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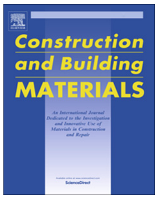

Anti-chemical resistance and mock-up test performance of cement asphalt mortar modified with polymer for ballast stabilizing

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HIGHLIGHTS

- Polymer component improves the rheology and ductility of cement asphalt mortar (CAM).
- Anti-acid resistance of CAM mixture is enhanced by asphalt membrane.
- Asphalt emulsion is weakened by engine oil that leads to the strength loss of CAM.
- Waterproofing ability of asphalt membrane enhances the freeze–thaw resistance of CAM.
- Stabilizing ballast by CAM promotes settlement resistance for railway structure.

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ABSTRACT

This study aims to evaluate the possibility of ballast stabilization by cement asphalt mortar (CAM) to decelerate the permanent settlement and improve the track structure durability. The influence of components dosage on the rheology, strength, and durability of nonionic CAM are investigated. CAM mixtures are fabricated by various asphalt/cement ratios and asphalt emulsion types (with and without polymer). The CAM samples are submerged into the sulfuric acid and engine oil condition to test the durability by conducting the unconfined compressive strength test. The actual settlement resistance of the combination between CAM and ballast is evaluated through the mock-up test. The test results reveal that adding polymer enhances the rheology of CAM mixture. It was found that CAM mixture with high asphalt emulsion obtains high acid resistance. Meanwhile, the engine oil condition leads to a great drop in strength. The mock-up test results suggest that the settlement of the ballast layer can be noticeably reduced by using CAM.

1. Introduction

The ballasted track system is shown to be ideal in railway structure since this form achieves many promising characteristics such as high damping capacity, fast drainage, noise absorption, and low construction cost [1]. Based on preliminary research, the main components that contribute to the durability of the ballasted track structure are the ballast particle quality and its inter-locking connections [2]. However, being subjected to constant load cycles from passing trains and with environmental exposure leads to aggregate deterioration problems. As a result, the continuous reduction in quality of ballast particle system causes the poor stress distribution and triggers permanent deformation [3]. Therefore, the need for maintenance work has been significantly increased through its service life to prevent the progressive rate of ballast degradation and geometric settlement. In recent years, several solutions have been proposed to sustain the durability of the ballasted track system to reduce cost and maintenance rates [3].

Regarding the design-based technologies to prevent permanent deformation and stress imposed on the ballast layer, the utilization of soft rail pads is considered as a conventional method with the stiffness of around 100 kN/mm. Although this solution helps minimize the settlement and ballast degradation in ballast layer, reports show that very soft elastic element may cause substantial rail deflection under high dynamic movements [3,4].

Recently, the conventional under-sleeper pads and under-ballast mats technique for stabilizing ballasted track bed are promoted by the utilization of new source of elastic material, waste tire rubber. This sustainable method is developed with the aim of wide application since the economic and environmental cost can

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be remarkably reduced. However, the actual long-term performance analysis is yet to be found [3,5].

At the initial stage of track-bed construction, reports reveal that the application of geogrids and bituminous sub-ballast can substantially increase the shear strength and bearing capacity of the ballast layer [6]. From large-scale test results, these methods can shorten the thickness of sub-ballast layer up to 30% without affecting the settlement resistance of the whole structure. The application of these techniques also mitigates ballast degradation phenomenon by reducing particle movement [6]. The bituminous sub-ballast layer has been gaining more attention since this technology can enhance the bearing capacity of track-bed, resolves the existing deflection problems from soft element method, and ensures the high durability performance. Although the frequency of maintenance can be lowered, the relatively high initial construction cost followed by its environmental impact problems may hinder wide application for a sustainable purpose [3–6].

Besides, there are also some alternative solutions which adapt the high demand in the maintenance process due to the high number of existing railway lines [3]. The following research focuses on the maintenance-based strategies which aim to lower the frequency of maintenance associated with a stiffer track structure. The concept of these methods relies on the increasing shear strength which improves the track stiffness. Based on recent research, railway track settlement and ballast particle deterioration can be significantly decelerated by the application of bonding materials in the ballast particle systems such as polyurethane, resin or asphalt emulsion [3,7,8]. Among them, polyurethane stabilization is considered to be the most effective solution to enhance the settlement resistance of the ballast layer [7]. Besides the polyurethane stabilization, the degradation of fouled ballast particles can also be solved by using stone blowing technique. In spite of the significant improvement on track deflection, studies on stone-blowing technique impose concern about the change in track behavior. Overall, the main limitation of these maintenance-free strategies lies on productivity during installation and the long-term durability [3,7,8]. Therefore, further research should take into account the durability and systematically conduct the life cycles analysis before applying to the actual site.

Regards to the ballast-less railway system, cement asphalt mortar is shown to be a very ideal solution in modern railway structure [9]. This interlayer track slab and concrete roadbed provide smoothness for a high-speed train, damping effect, and ensure the long-term durability for the whole structure. Moreover, with a fast and simple application, findings from China, Japan, and Europe promote this technique to be applied on large scale. However, since this technique can only be applied at the initial stage of construction, further study should be conducted to broaden its application on maintenance projects [9–11].

To cope with the above issues, this research aims to develop a new solution called Cement Asphalt Mortar Stabilized Ballast which is expected to meet the need for the development of more economical and durable solutions. The main concept is to create a novel bonding material between ballast particles by using flowable cement asphalt mortar [13,14]. The combination is expected to achieve the merits of the stiffness of cement and the ductility behavior of asphalt membrane. Within this coating material, the rutting resistance and durability of the ballast layer can be enhanced. Problems from dust released by fouled ballast can also be solved by this CAM layer. By simply pouring the fresh CAM mixture on top of ballast, the self-leveling behavior will lead the material to flow through the whole ballast system that allows it to be easily applied in railway maintenance projects.

Prior research on the mechanical properties of CAM with varying material ratios reveals that higher asphalt emulsion/cement (AE/C) ratio leads to a reduction in strength gain [12,16–18]. However, the increase in AE content leads to better ductility behavior of CAM due to the viscoelastic behavior of asphalt membrane [12,13]. The proper use of optimum initial mixing water and sand can improve the mixing stability of asphalt droplets in asphalt emulsion and thereby, enhancing the rheology of CAM mixture [13,14]. Also, the use of quick-hardening admixture provides a promising signal on early strength attainment for lesser traffic closures [13].

Recent research has been focused on the engineer properties of cement asphalt mortar modified with cationic (+) or anionic (−) emulsifier [15–18]. However, there is still much to be studied on the characteristics of CAM developed from nonionic emulsifier, especially on the durability and actual behavior from mock-up or real scale test. Reports indicate that the acid rain from nearby industrial zones may critically damage the railway structure [19,20]. Also, the lubricant oil from railway and train maintenance can erode the quality of the ballast track [19,20]. The accumulation of these aggressive chemicals will impose detrimental effect on the long-term performance of ballast structure. Hence, it should be taken into account the durability of CAM under severe environmental conditions before the actual application.

The main objective of this research is to investigate the durability of nonionic cement asphalt mortar under different severe curing conditions and evaluate the actual behavior of stabilized ballast with CAM. To achieve these purposes, two types of asphalt emulsion (AE) are employed in this research: nonionic asphalt emulsion (N) and nonionic asphalt emulsion modified with polymer (P). Then, from each type of asphalt emulsion, three levels of AE are used to develop test samples including 75%, 100%, and 125% by weight of cement (C). Based on suggestions from preliminary research on the durability of CAM and mortar [20–23], the severe curing conditions used in this study comprises of a high acid (3% concentration H_2S04), high engine oil environment, and Freeze-Thaw cycles (F-Ts). To develop systematical research on CAM with nonionic asphalt emulsion, all conditions underwent a mixing stability test and flowability test at the first stage. Then, the early strength of test specimens is recorded by using the unconfined compressive strength (UCS) test after 2hrs. The UCS test of 28 days samples is conducted on control, acid, engine oil, 3 F-T cycles, and 6 F-T cycles conditions. The scanning electron microscope (SEM) analysis is then applied on all 28 days specimens to correlate with the findings from the strength test. Finally, a mock-up test is conducted using the best CAM condition to study the actual behavior of the combination between ballast and CAM.

2. Materials and methods

2.1. Materials

In this study, the overall properties of nonionic asphalt emulsion are presented in Table 1. The polymer used to develop polymer asphalt emulsion is styrene-butadienestyrene provided

Table 1
Properties of nonionic asphalt emulsion.

