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Evaluating friction after polishing as an in-service skid resistance prediction tool for TS2010 materials

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Executive summary

In 2010 Transport Scotland published a new surface course specification (TSIA No 35, 2018), known as TS2010[1]. The specification requires a three stage approval process which includes laboratory testing, off-network trial and an on-network trial (a Type Approval Instillation Trial (TAIT)), after which the material is approved for further use dependant on six month in-service GripTester measurements. The disadvantage of such a TAIT is that materials will have to wait up to six months before being given approval and much longer before the long term skid performance of these materials are known. The aim of this study is to see if the Friction After Polishing (FAP) test, conducted using the Wehner-Schulze machine (W-Sm) can be used as an alternative for predicting what level of skid-resistance TS2010 materials will provide whilst in service and the test's potential to be used for approving TS2010 materials.

In order to establish the possibility to use the W-Sm as a skid performance predictive tool both trafficked and un-trafficked specimens of TS2010 material were sourced. Transport Scotland's Integrated Road Information System (IRIS) was used to identify a variety of in-service TS2010 materials to be cored from the trunk road; corresponding un-trafficked TS2010 materials were then supplied by the relative material supplier.

The W-Sm testing regime comprises two stages: the accelerated polishing stage, and the friction testing stage. Measurements made with the W-Sm are referred to as Friction After Polishing (FAP) measurements. To establish any changes in the behaviour of TS2010 materials the polishing phases reached a total of 180,000 roll overs with the friction of the specimens being tested at defined intervals.

Results from all specimens were compared with other factors such as SCRIM, traffic levels, road site categories, material age and texture depth. Analysis of these results indicates that it may be possible to predict, with a reasonable level of accuracy, the high speed friction (Est. L-Fn100) of TS2010 materials. It was not possible however to generate a model based on the data collected during this study that could predict the in-service skid performance of TS2010 materials as measured using SCRIM. Other conclusions include:

- The application of grit, which is applied to TS2010 materials when newly laid, has a marked positive effect on both the immediate and long term friction performance of TS2010 specimens when measured using the W-Sm.
- Due to the inconsistent presence of grit on the TS2010 materials tested, large variations in performance were recorded with the W-Sm and this occurred within a

[1] TS2010 materials is also specified in the manual of conrtact documents for highway works (Highways England, 2019) under Clause 942TS.

single mix design. As a result there were substantial differences in the general performance of TS2010 materials, and the performance of materials associated with specific sites.

- The main contributing factors for the modelling attempts not producing acceptable results were related to the W-Sm test regime not simulating what happens to the in-service material (trafficked specimens), and the effect weather has on the skid resistance performance road surfacings.
- The W-Sm seeks to simulate the polishing effect of vehicles but it does not necessarily replicate the combined effects of weathering and vehicle polishing experienced on the Scottish network.

Recommendations include developing a protocol for preparing untrafficked specimens to ensure grit is applied in a consistent manner for any future W-Sm testing. The use of W-Sm friction measurements should also be considered at Stage 2 of the TAIT process.

1 Introduction

In 2010 Transport Scotland published a new surface course specification (TSIA No 35, 2018), known as TS2010[2]. The aim of this specification was to provide a surface course with an increased service life, achieved through improved durability, and to increase the use of local aggregates to reduce haulage of aggregate across Scotland.

TS2010 materials utilise a process called gritting in order to alter the skid resistance properties of the materials. Gritting refers to the application of very small aggregate particles to the surface after the applictiaon of the asphalt matt. The grit particles are therefore imbedded into the thin bitumen layer on top of the asphalt matt, but remain accessable to vehicle tyres in order to affect the skid resistance properties of the material.

The TS2010 only requires the Polished Stone Value (PSV) of the coarse aggregate to be declared, rather than meet a specific value which is required for traditional surface courses. The specification ensures that the surface characteristics of the material provide adequate friction through strict grading requirements and in-service measurements of friction. To ensure that products meet the TS2010 specification, and that a safe level of skid resistance is met, a three stage type approval installation trial (TAIT) process is carried out:

1. A series of laboratory assessments are carried out on the mix design to ensure its conformity with the TS2010 specification.
2. An off network trial site is laid to assess the contractor's ability to correctly install the material. Laboratory specimens of this trial section are extracted and assessed for air voids content.
3. An on network trial is carried out on a section, typically but limited to low risk road (motorway or major trunk road). GripTester measurements are made at intervals of 4 weeks and 6 months.

Depending on the GripTester measurements from the on-road trials, a material is then approved for use in areas where the Site Class is equal or lower to that of the trial site.

The disadvantage of having such an approval process is that materials will have to wait up to six months before being given provisional approval for use and significantly longer before the long-term skid performance can be established through SCRIM surveys.

The aim of this study is to see if the Wehner-Schulze machine (W-Sm) can be used as an alternative test method for predicting what levels of skid-resistance will be provided in service, and the test's potential to be used as a future specification requirement for TS2010 materials. In addition, the report looks into to relations between W-Sm results and other factors, including SCRIM surveys, texture, traffic levels, and age.

[2] TS2010 materials is also specified in the manual of conrtact documents for highway works (Highways England, 2019) under Clause 942TS.

2 Specimens assessed

In order to establish whether the W-Sm could be used as a skid performance predictive tool, both trafficked and un-trafficked specimens were sourced. Trafficked specimens were selected using Transport Scotland's Integrated Road Information System (IRIS) with an intention of selecting older materials that represented a variety of trafficking conditions, suppliers, coarse aggregate sources and coarse aggregate sizes. For most mix designs, corresponding un-trafficked specimens were provided by material suppliers from either a newly laid surface or produced in a laboratory. It should be noted that as some of the un-trafficked cores were produced in a laboratory environment they were manufactured without gritting.

A total of 12 different TS2010 mixes were selected and tested from trafficked sites (Figure 2-1); for certain older mixes two sites were selected. A total of 11 different un-trafficked TS2010 materials were provided by suppliers.

For the purposes of anonymity each mix design was randomly assigned a letter for the purposes of referencing in this report.

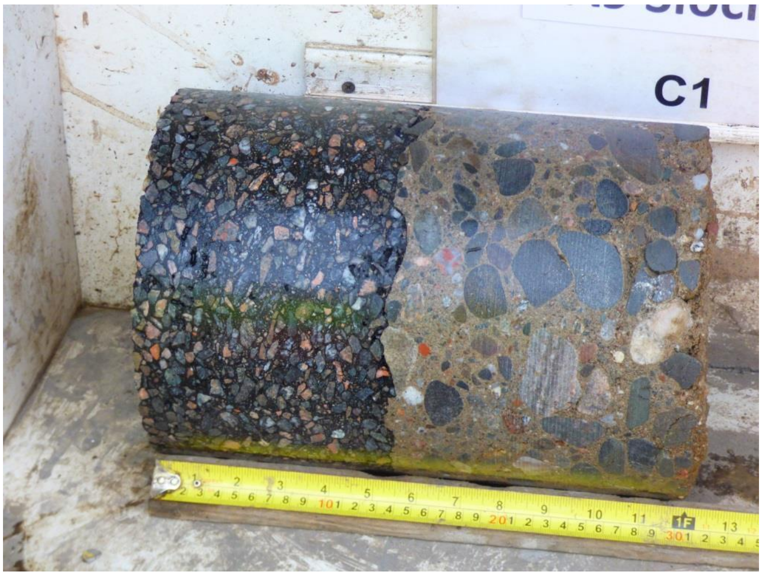


Figure 2-1 Trafficked core extracted at site, TS2010 surface course to the far left

3 Measurement equipment used

3.1 The Wehner-Schulze machine

The primary testing device used for this work was the Wehner-Schulze machine (W-Sm) (Figure 3-1). This device was originally developed by the Technical University of Berlin to characterise the friction performance of road specimens, in response to the simulated polishing action of motor vehicle tyres. Measurements made with the W-Sm are referred to as Friction After Polishing (FAP) measurements. FAP tests are comprised of two stages, the accelerated polishing stage, and the friction testing stage.

In the accelerated polishing stage, an accelerated traffic effect is created on the specimen surface through the action of three conical rubber rollers and a suspension of silicon dioxide powder and water. During the friction testing stage, the friction provided by the specimen is characterised by measuring the torque applied to the specimen resulting from three measuring rubbers rotating at approximately 100 km/h on a weighted head being dropped onto the specimen surface. After falling onto the specimen surface the friction measurement rubbers are allowed to slow to a stop, the torque measured at a speed of 60 km/h is converted to a dynamic friction coefficient and reported as values of $\mu_{PWS(60)}$. Water is always used in the characterisation of friction in order to identify the friction characteristics of specimens in the worst case scenario i.e. bald vehicle tyres in wet conditions.

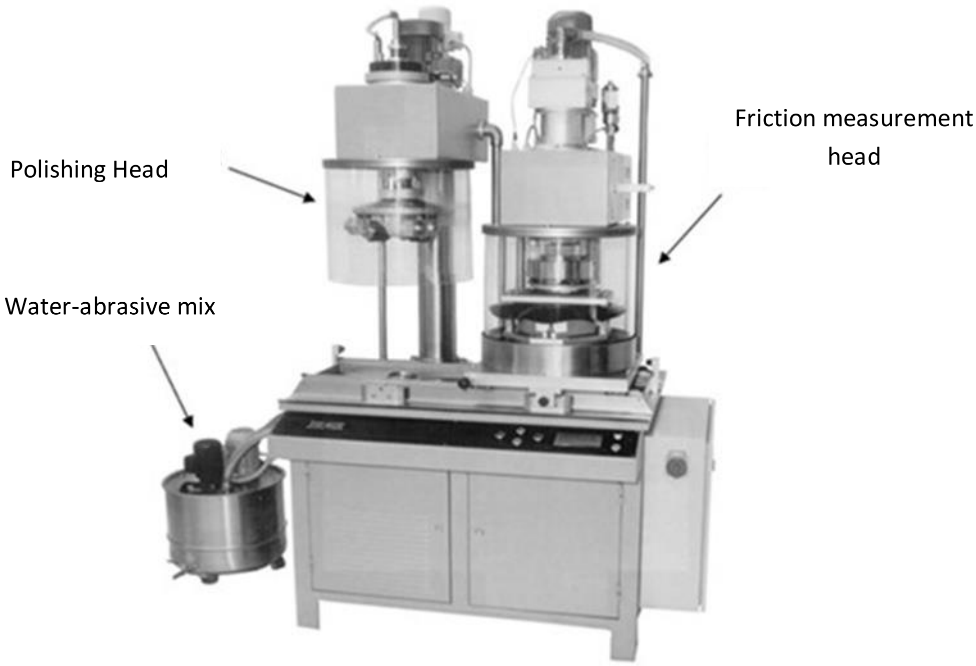


Figure 3-1 The Wehner-Schulze machine

3.2 The sideways-force coefficient routine investigation machine

The Sideways-force Coefficient Routine Investigation Machine (SCRIM) was used indirectly for this work through the use of third party data which was collected using this machine. The Sideway-force Coefficient Routine Investigation Machine (SCRIM) is the standard device for monitoring the side-force skid resistance condition of the UK trunk road network, and is also used by many local authorities.

To characterise skidding resistance SCRIM uses a smooth test tyre angled at 20 degrees to the direction of travel, mounted on an instrumented axle, to record a SCRIM Reading (SR) for every 10 m length of road. The SR is the average ratio between the measured side-force and the vertical load. SCRIM readings are speed-corrected to the standard test speed of 50 km/h, converted into SCRIM Coefficient (SC) and in some cases corrected for localised environmental variations and converted to Characteristic SCRIM Coefficient (CSC).

To characterise the texture depth performance of the trunk road network SCRIM uses a single point texture laser that creates a two dimensional texture profile of the road surface. The texture profile is then interrogated to provide a measure of Sensor Measured Texture Depth (SMTD) for each 10 m length of road.

3.3 High speed friction measurements

Some of the data analysis carried out as part of this work sought to use high speed locked-wheel friction data at 100 km/h (L-Fn100). Direct measurements of high speed friction were not available and so high speed friction measurements were inferred using the CSC and SMTD data detailed above. The exact procedure used is detailed in Section 5.3.1.

