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Evaluation of chip seal mixture design methods using modified Hamburg wheel tracking test and sweep test

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ABSTRACT

The objective of this study was to identify the most effective chip seal design method and chip sizes by conducting a modified Hamburg wheel tracking test and sweep test. Three chip seal design methods, including Austroads, McLeod, and Vietnam methods, were evaluated to design several chip seal mixtures with varying aggregate sizes (e.g., 12.5, 9.5, 4.75, and 2.36 mm) and binder types. To assess the performance of the chip seal mixtures, aggregate loss and bleeding susceptibility were measured. The sweep test was utilized to determine the amount of aggregate loss caused by the sweeping effect, while the modified Hamburg wheel tracking (HWT) test was developed to estimate the aggregate loss caused by the braking effect using a fixed pneumatic rubber tire. Additionally, a modified Hamburg wheel tracking test with a rolling pneumatic rubber tire was used to assess bleeding susceptibility, and the bleeding area was quantified using an image analysis process. The results indicated that the Austroads design method exhibited the lowest aggregate loss compared to the McLeod and Vietnam methods. Moreover, the consistent findings from both the sweep test and modified HWT test demonstrated the feasibility of using the modified HWT test to simulate aggregate loss caused by the braking effect. The bleeding percentage was found to be affected not only by the binder application rate but also by the aggregate size and the number of layers applied. The Austroads and McLeod chip seal mixtures exhibited an approximately 20 % lower bleeding percentage than that of the Vietnam mixtures. Finally, for a single chip seal, a 9.5 mm chip aggregate was determined to be the optimal size, while for a double chip seal, 4.75 mm and 2.36 mm chips were recommended.

1. Introduction

Chip seal is known as a surface treatment applied to an existing pavement surface. It consists of one layer (e.g., single chip seal) or more layers (e.g., double chip seal, triple chip seal) of asphalt emulsion and aggregate [1]. Chip seal is not only the predominant surface type in rural areas and developing countries, but it is also used as a technique to preserve, restore, and enhance the performance life of the pavement [2,3]. Despite several limitations such as increased traffic noise, dust, and windshield broken [4], chip seal provides a lot of advantages, including sealing and filling cracks, skid resistance, anti-glare, increase reflection for wet and night

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driving, and low cost [5,6]. In addition, it protects under layers of asphalt pavement from the effect of traffic, climate, and water [7–10].

To ensure the proper performance of the chip seal, a mix design should be performed to determine the binder application rate, aggregate application rate, and appropriate aggregate size. There are many chip seal mixture design methods currently used in the world, including McLeod, Austroads, New Zealand, Kearby, and Hanson [4,11–14]. The McLeod is the most popular chip seal design method used in America and Canada. This design method aims to calculate binder application rate based on aggregate gradation, absorption, shape, traffic volume, existing pavement condition and asphalt content of the binder [15]. Meanwhile, Austroads is a main design method in Australia. Austroads method was developed based on Hanson method principles of aggregate voids related to traffic volume and aggregate least dimension (ALD) with more detail on the adjustments of different traffic effects, surface texture, embedment, absorption, and aggregate characteristics [4]. However, many developing countries such as Vietnam and Philippines have not developed their own design method or found a suitable design method [16,17]. This reason may cause excessive aggregate loss when applied on high absorptive surface or excessive bleeding when applied on smooth surface, resulting in the reduction of service life of chip seal. Therefore, there is a need to compare and determine an optimal design method to be applied in these countries.

Aggregate loss and bleeding are two common distresses in chip seal [18,19]. There are several tests to determine the aggregate loss percentage of chip seal samples, such as Vialit test [20,21] and sweep test [9,20,22]. Meanwhile, the bleeding properties of chip seal were investigated by modified loaded wheel test [23], accelerated chip seal simulation device [24], third scale model mobile loading simulator, and Hamburg wheel tracking test [25,26]. The sweep test provides a high correlation between lab specimens and field specimens [27]. Sweep test was currently the most popular method for evaluating the aggregate loss susceptibility of chip seal [26]. However, it should be noted that not only sweeping but also braking effect causes aggregate loss. Although there was a lot of method to evaluate aggregate loss, it is still a lack of research on the aggregate loss of chip seal caused by braking wheel and rolling wheel. To simulate the effect of wheels on asphalt mixture, Hamburg wheel tracking test is widely used and available in many laboratories and research agencies [28–31]. Therefore, the using HWT test to simulate effect of braking wheel on surface of chip seal is a promising method. Besides, the bleeding susceptibility of chip seals was also investigated by Kumbargeri et al. [9]. In Kumbargeri's study, the surface of chip seal was analyzed by image processing after subjecting to bleeding test.

The main objective of this study is to determine the optimal chip seal mixture design method and chip sizes. To meet this objective, the performances of Austroads method, McLeod method, and the empirical method of Vietnam were evaluated by aggregate loss and bleeding susceptibility. Modified Hamburg wheel tracking test was developed to mimic effect of braking and rolling wheel on aggregate loss and binder bleeding, respectively. The bleeding area was determined by image analyze process. In addition, sweep test was employed to evaluate aggregate loss by sweeping action. To compare between design methods, several chip seal mixtures were considered with the similar design parameters such as traffic, weather conditions. Meanwhile, chip size and binder content were designed based on three mixture design methods. Research flowchart of current study is showed in Fig. 1.

2. Materials and test methods

2.1. Aggregate properties test

Fig. 2 shows four different chip sizes used in this study. The natural limestone aggregate in the local quarry was brought to the laboratory and sieved into four different sizes based on ASTM C136 standard [32]. The chip aggregate includes 12.5 mm, 9.5 mm, 4.75 mm, and 2.36 mm. The gradations of chip aggregate are displayed in Table 1.

After separating the aggregate into four chip sizes, several tests were conducted to determine the aggregate properties such as median particle size, flakiness index, average least dimension, bulk specific gravity, absorption, loose unit weight, and void content. These properties were measured to be used as input in the mixture design process. Table 2 illustrates the aggregate test procedure.

The properties of four chip size are shown in Table 3. In general, the bulk specific gravity of four aggregates ranged from 2.62 to 2.67 g/cm^3, absorption was approximately 1–2 %, loose unit weight of 1502 to 1537 kg/m^3, and void content of 42 %.

