Determination of the optimal number of coverages for the rolling of chip seals

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Abstract: This paper presents a method to determine the optimal protocol for rolling chip seals based on aggregate retention performance and aggregate embedment depth. To evaluate performance, the flip-over test (FOT), the Vialit test, the modified sand circle test, and the third-scale model mobile loading simulator (MMLS3) were employed. Two chip seal types (single and double) and three numbers of coverages (1, 3, and 5) were used as parameters to determine an optimal number of coverages. It was found from the aggregate retention test results and measured aggregate embedment depths that three coverages is the optimum number of coverages and the extra time needed for the two additional coverages cannot be justified.

Key words: chip seal, rolling, MMLS3, aggregate retention, embedment.

Résumé : Cet article présente une méthode pour déterminer le protocole optimal de roulage des enduits superficiels selon le rendement de rétention des agrégats ainsi que la profondeur d'encastrement des agrégats. Les essais suivants ont été utilisés pour évaluer le rendement : essai de renversement (FOT), essai Vialit, l'essai modifié du cercle de sable et un simulateur de chargement mobile à l'échelle 1:3 (MMLS3). Deux types d'enduits superficiels (simple et double) et trois passes de recouvrements (1, 3 et 5) ont été utilisés comme paramètres pour déterminer le nombre optimal de recouvrements. Les résultats des essais de rétention des agrégats et les profondeurs d'encastrement des agrégats mesurées ont montré que le nombre optimal de recouvrements est de trois mais que le temps supplémentaire requis pour poser les deux recouvrements additionnels ne peut être justifié.

Mots-clés : enduit superficiel, roulage, MMLS3, rétention des agrégats, encastrement.

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1. Introduction

Chip seals have been one of the most common preventive maintenance treatments in the United States over the past 75 years because they provide economical benefits to extend pavement life. Recent developments in materials and construction techniques make chip seals an effective alternative to thin asphalt overlays where the structural capacity of the existing pavement is sufficient to sustain its existing loads (Gransberg and James 2005).

The most common failures of chip seals are bleeding or flushing and aggregate loss on the top layer. Generally, a significant amount of aggregate loss occurs soon after construction with the initial trafficking and typically is caused by improper construction, inadequate chip seal design, and poor material selection (Transit New Zealand 2005). The aggregate loss in the early life of the chip seal can be reduced by improving the construction procedures.

In general, chip seal construction procedures consist of three steps: spraying emulsion, spreading a layer of aggregate, and rolling the layer of aggregate. To ensure the best chip seal performance, these steps should be continuous without any interruption. That is, having an adequate initial rolling using a sufficient number of rollers is an important factor in extending the service life of the chip seal (Committee of State Road Authorities 1986).

One of the areas in the chip seal construction procedure that can be improved with relatively low cost changes is the rolling process. The purpose of rolling is to achieve the desired aggregate embedment depth, which is the principal criterion in the chip seal design, by redistributing the aggregate and seating it in the binder (Benson and Galoway 1953). Another function of rolling is to achieve the bonding that results from proper embedment of the aggregates into the binder and from the most efficient orientation of the aggregates. Researchers have studied the chip seal construction system by roller type (Hudson et al. 1986), by rolling time (Gransberg et al. 2004), by roller pass (Hudson et al. 1986; Petrie et al. 1990), and by roller weight (Petrie et al. 1990) to improve the chip seal's quality and performance during its life (Gransberg and James 2005).

The required number of passes is important in the rolling process to achieve proper aggregate embedment and to interlock the aggregate particles. However, most construction

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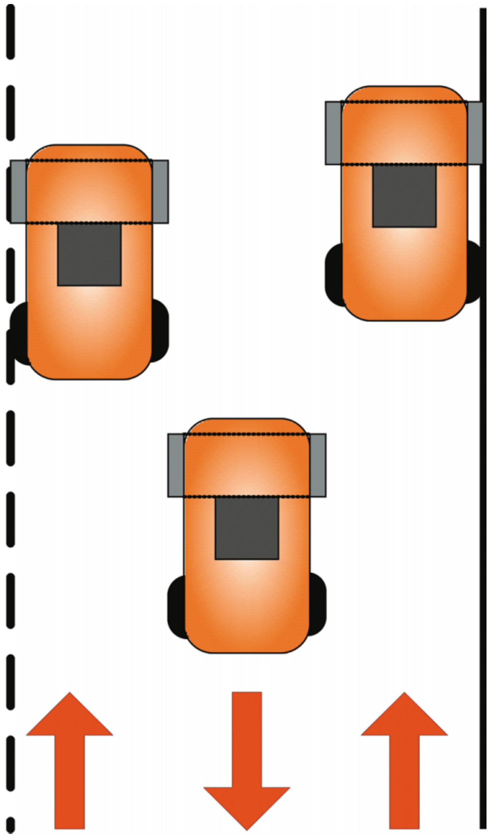
Fig. 1. Schematic diagram of three passes of one roller.



manuals do not require a specific number of rolling passes. Only 7 out of 39 states have a required number (3 or 4 passes) in their specifications. This study focuses on a method to determine the optimal number of rolling coverages in chip seal construction.

It is noted that the term *number of coverages* is used to count the number of rollings experienced by a section of road. For example, Fig. 1 shows one roller that passes three times to cover the entire lane with minimal overlap. In this case, the number of passes is three, but the number of coverages is only one.

Two types of chip seals, i.e., single and double, are used to evaluate the chip seal performance using aggregate retention tests and measurements of the depth that the aggregate is embedded into the emulsion. The aggregate retention performance is measured by the flip-over test (FOT), the Vialit test, and the third-scale model mobile loading simulator (MMLS3). The FOT is the part of the sweep test procedure (ASTM D 7000, ASTM 2004) that measures the amount of excess aggregate on the specimen and the Vialit test evaluates the adhesion performance between the aggregate and the emulsion. The MMLS3 has been used successfully to evaluate the performance of hot-mix asphalt (HMA) pavements (Lee 2004) and the aggregate retention of bituminous surface treatment pavements (Lee et al. 2006).