Properties		Requirement	Test results
Charge of particles		Nonionic	Nonionic
Viscosity (25 °C)		2–30	4.0
Sieve residue (1.18 mm) (% by mass)		Below 0.3	0.0
Storage stability (24 h, %)		Below 1	0.1
Cement mixing test (residue % by mass)		Below 1	0.2
Evaporation residue	Evaporation residue (% by mass)	Higher than 57	62.6
	Penetration (25 °C) 1/10 mm	60–300	83
	Ductility (15 °C) cm	Higher than 40	Higher than 100
	Toluene-soluble fraction (% by mass)	Higher than 97	99.2

by the Korean company. This type of emulsion is employed in this research based on the suggestion from prior works and experience [13–15]. Type II cement is used in this research with the chemical composition and physical properties shown in Tables 2 and 3, respectively. Based on the preliminary research, the application of construction sand (S) at a ratio of 0.5 by weight of cement enhances mixing stability noticeably [13]. Prior works also found that adding 14% quick hardening admixture (QA) by weight of cement accelerates the hydration process of CAM without rheology impact [13]. Hence, both sand and quick-hardening admixture are utilized in developing the optimum mixture. To reduce the use of water while maintaining the flowability, superplasticizer (Table 4) is mixed with water at a ratio of 2% by weight of cement. Regards to the excessive air bubble formed in the production of asphalt emulsion or during the mixing period, this issue is resolved by using 0.1% defoaming agent (D) by weight of cement. The properties of the defoaming agent are shown in Table 5. The mix design of this study is exhibited in Table 6.

2.2. Mixing method

Because the AE has 50% water content. When the AE is increased, it means the water is also increased in the mixture fabrication. Hence, the initial mixing water in those mixture with higher AE content is reduced to maintain the equivalent “final water” in all CAM mixture. For example, mixture with AE/C ratio of 75% has W/C ratio of 30%, meanwhiles, mixture with AE/C ratio of 125% has W/C of 20%. Based on the mixing methods from preliminary research, the wet mixing method is applied in this study. The high adsorption ability of cement particle to asphalt droplets in asphalt emulsion is remarkably reduced by mixing with water, the coalescence of asphalt on cement surface at an early stage is then retarded. Hence, this concept will help delay the demulsification process of asphalt emulsion and thereby, improving the mixing stability of the whole mixture with a low sign of agglomeration [13,14,16]. Regards to the mixing process, first, all dry components (C, QA, S, D) are pre-mixed with water modified with SP for approximately 2 min at a shear rate of 120 rpm. Asphalt emulsion is then added with an additional 2 min of thorough mixing at the same shear rate. Finally, the mixing speed is reduced to 60 rpm for 1 min before casting fresh mixture into samples. The mixing speed is reduced to minimize the formation of foam as well as ensure the stability of asphalt emulsion. To characterize the mechanical properties of nonionic CAM with and without polymer, the testing flowchart presented in Fig. 1 is followed.

2.3. Performance test

2.3.1. Mixing stability test

Among the rheology properties of fresh CAM, the mixing stability plays the most important role which critical impact on the particle formation of asphalt emulsion. The tests are conducted in

Table 2
Chemical composition of cement by percent.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O_3	f-Cao
21.56	4.15	2.64	61.18	2.35	3.01	0.65	0.81

Table 3
Physical properties of cement.

Fineness (residue on 80 μm sieve) (%)	Specific surface (m^2/kg)	Initial setting (min)	Final setting (min)	28 day compressive strength (MPa)	28 day flexural strength (MPa)
0.5	330	145	205	55	4

Table 4
Properties of polycarboxylic superplasticizer.

pH, 25 °C	Density (g/cm^3)	Mass average molecular weight	Sidechain density of carboxylic acid groups	Viscosity cP, impeller rotational velocity
6.2	1.116	50,000	1:5	896 cP, 20

Table 5
Properties of the defoaming agent (polyether mainly).

PH Index	Appearance	Moisture	Stacking Density	Solid Content	Operating Temperature
3–14	White powder solid	<1	0.99–1.2	100%	5–100 °C

Table 6
Mixture proportion of nonionic CAM (based on cement weight).

Mix	Cement (C)	Quick Hardening Admixture (QA)	Asphalt Emulsion (AE)	Sand (S)	Water (W)	Superplasticizer (SP)	Defoaming Agent (D)
N75	100%	14%	75% (N)	50%	30%	2%	0.1%
N100	100%	14%	100% (N)	50%	25%	2%	0.1%
N125	100%	14%	125% (N)	50%	20%	2%	0.1%
P75	100%	14%	75% (P)	50%	30%	2%	0.1%
P100	100%	14%	100% (P)	50%	25%	2%	0.1%
P125	100%	14%	125% (P)	50%	20%	2%	0.1%

*N = nonionic CAM without polymer; P = nonionic CAM with polymer.

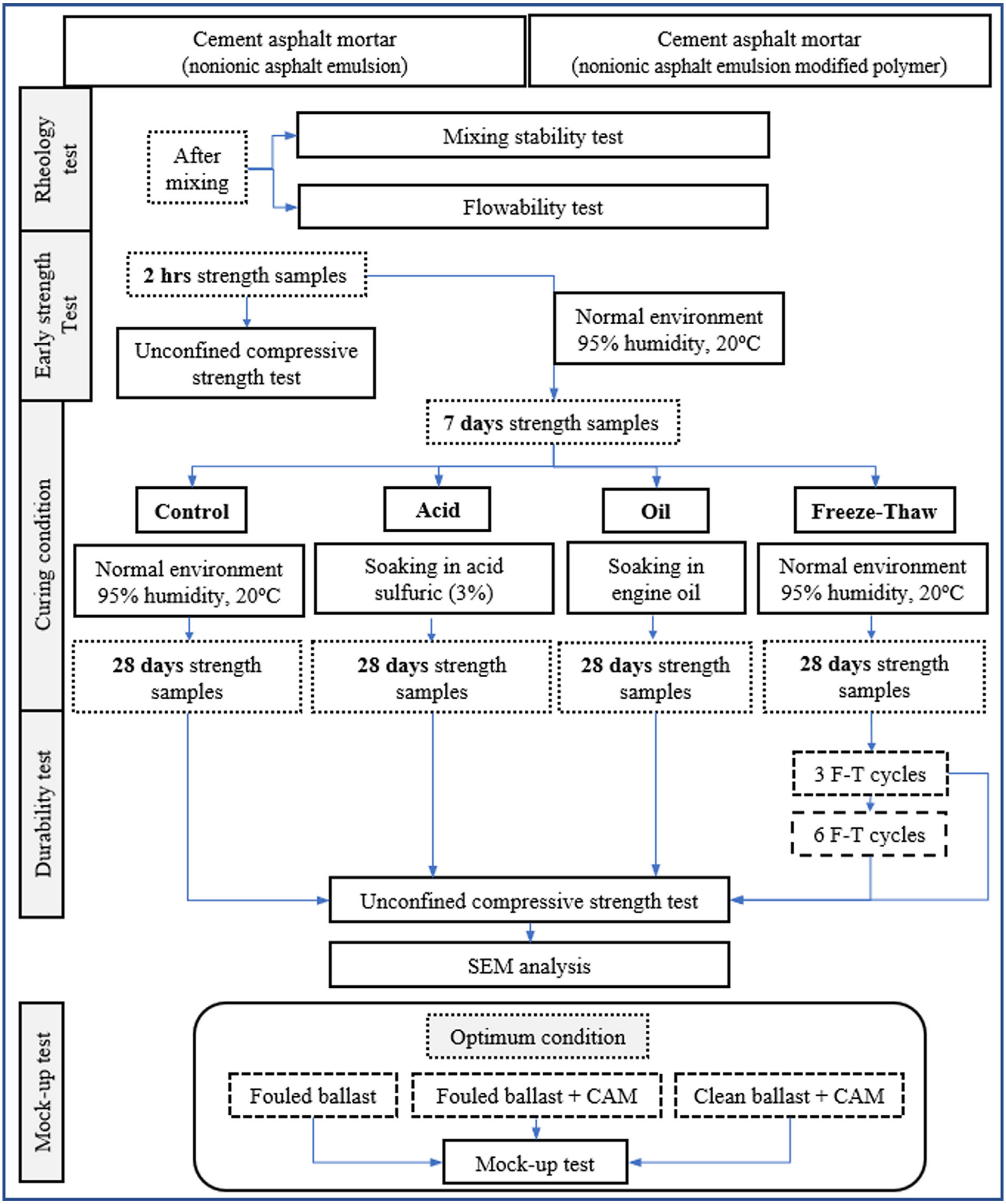


Fig. 1. The testing flowchart.