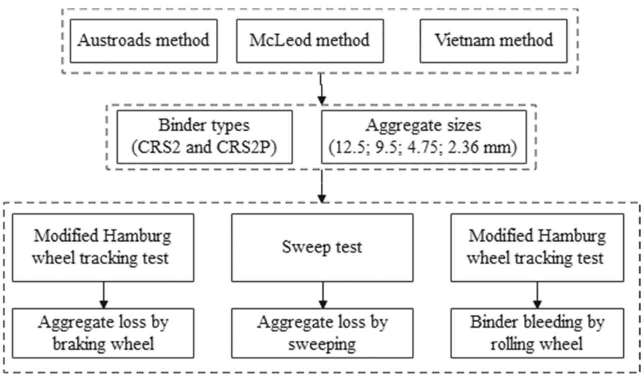


Fig. 1. Research flowchart.

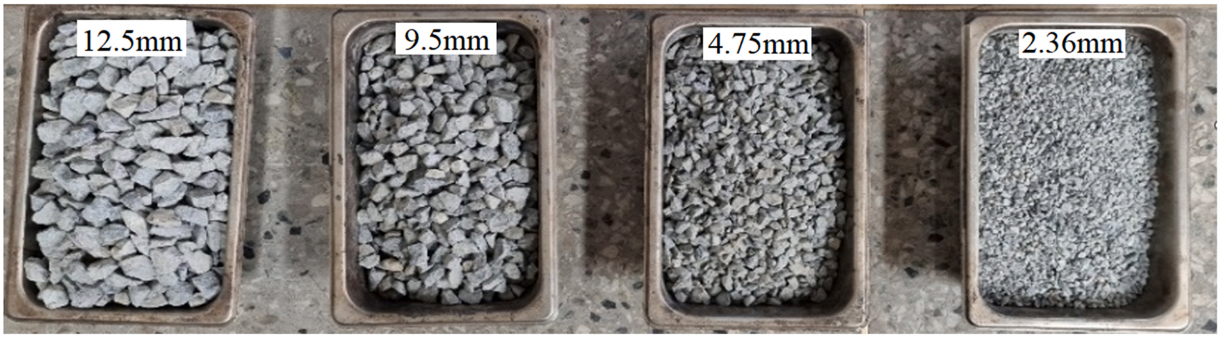


Fig. 2. Four chips aggregate used in this study.

Table 1
Aggregate gradations.

Sieve size (mm)	Retained Percentage (%)			
	12.5 mm	9.5 mm	4.75 mm	2.36 mm
19	0	0	0	0
12.5	90	10	0	0
9.5	100	90	10	0
4.75	100	100	90	10
2.36	100	100	100	90
1.18	100	100	100	100

2.2. *Asphalt emulsion*

Two types of asphalt emulsion, named CRS2 and CRS2P, were used in study. Both emulsions were cationic water-based emulsified asphalt. The CRS2P is the polymer-modified version of CRS2. The polymer provides elasticity, reduced temperature susceptibility, and durability thus increasing the performance of chip seal on aggregate loss resistance. Polymer-modified rapid-setting emulsions typically have earlier chip retention than conventional emulsions. The properties of emulsion are shown in Table 4.

2.3. *Mixture design method*

2.3.1. *Austroads design method*

To design chip seal mixture, the Austroads design method determined binder application rate and aggregate application rate [4]. As shown in Fig. 3, binder application rate was determined based on binder factor (B_F), which related to the traffic volume, mixture types (e.g., single seal, first layer or second layer of double seal mixture). Aggregate shape adjustment (V_a) was used to adjust the binder content of the mixture based on the flakiness index of chip aggregate. The traffic effect adjustment (V_t) was determined by whether the road is flat, downhill, or slow-moving area, and the percentage of heavy vehicles of the road. The binder application rate was calculated by Eq. (1). In addition, the aggregate application rate of the Austroads method was determined by the average least dimension of chip aggregate.

$$B_d = \left(V_f + V_a + V_t\right) \times ALD \times B_F \tag{1}$$

Where,

B_d: binder application rate (litter/m^2),
V_f: basic void factor,
V_a: aggregate shape factor,
V_t: traffic effect adjustment,
ALD: average least dimension,
B_F: binder factor.

The summary of design factors by the Austroads method is shown in Table 5, the average least dimension (ALD), aggregate shape adjustment (V_a), and binder factor (B_F) were determined by the material properties test. Meanwhile, a flat rural road with average daily traffic of 200 vehicles/lane/day of a developing country (Vietnam) was selected to determine the traffic effect factor.

2.3.2. *McLeod design method*

Similarly, McLeod designed chip seal mixture based on measurement of binder application rate and aggregate application rate [11]. As shown in Fig. 4, In the McLeod design method, several factors were considered, including absorption factor (A), traffic factor (T),

Table 2
Aggregate test procedure.

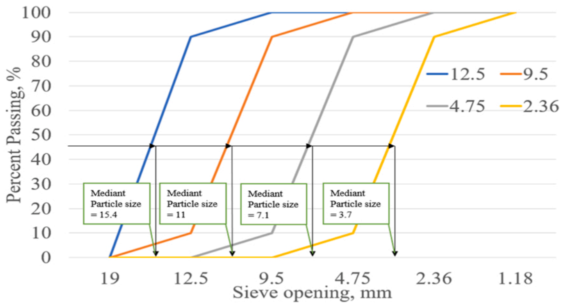
Property	Test method	Test procedure
Sieve analysis and Median Particle size, mm	ASTM C136 [32] and McLeod design method [11]	
Flakiness Index and Average Least Dimension, mm	Austroads AGPT04K-18 [4]	 
Bulk Specific gravity and Absorption	ASTM C127 [33] and ASTM C128 [34]	 
Loose Unit Weight and void content	ASTM C29 [35]	 

Table 3
Summary of aggregate properties.

Chip size	12.5 mm	9.5 mm	4.75 mm	2.36 mm
Median particle size, mm	15.4	11	7.1	3.7
Flakiness index, %	20.9	11.6	11.2	14.7
Average least dimension, mm	10.8	8.8	5.2	4.6
Bulk specific gravity	2.64	2.62	2.65	2.67
Absorption, %	1.9	0.96	1.01	1.32
Loose unit weight, kg/m^3	1502	1509	1520	1537
Void content, %	42.9	42.3	42.5	42.3

surface condition (S), average least dimension (ALD), and bitumen content in asphalt emulsion (R). The calculation of binder application rate is shown in Eq. (2). In addition, the aggregate application rate was based on the properties of the aggregate and properties of asphalt emulsion such as void in the loose aggregate (V), average least dimension (ALD) and asphalt content of the emulsion (R), and wastage factor (E) as shown in Fig. 5 Fig. 4[11].

Table 4
Properties of two asphalt emulsions.

