SURFACE RUN-OFF BEHAVIOUR OF BITUMEN EMULSIONS USED FOR THE CONSTRUCTION OF SEALS

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ABSTRACT

The application of seals as surfacing on South African roads has increased due to its dual advantage in performance potential and sustainability. The field performance of spray seals depends on a number of factors, and its defects measured predominantly by bleeding and ravelling of the seals.

During construction, viscosity is controlled such that the binder is sprayable, but not too low in viscosity as to run off the road surface. To avoid pavement distress resulting from loss of the binder or from inconsistent binder thickness after application, it is important to understand the run-off behaviour of seals.

Run-off tests were conducted in the laboratory by constructing surfacing seals with varying texture depths. These seals were constructed on a surface that would allow the user to change the angle of application in order to simulate the spraying of the seals on different road gradients. A movable/mobile spraybar was used to simulate typical conditions as for a spray tanker during construction. Run-off was measured through a gutter system where the emulsions was collected and weighed.

An analysis of the run-off results obtained from these experiments, revealed that the spray rate had the largest effect on run-off, followed by texture depth, and gradient.

1 INTRODUCTION

The field performance of bitumen binders as a tack coat in spray seals depends on a number of factors and defects in construction measured predominantly by bleeding and ravelling of the seals. Distress could be a result of the run-off of the binder from the road surface as this causes an inconsistent film thickness leading to potential ravelling and bleeding at the upstream and downstream regions, respectively.

One of the specific gaps in factual knowledge of bitumen emulsion performance is surface run-off behaviour. The practical recommended minimum spray rate (to prevent whip-off of aggregate) for emulsions and hot conventional binders is given as 0.7 ℓ/m^2 in the Technical Recommendations for Highways (TRH3) (2007).

The manual also recommends the maximum spray rate of an emulsion in order to prevent run-off of 1.5 ℓ/m^2 and 1.75 ℓ/m^2 for hot conventional binders, respectively. However, Muller *et al*. states that these spray rates are only applicable for coarse textured surfaces on a relatively flat gradient. Alternatively, these authors recommend maximum application rates as provided in Table 1.

These limits would require the user to choose a more viscous binder if the maximum spray is exceeded. Change to a more viscous (modified) binder implies greater costs, yet this would not be necessary if the same performance is guaranteed.

Table 1 Maximum emulsion application rates for 65% emulsion (Muller *et al.* (2012))

Grade	Macro texture (Muller *et al.*)		
	<0.7 mm	1.0 mm	>2.0 mm
<4%[(a)]	1.0[(b)]	1.5	1.7
4-6%		1.0	1.3
6-8%			0.8

(a) "Grade" refers to the maximum gradient/cross-fall combination

(b) Measured in ℓ/m^2

The objective of this research is to determine the surface run-off behaviour of bitumen emulsion under varying conditions of spray rate, gradient and texture depth at constant viscosity, in order to provide a better understanding of the behaviour of the material under preset conditions.

This research is limited to unmodified cationic spray grade emulsion (65%); this being one of the two most commonly used types of bitumen emulsion for chip seals in South Africa. The other is modified cationic spray grade (70%). The latter was not considered because, from the researcher's experience, it does not usually run off easily. In addition, only one surface temperature is considered for this study.

2 METHODOLOGY

To determine the run-off performance of emulsions for seals, laboratory scaled models of surfacing seals were constructed. Emulsion was then sprayed onto the surfaces using a spray bar mounted onto a conveyor. Pavement and emulsion temperatures are variables which have a potentially huge influence on performance; however, they are assumed to be constant for this experiment. Three variables, i.e. spray rate, gradient and texture depth, were evaluated as shown in Figure 1(a).

Run-off results were evaluated and an Analysis of Variance (ANOVA) done in order to determine the magnitude and significance of variables (See Figure 1(b)).