accordance with the KS M 2203 standard [23]. Initially, an asphalt emulsion is prepared to have 50% asphalt content on a deionized water solution. Then, 50 g of dry cement is mixed with 50 g of asphalt emulsion. The fresh slurry is subjected to a mixing speed of 120 rpm for 3 min. After this process, 150 g deionized water is then added to the mixture and the new combination is stirred at the shear rate of about 60 rpm for 2 min before filtering the whole mixture through a 1.18 mm sieve. The residue content is then oven dried for 2hrs to calculate the mixing stability status. The mixing stability status, P_r (%), of each mixture is recorded by using Eq. (1), having m, m_1, and m_2 as oven-dried weight of residue, asphalt emulsion, and cement weight, respectively.

$$P_r = \frac{m}{m_1 + m_2} * 100\% \tag{1}$$

2.3.2. Flowability test

The fast and simple application of CAM is mainly attributed to its self-leveling ability. To characterize this property of fresh CAM, the flow cone test is employed based on the KS F 2432 standard [24]. This test requires the use of a 400 ml steel flow cone, a steel plate, and a recording watch. The total time for a 400 ml fresh mixture to completely flow out of the steel cone to the steel plate is considered as the flow time. The flow cone test is applied three times on each condition to acquire the average value. Due to the high bonding of CAM on the inside surface of the steel flow cone, it should be taken into account that the steel apparatus should be cleaned carefully before conducting every test to achieve reliable results.

2.3.3. Unconfined compressive strength test

Due to the strict time required for fouled ballast maintenance, the strength development of CAM in this study is measured after 2 h. This short time is expected to simulate the strength gain of the mixture in the actual site. Meanwhile, the 28 days unconfined compressive strength is recorded since the whole CAM structure may gain nearly full strength after this period. This value will quantify the optimum performance of CAM.

Regards to the test sample preparation, after the homogenous mixing process, the fresh mixtures are cast into cylindrical samples with a size of 50 mm in diameter by 100 mm in height. With those samples subjected to early strength test, the mixtures are demolded 2 h before conducting the UCS test. The remaining samples are stripped out from the laminate mold after 24 h to ensure the shape stability. Then, they are transferred to a curing condition of 100% relative humidity and 20 °C until the testing day. By using the universal testing machine, the loading rate in this test is controlled at 1 mm/min [25,26]. 3 replicates are used to represent the average value of 1 condition.

2.3.4. Acid sulfuric and engine oil environment preparation

The whole mixing process and sample preparation during the first 7 days follow the previous section. However, after the first 7 days of 100% relative humidity (RH) and 20 °C curing, the samples are submerged in sulfuric acid or engine oil environment. As stated before, the acid rain from a nearby industrial region or lubricant oil from railway maintenance may cause durability deterioration for the CAM stabilized ballast system. Therefore, the need for evaluating the durability of CAM under these severe conditions is of importance.

In this research, the acid sulfuric condition is prepared by gradually pouring sulfuric acid into deionized water to obtain a 3% concentration [21]. Then, the solution is slowly stirred by a glass rod at a rate of 30 rpm. Due to the use of sulfuric acid, proper safety protection should be observed. Meanwhile, the preparation of the engine oil environment is simpler by obtaining used oil from the local automobile station with property shown in Table 7. The obtained engine oil is used to create the propose test condition without further step requirement.

The samples cured in acid or engine oil conditions are kept at room temperature of around 20 °C until reaching 28 days curing. Then, samples are cleaned by using a paper towel and let to dry at the same temperature for 2 h before conducting the UCS test.

Table 7
Properties of engine oil.

Parameter	Unit	Engine oil
Kinematic viscosity (40 °C)	mm^2/s	104
Kinematic viscosity (100 °C)	mm^2/s	13.3
Density (15 °C)	g/cm^3	0.86
Viscosity	–	133
Base number	mg KOH/kg	8.2
Ca	ppm	2400
P	ppm	600
S	ppm	4800
Zn	ppm	800

2.3.5. Freeze–thaw cycles test

Based on AASHTO T283 2014 [27], the F-T cycle test is conducted to investigate the durability of CAM samples under considerable freeze–thaw damage. First, 28 days samples are placed in a vacuum container with 25 mm of water above its surface. After sealing the lid, a vacuum of approximately 13–67 kPa is applied for around 10 min. Then, the samples are kept submerged in water for 10 min more after removing the pressure. These steps will help saturate the test specimens. Sealed plastic bag with 10 ml of water is prepared to contain the saturated specimen and is stored in a −18 °C freezer for 16 h. After which, the thawing period is triggered by submerging the frozen specimen into a water bath at 60 °C for 24 h. Finally, the temperature of the water bath was reduced to 25 °C and the specimens are kept in this condition for 2 more hours. This process represents 1 F-T cycle. Specimens from F-T cycles were let to dry at room temperature for 1 day before the UCS test. The average value of each condition is obtained by using three replicates.

2.3.6. SEM analysis

The Hitachi FE-SEM S-4700 SEM under high vacuum condition was used in this research to investigate the microstructure establishment of CAM. The microstructures of CAM mixtures modified with and without polymer are also compared. The aim of this analysis is expected to reassure the findings from UCS test results. To simplify the analyzation process, only CAM mixtures with AE/C ratio of 1.0 are used in this test.

2.4. Mockup test (simulative field testing of the ballast structures)

The mockup test is performed to evaluate the actual performance of the CAM stabilized ballast method. The combination of clean ballast and CAM is considered as the stabilizing method applied at the initial construction stage of railway structure. Meanwhiles, CAM mixture with fouled ballast will represent the actual ballast condition in maintenance & rehabilitation projects. In addition to the ballast types, clean ballast used in this test has an aggregate size ranging from 10 mm to 25 mm with the gradation size shown in Fig. 2. Meanwhile, the fouled ballast condition used in this test is the combination by weight of 80% clean ballast and 20% dust (sieve size lower than 10 mm).

The optimum CAM content for ballast covering is chosen from trial laboratory test and preliminary test suggestions [13,14]. It was found that 7–10% air void in ballast aggregate will allow fresh

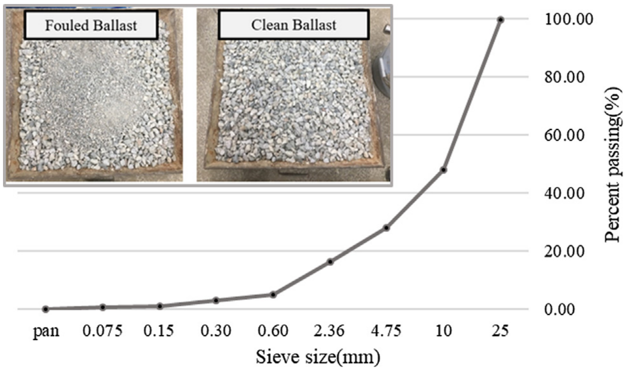


Fig. 2. The particle size distribution of ballast.

CAM mixture to completely flow through the ballast layer without excessive settlement at the bottom. The figurative model and actual apparatus used in the mockup test is shown in Figs. 3 and 4, respectively.