2. Objective

The primary objective of this research is to determine the optimal number of coverages for chip seal construction using samples obtained from actual field construction.

3. Materials

The choice of materials was based on the most common usage for chip seal construction in North Carolina (NC). CRS-2 emulsion, which is a cationic, rapid-setting type of emulsified asphalt, was used for the construction of the chip seal. Two types of aggregate were used with the CRS-2 emulsion: (*i*) Stalite, which is produced using a rotary kiln expanded lightweight slate (referred to as *lightweight*) with a 7.9 mm nominal maximum size of aggregate, and (*ii*) a 78M graded granite aggregate. Figure 2 shows the gradations for the two aggregate types.

4. Construction of the test sections

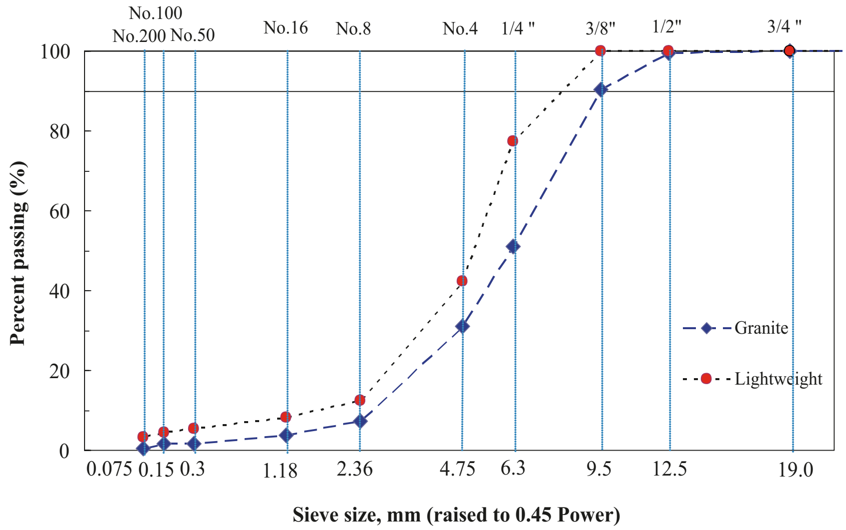
To evaluate rolling protocols, it is critical to test samples that are obtained directly from field construction. Test sections were constructed on SR 1131 near Bailey, NC in September 2006 to evaluate the effect of the number of coverages without being affected by the time delay between coverages. The experimental program includes the two seal types (single and double) and three numbers of coverages (1, 3, and 5), resulting in six sections. The number of coverages was designed with odd numbers because rollers must move forward during the last pass in the actual construction procedure in the field. Each of the six test sections was divided into two groups according to chip seal type and each of the two groups was composed of three sections so that the effects of the three numbers of coverages on aggregate loss performance could be evaluated. Two combination rollers that combine the use of a steel wheel drum on the front axle with four rubber tire wheels on the rear axle were used side by side to cover an entire lane.

Granite 78M aggregate was used for the single seal construction. For the double seal construction, granite 78M and Stalite were used for the bottom and top layers, respectively. Only one rolling coverage was applied to the bottom layer of the double seal using the combination roller. Three different numbers of coverage (1, 3, and 5) were applied on top of the single and double seals. The aggregate application rates (AARs) and the emulsion application rates (EARs) were determined from visual observations made by the North Carolina Department of Transportation (NCDOT) Division Supervisors from a trial construction. The aggregate applicate rate (AAR) and the emulsion application rate (EAR) for single seal are 9.2 kg/m^2 and 1.58 L/m^2, respectively. The AARs for double seal are 9.2 and 4.9 kg/m^2 for bottom (granite 78M) and top (Stalite) layers, respectively. The same EAR of 1.1 L/m^2 is used for both layers in double seal.

5. Specimen fabrication

One of the critical procedures in this research is fabricating the field sample so that it corresponds to the actual construction sequence. Thus, establishing the field sampling procedure was critical to this study. Figure 3 describes the developed sampling procedure. Figure 3*a* shows the placement of the templates on the existing pavement. Templates for the FOT and Vialit test and for the MMLS3 were affixed in the longitudinal direction to the ground paper that covers the existing pavement. The longitudinal layout helped to

Fig. 2. Aggregate gradations.



avoid the sample-to-sample variation in the transverse direction. The roller pattern in this study is a parallel pattern that uses two rollers to avoid overlapping coverage within a section, as shown in Fig. 3*d*. Figure 3*e* shows gathering the samples for delivery. To reduce the disturbance of aggregates on the sample during the collection of the samples, the samples were cured for 30 min at ambient temperature after completion of the rolling operation. Thus, the chip seal specimens became much more stable while they were being gathered due to the fact that the water in them had evaporated, thus causing an improved mechanical bonding between the emulsion and the aggregate. As shown in Fig. 3*e*, samples were placed on a wooden plate to minimize disturbance during the delivery. Collected samples on the wooden plates were stored on racks, as shown in Fig. 3*f*.

6. Test methods

6.1 Ignition oven test

The ignition oven method, which is specified in ASTM D 6307 (ASTM 2005), was adopted to determine the weight of residual aggregate and emulsion. This test method determines the amount of asphalt in HMA by burning the asphalt cement in an ignition furnace. The amount of emulsion is calculated by the difference in the weight of the original chip seal sample and the residual aggregate.

6.2 Flip-over test

The FOT specimens were fabricated on a 25.4 cm × 25.4 cm felt disk. The samples fabricated at the test sections were stored at room temperature (25 °C) and were fully cured at 35 °C for 24 h before the test. The specimen was turned vertically, and any loose aggregate was removed by lightly brushing the specimen. The specimens were weighed before and after the FOT to determine the amount of excess aggregate on the specimen.