2.1 Parameter Considerations

A cationic spray grade emulsion 65% was used for the experiment because there are a limited range of emulsions used to construct surfacing seals in South Africa. These include cationic spray grade (65% or 70%), SC-E1 (3% latex) and SC-E2 (5% latex) (Louw, 2012).

Polymer modified binders are more viscous and less prone to run-off compared to the unmodified binders. The more critical unmodified binder was therefore considered.

For this study, the choice of spray rates was made without considering whether it was a tack coat, penetration coat or cover spray. The only provision was that the spray rate be critical to a certain type of texture depth by considering the recommended spray rates as given in Section 1. This, however, did not include prime coats, because a bitumen emulsion does not usually seep through the pores of a finished base course. Bitumen droplets are kept to the surface by the attraction of the emulsifier and aggregate. If the existing base is porous, TRH3 (2007) recommends pre-treating the base with a diluted emulsion or applying a sand seal to choke the voids in the surface.

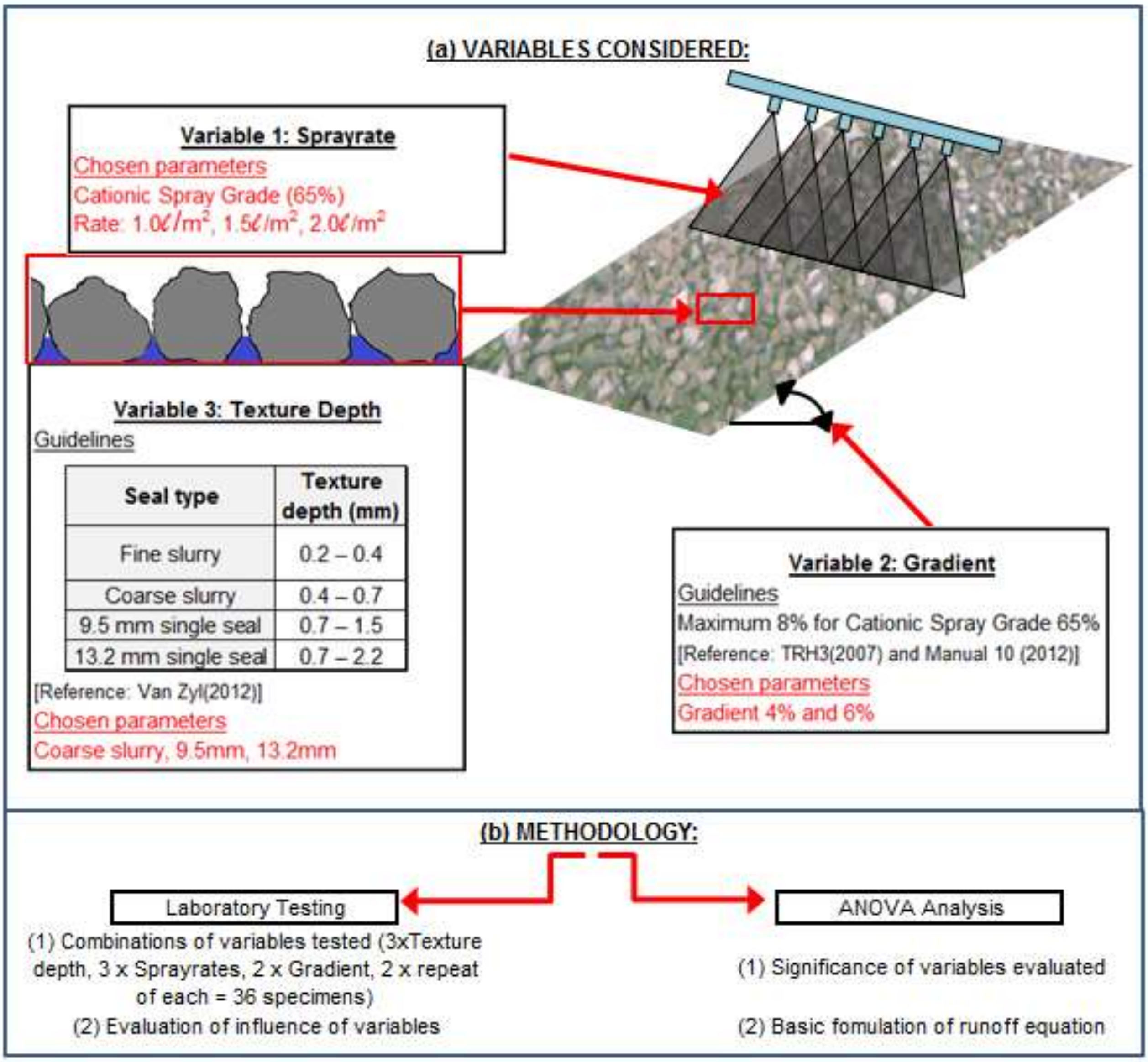


Figure 1 (a) Chosen variables and (b) methodology

It was, however, found that in order to make the analysis simpler, like-terms had to be compared, i.e. the gradients and spray rates chosen had to be consistent for sample seals selected.

