Bin 1 is conducted (i.e., the ratio of Bin 1 is filler 47: 3), which has a mix proportion of 47:3:22:16:12.

For each HMA mixture, the materials prepared are mixed and compacted in cylindrical Marshall specimens using a Marshall hammer at 75 blows per face (for heavy traffic), with a standard time and temperature as prescribed. During the mixing process, the percentage of asphalt content (4.5%, 5.0%, 5.5%, 6.0%, and 6.5%) is varied to determine the optimum binder content (OBC) of each mix. After that, the compacted specimens are taken out from a mold and cured for 24 hours at room temperature. Finally, ninety specimens are weighed and calculated for their respective volumetric properties, including AV, voids in the mineral aggregate (VMA), voids filled with bitumen (VFB), and their density.

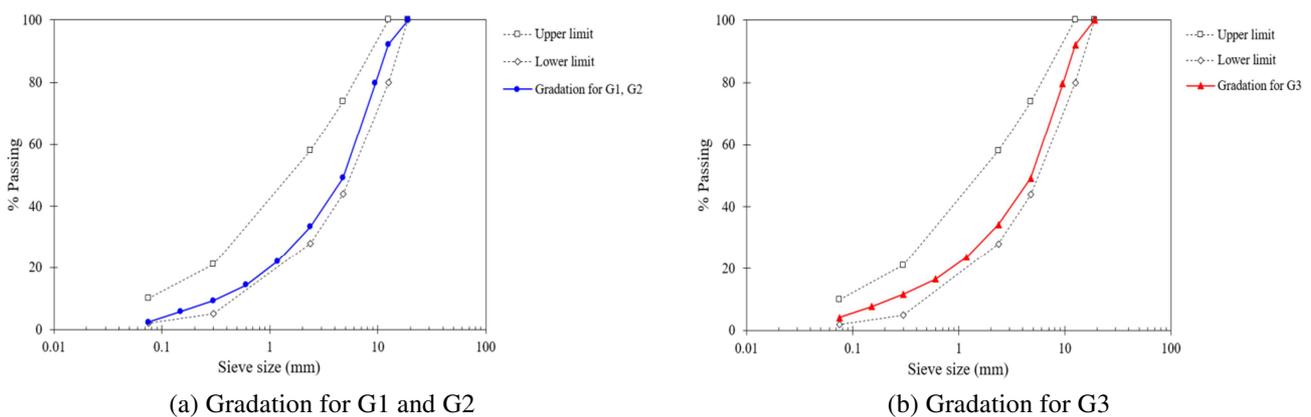


Fig. 4 Selected gradation for mixture design

3.3. Experimental program

3.3.1. Marshall stability and flow testing

The Marshall and flow test is carried out according to ASTM D6927 [26]. Fifteen compacted specimens of each mixture are soaked in a water bath at 60°C for 30 minutes, and then the outer surface is dried and placed on the Marshall machine (Fig.

5(a)). The conditioned samples are loaded with a constant rate of 50 mm/min until the maximum load is reached and then stability and flow values are recorded. After finishing the test, OBC is determined for the asphalt content corresponding to 4% AV and verified so that OBC meets the other criteria, namely the Marshall stability, Marshall flow, VMA, VFB, and density, as summarized in Table 6. It is important to note that, the OBC of each mixture obtained will be used to prescribe the asphalt content for the specimen fabrication in the ITS test, and its moisture susceptibility and corrosion resistance will be further calculated.

