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Performance Evaluation of Chip Seals in Idaho

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16. Abstract

The intent of this research project is to identify a wide variety of parameters that influence the performance of pavements treated via chip seals within the State of Idaho. Chip sealing is currently one of the most popular methods of maintenance for paved road surfaces. It entails spraying the pavement surface with asphalt (or "binder") and then immediately covering it with aggregate (or "chips") and using rollers to compress and settle the application. Chip sealing is used to seal non-structural cracks, increase surface friction, and improve ride quality. There are a variety of techniques and formulas ("design methods") for mixing the binder and aggregate used in chip sealing. In Idaho, these design methods lack uniformity: empirical methods are used, based on an informal rule-of-thumb, the experiences of the parties making the chip seal, and the materials that are readily available. This project compares the methods used in Idaho with several different design methods that have been developed in various parts of the world. The project's research focus is a series of laboratory experiments using different binders and aggregates obtained from all six Idaho Transportation Department districts. The results of these experiments have been compiled and analyzed, with the findings included herein. Chief among these findings, it was observed that the ratio of median size to flakiness index of the aggregate exhibits a better correlation with the percentage aggregate retained rather than the least dimension (as used in the commonly used McLeod Design Method). It was also found that the cleanness value of the aggregate is a critical factor for retaining aggregate -- i.e., keeping the chips on the treated road surface, rather than breaking free from the binder. This report concludes with a series of seven recommendations for improving chip sealing practice in Idaho, and with a list of eight areas worthy of additional research.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ACRONYMS

Acronym		Definition
AASHTO	–	American Association of State Highway and Transportation Officials
ALD	_	Average Least Dimension
ASTM	-	American Society for Testing and Materials
CFLHD	–	Central Federal Lands Highway Division
CV	–	Cleanness Value
FI	–	Flakiness Index
HFE	–	High Float Emulsions
ITD	–	Idaho Transportation Department
MnDOT	–	Minnesota Department of Transportation
PCI	–	Pavement Condition Index
TxDOT	–	Texas Department of Transportation

EXECUTIVE SUMMARY

Purpose of the Research: This research has two distinct purposes: First, it seeks to evaluate the effectiveness of Idaho's existing chip seal practice and to identify the specific causes of aggregate loss from the pavement surface. Secondly, alternative materials/methods are investigated to improve the current practice and alleviate the associated problems.

Background: An extensive literature review was conducted at the onset of this study to determine what research has already been performed in the field of chip sealing. The literature search revealed that chip sealing has been employed since 1920. At the time, it was executed only on low-volume gravel roads. Initially, when such chip sealing was performed, no particular design method was employed. It wasn't until 1934 that the first design method was formulated by Hanson. It was later modified and adopted by different countries worldwide. The average life of a chip seal application has been reported to be about 7 to 10 years. Over the years, chip sealing has evolved into one of the best and most popular preventive maintenance techniques available for paved road surfaces. The success of chip seals has been attributed to its low cost and high durability, compared to any other preventive maintenance techniques.

Chip sealing entails spraying the pavement surface with bituminous binder and then immediately covering it with aggregate (or "chips") and using rollers to compress and settle the application. The intent is to seal the non-structural cracks, increase surface friction, and improve the ride quality. In the past, there was no rationale in chip seal design. Recently, several different design methodologies have been developed in various parts of the world. The Idaho Standard Manual recommends the use of the Modified Kearby Design Method.

It is known that the performance of chip seal application depends on a variety of factors including the type of aggregate used, emulsion rates, construction techniques, weather, surface preparation, traffic control, and materials. The present study was initiated to explore the influence of aforementioned parameters on the performance of pavements treated via chip seals and to identify good practice for materials, design, and construction techniques to be implemented in the State of Idaho.

Scope of Work: To appraise how the chip sealing is carried out across the State of Idaho, a questionnaire was prepared and sent to the six Idaho Transportation Department (ITD) districts. To further evaluate the effectiveness of Idaho's existing chip seal practice, a myriad of laboratory experiments was devised to investigate the performance of several binders and different assortment of aggregates obtained from all the six ITD districts under a wide variety of conditions. The laboratory experiments entailed a combination of sieve analyses, flakiness index, loose unit weight, cleanness value, and Vialit tests. In addition, field observations were scheduled prior, during, and following a chip sealing application. The results of the laboratory tests were compiled and analyzed. The results from the laboratory experiments were used as input in both McLeod and Modified Kearby methods

Methodology: The selection of high-quality materials–i.e., aggregate and asphalt binder–is very important in the success of a chip seal project. In North America, transportation of aggregate is expensive; hence, aggregate which is available near the project site is generally used. In countries like New Zealand, where chip seal is widely popular for its durability, the high quality aggregate could be economically transported as far away as 500 miles from the site. The aggregate that is selected for chip seal applications should be tested for size (gradation test), shape (flakiness index test), cleanness (gradation and cleanness value tests), loose unit weight, toughness, and soundness. Use of larger aggregates result in more pavement noise. Another important factor to be considered in the selection of aggregate is that it should not contain more than 2 percent fines; i.e., materials passing No. 200 sieve. The shape of aggregate affects the overall performance of chip seal. By and large, cubical shape aggregates are preferable because traffic does not have significant impact on the final orientation of aggregate. The selection of binder should be based on good adhesion to the surface of the aggregate. Pre-coated aggregate have better compatibility with asphalt binders. There are primarily two kinds of binders: asphalt cement binders and emulsified asphalt binders. The asphalt cement binders, when used for chip seal projects, set faster and hence the road could be opened to the traffic sooner but the application temperatures should be high. The emulsified asphalt binders contain asphalt cement, an emulsifier, and water. Cationic emulsion binders typically have better bonding property with the aggregate; that is, they are electro-statically compatible with the aggregate and they are also sensitive to weather. If the amount of fines passing the No. 200 sieve is greater than 5 percent, then high float emulsions (HFE) are best suited for such aggregate. They allow a thicker asphalt film on the aggregate and this prevents the runoff of the asphalt.

In light of the preceding brief background, a laboratory test matrix was developed to investigate the characteristics of aggregates, binders, and the compatibility of the two constituents. Accordingly, gradation, flakiness index, loose unit weight, cleanness value, and Vialit tests were carried out on aggregates obtained from various districts within Idaho. Specifically, Vialit tests were performed on aggregates, in conjunction with different types of binders, at different temperatures in washed and unwashed forms. By performing the Vialit tests, aggregate retention was determined and plotted against the median size, the flakiness index, the cleanness values, and the void ratio of the aggregate used in the Vialit tests. Several types of binders were also considered. The aggregate was tested, both washed and unwashed, to determine the effect of fines on the retention of aggregate on the Vialit test plates. The influence of temperature on aggregate retention was verified by changing the curing temperature of binders in Vialit tests. The amount of initial displaced aggregate was determined when the aggregate was lightly swept after the laboratory rolling was performed. This was to replicate the initial loss of aggregate during brooming the chip sealing operation in the field. The initial loss of aggregate, as well as the loss of aggregate after the ball impact, was calculated for all districts. Four different types of binders were considered for Vialit testing, in conjunction with the District 5 aggregate.

One of the key design parameters is the chip seal aggregate's least dimension, which is obtained via the combination of median particle size and flakiness index values. In turn, the median size and flakiness index values are determined by plotting the percent aggregate passing through different sieves versus particle diameters. The sieve size corresponding to the 50 percent passing is defined as the median size of the particle. The flakiness index, however, is obtained using a slotted steel plate. Similarly, other design parameters are determined via loose unit weight of the aggregate, void ratio, aggregate absorption, which will enable the estimation of the spread rates of aggregate and binders for a given traffic volume and whip-off, as well as, existing pavement condition.

Emerging Conclusions: The following conclusions emerge from the present study. The highest aggregate retentions were observed in relation to those exhibiting the lowest flakiness index values and moderate median particle sizes. Aggregates obtained from District 5 presented these characteristics. This gives support to the point that aggregates containing more flakes (larger flakiness index) will have lower adhesion to the binder as compared to the aggregates that are more cubic. As a result, District 2's aggregate samples, which had the highest flakiness index value, had the lowest aggregate retention. This demonstrates that the aggregates which are more cubic in shape yield greater retention. Furthermore, it is evident that the ratio of median size and flakiness index of the aggregate exhibit a better correlation with the percentage aggregate retained rather than the least dimension, as commonly used in the McLeod Design Method. It is also determined that the cleanness value of the aggregate is a critical parameter in relation to aggregate retention, as evidenced by comparing the rate of retention for washed and unwashed aggregate.

As for the influence of temperature, it was found that the aggregate retention was least when the aggregate was cured at 14^{o}F and the highest when the curing temperature was 104^{o}F. The aggregate retention decreased as the curing temperature was increased to 140^{o}F. The aggregate retention hence is higher when the temperature of curing is 104^{o}F, which is the same as average daytime summer pavement surface temperature. The low retention at 14^{o}F indicates that the chip seal aggregate performs the worst, loosening up from the binder, in the cold winter days.

From the outcome of the experiments carried out in this research study, it is suggested that the use of washed aggregates, yielding better retention, is more advantageous than unwashed aggregates. In case the economy of the project does not permit the use of washed aggregates, care should be taken to obtain aggregates which have the least amount of fines.

Out of the 4 binder types considered in this research project, CRS-2P, exhibited the highest aggregate adhesion. Also, the binder which had higher aggregate retention rate had higher initial loss and the binder with lower aggregate retention had lower initial loss. Accordingly, we suggest that the CRS-2P binder should be used, but allow the traffic on the sealed pavement only after a longer duration of time. Since conditions in the field vary, the time duration is left to the designer's engineering judgment. It would be advisable to use a correction factor for the binder application rate by taking the initial loss of aggregate into account.

Chapter 1
Introduction

Chip sealing is a preventive pavement maintenance technique that is widely used to seal pavement. For optimum performance, chip sealing should occur when the cracks in the pavement are in a developing stage. If the cracks have deteriorated to a greater extent, then chip sealing is not an advisable technique. Performance evaluation of chip sealing in Idaho is very important, as the six districts of Idaho have been using different materials to implement chip seals. It is also helpful to study and analyze the performance characteristics of chip seals used by other countries and states. This chapter discusses the background and history of chip sealing, along with cost analysis and a discussion of the way chip sealing is carried out in the field.

Background

Preventive maintenance or pavement preservation is performed to achieve greater durability, savings, and comfort for the motorist. Maintenance of a pavement is also important because the deterioration of the pavement starts immediately after the construction is complete.(1) It is also important to curb the various impacts due to ambient weather and the traffic. A flexible pavement is typically designed with a layer of binder and aggregate, a base, subbase, and subgrade. The pavement may initially have small cracks in it due to various reasons such as weather (rain, snow, or cold temperatures), the existing surface, the geographical location, and the traffic. Small cracks widen to form larger cracks and allow water to seep through. Water that seeps through may deteriorate the base, subbase, and subgrade layers leading to a complete structural failure.(2)

Various preventive maintenance techniques have been adopted worldwide, including crack seal, chip seal, fog seal, cape seal, microsurfacing, and thin hot mix overlay.(2) Of these, chip sealing (also known as seal coating) is considered the preferred approach for many of Idaho roads, due to lower associated cost and the durability attributes. Apart from providing a better blockage to seeping water, chip sealing a road provides greater skid resistance for the commuters and also gives more durability to the pavement at a lesser expense. However, seal coating does not increase the structural capacity of the pavement.

The time at which the preventive maintenance is applied is a very important factor in the longevity of the pavement. Depending upon the size of the cracks on the pavement surface at the time of applying preventive maintenance, the durability of the chosen technique varies. If the cracks are too wide, the preventive maintenance may not be appropriate. In such cases rehabilitation of the pavement is recommended. When the cracks that start from the surface of the pavement are in the early stages of development, then preventive maintenance (including chip sealing) is the preferred procedure. Chip sealing is an economical method compared to other methods. The performance of a pavement drops from the day it is open to traffic and it begins to show variations in its performance when it reaches

75 percent of its design life.[2] This is generally a good target for the application of preventive maintenance as the pavement's deterioration might increase rapidly from that point. By adopting the appropriate preventive maintenance technique at the right time, the more-costly rehabilitation of the pavement can be avoided temporarily. The principal objective of the current study was to investigate the performance of various aggregate and binder combinations and to evaluate the viability of adopted design methods in the State of Idaho. Among the issues studied is the lack of uniformity in materials used by the six ITD districts.

Objectives of Research

This study has the following research objectives:

- To evaluate the effectiveness of Idaho's existing chip seal practice.
- To identify ways of improving the retention of chips (aggregate) in the binder after it has been applied to the paved surface.
- To study the materials used and suggest the material or materials to improve chip seal practice.

In the longer term, the work performed will contribute to help future effort (by the present researchers or others) to:

- To evaluate the performance of different kinds of binders.
- To develop a better rational design method based on experiments performed in this project.

Overview

This section is a general review of the literature concerning past practices in the field of chip sealing. The data compiled from various tests, performed on gradation, flakiness index (FI), cleanness value (CV) test, loose unit weight test and the Vialit test will be reviewed. Furthermore, the aggregate and binder compatibility for all six ITD districts and the performance of four different binders used will be discussed. This report also stresses on the significance of the amount of fines and their impact on the compatibility of aggregate and the binder. Finally, the effects of temperature on the adhesion of binder and the aggregate will be presented.

Literature Review

History

Chip Sealing has been defined by McLeod as: "A single application of asphalt binder followed by a single application of cover aggregate, both placed on existing bituminous surface."[3] The primary advantage of chip sealing is its low cost compared to other preventive maintenance techniques. Chip sealing prevents the cracks from widening and stops the water from seeping through the pavement.

Chip sealing has been in use since 1920. Initially, no particular design method was used, and at that time it was executed only on low-volume gravel roads.(2) The first design method was formulated in 1934 by F. M. Hanson. It was later modified and adopted by different countries worldwide. In North America, the pavement was traditionally left to deteriorate to poor condition before a maintenance technique was adopted.(4) This was primarily attributed to the lack of research in the field of chip sealing. In recent years, extensive research in the field of chip sealing has been performed in the countries of Australia, New Zealand, South Africa, and United Kingdom. The average life of chip seal has been reported to be about 7 to 10 years. Over the past nine decades, chip sealing has evolved as one of the best preventive maintenance technique available. The success of chip sealing has been credited to its low cost and high durability, as compared to any other preventive maintenance techniques.(2)

Cost Analysis

Pavement performance has been plotted in Figure 1 versus time (the life of the pavement).(5) The need for surface maintenance is determined by using the Pavement Condition Index (PCI) as the main assessment parameter.(6) The pavement condition index is a numerical value assigned to the pavement condition ranging from 0 to 100; 0 being the worst and 100 being the best. It is apparent from this study that by spending $1.00 on maintenance when the pavement is in fair to excellent condition (i.e., above 75 percent of pavement life), it can save up to $6.00 to $10.00 that would be necessary to rehabilitate later when the pavement reaches a poor condition, measured via PCI. The costs of various preventive maintenance techniques are compared in Table 1.(7) Even though crack seal seems to be the most economical, it is just a method to seal the cracks which appear on the surface of the pavement. The sealing is limited to such cracks, and not to the entire pavement. Chip seals and slurry seals were found to cost roughly the same and an overlay of 2 in. was found to be double the price of chip seal or slurry seal.

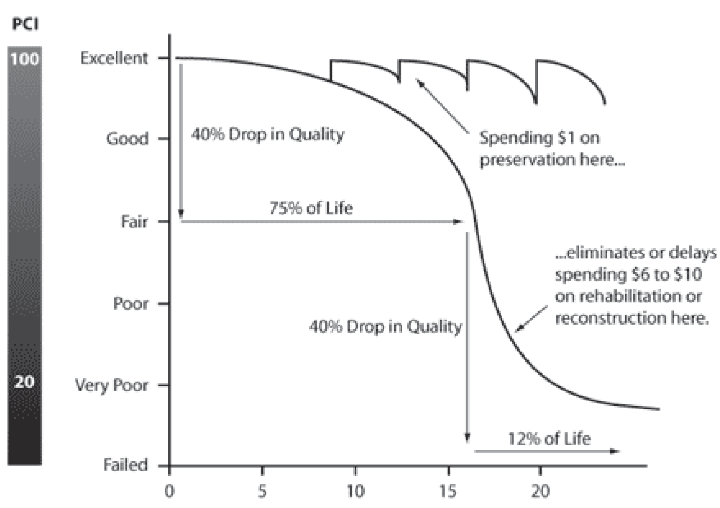


Figure 1. Pavement Condition Index (PCI) Versus Time (Years)(5)

Table 1. Cost Comparison of Various Preventive Maintenance Techniques[7]

Treatment	Cost Per Lane-Mile in U.S. Dollars ($)
2 in. Overlay	20,000 to 35,000
Slurry Seal	7,000 to 10,000
Chip Seal	7,000 to 10,000
Crack Seal	700 to 1,000

Chip Seal Design

The making of chip seals was a non-standardized “art” until Hanson, a New Zealander, started research in 1934 to determine the optimum design. Before Hanson, the amount of aggregate and the quantity of binder used was guess work, or trial-and-error, rather than the result of a rational design or formula.[2] Hanson formulated the first method to determine the proportion of aggregate to binder in 1934. Later (1953), Kearby developed a method which bears his name, and which was later modified by Epps et al. in 1973 (the “Modified Kearby Method”). In 1969 McLeod developed a method known as the McLeod Method. The Modified Kearby and McLeod methods are the two single methods most widely used in North America. Other states either use no formula at all, or use formulas based on their empirical experiences: i.e., they use individual designs their experience has shown to work. Other designs are also used elsewhere around the world: e.g., Road Note 39 (United Kingdom), TRH3 (South Africa), and AUSTROADS Sprayed Seal Design Method (Australia).[2]

Chip seal design generally includes consideration of various physical parameters: existing road surface, traffic volume and conditions, the number of heavy trucks, and ambient weather conditions. There are also economic considerations such as in the selection of aggregate, the distance to the source and type of aggregate and the kind of binder used. [1] Using these parameters, the amount of aggregate and binder needed are determined. Table 2 gives the estimates for the quantity of aggregate and binder for various aggregates in both modified Kearby and McLeod methods. The table includes the amounts of binders for various aggregates that might cause bleeding and raveling. It is also interesting to see that the ratio of aggregate to binder in both methods is almost the same.

Table 2. Comparison of Quantities of Aggregate and Binder Designed via Modified Kearby and McLeod Methods for Different Aggregate Types[2]

Design Method Nominal Aggregate Size	Rate of Material Used (gal/yd²)	Existing Surface Condition					
		Slight Bleeding		Normal		Slight Raveling	
		Modified Kearby	McLeod	Modified Kearby	McLeod	Modified Kearby	McLeod
⅜ in. Natural Aggregate	Emulsion Rate	0.25	0.18	0.29	0.22	0.33	0.27
	Aggregate Rate	21.2	17.1	21.2	17.1	21.2	17.1
⅝ in. Natural Aggregate	Emulsion Rate	0.29	0.30	0.33	0.34	0.37	0.39
	Aggregate Rate	24.6	25.6	24.6	25.6	24.6	25.6
⅜ in. Synthetic Aggregate	Emulsion Rate	0.54	0.27	0.58	0.32	0.62	0.36
	Aggregate Rate	17.1	14.0	17.1	14.00	17.1	14.0
⅝ in. Synthetic Aggregate	Emulsion Rate	0.51	0.3	0.55	0.35	0.59	0.39
	Aggregate Rate	14.3	18.3	14.3	18.3	14.3	18.3

Materials

The selection of good materials is very important in the success of a chip seal project. The selection generally includes the mixture of high quality aggregate and high quality binder, which provides good adhesion with the aggregate. In North America, transportation cost of aggregate is considered as an important factor, and hence aggregate which is available near the project site is generally used. In countries like New Zealand where chip seal is widely popular for its durability, better-quality aggregate is transported several hundred miles to the chip seal site.[4] The selection of the binder must be based on good adhesion to the surface of the aggregate.

Aggregate

The aggregate that is selected for chip seals must be tested for size (gradation test), shape (flakiness index test), cleanness (gradation and cleanness value test), loose unit weight, toughness, and soundness. If the aggregate is not embedded properly, it might lead to the loss of aggregate when the pavement is opened to the traffic. Also, use of larger aggregate results in more pavement noise.

Generally ⅜ in. is the nominal size of aggregate that is good for a single layer chip seal.[2] Another important factor to be considered in the selection of aggregate is that it should not contain more than 2 percent passing No. 200 sieve.[8] The shape of the aggregate affects the overall performance of chip seal. Janisch and Galliard found that the orientation of the embedded chips is also critical. They state: "As the orientation of the embedded chips is important, cubical aggregate shapes are preferred because traffic does not have a significant effect on the final orientation of aggregate."[9] The ratio of the quantity of flakes to the total aggregate quantity can be determined by flakiness index. The amount of fines in the aggregate could be determined either by running a cleanness value test or gradation. Precoated aggregate have better compatibility with binders.[2] Table 3 shows the percentage of chip seal projects that have utilized various aggregates in North America compared to Australia, New Zealand, South Africa, and the United Kingdom. In North America, most projects contain limestone, granite, and natural gravel.

Table 3. Percentage of Chip Seal Projects Utilizing Various Natural Aggregates[2]

Type	North America (%)	Australia, New Zealand, United Kingdom, South Africa (%)
Limestone	37	13
Quartzite	13	38
Granite	35	38
Trap Rock	13	25
Sandstone	10	25
Natural Gravels	58	25
Greywacke, Basalt	4	88

Note: Percentages do not add up to 100 because more than one type of aggregate is often used on projects.

Binders

There are two primary kinds of binders: asphalt cement binders and emulsified binders. Asphalt cement binders, when used for chip seals, set faster and hence the road could be opened to the traffic sooner but requires higher application temperatures.[2] The emulsified binders contain asphalt cement, an emulsifier, and water. Cationic emulsion binders typically have better bonding property with the aggregate; that is, they are electro-statically compatible with the aggregate and they are also less sensitive to weather. If the amount of fines passing the No. 200 sieve is greater than 5 percent, then high float emulsions (HFE) are more appropriate for such aggregate. They allow a thicker asphalt film on the aggregate and this prevents the runoff of the asphalt. The characteristics of various binders used by various states are presented in Table 4.[(2)] It is apparent here that the majority of State Department of Transportation's employ CRS-2 or CRS-2P types of binders.

Table 4. Asphalt Emulsion Binders Used in U.S., Canada and New Zealand[(2)]

Binder Type	U.S. Locations	Non-U.S. Locations
CRS-1	Nevada	None
CRS-1H	Kansas, Nevada	None
CRS-2	Connecticut, Iowa, Maryland Michigan, Montana, Nevada, New York, North Carolina, Oklahoma, Utah, Virginia, Washington, Wisconsin	Ontario
CRS-2H	Arizona, California, Texas	None
CRS-2P	Alaska, Arizona, Arkansas, Idaho, Iowa, Louisiana, Michigan, Minnesota, Mississippi, Montana, Nebraska, New York, North Carolina, North Dakota, Oklahoma, Texas, Washington, Wisconsin, Wyoming	New Zealand, Nova Scotia
HFRS	Alaska, Colorado, New York, Wisconsin	British Columbia, Manitoba, Ontario, Quebec, Saskatchewan, Yukon
HFRS-2P	Colorado, New York, North Dakota, Oregon, Texas, Wisconsin, Wyoming	Quebec, Saskatchewan

Construction Procedures

Although the amounts of aggregate and binder may be designed properly and the best materials selected, the field application of chip seal is the next crucial step. It is essential to note that suitable ambient temperatures should be considered during the construction. The general procedures for constructing a chip seal is first to sweep the dust off the existing pavement and then spray the binder, immediately spread the aggregate, apply pneumatic rollers and sweep the excess aggregate from the pavement. These steps are elaborated on further in the ensuing sections.

Sweeping

Sweeping (as shown Figure 2) is a very important step in the construction process and is carried out twice: before and after the construction of the chip seal. Before the construction of the chip seal, there might be dust, dirt, and debris on the pavement surface which should be cleaned, so that the binder seeps through the cracks properly and binds to the rock. Sweeping should be performed for the second time, after the binder and aggregate are spread and the binder is cooled. It should be noted that if the sweeping is carried out immediately after rolling, there would not be enough time for the aggregate to settle down.[2]

Figure 2. Rotary Brooming Process[2]

Spraying the Binder

Spraying the binder is another important construction process and if it is not carried out properly could lead to bleeding (i.e., excess binder is sprayed) or raveling (i.e., insufficient binder is sprayed). The velocity at which the binder is spread should be uniform throughout the nozzles (as shown in Figure 3). A computer-controlled sprayer is the most efficient method to maintain a constant application rate regardless of the speed of the truck.

Another potential problem is commonly known as "streaking," where longitudinal grooves or ridges appear on the seal coat surface. Streaking may be due to the incorrect spray height, misalignment of the nozzles, or clogged nozzles. Although undesirable, streaking can be eliminated if the distributor is calibrated properly.[9]

Figure 3. Asphalt Binder Sprayers[2]

Aggregate Spreaders

Aggregate spreaders (e.g., Figure 4) come into action immediately after the spraying of the binder. Two or three loaded trucks should follow the spreading truck so that if the spreader is emptied, the other can follow.[2] A self-propelled spreader is recommended.

Figure 4. Asphalt Binder Sprayer Followed by Aggregate Spreader Truck[2]

Rolling

Pneumatic rollers, such as depicted in Figure 5, carry out another important step in the construction of chip seal, and must be used efficiently. The number of rollers used is determined by the nominal size of the aggregate. The larger the nominal sizes, the fewer rollers are required.[10] Three rollers are usually required to roll the newly constructed seal.

Figure 5. Pneumatic Rollers[(2)]

Although chip sealing has its advantages, it should not be used in situations where the pavement cracks are wide. In these cases the rehabilitation should be done first. Proper planning is essential in order to take care of the pavement and check when it needs a preventive maintenance.

Survey Results of the Six ITD Districts

A questionnaire was prepared and sent to the six ITD districts to evaluate how the chip sealing is carried out in each district. Each questionnaire returned by the various districts is included in the Appendix A. Forty questions were asked in the survey and the answers returned from the districts were varied. The source of aggregate for District 2 was entered as quarry and the aggregate source for District 5 was entered as river bed. The questionnaires received had no uniform answers regarding the design methods employed. Some used McLeod method, some used Modified Kearby, and some used empirical methods. The binders used by the six districts were all asphalt cationic emulsions. The aggregate type and the design method varied from district to district. ITD does not perform in-house chip sealing. Districts used outside contractors for performing the construction with inspections by ITD field engineers. The need for application of chip seals every seven years was agreed upon by all. The survey responses from the six districts have been summarized in the Appendix A.

Field Observations

The field observation phase of the study consisted of identifying a chip sealing construction that was going to be scheduled during the summer and close to Idaho State University (the researchers' home institution). Through coordination with ITD District 5, an appropriate project was identified on State Highway 34, near Soda Springs. Accordingly, the job site was visited prior to the chip sealing application, during the operation, and several weeks after the completion. Figures 6 (a) and (b) illustrate the longitudinal and transverse cracks, respectively, prior to the scheduled chip sealing application. It is apparent from these two photos that the major (noticeable) transverse crack is much wider than the longitudinal one. There are various types of distresses initiating the cracks in pavements. One of the most common modes of HMA (hot-mix asphalt) pavement distress is referred to as top-down cracking.

Historically, it was surmised that these cracks are initiated at the bottom of the HMA layer, where the flexural stresses are greatest, and then propagate up to the surface. More recently, the mechanism of cracking is believed to be a combination of the high surface horizontal tensile stresses due to truck tires, age-hardening of the asphalt binder, and a low-stiffness upper layer due to high surface temperatures. Regardless of the cause of the cracks in the aforementioned highway, they were structural related (not micro-cracks) and they were not properly sealed prior to the chip sealing operation. In Figure 7, overlap of chip sealing applications is shown.

The same pavement, described above, was revisited twice in November 2008 and July 2009, respectively. Figures 8 and 9 demonstrate that the longitudinal crack, sealed by chip sealing process, remained sealed and there was no sign of the initial crack reflecting (or reappearing) through the binder/chips. The transverse crack, however, had reflected through the chip seal cover and had similar appearance as before chip sealing operation. This observation validates the recommended practice that chip sealing is an effective maintenance method as long as the cracks are not too extensive.

(a) **(b)**

Figure 6. (a) Longitudinal and (b) Transverse Cracks Observed Before Chip Seal Application

Figure 7. A Segment Where Chip Seal was Applied Twice

(a) (b)

Figure 8. (a) Longitudinal and (b) Transverse Cracks After 4 Months (Nov. 2008)

(a) (b)

Figure 9. (a) Longitudinal and (b) Transverse Cracks After 1 Year (July 2009)

Chapter 2
Laboratory Tests

Several tests used to evaluate chip seal aggregate, binders, and the compatibility of the two constituents are presented in this chapter. The gradation, flakiness index, loose unit weight, cleanness value, and Vialit tests were carried out on aggregates obtained from various districts within Idaho. Specifically, the Vialit test was performed on aggregate in conjunction with different types of binders, at different temperatures and for washed and unwashed forms. The test methods are as described in the following sections and Appendix B provides more details of the tests procedures.

Sieve Analysis

This experiment determines the particle size distribution for fine and coarse aggregate by sieving. It is based on AASHTO T-27 (ASTM C136) procedure, also known as the "Sieve Analysis of Fine and Coarse Aggregates."(11) Figure 10 shows a sieve shaker in which a sample of dry aggregate of known mass is separated through a series of sieves in descending order of their mesh sizes, which determines the particle size distribution. The main purpose of the experiment is to determine the median size of the aggregates in relation to various districts in Idaho. The sieves used were 8 in. in diameter with slot sizes: ⅜ in., ¼ in., No. 4, No. 8, No. 16, No. 50, and No. 200. The aggregate was taken in samples of 300 g (0.661 lb) at a time and the sieve shaking lasted about 5 minutes. The amount of aggregate retained on each of the sieves was weighed on an electronic scale (OHAS Scout Pro Digital Scale™) and the percent passing was calculated and plotted against the sieve size.

Figure 10. Sieve Shaker with Sieves

The median size of the aggregate was identified on grain-size distribution curves. The median size of the aggregate is defined as that size of the sieve at which the 50 percent of aggregate passes. The median size is used in designing the amount of aggregate and the binder for the Vialit test. Even though the graded aggregate was used in the laboratory tests conducted, the Minnesota Department of Transportation (MnDOT) manual for chip seals recommends using a one-size aggregate rather than graded aggregate.(12) According to MnDOT Chip Seal Manual, when graded aggregate is used some of the finer particles may block the binder to seep into the gaps in between the coarser aggregate.[12] Figure 11 illustrates the 1-size and graded aggregate.

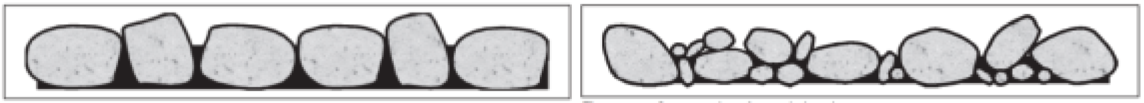


Figure 11. Cross-Sections of One-Size and Graded Aggregate for Chip Seals[12]

Flakiness Index Test

The procedure prescribed in the Central Federal Lands Highway Division (CFLHD) DFT-508 was used in determining the flakiness index of the aggregate.[12] Accordingly, the shape of the aggregate has been found to be a very important factor in the design for chip seals. The significance of this test is that it determines how flat or angular the particles are. As shown in Figure 12, when the traffic starts to move on the particles, the flatter aggregate tends to settle on their longer face. This causes bleeding of the binder; that is, the excess binder rises to the surface.

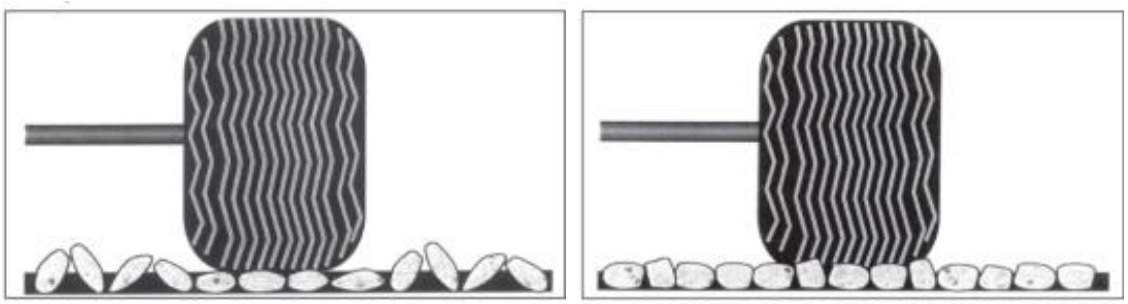


Figure 12. Cross Sections of Traffic Moving on Flat and Cubic Aggregate[12]

The flakiness index (FI) tests were performed using a metal plate approximately 0.0625 inches thick. The dimensions of the slots are as shown in Figure 13.