4 Measurement methodology

4.1 The collection of primary data using the Wehner-Schulze machine

The use of the W-Sm is defined in BS EN 12697-49:2014 (British Standards Institution, 2014). The standard test procedure is to polish a specimen for 90,000 roll overs and then conduct a single friction test. However, for the purposes of this work it was desirable to observe the change in friction behaviour with extended polishing conditions. To this end the test procedure for the specimens was extended to 180,000 roll overs and friction measurements made on each specimen intermittently, the exact test procedure was as follows:

- Conduct a single friction test,
- Polish to **1,500** roll overs,
- Conduct a single friction test,
- Polish for a further **10,500** roll overs,
- Conduct a single friction test,
- Polish for a further **18,000** roll overs
- Conduct a single friction test,
- Polish for a further **60,000** roll overs,
- Conduct a single friction test,
- Polish for a further **90,000** roll overs (total roll overs 180,000)
- Conduct a single friction test.

In order to assure the quality of the test results, a calibration check of the measuring friction rubbers is necessary. This was carried out before every friction test by making a friction measurement on a glass verification plate. If the measurements made on the glass plate were outside the range of 0.095 and 0.115 $\mu_{PWS(60)}$, the measuring rubbers were replaced and the calibration check repeated.

4.2 The collection of secondary data using Transport Scotland databases

For all sites on the Scottish trunk road network where an asphalt mix involved in this study had been laid, data were extracted from IRIS. Skid resistance and texture results were averaged providing an average CSC and average SMTD for each mix. These results were used with corresponding traffic data, site category and material age in subsequent analysis. It should be noted that in some cases SCRIM data was not used as the value had been averaged over too short a distance to be considered significant.

5 Results

It should be noted that initial methods designed to provide a coarse assessment of the ability of W-Sm to predict the skid resistance of surfaces as a function of trafficking were not successful. For example, an offset correlation method was attempted where friction after polishing data collected using the W-Sm was compared between untrafficked and trafficked specimens. It was expected that this data would produce distinct trendlines of friction versus polishing cycles for untrafficked and trafficked specimens. It was concluded that no consistent pattern or simple relation (offset) between trendlines existed. A full set of tabulated and graphical data can be found in the appendices.

This chapter presents the pertinent results of the study. In section 5.1 a comparison of measurements made on the un-trafficked specimens is carried out and the application of grit discussed. In section 5.2 the results from the testing carried out using the W-Sm are presented which provide some insight into the typical performance of TS2010 materials. In section 5.3 a multiple regression analysis is presented which yielded a model capable of predicting the high speed friction performance of TS2010 materials.

5.1 Comparison of un-trafficked specimens

Figure 5-1 presents the average results of the un-trafficked cores at both 0 roll overs (blue) and 90,000 roll overs (red). Results have been divided into gritted and ungritted specimens and also have their Polished Stone Value (PSV) identified as indicated at the top of the figure.

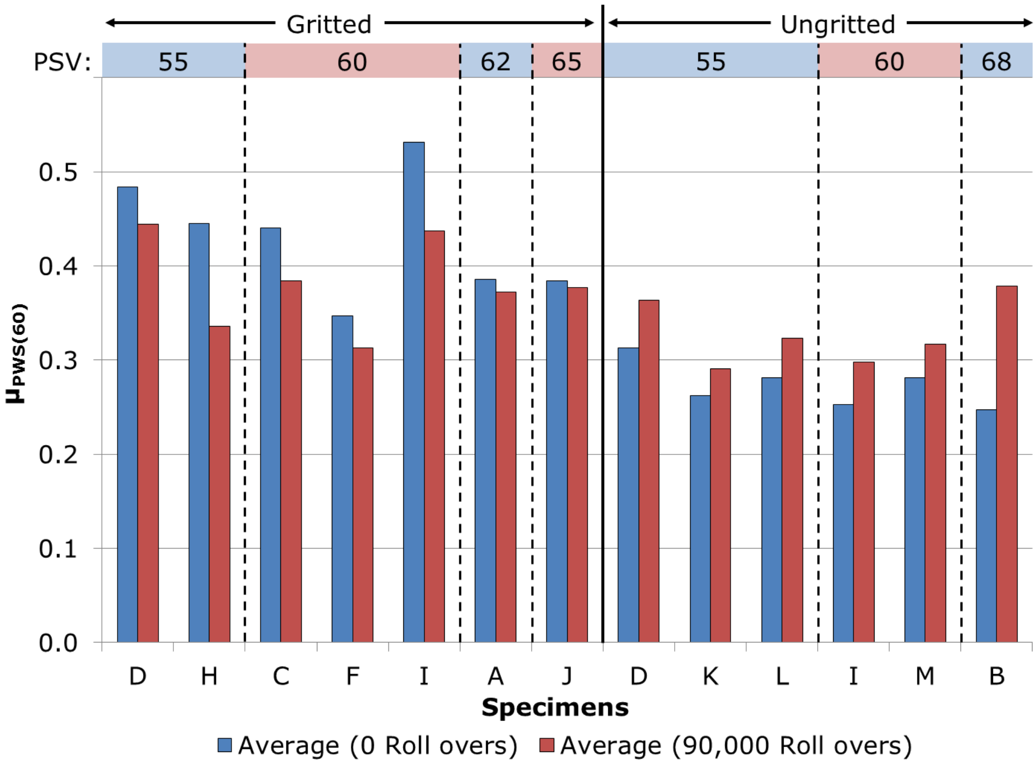


Figure 5-1 Average results of un-trafficked specimens after 0 and 90,000 roll overs

Figure 5-1 clearly shows a difference in behaviour between the gritted and ungritted specimens. In all cases gritted specimens lose initial friction after 90,000 roll overs whereas ungritted specimens increase in friction. The likely explanation for this pattern is that, with ungritted specimens, the W-Sm is initially testing aggregate coated in polymer modified bitumen but at 90,000 roll overs, once the bitumen film has split or been removed, the coarse aggregate is being tested. Gritted specimens have increased initial friction due to the presence of lightly coated grit covering the surface, it is likely that friction then drops owing to the polishing or removal of the grit. It is however noted that even after 90,000 roll overs the grit is still providing enhanced friction; this can be observed when comparing the gritted and ungritted results for specimens D and I.

When comparing W-Sm results against the PSV of the coarse aggregate there is no clear correlation. Specimens D (PSV 55) and I (PSV 60) gave the highest level of recorded friction of all un-trafficked specimens (gritted and ungritted) at both 0 roll overs and 90,000 roll overs. When tested under extended polishing conditions, i.e. 180,000 roll overs, this finding still holds true.

The higher PSV gritted samples A (PSV62) and J (PSV65) showed only a small reduction in friction between 0 roll overs and 90,000 roll overs. This contrasts with the highest ungritted PSV specimen B (PSV 68) which gave the largest absolute difference between 0 roll overs and 90,000 roll overs.

5.2 The behaviour of TS2010 materials

The typical behaviour of TS2010 materials is summarised in Figure 5-2 which presents the $\mu_{PWS(60)}$ measurements collected using the W-Sm. Figure 5-2 shows the typical performance for untrafficked specimens with (the red series) and without the application of grit (the green series). Specimens exposed to traffic and weathering collected from in-service roads are presented as the blue series. Lines of best fit are shown as power relationships[3] along with their mathematical definitions and coefficients of determination.

Data relating to untrafficked specimens are presented with reference to the friction measured at each polishing stage. The specimens extracted from in-service roads are presented with reference to the initial friction of the specimen[4] against the amount of trafficking received by the material.

[3] Power relationships represent the lines of best fit, and are also consistent with TRLs experience of similar polishing / friction relationships.

[4] The friction measured without extra polishing in the W-Sm.

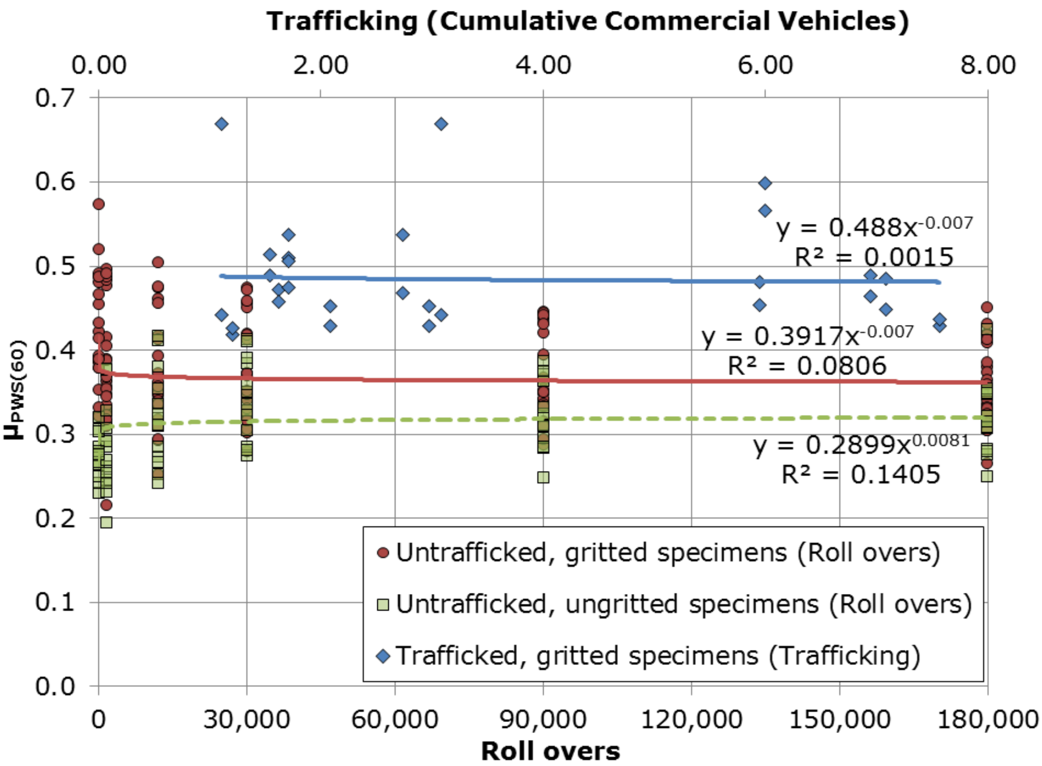


Figure 5-2 Summary $\mu_{PWS(60)}$ results

A specific difference in performance is observed between the lines of best fit presented in Figure 5-2. The first of note is the difference in performance between gritted and ungritted master specimens. It is clear that gritted specimens improve the friction of TS2010 materials and that this improvement is maintained with polishing. Figure 5-2 also shows that in all cases a large range in performance is observed with a range of 0.2 units being typical in all series. This demonstrates the range in performance of TS2010 materials in general and this is not greatly surprising given the range of materials used in TS2010 mixes. However, it was observed that large variations in performance can exist within a single mix design. For instance, Figure 5-3 shows the W-Sm results for material C. The untrafficked specimens (red) for this material are demonstrating a difference in performance of the order of 0.1 units at 90,000 and 180,000 roll overs. The four untrafficked specimens were taken from a newly laid site and grit had been applied.