6.3 Vialit test

The Vialit test was used to evaluate the aggregate retention. The Vialit test was developed by the French Public Works Research Group and standardized in British Standards (BS) 12272-3 (BSI 2003). The chip seal specimens obtained from the field were fabricated on 20 cm × 20 cm steel plates and cured at 35 °C in the oven for 24 h before test. A stainless steel ball is dropped three times from a height of 50 cm onto a chip seal tray that has been inverted for 10 s. Sample weights are measured before and after the ball drop to calculate the percentage of aggregate loss using eq. [1].

$$[1] \qquad \text{Aggregate Loss } (\%) = \frac{W_{\text{B,mixture}} - W_{\text{A,mixture}}}{W_{\text{B,mixture}}} \times 100$$

where $W_{\text{B,mixture}}$ and $W_{\text{A,mixture}}$ are the weights of the emulsion and aggregate on the chip seal specimen before and after the test, respectively.

6.4 Modified sand circle method

A modified sand circle method has been developed based on the Test Method T 240: Road surfaces texture depth (Roads and Traffic Authority 2009*a*) that measures the texture depth of a coarse road surface. This method describes the procedure for measuring the average textural depth of a chip seal. In the sand patch test (ASTM E 965, ASTM 1987), a known volume of sand is spread on dry pavement, the area covered with sand is measured, and the average depth is calculated as the sand volume divided by the covered area. As opposed to the sand patch test, the modified sand circle method adopts the use of a loose unit mass of sand (Roads and Traffic Authority 2009*b*) to calculate the average texture depth between the bottom of the pavement surface voids and the top of the surface aggregate particles.

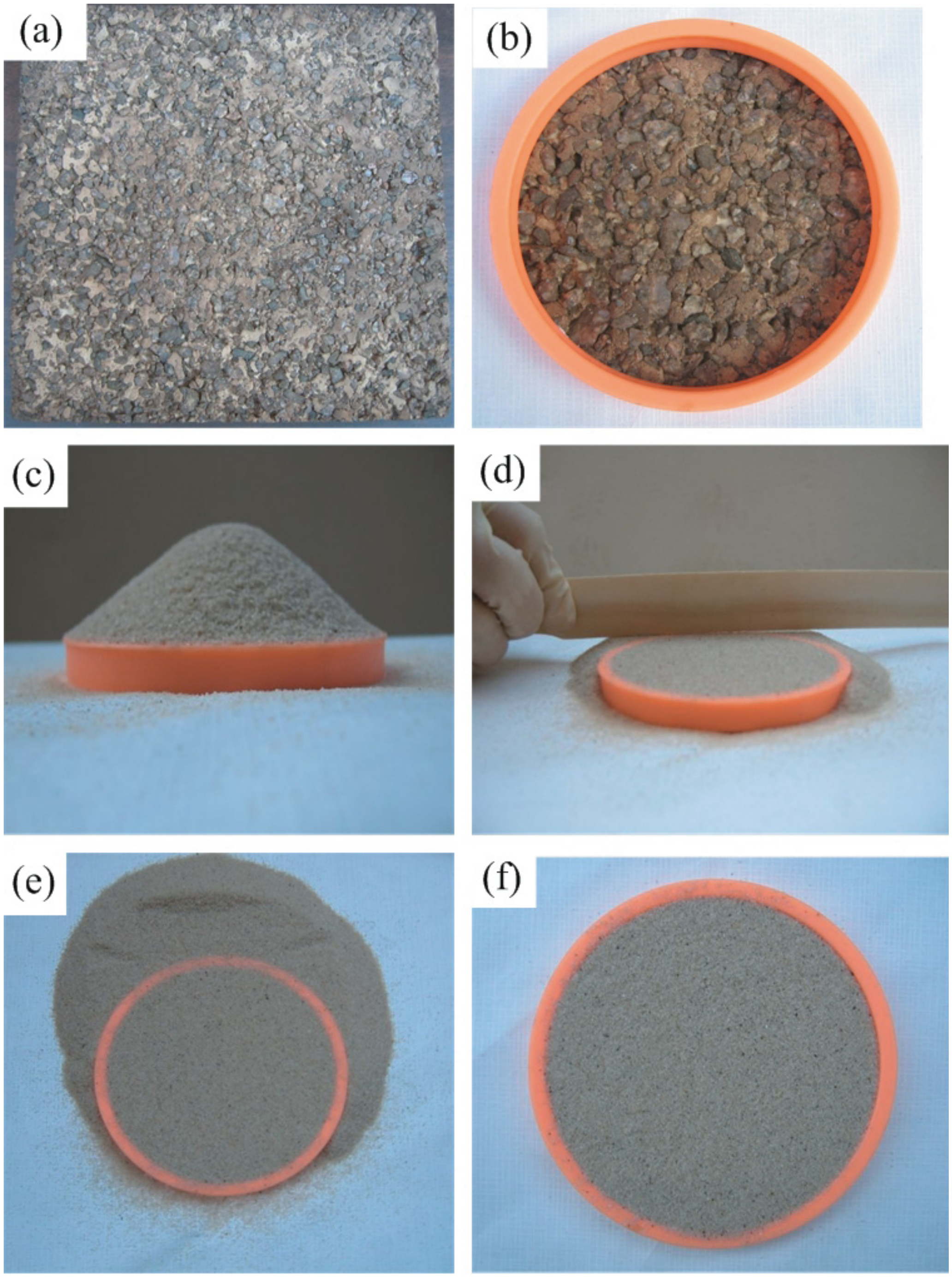
To directly measure the embedment depth of the aggregate in a chip seal structure, the emulsion must be removed from the structure. The seal behavior method (Austroads 2006) was used to eliminate the emulsion film from the field specimen. To maintain the aggregate structure after removing the emulsion, epoxy is poured onto the specimen to cover the entire surface. After the epoxy is cured completely, the chip seal specimen is submerged in a tray with kerosene and soaked for a minimum of 12 h to remove the emulsion. Figure 4*a* shows the bottom surface of the chip seal specimen, free of emulsion.

Fig. 3. Sample fabrication procedure: (*a*) affixed templates on the existing pavement; (*b*) spraying emulsion; (*c*) spreading aggregate; (*d*) compacting with rollers; (*e*) gathering samples; (*f*) delivering samples to laboratory.