In South Africa, the maximum super-elevation permitted on freeways is 10% (CSIR, 2000). Krammes and Garnham (1995) give the maximum super-elevations for various types of roads as 6% for urban freeways, 8% for rural freeways and 10% for rural dual carriage and single lane roads. TRH3 (2007) and Manual 10 (2012) recommend 8% as the maximum gradient on which the 65% emulsion can be used.

For this study, two super-elevations, 4% and 6%, were considered. 2% is the normal cross-fall of the road on which the binder is less likely to run off, and 8% was considered too steep, requiring the use of highly viscous or modified binders.

Texture depths that could simulate new construction and reseal were considered. For new construction, run-off is evaluated on top of the base; if a double seal is used, run-off is also evaluated on top of the first seal layer. Various types of surfacing seals used in South Africa were reviewed (TRH3, 2007) but the 13.2 mm, 9.5 mm and slurry seal were chosen as the 13.2 mm seal is composed of the largest aggregate size recommended for single seals to provide better skid resistance on rural high speed roads; the 9.5 mm seal is composed of the largest aggregate size recommended for tyre noise reduction in urban areas (TRH3, 2007); and the slurry seal simulates the texture of the top layer of a Cape seal or a pavement surface that has been pre-treated with a slurry in preparation for resealing.

2.2 Set-up and construction of testing apparatus

The setup of the conveyor system is shown in Figure 2(a). The conveyor is driven by a motor with variable speed adjustment.

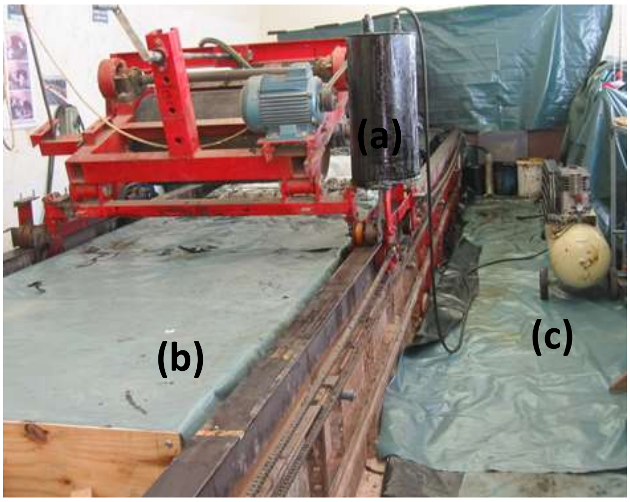


Figure 2(a)