Properties	CRS2		CRS2P	
	Minimum	Maximum	Minimum	Maximum
Viscosity, 122°F, sec.	150	400	150	400
Sieve test, %	-	0.1	-	0.1
Demulsibility, %	40	-	70	-
Storage stability, 1 day, %	-	1	-	1
Particle charge	Positive			
Residue by distillation, % by weight	65	-	65	-
Oil distillate, % by volume of emulsion	-	0.5	-	0.5
Penetration, 25 °C (77°F), 100 g, 5 s	120	160	90	150
Ductility, 25 °C (77°F), 5 cm/min, cm	100	-	50	-
Solubility in trichloroethylene, %	97.5	-	97	-

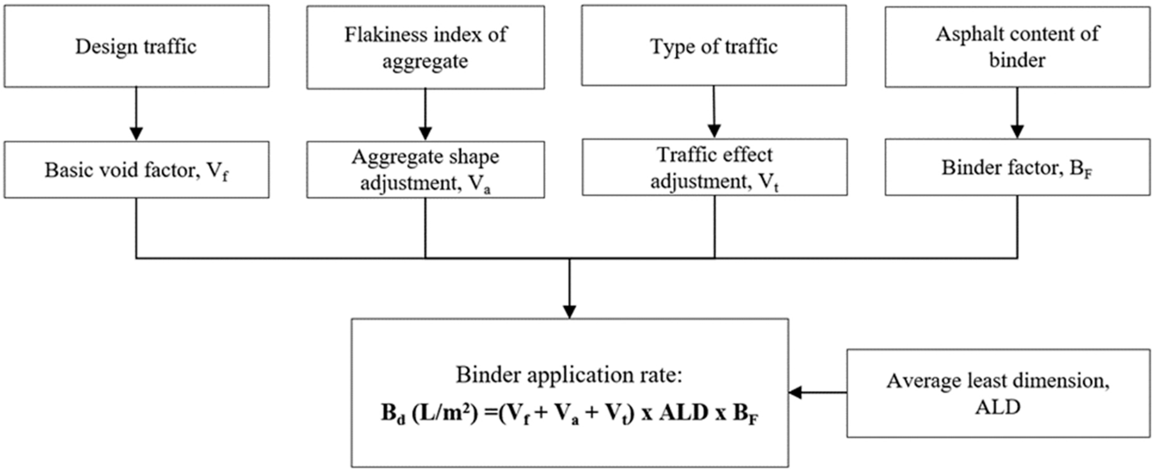


Fig. 3. Determination of binder application rate based on Austroads method.

Table 5
Summary design factors of Austroads method.

	ALD	V_a	V_f	V_t	B_F
12.5 mm	10.8	0	Single seal: 0.195	0.01 (rural road)	1.1 (bitumen content > 67 %)
9.5 mm	8.8	0.01	First layer of double seal: 0.151		
4.75 mm	5.2	0.01	Second layer of double seal: 0.195		
2.36 mm	4.6	0.01			

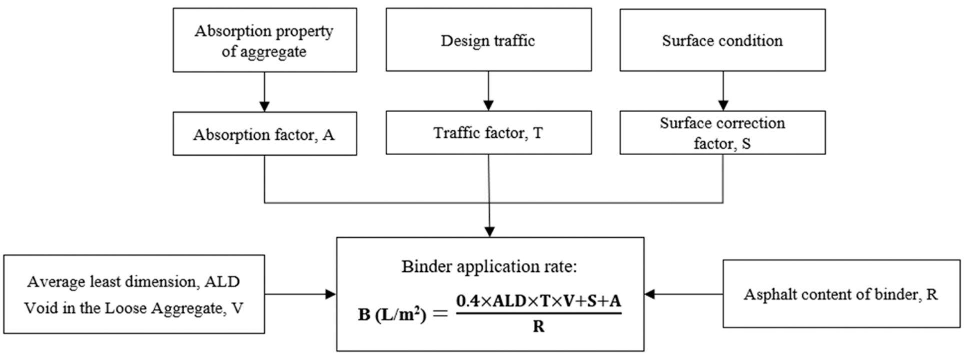


Fig. 4. Determination of binder application rate based on McLeod method.

$$B_d = \frac{0.4 \times ALD \times T \times V + S + A}{R} \quad (2)$$

Where,

B_d: binder application rate (litter/m^2),
ALD: average least dimension,
T: traffic factor,
V: voids in loose aggregate,
S: surface correction factor,
A: absorption factor,
R: bitumen content in emulsion.

The summary of design factors by McLeod method is shown in Table 6. Void in loose aggregate (V), average least dimension (ALD), bulk specific gravity (G), absorption factor (A), and residual asphalt content (R) were collected from properties tests. Meanwhile, the traffic and road conditions were similar to the Austroads design method, which was rural road of 200 vehicles/lane/day. Finally, the surface condition (S) was considered in laboratory conditions; hence, this value was fixed at 0 as recommended in the McLeod method [11].

2.3.3. Vietnam design method

In the current study, Vietnam's method for construction and mixture design of surface treatment using cationic emulsified asphalt was selected as a representative of developing countries. This method provided standard mixtures that were calculated and published by the Ministry [16]. However, binder application rate was re-calculated based on the content of bitumen in asphalt emulsion. This is because the standard asphalt emulsion used in Vietnam method was content of 60 % bitumen [16]. Therefore, the binder application rate was calculated based on Eq. (3).

$$B_d = \frac{0.4 \times ALD \times T \times V + S + A}{R} \quad (3)$$

Where,

B_d: binder application rate (litter/m^2),
B_{std}: standard binder application rate based on Vietnam method (litter/m^2),
R: bitumen content in asphalt emulsion.

2.3.4. Mixture proportion

Three different mixture design methods were used, including Austroads method (Australia) [4], McLeod method (USA) [11], and Vietnam method. For each method, total of four mixtures were designed, which were two single-layer mixtures (named 1 A and 1 C) and two double-layer mixture (named 2 A and 2 C). The mixture proportions, including binder application rate (B_d) and aggregate application rate (A_d), are shown in Table 7. In addition, traffic conditions used in three design methods were selected from the rural road of developing country, which were approximately 200 vehicles/lane/day [36].