In the preparation for the mockup test, 10 cm of sand layer is compacted to simulate the basement (Fig. 4a). Then, to ensure a good compacting for ballast layer, the 20 cm ballast layer is divided into two equal layers and thereby, compacting 10 cm of ballast layers respectively (Fig. 4b). This process will ensure the interlocking quality for the whole structure. After the compacting process, the freshly prepared CAM mixture is poured from the top of the ballast layer (Fig. 4c). The gravity of fresh CAM, the high flowability of the mixture, and the large air-void system in this layer will help the CAM to flow and cover the ballast particle. The new combination

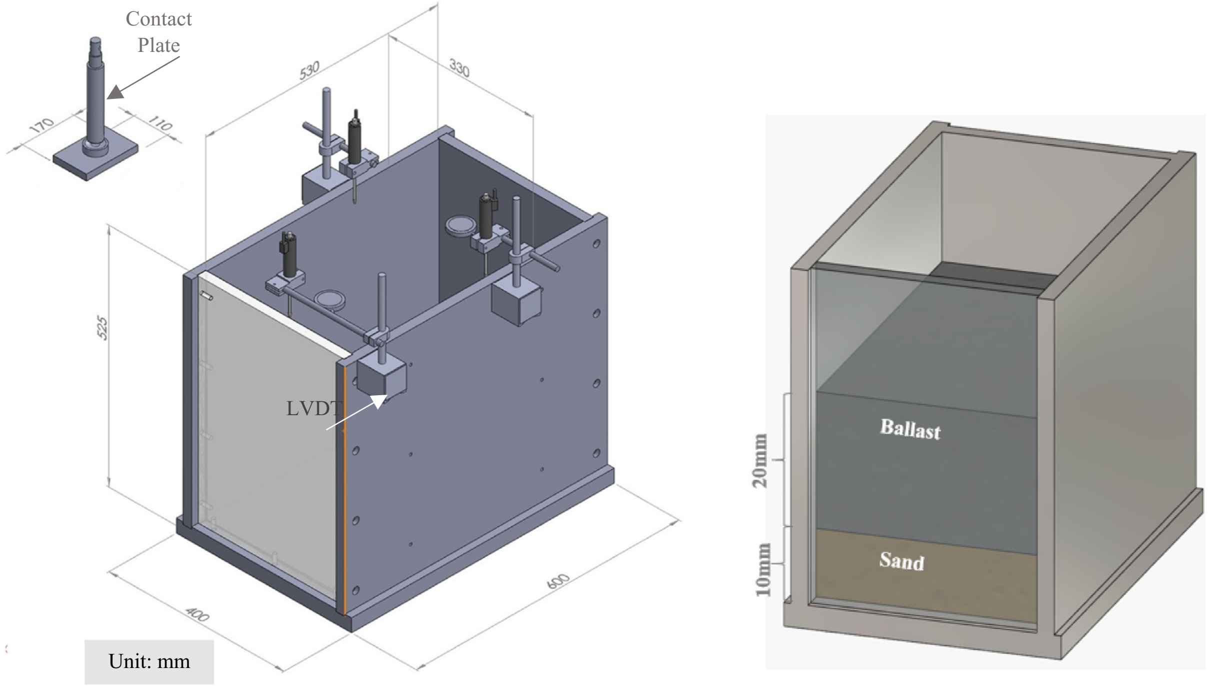


Fig. 3. The mockup test apparatus and the test model.


Compacting sand layer

Compacting ballast layer

Cement asphalt mortar preparing and pouring

Application of cyclic loading

Fig. 4. Mockup test set up showing: a) sand layer compacting, b) ballast layer compacting, c) CAM mixing and pouring, d) cyclic loads application.

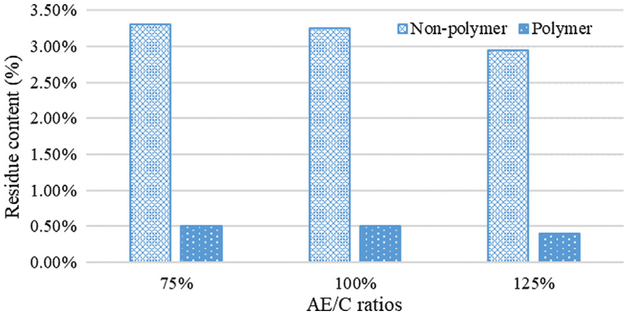


Fig. 5. Mixing stability test results of nonionic CAM mixture.

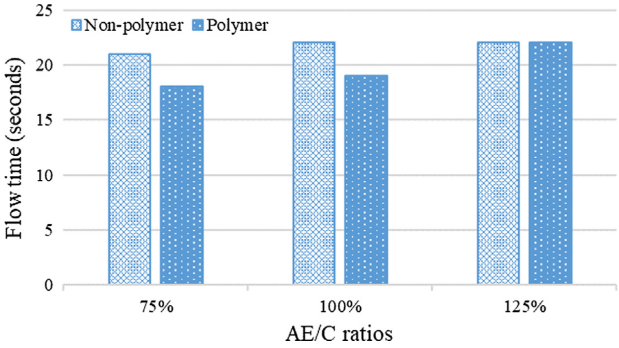


Fig. 6. Flowability test results of nonionic CAM mixture.

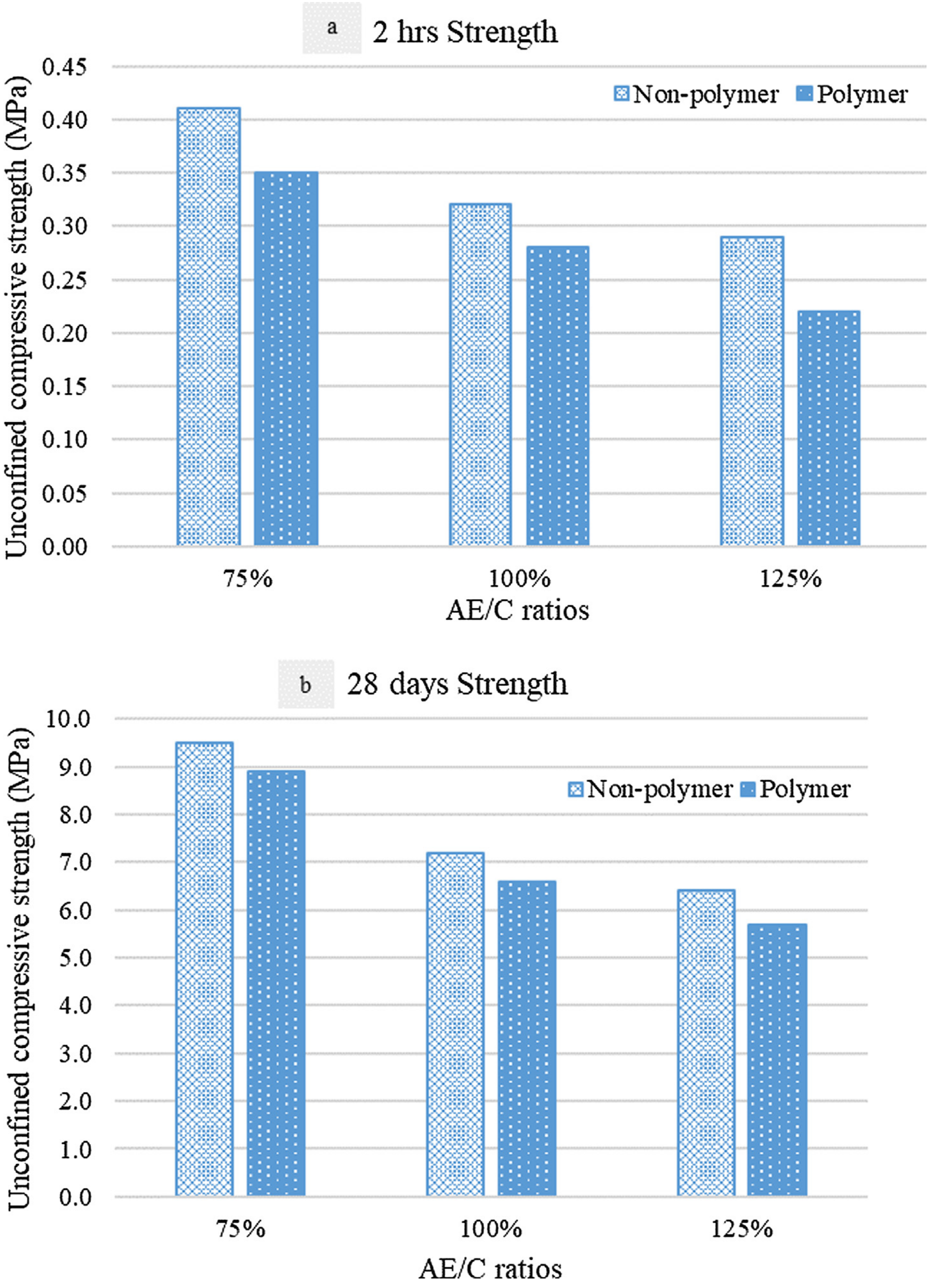


Fig. 7. Unconfined compressive strength test results for (a) 2 h, and (b) 28 days.

between ballast and CAM is let to rest for approximately 4hrs before applying the load.