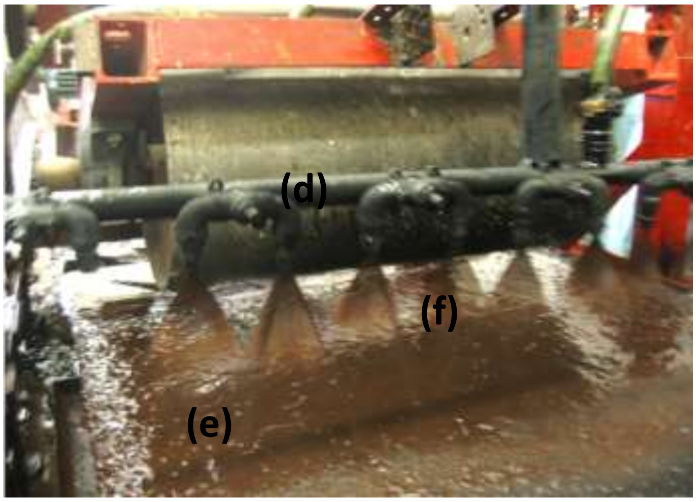


Figure 2(b)

Notes:

(a) Bitumen container containing emulsion at 60°C
(b) Conveyor track on which spraybar moves
(c) Compressor applying pressure for spraying
(d) Spraybar connected to conveyor system
(e) Seal surface platform as schematically illustrated in Figure 1(c)
(f) Bitumen emulsion being sprayed unto platform. See 1/3 overlap of spraying from each nozzle as illustrated in Figure 1(c)

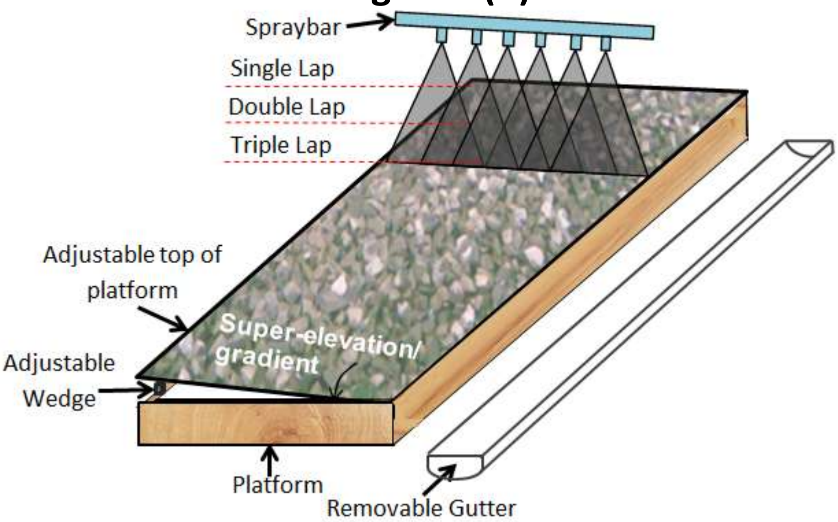


Figure 2(c)

Figure 2 (a) Overall view of conveyor system for spraying of seals in the laboratory (b) Spraybar system connected to conveyor (c) Seal spray platform

The front view of the conveyor is illustrated in Figure 2(b) and shows the spraybar distributor. The sprayer nozzle size is a 80/60 (flare angle of 80°) and has an outflow of approximately 150 litres per minute per meter length of the spray bar (Distin, 2008; Louw, 2012). Following recommendations by A E Copley Enterprises Pty Ltd (2011) a nozzle discharge rate of 18.18 ℓ/min is applied**,** this relates to a pressure of approximately 82.73 kPa. In order to allow for bends, restrictions and friction in the supply line a supply pressure of approximately 276 kPa was maintained as recommended.

Figure 2(b) illustrates the bitumen spray nozzles which are designed to spray a fan-shaped pattern, rather than a circular spray. Specifications are given for the spray angle (viewed from the front) to allow for a triple overlap as shown in Figure 2(c). To avoid overlapping interfering with adjacent fan sprays, spray nozzles are adjusted to an angle of 30° (as viewed in plan) and the nozzle height adjusted to 24 cm to achieve triple lap coverage of the fans.