2.4. Performance tests

2.4.1. Aggregate loss by sweep test

The purpose of this test was to evaluate the effectiveness and durability of chip seal surfaces, with the ALS being a key parameter in assessing their performance. Two different curing periods of 3 h and 24 h were examined in order to determine their impact on the aggregate loss by sweeping (ALS). By preparing at least three samples for each mixture, the results were able to be averaged and provided a more accurate representation of the performance of the chip seal surface. The sweep test used in this study aimed to

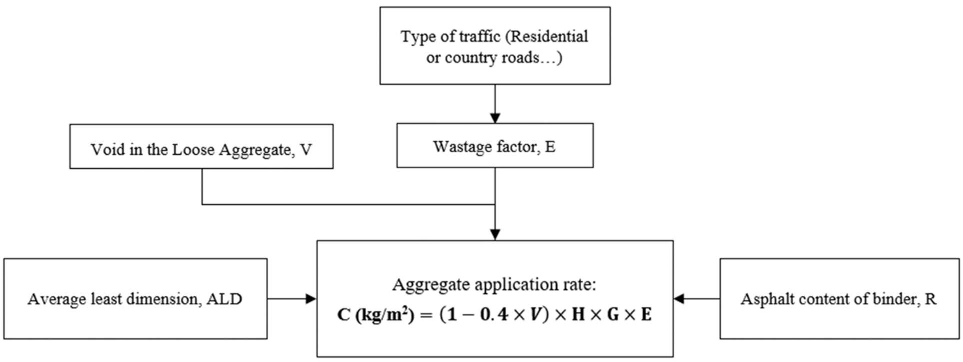


Fig. 5. Determination of aggregate application rate based on McLeod method.

Table 6
Summary design factor of McLeod method.

	V	ALD	G	A	E	T	S	R
12.5 mm	0.43	10.8	2.64	0.09	1.05 (rural road)	0.75 (rural road)	0 (laboratory condition)	0.67 (bitumen content)
9.5 mm	0.42	8.8	2.62	0.00				
4.75 mm	0.42	5.2	2.65	0.00				
2.36 mm	0.42	4.6	2.67	0.00				

Table 7
Mixture proportion of three design methods.

Surface Treatment	Mixture	Chip size, mm	**Austroads**		**McLeod**		**Vietnam**	
			B_d, kg/m^2	A_d, kg/m^2	B_d, kg/m^2	A_d, kg/m^2	B_d, kg/m^2	A_d, kg/m^2
Single chip seal layer	1 A	9.5	2.08	14.75	1.67	20.11	1.55	14.33
	1 C	2.36	1.09	7.85	0.87	10.71	0.85	9.22
Double chip seal layer	2 A							
	1st layer	4.75	0.98	8.32	0.99	12	1.15	15.2
	2nd layer	2.36	1.09	6.83	0.87	10.71	1.55	6.15
	2 C							
	1st layer	12.5	1.91	17.08	2.21	24.78	1.75	22.53
	2nd layer	4.75	1.23	8.78	0.99	12	2.35	12.16

quantify the loss of aggregate resulting from sweeping the chip seal surface with a broom. To conduct this test, the researchers followed the ASTM D7000 [37] protocol. The sample preparation process is illustrated in Fig. 6. Firstly, an asphalt felt disk was prepared with a diameter of 280 ± 3 mm, onto which asphalt emulsion was applied (Fig. 6a and Fig. 6b). The chip aggregate was then immediately sprayed onto the emulsion surface (Fig. 6c) and compacted using a hand compacter (Fig. 6d). The samples were subsequently cured at 25 ± 1 ℃, with two curing periods of 3 h and 24 h examined in this study. To ensure adequate sample representation, at least three samples were prepared for each mixture. After curing, the weight of each sample was measured before being subjected to the sweep test, which was conducted at 25 ± 1 ℃. As shown in Fig. 7, the sample was subjected to 0.83 gyrations per second for 60 s. The weight of the sample after the sweep test was then measured, and the percentage of ALS was calculated using Eq. (4).

$$ALS = \frac{A - B}{A - C} \times 100 \times 1.33 \tag{4}$$

Where,
ALS: aggregate loss by sweeping (%),
A: initial weight of sample (g),
B: final weight of sample (g),
C: weight of asphalt sample disk (g).

2.4.2. *Aggregate loss by modified HWT test*

This test aims to mimic the effect of braking on the aggregate loss of chip seal using Hamburg wheel tracking (HWT) machine. The sample preparation process is shown in Fig. 8. Firstly, asphalt concrete disks having the dimension of HWT specification were prepared [25]. In this study, Hot Mix Asphalt 13 mm mixture was used to prepare asphalt sample disks. Sample were compacted by Super Gyration Compactor with a height of 62 ± 1 mm, a diameter of 150 ± 1 mm, and air voids of 7 ± 1 % as shown in Fig. 6a. After cutting into HWT specification size, asphalt sample disks were conditioned at room temperature for 48 h to remove moisture. Then, asphalt emulsion and chip aggregate were applied on the surface of asphalt disk. A hand compactor was employed to compact chip aggregate. Finally, samples were cured at 25 ± 1 ℃ for 24 h before conducting aggregate loss test as shown in Fig. 8d.

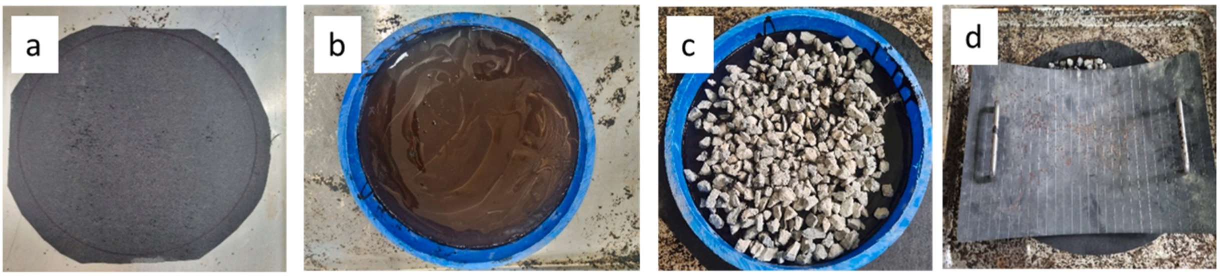


Fig. 6. Sample preparation process.

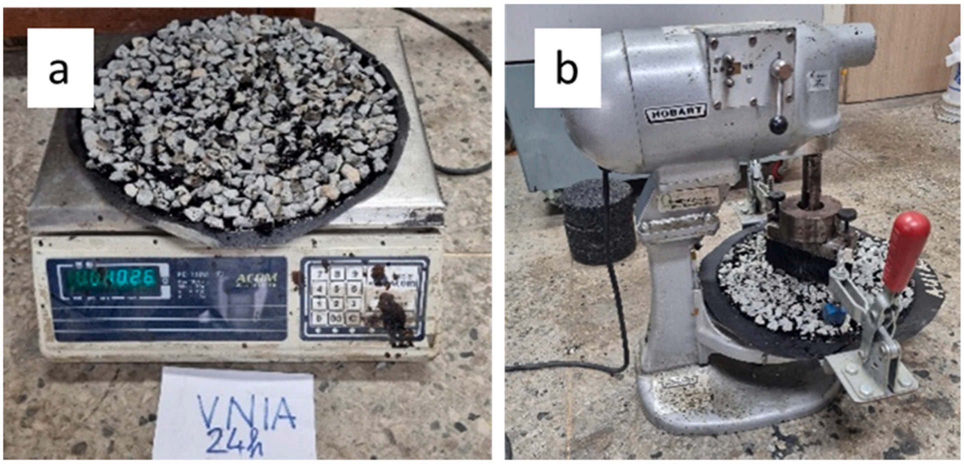


Fig. 7. Sweeping test procedure.