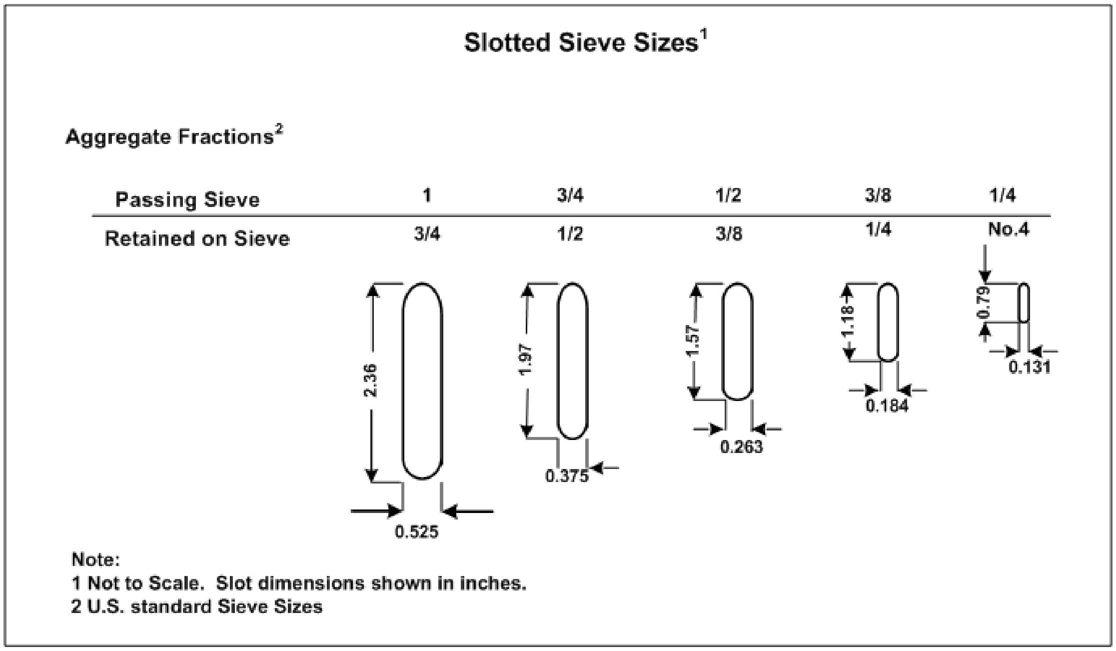


Figure 13. Flakiness Index Plate with the Dimensions of Each Slot

There are five slots for the five different size fractions of the aggregate. The slots are provided in such a way that the aggregate which passes through a sieve and is retained on the subsequent sieve in the sieve analysis, has a slot in the flakiness index test. For example, for the aggregate passing through ⅜ in. sieve and retained on ¼ in. sieve during the sieve analysis, will have a slot for such aggregate size range. Figure 15 shows flakiness index test being performed on ITD District 5 aggregate. From Figure 13, it is apparent that for the aggregate that passes through ⅜ in. sieve and retained on ¼ in. sieve the slot dimensions would be 1.18 in. in length and 0.184 inches in width. The ratio of the total aggregate passing to the total aggregate was found. That value represented in percentage gives the flakiness index value. The formula to calculate the flakiness index is demonstrated in Figure 14:

$$FI = \frac{Weight\ of\ Aggregate\ Passing}{Total\ Weight\ of\ the\ Aggregate\ Sample} \times 100$$

Figure 14. Equation for Calculating Flakiness Index

The flakiness index test is generally performed on a representative sample rather than the entire aggregate.

Figure 15. Conducting the Flakiness Index Test on ITD District 5 Aggregate

Loose Unit Weight

The loose unit weight of the aggregate was determined using ASTM C 29, also known as the "Standard Test Method for Bulk Density and Voids in Aggregate."[(13)] The loose unit weight of the aggregate is useful in calculating the void ratio. The factors that impact the loose unit weight are the gradation, shape and the specific gravity of the aggregate. As shown in Figure 16, a 0.1 ft^3 bucket was filled to the brim using a scoop and not more than 2 inches in height above the top of the bucket. The top of the filled-container was leveled off using a straight rod. The weight of the bucket and the aggregate were measured and the loose unit weight of the aggregate was determined.

Figure 16. Loose Unit Weight Bucket and the Scoop

The loose unit weight of the aggregate is given by the Figure 17:

$$W = \frac{M}{V}$$

Figure 17. Formula for Calculating Loose Unit Weight

where, *W* is the loose unit weight of the aggregate lb/ft^3; *M* is the mass of the aggregate that was loosely dropped in to the container, lb; and *V* is the known volume of the container, ft^3.

Cleanness Value Test

The cleanness value (CV) tests were performed according to the Idaho T-72 procedure, also known as "Evaluating Cleanness of Cover Coat Material."[14] The main purpose of the experiment was to find the amount of fines in the aggregate and also to identify the character of the fines. The aggregate was split to take a representative sample of about 1,000 ± 50 g (about 2.205 lb). A sand equivalent cylinder was taken and a 7 ml stock solution was poured in the cylinder. The sieves were placed on top of each other with a No. 8 sieve on top and a No. 200 sieve at the bottom. They were in turn attached to an 8 in. diameter funnel and then the funnel was rested on a 500 ml measuring graduate cylinder. The aggregate was then placed into a wide-mouth jar (see Figure 18) and water was added until the aggregate was just covered in water. Then the wide-mouth jar was agitated manually as specified in Idaho T-72 procedure known as the "Hand Method", i.e. the jar was rotated through a 1 ft (30 cm) diameter circle at a rate of approximately 3 rotations per second for a duration of 1 minute. The fines were allowed to settle and then they were transferred through the sieves and the funnel to the measuring cylinder. Water was further added until the measuring cylinder measured 500 ml. The cylinder was then rotated upside down repeatedly 10 times through an angle of 180^o. Figure 18 shows the cleanness value test apparatus used and Figure 19 shows the measuring cylinder being rotated to agitate the fines.

Figure 18. The Cleanness Value Test Apparatus Used

Figure 19. The Measuring Cylinder being Rotated 180°

The contents were then transferred to the sand equivalent cylinder up to the 15 in. mark. The contents were rotated 10 times upside down again. The cylinder was kept undisturbed on the laboratory table for 20 minutes and the height of the sediment was recorded. The formula to measure the cleanness value is given by the Figure 20:

$$CV = \frac{3.214 - (0.214 \times H)}{3.214 + (0.786 \times H)} \times 100$$

Figure 20. Formula for Calculating Cleanness Value

where, *CV* is the cleanness value in percentage and *H* is the height in inches of the fine particles sediment at the bottom of the sand equivalent cylinder.

Vialit Test

The intent of the Vialit test is to determine the loss of aggregate during laying of chip seals and to try to simulate the field application as much as possible. Additionally, this test was used to compare how the retained aggregate varies with and without fines at different temperatures. The test procedure was adopted from the Texas aggregate retention test with slight modifications.[15] Note that the Vialit test measurements are specified in metric units; however, the equivalent U.S. customary units are presented in parentheses. Apparatus used were a steel plate 20 cm x 20 cm (8 in. x 8 in.), a solid metal cylindrical roller, a Vialit stand, a stainless steel ball of $500 \pm 5\ g$ (about 1.103 lb), hot plates for heating the binder, and a thermometer. The surface of plates was roughened for better adhesion of the binder to the plates and to simulate the actual pavement's characteristics. Figure 21 shows the Vialit plate, the apparatus for heating the binder, and the test stand.

(a) **(b)**

(c)

Figure 21. Vialit Test Apparatus: (a) Plate, (b) Apparatus for Heating, and (c) Test Stand

Preparation of the Test Specimens

The representative samples of the amount, as much as designed per McLeod design method were considered for the test, out of which 3 samples were washed and dried in an oven and the other 3 samples were tested with the fines. The binder, whose specific gravity was previously measured in the laboratory, was heated to a temperature of 158^{o}F (70^{o}C). The plates were heated to a temperature to replicate the heat on the existing surface during summers when the pavement would be constructed. The binder was then poured manually on to the plate and then was spread on the plate using a small spatula. The aggregate was spread using a cardboard. The aggregate was rolled over by the roller 10 times. The plate was then lifted to an angle of 75^{o} and using a small broom was swept gently. The aggregate displaced was calculated and the specimen was allowed to cool for 24 hrs at room temperature and cured at various temperatures. The inverted sample was then placed on the Vialit test stand and the ball was dropped from the V holder on top of the apparatus, which was repeated 3 times within 10 seconds and the amount of aggregate displaced was calculated. Figures 22 (a) and (b) show the Vialit test plate with aggregate and binder before and after the steel ball impact.

(a) **(b)**

Figure 22. Vialit Test with Aggregate and Binder Sample, (a) Before and (b) After the Impact of the Ball

Limitations of the Vialit Test

Although the samples were prepared with an intention to replicate the actual pavement surface there might have been some discrepancies. The discrepancies included the spreading of aggregate, which was performed manually and cannot be compared to the computerized spreading in the field. Similarly, spraying the binder, the rolling and sweeping could not be simulated exactly as in field. Also the impact of the ball on the plate was not an exact model for repetitive single wheel load of the tires on the pavement that exists in the field. The surface of the plates was roughened with a sand paper initially and was heated to 158^{o}F (70^{o}C) before the asphalt was transferred on to the plate in order to simulate the conditions that are prevalent in the field.

The quantities of materials used in the Vialit test were designed using the McLeod method which is presented in the subsequent chapter. The amounts of materials were designed by taking various factors such as the existing pavement surface factor, weather conditions, flakiness index, and loose unit weight of the aggregates etc. Each of the design methods used a combination of the above factors to calculate the amounts of materials used, which are discussed in detail in Chapter 3.

Chapter 3
Design Methodologies

This chapter presents various design methodologies. Initially in United States, chip sealing was formulated based on users' rule of thumb; later, as a result of research in this field, design methods by Hanson, Kearby, and McLeod were used.[2] Some modifications have been made to these design methodologies over the years, which are now being used in different parts of the United States as well as New Zealand and the United Kingdom. The discussion presented in this chapter includes all the significant factors affecting each design method. District 5 aggregate showed the least flakiness index (FI) values and also had the least amount of fines. Therefore, District 5 aggregate is used in the numerical examples that are provided in this chapter.

McLeod Design Method

The McLeod design method for chip seals was developed by Norman McLeod in 1969.[3] The two main principles of the McLeod method are as follows:

> *"The application rate of the aggregate should be one stone thick. This amount would be constant irrespective of the amount of binder or the surface conditions."*
>
> *"At least 70 percent of the voids between the aggregate should be filled with asphalt."*

The McLeod method was adopted by the Asphalt Institute and the Asphalt Emulsion Manufacturers Association.[16] The various factors considered by McLeod were aggregate gradation, specific gravity of the aggregate, the void ratio of the aggregate, absorption, shape of the aggregate, traffic volume, existing pavement condition, and the residual asphalt content of the binder.

Details of the Design Factors

Median Particle Size

Median particle size is a theoretical sieve size through which 50 percent of the material passes. This is obtained from the plot showing the percent passing and the sieve size. Table 5 shows the data obtained after the gradation of 3,000 g (6.614 lb) of the aggregate of District 5 and the sieve sizes used for gradation. An aggregate splitter was used to split an exact amount needed. The plot in Figure 23 illustrates a representative relationship between the percentage of aggregate passing through a sieve and its sieve size in inches. The median size is plotted and the value is about 0.287 inches. The sieves used in the laboratory experiments were ½ in., ⅜ in., ¼ in., No. 4, No. 8, No. 16, No. 50, and No. 200. Similar graphs for other ITD districts are included in the Appendix C.

Table 5. Sieve Sizes and the Percentage Aggregate Passing, ITD District 5, Sample 1

Sieve Size	Percent Passing
½ in. (0.5 in.)	100
⅜ in. (0.375 in.)	99.88
0.25	29.14
0.187	1.43
0.0937	0.40
0.0469	0.37
0.0117	0.35
No. 200 (0.0029 in.)	0.20
0	0

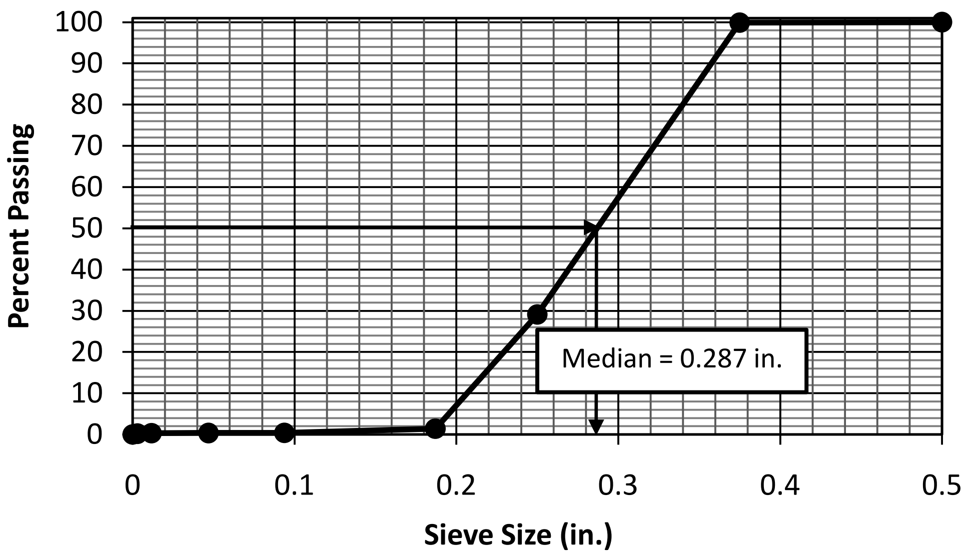


Figure 23. Representative Graph for Percent Passing (By Weight) Versus Sieve Size (in.) for ITD District 5 Aggregate, Sample 1

Flakiness Index

The percentage of flat aggregate particles by weight is defined as the flakiness index. The flakiness index test is an experiment performed on a representative sample of aggregate. The amount of the sample can vary from 300 to 500 g (0.661 to 1.102 lb). The FI is determined using a slotted steel plate as shown in Figure 13. As shown in Figure 13, the plate consists of slots of sizes: 0.575 in., 0.375 in., 0.263 in., 0.184 in., and 0.131 in. The aggregate passing through 1 in. slot and retained on ¾ in. slot pass through a slot with the width 0.575 in. The amount passing through and the amount being retained on each slot are documented. Similarly aggregate passing through ¾ in. and being retained on ½ in. sieve are tested

with the slot having a width of 0.375 in. and so on. In Chapter 2, this test was briefly explained and Figure 13 demonstrates the use of the flakiness index plate.
The flakiness index is expressed by Figure 24:

$$Flakiness\ Index\ = \frac{Total\ Weight\ of\ Aggregate\ Passing\ all\ the\ Slots \times 100}{Total\ Weight\ of\ Aggregate\ Retained + Total\ Weight\ of\ Aggregate\ Passing}$$

Figure 24. Formula for Calculating Flakiness Index Using Laboratory Results

The aggregate that was used in the gradation was then split into the following size portions:

- Aggregate passing through the ½ in. sieve and retained on ⅜ in. sieve (Size Portion A; for use with the third slot from left in Figure 13).
- Aggregate passing through the ⅜ in. sieve and retained on ¼ in. sieve (Size Portion B; for use with the fourth in Figure 13).
- Aggregate passing through the ¼ in. sieve and retained on No. 4 sieve (Size Portion C; for use with the fifth slot in Figure 13).

Note that the aggregates tested did not have portions for the first and second slots (from the left) of the flakiness index plate. The aggregate particles in each size portion were allowed to pass through the slotted sieves of the plate. The results obtained for ITD District 5, Sample 1, are tabulated in Table 6. The results of tests for other districts are included in Chapter 4.

Table 6. Result of Flakiness Index of ITD District 5, Sample 1

Size Portion: Sieve Size	Aggregate Retained on Slot (g)	Aggregate Passed through Slot (g)
A: ½ to ⅜ in.	5.24	0
B: ⅜ to ¼ in.	316.65	19.8
C: ¼ in. to No. 4	134.71	1.98
Total	456.6	21.78

In the first row of Table 6, the value of 5.24 g represents the weight of the particles in the Size Portion A that were retained on the third slot (from the left) of the flakiness index plate. In the same row, the value zero indicates that none of the particles in Portion A passed through the third slot.

Therefore in this case the flakiness index is:

$$Flakiness\ Index\ = \frac{21.78\ \times 100}{456.6 + 21.78} = 4.55\%$$

Figure 25. Calculation of Flakiness Index for District 5, Sample 1

Average Least Dimension

The average least dimension, or ALD (*H*), is a dimensional quantity that is a function of the median size of the aggregate and the flakiness index. It represents a reduced value of the aggregate median size due to the consideration of flakiness index. In accordance with the Texas Department of Transportation (TxDOT), the average least dimension represents the expected seal coat thickness in the wheel paths where traffic forces the aggregate particles to lie on their flattest side. The ALD's of other districts are included in Chapter 4. The ALD is calculated as follows:

$$H = \frac{M}{1.139285 + (0.011506)FI}$$

Figure 26. Formula for Calculating Average Least Dimension

Where:

H = Average Least Dimension, in.
M = Median Particle Size, in.
FI = Flakiness Index, percent.

For the above flakiness index and median size values, the average least dimension of the aggregate is:

$$H = \frac{0.287}{1.139285 + (0.011506)4.55} = 0.2408\ in.$$

Figure 27. Calculation of Average Least Dimension for District 5, Sample 1

Loose Unit Weight of the Cover Aggregate

The dry loose unit weight (*W*) is determined according to ASTM C-29 and it is an important factor in the calculation of the void ratio in loose condition. A metal container with a volume of 0.1 ft^3 was filled with aggregate loosely dropped from a height less than 2 feet. The loose unit weight is used to calculate the air voids expected between the stones after the initial rolling in a chip seal project. The value of the loose unit weight depends on the gradation, shape, and specific gravity of the aggregate. A sample calculation for determining the loose unit weight of the aggregate considered above is included here. The loose unit weight values of other districts are included in Chapter 4.

Weight of the container + aggregate = 6,908 g (a metric scale was used in the laboratory)
Weight of the container = 2,590 g
Weight of Aggregate = 6,908-2,590 g = 4318 g = 9.519 lb
Loose Unit Weight of Aggregate = $\frac{9.519}{0.1}$ = 95.19 lb/ft^3; here 0.1 is the volume of the cylinder in ft^3.

The experiment was repeated 6 times and the average of all the 6 values was obtained. The values obtained are tabulated in Table 7.

Table 7. Loose Unit Weight of ITD District 5 Aggregate Samples

Test Number	Loose Unit Weight of Aggregate (lb/ft^3)
1	95.19
2	95.54
3	97.73
4	96.60
5	95.52
6	95.30
Average	**95.98**

Voids in the Loose Aggregate

When the chips are spread using an aggregate spreader, there are always voids between the chips. These voids determine the amount of binder required. The void ratio is used to measure the amount of voids in the loose aggregate. Typically, after the rolling is performed, the void ratio is reduced to 30 percent and when the traffic is allowed on the sealed pavement the void ratio is further reduced to 20 percent. The void ratio is given in Figure 28:

$$V = 1 - \frac{W}{(62.4 \times G)}$$

Figure 28. Equation for Calculating the Void Ratio

where:

W = loose unit weight
G = specific gravity of the aggregate
V = void ratio

The results of the void ratio of the other districts are included in Chapter 4. In Figure 28, 62.4 lb/ft^3 is the density of water at 32^{o} F. This reference value is used when converting specific gravity of another material (e.g., aggregate) to units of weight per unit volume or in this case lb/ft^3.(12)

Aggregate Absorption

While designing the amount of aggregate and the binder, it is important to note that some amount of binder that is applied might be absorbed not only by the existing surface but also by the aggregate itself. For an aggregate which absorbs 2 percent of the binder applied, a correction factor *A* of 0.02 gal/yd^2 has been suggested.(12) The Minnesota Department of Transportation (MNDOT), one of the success stories in the field of chip sealing in the United States, suggests an absorption correction factor of 0.02 gal/yd^2 for the aggregate absorption of 1.5 percent. The aggregate absorption factor is used in the McLeod's seal coat design formula, presented in detail in Appendix D, to calculate the amount of aggregate and the amount of binder.

Traffic Volume

The traffic volume (number of vehicles per day) and also the long term traffic volume on the pavement have an impact in deciding the amount of binder to be used. When the traffic is allowed initially on a newly chip sealed road, it results in settling the aggregate on their side with smallest area. Due to this, the pavement appears to have less binder and more aggregate. If the traffic correction factor is not taken into consideration too much binder will be added and the pavement may bleed. Therefore, a correction factor for the traffic volume is important. The traffic volume correction factor *T* is used in calculating the designed amounts of aggregate and binder in McLeod design method. Table 8 provides the traffic correction factors for various traffic volumes.

Table 8. Traffic Correction Factor

Traffic – Vehicles per Day	Traffic Volume Correction Factor
Under 100	0.85
100 to 500	0.75
500 to 1,000	0.70
1,000 to 2,000	0.65
More than 2,000	0.60

Note that the above values, that are related to traffic decreasing the mat thickness, do not make allowance for absorption by the road surface or by absorptive aggregate in the asphalt.(16)

Traffic Whip-Off

The number of vehicles passing on the pavement initially displaces some of the aggregate to the sides onto the shoulders. A factor known as Traffic Whip-Off Factor (*E*) or the Aggregate Wastage Factor was considered to balance such wastage of aggregate and to make the sealing more economical. Generally, a Traffic Whip-Off Factor of 5 percent is used for low volume roads and a factor of 10 percent is used for high volume roads. The Traffic Whip-Off Factor *E* is used to calculate the design amounts of aggregate and binder in the McLeod method. Table 9 indicates the Traffic Whip-Off Factor.

Table 9. Aggregate Wastage Factor

Percentage Waste Allowed for Traffic Whip-Off and Handling	Traffic Wastage Factor, E
1	1.01
2	1.02
3	1.03
4	1.04
5	1.05
6	1.06
7	1.07
8	1.08
9	1.09
10	1.10
11	1.11
12	1.12
13	1.13
14	1.14
15	1.15

Existing Pavement Condition

The aggregate embedment and pavement binder absorption depends on the existing pavement condition: whether it is porous, oxidized, etc. The Existing Pavement Condition Factor, *S,* is used in calculating the amounts of aggregate and binder in the McLeod method. The surface factors for various conditions are given in Table 10.

Table 10. Surface Correction Factor

Existing Pavement Texture	Correction, S
Black, flushed asphalt surface	– 0.01 to – 0.06
Smooth, nonporous surface	0.00
Slightly porous, oxidized surface	+ 0.03
Slightly pocked, porous, oxidized surface	+ 0.06
Badly pocked, porous, oxidized surface	+ 0.09

McLeod Design Example for Idaho District 5, Sample 1

The following is an example of the McLeod design procedure for laboratory Vialit test plates using aggregate corresponding to District 5 taken from Sample 1. The equations used refer to previously described formulas and equation numbers are excluded for brevity.

Median Size = M = 0.287 in.
Flakiness Index = FI = 4.55%
Cleanness Value = CV = 94%
Loose Unit Weight = W = 95.19 lb/ft^3
Bulk Specific Gravity = G = 2.67 (Assumed)
Area of Plate = 0.0478 yd^2
Average Least Dimension is given by
$H = \frac{M}{1.139285+(0.011506)FI}$ = 0.2408 in.
Void Ratio = $V = 1 - \left(\frac{W}{62.4 \times G}\right)$ = 0.412
Aggregate Application Ratio = A = 46.8 (1-0.4V) ×H×G×E = 25.46 lb/yd^2
The values of E = 1.05 was considered for the above design example.
$B_1 = \frac{(2.244 \times H \times T \times V)+S+A}{R}$ = 0.1945 gal/yd^2 T = 0.6 as ADT> 2,000
$B_2 = \frac{(2.244 \times M \times T \times V)+S+A}{R}$ = 0.232 gal/yd^2 M is the same median
The values S = 0 and A = 0 have been taken considering the existing pavement to be smooth and the aggregate absorption to be less than 2 percent, respectively.
$B = \frac{B_{1+}B_2}{2} = 0.213\ gal/yd^2$
B_1 is the amount of binder calculated using the average least dimension into account and B_2 is the amount of binder calculated by taking the median size of the particle into account.
Amount of aggregate for the Vialit test= A = 25.4 × 0.0478 = 0.90 lb = 552.92 g
Amount of binder for the Vialit test = B = 0.213 × 0.0478 = 0.01 gal = 38.53 cc = 40.46 g

Note that the last two values for the amount of aggregate and the amount of binder for use with Vialit tests were converted to grams (g) for laboratory use. The design procedures for all the other ITD districts are included in Appendix D.

Modified Kearby Design Method

Initially, the Kearby method of chip seal design was developed by J. P. Kearby in 1953.[17] The design method was later modified by Epps et al. in 1981; thus, the name Modified Kearby Design Method.[18] It was first proposed to TxDOT by the Texas Transportation Institute in 1981. The Modified Kearby is still the method most commonly used by Texas Department of Transportation today. A design method such as the Modified Kearby Method or the McLeod Method is used to determine the initial binder and aggregate application rates, but these design methods alone are not sufficient as field conditions will require adjusting both binder and aggregate rates.

Similar to the McLeod Method, the Modified Kearby Design Method requires knowledge of some physical characteristics of the aggregate. These are the unit weight, bulk specific gravity, and the quantity of aggregate needed to cover 1 yd^2 of roadway. After the aggregate is identified, laboratory tests such as the dry loose unit weight test, specific gravity test, and the board test should be carried out.

Details of Design Factors

Aggregate Spread Rate

The aggregate spread rate is determined using the average particle size and the percentage by weight of the aggregate. The average particle size is the average of the sizes of two consecutive sieve sizes that the aggregate has passed through and retained on. For example, if the aggregate passed through ½ in. sieve and retained on ⅜ in. sieve then the average particle size is approximately equal to 0.4375 in. = (0.5+0.375)/2. The percentage of each particle size is defined as the difference between percentage passing through a sieve and the percentage passing in the subsequent sieve. Tables 11 and 12 illustrate the calculation of percentage of each size (for ITD District 5, Sample 1).

Table 11. Determination of Percentage Aggregate for ITD District 5, Sample 1

Sieve Size	Percent Passing	Percent Aggregate
½ in. (0.5 in.)	100	100-99.88= 0.12%
0.375	99.88	99.98-29.14=70.84%
0.25	29.14	29.14-1.43=27.71%
0.187	1.43	1.43-0.40= 1.03%
0.0937	0.40	0.40-0.37= 0.03%
0.0469	0.37	0.37-0.35=0.02%
0.0117	0.35	0.35-0.20=0.15%
No. 200 (0.0029 in.)	0.20	0.20-0=0.2%
0	0	0

Table 12. Determination of Average Particle Size

Average Size (in.)	Percent Each Size	Average Particle Size (in.)
0.4375	0.0012	0.000525
0.3125	0.7074	0.2210625
0.2185	0.2721	0.05945385
0.14	0.0103	0.001442
0.0585	0.0003	0.00001755
0.0293	0.0002	0.00000586
0.0073	0.0015	0.00001095
0.00145	0.002	0.0000029
Average Particle Size (in.)		0.282

The average particle size of the aggregate was then multiplied by the percentage of each size of the aggregate and then the sum of their products was calculated. The value obtained is considered as the average particle size of the entire aggregate. The value of S is obtained by determining the average number of aggregate pieces that can fit in a yard. However, because the average particle size is in inches, a conversion between yard and inches must be made. The value of 36 in Figure 29 represents (3 ft/yd) (12 in./ft) = 36 in./yd. If the average particle size is 0.282 in., then *S* would be given by:

$$S = \frac{36}{Average\ Particle\ Size} = \frac{36}{0.282} = 127.66\ yd^2/yd^3$$

Figure 29. Sample Calculation for Spread Ratio

Therefore, the aggregate spread rate is 1 yd^3 of aggregate over 127.66 yd^2 of area. Substituting the value of *S* in the Figure 30 the quantity of aggregate in lb/yd^2 can be determined.

$$Q = \frac{27 \times W}{S}$$

Figure 30. Formula for Calculating the Weight of Aggregate

where:

S = quantity of aggregate required in square yards per cubic yard (yd^2/yd^3);
W = dry loose unit weight in pounds per cubic foot (lb/ft^3); and
Q = aggregate quantity (lb/yd^2).

The factor 27 is a conversion factor for converting yd^3 to ft^3. The units for *Q* are balanced as follows:

$$Units\ of\ Q: \left[\frac{ft^3/yd^3 \times lb/ft^3}{yd^2/yd^3}\right] = \left[\frac{lb}{yd^2}\right]$$

Asphalt Application Rate

Once the aggregate properties and existing roadway conditions are known, the Asphalt Application Rate for asphalt cement for the Modified Kearby Method can be obtained from the Figure 31 below:

$$A = 5.61 \times \frac{E}{d} \times \left(1 - \frac{W}{62.4 \times G}\right) \times T + V$$

Figure 31. Asphalt Application Rate as Calculated by the Modified Kearby Method

Where:

A = asphalt rate in gal/yd^2 at 60°F
E = embedment depth, in.
G = dry bulk specific gravity of the aggregate
T = traffic correction factor
V = correction for surface condition
62.4 = unit weight of water at 32°F; a reference value used to convert aggregate specific gravity, *G*, to unit weight with units of lb/ft^3.(12)

The embedment depth is given by the formula within Figure 32:

$$E = e \times d$$

Figure 32. Formula to Calculate Embedment Depth

Where:

d = average mat depth, in.
e = percent embedment expressed as a decimal from Figure 34.

The average mat depth, in inches, is given by Figure 33:

$$d = 1.33 \frac{Q}{W}$$

Figure 33. Formula to Calculate Average Mat Depth

Where:

Q = aggregate quantity determined from the board test in lb/yd^2
W = dry loose unit weight in lb/ft^3
D = average mat depth in inches.

Knowing the value of the average chip seal mat depth and considering the given curve in Figure 34, the percentage of average embedment can be obtained. Tables 13 and 14 indicate the traffic and surface factors, respectively.

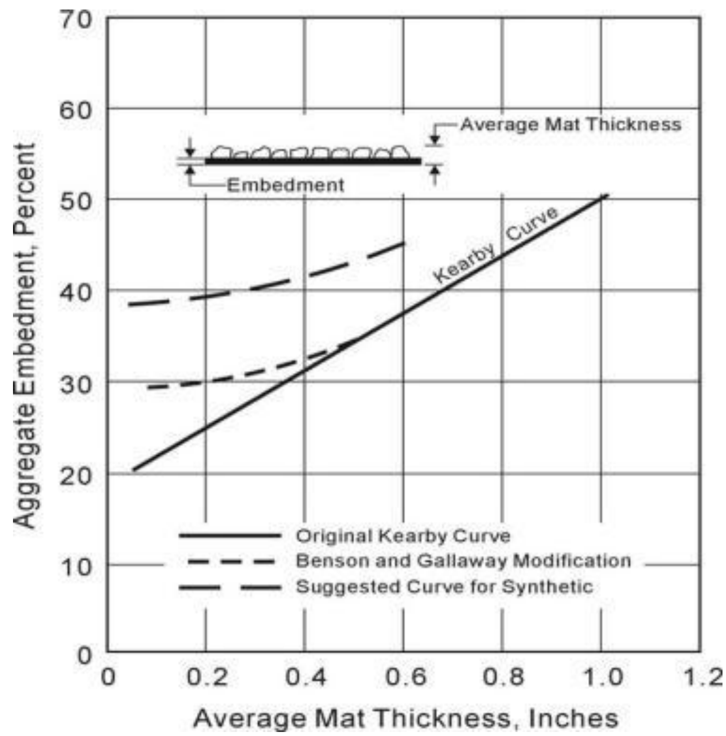


Figure 34. Relation of Percent Embedment to Mat Thickness for Determining Quantity of Asphalt[18]

Table 13. Traffic Correction Factor for Modified Kearby Method

Traffic-Vehicles per Day per Lane	Traffic Correction Factor (*T*)
>1,000	1.00
500-1,000	1.05
250-500	1.10
100-250	1.15
<100	1.20

Table 14. Surface Correction Factor for Modified Kearby Method

Description of Existing Surface	Correction for Surface Condition (*V*), gal/yd^2
Flushing, Slightly Bleeding Surface	-0.06
Smooth, Nonporous Surface	-0.03
Slightly Porous, Slightly Oxidized Surface	0.00
Slightly Pocked, Porous, Oxidized Surface	+0.03
Badly Pocked, Porous, Oxidized Surface	+0.06

The surface factor depends on the pavement's local surface conditions and should be adjusted according to the variations on the surface at the particular site of application.

Adjustment for Asphalt Emulsions or Cutbacks

When emulsions are used, the water content in the emulsion should be taken into account. The following equation gives the recommended emulsion application rate.

$$A_{recommended} = A + K\,(A_{theoretical} - A)$$

Figure 35. Formula to Calculate the Recommended Application Rate for Emulsions

Where:

$A_{recommended}$ = recommended quantity of emulsion
A = asphalt application rate from Figure 31
K = seasonal adjustment factor as shown below
$A_{theoretical}$ = theoretical quantity of emulsified asphalt, (A/R).
R = percent residual asphalt in the emulsion expressed as a decimal. Check with supplier to determine percent residual asphalt content of emulsion.

Tables 15 and 16 indicate the seasonal correction factor for cut back and emulsion in Modified Kearby Method respectively.

Table 15. Seasonal Correction Factors for Modified Kearby Method

Season of Construction	Correction Factor
Spring	0.60
Summer	0.40
Fall	0.70
Winter	0.90

Table 16. Seasonal Correction Factors for Modified Kearby Method (Emulsions)

Season of Construction	Correction Factor
Spring	0.70
Summer	0.60
Fall	0.80
Winter	0.90

The *K* factors were not verified by extensive controlled field experiments and were suggested to be used as a guideline.

District 5 Modified Kearby Design Method Example

The following is an example of the Modified Kearby design procedure using aggregate corresponding to District 5 taken from Sample 1. The equations used refer to previously described formulas and equation numbers are excluded for brevity.

Area of the Plate = 0.0478 yd^2
Loose Unit Weight of aggregate = W = 95.19 lb/ft^3
Void Ratio = 0.413
Traffic factor = T = 1 (The *ADT* assumed to be > 2,000)
Surface Factor = -0.03 (Assumed to be a smooth nonporous).
Average Particle Size = 0.282, 0.285, 0.284, 0.280, 0.278, 0.283; Avg = 0.282 in.
Aggregate Spread Rate = $S = \frac{36}{Average\ Particle\ Size} = \frac{36}{0.282} = 127.66$ yd^2/yd^3
Quantity of aggregate (Q in lb/yd^2):
$S = 27 \times \frac{W}{Q}$; $Q = 27\frac{W}{S} = 20.457\ lb/yd^2$
Average mat depth, d, in.:
$d = 1.33 \times \frac{Q}{W} = 0.2813\ in.$
Embedment Depth E, in.:
$E = d \times e$
Where, e is percentage embedment which is determined using a Figure 34. Here it was 0.3.
E = 0.0844 in.
The asphalt spread ratio C in gal/yd^2:
$C = 5.61 \times E \times Void\ Ratio \times T\ (Traffic\ factor) +\ Surface\ Factor$
$C = 5.61 \times 0.0844 \times 0.412 \times 1 - 0.03 = 0.165\ gal/yd^2$

New Zealand Chip Seal Design Method

The New Zealand Chip Seal Design Method is based on the Hanson's method.[19, 20] The application rates are determined using the size of chips used, the ratios of average size, the least and the greatest dimensions to the residual asphalt void spaces (or the unfilled voids as seen in Figure 36). The major assumptions to be considered for sealing pavements are as follows:

1. When uniform sized aggregate are used the voids are usually 50 percent of the total volume.
2. When the rolling is performed it reduces the voids in the aggregate to 30 percent of the total volume.
3. When the traffic is allowed then the void spaces reduce to 20 percent of the total volume.
4. As the aggregate particles lie on their flat side after the rolling is performed and the traffic is allowed on the pavement, the average thickness of the surface treatment is equal to the average least dimension of the aggregate.
5. The residual asphalt should fill ⅔ of the average least dimension.