An adjustable platform (dimensions 2.44 m x 1.22 m x 0.021 m) as shown in Figure 2(c) was fabricated and placed in the conveyor trough so that it could raise the spray board off the trough surface. The platform provided space to place the gutters that would be used to collect run-off when the run-off tests commenced.

The three types of seals were then constructed on boards to be placed respectively onto the platform and a sand patch test (SANS 3001-BT11:2012) performed to confirm that the desired macro-texture had been attained before commencement of testing variables as shown in Figure 1(a).

3 RESULTS

3.1 Visual observations of individual parameters

Results are illustrated in graph form in Figure 3. Inspection of the data shows that a linear increase (and trend line fit) can be expected in the amount of run-off per square metre as the spray rate increases. The linear approach will be discussed further in the analysis of statistical parameters.

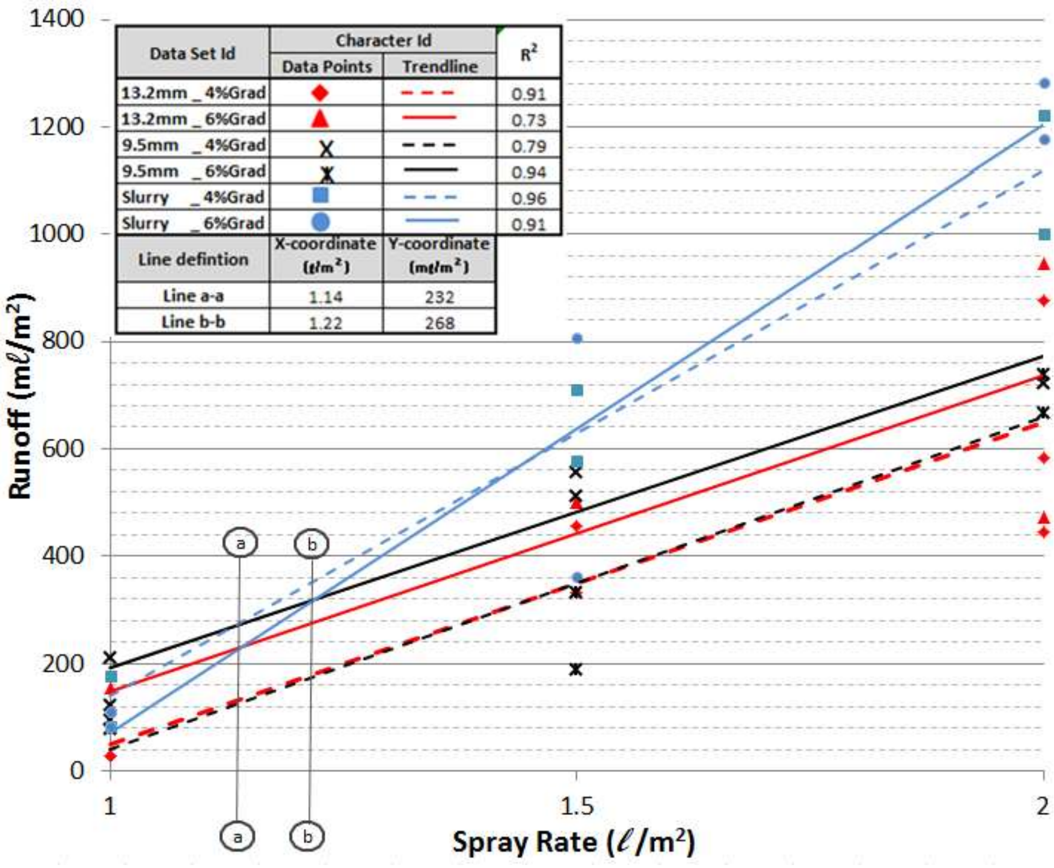


Figure 3 Results for amount of run-off per spray rate

Interestingly, the slope of the lines indicated in Figure 3 for seals 13.2 mm and 9.5 mm were similar but an increase in the gradient is observed when compared to a slurry surface. This indicates that there is a significant increase in run-off with an increase of spray rate when comparing the 9.5 mm and 13.2 mm with that of the slurry seal.