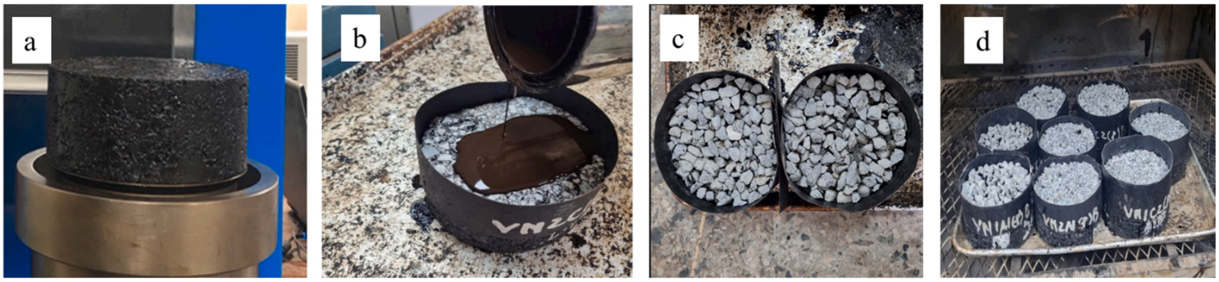


Fig. 8. Sample preparation process compaction of asphalt disk (a), apply asphalt emulsion(b), apply aggregate (c), and curing of samples (d).

To simulate braking effect, Hamburg wheel tracking machine was modified to use the pneumatic wheel. As shown in Fig. 9a, a pneumatic wheel has a diameter of 200 ± 5 mm and a width of 50 ± 1 mm. A lock part was developed to assembly pneumatic wheel and HWT machine as displayed in Fig. 9a. Based on the author team's experience and previous research [25,26], the chip seal samples were subjected to 10 cycles of HWT test. The applied load of 175 ± 2 N was suitable to determine aggregate loss caused by braking effect as shown in Fig. 9b. This test weas performed under temperature of 25 ± 1 °C. The initial and final weight of sample were measured to calculate aggregate loss by braking (ALB) as shown in Eq. (5).

$$ALB = \frac{A - B}{A - C} \times 100 \tag{5}$$

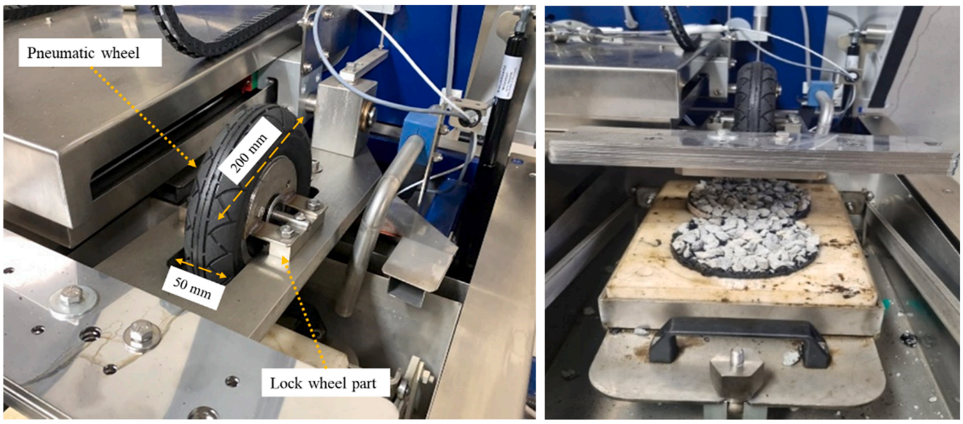


Fig. 9. Modified Hamburg wheel tracking (a), aggregate loss test by modified HWT (b).

Where,

ALB: aggregate loss by braking (%),
A: initial weight of sample (g),
B: final weight of sample (g),
C: weight of asphalt sample disk (g).

2.4.3. Binder bleeding by modified HWT test

Modified HWT test was used to determine bleeding percentage of chip seal mixture under rolling pneumatic wheel. A pneumatic wheel has a diameter of 200 ± 5 mm and the width of 50 ± 1 mm. The sample preparation process was similar with aggregate loss by modified HWT as mentioned in previous section. In this test, samples were cured for 24 h before testing. Based on the previous research [25,26], the sample was subjected to HWT test until 2500 cycles. After curing, sample was placed in HWT machine and tested. During test process, the surface condition of samples at cycle numbers of 0, 200, 500, 1000, and 2500 cycles were captured using a high-resolution electron microscope camera. As shown Fig. 10, the distance between camera and the surface of sample was 30 cm.

In this study, the image analysis program was developed based on Python programing langue and OpenCV library [38,39]. For each image, the bleeding area was calculated by count the number of black pixels. The image analysis process was developed by the following steps. First, the histogram of input image was calculated. Secondly, the maximum change of pixel number was selected based on calculated histogram. Then, this image was converted to gray image to remove noise and detect black area as shown in Fig. 11. Finally, the number of black pixels were counted, and these values were converted to square millimeter [40]. It should be noted that this program is automatically calculated bleeding area. However, to improve accuracy, several trackbars were added to program, including an upper threshold, lower threshold, and blur scale. By adjusting trackbars the lower threshold and upper threshold, as well as the blur scale of the image were changed. The percent of bleeding area after modified HWT was determined by Eq. (6).

$$P = \frac{A_{black}}{A_{total}} \times 100 \tag{6}$$

Where,

P: Percentage of bleeding (%),
A_{black}: bleeding area (mm^2),
A_{total}: area of image (mm^2).