The contact point between the cyclic loading ballast layer is the steel plate which size of 110 × 170 mm. The maximum axial load of 22 kN with the controlled loading rate of 10 Hz is applied in the test. Each ballast stabilizing condition is undergone 10,000 cycles of load. The load cell system and two LVDTs connected at the edge of the contact plate are used to record the load and displacement results (Fig. 4d).

3. Test results and discussions

3.1. Mixing stability test

The mixing stability test results of CAM mixtures are portraited in Fig. 5. Unlike the CAM mixture modified with normal asphalt emulsion, it was found that asphalt droplets are very stable in asphalt emulsion with the polymer during the mixing period. The residue content of non-polymer mixture was approximately 3%, meanwhile, this value of polymer mixture was significantly lower at 0.5%. The mixing stability gap between two asphalt emulsion types is smaller when the AE/C ratio is increased from 0.75 to 1.25. The whole polymer CAM mixture shows smooth texture with no sign of particle formation. Besides, the agglomeration phenomenon was not recorded in this condition. It can be explained that the polymer component in asphalt emulsion may protect the asphalt droplets from the absorption energy of the cement particles and thereby, sustaining the durable condition of asphalt emulsion at an early stage. Hence, the demulsification process of asphalt emulsion can be delayed with the used of asphalt emulsion modified polymer.

3.2. Flowability test

The flowability test results of CAM mixtures are represented in Fig. 6. It should be noted that mixtures with a high AE/C value will

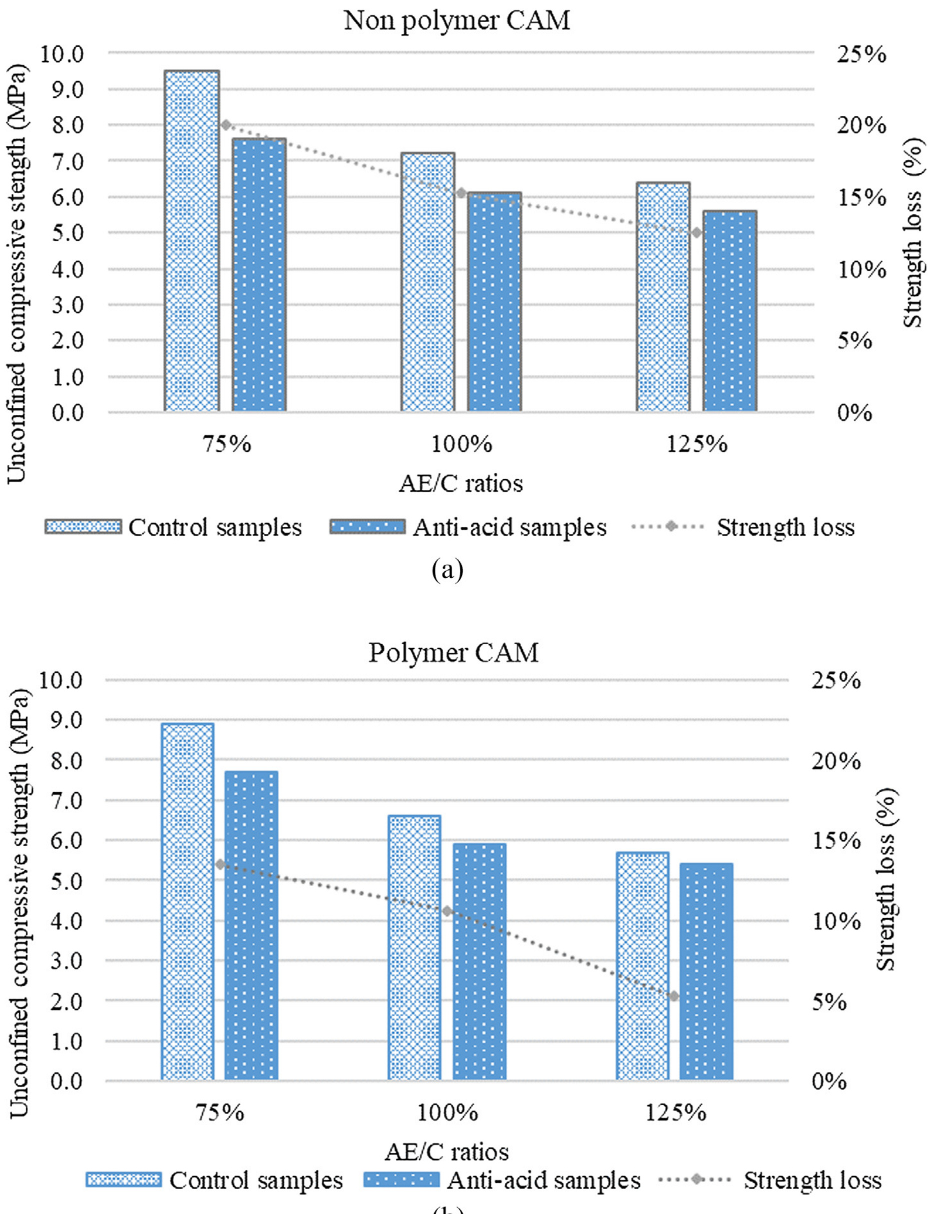


Fig. 8. Anti-acid resistance results of CAM mixture: a) Non-polymer CAM, b) Polymer CAM.

release more trapped water into the mixture after the AE demulsification process. Hence, the initial mixing water was reduced in mixture with high AE content to control the total water for cement hydration process. Therefore, the mixing water of mixtures with 75%, 100% and 125% AE content are designed at 30%, 25% and 20% by weight of cement content. Due to the reduction in the initial water, the flowability of CAM mixture is slightly affected. The test results confirmed the findings from mixing stability test that polymer CAM mixtures achieve much better flowability with flow time of about 18 s. Meanwhile, this value of non-polymer CAM mixture took longer with 21 s. Due to the formation of bigger CAM particles that retained on the 1.18 sieve size, the flow speed of non-polymer mixture may be hindered by the accumulation phenomenon at the nozzle of the steel cone. Besides, it was found that using higher AE/C ratio to mixtures is likely to increase the viscous of CAM mixture with polymer content. As a result, at 1.25 AE/C ratio, the flowability of mixtures with both asphalt emulsions is relatively about the same at 22 s.

3.3. Unconfined compressive strength test

The strength development of nonionic CAM mixtures is measured at an early age (Fig. 7a) and at 28 days (Fig. 7b). Regards to the effect of AE/C ratio, the test results agree with the findings from the preliminary study that a higher AE/C ratio leads to a noticeable drop in strength. For example, the 2 h UCS of non-polymer mix N1, N2, N3 are 0.41, 0.32, and 0.29 MPa respectively. It can be explained by the covering of asphalt emulsion onto the cement particles which retarded the hydration process. In fact, it was found that the coalescence of asphalt droplets in cement particles will prevent them from hydration. In addition to the effect of asphalt emulsion, the test results reveal that CAM mixtures modified with polymer obtain lower strength compared to the non-polymer mixture. Due to the slow demulsification process of polymer mixtures, as shown in the mixing stability test, the differences in strength between two CAM mixtures are pronounced at an early age, however, it becomes smaller after 28 days. The highest