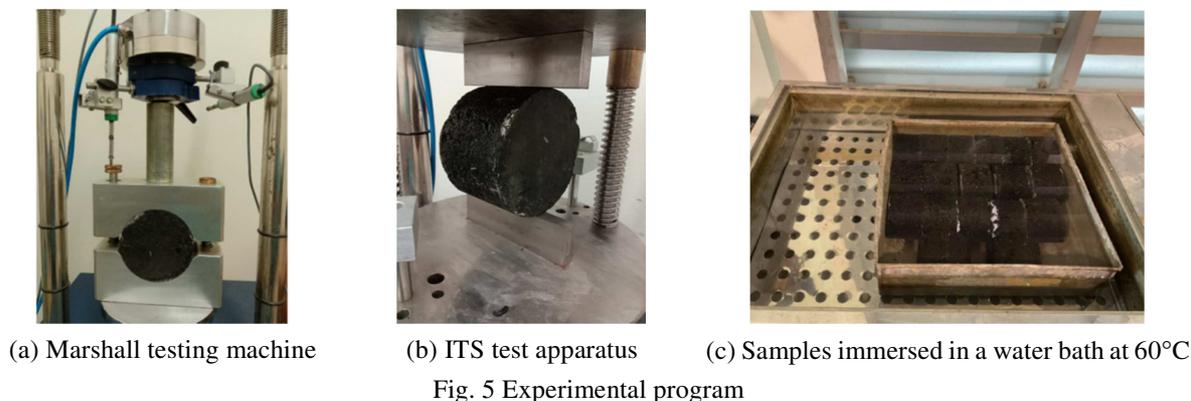


Table 6 Volumetric and mechanical properties obtained from Marshall testing

Mixtures	OBC (%)	AV (%)	Density (g/cm ³)	VMA (%)	VFB (%)	Stability (kN)	Flow (0.25 mm)	Marshall quotient (N/0.25 mm)
CM	5.0	4	2.405	14.7	73	8.1	10.1	792
PM-PL	5.4	4	2.386	15.6	73	13.4	9.5	1,416
PM-CR	5.5	4	2.375	16.5	74	10.6	10.2	1,039
FM-PA	5.2	4	2.400	14.6	73	11.5	10.3	1,117
FM-EA	5.5	4	2.378	15.2	74	12.8	10.0	1,285
FM-RA	5.5	4	2.330	17.0	72	10.0	10.0	1,000
DOH specification	3-7	3-5	-	> 14	65-75	> 8.00	8-16	> 712

3.3.2. ITS test and moisture susceptibility

The ITS test of asphalt mixtures is conducted based on ASTM D6931 [27]. Six specimens from each mixture are fabricated with the OBC obtained from the Marshall and flow testing sequence (Table 6), and then divided into dry and wet sample conditions. For the wet condition, the specimens are immersed in a water bath at 60°C for 24 hours and then are immersed in another water bath at 25°C for 2 hours before the test. For the dry condition, the samples are kept at a controlled room temperature of 25°C. Following the ITS test, the specimens are placed on the steel loading strips of the testing machine (Fig. 5(b)). The load is applied to the specimens at a constant rate of 50 mm/min, and the maximum load is recorded. Finally, the ITS value is calculated using the following equation:

$$ITS = \frac{2000P_{\max}}{\pi DH} \quad (2)$$

where *ITS* is the indirect tensile strength (kPa), P_{\max} is the maximum load (N), *D* is the specimen diameter (mm), and *H* is the specimen thickness (mm).

One of the environmental factors influencing the durability of the asphalt concrete is moisture. Moisture damage occurs primarily when the mixture's adhesion bond strength between the binder and the aggregate deteriorates [12]. The moisture susceptibility test according to ASTM D4867 is performed for a total of 36 specimens [28]. A TSR value is usually used to evaluate the moisture sensitivity of the mixtures. Higher TSR values indicate superior moisture damage resistance. A TSR value with a minimum of 80% is required for HMA mixtures which are expressed according to the following equation:

$$TSR = \frac{ITS_w}{ITS_D} \times 100 \quad (3)$$

where ITS_w and ITS_D are the average ITS of the samples under wet and dry conditions, respectively.

3.3.3. Immersion test

Distilled water (pH = 7) and three types of corrosion solutions, namely acid (pH = 3.5), sulfate (pH = 8.5), and alkaline (pH = 10) solutions, are prepared for the immersion test. In the consideration of temperature effects, the water solutions under 60°C temperature are prepared. It is known that, in most cases, the pavement temperature can reach 60°C in summer [21]. The main goal of this study is to compare the mechanical deterioration among the asphalt mixtures containing different waste materials exposed to corrosion solutions based on the short-term investigation. A period of 24 hours (1 day) and 72 hours (3 days) is chosen for investigating the short-term deterioration including reducing the time of testing. However, the corrosion resistance investigation of the asphalt mixtures for the short term has been studied and supported by Zhou et al. [14], Chen et al. [16], Zou et al. [21], and Setiadji et al. [29].