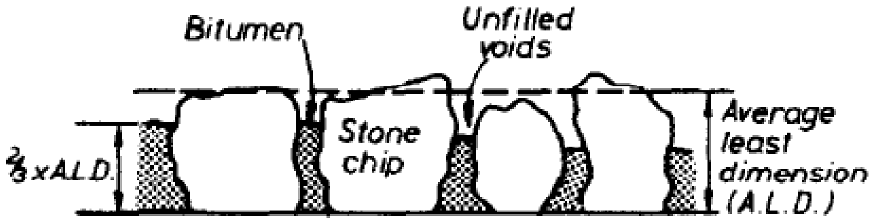


Figure 36. Typical Cross-Section of Chip Seals[20]

The equation for the residual asphalt rate was determined by the equation in Figure 37:[20]

$$R = (0.138\,ALD + e)T_f$$

Figure 37. Formula to Calculate Residual Bitumen Application Rate Using the New Zealand Chip Seal Design Method

Where:

R = Residual Bitumen (After diluents evaporates) Application rate at 15°C (l/m^2)

ALD = Average Least Dimension of the aggregate (one sized, cubic, crushed aggregate)

E = Average texture depth of the surface to be sealed (l/m^2)

T_f = Adjustment for compaction.

The representative samples could not be calculated as the average texture depth of the surface can be determined only in the field, and the tests conducted were all based on laboratory experiments.

Sand Circle Test

The average texture depth of the surface to be sealed can be calculated using the sand patch method. In this method, 45 ml of sand particles (ranging from 300 to 600 microns) are spread in a circular shape on the existing surface, as shown if Figure 38. The sand is spread until it is level with the surface. The diameter of the circle is measured and the area is calculated. The average texture depth is calculated from the ratio of the known sand volume (45 ml) and the calculated area.

Figure 38. Sand Circle Method Being Performed

United Kingdom's Design Method for Surface Dressing

The method of surface dressing design in United Kingdom known as Road Note 39 was initiated by Jackson in 1963. Like the New Zealand Chip Seal Design Method, it was also formulated on the principles presented by Hanson in 1934.[21] As Hanson suggested, the voids in the surface dressing aggregate are about 50 percent, they are later reduced to 30 percent when the rolling is performed and further reduced to 20 percent when traffic is allowed. Considering the voids to be around 50 to 70 percent and applying binder in these voids yields better results.

The basic principles of Road Note 39 are as follows:

1. The aggregate size is selected based on the expected long-term embedment, which is considered as a factor relating to the intensity of the traffic and the hardness of the existing surfacing.
2. The amount of binder is selected such that it can hold the chips and also minimize the possibility of it bleeding.

The various factors that are considered to be important are the traffic categories (commercial versus ordinary vehicles), the road hardness, the surface condition (that is, if it is binder-rich, normal or porous), the location and the geometry of the site, skid resistance, and the weather conditions.

Details of Design Factors

The Road Note 39 Method uses the average least dimension of the aggregate to determine the application rates of binder and aggregate. The average least dimension in the Road Note is determined in two ways. The first method is to take a sample of 200 chips and measure the least dimension of the aggregate manually and then take the average of all the values. The second method is to consider the median size of the particle and the flakiness index of the particle and then apply these values in the nomograph exhibited in Figure 39 to obtain the average least dimension by joining the median size and flakiness index (percent).

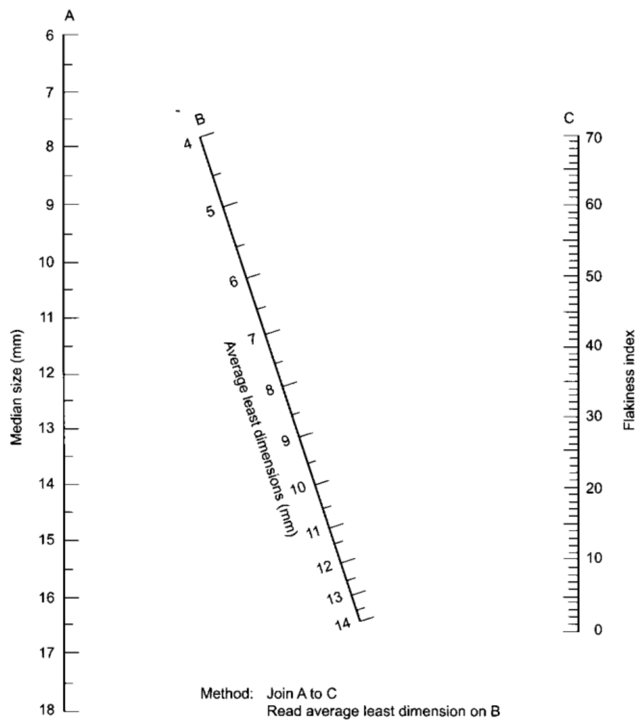


Figure 39. Determination of Average Least Dimension of the Aggregate

The overall weighing factor, a factor used in surface dressing design, is the sum of various factors such as the traffic, condition of the surface, climate, and materials factors. The factors for various cases have been listed in Table 17. As an example, a hypothetical overall weighing factor was calculated assuming the use of District 5 aggregate in Idaho. For District 5, the aggregate was cubical; therefore the aggregate factor is 0. Considering the climatic conditions in Idaho to be temperate, the climatic factor is also 0. If the existing surface is considered as an average bituminous pavement, then the existing surface factor is -1. Assuming an average traffic count is more than 2,000 vehicles/lane/day (obtained from District 5 engineering office), the traffic factor is -3. Therefore the overall weighing factor 'F' for District 5 of Idaho would be 0+0+ (-1) + (-3) = -4.

Table 17. The Factors to be Considered in Calculating the Binder Spread Rate

Traffic Factor		
Traffic Type	Vehicles/Lane/Day	Factor
Very Light	0-50	3
Light	50-250	1
Medium	250-500	0
Medium-Heavy	500-1500	-1
Heavy	1500-3000	-3
Very Heavy	3000+	-5
Existing Surface Factor		
Untreated or Prime Base		6
Very Lean Bituminous		4
Lean Bituminous		0
Average Bituminous		-1
Very Rich Bituminous		-3
Climatic Conditions		
Wet and Cold		2
Wet and Hot		1
Temperate		0
Semi Arid (Hot & Dry)		-1
Arid (Very Hot & Very Dry)		-2
Types of Chips		
Round/ Dusty		2
Cubical		0
Flaky		-2
Pre-Coated		-2

After the determination of the overall weighing factor and the average least dimension of the aggregate, the binder application rate could be determined using the Figure 40.

$$R = 0.625 + (F \times 0.023) + [0.0375 + (F \times 0.0011)] \times ALD$$

Figure 40. Formula to Calculate the Binder Application Rate Using the United Kingdom's Design Method for Surface Dressing

Where:

F = Overall weighting factor

ALD = The average least dimension of the chippings (mm)

R = Basic rate of spread of bitumen (kg/m^2)

In addition to the factors in Table 17, other correction factors for traffic speed and road gradient are taken into account and the binder spread are calculated again. These correction factors are indicated in the Table 18.

Table 18. Traffic, Speed, Road Gradient Correction Factors

Binder Type	Basic Spray Rate	Flat Terrain and Moderate Traffic Speed	High Speed Traffic Down-Hill Grades >3%	Low Speed Traffic up-Hill Grades >3%
MC 3000	*R*	*R*	$R \times 1.1$	$R \times 0.9$
300 Penetration	*R*	$R \times 0.95$	$R \times 1.05$	$R \times 0.86$
80/100 Penetration	*R*	$R \times 0.90$	$R \times 0.99$	$R \times 0.81$
Emulsion	*R*	$R \times \left(\frac{90}{\%\ Binder}\right)$	$R \times \left(\frac{99}{\%\ Binder}\right)$	$R \times \left(\frac{81}{\%\ Binder}\right)$

The aggregate spread rate is given by the Figure 41.

$$Aggregate\ Spread\ Rate\ \cong Loose\ Density\ \times ALD$$

Figure 41. Formula to Calculate the Aggregate Spread Rate

Where:

Loose Density is in g/m^3

ALD = Average least dimension (m)

The various factors that are considered to be important are the traffic categories (commercial versus ordinary vehicles), the road hardness, the surface condition (that is, if it is binder-rich, normal or porous), the location and the geometry of the site, skid resistance, and the weather conditions.

Among various design methods described in this report, only the McLeod approach was employed to perform sample design calculations to obtain the Vialit test results. The results and discussions of all the tests conducted are analyzed in the subsequent chapter.

Chapter 4
Analysis of Results and Discussions

This chapter presents analyses of the experimental data collected during this research project. The data represent the compilation of experimental results of tests performed on samples collected from all six ITD districts. Furthermore, the results correspond to the aggregate median sizes, the aggregates retained on the Vialit test plates after initial sweeping and the steel ball impact, the flakiness index, the loose unit weight, the aggregate void ratio, and the aggregate cleanness value. Correlations are examined among the data for median sizes, the flakiness index values, and void ratios versus the aggregates retained on the Vialit test plates.

Median Size of the Aggregate

The median particle size of the aggregate is used in determining the value of the chip seal aggregate average least dimension. This parameter in turn enters the design calculations for identifying the amount of chip seal binder and the amount of aggregate. As discussed in the previous chapters, the percentage of aggregate passing through different sieves is plotted against sieve sizes. The sieve size corresponding to the 50 percent passing is defined as the median size of the particle. An example of finding this value for District 5 aggregate gradation sample was provided in Figure 23 (Figure 23 was a sample; the figures of the median sizes of all the samples from the 6 districts are presented in Appendix C). As shown in Figure 23, the sieve size for 50 percent passing is 0.287 in. The aggregate median sizes of all the 6 districts are tabulated in Table 19. It should be noted that the values in this table are for samples that were collected from a single source in each district and may not accurately represent the district as a whole.

Table 19. Chip Seal Aggregate Median Size Values for the Six ITD Districts and the Corresponding Mean and Standard Deviation Values (Samples Obtained from a Single Source in Each District)

	Dist. 1	Dist. 2	Dist. 3	Dist. 4	Dist. 5	Dist. 6
	0.359	0.246	0.269	0.272	0.288	0.352
	0.358	0.242	0.260	0.271	0.288	0.352
	0.359	0.239	0.271	0.272	0.289	0.352
	0.359	0.239	0.271	0.271	0.284	0.359
	0.358	0.242	0.270	0.270	0.286	0.353
	0.358	0.241	0.270	0.270	0.287	0.353
Mean	**0.359**	**0.242**	**0.269**	**0.271**	**0.287**	**0.354**
St. Dev., σ_{n-1}	**0.0006**	**0.0029**	**0.0042**	**0.0009**	**0.0018**	**0.0027**

Table 19 shows that there is a relatively large range of values for the average median size for the aggregates in Idaho. The median size for Districts 1 and 6 were found to be very close to each other and so were Districts 3 and 4. District 2 had the least median size of 0.242 in. and District 5 had the median size average of about 0.287 in. The mean of the median sizes are plotted in a bar chart format for all the 6 ITD districts in Figure 42.

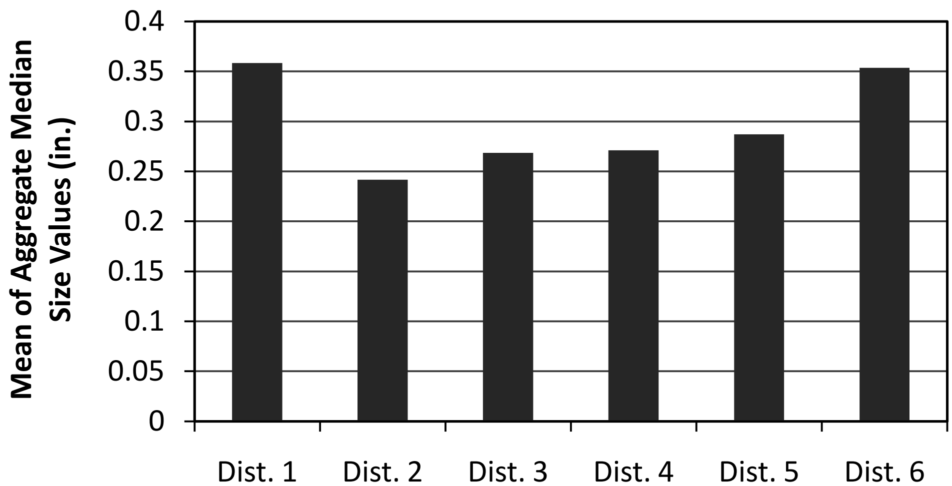


Figure 42. Bar Chart of Median Aggregate Size of All 6 ITD Districts

Flakiness Index of the Aggregate

As presented in Chapters 2 and 3, the flakiness index of the chip seal aggregate is obtained via an experiment specially designed to determine the percentage of flat particles in a given sample. The values of the flakiness index for different Idaho districts are tabulated in Table 20.

Table 20. Aggregate Flakiness Index Values of All the Six ITD Districts and the Corresponding Mean and Standard Deviation Values

	Dist. 1	Dist. 2	Dist. 3	Dist. 4	Dist. 5	Dist. 6
	16.20	21.58	9.11	9.08	4.55	12.42
	17.02	23.14	9.16	9.68	5.40	11.45
	16.32	19.03	9.85	10.73	5.77	11.48
	15.95	22.25	8.58	8.25	5.81	9.51
	18.60	19.38	8.53	9.07	5.72	11.32
	17.70	21.04	10.13	10.61	5.41	12.10
Mean	**16.97**	**21.08**	**9.23**	**9.57**	**5.44**	**11.38**
St. Dev., σ_{n-1}	**1.02**	**1.80**	**0.65**	**0.97**	**0.47**	**1.01**

As shown in Table 20, the flakiness index values of District 1 and 2 are higher when compared with other districts. District 5 has the lowest flakiness index; thus indicating that District 5's aggregate particles are cubical when compared to any other district and District 2's aggregate particles are flakier (flatter) than others. A bar chart representation is shown in Figure 43, summarizing all the mean values of the flakiness index for various districts in Idaho.

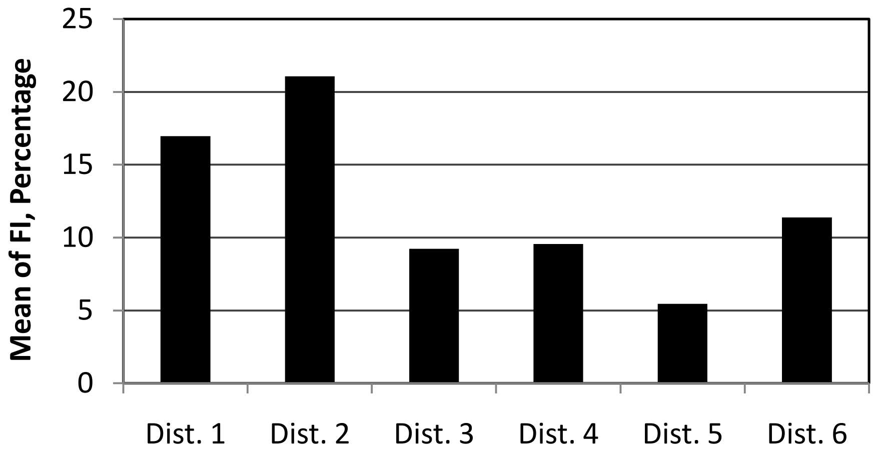


Figure 43. Mean Aggregate Flakiness Index Values of the Six ITD Districts

Average Least Dimension

The average least dimension of the aggregate is important in seal coating application as it is a factor which involves both shape and size of the aggregate. The formula for the average least dimension of the aggregate was given in the Figure 26. The average least dimensions evaluated for different districts are tabulated in Table 21.

Table 21. Aggregate Average Least Dimensions of ITD Districts

District	Average Least Dimension *H* (in.)
1	0.269
2	0.175
3	0.216
4	0.217
5	0.239
6	0.278

A regression analysis was performed on the average least dimension of the aggregate and the aggregate retained after testing the sample through the Vialit test. Another analysis was also performed by considering a factor involving (Median Size)*100/ Flakiness Index ((*M/FI*)*100) and the aggregate retained through the Vialit test. The parameter (*M/FI*) does not involve the constants that are present in the equation of average least dimension; i.e Figure 26. The latter analysis showed a better linear relationship between the parameter (*M/FI*)*100 and the aggregate retained than the analysis involving average least dimension. As shown in Figures 44 and 45, the R^2 values are approximately 0.16 and 0.91, respectively.

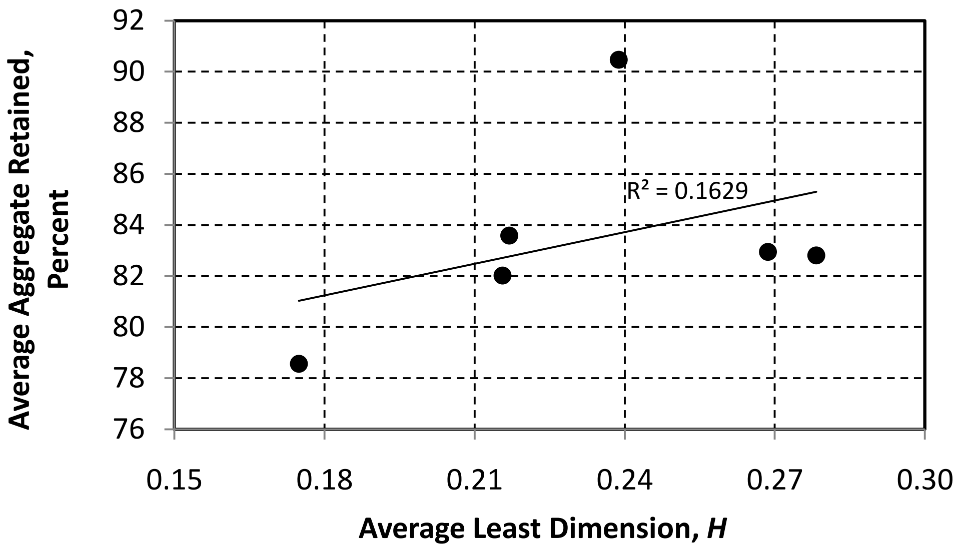


Figure 44. Regression Analysis for Percent Aggregate Retained versus Average Least Dimension, *H*

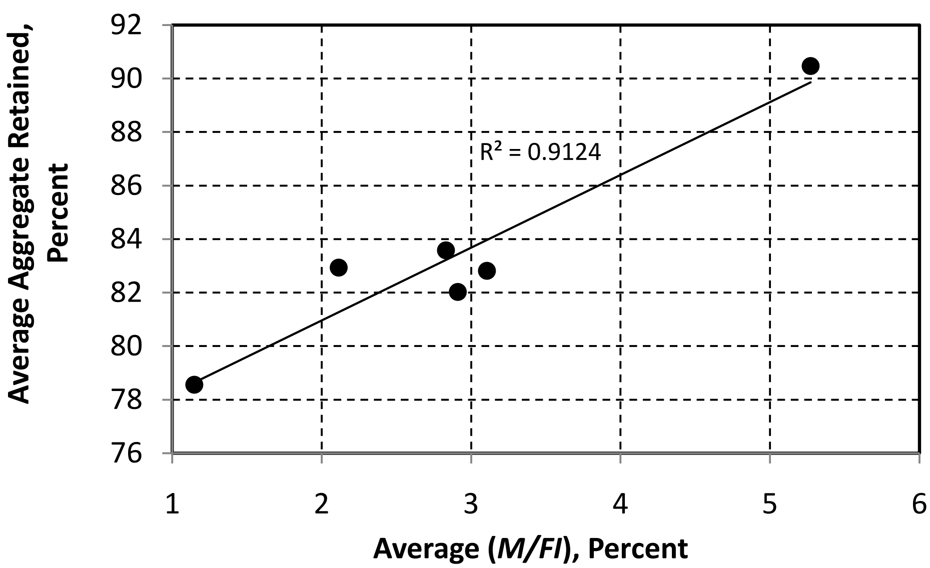


Figure 45. Regression Analysis for Percent Aggregate Retained versus (*M/FI*) as a Percent of Aggregate

From Figure 45, with R^2 of 0.91, it can be observed that the parameter (*M/FI*) shows a much better correlation with the percentage of aggregate retained when compared to the average least dimension of the aggregate. This may lead to a prospective change in the design methodology. Using (*M/FI*) might yield a better result than using the average least dimension of the aggregate

Loose Unit Weight of the Aggregate

The loose unit weight of the aggregate enters the calculation of the design values of the aggregate and binder application rates. It is apparent that the loose unit weight is related to the void spaces among the aggregate particles, which in turn will affect the amount of the binder to be sprayed to fill the voids. The loose unit weight of the aggregate for various districts has been tabulated in the Table 22.

Table 22. Loose Unit Weight for Aggregates from the 6 ITD Districts and the Corresponding Mean and Standard Deviation Values

	Dist. 1	Dist. 2	Dist. 3	Dist. 4	Dist. 5	Dist. 6
	92.02	93.87	90.58	92.53	95.20	89.40
	90.73	96.87	92.35	90.13	95.54	88.80
	91.68	96.69	95.59	94.86	97.33	91.62
	92.90	94.30	89.35	90.18	96.60	86.50
	91.16	95.52	90.65	90.43	95.52	83.32
	91.75	95.76	91.02	90.89	95.30	83.27
Mean	**91.71**	**95.50**	**91.59**	**91.50**	**95.92**	**87.15**
St. Dev., σ_{n-1}	**0.75**	**1.22**	**2.18**	**1.87**	**0.86**	**3.40**

The bar chart of Figure 46 shows the variations of the mean loose unit weights for different districts.

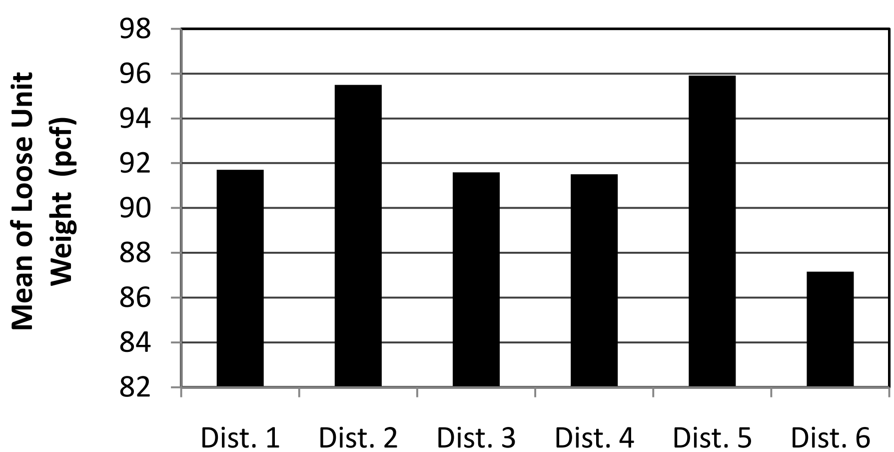


Figure 46. Bar Chart Representation of Mean Loose Unit Weight of the Aggregate

The loose unit weight of the aggregate from District 6 is the lowest value among all the 6 districts. The void ratio's for all 6 districts are tabulated in Table 23. When comparing Tables 22 and 23, one can see that the smallest void ratio corresponds to the largest loose unit weight value (District 5), while the largest void ratio corresponds to the smallest loose unit weight value (District 6).

Table 23. Aggregate Void Ratios of the Six ITD Districts

District No.	Void Ratio
1	0.449
2	0.427
3	0.450
4	0.450
5	0.412
6	0.477

The analysis performed for the average least dimension was carried out for the void ratio as well. The void ratio was plotted against the percent aggregate retained on the Vialit test plates. The results are shown in Figure 47. It can be observed that the correlation between the void ratio and the percent aggregate retained was very minimal. The R^2 value was approximately 0.018. Hence, it was observed that the void ratio had little influence on the average percentage aggregate retained. It is interesting to note that the void ratio is not one of the factors in deciding the application rates of binder and aggregate in the Modified Kearby design method. However, the void ratio plays an important role in the calculation of aggregate and binder application rates in the McLeod design method. Further experiments (relative density and gradation) may need to be performed to evaluate the significance of void ratio in the design methods for chip seals.

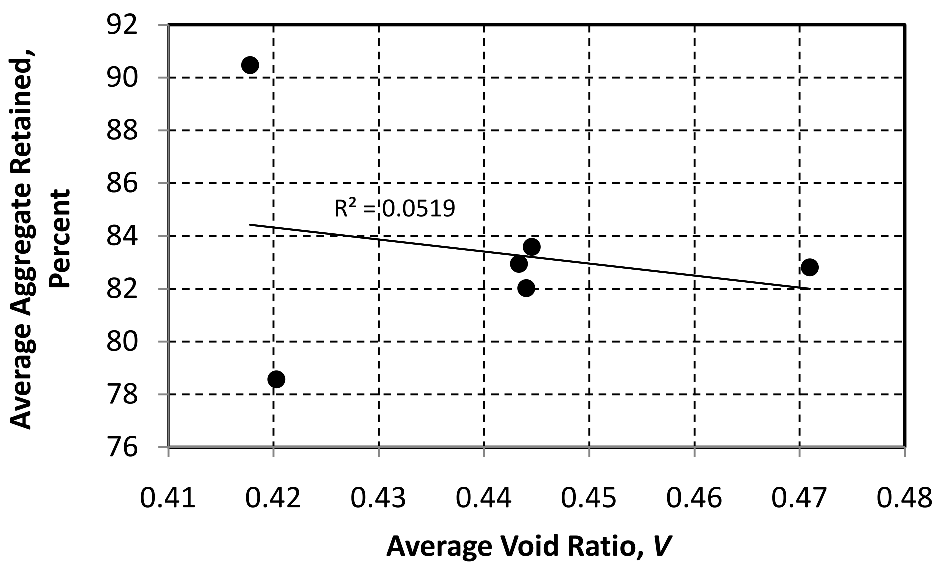


Figure 47. Regression Analysis of Percent of Aggregate Retained versus Void Ratio

Vialit Test Results

The McLeod design procedure with smooth, nonporous surface condition was used to obtain the amount of aggregate and binder to be used for the Vialit test plates (for details see Appendix B.5). The

Vialit test was performed in such a way that the plate was heated to a warm temperature and the binder was heated to 70°C (158°F). Note that the temperature experiments were performed in Celsius; however, in this section the Fahrenheit equivalent temperatures are provided in parentheses. The binder was applied on the plate and the designed amount of aggregate was spread over the binder. The Vialit test roller was rolled ten times to the Vialit test sample plate. The sample was allowed to cool and then cured for two days before the test was performed. A roller being used for Vialit test is shown in Figure 48. Additional pictures concerning all the experiments performed are included in Appendix B.

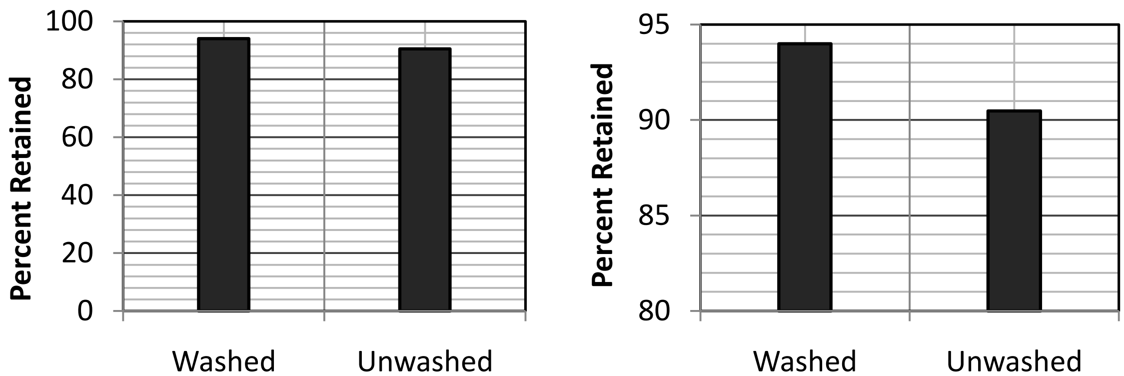
Figure 48. Roller Used for Vialit Test

The standard test procedure for the Vialit test and the aggregate retention tests are included in the Appendix B. In experiments where various temperatures were considered, the samples were kept at room temperature for one day, and then cured at the required temperature for another day. As per the literature review, it was found that the more cube-like particles yield greater compatibility with the binder.(2) Hence, District 5 aggregate, which was the most cube-like among all the districts, was used in the Vialit test. Because of the limited scope of the project and also to test one variable at a time, we did not include aggregates from other districts in the Vialit test. The aggregate retention test was also performed for various cases including washed and unwashed samples, different binders, and varying temperatures. Table 24 shows the Vialit test aggregate retention percentage for washed and unwashed aggregate with CRS-2R binder at room temperature 77°F (25°C).

Table 24. Aggregate Retention for District 5 and CRS-2R at Room Temperature

	Washed	Unwashed
	95.13	89.44
	95.04	91.29
	92.60	90.68
	93.24	90.42
Mean	**94.00**	**90.47**

Table 24 clearly illustrates in the case of washed samples, the amount of aggregate retained is higher when compared to the unwashed samples. The bar chart in Figure 49 illustrates the variation between retention rates of washed and unwashed aggregates. Analysis of Variance (ANOVA) determines the significant variations in the mean values of two different sets of data. In this case, the analysis was performed to determine the statistical significance of the difference between the mean aggregate retained when washed versus the unwashed aggregate. ANOVA requires the consideration of the level of confidence (called the *p*- value) in the analysis. Generally, the *p*-value is considered to be 0.05. This means that if the *p*-value is less than 0.05, it can be said with 95 percent confidence that there is a significant variation in the mean of at least one set of data. The *p*-value obtained in this test was 0.003, which was less than 0.05. Therefore, there is a significant variation in the mean of the two tests (95 percent confidence). The results of ANOVA are included in Appendix E.



(a) **(b)**

Figure 49. Vialit Test Results: ITD District 5 Aggregates, CRS-2R Binder, and 77°F (25°C): (a) Vertical Scale Starting from Zero; (b) Vertical Scale Starts from 80 Percent

Moreover, the Vialit test was conducted on different binders with only District 5 aggregate at a constant temperature. The Vialit test was also performed on various binders. CRS-2S, CRS-2R, CRS-2P, and CRS-2R were the different binders that were used in conducting the Vialit test. The aggregate used was obtained from District 5 and the curing temperature was 77°F (25°C) for the two days duration. The results attained are included in Table 25.

Table 25. Vialit Test Aggregate Retention Test for Various Binders at 77°F (25°C) and ITD District 5 Aggregates

	CRS-2R	CRS-2P	CRS-2L	CRS-2S
	89.44	91.19	87.73	88.64
	91.29	93.80	93.06	89.70
	90.68	92.78	90.37	89.32
Mean	**90.47**	**92.59**	**90.37**	**89.22**

Table 25 reveals that the binder CRS-2P gave better results for the same aggregate (District 5) and at the same temperature of 77°F (25°C). The ANOVA test was performed to determine the amount of aggregate retained when different binders were used. The test yielded a *p*-value of 0.147, which is higher than 0.05. Therefore, there was not a significant variation among the different binders tested (95 percent confidence). However, the CRS-2P showed more retention when compared to other binders. It should be noted that because of the small sample sizes used (only three Vialit tests for each case), there is a low level of confidence in comparing the average values. The results of the ANOVA are included in Appendix E.

The bar charts in Figure 50 show the difference between the aggregate retained in relation to different binders.

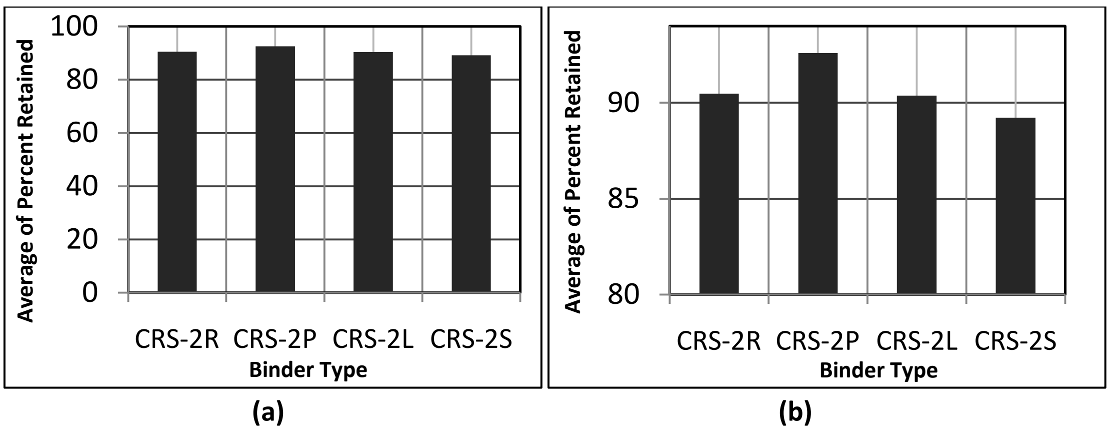


Figure 50. Average Percentage of Aggregate Retained in Vialit Tests: District 5 Aggregates, at 77°F (25°C), Using Various Binders

The Vialit test was also performed at different temperatures. The variations found were significant. The samples that were cured at higher temperatures were found to have retained more compared to the aggregate samples that have cured and tested at lower temperatures. The temperatures that were used for curing were -10°C (14°F), 25°C (77°F), 40°C (104°F), and 60°C (140°F); a similar temperature range was used in another research project.[18] The results obtained are tabulated in Table 26.

Table 26. Vialit Test Aggregate Retention (Percent Retained by Weight) for Unwashed District 5 Aggregates, CRS-2R Binder, Cured, and Tested at Various Temperatures

	14°F (-10°C)	77°F (25°C)	104°F (40°C)	140°F (60°C)
	54.83	89.44	95.58	93.4
	52.93	91.29	97.12	94.6
	55.06	90.68	95.32	92.8
Mean	**54.27**	**90.47**	**95.92**	**93.6**

A graph plotted between the temperatures and the aggregate retained (see Figure 51) clearly illustrates that temperature plays a crucial role in the aggregate retention in the Vialit test. The ANOVA test was performed to determine the statistical significance in the mean difference of the amount of aggregate retained when the Vialit test sample was cooled at different temperatures. The *p*-value obtained was 0 which was less than 0.05. Therefore, there was a significant difference in the amount of aggregate retained when the Vialit test samples where cured at various temperatures (95 percent confidence). The results of the test are included in Appendix E.