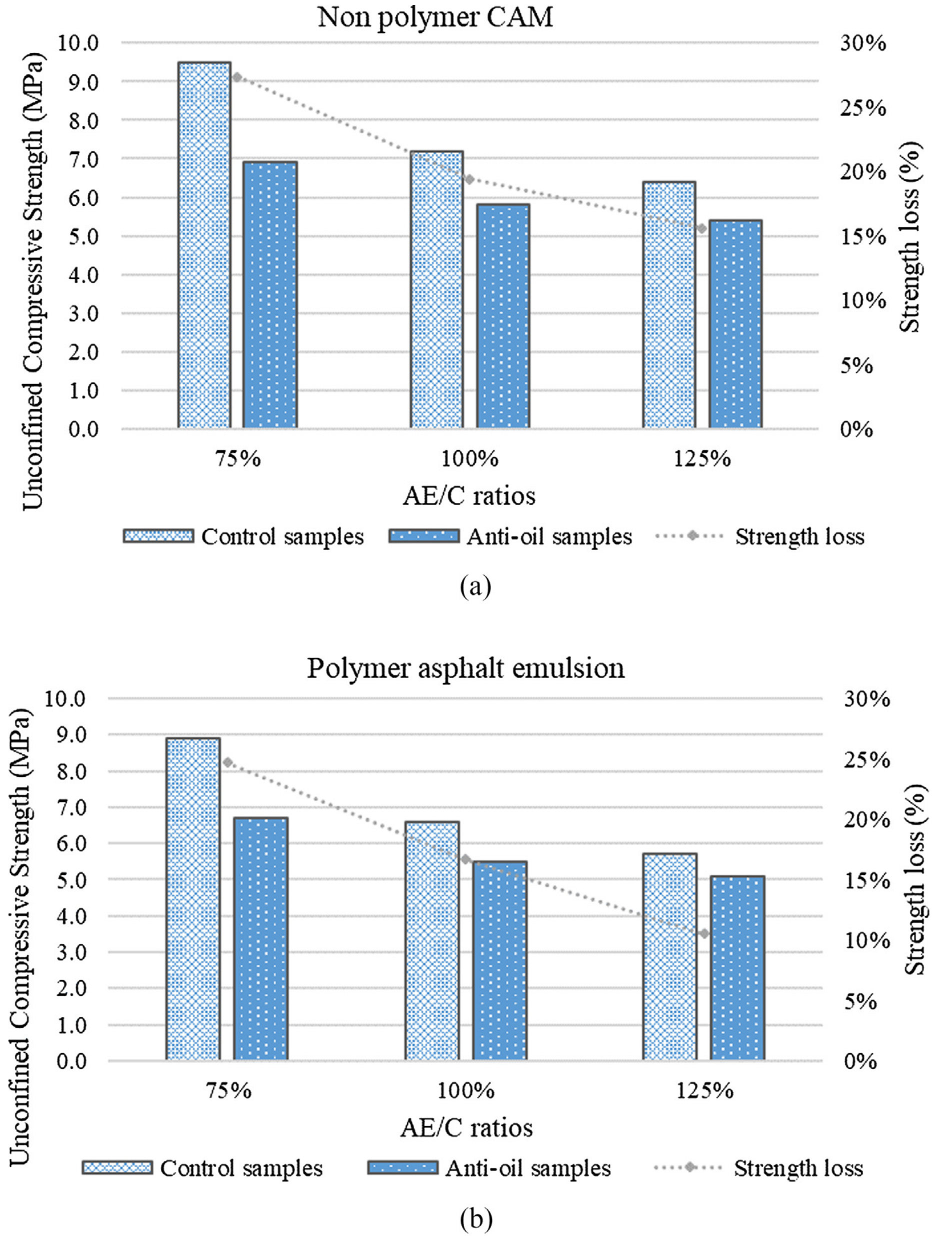


Fig. 9. Anti-engine oil resistance results of CAM mixture: a) Non-polymer CAM, b) Polymer CAM.

compressive strength value of 9.5 MPa is recorded in non-polymer mixture with AE/C ratio of 0.75, meanwhile, this value of polymer mixture is 8.9 MPa. Although CAM mixtures with polymer obtain homogenous particle distribution, the advantageous contribution to strength development of CAM is negligible.

3.4. Anti-chemical resistance

3.4.1. Anti-acid resistance

Fig. 8 illustrates the unconfined compressive strength of CAM mixtures after subjected to the acidic environment. Results show that all CAM mixtures suffered from strength loss with the loss percentage ranging from 5 to 20%. Although mix N1 with AE/C content of 0.75 achieve the highest UCS value, the greatest drop in strength was recorded in this condition after soaking in acid solution. It is interesting that the higher the AE/C content, the stronger the durability of CAM mixture to H_2S04 environment. It can be explained by having the cement asphalt hydration product particles being covered by an asphalt membrane layer and thereby, protecting from acid melt and decomposition. This occurrence agrees with the findings from Harada [19] which reveals that the covering of asphalt emulsion provides strong resistance to acid for asphalt cement mortar. Polymer CAM mixture also shares the same trend as non-polymer CAM mixture under acid damage. Moreover, although the polymer CAM mixtures obtain relatively low strength compared to non-polymer CAM mixtures, they show much better resistance to sulfuric acid with lower strength reduction. For example, when the AE/C ratio is increased from 75% to 125%, the strength of non-polymer samples ranges from 20% to 13%, meanwhile, this value of polymer sample varies from 13% to 5%. Therefore, the polymer components may help enhanced the acid resistance of concrete which was also concluded in the research of Schmidt [21] and De-Belie [22].

3.4.2. Anti-oil resistance

The engine oil resistance of CAM mixture is presented in Fig. 9. After submerging in engine oil condition for 3 weeks, all test samples show a significant drop in strength development. The reduction depends greatly on the AE/C ratio and the emulsifier type. However, almost all CAM samples still maintained the UCS of more than 80% compared to the control condition. It was found that the

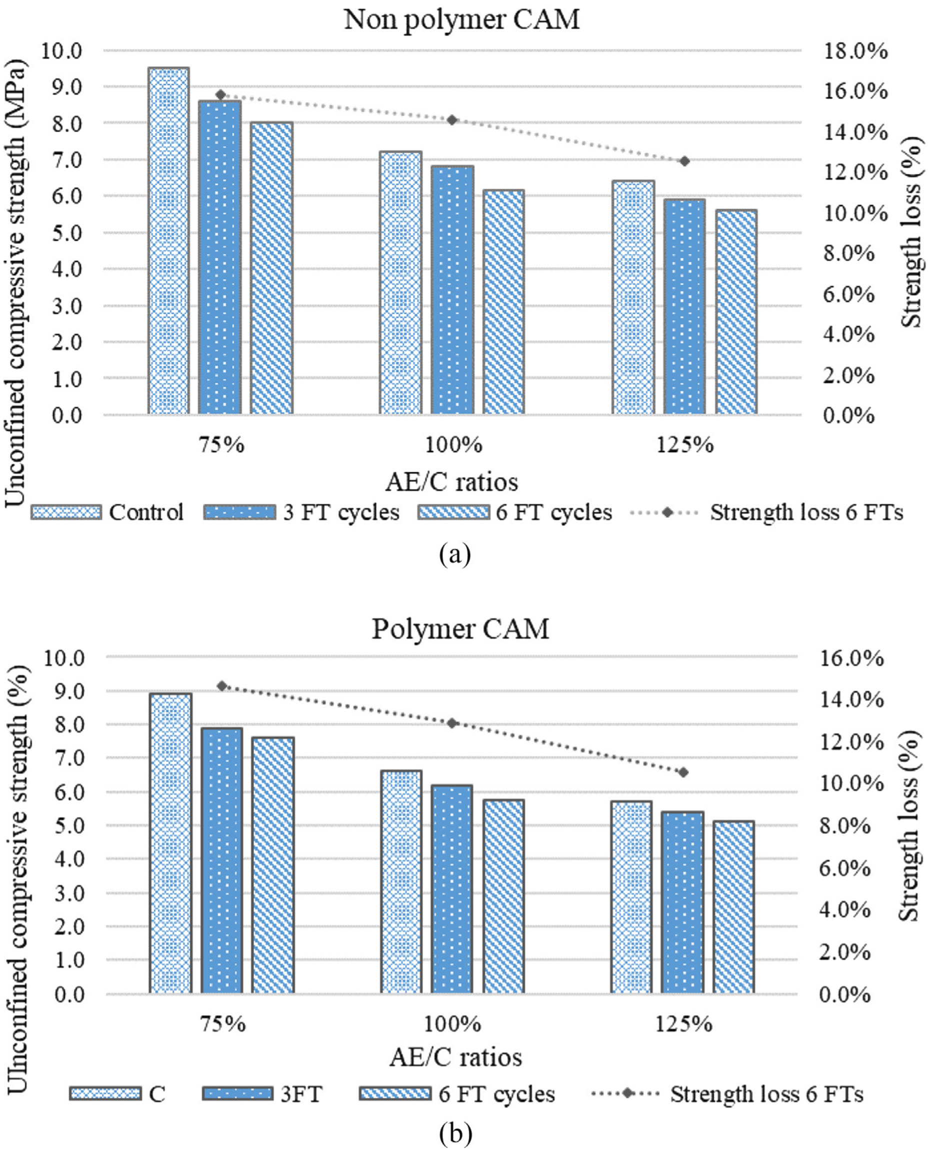
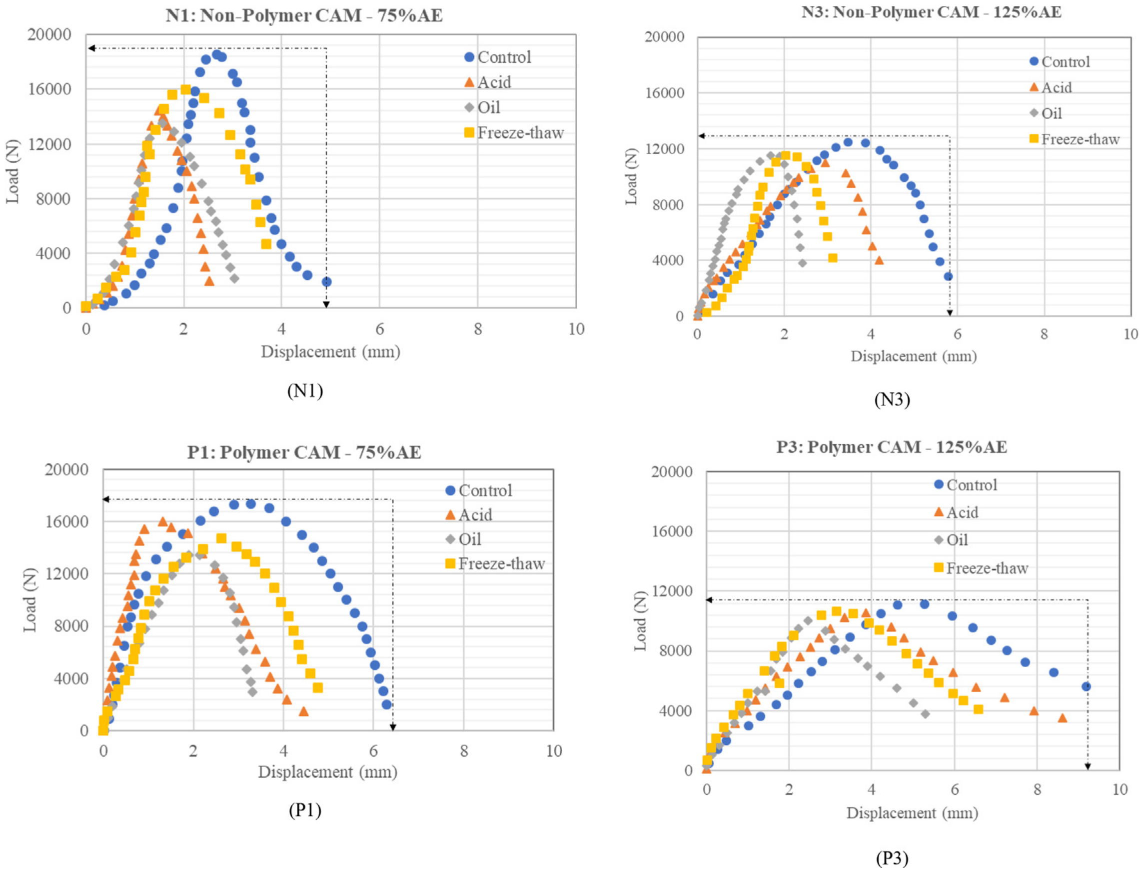