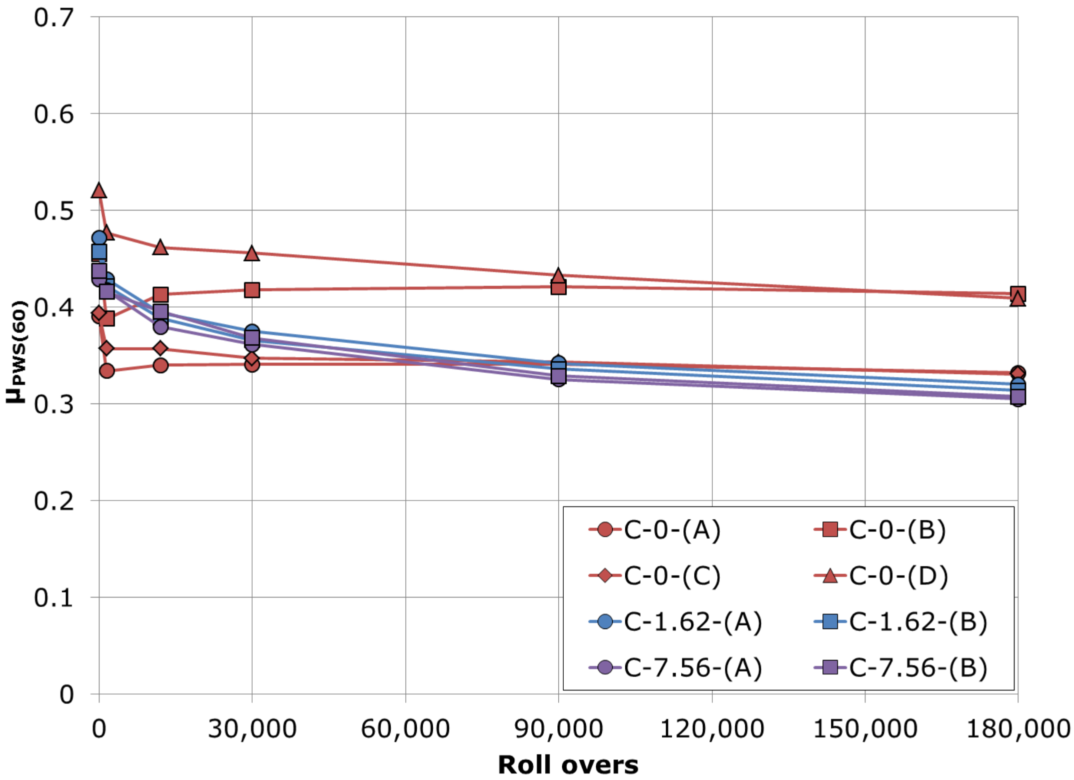


Figure 5-3 Wehner-Schulze machine results for material C[5]

As noted in Chapter 5.1, ungritted specimens behave as it would be expected for thin surface course materials, or stone mastic asphalts to behave, that is to say their friction improves with wear as the aggregate materials are exposed, then a slow decline in friction is observed related to the polishing of the aggregate. The application of grit seems to invert the initial part of this behaviour as an initial rapid reduction in friction is observed followed by a steady decline. It should be stated however, that in all cases where gritted and ungritted specimens were directly compared, that the gritted specimens always produced higher friction values than the ungritted specimens, an example of this is presented in Figure 5-4.

[5] The legend is formatted with respect to each mix design, the number of cumulative commercial vehicles passed over the surface in millions, and, a unique identifier for the specimen assessed. For instance, C – 1.62 – (B) is mix C, with 1.62 million commercial vehicles having passed over it, and is specimen B.

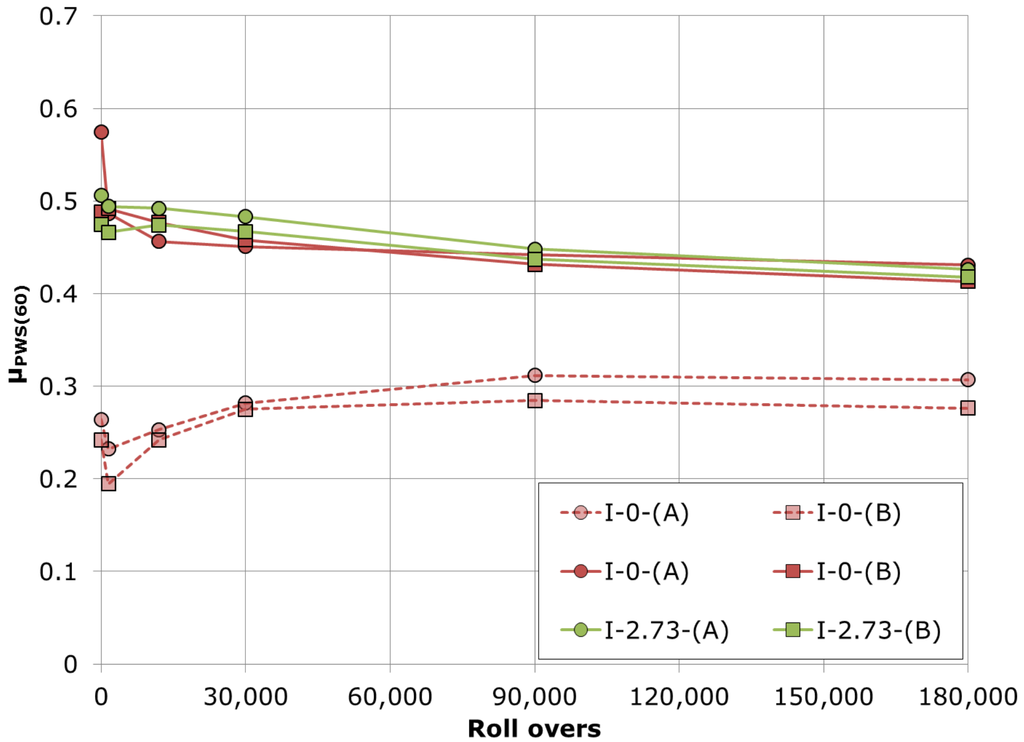


Figure 5-4 Wehner-Schulze machine results for material I[6]

A difference in performance of the order of 0.1 units is observed in Figure 5-2 between the untrafficked gritted specimens and in-service specimens. Interestingly, it is observed that in general, this difference is consistent. This is evidenced by the power function of the lines of best fit for both categories being the same (-0.007).

Whilst this may be true for a general case, the same cannot be said at a site-specific level of detail. This is demonstrated in Figure 5-5 and Figure 5-6 which presents material specific comparisons between untrafficked and trafficked specimens for A and C. What these figures show is that the power function of the lines of best fit[7] for the untrafficked specimens do not match those of the trafficked specimens. This shows that a site specific relationship between number of roll overs in the W-Sm and in service trafficking could not be developed.

[6] Broken lines represent un-gritted specimens

[7] A power relationship has been used as this is the relationship demonstrated in Figure 5-2.

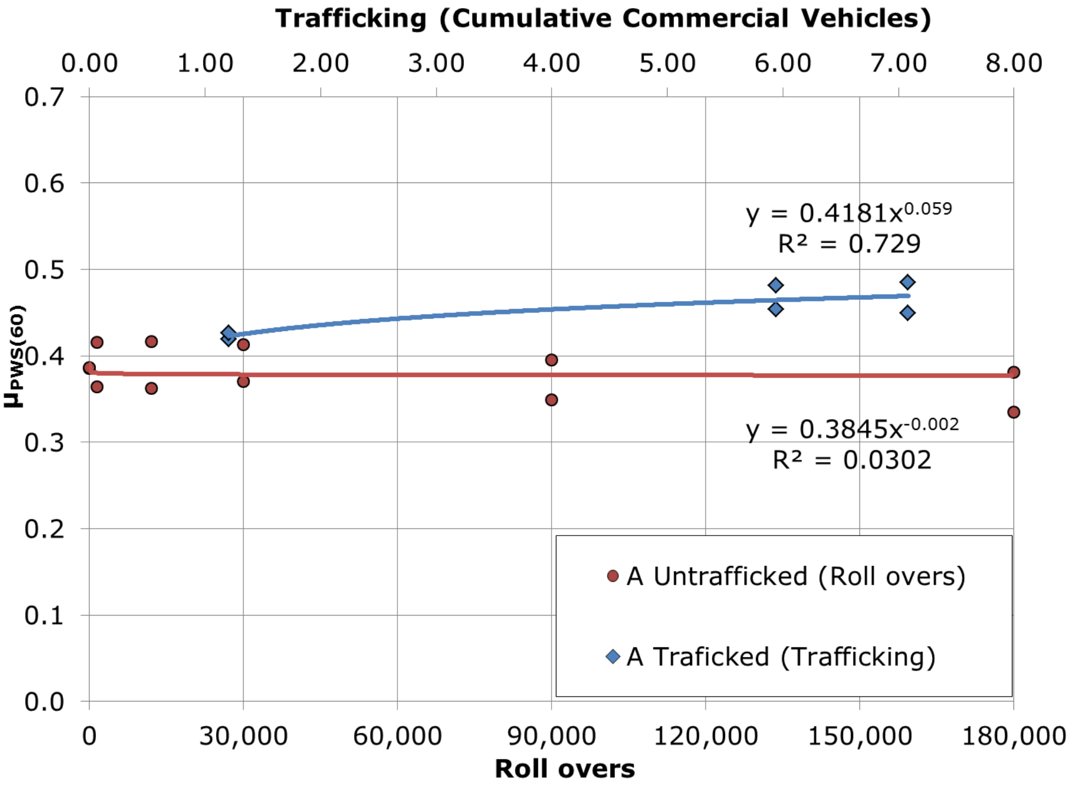


Figure 5-5 Material A $\mu_{PWS(60)}$ results

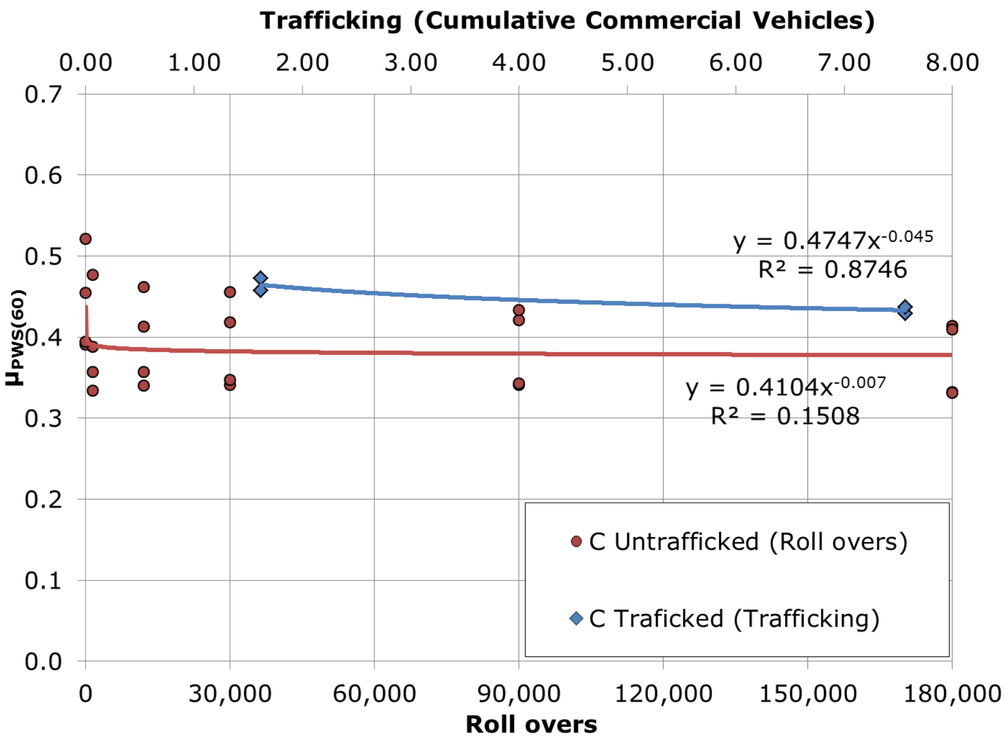


Figure 5-6 Material C $\mu_{PWS(60)}$ results

The difference between the general and specific cases is likely to be related to site specific conditions such as weathering, the typical vehicle manoeuvres performed, and winter maintenance procedures. Given that the W-Sm does not replicate weathering, is limited to replicating a single vehicle manoeuver, and cannot replicate winter maintenance characteristics, material performance characterised in the W-Sm is indeed only representative of the general characteristics of TS2010 materials.

5.3 Predicting in-service friction performance

5.3.1 Predicting in-service SCRIM Coefficient

Multiple attempts were made at developing a model capable of predicting the SCRIM performance of any given site, based on friction measurements of untrafficked specimens in the W-Sm, and site specific information such as trafficking level and age. However, these attempts did not yield acceptable results, summaries of these modelling exercises are shown in the following figures.

To assess the performance of the models, the predicted performance of the materials was compared with the actual, measured values. Figure 5-7 shows predicted SC versus actual SC for all sections of the TS network where a mixture in this study has been laid. The model uses the month of the year the SCRIM survey was taken, the age of the material when tested by SCRIM, the trafficking level and the friction of the untrafficked specimen as measured using the W-Sm at 90,000 roll overs. Figure 5-8 shows a similar approach but the model tries to predict the CSC measured for the sites where trafficked specimens were taken and then polished at 90,000 rollovers. Finally, Figure 5-9 shows a model that attempts to predict the average CSC (taken from all available SCRIM data) using age, trafficking level and the W-Sm friction of untrafficked specimen at zero rollovers.