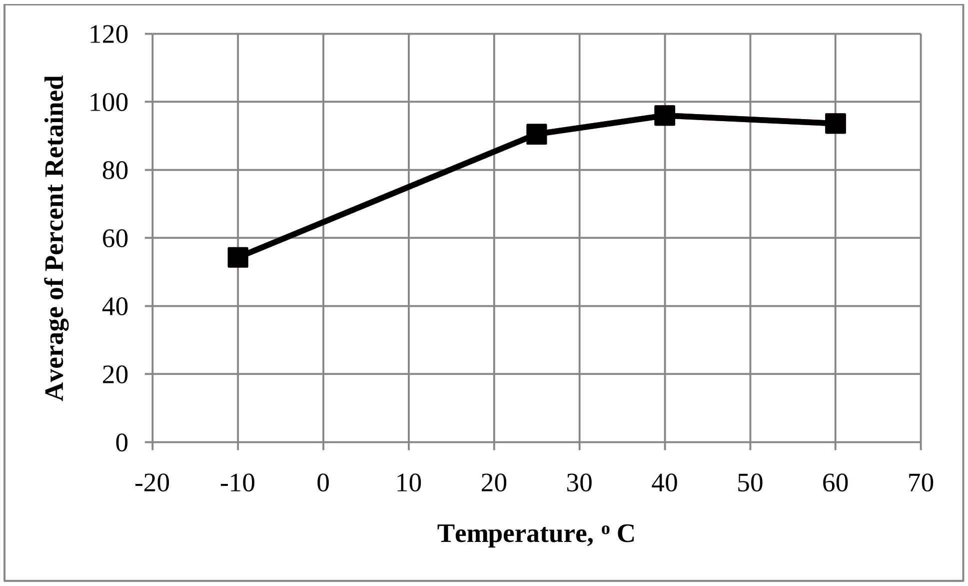


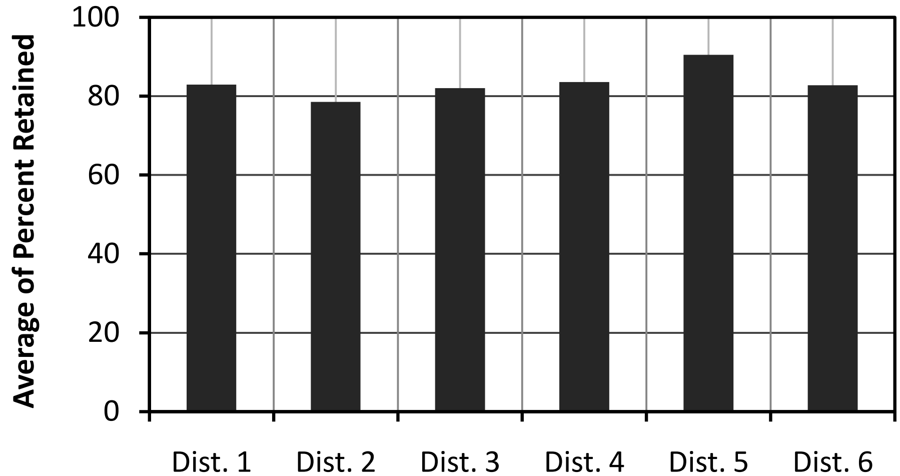
Figure 51. Vialit Test Results: ITD District 5 Aggregates and CRS-2R Binder

The aggregate retention values for all districts at 77°F (25°C) temperature, unwashed and with CRS-2R binder are tabulated in Table 27.

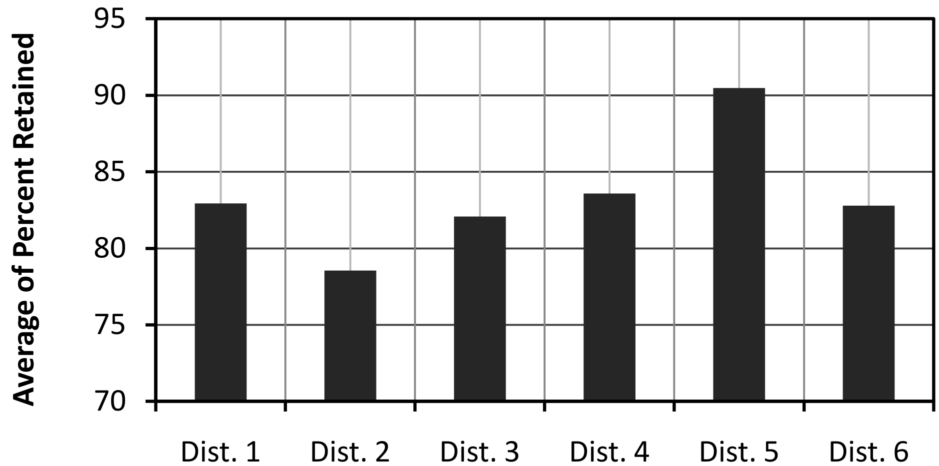
Table 27. Vialit Test Aggregate Retention (Percent Retained by Weight) at 77°F (25°C) Temperature, Unwashed Aggregates with CRS-2R Binder for All ITD Districts

	Dist. 1	Dist. 2	Dist. 3	Dist. 4	Dist. 5	Dist. 6
	82.80	75.57	83.67	83.43	89.44	80.54
	84.70	82.80	78.41	82.86	91.29	81.18
	81.33	77.31	83.99	84.46	90.68	86.70
Mean	**82.94**	**78.56**	**82.02**	**83.58**	**90.47**	**82.81**

The bar charts in Figure 52 show the percentage of aggregate retained for all the districts with the CRS-2R binder and cured at room temperature. It can be observed that the aggregate retention for District 5, which has the least flakiness index and a moderate value of median size, is higher than all other districts. It can also be observed that District 2, which has the largest value of flakiness index, has the least retention. There was an approximate 11.9 percent difference in the aggregate retained between the District 5 and District 2, the highest and the lowest retention districts, respectively. It is also interesting to note that Districts 1 and 6, which have large median size and different flakiness index values, have almost similar retention values and the aggregate retention value for Districts 3 and 4 were also found very close to Districts 1 and 6. When ANOVA was performed to determine the amount of aggregate retained when aggregates from different districts were used, there was significant statistical difference between the mean values. The *p*-value obtained for this test was 0.003. Hence it could be validated with 95 percent confidence that there was a significant difference between the amounts of aggregate retained across various districts. The details of the ANOVA are included in Appendix E.



(a)



(b)

Figure 52. Vialit Test Results with CRS-2R Binder, at 77°F (25°C), for All ITD Districts: (a) Vertical Axis Starting at Zero; and (b) Vertical Axis Starting at 70 Percent

Apart from the analysis of aggregate retained on the plate after the Vialit test, another significant analysis was the comparison of initial aggregate swept (which simulates the sweeping of aggregate in the field after the rolling). This analysis provides vital information regarding the initial loss of aggregate. The initial loss of aggregate causes damage to vehicles because chips thrown by tires may damage windshields. Figures 53 illustrate the bar chart representation of the amount of aggregates swept initially with the broom and the kind of binder used. Table 28 shows the numerical values of the average amount of District 5 aggregates swept away for different binders. The bar charts illustrated by

Figures 54 (a) and (b) are the full scale and partial scale plots of the variations shown by the 6 districts in retaining the aggregate when a Vialit test were performed. It can be concluded from these charts that after the ball impact, District 5 had the best retention and District 2 had the worst retention. This can be attributed to the fact that District 2 aggregate had the highest flakiness index. Interestingly, summary of a recently- conducted survey also indicated performance problems associated with the District 2 aggregate. The initial displacement of aggregate was calculated by using the aggregate retention test of Texas Department of Transportation.[15] The binder, heated up to 158°F (70°C), was sprayed on a plate (8 in. by 8 in.) on which a specified amount of aggregate (designed as per the McLeod Design Method) was spread. The combination of aggregate and binder placed on the plate was rolled with a roller. The sample was then allowed to cool and then tilted to an angle of approximately 75°. The aggregate was then gently swept with a broom and the amount of aggregate was weighed to determine the amount of aggregate initially displaced.

Table 28. Amount of Aggregate (grams) Swept from Different Binders for District 5 Aggregates at 77°F (25°C)

CRS-2R	CRS-2P	CRS-2L	CRS-2S
153.7	155.8	150.8	135.9

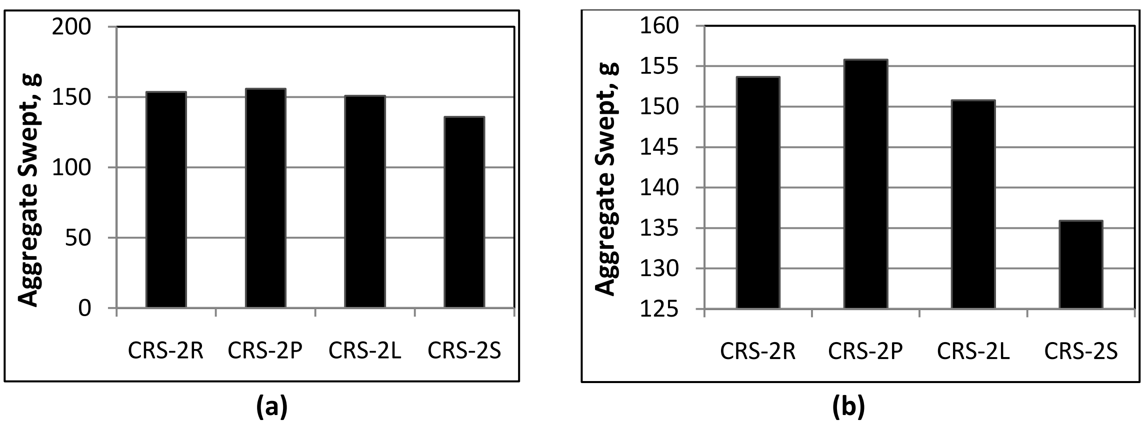


Figure 53. Amount of Aggregate Swept versus the Type of Binder for District 5 Aggregates, at 77°F (25°C): (a) Vertical Scale Starting at Zero; and (b) Vertical Scale Starting at 125 g

The chart clearly shows that CRS-2P, although it displays a greater retention, exhibited a large amount of aggregate lost by initial sweeping. The initial loss of aggregate was found to be the least for CRS-2S, which had a loss of about 136 grams from an initial amount of 552 grams. CRS-2P had the highest initial loss of aggregate: about 156 grams from an amount of 552 grams. This analysis shows that the embedment depth for CRS-2P should be greater as there is a greater initial loss. When CRS-2P is used, it is advantageous to allow as much time as possible before resuming traffic after chip seal application. The amount of the aggregates' initial loss for each district is tabulated in Table 29. The corresponding bar chart, which shows variations of the aggregate swept, is presented in Figure 54.

Table 29. Amount of Aggregate (grams) Swept from Different Districts' Samples

District 1	District 2	District 3	District 4	District 5	District 6
133.7	52.37	91.4	99.15	130.7	134.7

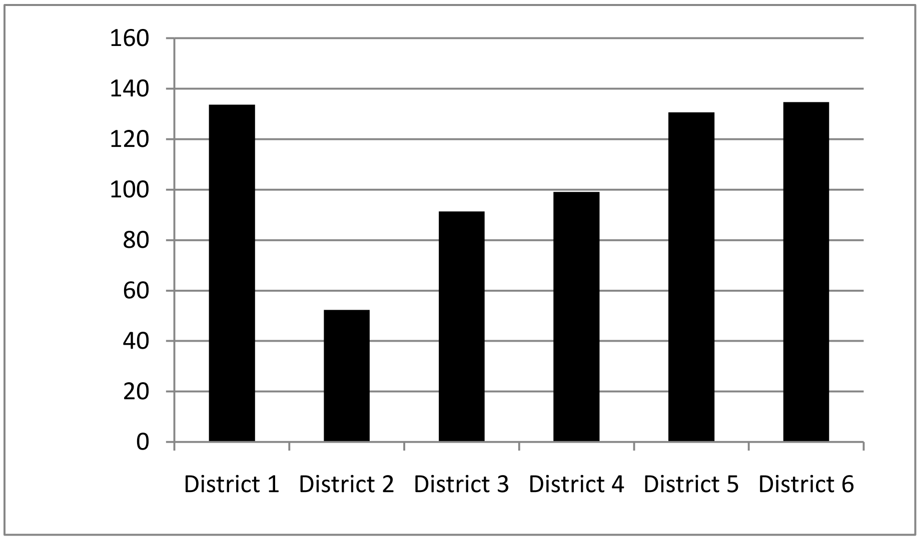


Figure 54. The Amount of Aggregate Loss Due to Sweeping for All Districts (CRS-2R binder, at 77°F or 25°C)

From Figure 54, the amount of aggregates swept from the District 2 sample was the least. District 2 had the least median size and the highest flakiness index value. Districts 1 and 6, on the other hand, had the aggregate median size that showed greater initial loss.

Cleanness Value Index

The sieve analysis shows the percentage of fines in the aggregate sample, but does not include the dust around the aggregate particles. Cleanness value includes the amount of fines present in the voids as well as the fines attached to the particles. From the MNDOT Chip Sealing Manual, we know that the percentage of fines should not be more than one percent.(12) To determine the exact amount of fines, the cleanness value index might be a more representative method. Further research may be performed to incorporate cleanness as one of the factors in the McLeod design method (rather than taking it roughly as 1 percent, as did MNDOT). Table 30 lists the cleanness values and the heights of fines collected at the bottom of the sand equivalent cylinder at the end of the cleanness value test for each district.

Table 30. The Aggregate Cleanness Value Percent and the Height of Fines Collected in the Sand Equivalent Cylinder

District	CV (Percent)	Height of Sediment (in.)
1	87.57	0.44
2	79.04	0.81
3	92.21	0.27
4	90.60	0.33
5	92.32	0.26
6	88.66	0.40

A regression analysis was performed on the CV data available and the percentage of fines (the percentage passing through the No. 200 sieve) collected after the sieve analysis. The results obtained are plotted in the Figures 55 and 56. The plots had regression values of 0.844 and 0.870, showing a correlation between the percentage of fines from the sieve analysis, and the amount of fines collected in the CV test, and the percentage CV calculated. Using these regression analyses, a factor which accounts not only for the amount of fines in the aggregate sample but also considers the cleanness of the aggregate can be developed.

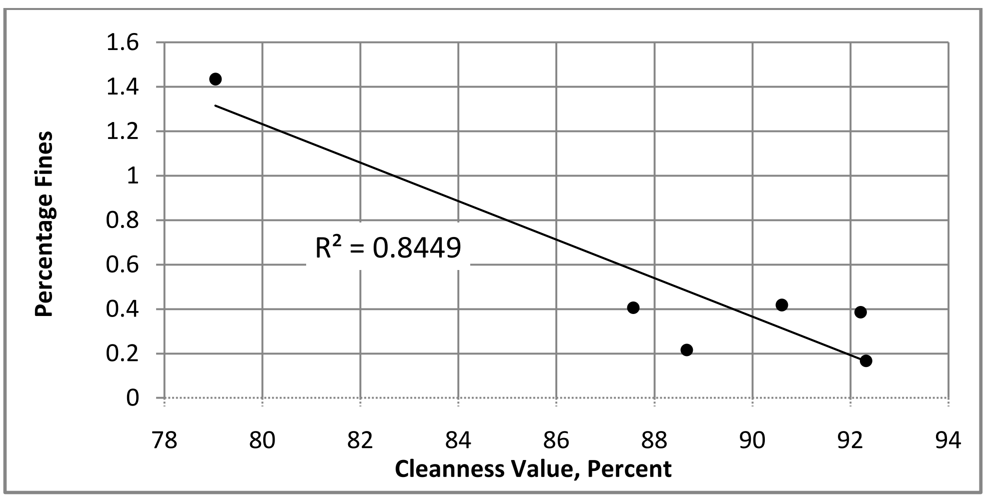


Figure 55. Percentage Fines versus Cleanness Value

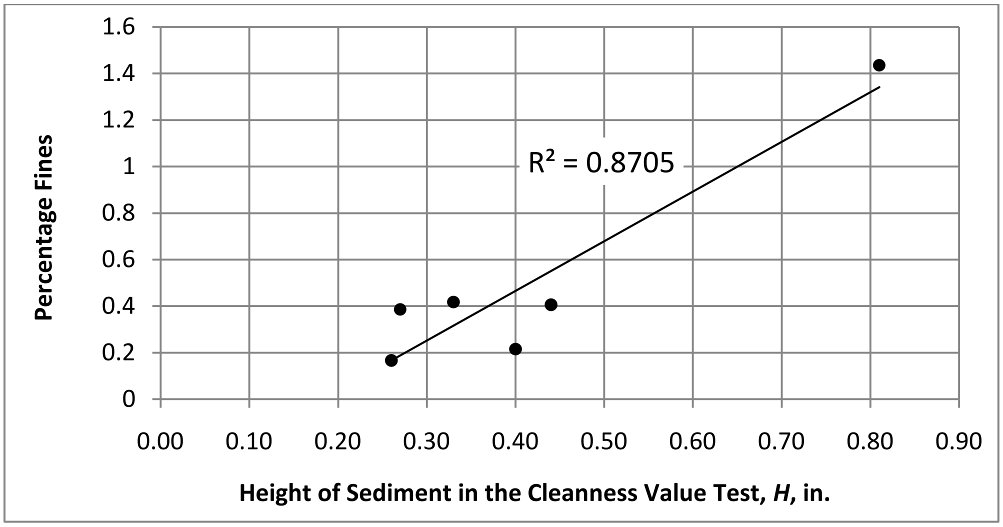


Figure 56. Percentage Fines versus Height of Sediment

The factor developed should be applied in the design methods used. The intension of the factor is to yield a more efficient design method for designing the amounts of aggregate and binder to be used in the construction of chip seals.

The conclusions of the analyses are discussed in Chapter 5.

Chapter 5
Conclusions and Recommendations

A performance assessment of chip seal practice in the State of Idaho was carried out. The study addressed some of the concerns associated with the performance and variations of chip seal materials used by the ITD's 6 districts. In addition, the work considered the binder adhesion characteristics of the chip seal aggregates through a series of laboratory Vialit tests. For the Vialit tests, the proportion of aggregate and binder for chip sealing was determined using the McLeod Design Method. By performing the Vialit tests, the aggregate retention was determined and plotted against the median size, the flakiness index, the cleanness values, and the void ratio of the aggregate used in the Vialit tests. Several types of common binders were also considered. The aggregate was tested, both washed and unwashed, to determine the effect of fines on the retention of the aggregate on the Vialit test plates. The influence of temperature on aggregate retention was verified by changing the curing temperature of binders in Vialit tests. The amount of initial displaced aggregate was determined when the aggregate was lightly swept after laboratory rolling was performed. This was to replicate the initial loss of aggregate during the chip sealing operation in the field due to traffic. The initial loss of aggregate as well as the loss of aggregates after the ball impact was calculated for all districts. Four different types of binders were considered for Vialit testing in conjunction with District 5 aggregate.

Aggregate Median Size and the Flakiness Index Values

To obtain the average least dimension, *H*, values (see Figure 26), the materials acquired from different districts were tested to determine the median size and the flakiness index values first. The average least dimension, when plotted against the average aggregate retention for all districts, showed a great deal of variation. An aggregate with the lowest flakiness index and moderate median size (e.g., District 5 aggregate) had the highest aggregate retention. This gives support to the point that aggregates containing more flakes (larger flakiness index) will have lower adhesion to the binder as compared to the aggregates that are rounder. As a result, aggregate supplied by District 2, which had the highest flakiness index value, had the lowest aggregate retention. This suggests that the aggregates which are more round in shape yield greater retention. A regression analysis between average least dimension and the aggregate retention (see Figure 44) of the different districts showed low correlation. The analysis performed between the percent value of *M/FI*, which is the ratio of median size and the flakiness index values, and the aggregate retention (see Figure 45) yielded a much better correlation. This improvement of correlation indicates that the *M/FI* parameter may need to be implemented in the chip seal design instead of the average least dimension. However, it is felt that a larger sample of data is needed to substantiate the effectiveness of this new parameter.

Significance of Void Ratio in the Design

The void ratios calculated for different districts did not vary as much as the corresponding median sizes or the flakiness index values. A regression analysis showed a very low correlation between the void ratio and the aggregate retention in the Vialit tests. It is also interesting to note that the modified Kearby Method does not include void ratio as a parameter in calculating the amount of binder.

Temperature Effects on Aggregate Retention

In an attempt to determine the aggregate retention characteristics in relation to temperature variation, the aggregate samples were kept at the room temperature for 1 day, and then cured at different temperatures: 14^{o}F, 77^{o}F, 104^{o}F and 140^{o}F for an additional day and immediately tested at the same temperature. It was found that the aggregate retention was least when the aggregate was cured at 14^{o}F and the highest when the curing temperature was 104^{o}F. The aggregate retention decreased as the temperature of curing was increased to 140^{o}F. The aggregate retention hence is higher when the temperature of curing is 104^{o}F, which is similar to the average daytime summer pavement surface temperature. The low retention at a temperature of 14^{o}F, indicates that the chip seal aggregates perform the worst (loosens up from the binder) on the cold winter days.

Effect of the Fine Particles

The aggregate exhibited a higher retention when a Vialit test was conducted on a washed sample, versus a sample of representative aggregate containing fine particles (i.e., in the condition that were supplied). The average aggregate retention for a washed sample was 94 percent compared to a lower value of about 90 percent for unwashed samples. Even if a washed sample is used for chip sealing there might be some fines formed due to the abrasion between the aggregate during their transportation and handling. From the experiments carried out in this research study, it is suggested that the use of the washed aggregate is more advantageous. In case the economy of the project does not permit the use of washed sample, care should be taken to obtain an aggregate which has the least amount of fines.

Effects of the Binder

Four different binders were considered in this research project. The effects of the binders were considered only with the aggregate from District 5 and cured at 77^{o}F. The results obtained showed that the CRS-2P binder had better aggregate adhesion when compared to the other binders. An analysis was also performed to identify which binder had a higher initial loss of aggregate (i.e., due to sweeping only and before the ball impact on the Vialit plate). This analysis showed that CRS-2P had a higher retention of the aggregate after the curing. Interestingly, the binder's aggregate retention after the Vialit test ball impact was directly proportional to their initial loss of aggregates. The binder which had higher aggregate retention rate had higher initial loss and the binder with lower aggregate retention had lower initial loss. This analysis suggests use of the CRS-2P binder, but allowing as much time as possible before releasing traffic on the sealed pavement. It would be advisable to use a correction factor for the binder application rate by taking the initial loss of aggregate into account.

Recommendations

Based on the literature search carried out for this research project and the results of the laboratory experiments, the following recommendations are made for improving the chip seal performance in Idaho:

1. The materials used should be clean and one sized. In countries such as Australia and New Zealand where seal coating has been very successful, good quality aggregates are transported from places several hundred miles from the job site.

2. There was a great deal of variation in the characteristics of the aggregate supplied by different districts in Idaho. Based on the Vialit tests performed in the laboratory, aggregate supplied by District 5 was found to have the maximum amount of aggregate retention. Using aggregate similar to what was supplied by District 5 throughout the State of Idaho would be recommended.

3. Based on the same Vialit tests, the aggregate retention was found to be higher in the case of washed aggregate when compared to unwashed aggregate. Using washed aggregate is recommended. In at least one state, the maximum allowable percent of fines passing through No. 200 sieve and retained on the pan is one percent (MNDOT manual for chip seal design).[(12)]

4. A regression analysis performed on the Cleanliness Value (CV) data and the amount of fines collected in the sieve analysis yielded a regression close to 1, which signifies a correlation between the cleanness and the amount of fines.

5. During our visit to ITD and the field investigation, it was observed that no specific method was followed for chip seal design. The Idaho Standard Manual Section 520.00 recommends the use of the Modified Kearby Design Method.[(22)] The amount of aggregate and the amount of binder are applied as per rule of thumb. It is recommended that a design method be implemented.

6. MNDOT uses the McLeod Design Method, and it has proven successful in other states as well. Minnesota has weather conditions that are somewhat similar to Idaho. McLeod Design Method has the potential to be adopted in the State of Idaho with some modifications.

7. It was observed that the CRS-2P binder, which had maximum aggregate retention after the Vialit test impact, had a large initial aggregate loss due to sweeping. Using CRS-2P as the binder of

choice would be recommended. More time should be given for the binder to develop better adhesion to the aggregates before sweeping and releasing the traffic on the sealed pavement. Since conditions in the field vary, the time duration is left to the designer's engineering judgment. In a recent NCHRP report by Shuler, et al., a new test procedure is presented for predicting the time required before brooms or uncontrolled traffic can be allowed on the surface of the emulsion-based chip sealed roads.(23) ITD may wish to adopt this test method.

The following are the recommendations for future research:

1. It is recommended that a larger sample of aggregate data be obtained to substantiate the effectiveness of the parameter representing the ratio of aggregate median size to the flakiness index (*M/FI*) on the aggregate retention rate.

2. Additional research should consider utilizing a more realistic simulation of the impact of traffic loads than the dropping ball of the Vialit test. A likely candidate for this is the Hamburg Wheel Test, which uses a rotating wheel on the prepared sample.

3. The use of a digital imagery technique in conjunction with the finite element analysis is recommended. This type of research is currently being conducted in New Zealand to calculate the average embedment depths of the aggregate and their relationship with the distress caused on the pavement due to loading, and the distress caused over the course of time.(24)

4. Additional field monitoring is required. A timely study and analysis has to be performed to check the pattern of cracks formed on the pavement.

5. Considerable disparity in the aggregate retention was observed when the temperature of curing varied. Therefore, performing additional temperature-controlled experiments in the lab is recommended.

6. Additional numbers of aggregate retention tests should be performed to identify how the retention varies with different types of binders. Additional binders should also be tried to determine which binder gives the maximum aggregate retention.

7. The application rates of different chip seal design methods should be compared and a cost analysis should be performed to know which one yields a more economical design method for the conditions in Idaho.

8. The cleanness value of the aggregate includes the fines attached to the aggregate particle as well, hence a chip seal design factor should be developed using the cleanness value of the aggregate and should be incorporated in the design method. In this way, the actual amount of fines in and around the aggregate are accounted for, while designing the amounts of aggregate and binder.

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Appendix A

IDAHO CHIP SEAL PRACTICE
SURVEY QUESTIONS
FEBRUARY 2008

1. **Please describe your role – in relation to responsibilities for chip seal applications within your department?**

   RESPONSES:
   District 1: District 1 Materials Engineer ITD official
   District 2: District 2 Materials Engineer ITD official
   District 3: District 3 Materials Engineer ITD official
   District 4: District 4 Materials Engineer ITD official
   District 5: District 5 Materials Engineer ITD official
   District 6: District 6 Materials Engineer ITD official
   Central Office: Pavement Development Engineer, Plans, and Contracts Review

2. **What proportion of the roadway in your jurisdiction has been treated by chip sealing method:**

   a. Total centerline miles: _______________
   b. Total miles treated with chip seal: _____________________
   c. Rural – Local
   d. Rural – Collector
   e. Rural – Arterial
   f. Rural – Interstate
   g. Urban – Collector
   h. Urban Arterial
   i. Urban – Interstate

   RESPONSES:
   District 1: Essentially 100%
   District 2: 1,350 Centerline miles, 1200 (Some PCC pavement not chip sealed)
   District 3: 100% of Flexible pavement lines
   District 4: 100% Asphalt surface roads.
   District 5: All interstate, U.S. and state highways.
   District 6: No Response
   Central Office: Probably 99% pavements in ITD roadway miles are asphalt. Almost all of these are regularly chip sealed.

3. **How frequently do you apply the chip seal treatment:**

   a. Every 5 years
   b. Every 6 years
   c. Every 7 years
   d. Others; specify:

RESPONSES:
District 1: Every 7 years but depends on funding.
District 2: 8 year cycle unless something shows it needs it sooner.
District 3: Every 7 years but depends on funding.
District 4: Every 7 years but depends on funding.
District 5: Every 7 years but depends on funding.
District 6: Every 7 years
Central Office: Every 7 years

4. Do you have any plans for near future chip seal treatments within:

a. Next year
b. Next two years
c. Next three years
d. Others; specify: ___________________________

RESPONSES:
District 1: Next Year, Every year.
District 2: Every year.
District 3: Every year
District 4: Every year.
District 5: Every year.
District 6: Next Year.
Central Office: Chip seal practices are anticipated in all areas each construction season.

5. What is the typical life span of a chip seal:

a. High-volume roads
b. Low-volume roads

RESPONSES:
District 1: No sealing for high volume roads and 5 to 20 years for low volume.
District 2: 8 years for high volume roads and 15 years for low volume roads.
District 3: 5+/- years for high volume roads and 7+/- years for low volume roads.
District 4: 5+/- years for high volume roads and 7+/- years for low volume roads.
District 5: 5+/- years for high volume roads and 7+/- years for low volume roads.
District 6: 5 years for high volume roads and 7 years for low volume roads
Central Office: 5 years for high volume roads and 6 years for low volume roads.

6. **Approximately, what portion (%) of the chip seal treatment is applied by the in-house crews:**
    a. High-volume roads:
    b. Low-volume roads:

    <u>**RESPONSES:**</u>
    District 1: Not Applicable
    District 2: Not Applicable
    District 3: Not Applicable
    District 4: Not Applicable
    District 5: Not Applicable
    District 6: Not Applicable
    Central Office: Chip Sealing done by contractor.

7. **Please rate the performance of chip seal projects applied by the in-house crew:**

    a. Excellent
    b. Good
    c. Fair
    d. Poor
    e. Unacceptable
    f. Not applicable

    <u>**RESPONSES:**</u>
    District 1: Not Applicable
    District 2: Not Applicable
    District 3: Not Applicable
    District 4: Not Applicable
    District 5: Not Applicable
    District 6: Not Applicable
    Central Office: Chip Sealing done by contractor.

8. **Please specify the type of problems associated with chip sealing projects applied by the in-house crew:**

    a. Loss of aggregate (raveling)
    b. Premature bleeding (flushing)
    c. Spread rates of aggregate
    d. Spread rates of emulsion
    e. Construction techniques
    f. Weather
    g. Distress level (extensive cracks)
    h. Surface preparation
    i. Traffic volume
    j. Timing (premature resuming of traffic)
    k. Others; specify: ____________________

RESPONSES:
District 1: Not Applicable
District 2: Not Applicable
District 3: Not Applicable
District 4: Not Applicable
District 5: Not Applicable
District 6: Not Applicable
Central Office: Historically chip sealing from inside was better than contractors.

9. Please rate the performance of chip seal projects applied by contractors:

a. Excellent
b. Good
c. Fair
d. Poor
e. Unacceptable
f. Not applicable

RESPONSES:
District 1: Good recently
District 2: Good to fair with a few poor
District 3: Good
District 4: Good
District 5: Excellent, Good.
District 6: Good
Central Office: No Response

10. Please specify the type of problems associated with chip sealing projects applied by contractors:

a. Loss of aggregate (raveling)
b. Premature bleeding (flushing)
c. Spread rates of aggregate
d. Spread rates of emulsion
e. Construction techniques
f. Weather
g. Distress level (extensive cracks)
h. Surface preparation
i. Traffic volume
j. Timing (premature resuming of traffic)
k. Others; specify: ____________________

RESPONSES:
District 1: Spread Rates of aggregate.
District 2: Raveling, premature bleeding, spread rates of emulsion, weather, traffic volume, timing, traffic speed, excessive turning, pulling out onto seal coat.

District 3: Raveling a potential problem
District 4: Raveling.
District 5: Spread rate of emulsion (high), Traffic volume, and timing (premature resume of traffic)
District 6: Raveling
Central Office: Late season seal coating, including weather distributor problems, non-rubberized, polymerized emulsion.

11. What design procedure does your organization use in relation to chip seals:

a. McLeod method
b. Kearby method
c. Modified Kearby method
d. Asphalt Institute method (MS-19)
e. Empirical method (based on past experience)
f. No formal design method
g. In-house developed design technique – please describe separately

RESPONSES:
District 1: McLeod method, Kearby method.
District 2: Kearby.
District 3: Kearby.
District 4: Empirical method, based on past experience.
District 5: Empirical method, no formal method.
District 6: McLeod method, Kearby method.
Central Office: Usually use rates that have been used previously in that area or with the material source. McLeod under development.

12. Who is responsible for the design:

a. In-house designers
b. Designers retained by the contractors
c. Other design consultants
d. Others – specify: ______________________

RESPONSES:
District 1: Contractors retain designers to verify mix design.
District 2: District Materials Engineer does initial design and adjusted by contractor and inspectors based on their experience.
District 3: Contractors
District 4: In house designers, contractors just propose the rates.
District 5: Chip gradation and estimated spread rates are stipulated in contract with adjustments to rates made as needed dependant on roadway conditions. Adjustments made in conjunction with Contractor and Engineer.
District 6: Designers retained by contractors
Central Office: Designers retained by the contractors.

13. What are the design criteria combination

a. Asphalt binder rate (please define)
b. Aggregate rate (please define)
c. Traffic volume (please define)
d. Others – specify: _____

RESPONSES:

District 1: 0.32 +/- gal/yd^2, 25 lb/yd^2
District 2: Asphalt binder rate, aggregate rate (28 lb/yd^2), traffic volume, and grade of road, shade, stopping and starting on a hill.
District 3: 0.32 gal/yd^2 and 28 lb/yd^2.
District 4: Asphalt binder rate, aggregate rate.
District 5: 0.35 gal/yd^2, 25 lb/yd^2.
District 6: Asphalt binder rate and aggregate rate
Central Office: Asphalt binder rate, aggregate rate.

14. What criteria are used to identify the readiness of pavements for chip sealing application:

a. Distress level (extent of cracking: severe, moderate, slight, none)
b. Skid number
c. Pavement condition rating
d. Average 18 kip wheel loads
e. Average annual maintenance cost
f. Date of last surface
g. Others – specify: ______________________

RESPONSES:

District 1: Distress Level, Skid Number
District 2: Distress level, skid number, pavement condition rating, Is existing road starting to ravel, or are there other problems. Seems to be raveling problem with new pavements. May be applying fog coats in the future. An aggregate problem has been observed. District is experimenting with Microdeval testing.
District 3: ITD waits 3 years after the pavement construction. Date of last surface, skid number, distress levels.
District 4: Skid Number.
District 5: Skid number, date of last surface
District 6: Distress level, skid resistance, Pavement condition rating and date of last surface.
Central Office: Distress level, skid number, pavement condition rating and date of last surfacing.