Hence, a total of 168 specimens are separately immersed in a water bath which contains both distilled water and corrosion solutions at 60°C for 24 and 72 hours (Fig. 5(c)), and then the specimens are soaked in another water bath at 25°C for 2 hours before ITS testing. In this study, the effect of the corrosion solutions can be assessed by the corrosion resistance factor (f_c). The f_c value is defined as the ratio of the ITS of the specimens soaked in the corrosion solutions to that of the ITS of the specimens soaked in the distilled water. The greatest f_c represents the strongest ability in terms of corrosion resistance of the mixtures. The f_c value can be calculated using the following equation [16, 19]:

$$f_c = \frac{ITS_c}{ITS_w} \quad (4)$$

where ITS_w and ITS_c are the indirect tensile strengths of samples soaked in the distilled water and the corrosion solutions, respectively.

4. Results and Discussion

4.1. Marshall test

The ITS, TSR, and immersion tests are conducted on each mixture at its OBC characteristic, which assumes that these mixtures have similar volumetric properties. Consequently, the OBC and volumetric properties should meet the requirements used. As shown in Table 6, the results of OBC are 5%, 5.4%, 5.5%, 5.2%, 5.5%, and 5.5% for the mixtures of CM, PM-PL, PM-CR, FM-PA, FM-EA, and FM-RA, respectively. The volumetric and the stiffness properties are considered to help characterize the Marshall mixtures. The volumetric properties consist of the bulk density, AV, VMA, and VFB, as shown in Table 6, which satisfy the DOH specification. The Marshall stability to flow ratio (Marshall quotient (MQ)), as explained in the stiffness of mixtures, is presented in Table 6. As seen, the MQ value of both the PM and FM mixtures is higher than that of CM. For example, an increase in MQ is about 77%, 60%, 39%, 30%, and 25% for the mixtures of PM-PL, FM-EA, FM-PA, PM-CR, and FM-RA, respectively. In summary, the volumetric and stiffness properties meet the standard requirement, allowing them to be used to assess the durability of the mixtures.

4.2. Tensile strength

In this study, the moisture damage analysis of the mixtures can be conducted in two stages. The first stage is conducted based on ASTM D4867 [28]. The results obtained in this stage are used to verify the moisture sensitivity performance of each mixture.

The ITS and TSR results are given in Table 7. It can be observed that the modified mixtures provide a higher ITS value compared to CM. The TSR values are greater than 80%, which are the minimum values required by the DOH specification for all mixtures. For the second stage, the ITS and TSR values of the samples soaked in different corrosion solutions are calculated. The ITS of the HMA mixtures for this stage (after the immersion of 24 hours) is depicted in Fig. 6. It is observed that the tensile strength of all mixtures tends to reduce under the corrosion solutions, as compared to the case under the distilled water.

The reduction in ITS of the specimens is due to the effect of corrosion solutions as shown in Fig. 7. The ITS reduction is defined as the ratio of the difference between the ITS after being immersed in distilled water and corrosion solutions to the ITS after being immersed in distilled water [19]. As shown in Figs. 7(a) and (b), the decreased range of ITS depends on the type of corrosion solutions, immersion time, and type of the mixtures. As observed, the reduction in ITS of the specimens after the immersion of 72 hours is higher than that after the immersion of 24 hours. In the alkaline solution for the immersion of 24 hours, the ITS reduction (Fig. 7(a)) of the CM, PM-PL, PM-CR, FM-PA, FM-EA, and FM-RA mixtures is 17.3%, 9.7%, 4.4%, 10.7%, 5.7%, and 18.7% respectively. These ITS reduction increases by 26.8%, 22.4%, 19.7%, 20.6%, 13.9%, and 31.8% respectively, for the immersion of 72 hours (Fig. 7(b)). In the sulfate solution for the immersion of 72 hours, the ITS reduction is 32.9%, 18.3%, 45.5%, 27.6%, 23.8%, and 34.2% respectively. After the specimens are immersed in the acid solution for 72 hours, the ITS reduction is 33.3%, 23.2%, 26.2%, 38.6%, 22.1%, and 36.1% respectively.