To add context, data are presented with reference to the repeatability of SCRIM. Given that repeatability is simply an expression of a standard deviation, for a modelling exercise to be considered acceptable, it should be expected for:

- 68% of the data to fall within 1 standard deviation
- 96% of the data to fall within 2 standard deviations
- 99.7% of the data to fall within 3 standard deviations
- The data to lie roughly along the 1:1 line

None of the following figures achieve this.

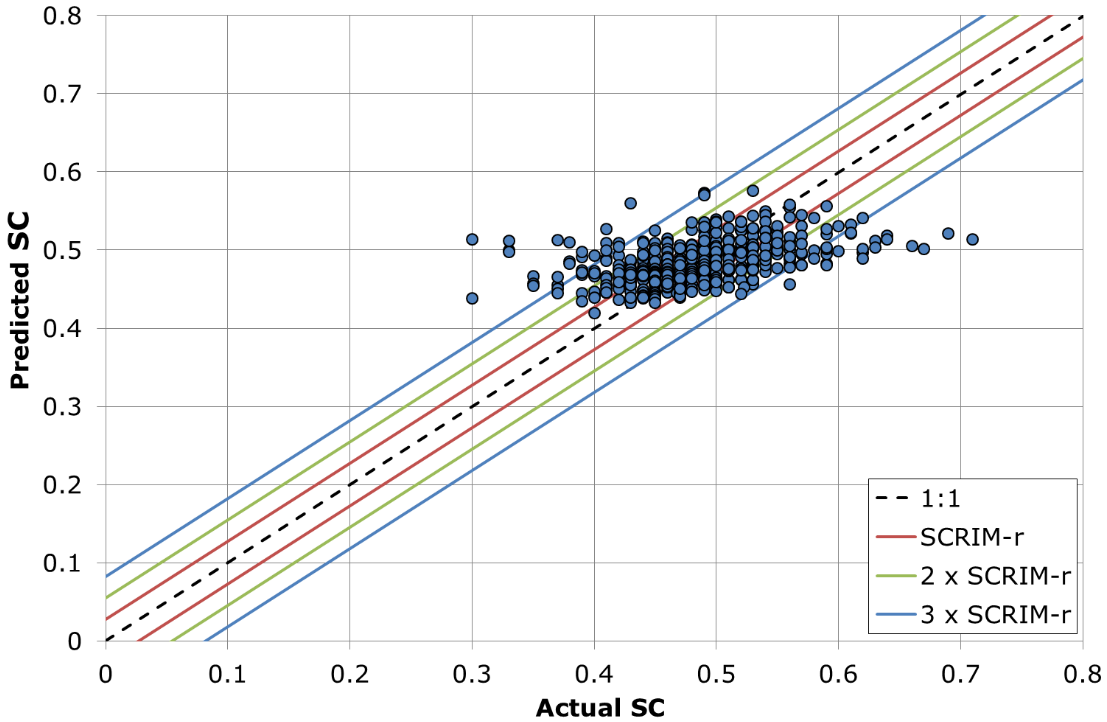


Figure 5-7 Predicted Vs Actual SC for all sections of TS network (90,000 roll overs).

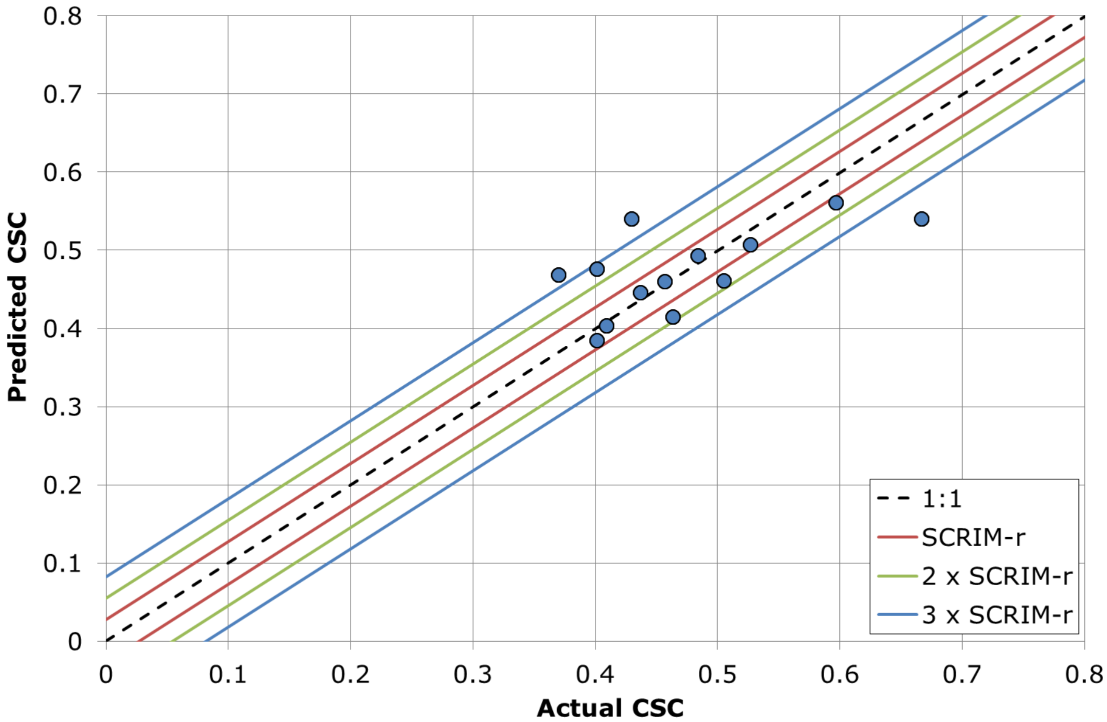


Figure 5-8 Predicted Vs Actual CSC for trafficked specimens (90,000 roll overs).

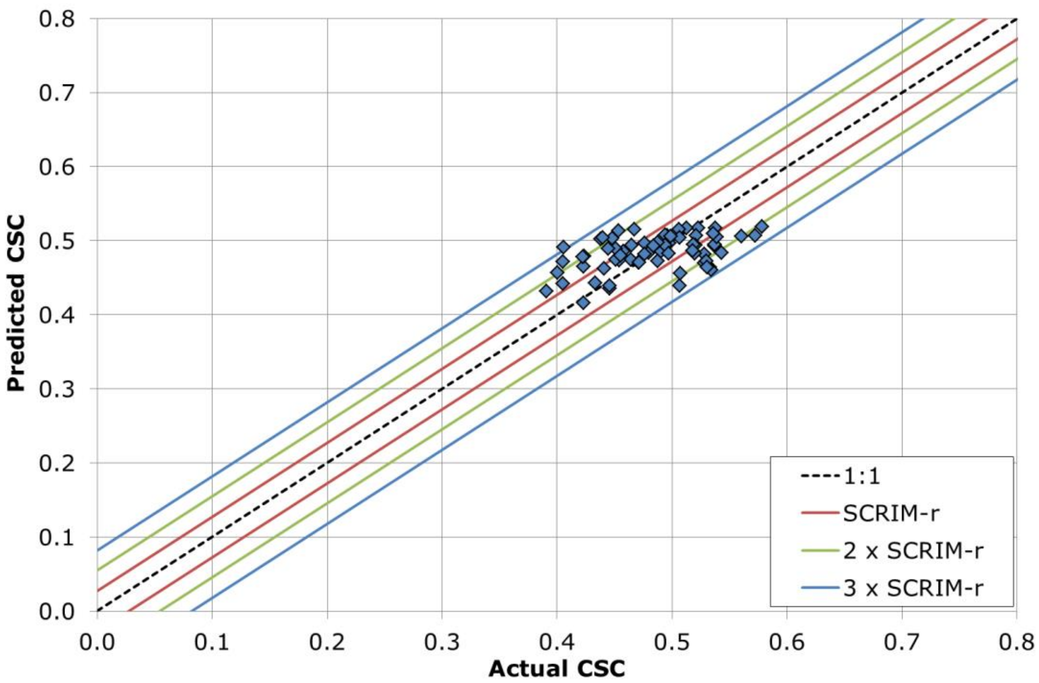


Figure 5-9 Predicted Vs actual average CSC for materials (zero roll overs)

It is believed that there were two main contributing factors for the modelling attempts not producing acceptable results. The first is that, as demonstrated by Figure 5-2 there is a difference in the reaction of materials on site compared to the reaction of materials tested in the W-Sm. Whilst the W-Sm does seek to simulate the polishing effect of vehicles it does not necessarily replicate the combined effects of weathering and vehicle polishing. This, coupled with the variation in prevailing weather across the TS network suggests that a site specific model is not possible without the inclusion of possibly weather data which was not available for this task.

The second factor is that the W-Sm measures dynamic friction (locked-wheel friction) at a speed of 60 km/h. The currently accepted characterisation of SCRIM is that it makes measurements at 34% wheel slip and 50 km/h. The use, therefore, of W-Sm friction data as a predictor of SCRIM measurements could be inappropriate[8]. A more appropriate prediction to make may therefore be locked-wheel high speed friction.

With these considerations in mind two changes were made to the modelling procedure:

1. In order to normalise the effect of weather, average data were calculated for each material type over the entire Transport Scotland network and used in place of site specific data.
2. Average Characteristic Skid Coefficient (CSC) and Sensor Measured Texture Data (SMTD) data were used to estimate the high speed locked-wheel friction of the material types and this estimation was used in the place of SCRIM data

[8] Equation 5-1 from (Roe, Parry, & Viner, 1998) also demonstrates that direct comparison of high speed locked-wheel friction and SCRIM measurements is not possible without the inclusion of the texture depth parameter.

Locked-wheel high speed friction was estimated by combining Equation 5-1 (Roe, Parry, & Viner, 1998) and Equation 5-2 (Department for Transport, 2015).

$$L - Fn100 = 0.00367SR + 0.411(1 - e^{-SMTD})$$

Where:

- L-Fn100 = Locked-wheel friction at 100 km/h
- SR = SCRIM Reading
- SMTD = Sensor Measured Texture Depth (mm)

Equation 5-1 (Roe, Parry, & Viner, 1998)

$$SR = \frac{(CSC \times 100)}{0.78}$$

Where:

- SR = SCRIM Reading
- CSC = Chatacteristic SCRIM Coefficient

Equation 5-2 (Department for Transport, 2015)

5.3.2 Predicting typical high speed friction

With the amendments mentioned in the previous section applied, a model for predicting the Est. L-Fn100 of TS2010 materials was developed. The model was created using the multiple linear regression technique where:

- The dependent variable (Y) = Est. L-Fn100
- The independent variables (X_n) were:
    1. Age of the material in years
    2. The trafficking rate in commercial vehicles / lane / day
    3. The $\mu_{PWS(60)}$ value of the untrafficked specimen of the same material without any polishing applied.

The independent variables were considered separately for each site class before the modelling exercise was carried out. The relationships between each independent variable, and the dependent variable, are shown in Figure 5-10, Figure 5-11 and Figure 5-12.