15. What are the pavement characteristics and associated deterioration symptoms:

a. Type of underlying pavement
b. Percent shallow/deep rutting
c. Percent patching
d. Percent base failure
e. Percent block cracking
f. Percent alligator cracking
g. Percent longitudinal cracking
h. Percent transverse cracking

RESPONSES:
District 1: Percent alligator, longitudinal and transverse cracks.
District 2: Percent alligator, longitudinal and transverse cracks.
District 3: Question not applicable.
District 4: All.
District 5: Not Applicable.
District 6: Age and skid resistance
Central Office: Type of underlying pavement percent block cracking and skid number.

16. What is the contract bidding process and are there prequalified list of contractors for bidding on chip seal projects:

a. Contract bidding process (yes or no)
b. Cost (unit price – low bid, lump sum/firm fixed price, design-build, etc)
c. Prequalified list (if yes, how many) no, not allowed to in the state

RESPONSES:
District 1: Low bid contract bidding process
District 2: Low bid contract bidding process.
District 3: Low bid contract bidding process
District 4: Low bid contract bidding process.
District 5: Low bid contract bidding process.
District 6: Low bid contract bidding process.
Central Office: Low bid contract bidding process.

17. Are there warranties built-in the chip seal contracts/projects

a. Yes
b. No

RESPONSES:

District 1: No, penalties/ bonuses based on QA program.
District 2: No prices would be increased dramatically.
District 3: No
District 4: No.
District 5: No.
District 6: No.
Central Office: No.

18. When is the typical chip seal construction season? and what type of precautions do you take to ensure the success of chip sealing application.

a. Season
b. Precautions

RESPONSES:

District 1: June 15 to September 1, Precautions for surface temperature.
District 2: June 15 to September 1. The end of July or mid August is more typical of when seal coat season end in District 2. Precautions are taken for temperature, wet surface, shady areas, mindful of wind, slope, and grade of roadway.
District 3: June 15 to September 1
District 4: June 15 to September 1. Precautions are taken for wind speed as per specifications.
District 5: June 15th to September 1.
District 6: Up to September 1st. Usual Precautions are taken.
Central Office: Up to September 1st. Usual Precautions are taken.

19. What is the average daily traffic on the roads with chip seals

a. ADT < 500
b. ADT < 1,000
c. ADT < 2,000
d. ADT < 5,000
e. ADT < 20,000
f. ADT > 20,000

RESPONSES:

District 1: Usually less than 5,000.
District 2: If ADT less than 500 than gravel and Chip sealing done for any ADT in between 1,000 and 5,000.
District 3: Usually less than 5,000.
District 4: Usually chip sealing done for pavements with ADT less than 5,000 per lane.
District 5: Usually less than 5,000.
District 6: ADT less than 20,000.
Central Office: Usually chip sealing done for pavements with ADT less than 20,000 per lane.

20. What type of aggregate is used for chip sealing applications? Do they differ for different roadway projects?

a. Source
b. Natural aggregate (limestone, quartzite, granite, sandstone, others – specify)
c. Crushed slag aggregate
d. Light weight aggregate
e. Synthetic aggregate
f. Other; specify

RESPONSES:

District 1: Crushed natural aggregate from a local source.
District 2: Sources provided by contractor.
District 3: Crushed natural aggregate from a source.
District 4: Crushed aggregate from a source, generally fractured basalt.
District 5: Crushed natural aggregate from a source.
District 6: Natural aggregate
Central Office: Designers retained by the contractors.

21. What are the gradation characteristics

a. Size range
b. Most commonly used size
c. Uniformly graded
d. Well graded
e. Special gradation – please specify

RESPONSES:

District 1: ⅜ in. maximum nominal size in standard specifications, 1 sized chips, and non graded aggregate used.
District 2: ⅜ in. maximum nominal size in standard specifications, 1 sized chips, and non graded aggregate used.
District 3: ⅜ in. maximum nominal size in standard specifications, 1 sized chips, and non graded aggregate used

District 4: ⅜ in. maximum nominal size in standard specifications, 1 sized chips, and non graded aggregate used.
District 5: ⅜ in. maximum nominal size in standard specifications, 1 sized chips, and non graded aggregate used.
District 6: ⅜ in. maximum
Central Office: ⅜ in. (centimeters) maximum 1 sized chips.

22. What are other pertinent characteristics of aggregates

a. Cleanness (is there a requirement for material passing No. 200 sieve) Precoated (what type)
b. Flakiness
c. Angularity
d. Loose unit weight

RESPONSES:

District 1: 80% clean, flakiness according to McLeod and angularity, one fracture face or more as per AASHTO TP-61 method 1.
District 2: 80% for cleanness moistens chips before sealing, no flakiness, and loose unit weight and one fractured face or more as per AASHTO TP-61 method 1.
District 3: 80% for cleanness moistens chips before sealing, no flakiness, and loose unit weight and one fractured face or more as per AASHTO TP-61 method 1.
District 4: 80% for cleanness, no precoat, flakiness, and loose unit weight. 1 fractured face or more per AASHTO TP-61 method 1
District 5: No Response
District 6: Cleanness and angularity
Central Office: Cleanness loose unit weight and angularity. Flakiness under development.

23. What is the unit price for different types of aggregates typically used and the rate of application

e. Natural
f. Light weight
g. Synthetic
h. Others - specify

RESPONSES:
District 1: District 1 pays for all materials except for asphalt.
District 2: 28 lb/yd^2, cannot tell difference in prices.
District 3: Not Applicable
District 4: Natural.
District 5: Natural.
District 6: No Response
Central Office: Natural.

24. What type of binders do you use (criteria) and what are the unit price and rate of application

a. Asphalt emulsion
b. Performance-based asphalts (PBA)
c. Asphalt rubber binder
d. Rejuvenating emulsion
e. Others (including modifiers)– specify polymer

RESPONSES:
District 1: Asphalt emulsion 0.32 gal/yd^2.
District 2: Asphalt emulsion 0.35 to 0.45 gal/yd^2.
District 3: Asphalt emulsion.
District 4: Asphalt emulsion.
District 5: Asphalt emulsion CRS-2R
District 6: Asphalt emulsion
Central Office: Asphalt emulsion.

25. Do you conduct any test to verify the binder-aggregate adhesion properties

a. No
b. Yes (please specify)

RESPONSES:
District 1: Cationic Asphalt is specified.
District 2: Cationic Asphalt is specified. Do not do very often.
District 3: Cationic Asphalt is specified.
District 4: Cationic Asphalt is specified.
District 5: Cationic Asphalt is specified.
District 6: No
Central Office: No.

26. What other types of chip seals has your organization used in the past

a. Multiple application system (double, triple, racked-in, sandwich seal, inverted double seal, cape seal) – please specify
b. Proprietary application system (fiber/geotextile reinforced seal coating systems)

RESPONSES:

District 1: Double chip seal and Sem Materials Ralumac procedure.

District 2: Double, sandwich. District 2 has used Sem Roadarmor. This process failed miserably. District 2 will try "Safe lane" on bridge decks. District 2 constructs a significant number of projects using Stress Absorbing Layer of Straight Asphalt (SALSA). This is not a chip seal, however uses similar construction techniques. (HQ clarification – also similar to SAMI crack mitigation layer)

District 3: Double chip seal

District 4: Double chip seal.

District 5: No response.

District 6: Multiple application systems

Central Office: Multiple application systems.

27. What type of binder distributor equipment do you use

a. Computerized controls
b. Makes and models

RESPONSES:

District 1: Computerized controls.

District 2: Computerized controls.

District 3: Distributors have computerized controls.

District 4: Not known, Contractor should use uniform distributors.

District 5: No response.

District 6: Computerized controls.

Central Office: Computerized controls.

28. What type of aggregate spreader do you use

a. Computerized controls
b. Makes and models

RESPONSES:

District 1: Not computerized.

District 2: Not computerized.

District 3: Not computerized.

District 4: Unknown.

District 5: No response.

District 6: Computerized controls

Central Office: Designers retained by the contractors.

29. What roller types do you use in case of (static steel, vibratory steel, pneumatic-tired, combination pneumatic/steel, others-specify)

RESPONSES:
District 1: Pneumatic –Tired roller.
District 2: Pneumatic –Tired roller.
District 3: Pneumatic –Tired roller.
District 4: Pneumatic –Tired roller.
District 5: Pneumatic –Tired roller.
District 6: Pneumatic –Tired roller.
Central Office: Designers retained by the contractors.

30. Do you have a formal inspection process (who is responsible)

a. No
b. Yes (please specify)

RESPONSES:
District 1: Yes, Inspection by Residential Engineer
District 2: Yes, Inspection by Residential Engineer
District 3: Yes, Inspection by Residential Engineer
District 4: Yes, Inspection by Residential Engineer.
District 5: Yes, Inspection by Residential Engineer.
District 6: Yes, ITD instructors.
Central Office: Yes, ITD inspectors.

31. Do you perform any field tests to monitor the binder quality

a. No
b. Yes (please specify)

RESPONSES:
District 1: Yes, binder subjected to viscosity and sieve tests.
District 2: Yes, binder subjected to viscosity and sieve tests.
District 3: Yes, binder subjected to viscosity and sieve tests.
District 4: Yes, binder subjected to viscosity and sieve tests.
District 5: Yes, binder is subject to viscosity.
District 6: Yes, viscosity.
Central Office: Yes.

32. Do you have any specific programs for maintaining the seal-coated roadways

a. No
b. Yes (please specify)

RESPONSES:
District 1: No.
District 2: No.
District 3: No.
District 4: No.
District 5: No.
District 6: No.
Central Office: No.

33. What type of deterioration symptoms are common in your chip seal projects

a. Crack reflection
b. Transverse cracks
c. Longitudinal cracks
d. Corrugation
e. Alligator cracking
f. Streaking
g. Raveling
h. Bleeding
i. Potholes
j. Others – please specify

RESPONSES:
District 1: All, but generally chip sealing is performed before they show up.
District 2: All except pot holes. Snowplow, equipment moving during construction tear chip seals.
District 3: Raveling, worn out by snowplows sometimes.
District 4: Crack reflection, streaking, raveling, and bleeding.
District 5: No response.
District 6: Raveling, bleeding
Central Office: All.

34. Please indicate which one of the following type of distresses have been the underlying cause of chip seal failures in your jurisdiction

a. Inadequate original pavement structural/functional support (subgrade/drainage)
b. Weather
c. Traffic
d. Inadequate time before the resumption of traffic
e. Aggregate – improper rate
f. Aggregate – spread too early
g. Aggregate – spread too late
h. Aggregate – dirty or dusty
i. Aggregate – gradation
j. Aggregate – too damp
k. Insufficient rolling

l. Binder – improper application rate
m. Binder – improper temperature
n. Binder – improper viscosity
o. Others – please specify

RESPONSES:

District 1: Aggregate dusty or dirty and improper application of binder.
District 2: Weather, inadequate time before resumption of traffic improper aggregate and binder rates and insufficient rolling.
District 3: Any one of these.
District 4: Aggregate dirty and dusty.
District 5: Weather, traffic, inadequate time before resumption of traffic, dirty or dusty improper aggregate and binder rates and improper temperature.
District 6: Weather, inadequate time before resumption of traffic improper aggregate and binder rates and insufficient rolling.
Central Office: Inadequate original pavement, weather, traffic, aggregate dirty and dusty, aggregate too damp and non rubberized non polymerized binder.

35. What is the most common complaint you receive from the public regarding chip seals

a. Road noise
b. Loose aggregate
c. Excessive dust
d. Ride quality
e. Appearance
f. Others – please specify

RESPONSES:

District 1: Road noise some times and loose aggregate.
District 2: Loose aggregate, excessive dust and ride quality.
District 3: Loose aggregate.
District 4: Loose aggregate.
District 5: Loose aggregate.
District 6: Loose aggregate.
Central Office: Road noise, excessive dust and broken windshields.

36. Which remedial techniques do you use to maintain chip seals

a. Crack sealing
b. Seal patch
c. Sanding or chat
d. Lime slurry
e. Fog seal
f. Local strengthening
g. Others – please specify

RESPONSES:
District 1: Fog seal
District 2: Fog seal, sanding or chat.
District 3: Fog seal.
District 4: Fog seal.
District 5: Fog seal.
District 6: Fog seal.
Central Office: Choke sand and fog sealing.

37. What type of existing road-surface preparation is performed prior to the application of chip seal

a. Cleaning and crack sealing
b. Fog coat
c. Cold mix patches to repair
d. Geotextile to retard reflective cracking
e. Others – please specify

RESPONSES:
District 1: Cleaning and crack sealing
District 2: Cleaning, crack sealing and cold mix patches to repair.
District 3: Cleaning, crack sealing and cold mix patches to repair.
District 4: Cleaning. crack sealing only for bad cracks.
District 5: Cleaning and crack sealing.
District 6: Cold mix patches to repair.
Central Office: Cleaning, cold mix patches to repair. Crack sealing rarely done.

38. How long elapses between the binder spray operation and aggregate spread

RESPONSES:
District 1: Should be done within 3 minutes after applying binder.
District 2: Should be done within 3 minutes after applying binder.
District 3: Immediate.
District 4: Should be done within 3 minutes after applying binder.
District 5: Immediately.
District 6: Immediately.
Central Office: Should be done within 3 minutes after applying binder.

39. How long elapses between aggregate spread and initial rolling

RESPONSES:
District 1: Should be done within 5 minutes after spreading the aggregate.
District 2: Should be done within 5 minutes after spreading the aggregate.
District 3: Should be done within 5 minutes after spreading the aggregate.
District 4: Immediately after aggregate is spread.
District 5: Immediately

District 6: Immediately
Central Office: Should be done within 5 minutes after spreading the aggregate.

40. How long elapses between final rolling and initial brooming

RESPONSES:
District 1: The night chip sealing is performed after shutting of pilot cars.
District 2: The night chip sealing is performed after shutting of pilot cars.
District 3: Broomed before resuming seal coat activities, needs to be cool enough to not displace chips
District 4: The night chip sealing is performed after shutting of pilot cars.
District 5: The next day morning.
District 6: 24 hrs.
Central Office: The night chip sealing is performed after shutting of pilot cars.

Appendix B
Test Procedures
and Selected Laboratory and Field Pictures

Sieve Analysis

Aim: The primary aim of the sieve analysis for aggregate used in Vialit test is to determine the median size of the particle.

Definitions: The median size of the particle is the size of the sieve through which 50 percent of aggregate can pass through. It can be determined by plotting a graph between the percent of aggregate passing through a particular sieve and its sieve size in inches. (centimeters).

Equipment: A mechanical sieve shaker, an aggregate splitter, sieve sizes 0.5 in., 0.375 in., 0.25 in., 0.187 in., 0.0937 in., 0.0469 in., 0.0179 in., 0.0029 in. sieves and a pan. An electronic weighing scale was also used.

Materials Used: Aggregate unwashed.

Procedure:

- The aggregate sack from each district was split into 6 representative samples of 3,000 g each.
- From the representative samples, gradation is performed by allowing 300 g at a time of the sample through the above mentioned sieves in the same order.
- The lid is closed and the mechanical sieve shaker is turned on for 5 minutes.
- The weights of the aggregate retained on each size are jotted down.

Note: It is easier to collect the aggregate retained on 0.375 in., 0.25 in. and 0.187 in. sieve and keep them aside for the first two sieve analysis performed on every representative sample. In this way you need not do the sieve analysis again for the flakiness index test.

Calculations:

$$\%\ Passing\ through\ each\ sieve = \frac{Cumilative\ Agg\ Retained - Weight\ Retained\ on\ the\ Sieve}{Cumilative\ Agg\ Retained} \times 100$$

The percentage obtained through above calculations is then plotted against their sieve size and the sieve size through which 50 percent of aggregate passes is determined as the sieve size.

(a) **(b)**

Figure 57. (a) and (b) Sieves Used for Gradation and the Mechanical Sieve Shaker Used

(a) **(b)**

Figure 58. (a) Aggregate Splitting, and (b) Sieve Analysis for a Representative Sample

Flakiness Index Test

Aim: The aim of the experiment is to determine the percent of flakes present in an amount of aggregate.

Equipment: A vertical slotted flakiness plate, 0.5 in., 0.375 in., 0.25 in. and 0.187 in. sieves, a pan, and a weighing scale.

Materials Used: The aggregate passing through 0.5 in. sieve and retained on 0.375 in. sieve, the aggregate passing through 0.375 in. sieve and retained on 0.25 in. sieve and the aggregate passing through 0.25 in. sieve and retained on 0.187 in. sieve. The weight of total aggregate should be around 500 g per sample.

Procedure:

- The plate has slots for aggregate that passed and retained as above mentioned aggregate. The aggregate is passed through respective slots on the vertical slotted flakiness plate.
- The weight of aggregate that passes through and retained on each and every slot is calibrated and jotted down.

Calculations:

$$Flakiness\ Index\ (\%) = \frac{(Total\ aggregate\ passing) \times 100}{(Total\ aggregate\ passing + Total\ aggregate\ retained)}$$

Figure 59. Flakiness Index Test Being Performed by Placing the Aggregate in the Slotted Plate

(a) **(b)**

Figure 60. (a) Aggregate Retained on Each Slot, and (b) Aggregate Passed Through Each Slot and the Apparatus Used

Loose Unit Weight of the Aggregate

Aim: The aim of the experiment is to determine loose unit weight of aggregate and subsequently determine the void ratio of the aggregate sample.

Equipment: The apparatus required is a tamping rod a cylinder which measures a volume of 0.1 ft^3 and a scoop and a weighing scale.

Materials Used: Aggregate unwashed.

Procedure:

- The measure was filled to overflowing with the help of a scoop. The aggregate should not be discharged from more than 2 in. above the top of the measure.
- The aggregate should be leveled with the help of a tamping rod.
- The aggregate and the measuring cylinder should be weighed on the scale and the weight should be jotted down.
- The aggregate should be removed from the cylinder and the weight of the empty cylinder should be jotted down.

Using the calculations below the loose unit weight of the aggregate can be calculated.

Weight of the Cylinder + aggregate = a

Weight of the aggregate = b

The loose weight of aggregate = $a - b$ grams

The loose weight of aggregate in lb = $(a - b) \times 2.2046$ lb

The loose unit weight of aggregate = loose weight / volume of the cylinder

The loose unit weight of aggregate = $W = \frac{(a-b)\times 2.2046}{0.1}\ \mathrm{lb/ft^3}$

Figure 61. Equipment Used for the Aggregate Loose Unit Weight Experiment

Cleanness Value Test

Aim: The main aim of the experiment is to determine the amount of fines present in a given aggregate sample.

Equipment: A Sand Equivalent solution, 10 ml measuring cylinder, 500 ml measuring cylinder, 15 in. measuring cylinder, a CV jar, 8 in. diameter funnel, 0.0937 in. sieve, a 0.0029 in. sieve and a stop watch.

Materials Used: 1,000 ± 50 grams representative sample of any aggregate.

Procedure:

- Take 7 ml of sand equivalent solution and place it in the 15 in. measuring cylinder
- Pour the aggregate representative sample in the CV jar slowly so that the aggregate settles down uniformly.
- Fill the jar to the height of aggregate with water and keep the jar untouched for 1 minute
- Agitate the jar manually, by rotating it 360^0 about the vertical axis (like a pancake motion) in 1 direction. The diameter of the circle should be around 6 in.
- The mixture should immediately be placed in the 500 ml measuring cylinder through the 0.0937 in., and 0.0029 in. sieves and the funnel.
- Water should be poured on the aggregate and that water should be allowed into the measuring cylinder until it reaches the 500 ml mark.
- By closing the mouth of the measuring cylinder with a cork firmly, the cylinder should be rotated 180^o up and down for 10 times. Care should be taken the cylinder should be rotated 1 full 180^o before it is turned in the opposite direction.
- Now transfer the water to the 15 in. measuring cylinder up to the 15 in. mark and repeat the rotation 10 times again.
- The 15 in. measuring cylinder should be kept on a table undisturbed for 20 minutes. The time can be set up using the stop watch.
- At the end of twenty minutes the height of the fines sediment in the 15 in. measuring cylinder should be jotted down.

Calculations:

$$CV(\%) = \frac{3.214 - (0.214 \times H)}{3.214 + (0.786 \ \times H)}$$

Where, *CV* is the Cleanness Values in percent and *H* the height of the sediment in inches.

(a) **(b)**

Figure 62. (a) The Apparatus Used for Cleanness Value Test, and (b) The Measuring Cylinder with the Fines and the Water Being Rotated 180^{o} Upside Down for 10 Times

Figure 63. The Amount of Fines Deposited After 20 Minutes

Vialit Test Procedure Carried Out in the Laboratory

Aim: The aim of the Vialit test experiment was to calculate the loss of aggregate during constructing chip seals and trying to simulate the field application as much as possible and try to compare how the retention varies with and without fines in the aggregate, and at different temperatures. Note that the measurements for these tests were done in metric units, but U.S. Customary units are also given here.

Equipment: Steel plate 20 cm by 20 cm (8 in. by 8 in.), solid metal cylindrical roller, Vialit stand, a stainless steel ball of 500 $\pm 5\ g$ (about 1.102 lb), hot plates, thermometer, a clamping stand, tin cans to hold the binder, and a can to hold water in which the binder tin can is placed while heating.

Materials Used: Representative sample of an aggregate and an asphalt emulsion binder.

Procedure:

- A representative sample of aggregate equal to the amount designed according to McLeod method was used.
- The binder whose specific gravity was measured already was heated to a temperature of 70^{o}C (158^{o}F). The plates were heated to a temperature just to replicate the heat on the existing surface during summers when the chip sealing is performed.
- The plate is then placed on a weighing scale. The measurement is set to zero.
- The binder was then transferred on the plate till the scale reads the amount of binder designed and the binder is spread across the plate uniformly using a spatula.
- The aggregate was then transferred on to the plate with the binder and is spread manually so that it is uniform throughout.
- The plate is immediately rolled with the solid metallic roller. It is rolled 10 times.
- The plate is then tilted 75^{o} and swept using a brush. The amount of aggregate lost is weighed and jotted down.
- Then the plate is allowed to cool at room temperature for 24 hrs.
- It can then be cured at different temperatures. It was placed in a freezer at -10^{o}C (14^{o}F) for a certain experiment and in an oven at 40^{o}C (104^{o}F). If the experiment does not include temperature analysis then it could be cured at room temperature. The general time for curing is 24 hrs.
- The weight of the plate is measured.
- After curing, the plate is placed on the Vialit stand facing downwards and the ball is dropped from the top of the stand 3 times in 10 seconds.
- The weight of the plate is measured now again.

Calculations:

The difference between the weights measured before and after the dropping of the ball gives the aggregate displaced at the impact.

The difference between the initial design amount of aggregate taken and the loss of aggregate due to sweeping or any reason other than the impact gives the total amount of aggregate retained after impact.

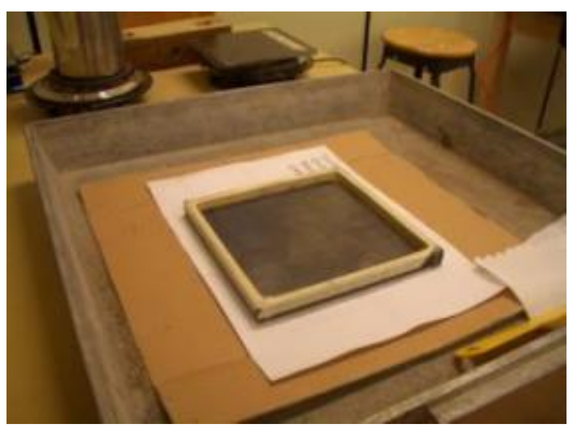
$$\%\,agg\ retained\ = \frac{Amount\ of\ agg\ retained - Amount\ of\ agg\ displaced}{Amount\ of\ agg\ retained} \times 100$$

(a)

(b)

Figure 64. (a) The Aggregate Materials Used for the Vialit Test, and (b) Different View of the Same Materials and a Typical Binder Container (The White Container)

(a)



(b)

Figure 65. (a) The Binder and the Plates Being Heated on Electric Burners, and (b) A Heated Plate Placed for Binder Application

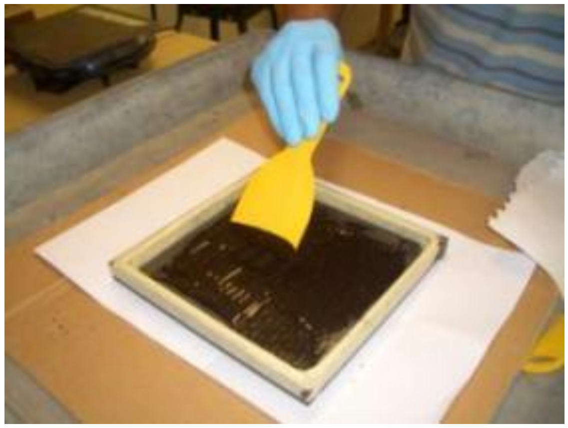
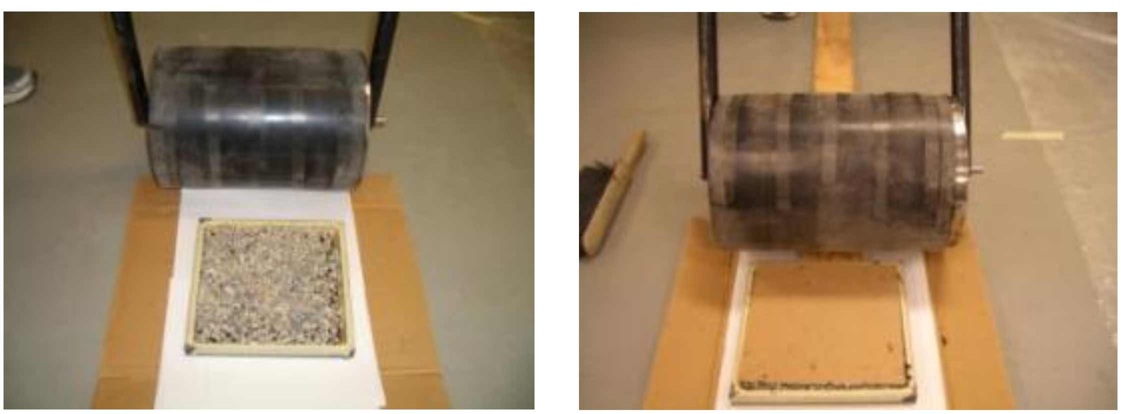


Figure 66. The Binder Being Applied on the Plate

(a) **(b)**

Figure 67. The Aggregate (a) Before and (b) After Spreading on the Plate



(a) **(b)**

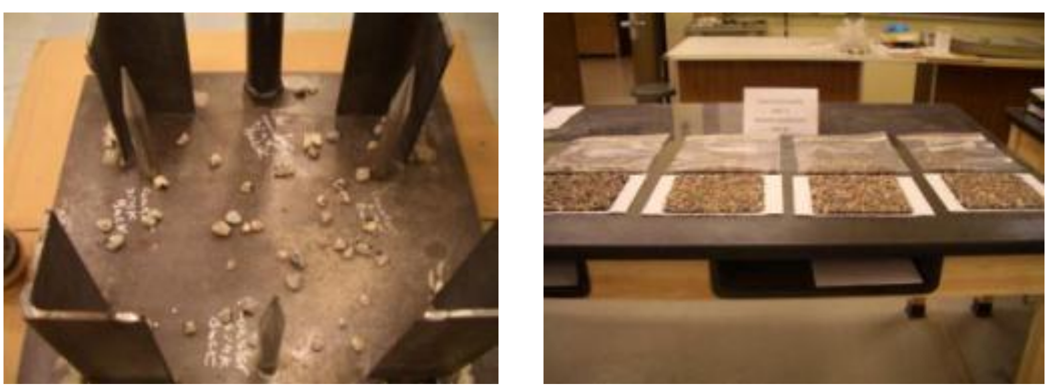
Figure 68. Vialit Test (a) Before and (b) During Application of the Roller to a Plate Specimen

(a) **(b)**

Figure 69. (a) View of a Vialit Plate Specimen After Sweeping, and (b) The Plate After Curing and About to be Tested.

(a) **(b)**

Figure 70. (a) The Plate Placed on the Vialit Test Equipment (The Aggregate and Binder are on the Reverse Side), and (b) The Ball Being Dropped.



(a) **(b)**

Figure 71. (a) Aggregate Collected After the Impact, and (b) Aggregate Retained on Several Plates After Ball Impact Along with the Swept Aggregate

Summary of the Standard Experiments Performed

Table 31 provides a summary of the standard experiments described in Sections B.1 to B.5.

Table 31. Standard Experiment Procedures

Procedure	Test
Sieve Analysis and the Median Size	ASTM C 136 (AASHTO T-27)
Flakiness Index	TEX-224-F
Loose Unit Weight	ASTM C29
Cleanness Value Index	ITD-72
Vialit Test	Modified version of Texas Aggregate Retention Test (TEX-216-F)

Selected Field Visit Pictures

(a) (b)

Figure 72. Two Views of the Aggregate Used at the Chip Sealing Site

(a) (b)

Figure 73. (a) Fresh Oil, and (b) Windshield Damage Warning Signs at the Chip Sealing Site

(a)

(b)

Figure 74. (a) Transverse and (b) Longitudinal Cracks Observed Before Chip Seal Application

(a)

(b)

Figure 75. (a) Sweeping Before Application of the Binder, and (b) The Spraying of the Binder

(a) (b)

Figure 76. (a) The Aggregate Being Carried, and (b) Aggregate Spread on the Area Where the Binder was Sprayed

(a) (b)

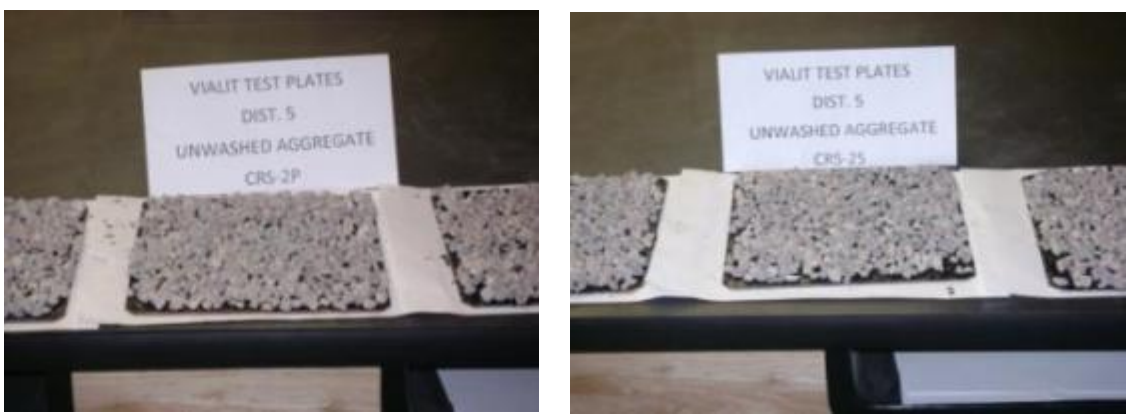
Figure 77. (a) View of the Variation in Applying the Binder Showing Excess Binder, and (b) Pneumatic Rollers Being Used to Roll the Surface After Chip Sealing is Performed

Figure 78. Close-Up View of the Newly Placed Chip Seal Aggregate in the Field

Selected Pictures of Vialit Test Plates

(a) (b)

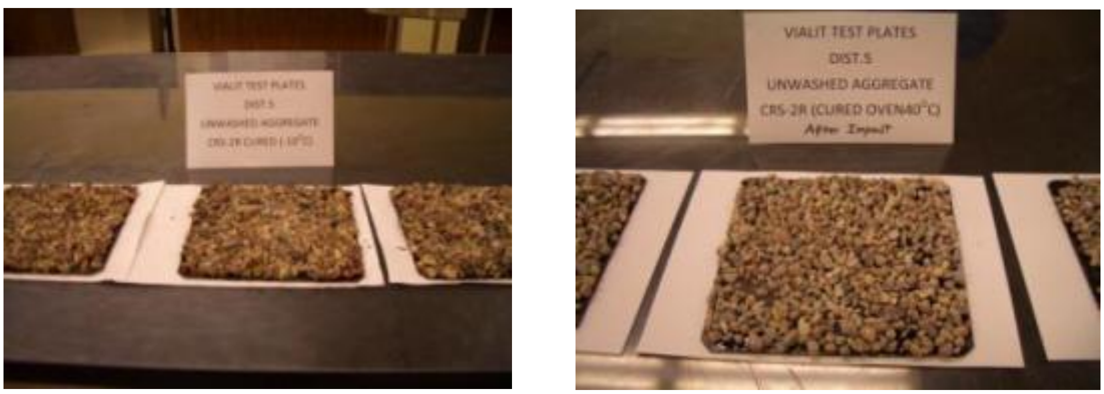
Figure 79. Vialit Test Plates After Tests Were Performed for Unwashed ITD District 5 Aggregate and (a) CRS-2R and (b) CRS-2L Binders



(a) (b)

Figure 80. Vialit Test Plates After Tests Were Performed for Unwashed ITD District 5 Aggregate and (a) CRS-2P and (b) CRS-2S Binders

Figure 81. Vialit Test Plates After Tests Were Performed for Washed ITD District 5 Aggregate and CRS-2R Binder

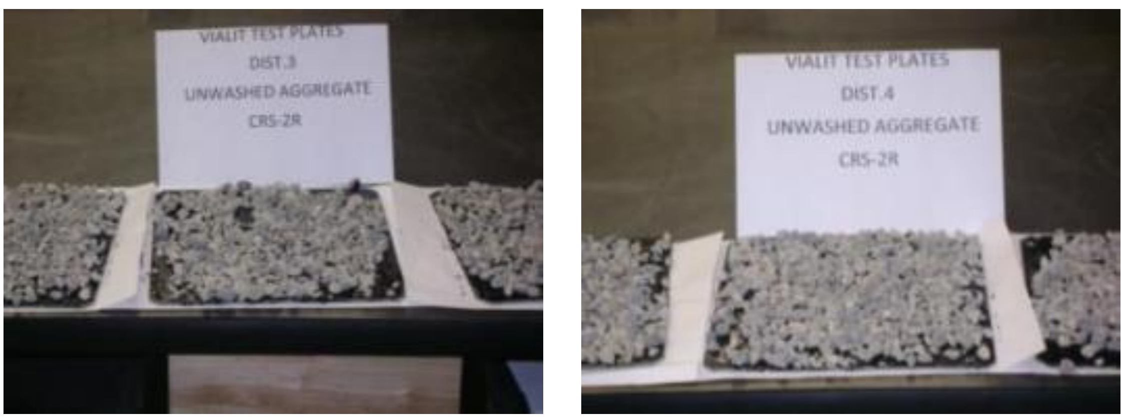


(a) **(b)**

Figure 82. Vialit Test Plates After Tests Were Performed for Unwashed ITD District 5 Aggregate and CRS-2R Binder and Cured at (a) 14^{o}F (-10^{o}C) and (b) 104^{o}F (40^{o}C)