Figures 4*b* to *f* show the steps involved in determining the embedment depth of the chip seal using the modified sand circle method. First, it must be noted that it is difficult to maintain a circular form as the sand is spread on the chip seal and, therefore, difficult to determine the area accurately. In the modified sand circle method, a ring is used to confine the spread of the sand within the circle. In Fig. 4*b*, the inverted specimen is covered with Tyvek®, a brand of flash-spun high-density polyethylene fibers, which has a hole with the same diameter as the ring. Figure 4*b* shows the ring seated on the Tyvek®. The exposed area seen in Fig. 4*b* is used to measure the embedment depth. Figure 4*c* shows the sand that is on top of the surface of the specimen, overfilled to create a central cone form. Next, the excess sand is carefully screened off with a straightedge to provide a surface level with the top of the ring, as seen in Fig. 4*d*. Figure 4*e* shows the screened-off sand. Finally, the excess sand is completely removed, as shown in Fig. 4*f*, so that the sand remaining within the ring can be weighed.

It is noted that the weight of the sand remaining in the ring that is on the chip seal specimen is composed of the weight of the sand that fills the ring *and* the weight of the sand that fills the voids in the chip seal specimen. Therefore, the weight of the sand that fills the voids of the inverted specimen can be determined by subtracting the weight of the sand that fills the ring from the weight of the sand remaining on the specimen. The average embedment depth is then calculated using eq. [2].

Fig. 4. Modified sand circle test procedure: (*a*) surface texture after emulsion is dissolved and eliminated; (*b*) ring on surface of specimen; (*c*) poured sand in ring; (*d*) leveling off excess sand with a straight-edge; (*e*) excess sand removed from circle; (*f*) excess sand cleaned from sample.



[2] $$\text{Average embedment depth} = \frac{1272M}{Dd^2}$$

where

- D is the loose unit mass of the sand (g/cm^3);
- d is the diameter of the ring (mm);
- M is the mass of the sand (W_2–W_1);
- W_1 is the the weight of sand that fills the ring without the chip seal specimen; and
- W_2 is the the weight of the sand remaining in the ring.

6.5 Third-scale model mobile loading simulator performance test

The MMLS3 is a third-scale unidirectional vehicle load simulator that uses a continuous loop for trafficking. It is comprised of four bogies with only one wheel per bogie. These wheels are pneumatic tires that are 30 cm in diameter, approximately one-third the diameter of a standard truck tire. The wheels travel at a speed of about 5500 wheel applications per hour, which corresponds to a dynamic loading of 3.3 Hz on the pavement surface. This loading consists of a

Fig. 5. Correlation between total aggregate weight and retained aggregate weight on 6.35 mm sieve for granite 78M.

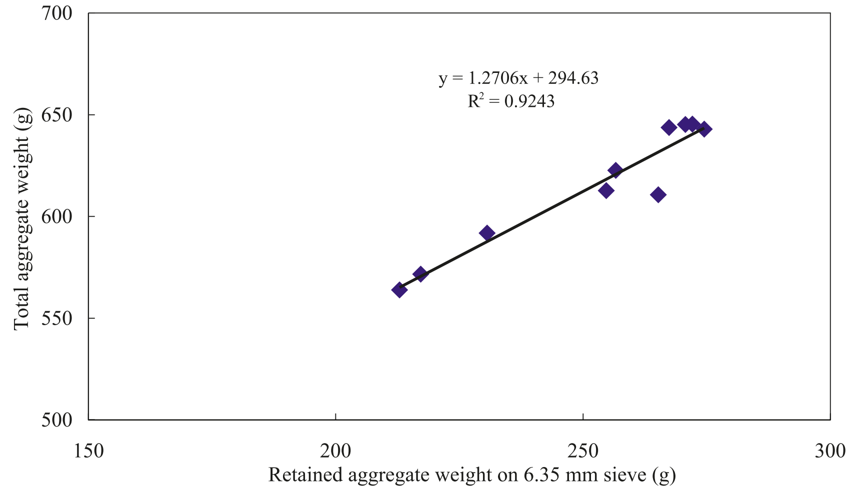


Fig. 6. Flip-over test results: (*a*) single seal, (*b*) double seal.