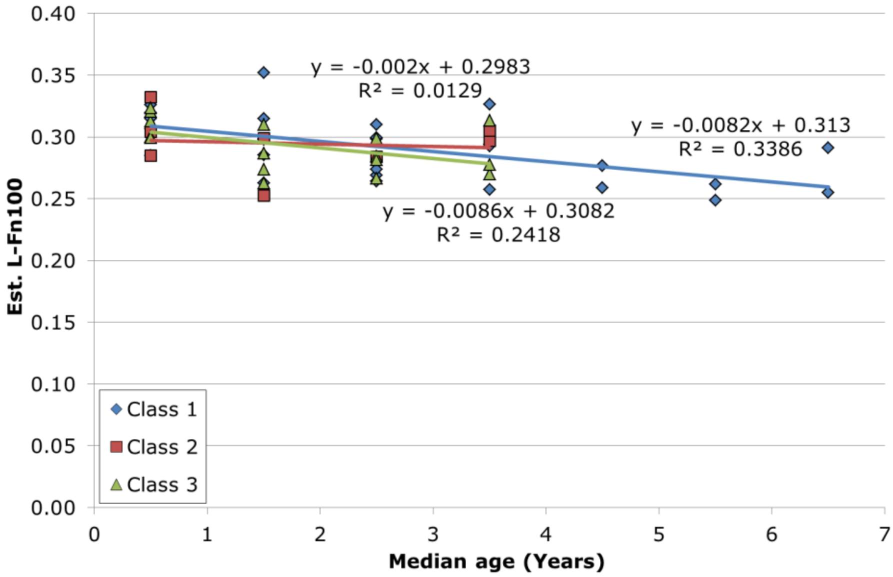


Figure 5-10 Age Vs Est. L-Fn100

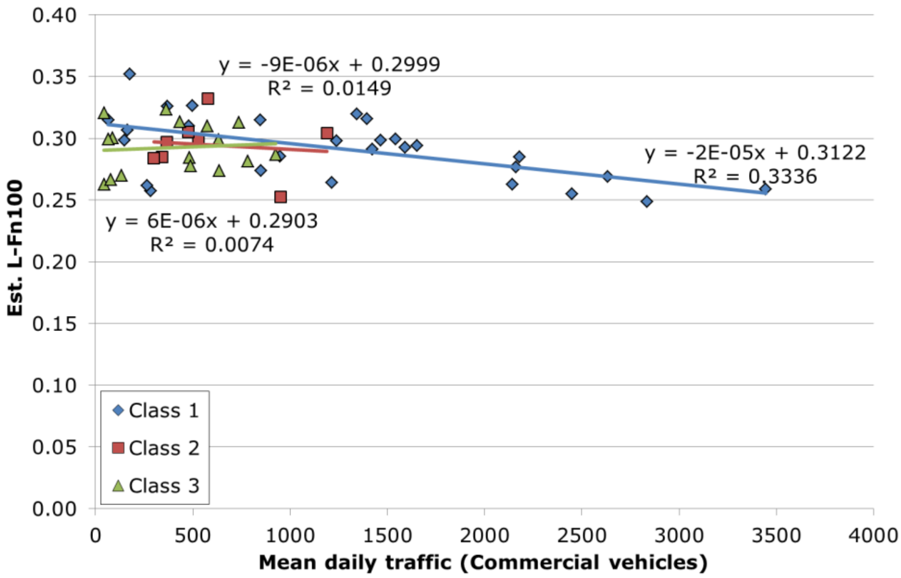


Figure 5-11 Trafficking Vs Est. L-Fn100

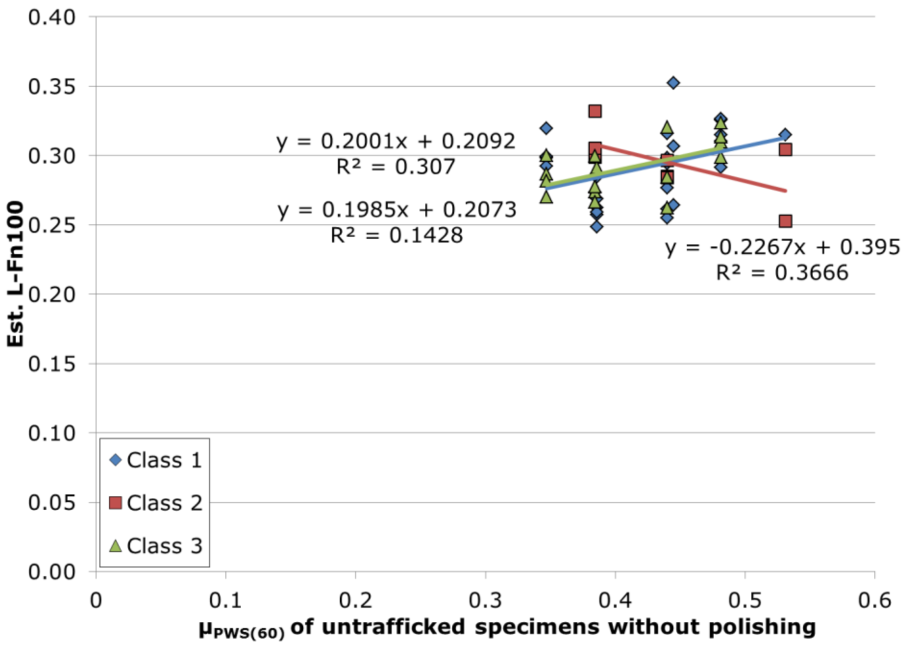


Figure 5-12 Friction of master specimen Vs Est. L-Fn100

These figures show that there is a general agreement between the relationships observed on sites with site class 1 and 3. The lines of best fit for these site classes are very similar, except for the relationship between trafficking and Est. L-Fn100 where the amount of data available for site class 3 has a small range and is being affected by a cluster of points towards the lower end of this range.

Also demonstrated by these figures is that data collected from class 2 sites does not follow the same relationships as those collected from class 1 and 3 sites. This is demonstrated most dramatically in Figure 5-12 which presents a negative correlation between friction measured in the W-Sm on the untrafficked specimens and the friction of the corresponding materials on site. It is the authors' opinion that the discrepancy in performance with the other site classes is due to a limited amount of data being available for class 2 sites (Approximately 5% of the total data assessed), and, that these relationships are produced by chance.

For this reason, the modelling exercise was carried out on data pertaining to class 1 and 3 sites only, but, the results of the modelling were applied to data from class 2 in the assessment of the model.

The results of the regression analysis is presented in Equation 5-3.

$$Est. L - Fn100 = \left(0.187 \times \mu_{PWS(60)}\right) - (0.00722 \times Age) - (4.137e^{-6} \times Traffic) + 0.235$$

Where:

- Est. L-Fn100 = The estimated high speed locked-wheel friction of the material

- $\mu_{PWS(60)}$ = the friction of the requisite untrafficked specimen as measured using the W-Sm
- Age = The age of the material in years
- Traffic = The trafficking rate of the material in Commercial Vehicles / Lane / Day

Equation 5-3 High speed friction prediction model

To assess the performance of the model, the Est. L-Fn100 of the materials on the Transport Scotland network were predicted using the model, and compared to the Est. L-Fn100 values calculated from the skid resistance and texture data. Context for these results was added in the same way as previous modelling exercises but using the repeatability of the Pavement Friction Tester[9] (PFT) instead of SCRIM. These data are presented in Figure 5-13.

A more comprehensive analysis of model performance is presented in Figure 5-14. This figure shows the cumulative distribution of the absolute model residual values[10] and compares this against the residual values that would be expected during measurement given the repeatability of the PFT.

In short, the further "left" the predicted values in Figure 5-14 appear, the better the model's ability to predict friction. Additionally the model can be considered "valid" if its predictive power is better than that of the repeatability of the device it is trying to replicate, the PFT in this case.

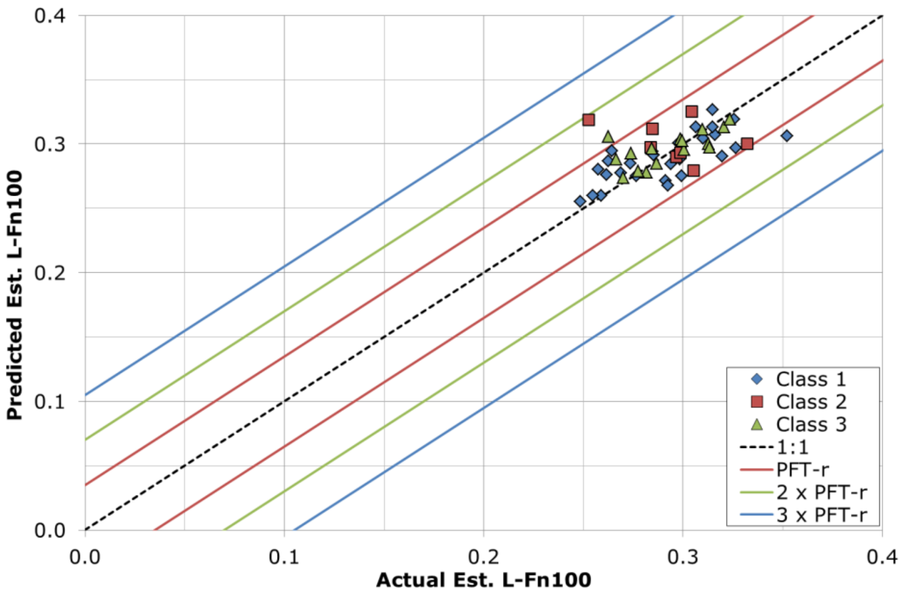


Figure 5-13 Predicted Vs. Actual Est. L-Fn100 values

[9] The instrument used in the UK for measuring high speed locked-wheel friction.

[10] The absolute value of the Predicted Est. L-Fn 100 - Actual Est. L-Fn 100.

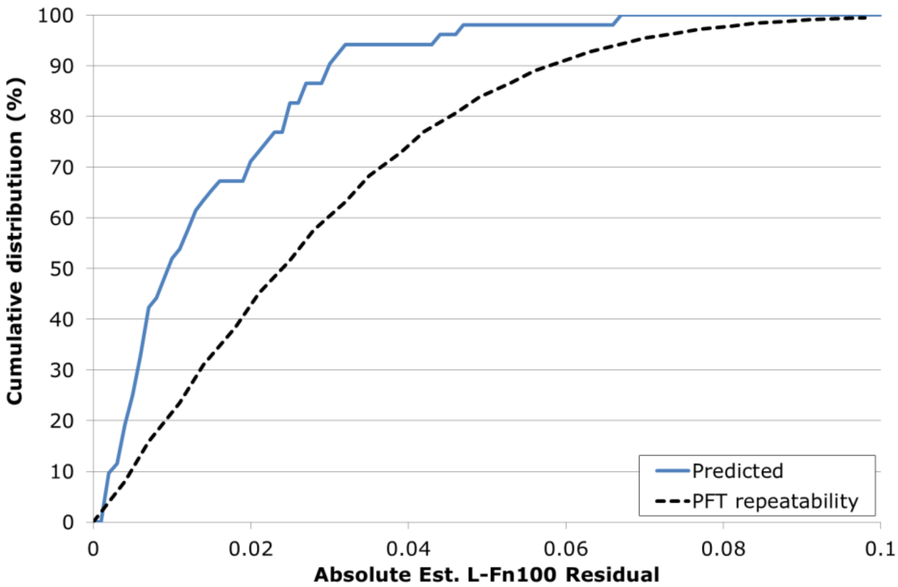


Figure 5-14 Distribution of absolute model residuals

Figure 5-13 shows that all of the data lie within two standard deviations of the 1:1 line and that the general trend for the data is to follow the 1:1 line. This satisfies the criteria for an acceptable result presented in the previous sub section. These observations are compounded by Figure 5-14 which demonstrates that, with the exception of a tiny amount close to the mean, all of the residual values are less widely distributed than the PFT repeatability.

These results are encouraging and suggest that it is possible to predict, with a reasonable level of accuracy, the general L-Fn100 properties of TS2010 materials. However, it should be noted that a site-by-site prediction is not at this stage possible owing to the lack of knowledge regarding the effect of weathering.

5.3.3 Comparison between the use of the Wehner-Schulze machine and PSV test

One of the major objectives of this work is to understand whether the Wehner-Schulze machine can offer a more appropriate solution to the specification of TS2010 materials than the PSV test. To assess this, the modelling exercise detailed in the previous section was repeated, but taking PSV as a model input instead of $\mu_{PWS(60)}$. All of the variables assessed in this analysis are presented in Table 5-1.

Table 5-1 Variables used in PSV modelling exercise

Dependent variable	CSC
Independent variable 1	PSV
Independent variable 2	Material age (years)
Independent variable 3	Trafficking level (CV/Lane/Day)

Dependent variable	Est. L-Fn100
Independent variable 1	PSV
Independent variable 2	Material age (years)
Independent variable 3	Trafficking level (CV/Lane/Day)

In addition to assessing PSV, it was also sought to assess the predictive power of friction measurements made using the Wehner-Schulze machine at a lower test speed than the standard speed of 60 km/h. In order to do this, Wehner-Schulze friction measurements made at 17 km/h[11] ($\mu_{PWS(17)}$) were used as a model input instead of $\mu_{PWS(60)}$. All of the variables assessed in this analysis are presented in Table 5-2.