(a) **(b)**

Figure 83. Vialit Test Plates After Tests Were Performed for CRS-2R Binder and Washed (a) ITD Districts 1 and (b) ITD District 6 Aggregate



(a) **(b)**

Figure 84. Vialit Test Plates After Tests Were Performed for CRS-2R Binder and Washed (a) ITD District 3 and (b) ITD District 4 Aggregate

Figure 85. Vialit Test Plates After Tests Were Performed for Washed ITD District 2 Aggregate and CRS-2R Binder

Appendix C

Additional Charts for Determining the Median Sizes

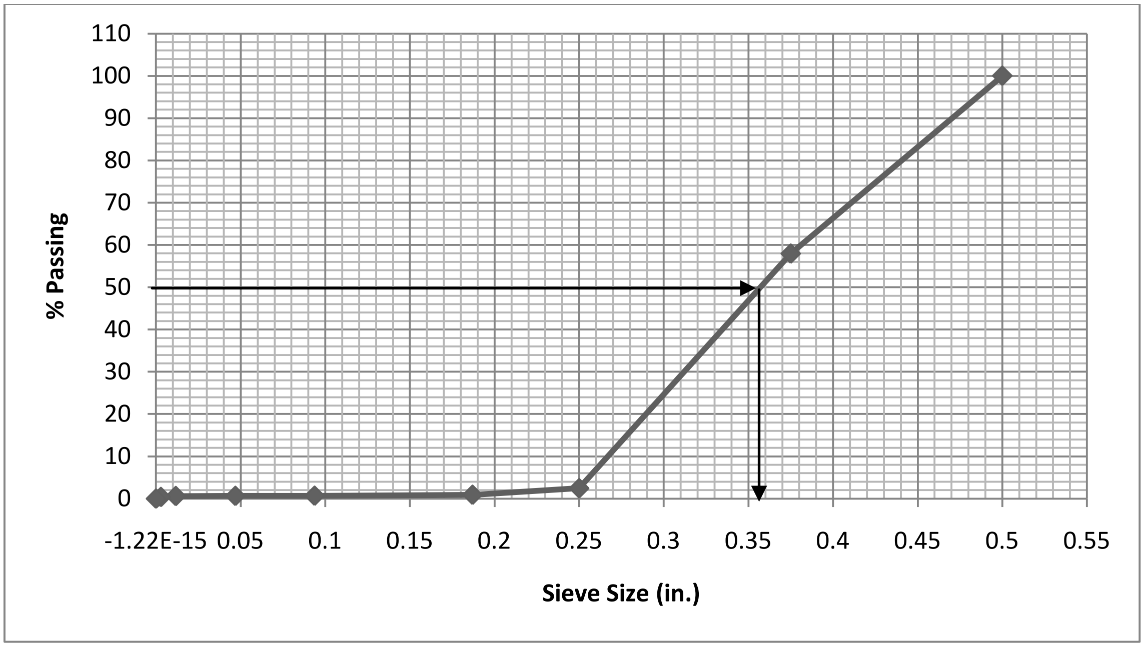


Figure 86. Sieve Analysis for District 1, Sample 1

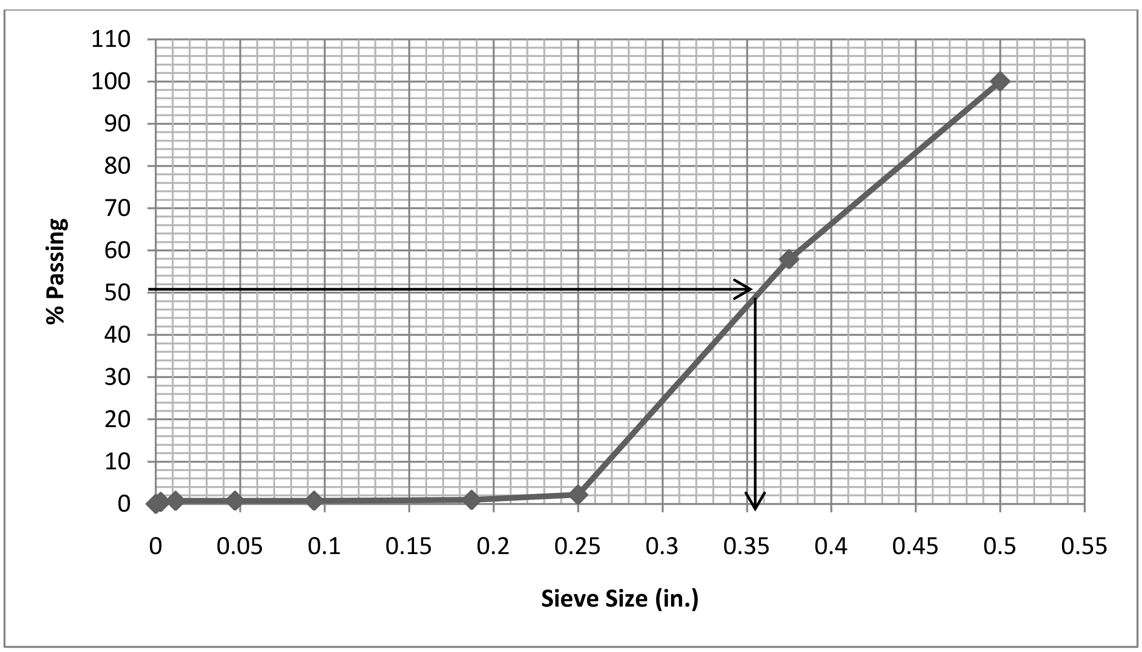


Figure 87. Sieve Analysis for District 1, Sample 2

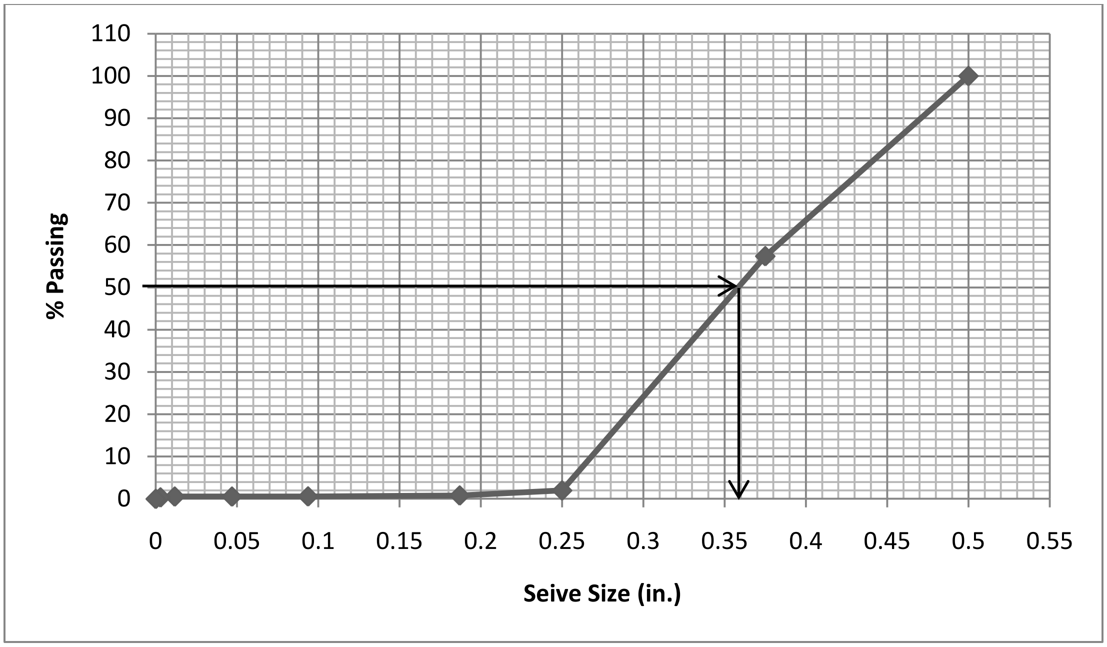


Figure 88. Sieve Analysis for District 1, Sample 3

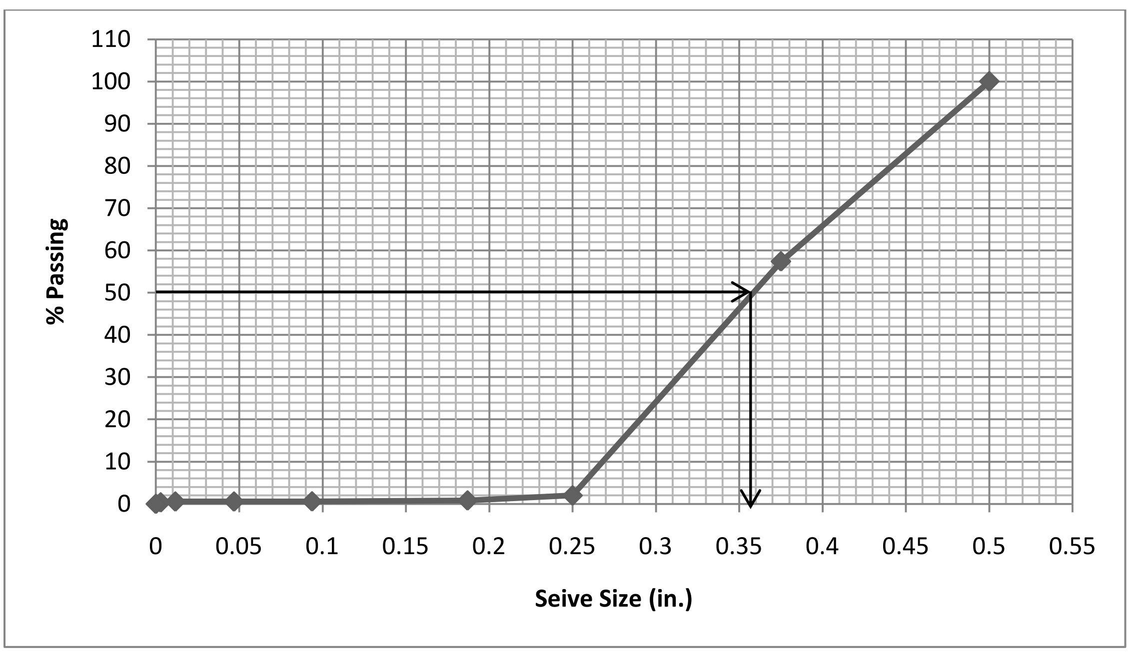


Figure 89. Sieve Analysis for District 1, Sample 4

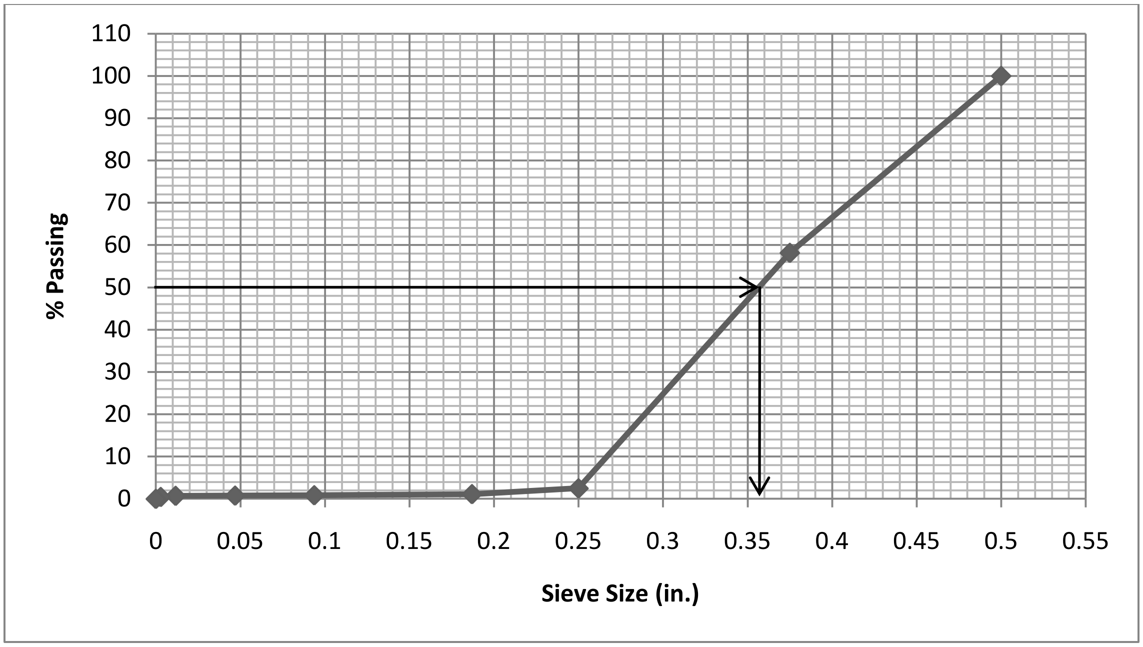


Figure 90. Sieve Analysis for District 1, Sample 5

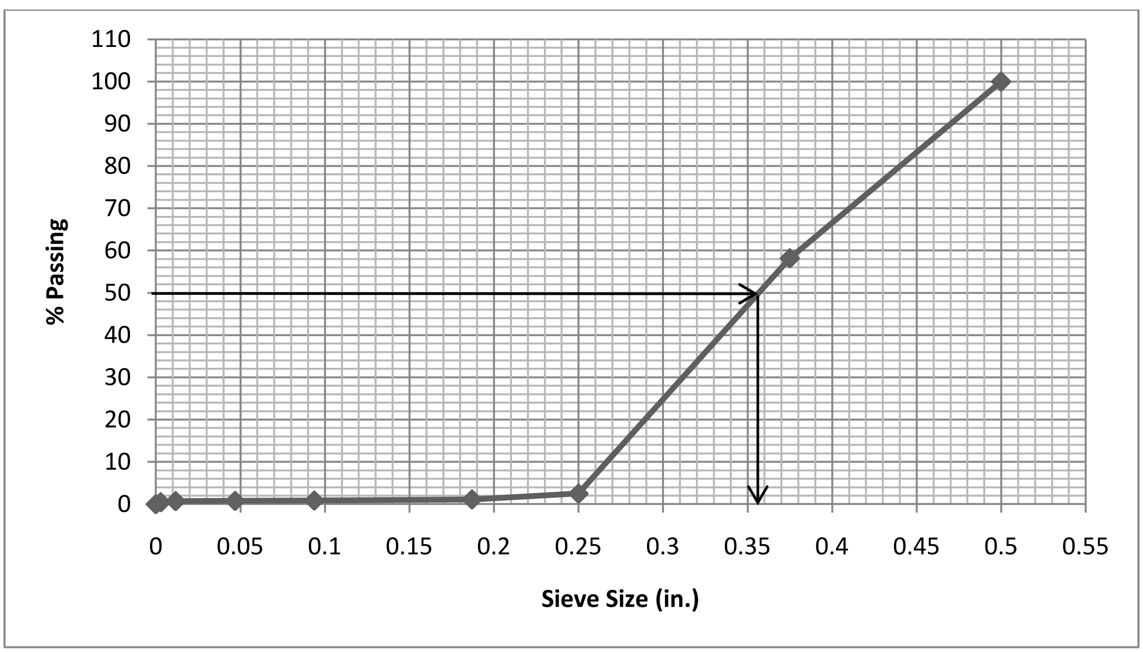


Figure 91. Sieve Analysis for District 1, Sample 6

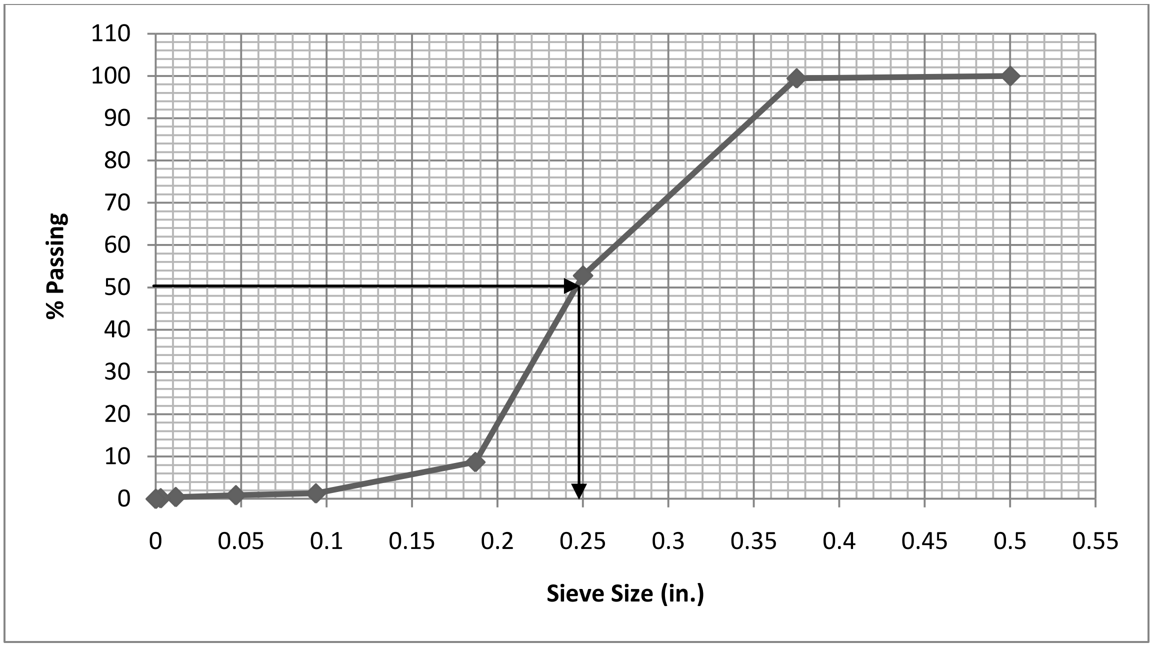


Figure 92. Sieve Analysis for District 2, Sample 1

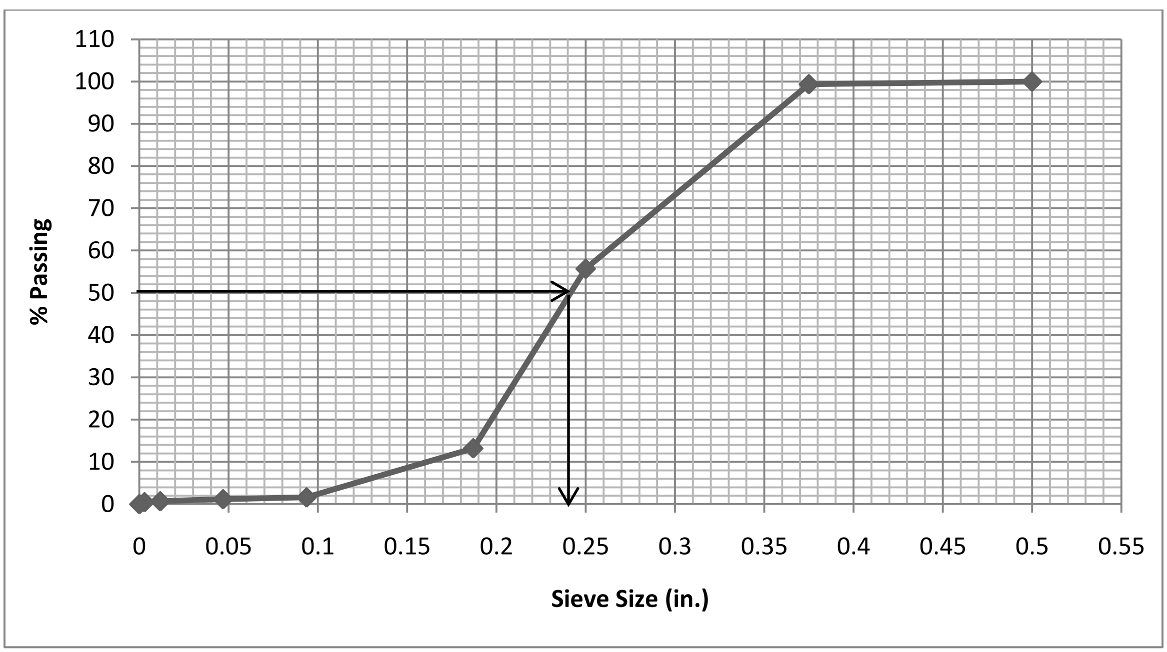


Figure 93. Sieve Analysis for District 2, Sample 2

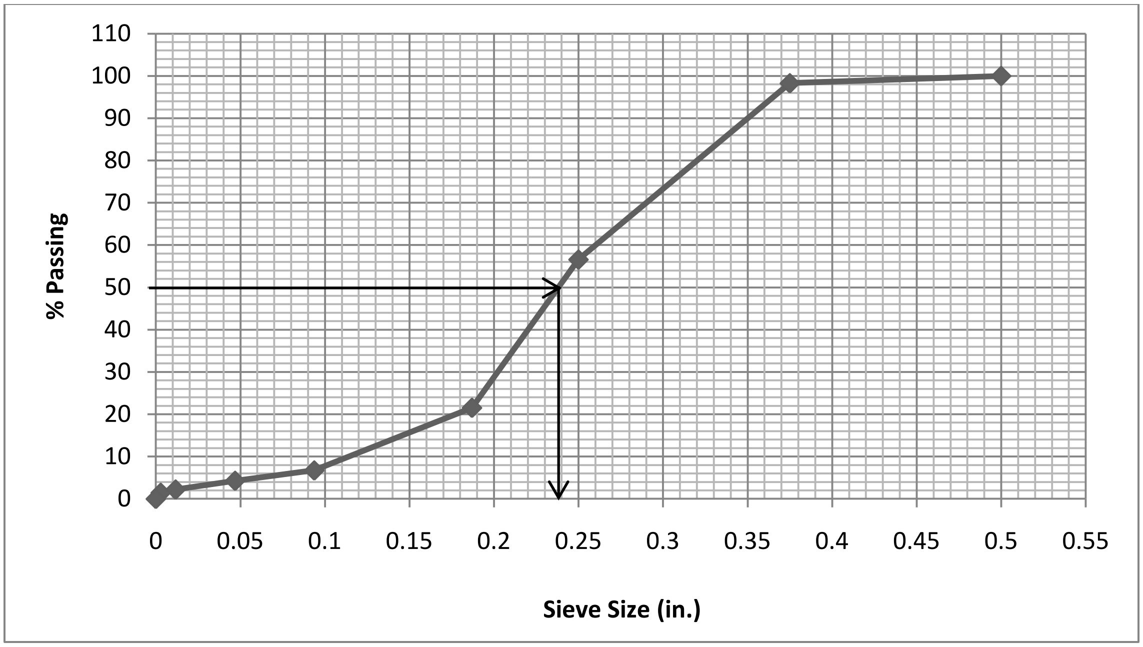


Figure 94. Sieve Analysis for District 2, Sample 3

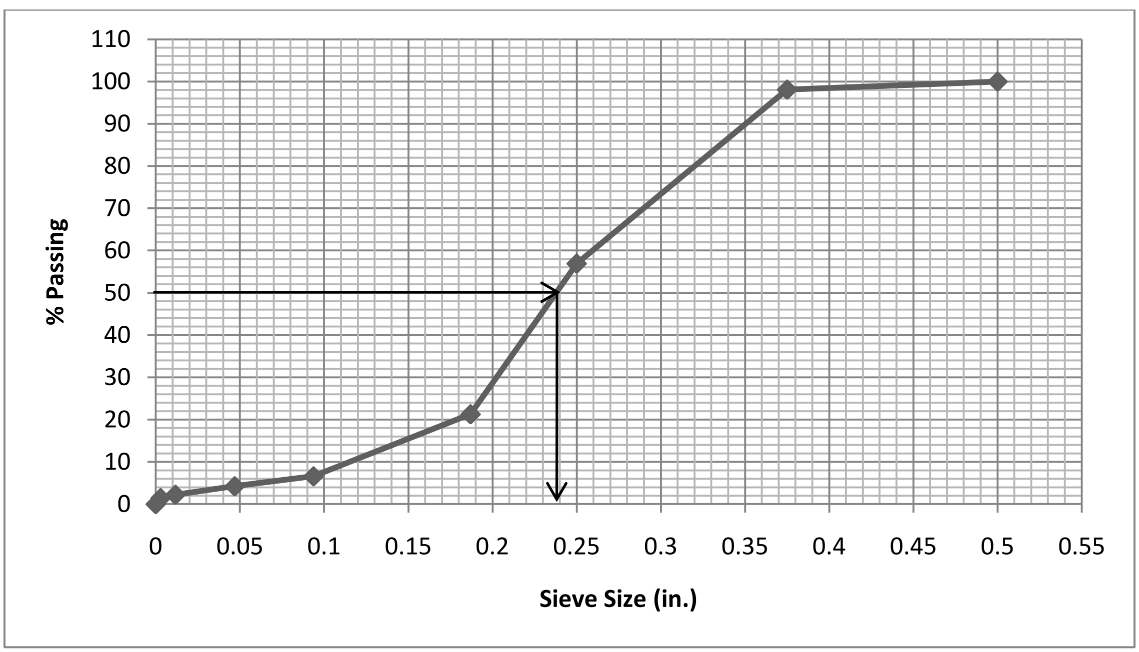


Figure 95. Sieve Analysis for District 2, Sample 4

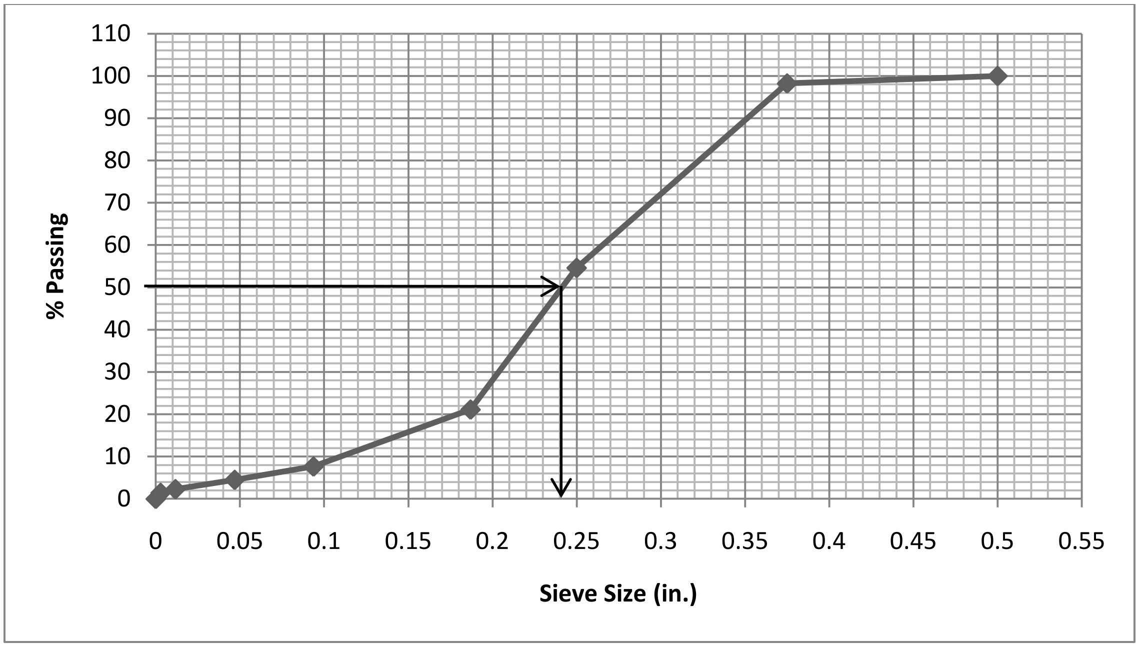


Figure 96. Sieve Analysis for District 2, Sample 5

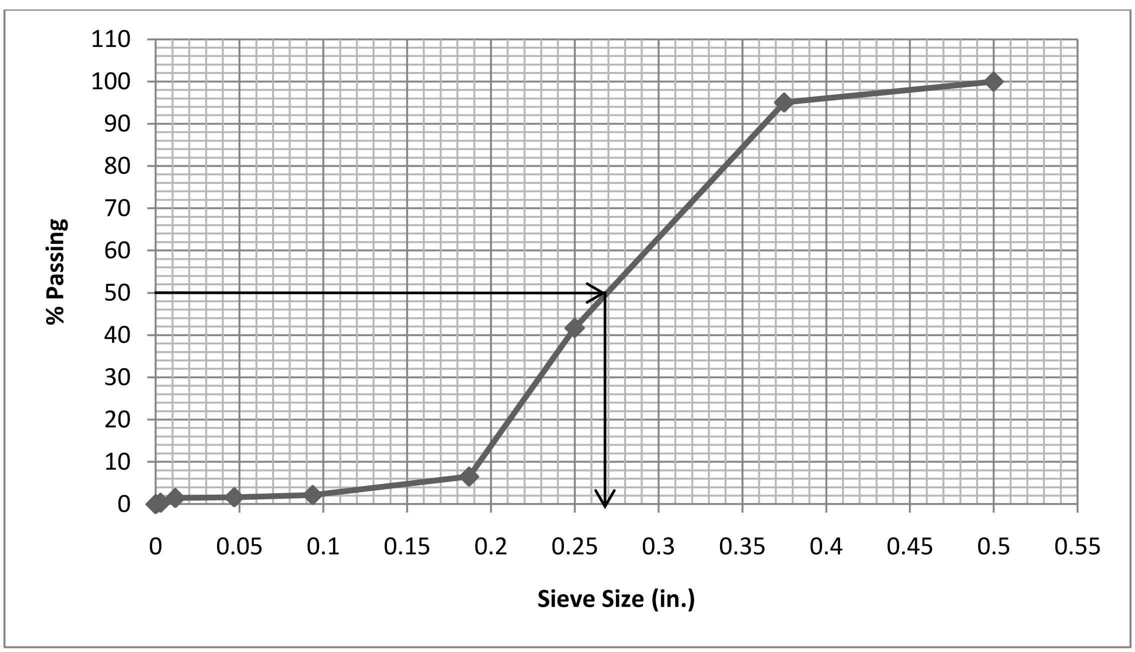


Figure 97. Sieve Analysis for District 3, Sample 1

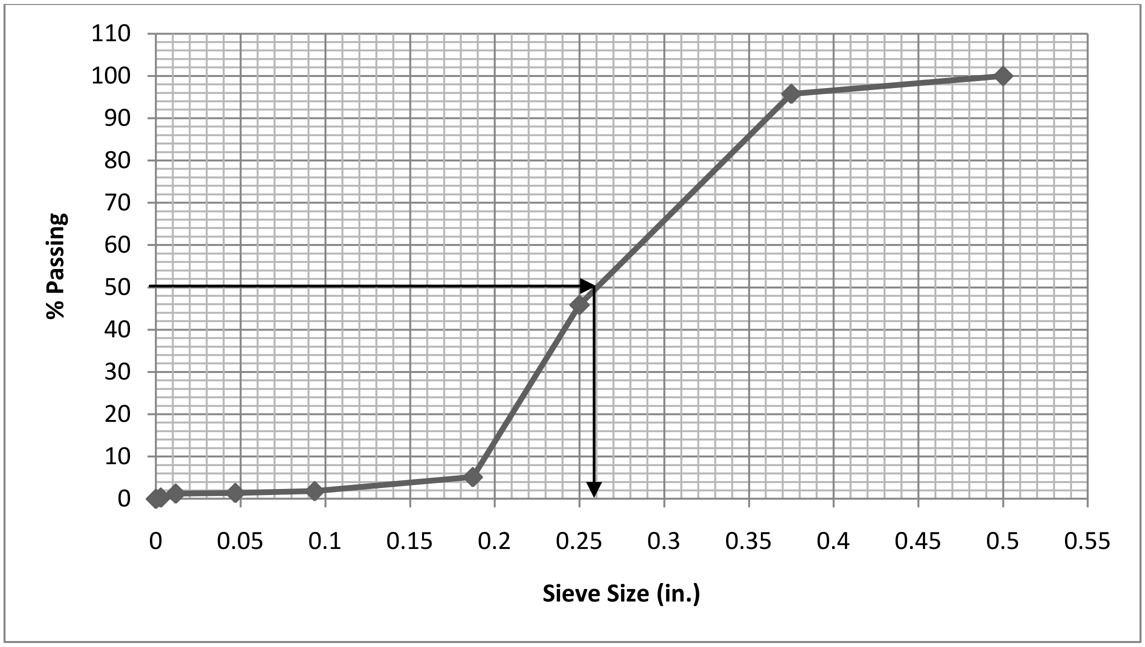


Figure 98. Sieve Analysis for District 3, Sample 2

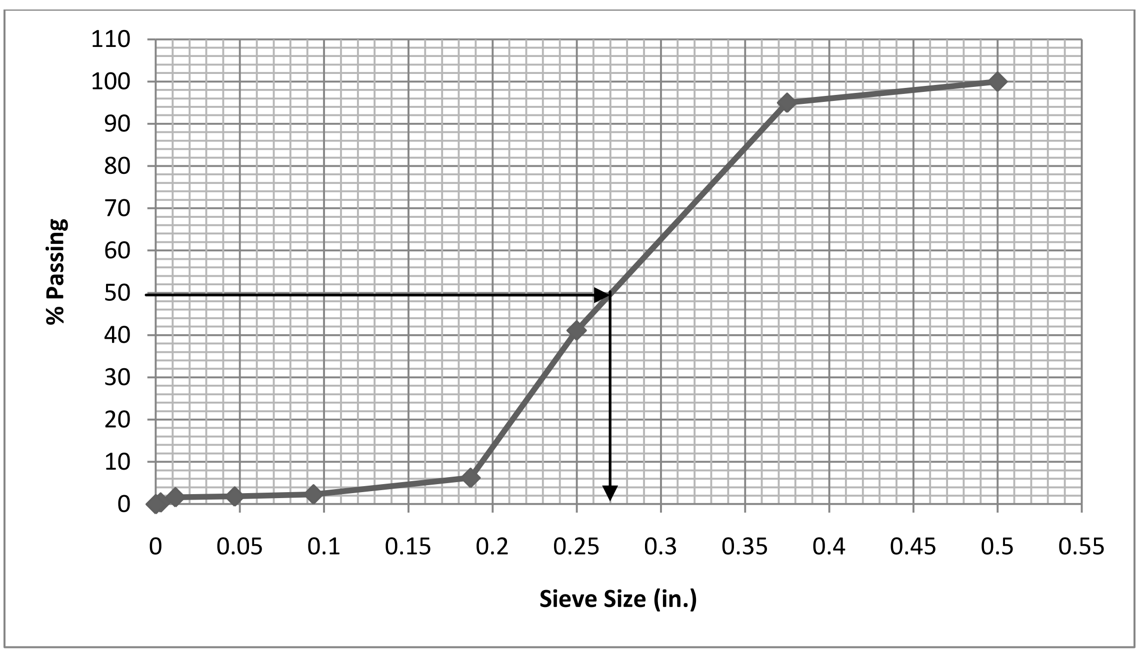


Figure 99. Sieve Analysis for District 3, Sample 3

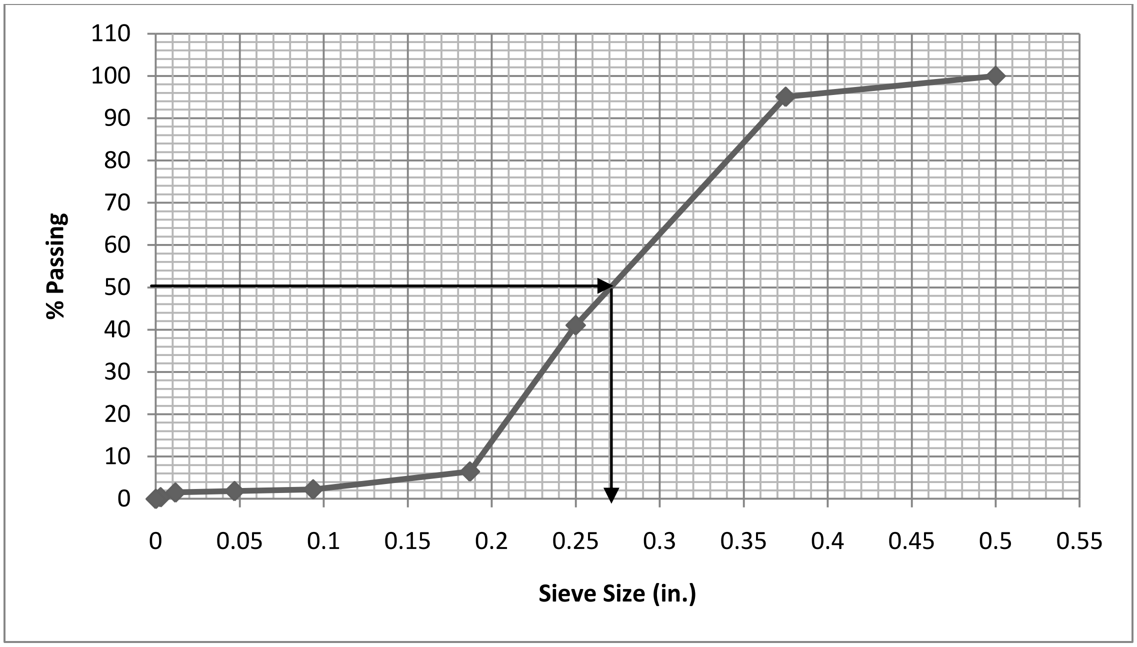


Figure 100. Sieve Analysis for District 3, Sample 4

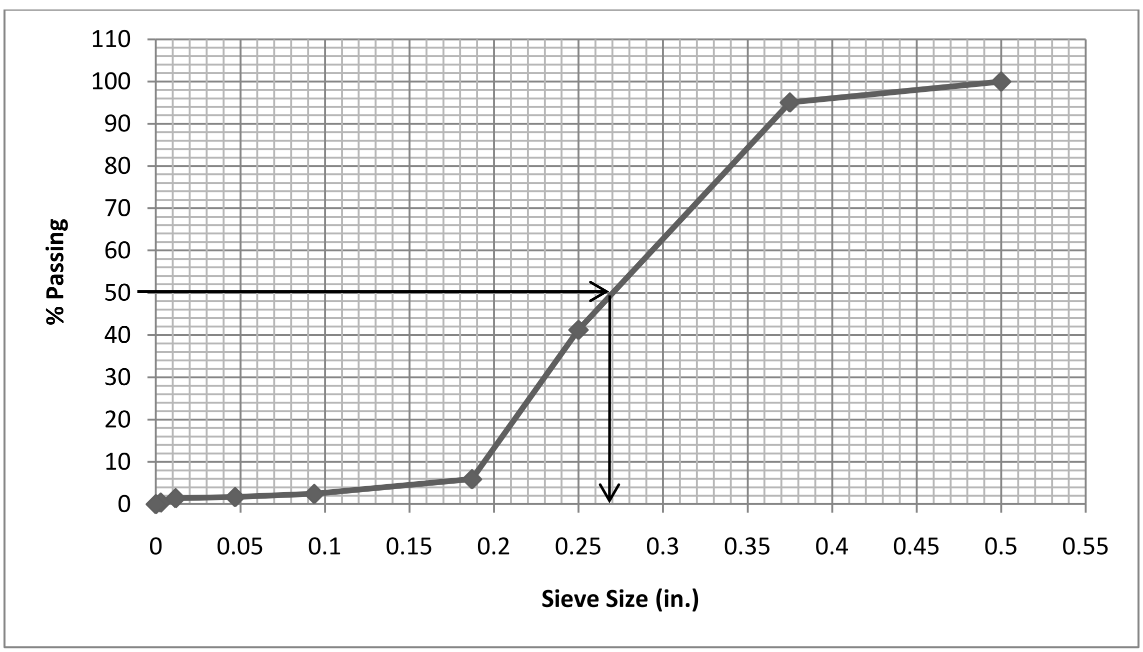


Figure 101. Sieve Analysis for District 3, Sample 5

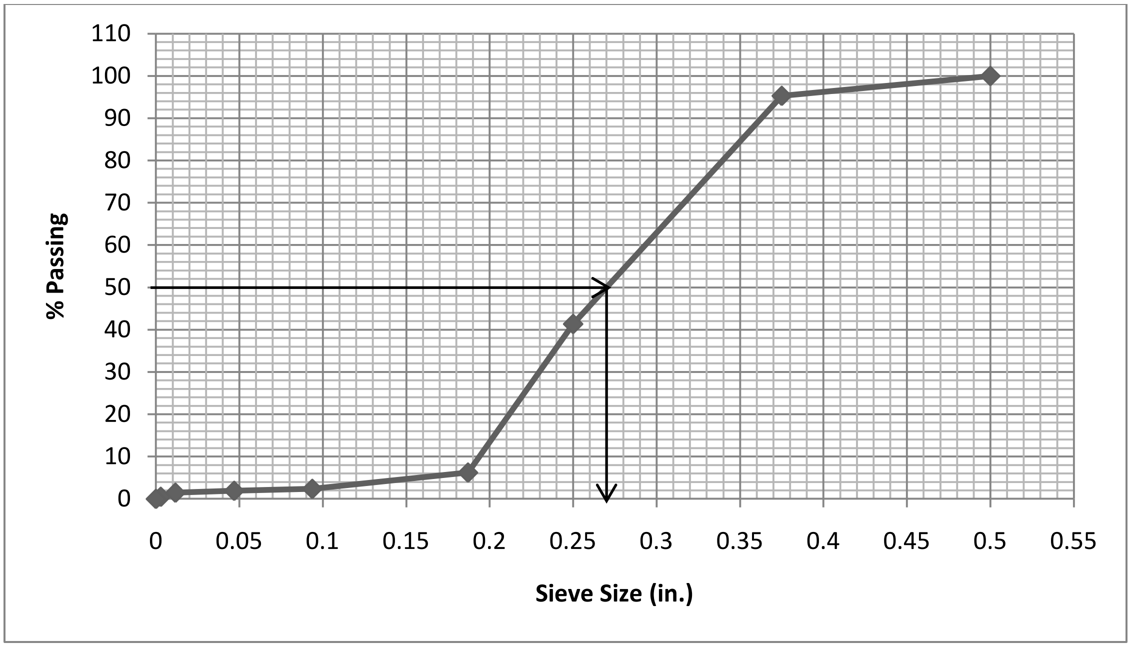


Figure 102. Sieve Analysis for District 3, Sample 6

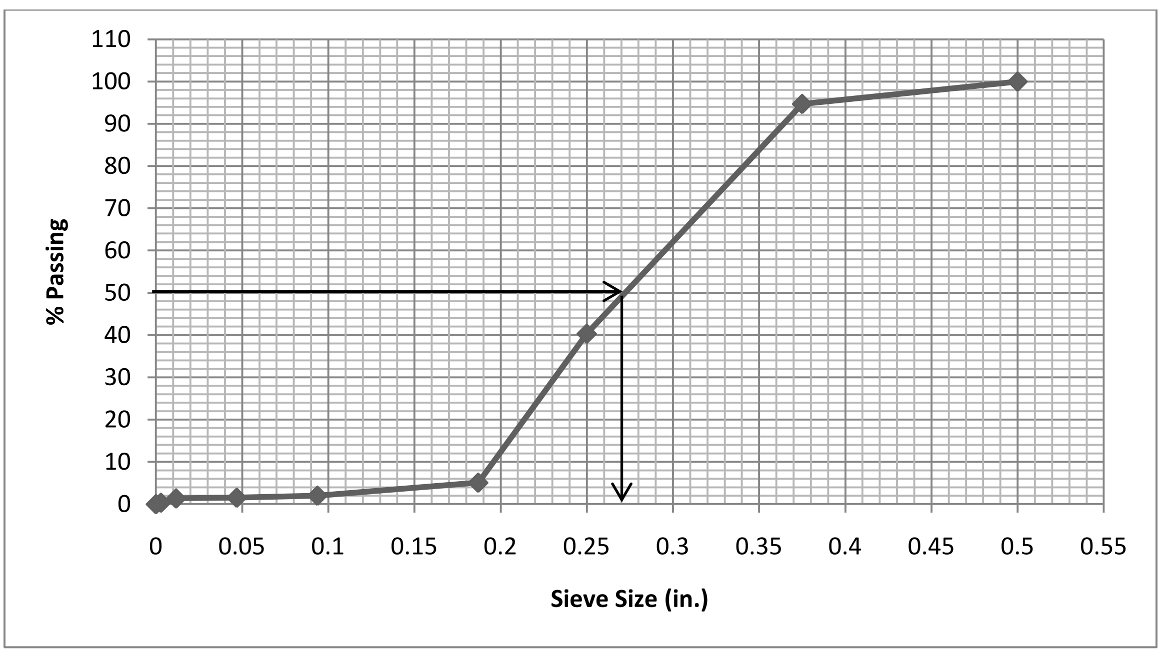


Figure 103. Sieve Analysis for District 4, Sample 1

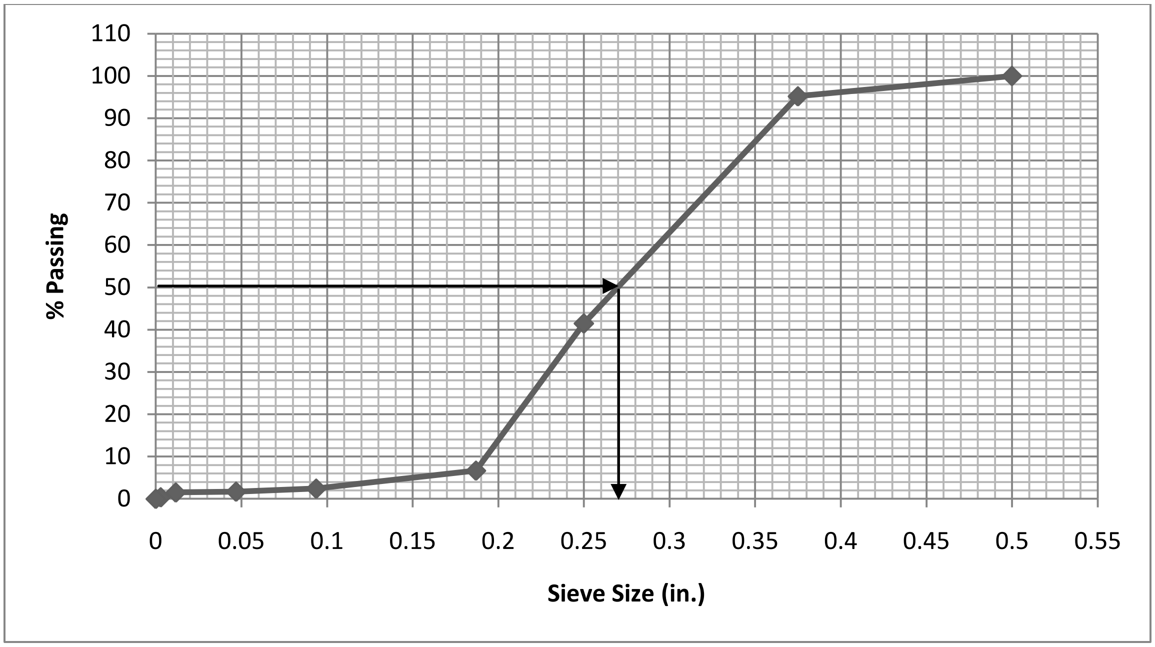


Figure 104. Sieve Analysis for District 4, Sample 2

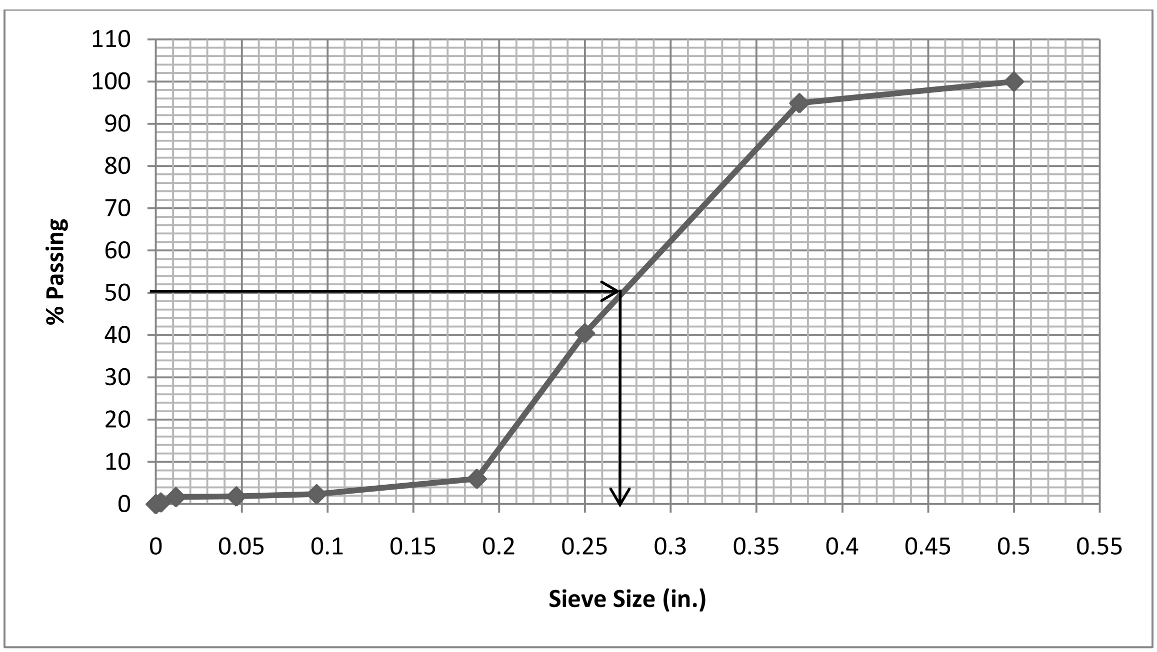


Figure 105. Sieve Analysis for District 4, Sample 3

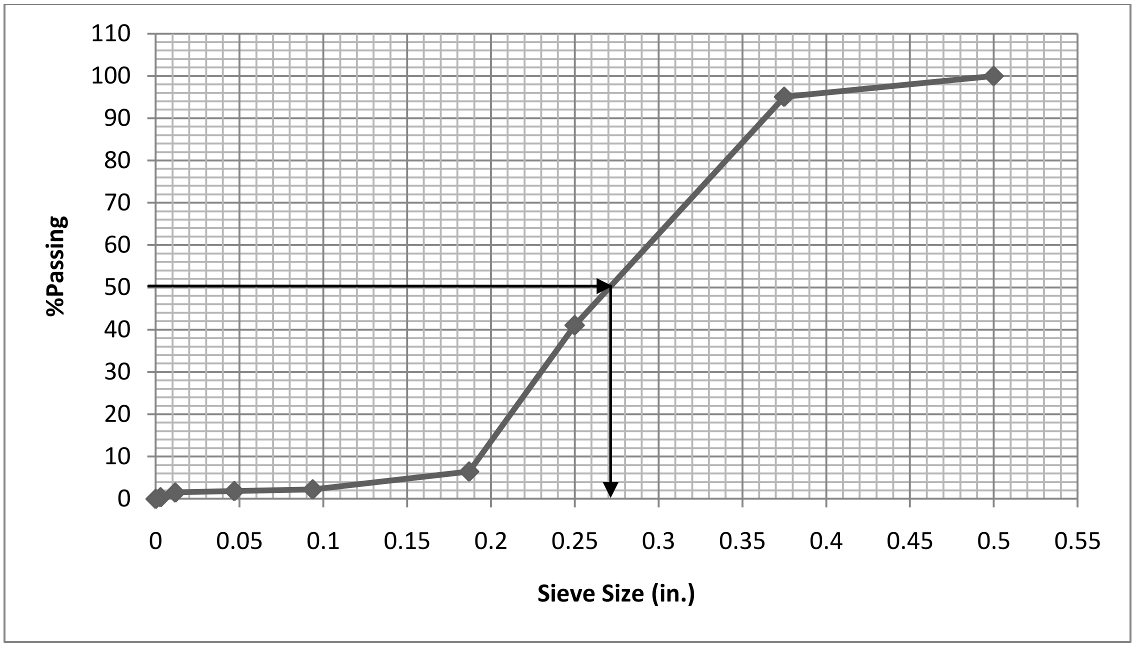


Figure 106. Sieve Analysis for District 4, Sample 4

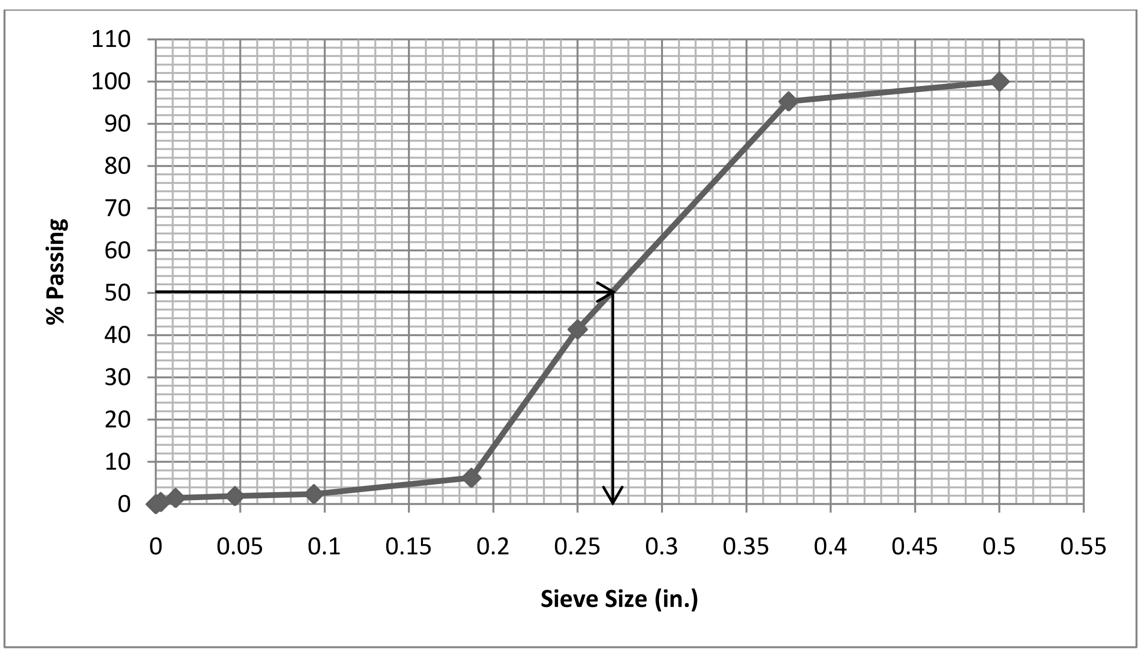


Figure 107. Sieve Analysis for District 4, Sample 5

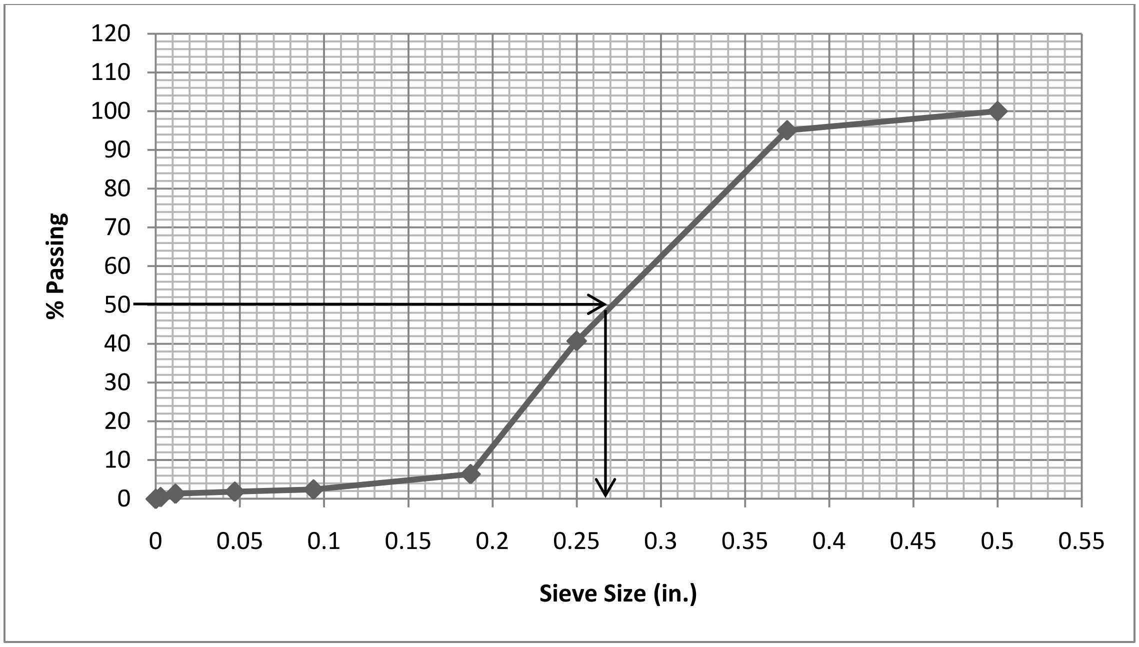


Figure 108. Sieve Analysis for District 4, Sample 6

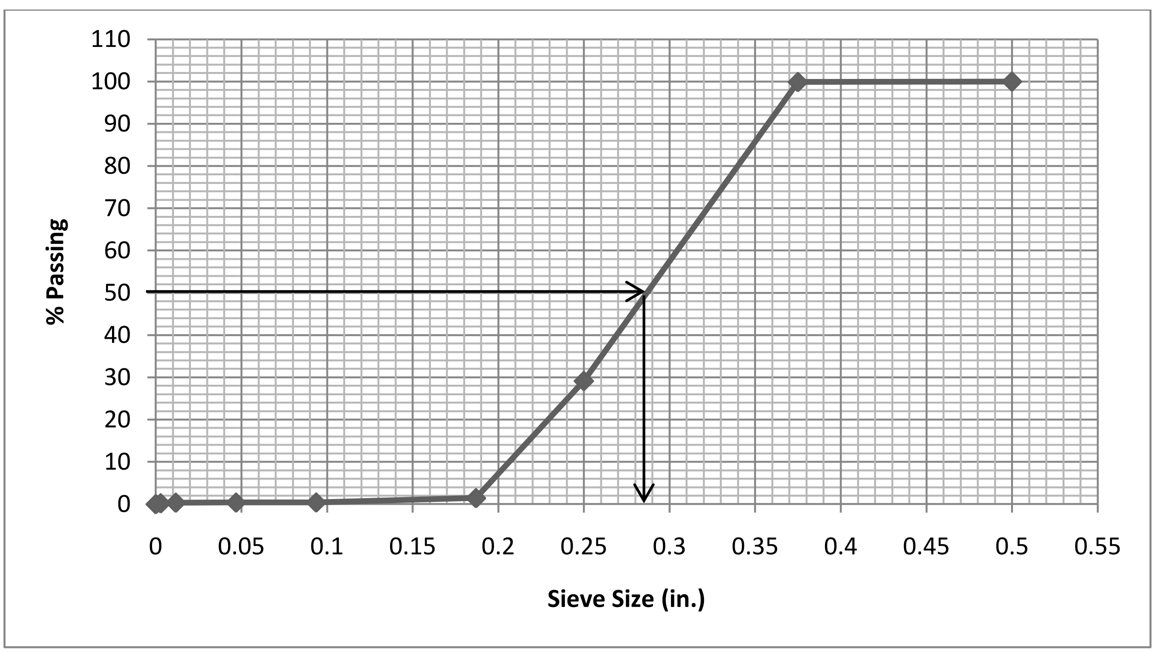


Figure 109. Sieve Analysis for District 5, Sample 1

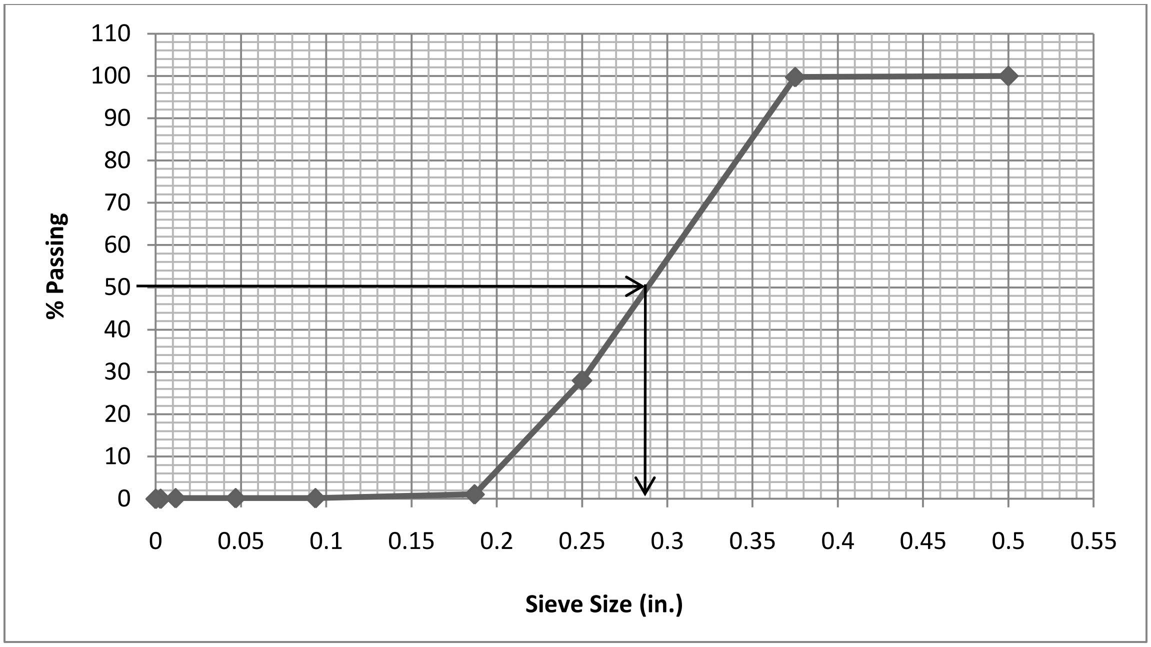


Figure 110. Sieve Analysis for District 5, Sample 2

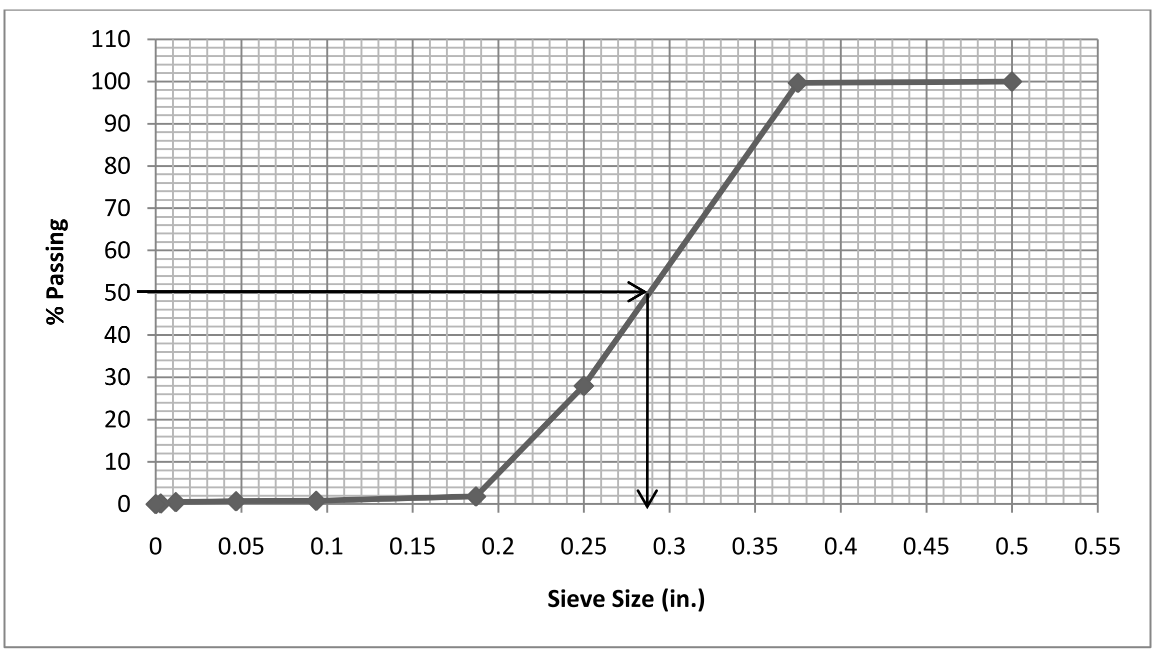


Figure 111. Sieve Analysis for District 5, Sample 3

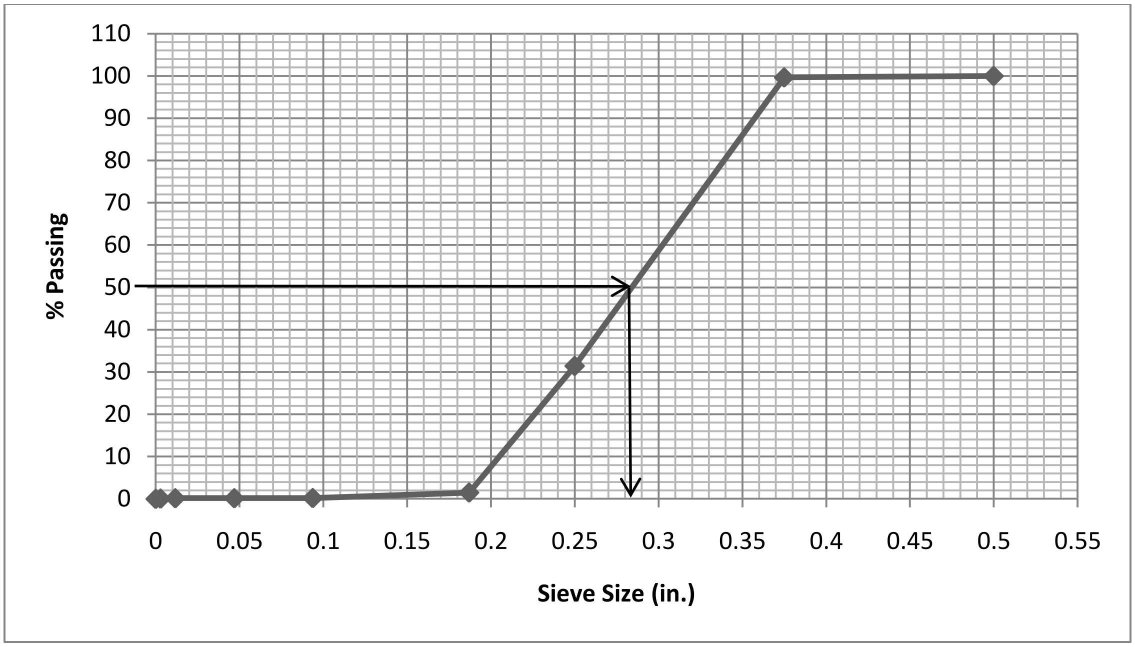


Figure 112. Sieve Analysis for District 5, Sample 4

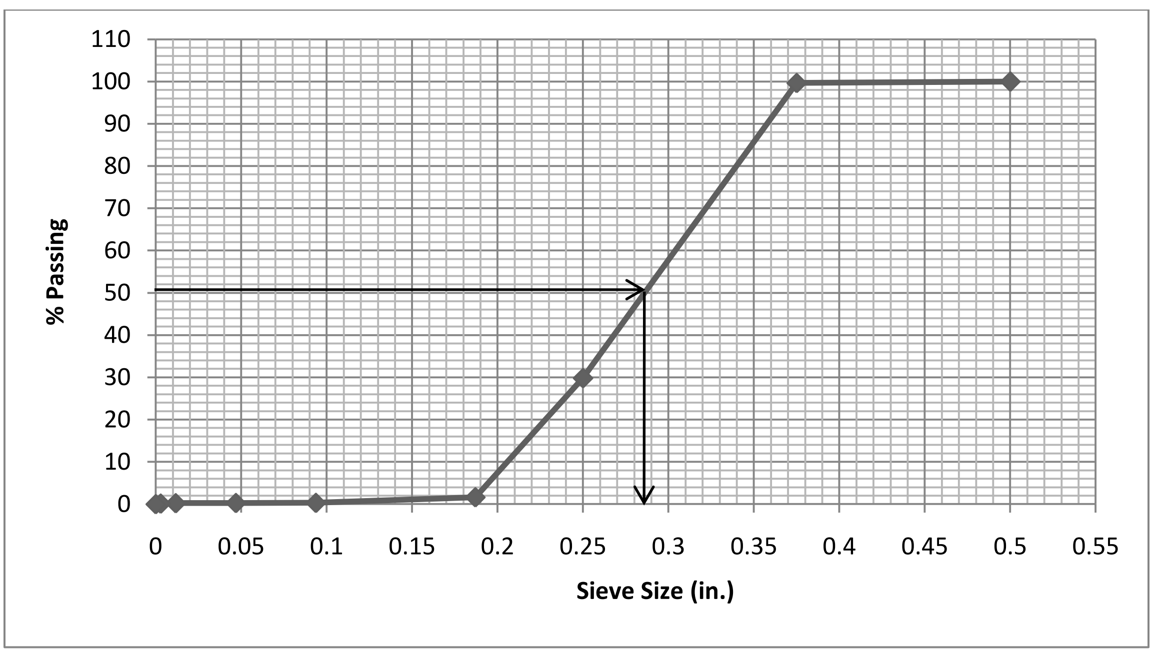


Figure 113. Sieve Analysis for District 5, Sample 5

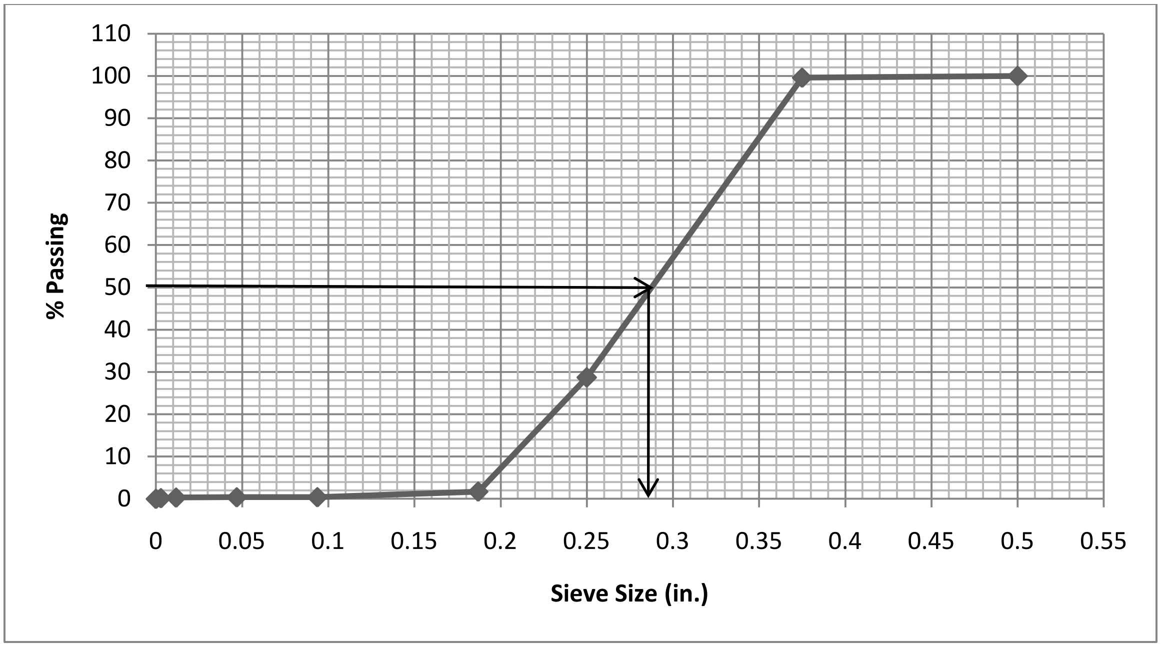


Figure 114. Sieve Analysis for District 5, Sample 6

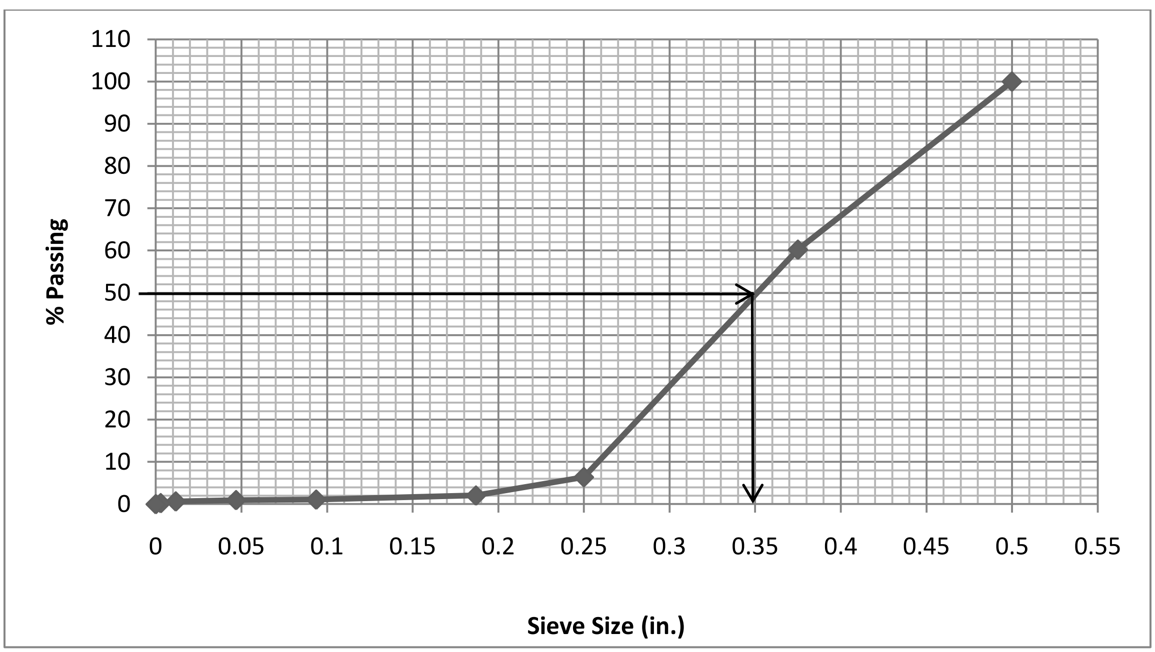


Figure 115. Sieve Analysis for District 6, Sample 1

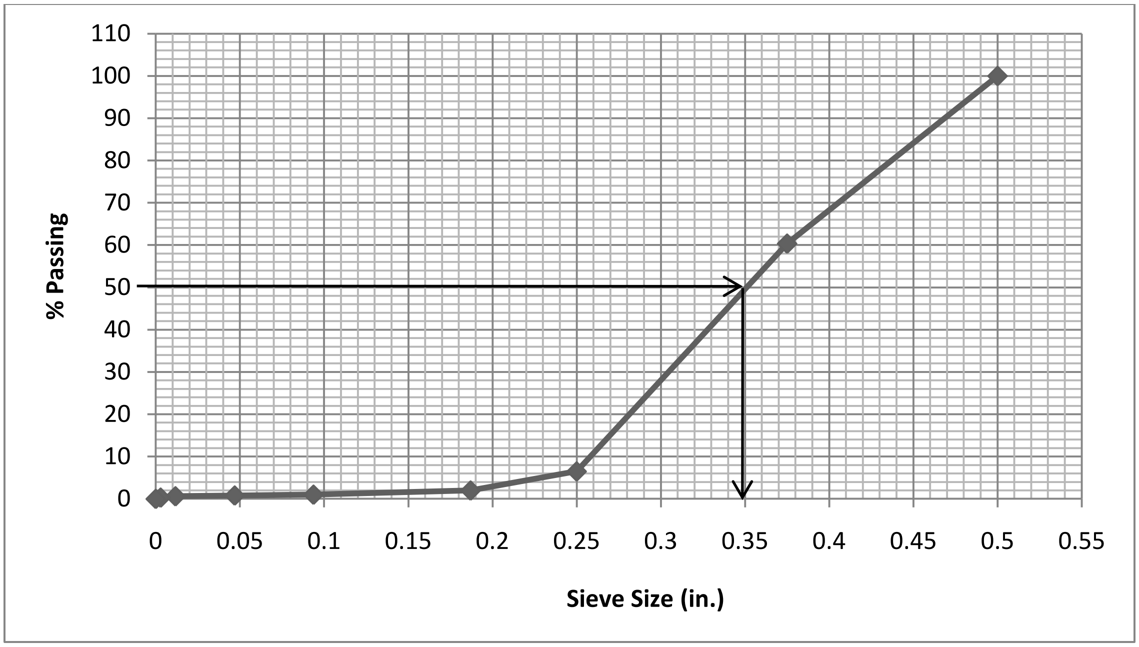


Figure 116. Sieve Analysis for District 6, Sample 2

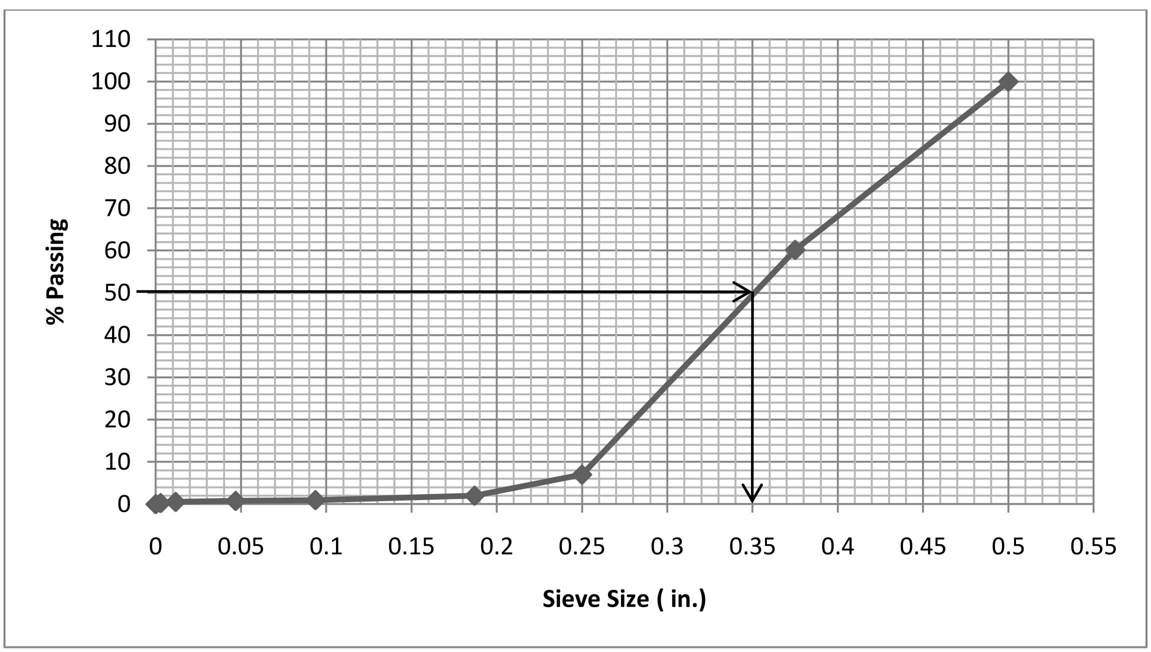


Figure 117. Sieve Analysis for District 6, Sample 3

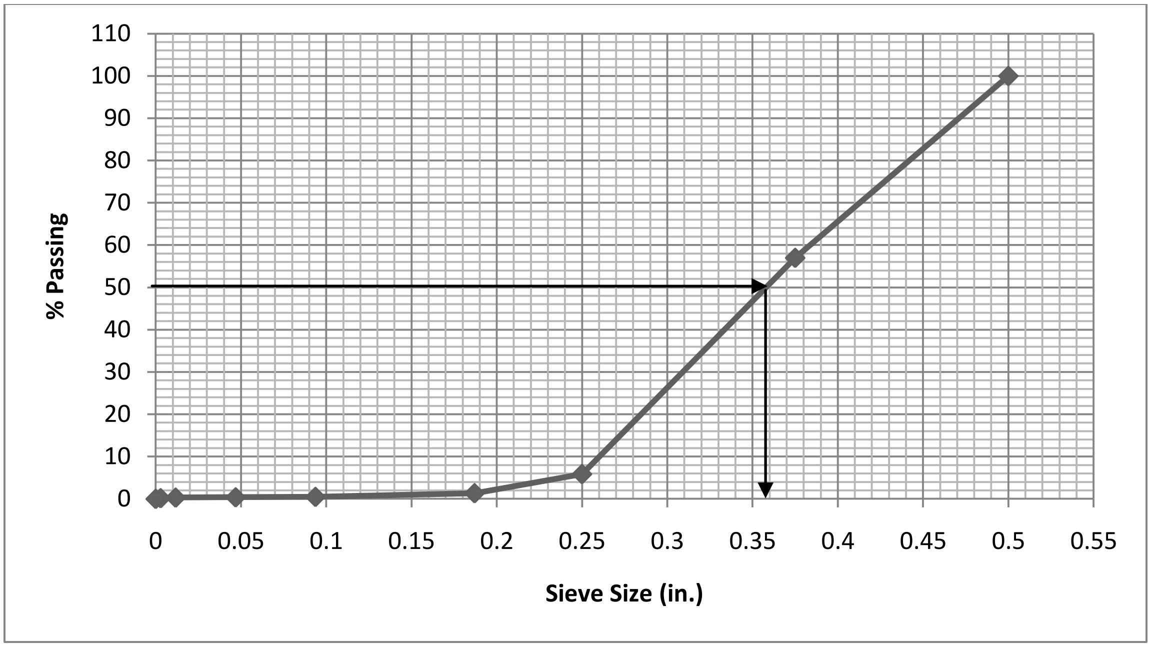


Figure 118. Sieve Analysis for District 6, Sample 4

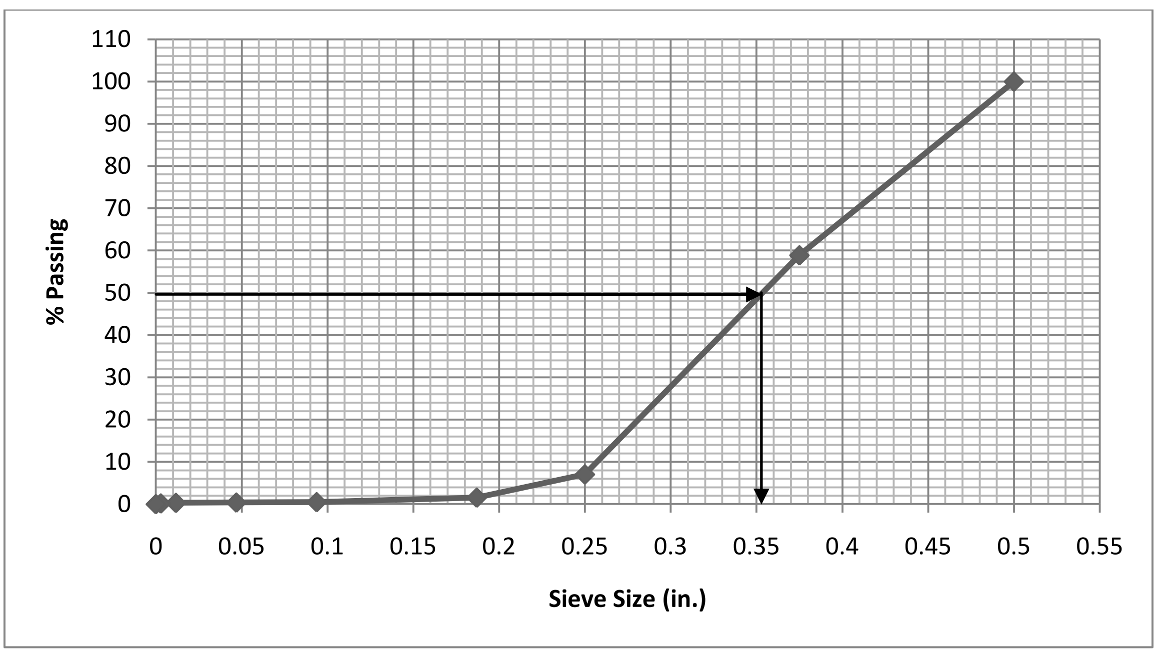


Figure 119. Sieve Analysis for District 6, Sample 5

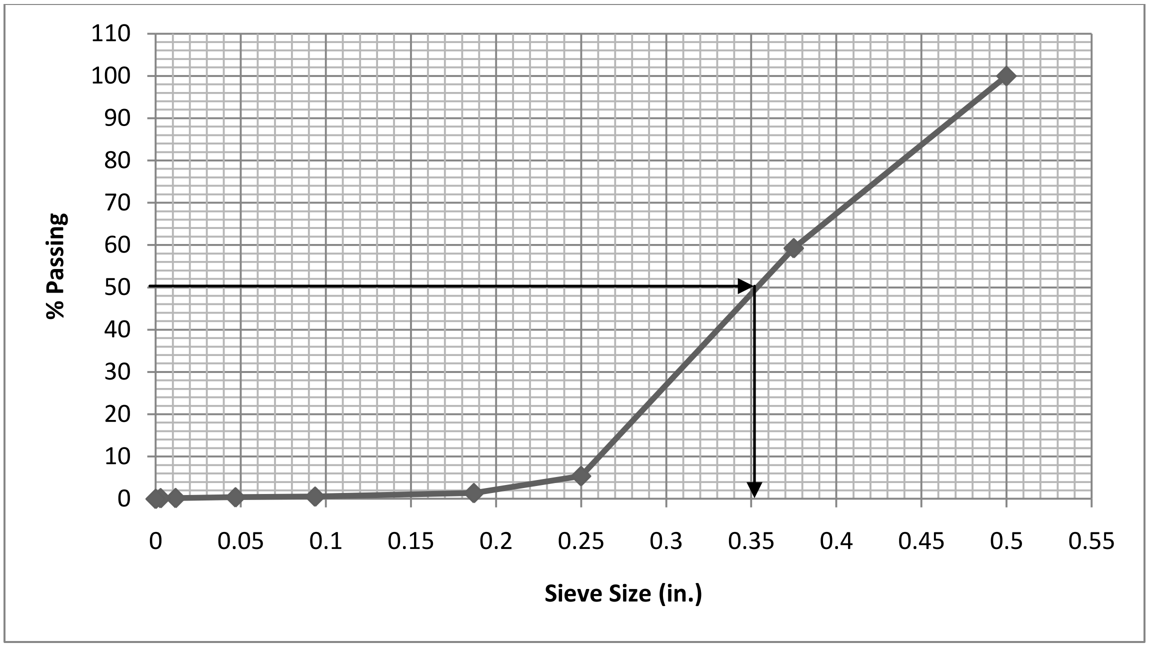


Figure 120. Sieve Analysis for District 6, Sample 6

Appendix D

Sample Design Calculations

ITD District 1 McLeod Design Method:

Median Size = M = 0.359

Flakiness Index = FI = 16.86%

Cleanness Value = CV = 92.4%

Loose Unit Weight = W = 91.7 lb/ft^3

Bulk Specific Gravity = G = 2.67 (Assumed)

Area of Plate = 0.0478 yd^2

Average Least Dimension = $H = \frac{M}{1.139285+0.011506\,(FI)}$ = 0.269 in.

Void Ratio = $V = 1 - \left(\frac{W}{62.4\times G}\right)$ = 0.449

Aggregate Application Ratio = C = 46.8 (1-0.4V) ×H×G×E = 28.95 lb/yd^2

$B_1 = \frac{(2.244\times H\times T\times V)+S+A}{R}$ = 0.242 gal/yd^2

$B_2 = \frac{(2.244\times M\times T\times V)+S+A}{R}$ = 0.324 gal/yd^2

$B = \frac{B_{1+}B_2}{2} = 0.283$ gal/yd^2

Amount of Aggregate = 28.95 × 0.0478 = 1.38 lb = 627.7 g

Amount of Binder = 0.283 × 0.0478 = 0.013 gal = 51.2 cc

Note that the last two values for the amount of aggregate and the amount of binder for use with Vialit tests were converted to metric units for laboratory use.

ITD District 2 McLeod Design Method:

Median Size = M = 0.2408

Flakiness Index = FI = 21.318%

Cleanness Value = CV = 79.18%

Loose Unit Weight = W = 95.5 lb/ft^3

Bulk Specific Gravity = G = 2.67 (Assumed)

Area of Plate = 0.0478 yd^2

Average Least Dimension = $H = \frac{M}{1.139285+0.011506\ (FI)}$ = 0.174 in.

Void Ratio = $V = 1 - \left(\frac{W}{62.4 \times G}\right)$ = 0.427

Aggregate Application Ratio = C= 46.8 (1-0.4V) ×H×G×E = 18.93 lb/yd^2

$B_1 = \frac{(2.244 \times H \times T \times V) + S + A}{R}$ = 0.149 gal/yd^2

$B_2 = \frac{(2.244 \times M \times T \times V) + S + A}{R}$ = 0.2066 gal/yd^2

$B = \frac{B_{1+}B_2}{2} = 0.1778\ \text{gal/yd}^2$

Amount of Aggregate = 18.93 × 0.0478 = 0.90 lb = 410.44 g