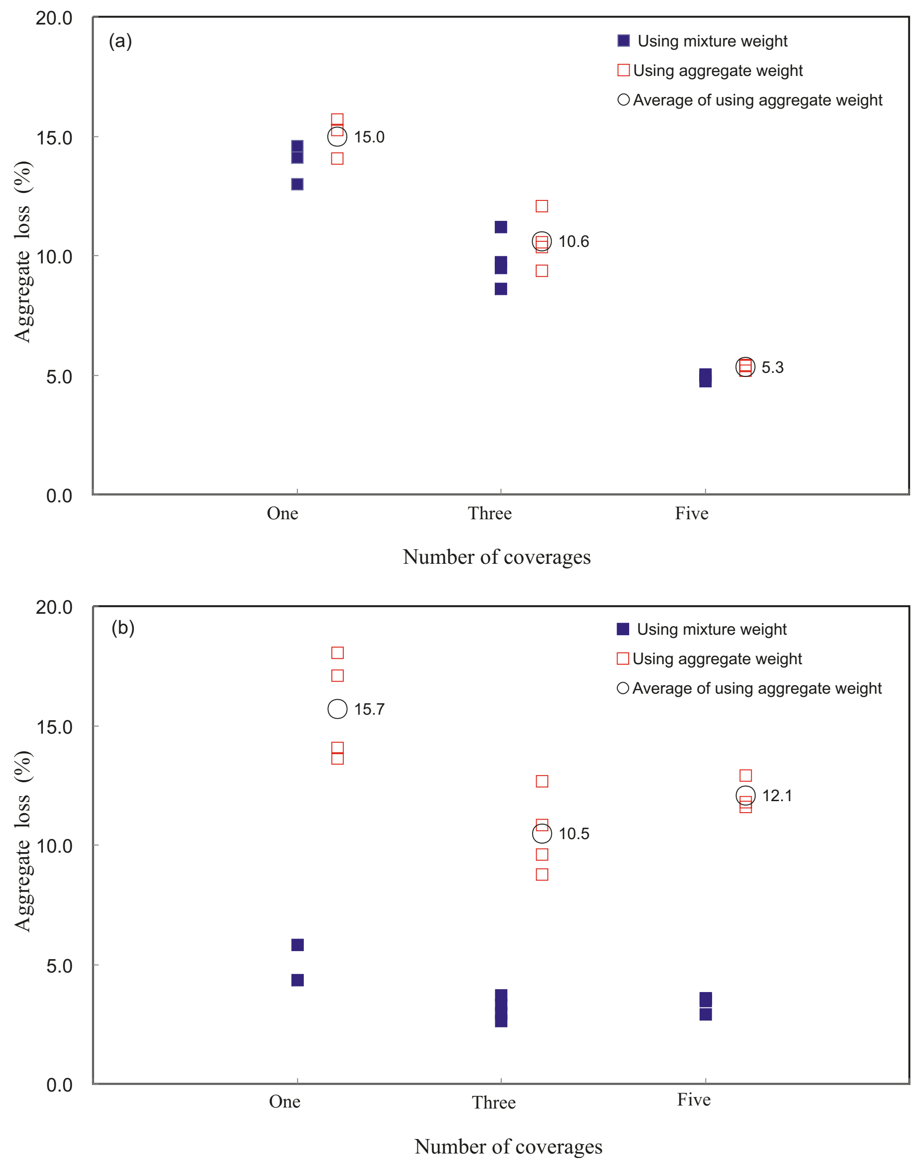


Fig. 7. Average aggregate loss determined from Vialit test.

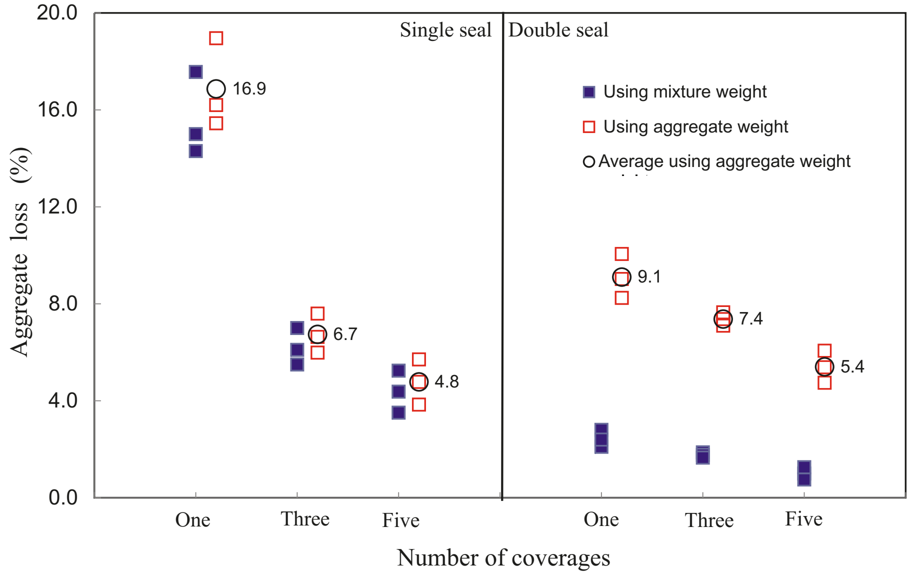
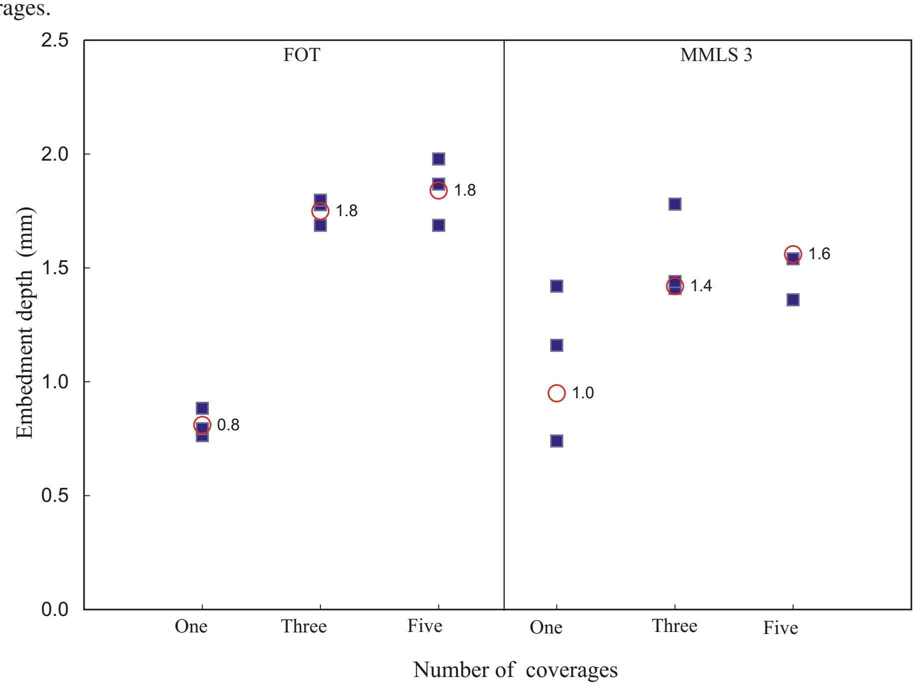


Fig. 8. Embedment depth of flip-over test (FOT) and third-scale model mobile loading simulator (MMLS3) single seal samples as a function of the number of coverages.



0.3 s haversine loading time and a rest period of 0.3 s. The dynamic load on the pavement surface by the MMLS3 in motion is measured by a Flexiforce® pressure sensor. The mean value of maximum dynamic loads from the four wheels is approximately 3.57 kN. The contact area is approximately 34.0 cm^2 measured from the footprint of one MMLS3 wheel inflated to 699.8 kPa, thus resulting in a surface contact stress of approximately 1048.7 kPa (Lee 2004).