3. Results and discussions

3.1. Aggregate loss by sweep test

Fig. 12 shows the aggregate loss of Vietnam mixtures by sweep test with different curing periods and asphalt emulsion types. Overall, mixture 1 A and mixture 2 A showed lower percentage aggregate loss than that of mixture 1 C and 2 C. This phenomenon may be due to the mixture 1 A and 2 A provided higher interlocking effect between aggregate particles, resulting in more effective absorption load compared to mixture 1 C and 2 C. Double chip seal layer (mixture 2 A and mixture 2 C) presented a better resistance to stripping than single chip seal layer (mixture 1 A and 1 C). The blending of two type aggregates could provide larger contact area between aggregate and asphalt emulsion. Therefore, the resistance to stripping was improved. In addition, curing time and asphalt emulsion also played important role to reduce aggregate loss by sweeping. The aggregate loss of mixtures with 3 h curing was approximately twice than 24-hour-curing mixtures. Meanwhile, asphalt emulsion modified polymer (CRS2P) acquired a better resistance to stripping than normal asphalt emulsion. To reduce the number of sample preparation, mixture 1 A and mixture 2 A with 24 h curing were selected to conducted further experiments.

Fig. 13 illustrates the aggregate loss of three design methods. In general, mixture 2 A presented the lowest aggregate loss, which were approximately 50 %. As discussed in previous, blending two aggregate types provided more interlocking and contact surface with asphalt emulsion, resulting in better resistance to aggregate loss. Among three mixture design methods, Austroads design method showed the lowest aggregate loss in both single chip seal (mixture 1 A) or double chip seal (mixture 2 A). The lowest aggregate loss of Austroads method was 5.1 % compared to that of 8.2 % and 5.6 % of Vietnam method and McLeod method, respectively. This may be due to Austroads mixture design method pays more attention to the interlock of aggregates rather than the content of asphalt emulsion [4]. It can be concluded that the difference aggregate used in design method could affect aggregate loss of chip seal mixture. In addition, the improvement of polymer modified asphalt emulsion on resistance to aggregate loss can be again confirmed. As shown in Fig. 13, the aggregate loss of CR2P mixtures were extremely lower than that of CR2 mixture, especially in Vietnam design method. The aggregate loss of mixture 2 A was 0.6 % compared to that 1.1 % and 1.5 % of Austroads and McLeod method, respectively.

3.2. Aggregate loss by modified HWT test

Fig. 14 shows the aggregate loss by modified Hamburg wheel tracking test. Overall, mixture designed by Austroads method showed the lowest aggregate loss. The highest aggregate loss of Austroads method was 29 % compared to that of 35 % and 32 % of Vietnam method and McLeod method. It should be noted that aggregate loss caused by modified HWT was extremely higher than aggregate loss by sweeping test. This is because modified HWT test aims to mimic the effect of braking wheel on surface of chip seal. In addition, the

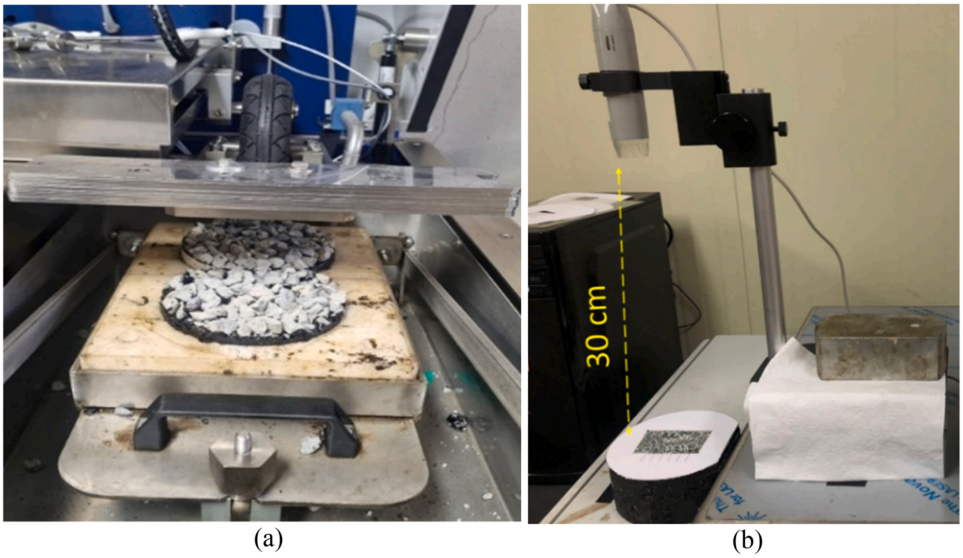


Fig. 10. Binder bleeding by HWT test (a) and camera test setup (b).

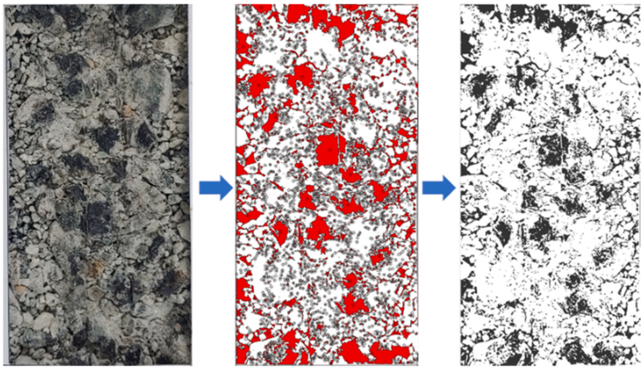


Fig. 11. Image analysis process.

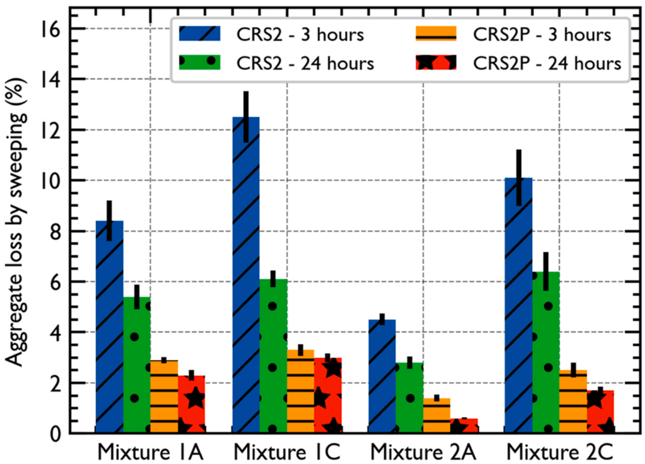


Fig. 12. Aggregate loss of Vietnam mixtures by sweep test.