Table 7 ITS and TSR

Mixtures	Indirect tensile strength, ITS (kPa)		Tensile strength ratio, TSR (%)
	Dry condition, ITS_D	Wet condition, ITS_W	
CM	601.8	503.3	83.64
PM-PL	1,737	1,443	83.06
PM-CR	943.5	792.5	84.00
FM-PA	651.3	545.8	83.80
FM-EA	996.0	811.1	81.44
FM-RA	760.7	655.1	86.12

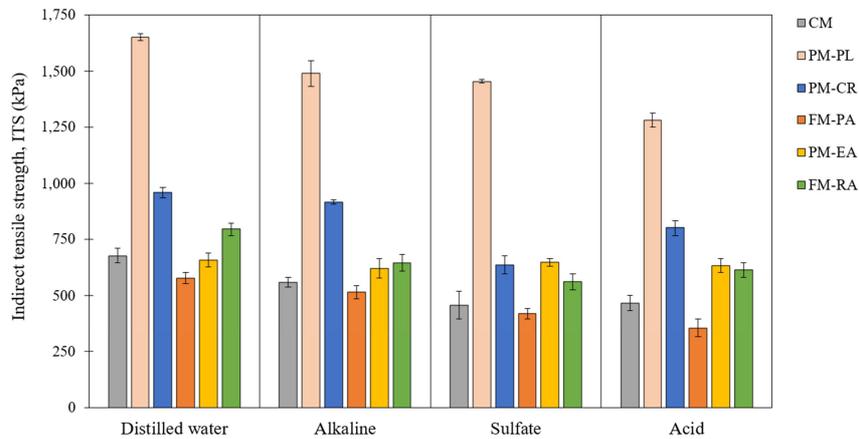


Fig. 6 Effect of water solutions on ITS after 24 hours

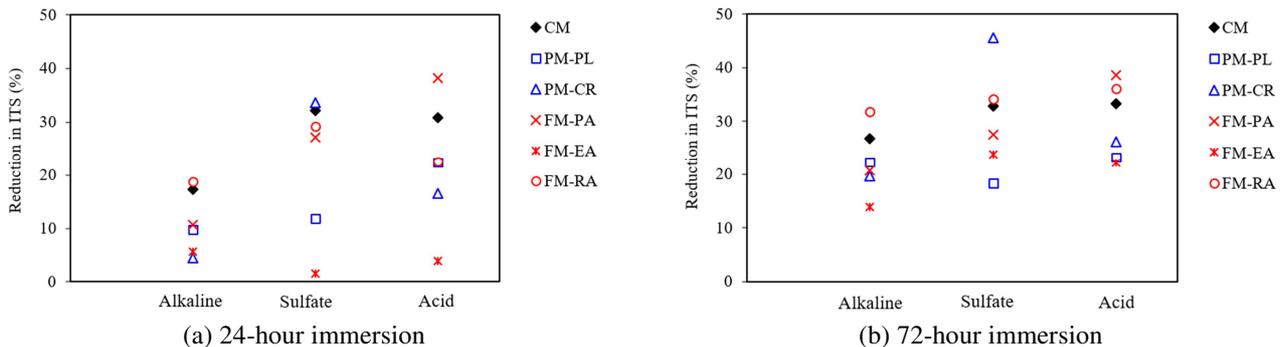


Fig. 7 Reduction in the ITS of various mixtures

The results of statistical studies on the tensile strength of the asphalt mixes immersed in various water solutions reveal an interesting finding. A hypothesis is made: after 24 hours of immersion in distilled water and corrosion solutions, there is no difference in the ITS values for each mixture. The statistical t-test on pair-wise differences is used to evaluate this hypothesis at a 95% confidence level. The result of the hypothesis test is summarized in Table 8. As observed from Table 8, the p-values for CM (G1) are lower than the threshold value of 0.05 under all corrosion solutions. It indicates that the alkaline, sulfate, and acid solutions have a significant impact on the ITS reduction of CM. For the PM group (G2), the p-values are only significant for PM-PL and PM-CR under acid and sulfate solutions, respectively. The FM group (G3) reveals that the mixtures of FM-PA and FM-EA can withstand all corrosion solutions provided in this study. For the FM-RA sample, a significant effect is found under both the acid and sulfate solutions.