Lee et al. (2006) developed a test protocol for the performance evaluation of chip seals using MMLS3 to measure the aggregate retention performance. The detailed test procedure is described in Lee et al. (2006). A brief outline of the test method is given below.

First, a field specimen is cured for 24 h at 35 °C and 30 ± 3% relative humidity before testing, as specified in the ASTM D 7000 (ASTM 2004). Then, the edges of the cured specimen are trimmed to produce a specimen that is 18 cm wide and 35 cm long. The 18 cm width of the rectangular specimens is the same as the width of the wheel path under wandering MMLS3 loading. This design is necessary because it was found from former research that the aggregate that is lost under MMLS3 loading falls onto the untrafficked

Fig. 9. Aggregate loss measured from the third-scale model mobile loading simulator test after 12 940 wheel passes: (*a*) single seal, (*b*) double seal.

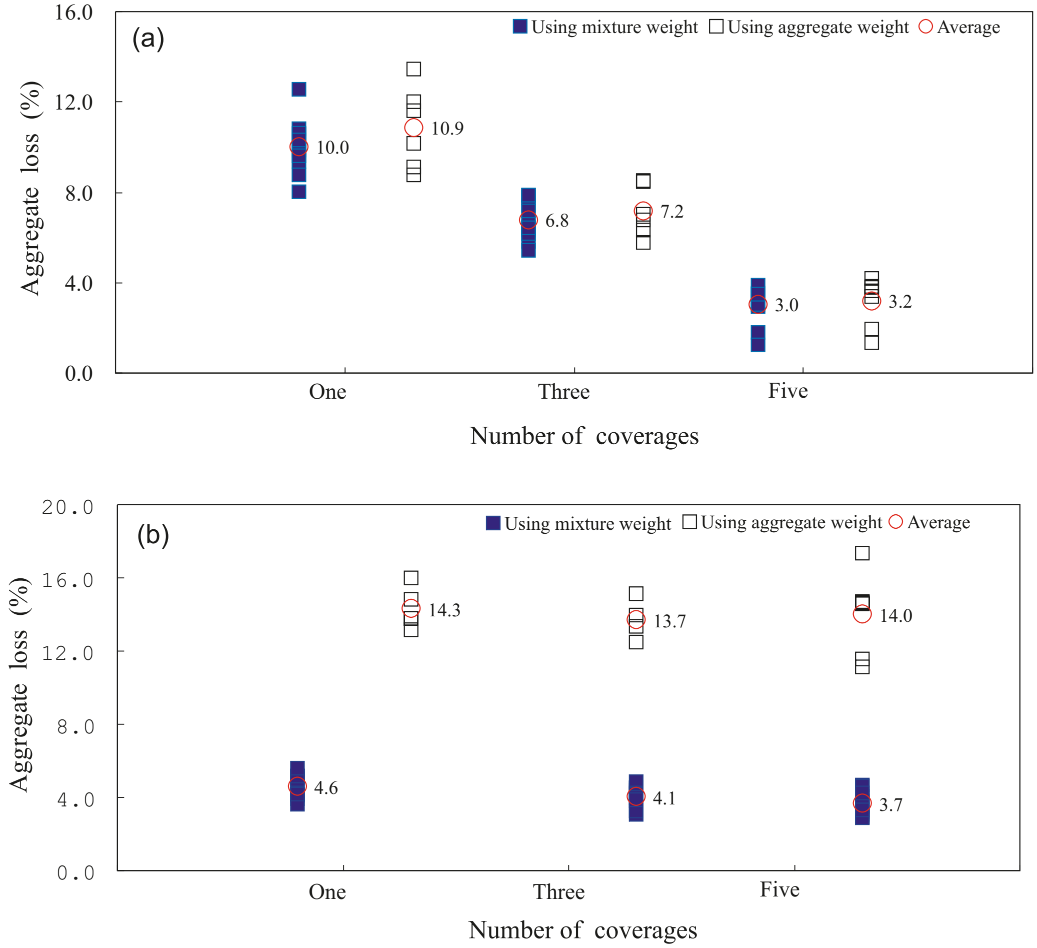


Table 1. Summary of average percentage of aggregate loss and embedment depth.

		Number of coverages		
Test method	Chip seal type	One	Three	Five
Vialit (%)	Single	16.9	6.7	4.8
	Double	9.1	7.4	5.4
FOT (%)	Single	16.0	10.6	6.3
	Double	15.7	10.5	12.1
MMLS3 (%)	Single	10.9	7.2	3.2
	Double	14.3	13.7	14.0
Embedment depth (mm)	Single (FOT)	0.81	1.76	1.84
	Single (MMLS3)	0.95	1.42	1.56

Note: FOT, flip-over test; MMLS3, third-scale model mobile loading simulator.

Table 2. Summary of statistical analysis results (analysis of variance test).

Test method	Chip seal types	F-Test	P-value	Conclusion
Vialit	Straight	23.10	0.0015	Reject H_0
	Double	4.74	0.0583	Reject H_0
FOT	Single	3.49	0.0813	Reject H_0
	Double	144.55	<0.0001	Reject H_0
MMLS3	Single	7.79	0.0043	Reject H_0
	Double	0.15	0.8664	**Accept H_0**

Note: FOT, flip-over test; MMLS3, third-scale model mobile loading simulator.

area, causing errors in the aggregate loss calculation (Lee et al. 2006). The trimmed specimen was mounted on a thin steel plate fastened to a steel base plate and then measured before and after the MMLS3 loading to determine the aggregate loss. MMLS3 loading was applied after a 3 h temperature preconditioning period at 25 °C. The aggregate loss during the initial traffic loading in the field (normally occurring within half a day) was measured after one wandering cycle of MMLS3 loading for 10 min (equivalent to 990 wheel loads). Then, MMLS3 loading was applied and the weight of the specimen was measured at the end of a 2 h loading period (equivalent to 11 950 wheel loads) to evaluate the aggregate retention performance of the chip seal under traffic (Lee et al. 2006).