Table 5-2 Variables used in $\mu_{PWS(17)}$ modelling exercise

Dependent variable	CSC
Independent variable 1	$\mu_{PWS(17)}$
Independent variable 2	Material age (years)
Independent variable 3	Trafficking level (CV/Lane/Day)

Dependent variable	Est. L-Fn100
Independent variable 1	$\mu_{PWS(17)}$
Independent variable 2	Material age (years)
Independent variable 3	Trafficking level (CV/Lane/Day)

To provide some context to these assessments, and to act as a control, a third modelling exercise was carried out to predict CSC and Est. L-Fn100 without any friction input at all. That is to say, using material age and trafficking level only. All of the variables assessed in this analysis are presented in Table 5-3.

[11] The author's view of the SCRIM measurement speed.

Table 5-3 Variables used in control modelling exercise

Dependent variable	CSC
Independent variable 1	Material age (years)
Independent variable 2	Trafficking level (CV/Lane/Day)

Dependent variable	Est. L-Fn100
Independent variable 1	Material age (years)
Independent variable 2	Trafficking level (CV/Lane/Day)

The results from all of the modelling exercises carried out are presented graphically in Appendix D. For clarity and simplicity, these results have been summarised and presented in Table 5-4 as the adjusted R^2 values of the model outputs.

Table 5-4 shows that the best predictors of CSC are PSV and $\mu_{PWS(17)}$ as the adjusted R^2 values for these variables are the highest at 0.32 and 0.33 respectively. However, the improvement in predictive power over $\mu_{PWS(60)}$ is slight and the R^2 values overall are quite low. Table 5-4 also shows that the best predictor of L-Fn100 is PSV, and that the improvement in predictive power over $\mu_{PWS(60)}$ is slight.

An observation of note from Table 5-4 is that the selection of the friction variable can have a substantial impact on the predictive power of the model. There are for instance friction variables that do not improve the predictive power of the models at all, that is to say, the same predictive power can be gained by omitting some friction variables.

Table 5-4 Adjusted R^2 values for each of the model outputs

	Dependent variable	
Independent friction variable	**CSC**	**L-Fn100**
$\mu_{PWS(60)}$	0.27	0.46
$\mu_{PWS(17)}$	0.33	0.31
PSV	0.32	0.58
None	0.27	0.31

6 Discussion and conclusions

This chapter discusses the key observations of the work carried out and presents suggestions as to where the use of the W-Sm could improve the current TS2010 approval procedure.

6.1 Use of grit

Crushed grit is applied to the surface of TS2010 at the point of laying to increase its early-life skid resistance. Newly-laid TS2010 mixtures possess a thicker binder film than most conventional asphalts and the binder film can prevent the microtexture on the aggregate particles making contact with a tyre, resulting in lower wet friction than might normally be expected. This is clearly demonstrated by the W-Sm results in Figure 5-1 when gritted and ungritted samples for the same design mixture are tested after 0 roll overs and 90,000 roll overs. Gritted specimens D and I show significantly higher friction than ungritted specimens and the observations is still true after 90,000 to 180,000 roll overs.

It is observed that the application of grit has a marked effect on both the immediate and long term friction performance of TS2010 materials**.** The application of grit dramatically affects the short term friction behaviour of TS2010 materials. Results show that not applying grit to TS2010 materials results in an initial increase in friction, whereas the application of grit results in an initial decrease in friction. However, it should be noted that the application of grit has, in all cases, a positive effect on the skid resistance of the materials assessed compared to those where no grit was applied.

It is also likely that the presence or rate of gritting could explain the variation or large variations in performance that can exist within a single mix design (see Figure 5-3). Similarly, the presence or retention of grit is likely to have an influence on the long term performance of the material as measured by the W-Sm. The latter, in combination with other factors such as weather and trafficking conditions, are likely to explain why the W-Sm is unable to predict the level of skid-resistance that will be provided in service.

6.2 Using W-Sm to predict SCRIM Coefficient

It was not possible to generate a model based on the data collected during this study that could predict the in-service friction as measured by SCRIM. It is likely that the main contributing factors for the modelling attempts not producing acceptable results are related to the W-Sm not simulating what happens to the in-service material, and the effect weather has in –service materials.

Figure 5-2 shows that there is a clear difference in the reaction of materials on site compared to the reaction of untrafficked materials when tested in the W-Sm. The effects of real traffic, weather, winter maintenance, etc. are clearly not replicated in the W-Sm. Polishing of untrafficked specimens in the W-Sm appears to bear little resemblance to the polishing experienced by in-service samples. There also appears to be substantial differences in the general performance of TS2010 materials, and the performance of materials associated with specific sites. Some of this variation could be explained by the non-uniform distribution of grit described above.

In order to normalise the effect of weather, average SCRIM data was calculated for each material type over the entire Transport Scotland network and used in place of site specific data. It is of note that the model that came closest to being acceptable used average SCRIM data, age, trafficking and W-Sm friction without polishing, i.e. the in-service W-Sm friction measured prior to any polishing.

It was concluded that while the W-Sm seeks to simulate the polishing effect of vehicles it does not necessarily replicate the combined effects of weathering and vehicle polishing experienced on the Scottish network. Coupled with the variation in prevailing weather across the TS network, a site-specific model to predict SCRIM was not possible without the possible inclusion of weather data which was not available for this task.

6.3 Comparison between W-Sm and PSV tests

The W-Sm measures dynamic friction (locked-wheel friction (100% wheel slip)) at a speed of 60 km/h. The currently accepted Characterisation of SCRIM is that it makes measurements at 34% wheel slip. The use, therefore, of W-Sm friction data as a predictor of SCRIM measurements could be inappropriate. It was considered that a more appropriate prediction was to attempt to predict locked-wheel high speed friction. This prediction was successful in that it has been shown that the general friction performance of materials can be estimated using the developed model.

Following this exercise, further modelling exercises were carried out to compare the predictive power of models based on W-Sm friction data at 60 km/h and 17 km/h, PSV, and using only material age and trafficking level. The results from these exercises were surprising in that they showed that using PSV in place of W-Sm friction data produced subtly better predictions of SCRIM value and high speed locked wheel friction of any of the modelling exercises carried out. In addition it was demonstrated that an “almost-as-good” prediction can be made when only trafficking level and material age are used as model inputs.

These findings are possibly not all that surprising given that TS2010 materials are currently selected, in part, based on the PSV characteristics of their constituent aggregates, rather than the FAP performance. What is suggested however, is that the current way in which TS2010 materials are specified is consistent enough that the very general friction performance of the materials can be relatively accurately predicted based on the currently specified parameters. Little value would be added therefore through the adoption of FAP as an additional characterisation methodology.

However, these conclusions are based on the current methodology of selecting materials based in part on aggregate PSV rather than the FAP characteristics of the mix. Should the situation be reversed it would be expected that FAP measurements would provide a better prediction of locked-wheel high speed friction than PSV.

6.4 Additional analysis

The prediction model in Equation 5-3 uses W-Sm friction results on untrafficked specimens, material age and traffic. The results are encouraging and suggest that it is possible to predict, with a reasonable level of accuracy, the general L-Fn100 properties of TS2010 materials.

However, it should be noted that a site-by-site prediction is not at this stage possible owing to the lack of knowledge regarding the effect of weathering.

The modelling exercise showed no substantial difference in the Est. L-Fn100 performance of materials installed on Class 1 and Class 3 sites (Figure 5-10 to Figure 5-12). The overall performance of materials on roads with these site classes was surprisingly similar. A similar observation was made as part of the work reported in PPR893 (Martin L A, 2019) which assessed the GripTester measurements made on SMAs on the Scottish trunk road network.

In addition, it is prudent to highlight the difference in friction performance between various specimens of nominally the same material (see for example Figure 5-3, or Figure 5-2). Given that these differences in performance appear to (in some cases) prevail, in spite of the specification of materials and application techniques, it should also be concluded that additional steps should be taken to limit the variability in TS2010 performance such as:

- the specification of FAP performance,
- the assessment of visual consistency of the surface, and
- limiting the times of year or weather conditions under which materials can be laid or extracted for evaluation.

7 Recommendations

It was concluded that the non-uniform presence of grit was a variable that was poorly controlled in this study. Any future work should introduce a protocol to ensure untrafficked specimens used for testing purposes are gritted in a consistent way as the grit can influence the results measured in the W-Sm.

It is recommended that the use of friction measurements made using the W-Sm could be considered at Stage 2 of the TAIT process[12]. The friction characteristics of specimens extracted for air voids content could be tested in the W-Sm so that an estimate of L-Fn100 could be made of the material at various ages and trafficking levels.

Some of the variability observed in the performance of the materials assessed could be associated with variability in the application of grit to the surfaces. Since the specimens were extracted, Transport Scotland have put measures into place to improve the consistency of the application of grit. It is therefore recommended that the effect of these measures be quantified through laboratory or full scale testing.

It is recommended that further research be carried out into the effects of site specific factors on the skid resistance performance of TS2010 materials. In addition it is recommended that work is continued into the efficacy of the PSV and FAP tests in reducing the variability in material performance, and predicting the on-site performance of TS2010 materials. This work should be carried out in conjunction with work seeking to understand the impact of site specific factors on TS2010 materials to allow a holistic approach.

[12] An off network (Stage 2) trial site is laid to assess the contractor’s ability to correctly install the material. Laboratory specimens of this trial section are extracted and assessed for air voids content.

8 Bibliography

British Standards Institution. (2014). *BS EN 12697-49:2014 Bituminous mixtures. Test methods for hot mix asphalt. Determination of friction after polishing.* London: British Standards Institution.

Department for Transport. (2015). *HD 28/15 - Skid resistance (DMRB 7.3.1).* London: The Stationery Office.

Highways England. (2019). *Manual of contract documents for highways works volume 1 specification for highway works - Clause 942TS.* London: Highways England.

Martin, L. A. (2019). *PPR893 An analysis of early-life skid resistance of SMAs on the Scottish trunk road network.* Wokingham: TRL.

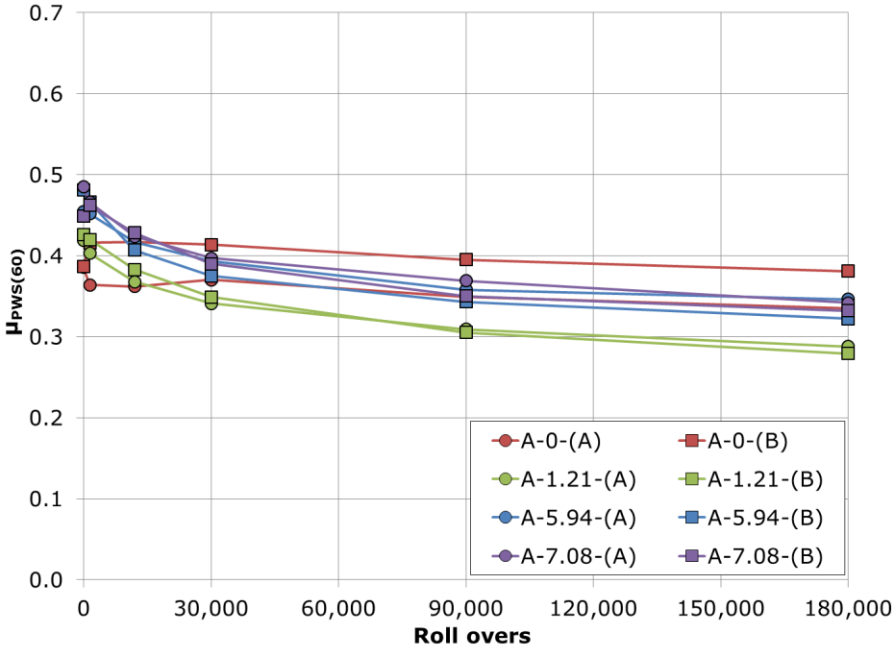
Roe, P. G., Parry, A. R., & Viner, H. E. (1998). *TRL367 High and low speed skidding resistance: the influence of texture depth.* Wokingham: TRL.