Table 8 Result of the hypothesis test

Different water source pairing	p-value					
	G1	G2		G3		
	CM	PM-PL	PM-CR	FM-PA	FM-EA	FM-RA
Distilled water and alkaline solution	0.00	0.24	0.76	0.35	0.85	0.40
Distilled water and sulfate solution	0.01	0.34	0.04	0.23	0.63	0.01
Distilled water and acid solution	0.00	0.04	0.19	0.18	0.87	0.03

4.3. Moisture susceptibility

The results of the moisture susceptibility resistance test under corrosion conditions for various mixtures show that the tensile strength and TSR values reduce after immersion in the alkaline, sulfate, and acid solutions. Fig. 8 displays the moisture susceptibility as an effect of different water solutions on the six asphalt mixtures after the immersion of 24 hours. There is an obvious decrease in TSR under different water solutions. As observed in Fig. 8, the TSR values of all mixtures under the distilled water are more than 80%. The TSR of the CM, PM-PL, PM-CR, and FM-RA mixtures are also still more than 80% after being soaked in the alkaline solution. On the other hand, the TSR value is observed to be below 80% for the FM-PA and FM-EA mixtures, which may indicate poor resistance to alkaline environments. As seen in Fig. 8, the immersion in the sulfate solution for the TSR of the CM, PM-PL, PM-CR, FM-PA, FM-EA, and FM-RA mixtures are 76.2%, 83.8%, 67.5%, 64.6%, 65.0%, and 73.8% respectively. For the immersion in the acid solution, the TSR values are 77.6%, 73.7%, 84.9%, 54.7%, 63.5%, and 80.7% respectively. Obviously, for the same mixture, the acid solution has the highest damaging effect on the tensile strength and TSR, followed by the sulfate solution, alkaline solution, and distilled water.

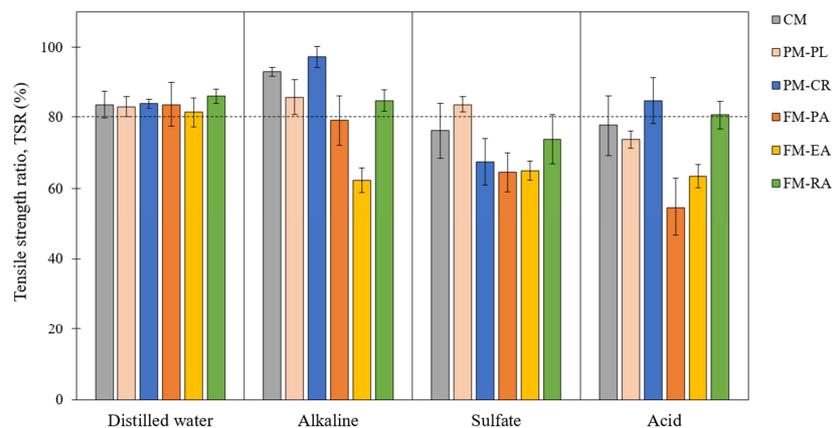


Fig. 8 Effect of water solutions on TSR after 24 hours

4.4. Corrosion resistance evaluation

The basic concept of the corrosion resistance factor (f_c) for the asphalt mixtures is that the mixtures can well withstand corrosion solutions under different environments with time. In this study, the f_c value is used as an evaluation index for

indicating the corrosion resistance of the three sample groups (i.e., CM, PM, and FM groups). From the test result, the corrosion mechanism under the effect of the alkaline solution, the sulfate solution, and the acid solution can be explained in the following manner. To compare the corrosive effect of different water solutions, only the SEM images for the PM-PL mixture are selected in this study. The microstructure of the PM-PL mixture obtained from the SEM test is depicted in Fig. 9.