A slight difference of the two different gradients was observed when evaluating the slurry seal. In the absence of texture depth, run-off-behaviour of the applied spray rate is increased in comparison with the other two type seals investigated, showing that the spray rate should be of most concern when applying a coat onto a slurry surface.

In contrast, the results for run-off between the 13.2 mm and 9.5 mm are similar at a 6% gradient and with some minor differences between the values of these two seals, at a 4% slope.

Line a-a and b-b indicates the point at which the 13.2 mm and 9.5 mm seal yields higher run-off values than that of the slurry seal for a 6% gradient after which texture depth influences the results

The consonance of these two seal types at the two respective gradients, indicate an influence of the gradient on run-off with an increase in spray rate and to a lesser degree by texture depth.

Figure 4 shows the average percentage run-off. This value is calculated by taking the ratio of the average run-off to the original spray rate for the test undertaken.

Comparing the three different seals for a 4% gradient, an increase in the percentage run-off is observed for 1.0 ℓ/m^2 spray rates as the texture depth decreases. However, values for a spray rate of 1.5 ℓ/m^2 is higher for the 13.2 mm than the 9.5 mm seal, but then again increases for the 2.0 ℓ/m^2 as the texture depth decreases. For the gradient at 6 % results at 1.0 ℓ/m^2 for the 9.5 mm seal is slightly higher than the other two tested seals.

A possible reason for these increase and subsequent decrease of run-off at a 4% gradient is that the 9.5 mm seal has a higher density of protruding aggregates compared to the 13.2 mm seal. When the binder is sprayed onto the seal surface, it flows following a path though the "valleys" created by the aggregate (see Figure 5(a)).

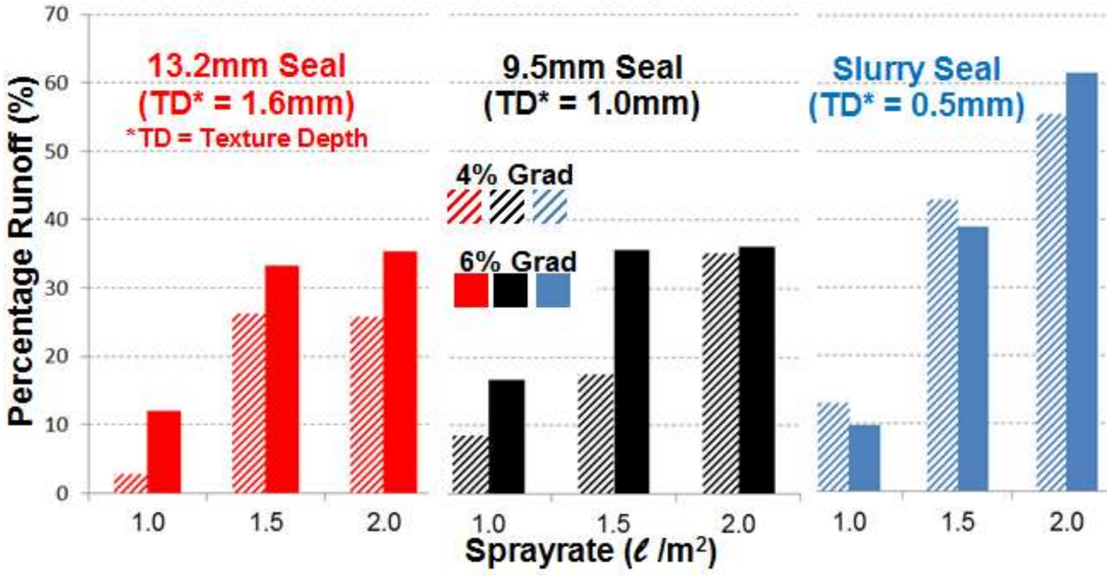
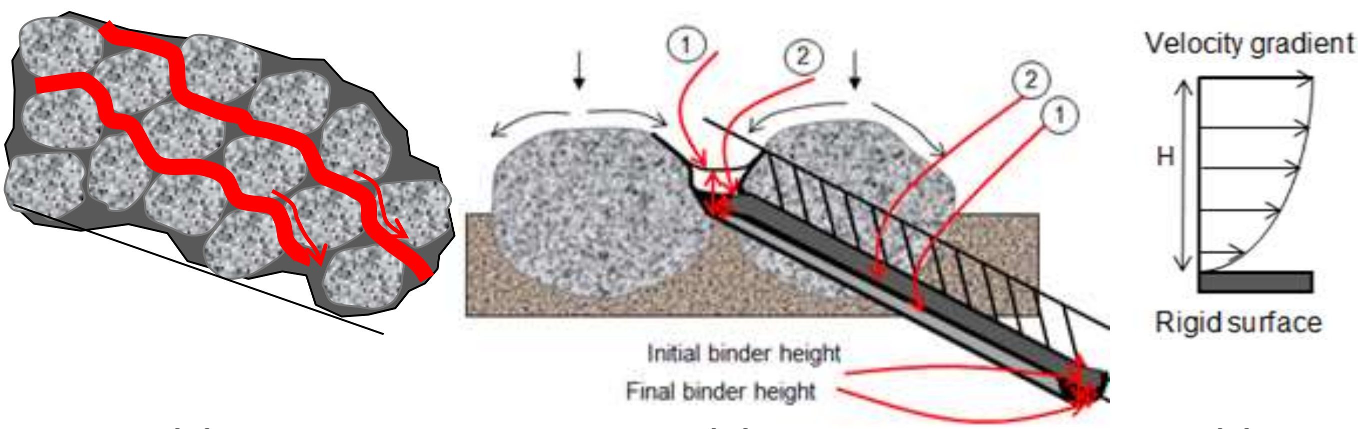