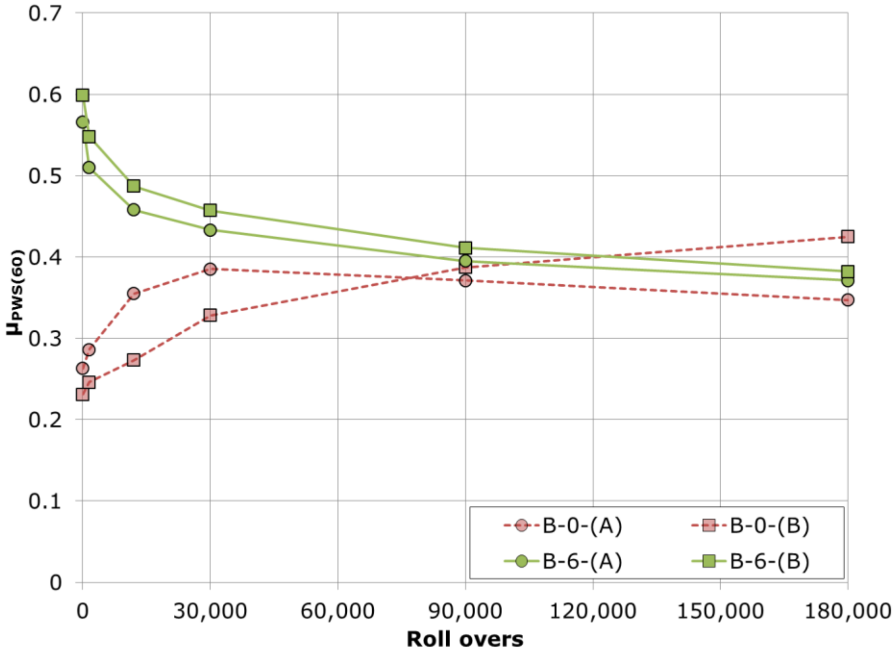
TSIA No 35. (2018). *Transport Scotland Interim Amendment No. 35, TS2010 Surface Course Specification and Guidance.* Glasgow: Transport Scotland: Standards and Traffic and Economics Branch.

Appendix A Data plots

Graphical representations of the data collected using the Wehner-Schulze machine are presented here. Data are represented with respect to each mix design, the number of cumulative commercial vehicles passed over the surface in millions, and, a unique identifier for the specimen assessed. For instance, A – 5.94 – (A) is mix A, with 5.94 million commercial vehicles having passed over it, and is specimen A.

In addition, specimens are also distinguished between those that have had grit applied and those that have not. Gritted specimens are presented with solid series markers and solid lines, whereas ungritted specimens are presented with shaded series markers and broken lines.