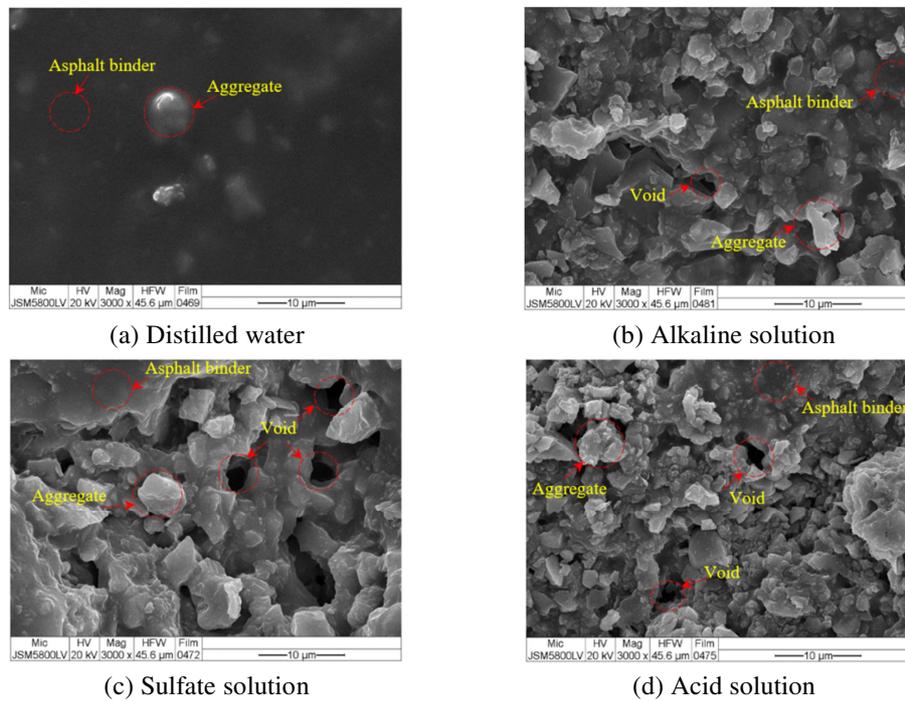


Fig. 9 SEM of the PM-PL mixture after soaked in different water solutions

4.4.1. Effect of the alkaline solution

Fig. 10 shows the changes in the f_c value of the six asphalt mixtures after being immersed in the alkaline solution for 24 and 72 hours. f_c ranges from around 0.81 to 0.96 after 24 hours, and then that value dwindles to about 0.68 to 0.86 after 72 hours. As seen in Fig. 9, the f_c factor of the CM, PM-PL, PM-CR, FM-PA, FM-EA, and FM-RA mixtures after the immersion of 72 hours is 0.73, 0.78, 0.80, 0.79, 0.68, and 0.86 respectively. Because the alkaline solution reacts with the asphalt film, the water penetrates the asphalt-aggregate interfaces, leading to a reduced bonding capacity [16]. As seen in Fig. 9(a), for the sample soaked in the distilled water, a relatively smooth surface is observed, and hardly any voids are displayed. Fig. 9(b) shows the SEM image of the PM-PL mixture after 72-hour immersion in the alkaline solution. Little deterioration to the surface is observed, with much smaller voids compared with that of the sulfate and acid solutions. Based on the f_c obtained, the corrosion resistance of the asphalt mixtures against the alkaline solution can be ranked from low to high in the following order: PM-CR, FM-EA, PM-PL, CM, FM-PA, CM, and FM-RA.