Amount of Binder = 0.2066 × 0.0478 = 0.0098 gal = 37.09 cc

Note that the last two values for the amount of aggregate and the amount of binder for use with Vialit tests were converted to metric units for laboratory use.

ITD District 3 McLeod Design Method:

Median Size =M= 0.268

Flakiness Index = FI = 9.233%

Cleanness Value = CV = 92.4%

Loose Unit Weight = W = 91.59 lb/ft^3

Bulk Specific Gravity = G = 2.67 (Assumed)

Area of Plate = 0.0478 yd^2

Average Least Dimension = $H = \frac{M}{1.139285+0.011506(FI)}$ = 0.215 in.

Void Ratio = $V = 1 - \left(\frac{W}{62.4 \times G}\right)$ = 0.45

Aggregate Application Ratio = C= 46.8 (1-0.4V) ×H×G×E = 23.13 lb/yd^2

$B_1 = \frac{(2.244 \times H \times T \times V)+S+A}{R}$ = 0.1944 gal/yd^2

$B_2 = \frac{(2.244 \times M \times T \times V)+S+A}{R}$ = 0.242 gal/yd^2

$$B = \frac{B_{1+}B_2}{2} = 0.2182\ \text{gal/yd}^2$$

Amount of Aggregate = 23.13 × 0.0478 = 1.1056 lb = 501.5 g

Amount of Binder = 0.2182 × 0.0478 = 0.01023 gal = 39.48 cc

Note that the last two values for the amount of aggregate and the amount of binder for use with Vialit tests were converted to metric units for laboratory use.

ITD District 4 McLeod Design Method:

Median Size = M = 0.266

Flakiness Index = FI = 9.57%

Cleanness Value = CV = 90.6%

Loose Unit Weight = W = 91.5 lb/ft^3

Bulk Specific Gravity = G = 2.67 (Assumed)

Area of Plate = 0.0478 yd^2

Average Least Dimension = $H = \frac{M}{1.139285+0.011506(FI)}$ = 0.213 in.

Void Ratio = $V = 1 - \left(\frac{W}{62.4\times G}\right)$ = 0.45

Aggregate Application Ratio = C= 46.8 (1-0.4V) ×H×G×E = 22.91 lb/yd^2

$B_1 = \frac{(2.244\times H\times T\times V)+S+A}{R}$ = 0.1926 gal/yd^2

$B_2 = \frac{(2.244\times M\times T\times V)+S+A}{R}$ = 0.24 gal/yd^2

$B = \frac{B_{1+}B_2}{2} = 0.2163\ \text{gal/yd}^2$

Amount of Aggregate = 22.91 × 0.0478 = 1.1095 lb = 496.73 g

Amount of Binder = 0.2163 × 0.0478 = 0.01033 gal = 39.13 cc

Note that the last two values for the amount of aggregate and the amount of binder for use with Vialit tests were converted to metric units for laboratory use.

ITD District 5 McLeod Design Method:

Median Size = M = 0.283

Flakiness Index = FI = 5.47%

Cleanness Value = CV = 94%

Loose Unit Weight = W = 96.719 lb/ft^3

Bulk Specific Gravity = G = 2.64 (Assumed)

Area of Plate = 0.0478 yd^2

Average Least Dimension = $H = \frac{M}{1.139285+0.011506(FI)}$ = 0.235 in.

Void Ratio = $V = 1 - \left(\frac{W}{62.4 \times G}\right)$ = 0.412

Aggregate Application Ratio = S = 46.8 (1-0.4V) ×H×G×E = 25.46 lb/yd^2

$C_1 = \frac{(2.244 \times H \times T \times V) + S + A}{R}$ = 0.1945 gal/yd^2; T=0.6 as ADT> 2000.

$C_2 = \frac{(2.244 \times M \times T \times V) + S + A}{R}$ = 0.232 gal/yd^2 M is the same median

$B = \frac{B_{1+}B_2}{2} = 0.213 \text{ gal/yd}^2$

Amount of Aggregate = A = 25.4 × 0.0478 = 0.90 lb = 552.92 g

Amount of Binder = B = 0.213 × 0.0478 = 0.01 gal = 38.53 cc = 40.46 g

Note that the last two values for the amount of aggregate and the amount of binder for use with Vialit tests were converted to metric units for laboratory use.

ITD District 6 McLeod Design Method:

Median Size = M = 0.353

Flakiness Index = FI = 11.375%

Cleanness Value = CV = 81%

Loose Unit Weight = W = 87.15 lb/ft^3

Bulk Specific Gravity = G = 2.67 (Assumed)

Area of Plate = 0.0478 yd^2

Average Least Dimension = $H = \frac{M}{1.139285+0.011506(FI)}$ = 0.278 in.

Void Ratio = $V = 1 - \left(\frac{W}{62.4\times G}\right)$ = 0.477

Aggregate Application Ratio = C = 46.8 (1-0.4V) ×H×G×E = 29.5 lb/yd^2

$B_1 = \frac{(2.244\times H\times T\times V)+S+A}{R}$ = 0.266 gal/yd^2

$B_2 = \frac{(2.244\times M\times T\times V)+S+A}{R}$ = 0.338 gal/yd^2

$B = \frac{B_{1+}B_2}{2} = 0.302\ \text{gal/yd}^2$

Amount of Aggregate = 29.5 × 0.0478 = 1.41 lb = 639.62 g

Amount of Binder = 0.302 × 0.0478 = 0.0144 gal = 54.64 cc

Note that the last two values for the amount of aggregate and the amount of binder for use with Vialit tests were converted to metric units for laboratory use.

Appendix E

Analysis of Variance (ANOVA) for Selected Data in Chapter 4

Table 32. ANOVA Results of Washed and Unwashed Aggregate from Table 24

Aggregates Washed/ Unwashed	Sum of Squares	Degrees of Freedom (df)	Mean Square	F	Significance
Between Groups	25.134	1	25.134	22.591	0.003
Within Groups	6.675	6	1.113		
Total	31.809	7			

The results of the statistical analysis of data for Table 24:

Null Hypothesis: The mean aggregate retention was equal across the washed and unwashed aggregates.

Alternate Hypothesis: The aggregate retention when washed aggregate was used was significantly different than when unwashed aggregate was used.

ANOVA to test the hypotheses was significant at 0.05 level, with a p-value of 0.003 and F-statistic of 22.591.

Therefore null hypothesis cannot be accepted. The mean aggregate retention differs across the two categories.

Table 33. ANOVA Results for Aggregate Retained When Different Binders Were Used for Table 25

Aggregate Retained	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	17.727	3	5.909	2.361	0.147
Within Groups	20.019	8	2.502		
Total	37.747	11			

Table 34. Multiple Comparisons of Data for Table 25

Dependent Variable Aggregate Retained	(I) Binder	(J) Binder	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Scheffe	CRS-2R	CRS-2P	-2.12000	1.29162	0.483	-6.6312	2.3912
		CRS-2L	0.08333	1.29162	1.000	-4.4278	4.5945
		CRS-2S	1.25000	1.29162	0.816	-3.2612	5.7612
	CRS-2P	CRS-2R	2.12000	1.29162	0.483	-2.3912	6.6312