Figure 4 Average percentage run-off per spray rate

As observed in the laboratory, the binder did not flow over the aggregate unless the latter was substantially embedded into the surface compared to the surrounding aggregate, which was rare. As the binder flows, the speed of the portion adjacent to the aggregate is much less than the speed of the portion far away from the aggregate (see 1 and 2 respectively, in Figure 5(b)).



(a) **(b)** **(c)**

Figure 5(a) Flow path of the binder for seals with large stone sizes (plan view) (b) Flow between the aggregates (cross-sectional view). (1) Low speed (2) High speed (c) Liquid flow over a rigid surface

This can also be explained by simple kinematics of a fluid (as shown in Figure 4(c)). As the distance H from the rigid surface becomes larger, a higher velocity is experienced at that distance. Since the aggregates in 9.5 mm seal are close to each other, the flowing binder is subjected to a larger area of rigid surface and hence a lower speed. Also, once the protruding aggregate is in the binder path, it inhibits or slows down the flow of the binder and the binder tends to build up behind the aggregate.

This reason, however, does not explain the results for 4% at 1.0 ℓ/m^2. Possibly, adsorption plays a large role and this reasoning is substantiated through observations (time trials) during these tests which indicated that at a spray rate of 1.0 ℓ/m^2, initiation of flowing compared to that of a spray rate of 1.5 ℓ/m^2, was considerably longer.

3.2 Statistical parameters (combined evaluation)

The variables spray rate, gradient and texture depth was evaluated through statistical analysis, using the software package SPSS. The statistical analysis was firstly done to evaluate the regression model and secondly to determine if all predictors are significant in the model. Note that the significance of predictors should not be confused with the magnitude of effect of each of these variables.

Table 2 shows the regression statistics by employing linear regression and incorporating all laboratory results as shown graphically in Figure 3. The analysis shows that the linear fitted regression line gives a high correlation (R^2). This does not necessarily indicate a good fit or that a linear regression is sufficient to describe the data, but only that there is a high correlation between the data and the fitted line.