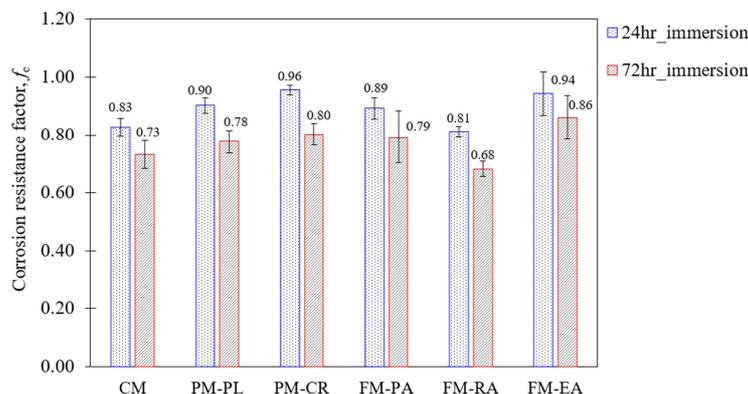


Fig. 10 Corrosion resistance factor of various mixtures under alkaline solutions

4.4.2. Effect of the sulfate solution

When the asphalt mixture is immersed in the sulfate solution, the interface between the asphalt and aggregates is potentially invaded due to different surface tensions between the sulfate solution and the distilled water [17]. Fig. 10 represents the varying degree of sulfate corrosion for all mixtures. Among all the mixtures, f_c ranges from around 0.66 to 0.98 after 24 hours, and dwindles to about 0.54 to 0.82 after 72 hours. As seen in Fig. 11, the f_c factor of the CM, PM-PL, PM-CR, FM-PA, FM-EA, and FM-RA mixtures for the immersion after 72 hours is 0.67, 0.82, 0.54, 0.72, 0.66, and 0.76 respectively. Based on the f_c obtained, the corrosion resistance of the asphalt mixtures against the sulfate solution can be ranked from low to high as follows: FM-EA, PM-PL, FM-PA, FM-RA, CM, and PM-CR. Fig. 9(c) shows the SEM image of the PM-PL mixture after the immersion of 72 hours in the sulfate solution, with the sample's rough surface and voids visible. It is observed that the adhesion of the asphalt-aggregate interfaces is destroyed.

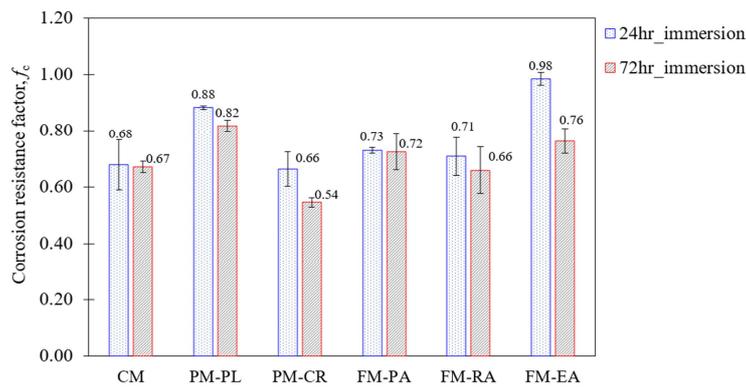


Fig. 11 Corrosion resistance factor of various mixtures under sulfate solutions

4.4.3. Effect of the acid solution

Fig. 12 shows the f_c of different asphalt mixtures affected by immersion in the acid solution. It can be seen from Fig. 12, after immersion in the acid solution, the f_c of all mixtures ranges from around 0.62 to 0.96 after 24 hours, and then decreases to about 0.61 to 0.78 after 72 hours. As seen in Fig. 12, the f_c factor of the CM, PM-PL, PM-CR, FM-PA, FM-EA, and FM-RA mixtures after the immersion of 72 hours is 0.67, 0.77, 0.74, 0.61, 0.64, and 0.78 respectively. The acid solution can penetrate the void of specimens, and corrodes the asphalt binder and aggregates [16]. In other words, the adhesion between the asphalt and aggregates is reduced with the presence of acid solution. Fig. 9(d) shows the SEM result for the internal microstructure of the PM-PL mixture under the effect of the acid solution erosion. It can be seen that small fractions and voids are visible as a result of acid solution attacks. These results are supported by the work of Feng et al. [20], of which it was understood that the acid reacted with the suboxide in the limestone aggregates to form an emulsifying agent, causing the bitumen coating to peel off from the limestone particles. The order of corrosion resistance performance of the asphalt mixtures versus the degree of corrosion in the acid solution from best to the worst is as follows: FM-EA, PM-CR, PM-PL, FM-RA, CM, and FM-PA.