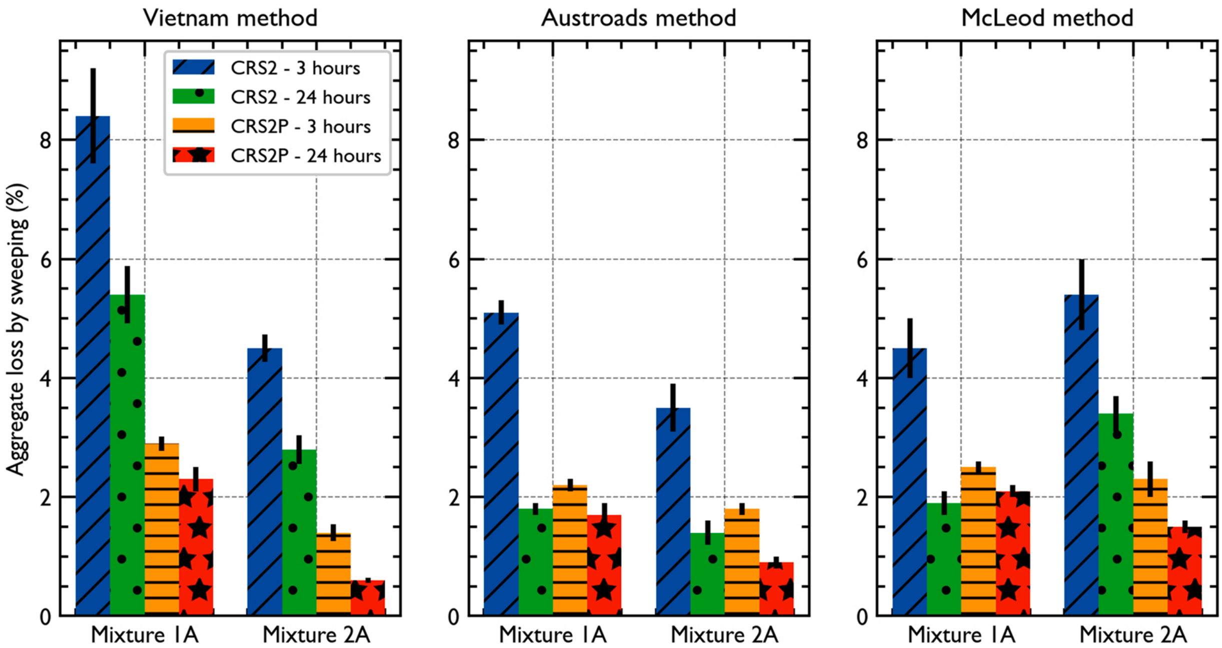


Fig. 13. Aggregate loss by sweeping of three design methods.

apply load of modified HWT was 175 ± 2 N, which was heavier than sweeping action of a broom in sweep test. The surface conditions of mixture 1 A and 2 A are shown in Fig. 15. Based on the author team's trial experiment and other research, the apply load of 175 ± 2 N and repeated cycle of 10 were suitable to simulate the effect of braking. The heavier apply load or more cycles seem not affect surface conditions of chip seal [25,26]. Considering asphalt emulsion, mixtures with CRS2P presented the better resistance to aggregate loss by braking in three design methods. This phenomenon can by explain by the higher polymer content in asphalt emulsion could provide more adhesive strength between aggregate and surface of asphalt disk.

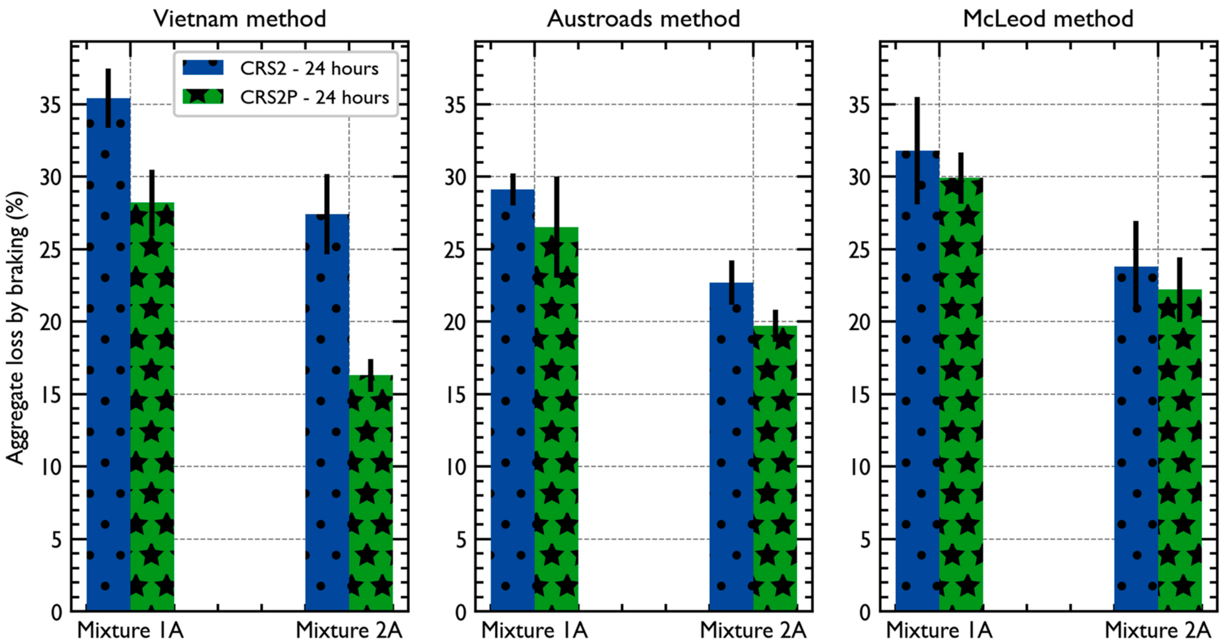


Fig. 14. Aggregate loss by modified HWT of three design methods.

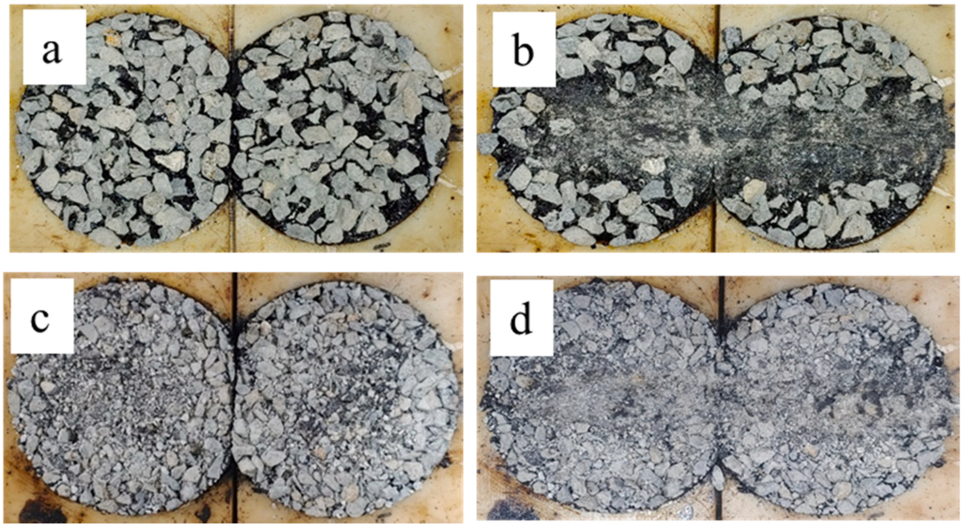


Fig. 15. Surface conditions of 1A-before (a), 1A-after (b), 2A-before (c), 2A-after (d).