Table 2 Standard statistical data of analysis

REGRESSION STATISITCS	
Multiple R	0.90
R Square	0.81
Adjusted R Square	0.79
Standard Error	163.30
Observations	35.00

In order to determine the suitability for regression the residuals of each independent variable was evaluated. Graphical analysis of the residual plots (not included in this article) for the variables texture depth and gradient revealed scattered and random results (i.e. no pattern to the residuals unbiased and homoscedastic) but the variable, spray rate, showed some tendency towards unbiased and heteroscedastic scattering. This implies that for the first two variables, linear regression suitably models the behaviour of the predictors but that the possibility exists that the variable spray rate can lean towards nonlinear model behaviour.

From visual observation and analysis a notable percentage increase is observed, in the behaviour when compared to the spray rate, especially for the slurry seal at 1.5-2.0 ℓ/m^2. Possibly, the reason for this is that weight/film thickness of the binder is a function of spray rate and determines the energy possessed by the binder, i.e. the kinetic and potential energy (K.E = 0.5*m*v^2 and P.E = mgh, where K.E = kinetic energy (joules), m = mass (kg), v = velocity (m/s), P.E = potential energy (joules), g = gravitational force (m/s^2) and h = height to the ground (m)). The total energy increases as binder thickness increases. Binder film thickness also determines the rate at which the binder loses heat, i.e. thicker binders take a longer time to lose heat and hence to stop flowing. This formula substantiates the possibility of nonlinear behaviour of this particular variable. Considering this theory more data points are needed for evaluation and particularly temperature dependent trials.

Nonetheless, a normal probability plot of all residuals (for all variables) revealed a straight line pattern indicating that the normality of errors assumption is correct and linear regression acceptable for the overall model.

In addition, an increase in the Adjusted r^2 was observed with increasing the number of predictors indicating that all variables were necessary and no saturation of the model prediction occurred. Too many predictors are more likely to reduce the precision of coefficient estimates and predicted values.

Results for the Analysis of Variance (ANOVA) are given in Table 3 and the equation for the prediction of amount of run-off is given in Equation 1 (for unstandardized coefficients):

Run-off= -675.35+766.92(spray rate in mℓ) + 47.07(gradient in %) – 221.27(texture depth in mm)

Equation 1

As can be seen from Table 3, the p-value for spray rate and texture depth is under the expected significance level of 0.05 which implies that each of these two variables has a 95% probability that they have an effect on the run-off result, which is expected.

Gradient as a variable falls within the 90% confidence interval only indicating a relatively high assurance of significance, but not as high as the other predictors.

Comparing the t-statistics (which is connected to the standardised coefficients) of the variables, it is shown that spray rate has the most influence on run-off, followed by texture depth and then gradient. These statistics thus indicates that although small, the gradient has some magnitude of influence.

Table 3 ANOVA analysis of laboratory results

	ANOVA			
	Coefficients	**T-stat**	**P-value**	**Significance F**
Intercept	-675.35	-3.54	1.27 X 10^{-3}	2.91 X 10^{-11}
Texture Depth	-221.27	-3.64	9.81 X 10^{-4}	
Gradient	47.07	1.70	1.00 X 10^{-1}	
Spray Rate	766.92	11.15	2.26 X 10^{-12}	

In addition, the F-statistic test shows that the overall significance of the model is valid. These results indicate that the equation can be used as proposed for the envelope of parameters tested here.

4 CONCLUSIONS

The ANOVA model for run-off behaviour predicts the significance of variables to be ranked spray rate, texture depth and gradient in descending order.

Visual observations show some disparities in the magnitude of effects depending on the texture depth. Spray rate has the greatest influence with slurry, but that greater care should be taken in considerations between the 13.2 mm and 9.5 mm seal where higher percentage yield values were obtained for the 13.2 mm than for the 9.5 mm in some cases. Wrongful assumptions by which decreased texture depth implies increased percentage run-off could be invalid.

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