In actual chip seal construction, the chip seal is broomed after several days under traffic. In the MMLS3 test procedure, no brooming is applied and therefore the aggregate loss owing to brooming is included in the total aggregate loss measured from the MMLS3 test. The MMLS3 test is used to measure the total aggregate loss because: (*i*) the aggregate loss performance before brooming is as important as that after brooming in terms of the windshield damage factor; and (*ii*) agencies pay for the entire volume of aggregate, including extra aggregate collected from brooming.

7. Test results and discussion

7.1 Ignition oven test

The total weight of the cured single seal specimen obtained in the field is composed of three separate weights, i.e., the weight of the felt disk, the weight of the residual asphalt, and the weight of the aggregate. Because the weight of the felt disk is measured prior to chip seal sample fabrication, the aggregate weight before testing can be determined, if the asphalt weight is known. The asphalt weight is determined using the ignition oven test by subtracting the weight of the residual aggregate after the ignition oven test and the weight of the felt disk from the weight of the tested specimen before the ignition oven test. Thus, the weight of the aggregate in the original, untested chip seal specimen can be determined once the weight of the asphalt and the weight of the felt disk are subtracted from the weight of the original chip seal specimen.

This concept becomes more complex with the double seal because the residual aggregate from the ignition oven test is composed of aggregates from both the bottom (granite 78M) and top (Stalite) layers, whereas the weight of the aggregate to be used in the percentage aggregate loss calculation should be only the weight of the top layer aggregate to be consistent with the values from the single seal. The following method was developed to estimate the weight of the aggregate in the top layer of the double seal. It was found from single seal experiments with granite 78M specimens that a strong correlation exists between the total aggregate weight and the weight of aggregate retained on a 6.35 mm sieve. This relationship is depicted in Fig. 5 and presented as follows based on regression analysis:

$$[3] \qquad W_{\mathrm{Total}} = 1.2706 \times W_{6.35} + 294.63$$

where W_{Total} and $W_{6.35}$ are the weights of the total aggregate and the aggregate retained on a 6.35 mm sieve, respectively.

Chip seal specimens after testing are burnt in the ignition oven to determine the weight of the asphalt and aggregate. To determine the weight of the aggregate from the top layer (i.e., Stalite) only, the residual aggregate is first sieved through a 6.35 mm sieve. Then, the granite 78M aggregate is separated from the residual aggregate retained on the 6.35 mm sieve using their difference in color. Once the weight of the granite aggregate retained on the 6.35 mm sieve is determined, this weight is used in eq. [3] to determine the weight of the total granite aggregate. Because the granite 78M is used in the bottom layer, it is reasonable to assume that no loss of this aggregate occurs during testing on the surface. Finally, the weight of the granite 78M aggregate, the weight of the residual asphalt, and the weight of the felt disk are subtracted from the weight of the chip seal specimen before testing to determine the weight of the Stalite in the original specimen before testing.

7.2 Flip-over test results

The FOT measures the amount of excess aggregate on the specimen. The aggregate loss performance is shown in Figs. 6*a* and *b* as a function of the number of coverages and chip seal types. Both figures have three symbols, a filled symbol, an empty symbol, and a large empty symbol. The large empty symbol indicates the averages of the data for each number of coverage. The percentage of aggregate loss represented by the filled symbols is determined using the total mixture weight, whereas that represented by the empty symbols is calculated using the weight of the aggregate in the denominator. The percentage of aggregate loss that is calculated using the aggregate weight is slightly higher than the percentage of aggregate loss determined using the mixture weight, because the aggregate weight is smaller than the mixture weight. It is clearly demonstrated in this figure that, as the number of coverages increases, the aggregate loss decreases, in this case from 15.0% to 5.3%. The percentage of aggregate loss at three coverages is 10.6%. This percentage is about the same as the maximum allowable aggregate loss of 10% specified in the Alaska chip seal guide (McHattie 2001).

Figure 6*b* shows the aggregate loss performance of the double seal. Two important observations can be made from this figure. First, the values based on the mixture weight are significantly different from those using the aggregate weight. It is noted that the aggregate weight used in calculating the values for the empty symbols is the weight of the aggregate in the top layer only (i.e., Stalite), which is determined using the method presented in the previous section. Because the denominators represented in the empty symbols (i.e., the aggregate weights) are much smaller than those in the filled symbols (i.e., the mixture weights), this trend is obvious. It is interesting that the percentage of aggregate loss in the single seal is similar to that in the double seal when only the weight of the aggregate in the top layer is used in the percentage of aggregate loss calculation. For example, the percentages of aggregate loss for one coverage and three coverages are about 15% and 10%, respectively, as seen in Fig. 6*a* and *b*. It is not clear why the values for the five coverages are quite different.

The second observation from Fig. 6*b* is that a significant decrease in aggregate loss is evident from one coverage to three coverages, but no significant improvement in aggregate loss performance occurs between three and five coverages. Considering this trend and the economic factors involved in rolling, three coverages seems to be the optimal number of coverages for the double seal. It is noted that about a 10% aggregate loss found in both single and double seals meets the maximum allowable aggregate loss of 10% specified in the Alaska chip seal guide (McHattie 2001).

7.3 Vialit test results

The Vialit test measures the adhesion between binder and aggregate. The adhesion is evaluated as the measurement of aggregate loss due to the shock of impact. The average aggregate loss of the three replicates from the Vialit test was calculated and is plotted in Fig. 7 against the number of coverages. It must be noted that the aggregate loss determined from the Vialit test using eq. [1] is based on the mixture weight, i.e., the combined weights of the emulsion and aggregate. The use of the mixture weight is necessary because the emulsion weight and the aggregate weight cannot be determined separately. The ignition oven test cannot be applied to the Vialit test because the steel plate cannot be incinerated in the oven. The aggregate loss based on the aggregate weight is estimated from the FOT data, shown in Fig. 6*a* and *b*. The difference in percentage of aggregate loss due to the difference in the mixture weight and aggregate weight is determined from Fig. 6*a* and *b*. This difference is then applied to the aggregate loss based on the mixture weight determined from the Vialit test to estimate the aggregate loss based on the aggregate weight. The results are presented in Fig. 7.