Fig. 10. Freeze-thaw resistance results of CAM mixture: a) Non-polymer CAM, b) Polymer CAM.



(N1)

(N3)

(P1)

(P3)

Fig. 11. Load-displacement curve of CAM mixture: (N1) 75%AE, (P1) 75%AE + polymer, (N3) 75%AE, (P3) 125%AE + polymer.

asphalt membrane is prone to dissolve in the engine oil environment since they are both crude oil derivation [15]. The strength loss in CAM mixtures under engine oil condition is more prominent at lower AE/C ratios. The test results also indicate that the strength drop was more pronounced in non-polymer CAM mixtures. For instance, at AE/C ratio of 125%, the strength loss in polymer mixture is about 12%, meanwhile, this value of non-polymer mixture is 16%. Hence, it can be concluded that the polymer may improve the dissolving resistance of asphalt emulsion to some extent although the effectiveness is not obvious.

3.5. Freeze–thaw resistance

The freeze–thaw resistance of nonionic CAM is shown in Fig. 10. It was noticeable that the UCS of mixtures with high AE/C ratio received very small strength drop after undergoing many F-T cycles. It may be attributed to the waterproofing ability of asphalt membrane which covers the cement hydration product. The F-T damage associated with high moisture content imposed a remarkable drop in mixture with low AE/C ratio. As found in 6 F-T cycles damage results, at 75%AE content, the strength drop of non-polymer and polymer mixture are 15.6% and 12.9%, respectively. In addition, it should be noted that the strength reduction of non-polymer CAM mixtures is noticeable after the first three cycles. However, applying three more cycles did not lead to the obvious drop in the strength of CAM. Regards to mixtures modified with polymer, the test results show that adding polymer to the asphalt emulsion did not provide the clear effect to the F-T resistance of CAM mixture. The strength reduction of polymer CAM mixtures is relatively the same as non-polymer CAM mixtures.

3.6. Load–displacement curve

Observing the failure behavior of samples under different conditions shows that after reaching the peak stress, almost all samples gradually decrease to the failure point without any abrupt behavior (Fig. 11). As shown in the increased AE/C ratio, this softening trend was mainly contributed by the asphalt membrane with viscoelastic behavior. Regards to the effect of polymer, it was

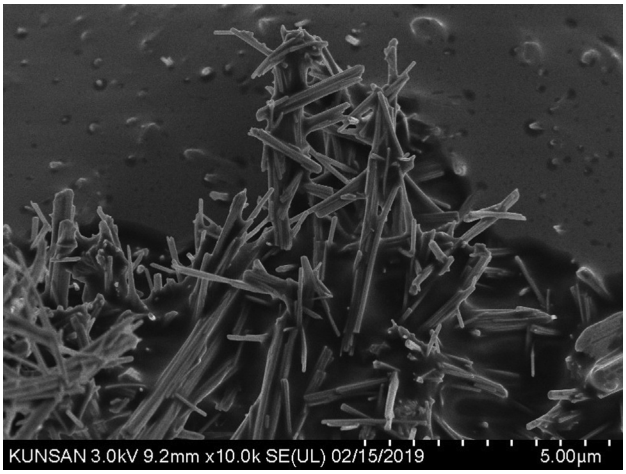


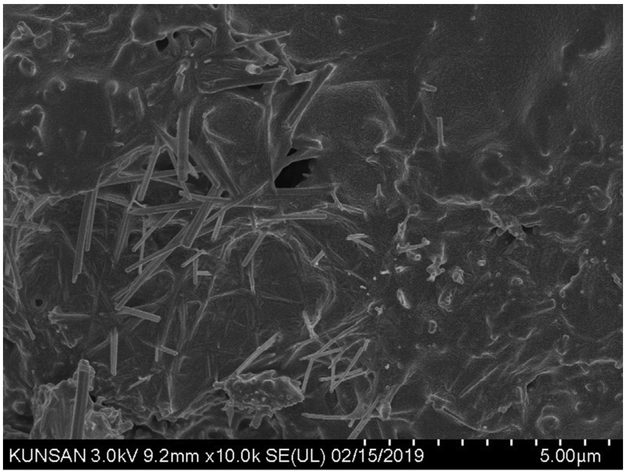
Fig. 12. The development of cement hydration product in asphalt emulsion environment.

noticeable that CAM mixtures modified with polymer achieve much better ductile behavior compared to non-polymer CAM mixtures. The contribution from the natural characteristic of polymer and the better CAM particle distribution recorded from mixing stability test may be responsible for this prominent behavior. Especially, the ductility characteristic is more obvious when the AE/C is increased. Hence, it should be taken into account the incorporation of optimum polymer content in asphalt emulsion to promote the damping effect of CAM layer. Due to the dissolving effect of asphalt emulsion in engine oil conditions, the ductility effectiveness of CAM mixture in engine oil is lower than mixtures suffered from acid solution or F-T cycles damage.