3.3. Binder bleeding by modified HWT test

The bleeding percentage by modified HWT test of the three design methods are shown in Fig. 16. Generally, the increase in number of cycles caused the increase in percentage of bleeding. Mixtures designed by Austroads method presented a lower asphalt bleeding than that of McLeod method and Vietnam method. Percentage bleeding of mixture 2 A of Austroads method was 6.2 % after 2500 cycles, while McLeod and Vietnam method were 8.1 % and 7.9 %, respectively. It can be observed that mixture 2 A with CRS2P asphalt emulsion showed the lowest bleeding percentage among three design methods. Especially, at 1000 rolling cycles, the mixture 2 A designed by Austroads method was 5.0 % compared to that of 5.5 % and 6.5 % corresponding to Vietnam and McLeod method, respectively. This may be due to the high content of polymer caused the more viscosity in asphalt emulsion, which was beneficial in prevention of bleeding phenomenon.

4. Conclusions

This study aims to evaluate the performance of different chip seal design method and the effect of chip size on the performance of chip seal. Three design methods were considered, including Vietnam method, Austroads method, and McLeod method. Four chip sizes

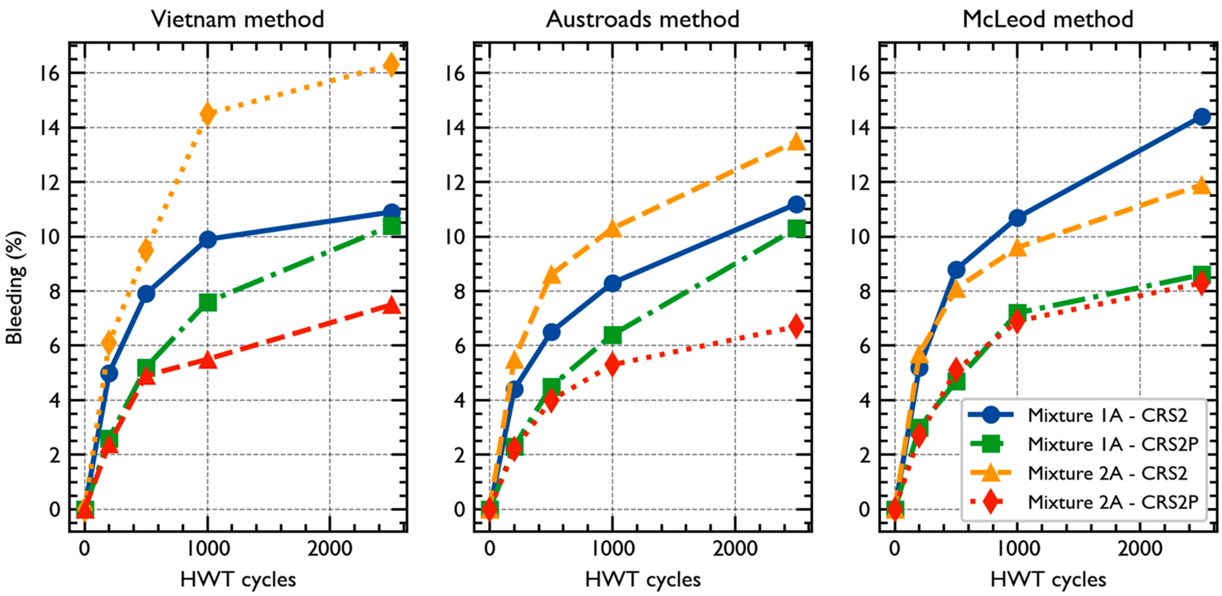


Fig. 16. Bleeding percentage of the three design methods.

were considered, which were 12.5 mm, 9.5 mm, 4.75 mm, and 2.36 mm. Two asphalt emulsion types (e.g., CRS2 and CRS2P) were used. The aggregate loss was determined by sweep test. In addition, modified Hamburg wheel tracking test with fixed pneumatic rubber tire was used to simulate the aggregate loss by braking. Finally, the bleeding susceptibility of chip seal mixtures was evaluated by the modified Hamburg wheel tracking test with rolling pneumatic rubber tire and analyzed by developed image analysis program. The following key findings can be drawn:

- In this study, the recommended aggregate sizes for single chip seal and double chip seal were mixture 1 A (9.5 mm) and mixture 2 A (4.5 mm and 2.36 mm), respectively. These aggregate sizes demonstrated superior adhesive and interlocking effects, as well as better stress absorption.
- The modified Hamburg wheel tracking test was found to be a promising method for simulating the effects of braking and rolling wheels on chip seal mixtures. To simulate the braking effect, a load of 175 ± 2 N and 10 Hamburg wheel tracking cycles were recommended for the chip seal sample surface.
- The results showed that the performance of chip seal was influenced not only by the binder application rate but also by the ratio between aggregate sizes, which had a significant impact on the interlocking effect.
- While the binder application rate was the main factor affecting bleeding percentage, the aggregate size and the number of chip seal layers also had some influence on the bleeding susceptibility of the chip seal.
- In single chip seal, the adhesive effect between binder and aggregate was crucial for performance, so a high binder application rate was necessary. However, in double chip seal, the interlocking effect between aggregate could replace some reliance on the binder, and hence, the binder application rate of double seal could be reduced.
- The Austroads design method effectively utilized both the adhesive effect of binder and the interlock effect of aggregate, resulting in high resistance to aggregate loss and asphalt emulsion bleeding.

In general, the current study results show that the Austroads design method is currently the most effective design method for chip seal. The optimal chip size for single seal is 9.5 mm, while the optimal chip size for double seal first layer and double chip seal second layer is 4.75 mm and 2.36 mm respectively. The authors recommend a further study to evaluate broader set of design methods and test conditions such as moisture susceptibility, freeze-thaw effect on the performances of chip size mixture.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Data availability

No data was used for the research described in the article.

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