		CRS-2L	2.20333	1.29162	0.453	-2.3078	6.7145
		CRS-2S	3.37000	1.29162	0.158	-1.1412	7.8812
	CRS-2L	CRS-2R	-.08333	1.29162	1.000	-4.5945	4.4278
		CRS-2P	-2.20333	1.29162	0.453	-6.7145	2.3078
		CRS-2S	1.16667	1.29162	0.844	-3.3445	5.6778
	CRS-2S	CRS-2R	-1.25000	1.29162	0.816	-5.7612	3.2612
		CRS-2P	-3.37000	1.29162	0.158	-7.8812	1.1412
		CRS-2L	-1.16667	1.29162	0.844	-5.6778	3.3445

The results of the statistical analysis of data in Table 25:

Null Hypothesis: The mean aggregate retention was not different across different binders used.

Alternate Hypothesis: The mean aggregate retention is significantly different across different binders

ANOVA to test the hypotheses was significant at 0.05 level, with a p-value of 0.147 and F-statistic of 2.361.

Therefore null hypothesis was accepted. The mean aggregate retention does not differ across different binders.

Table 35. ANOVA Results for Aggregate Retained at Various Temperatures for Table 26

Aggregate Retained					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3483.525	3	1161.175	1149.147	0.000
Within Groups	8.084	8	1.010		
Total	3491.609	11			

Table 36. Multiple Comparisons of Data for Table 26

(Note: These Data are Kept in °C Since Statistical Analyses Were Performed for °C)

	Temp. (°C)	Temp. (°C)	Mean Difference	Standard Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Scheffe	-10	25	-36.19667	.82076	.000	-39.0633	-33.3301
		40	-41.73333	.82076	.000	-44.5999	-38.8667
		60	-39.32667	.82076	.000	-42.1933	-36.4601
	25	-10	36.19667	.82076	.000	33.3301	39.0633
		40	-5.53667	.82076	.001	-8.4033	-2.6701
		60	-3.13000	.82076	.033	-5.9966	-0.2634
	40	-10	41.73333	.82076	.000	38.8667	44.5999
		25	5.53667	.82076	.001	2.6701	8.4033
		60	2.40667	.82076	.104	-0.4599	5.2733
	60	-10	39.32667	.82076	.000	36.4601	42.1933
		25	3.13000	.82076	.033	0.2634	5.9966
		40	-2.40667	.82076	.104	-5.2733	0.4599

<u>The results of the statistical analysis of data in Table 26</u>

Null Hypothesis: The mean aggregate retention was equal across the different temperatures.

Alternate Hypothesis: The mean aggregate retention across different temperatures was significantly different.

ANOVA to test the hypotheses was significant at 0.05 levels, with a p-value of 0.000 and F-statistic of 1149.147.

Therefore null hypothesis cannot be accepted. The mean aggregate retention when the aggregate was cured at -10°C (14°F) was significantly different from the other temperatures. The mean aggregate retention when the aggregate was cured at 25°C was significantly different from other temperatures. The aggregate retention when aggregate was cured at 40°C (104°F) was significantly different from the aggregate retained when the sample was cured at -10°C (14°F) and 25°C (77°F) were found to be significantly different, but there was no significance in the difference in mean aggregate retention of aggregate cured at 40°C (104°F) and 60°C (140°F).

Table 37. ANOVA Results for Aggregate Retained When Different ITD District Aggregates Were Used (Data in Table 27)

Aggregate Retained	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	227.700	5	45.540	6.843	0.003
Within Groups	79.859	12	6.655		
Total	307.559	17			

Table 38. Multiple Comparisons for Data in Table 27

	(I) District	(J) District	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Scheffe	District 1	District 2	4.38333	2.10633	0.531	-3.9172	12.6838
		District 3	0.92000	2.10633	0.999	-7.3805	9.2205
		District 4	-0.64000	2.10633	1.000	-8.9405	7.6605
		District 5	-7.52667	2.10633	0.085	-15.8272	0.7738
		District 6	0.13667	2.10633	1.000	-8.1638	8.4372
	District 2	District 1	-4.38333	2.10633	0.531	-12.6838	3.9172
		District 3	-3.46333	2.10633	0.742	-11.7638	4.8372
		District 4	-5.02333	2.10633	0.393	-13.3238	3.2772
		District 5	-11.91000*	2.10633	0.004	-20.2105	-3.6095
		District 6	-4.24667	2.10633	0.563	-12.5472	4.0538
	District 3	District 1	-0.92000	2.10633	0.999	-9.2205	7.3805
		District 2	3.46333	2.10633	0.742	-4.8372	11.7638
		District 4	-1.56000	2.10633	0.988	-9.8605	6.7405
		District 5	-8.44667*	2.10633	0.045	-16.7472	-0.1462
		District 6	-0.78333	2.10633	1.000	-9.0838	7.5172
	District 4	District 1	0.64000	2.10633	1.000	-7.6605	8.9405
		District 2	5.02333	2.10633	0.393	-3.2772	13.3238
		District 3	1.56000	2.10633	0.988	- 6.7405	9.8605
		District 5	-6.88667	2.10633	0.040	-15.1872	1.4138
		District 6	0.77667	2.10633	1.000	-7.5238	9.0772
	District 5	District 1	7.52667	2.10633	0.085	-0.7738	15.8272
		District 2	11.91000*	2.10633	0.004	3.6095	20.2105
		District 3	8.44667*	2.10633	0.045	0.1462	16.7472
		District 4	6.88667	2.10633	0.130	-1.4138	15.1872
		District 6	7.66333	2.10633	0.078	-0.6372	15.9638
	District 6	District 1	-0.13667	2.10633	1.000	-8.4372	8.1638
		District 2	4.24667	2.10633	0.563	-4.0538	12.5472
		District 3	0.78333	2.10633	1.000	-7.5172	9.0838
		District 4	-0.77667	2.10633	1.000	-9.0772	7.5238
		District 5	-7.66333	2.10633	0.078	-15.9638	0.6372

<u>The results of the statistical analysis of data in Table 27:</u>

Null Hypothesis: The mean aggregate retention was equal across all districts of Idaho.

Alternate Hypothesis: The mean aggregate retention was significantly different across the 6 districts of Idaho

ANOVA to test the hypotheses was significant at 0.05 level, with a p-value of 0.003 and F-statistic of 6.843.

Therefore null hypothesis cannot be accepted. The mean aggregate retention of District 5 significantly varied from all the remaining districts. The mean aggregate retention among other districts was not significant.