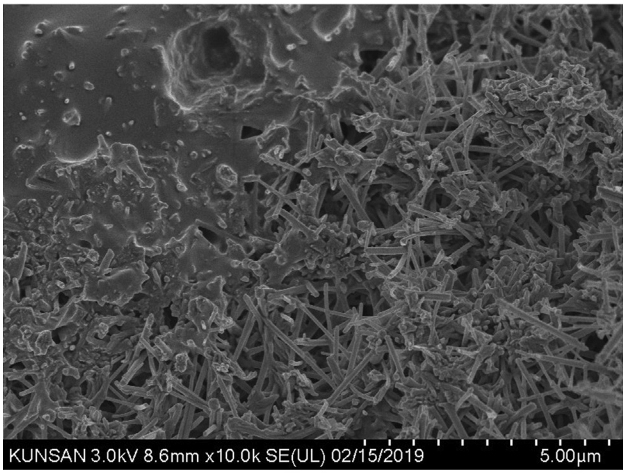
3.7. SEM analysis

As can be seen from Fig. 12, cement hydration product can develop in the asphalt emulsion environment. However, excessive use of AE may lead to a thick covering of cement particle and thereby, lowering the reaction between cement and water [13]. Regarding the differences between non-polymer and polymer CAM mixtures (Fig. 13), the SEM test results reveal that polymer mixture has a better combination between cement hydration product and asphalt membrane with homogenous dispersion. However, the presence of denser asphalt membrane may fully cover the cement particles which lead to the poor strength gain of CAM mixture. Although thick asphalt membrane enhanced the ductility performance of polymer CAM mixtures; however, this coverage may lower the development of cement hydration product, which reduce the UCS strength noticeably.

Meanwhile, in non-polymer mixture, the formation of cement hydration products is more pronounced with an obvious structure of ettringites shown in Fig. 13b. Therefore, the development of cement hydration product of non-polymer mixture outperformed the mixture with polymer. This finding agrees with the results of the UCS test.



(a)



(b)

Fig. 13. SEM test analysis of (a) polymer CAM and (b) non-polymer CAM.

3.8. Mock-up test

Fig. 14 presents the mock-up test results of cement asphalt mortar stabilized ballast. Based on the suggestion from UCS test results, the optimum condition used for the mockup test is mix N100 shown in Table 6. Observing the first condition of fouled ballast without CAM stabilizing method, the settlement value increases sharply within the first 1000 cycles (from 0 to around 2.5 mm). Thereafter, due to the tight connection and re-organized ballast structure, the subsidence value of the first condition increases gradually from 2.5 to around 3.4 mm. Meanwhile, the settlement values of both CAM stabilized conditions show a steady increase throughout 10,000 load cycles. The application of CAM proposes promising results in settlement resistance for ballast layer. Based on the test results, fouled ballast with CAM obtains the lowest subsidence value of about 1.5 mm. Meanwhile, this value of clean ballast with CAM is about 2 mm. This may be due to the dust layer formed in fouled ballast that absorbs the free water from the demulsification process of asphalt emulsion in CAM. This will help accelerate the hydration process of cement and thereby, developing fast strength establishment of CAM mixture in the 2nd condition. Also, as can be seen from Fig. 15, about 1/3 of the ballast layer is filled with numerous fine aggregate clouds of dust. This densification may help provide the strong interconnection between unbound ballast particles to some extent and thereby, creating a better settlement resistance. However, in the long-term strength gain (28 days), it is expected that the clean ballast with CAM will achieve the higher strength and settlement resistance due to the complete flow of CAM in the whole ballast system. The promising results from this test will promote the effectiveness of fouled ballast stabilized by CAM for maintenance projects with short traffic closure time.

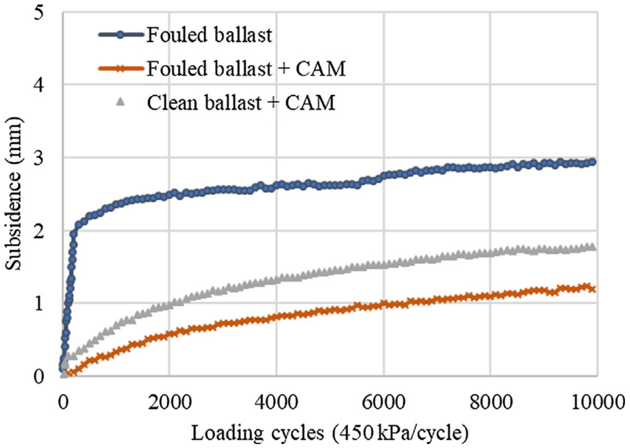


Fig. 14. Mockup test results of different stabilized ballast methods.

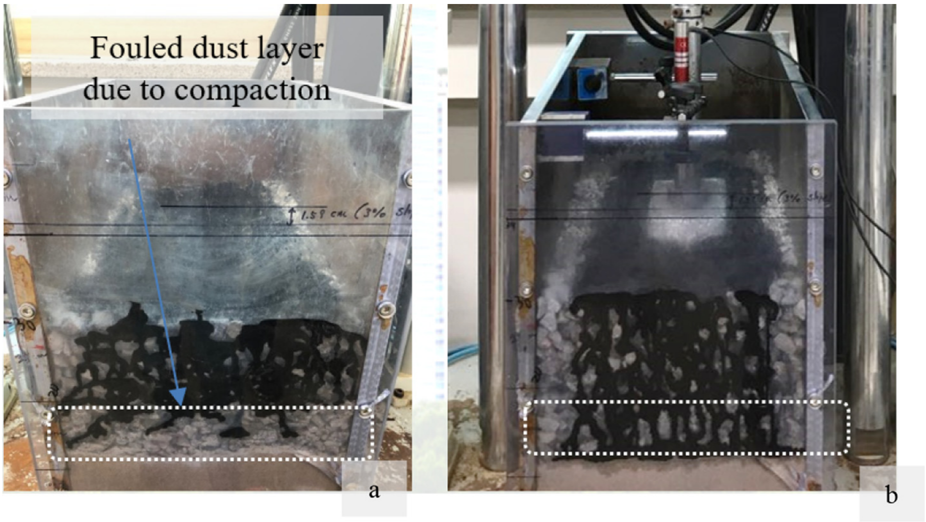


Fig. 15. The flow performance of CAM in (a) fouled ballast and (b) clean ballast structures.

4. Conclusion

The proposed research systematically investigates the mechanical performance of CAM stabilized ballast using nonionic asphalt emulsion. The rheology of the fresh mixture is investigated by varying different AE/C ratios and asphalt emulsion types (with and without polymer). The durability of CAM is evaluated by submerging 7 days strength samples into the sulfuric acid and engine oil conditions. After 28 days, the damaged samples underwent UCS test to figure out the strength loss compared to control condition. A mockup test is incorporated in this research to determine the actual performance of this stabilizing method. The following findings can be drawn from this study:

- The rheology of CAM is improved by using asphalt emulsion modified with polymer. This component helps enhance the mixing stability of fresh mixture and delay the demulsification process. Hence, polymer mixture obtains better flowability with the minimum sign of agglomeration phenomenon.
- The UCS test results reveal that adding polymer will retard the strength gain of CAM at an early age compared to the samples without this admixture. The 28 days strength results also follow this trend since all non-polymer mixtures outperformed the remained condition. However, the CAM mixture with polymer received much better ductile behavior with a longer time in reaching peak stress. This may be attributed to the ductility characteristic of polymer itself and the homogenous particle distribution of polymer mixture (good mixing stability).
- The asphalt membrane behaves as a barrier that protects the cement hydration product from the attack of acid sulfuric environment. This ability is more prominent when the AE/C ratio is increased. It is interesting to mention that adding polymer also contribute to the acid resistance of CAM.
- It should be noted that asphalt emulsion dissolves in an engine oil environment. Hence, the UCS of engine oil mixture dropped heavily compared to the control condition. The effectiveness of polymer in engine oil resistance can be considered since mixture with polymer show smaller strength loss compared to non-polymer mixture.
- All CAM mixtures show strong resistance to F-T cycles due to the waterproofing ability of the asphalt layer. The asphalt emulsion may also cover the air void system in cement hydration product and thereby, lowering the effect of moisture damage from the F-T cycles. The higher the AE/C content in CAM mixture, the better the F-T resistance can be achieved.
- The SEM analysis reveals that the cement hydration product in non-polymer CAM develops faster compared to that with polymer.
- As found in the mockup test results, the new combination between the CAM and the ballast layer show strong resistance to permanent deformation compared to the controlled condition. In short time strength development, the dense fouled ballast structure with CAM outperformed the clean ballast structure with CAM.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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