For both seal types, the aggregate loss decreases as the number of coverages increases. In the case of the single seal, a large reduction in aggregate loss is evident between one coverage and three coverages and only a small change in aggregate loss takes place between three coverages and five coverages. This finding indicates that no significant improvement in adhesion between binder and aggregate exists between three coverages and five coverages. Also, it is noted that the NCDOT's specifications specify a 10% aggregate loss as the maximum allowable aggregate loss for chip seals. According to this criterion, both three and five coverages meet the specification.

Unlike the single seal, a large reduction in aggregate loss is not apparent in the trend shown in the data for the double seal. This difference can be explained by the fact that lost aggregates in the double seal are composed of Stalite from the top layer only, whereas in the percentage of aggregate loss calculation in the double seal, the entire weight of both layers is used in the denominator. Based on the results shown in Fig. 7, three coverages are a proper number of coverages considering both aggregate loss performance and cost effectiveness.

7.4 Modified sand circle test results

The embedment depth of the single seal is measured from the FOT and MMLS3 test specimens using the modified sand circle method. The results are shown in Fig. 8 as a function of the number of coverages. These specimens were compacted in the field using a combination roller. In Fig. 8, only one FOT sample was available for each number of coverages; therefore, the one data point shown in Fig. 8 is an average of the three replicate measurements for each sample. Figure 8 shows that a significant increase in embedment depth is evident from one coverage to three coverages. However, only a slight change in embedment depth is evident between three and five coverages.

Figure 8 also shows the embedment depth of a single seal after 2 h 10 min of MMLS3 trafficking. The same trend seen in Fig. 8 for the FOT results is also evident for the MMLS3 results. As Hudson et al. (1986) found, the surface texture depth is changed significantly up to three roller passes and an obvious change in embedment depth in the chip seal occurs between one coverage and three coverages. Considering the trends from Fig. 8, three coverages seem to be the optimal number of coverages for the single seal.

7.5 Third-scale model mobile loading simulator test results

To determine the aggregate loss due to MMLS3 loading, the aggregate loss is measured at two separate times: (*i*) after one wandering cycle of MMLS3 loading to simulate an initial traffic loading in the field; and (*ii*) after a two hour traffic period to evaluate the aggregate retention performance under traffic. Figure 9*a* and *b* show the percentage of aggregate loss during the 2 h 10 min (12 940 wheel passes) duration of the aggregate retention test on single and double seals, respectively. Figure 9*b* shows the aggregate loss performance of the double seal. The same observation as made in Fig. 6*b* is made here. The values of aggregate loss are significantly different as a function of the weights used in the calculations. It is noted that the aggregate weight used in calculating the values represented by the empty symbols is the weight of the aggregate in the top layer only (i.e., Stalite), which is determined using the method presented in previous section (Ignition Oven Test). Because the denominators represented by the empty symbols (i.e., the aggregate weights) are much smaller than those represented by the filled symbols (i.e., the mixture weights), this trend is obvious. Contrary to the FOT results (seen in Fig. 6*a* and *b*, the significant decrease in aggregate loss is not apparent as a function of the number of coverages. A slight improvement in aggregate loss performance occurs between one and three coverages. For example, the percentages of aggregate loss for one coverage and three coverages are about 14.3% and 13.7%, respectively, as seen in Fig. 9*b*. It is not clear why the values for the different coverages are slightly different.

8. Comprehensive analysis

The objective of this paper is to determine an optimal number of coverages. A total of six test programs were completed to evaluate the performance of two seal types (single and double seal) under three different numbers of coverages (1, 3, and 5).

Table 1 summarizes the percentage of average aggregate loss from three aggregate retention tests and the aggregate embedment depth using MMLS3 and FOT samples. The decrease of aggregate loss against the number of coverages was clearly shown in Table 1. Also, the change of aggregate embedment depth as function of the number of coverages indicates that the optimal number of coverage is the three coverages in the single seal.

Statistical analysis was conducted to determine if the differences found in the means are statistically significantly. Analysis of variance (ANOVA) was used to test for differences among the three groups (1, 3, and 5 coverages). The results of these ANOVA tests are shown in Table 2. The differences among the three groups are significant because the p-values are greater than the alpha level of 0.05, with the exception of the MMLS3 result of the double seal. The MMLS3 test of the double seal indicates no significant differences among the three different coverages. It should be noted that the aggregate in a multiple seal layer will become rearranged and compacted under traffic to reach a theoretical optimal packing arrangement (Ball et al. 2005). These mechanisms in the field are well simulated by the MMLS3 wheel loading. It is believed that, due to the compaction mechanism of the double seal under MMLS3 loading, the MMLS3 does not create a difference in the percentage of the aggregate loss. Considering these results and the economic factors involved in rolling time, three coverages seems to be the optimal number of coverages for the double seal.

9. Conclusions

To determine an optimal number of coverages for chip seal pavements, the MMLS3, FOT, Vialit, and modified sand circle tests were performed. Based on the test data obtained from this study, the following conclusions are drawn to support the determined optimal number of coverages:

- As the number of coverages increases, the performance of aggregate loss generally decreases.
- The Vialit test results indicate that significant improvement in adhesion between binder and aggregate does not exist between three and five coverages.
- The aggregate loss percentages obtained from the MMLS3 test are smaller than those of the other tests because some extra aggregate particles can be seated into the emulsion by the MMLS3 wheel loading. This observation can be extended to claim that the conventional aggregate retention tests, which determine the aggregate loss before significant trafficking, are conservative test methods for determining aggregate retention performance.
- The modified sand circle method indicates that a slight change occurs in the embedment depth between three and five coverages. The implication is that the additional two coverages are not cost effective; that is, they do not offer enough improvement in aggregate retention performance to justify the associated additional costs.
- The optimal number of coverages for both single and double seals construction is three, according to aggregate retention test results and measurements of the aggregate embedment depth using the modified sand circle test. Five coverages seems to improve the aggregate retention perdormance further; however, the extra time needed for the two additional coverages makes rolling patterns with five coverages impractical.

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