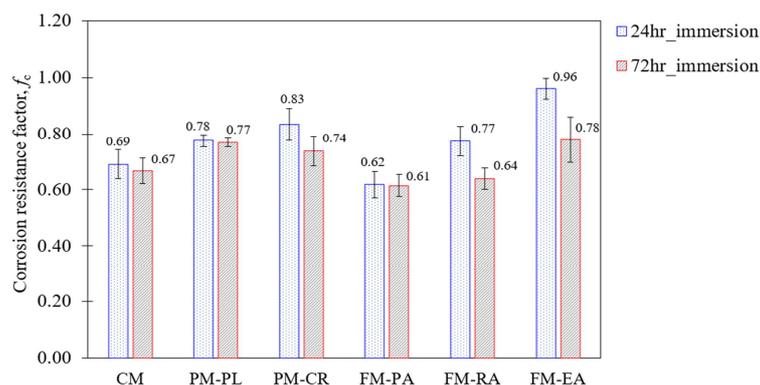


Fig. 12 Corrosion resistance factor of various mixtures under acid solutions

4.5. Overall ranking of the mixtures

The performance among the six mixtures based on the results obtained from this study is ranked from 1 to 6. For each test, the highest performance is ranked as 1, and the lowest is ranked as 6 [30]. For instance, the order of the ITS value for the alkaline immersion condition from best to the worst is PM-PL, PM-CR, FM-RA, FM-EA, CM, and FM-PA; therefore, they are ranked as 1 to 6 respectively. After the overall ranking for each mixture is conducted, the mixture with the least summation value is ranked as 1, as shown in Table 9. As summarized from Table 9, using the waste PM asphalt mixtures (i.e., PM-PL and PM-CR) can help improve environmental damage much better than FM mixtures (i.e., FM-PA, FM-EA, and FM-RA) and CM. When only the corrosion resistance is considered, however, the FM-EA mixture has better performance than the other samples. The order of the asphalt mixture performance from the best to the worst is PM-PL, PM-CR, FM-EA, FM-RA, CM, and FM-PA, respectively.

Table 9 Ranking for the mixtures based on their performance under different water solutions

Experiment test	Test conditioned	Ranking					
		G1	G2		G3		
		CM	PM-PL	PM-CR	FM-PA	FM-EA	FM-RA
Marshall test	MQ	6	1	4	3	2	5
ITS test	Distilled water	4	1	2	6	5	3
	Alkaline	5	1	2	6	4	3
	Sulfate	5	1	3	6	2	4
	Acid	5	1	2	6	3	4
TSR	Distilled water	4	5	2	3	6	1
	Alkaline	2	3	1	5	6	4
	Sulfate	2	1	4	6	5	3
	Acid	3	4	1	6	5	2
Corrosion resistance	Alkaline	5	3	1	4	2	6
	Sulfate	5	2	6	3	1	4
	Acid	5	3	2	6	1	4
Summation of ranking		51	26	30	60	42	43
Overall ranking		5	1	2	6	3	4

5. Conclusions

This study evaluated the corrosive effect of four different water solutions on the performance of various asphalt mixtures containing industrial waste materials. Based on the results and analysis of this study, the following findings can be drawn:

- (1) Corrosion solutions play an important role in reducing the tensile strength and durability of asphalt mixtures. For CM, the sulfate and acid solutions had a greater effect than the alkaline solution. The ITS reduction was approximately 27%, 33%, and 34%, when the sample was exposed to the alkaline, sulfate, and acid solutions, respectively. In addition, the PM and FM mixtures exhibited the highest strength reduction by about 25% and 32%, respectively, when immersed in the acid solution.
- (2) Regarding moisture susceptibility, the asphalt mixtures immersed in the corrosion solutions resulted in a variation in the TSR values. The mixtures PM-PL, PM-CR, and FM-RA showed good resistance under the alkaline environment. Only the PM-PL sample met the DOH specification when soaked in the sulfate solution. The PM-CR and FM-RA mixtures depicted a TSR value above the minimum requirement.
- (3) The corrosion resistance factor (f_c) value of the asphalt mixtures obtained in this study indicated the ability of the mixtures to withstand different corrosion solutions. Among the mixtures, and by only considering the f_c values, it was revealed that the mixture FM-EA achieved the best effect in terms of resisting both alkaline and acid solutions at 0.86 and 0.88, respectively. The PM-PL mixture seemed to improve the HMA mixture under the sulfate environment, which exhibited the highest f_c value of 0.82.

- (4) Based on the overall ranking of the mechanical tests under different corrosion solutions, the PM mixtures showed much better performance than the FM mixtures. Among the various mixtures, the PM-PL mixture is highly recommended for enhancing the properties of the other mixtures. However, there is a lack of the corrosion resistance evaluation for dry-wet cycle corrosion environments, and a long-term investigation is required.

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Conflicts of Interest

The authors declare no conflict of interest.

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