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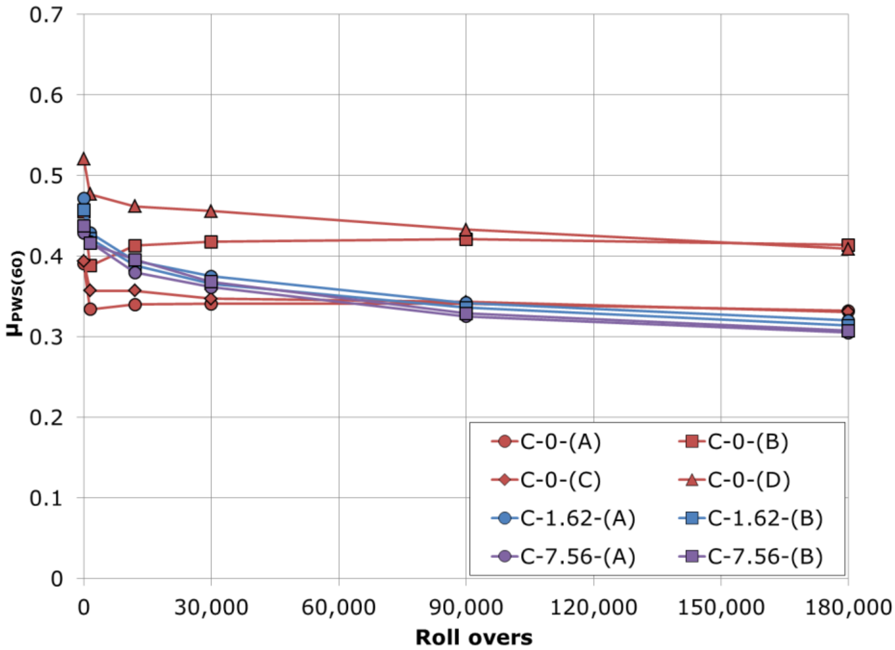
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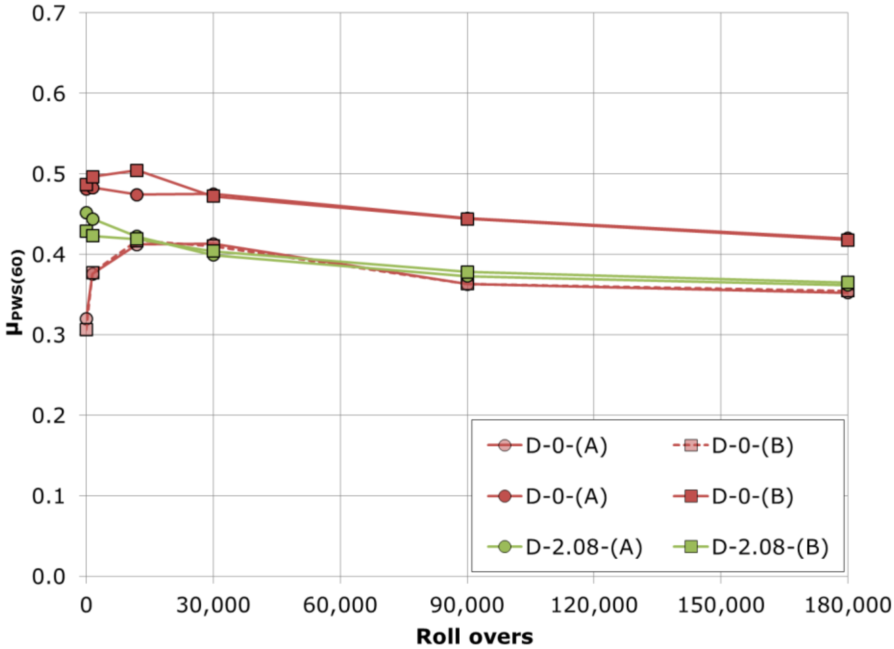
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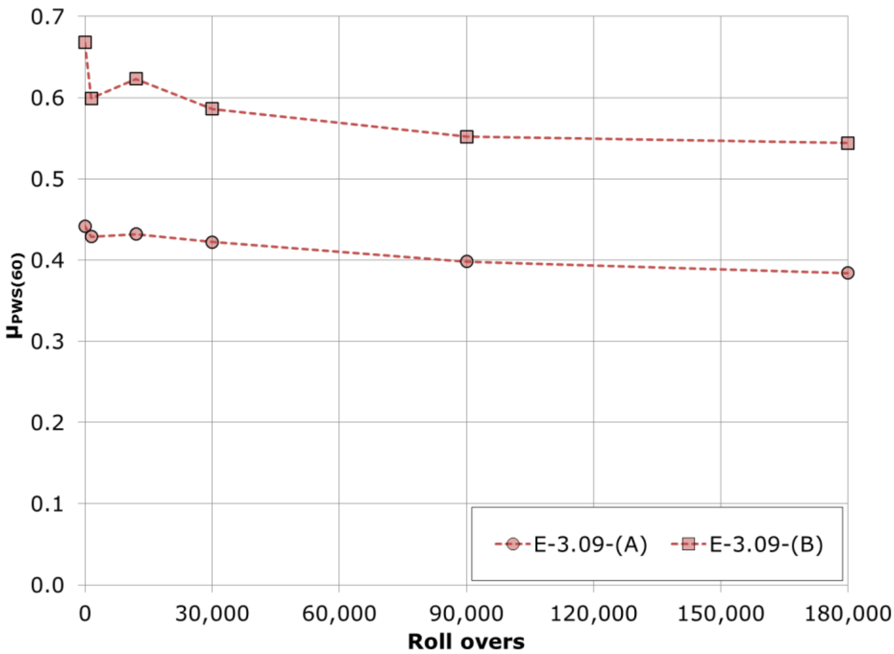
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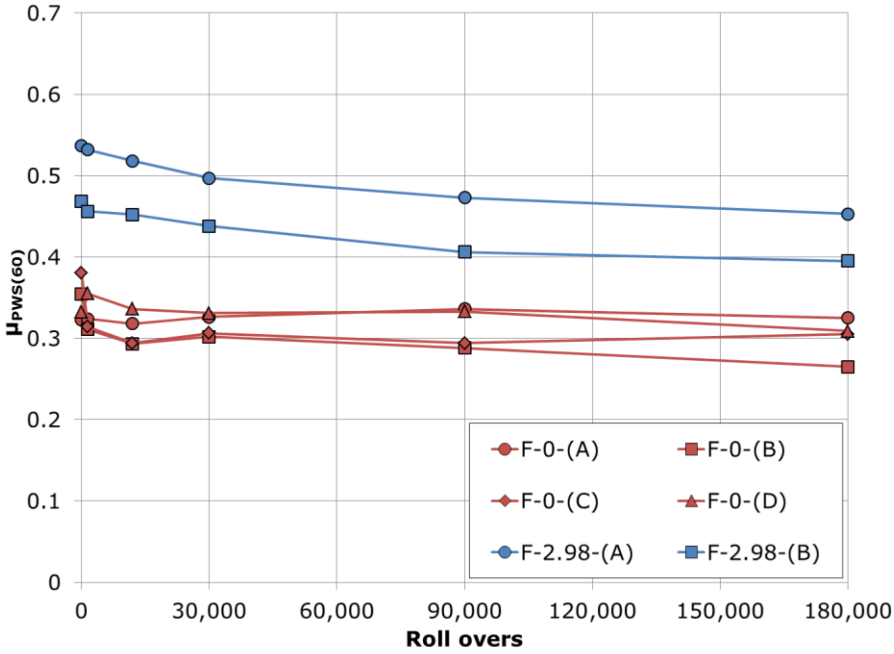
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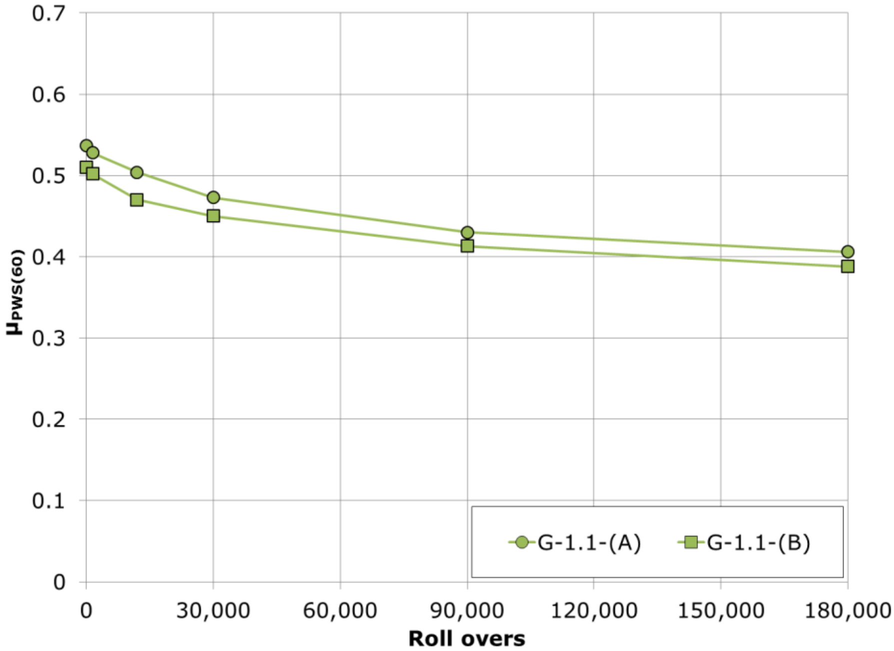
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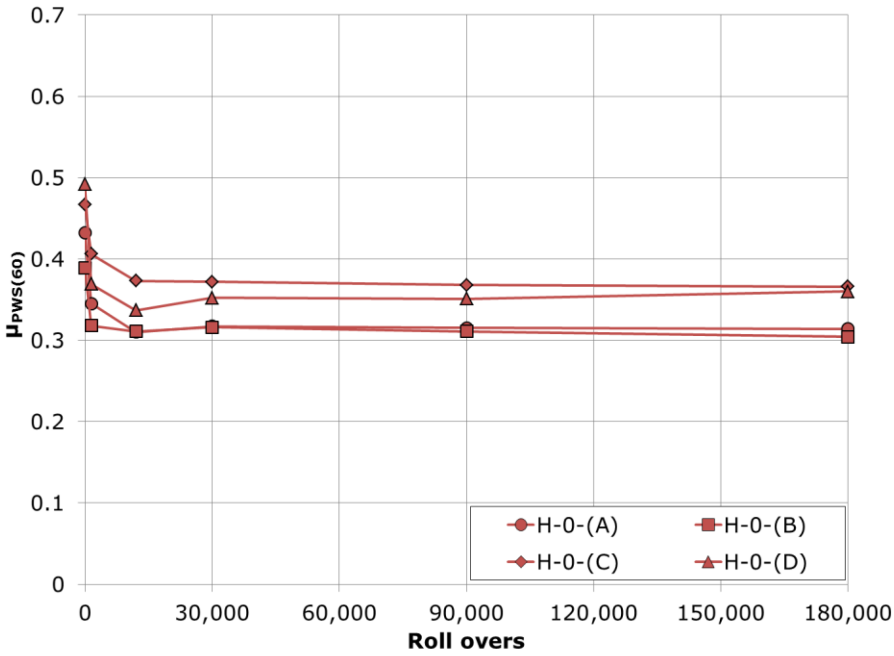
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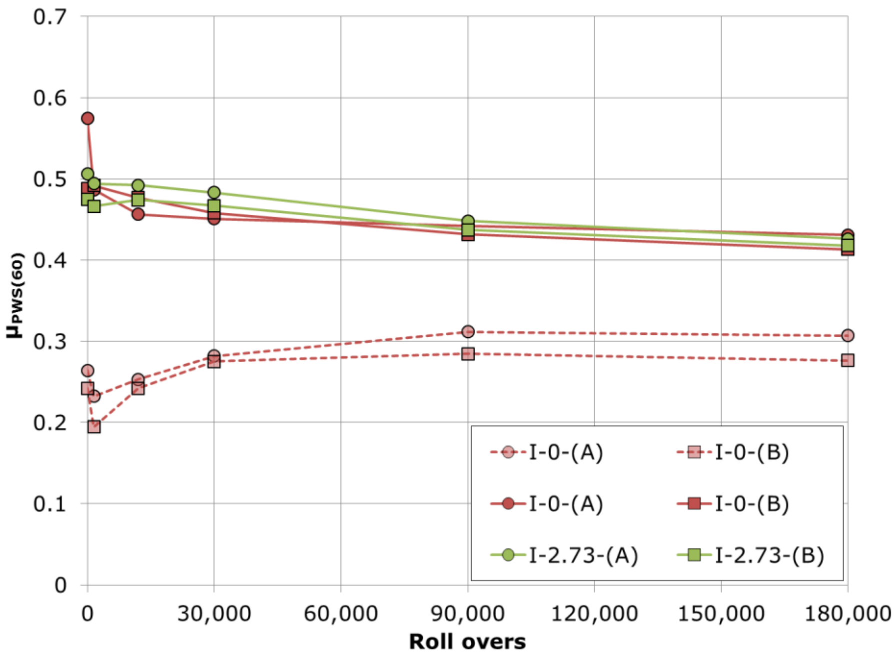
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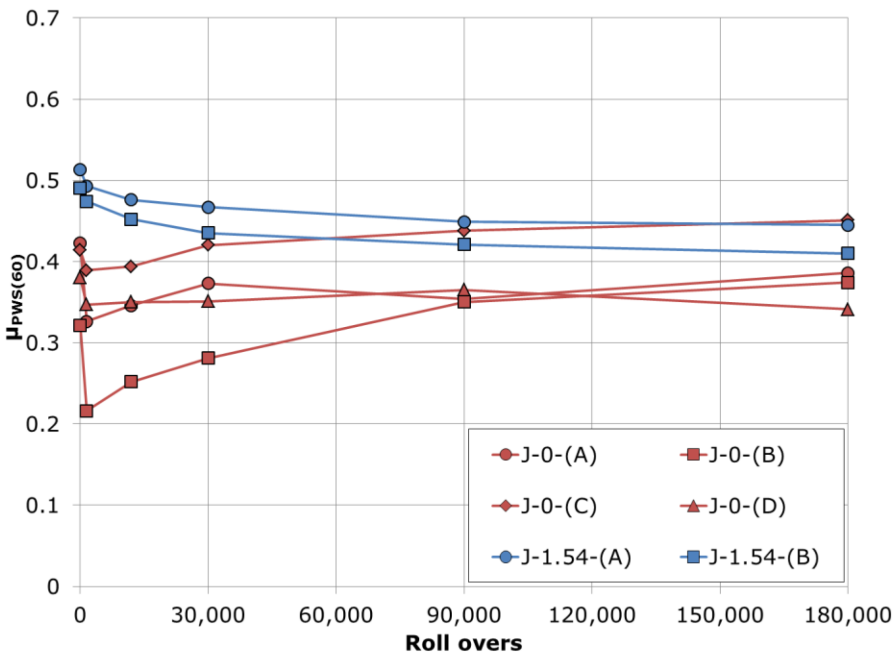
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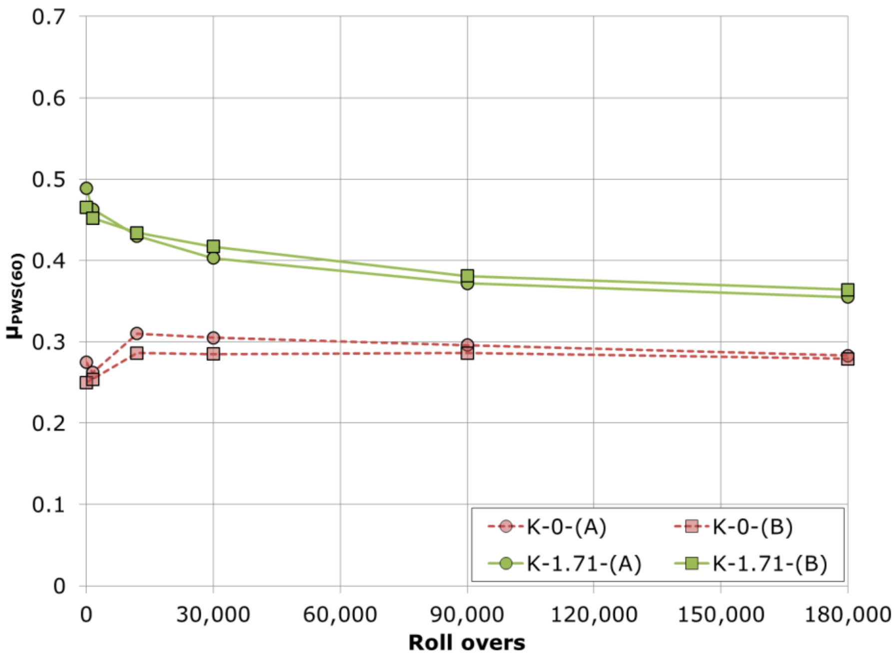
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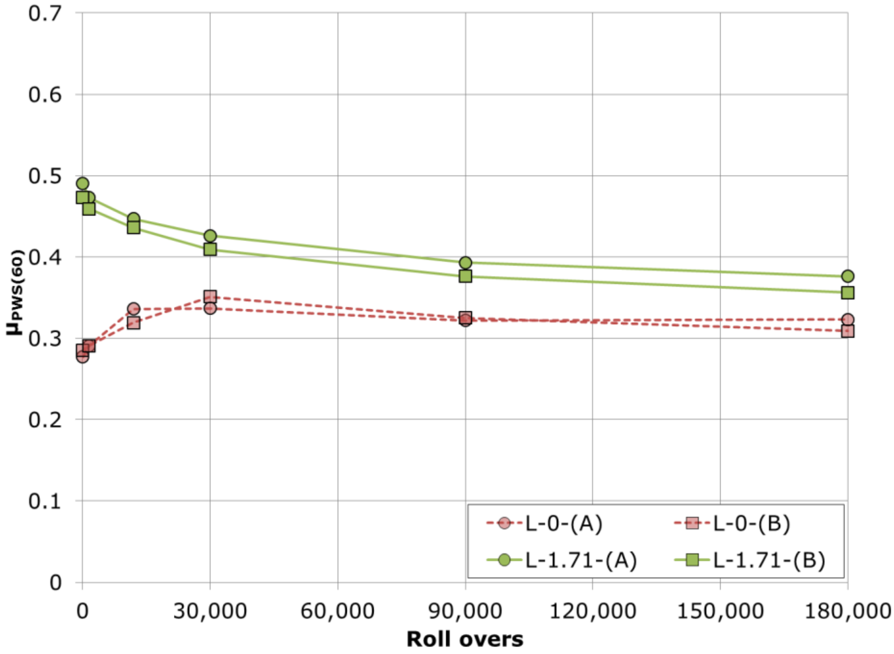
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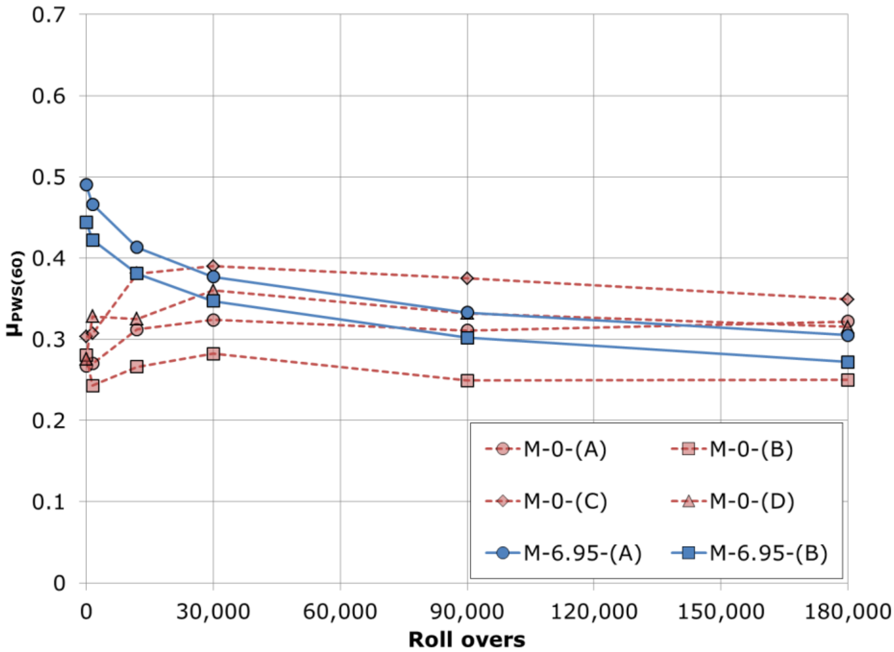
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Roll overs
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M-0-(C)
M-0-(D)
M-6.95-(A)
M-6.95-(B)

Appendix B Wehner-Schulze machine data

Unique identifier	Mix			Age and trafficking		$\mu_{PWS(60)}$ at roll overs:						$\mu_{PWS(17)}$ at 0 roll overs:
	Code	Aggregate size	Gritted	Age (yrs)	Cumulative CV (millions)	0	1,500	12,000	30,000	90,000	180,000	
A-0-(A)	A	0/10	Y	Master specimen		0.386	0.364	0.362	0.370	0.349	0.335	0.559
A-0-(B)	A	0/10	Y	Master specimen		0.386	0.416	0.417	0.413	0.395	0.381	0.592
A-1.21-(A)	A	0/10	Y	6.6	1.21	0.419	0.403	0.368	0.341	0.309	0.288	N/A
A-1.21-(B)	A	0/10	Y	6.6	1.21	0.426	0.42	0.383	0.349	0.305	0.279	N/A
A-5.94-(A)	A	0/10	Y	5.7	5.94	0.454	0.452	0.417	0.393	0.358	0.346	N/A
A-5.94-(B)	A	0/10	Y	5.7	5.94	0.481	0.466	0.407	0.375	0.343	0.322	N/A
A-7.08-(A)	A	0/10	Y	3.9	7.08	0.485	0.466	0.424	0.397	0.369	0.342	N/A
A-7.08-(B)	A	0/10	Y	3.9	7.08	0.449	0.462	0.428	0.39	0.35	0.332	N/A
B-0-(A)	B	0/10	N	Master specimen		0.263	0.286	0.355	0.385	0.371	0.347	0.602
B-0-(B)	B	0/10	N	Master specimen		0.231	0.246	0.273	0.328	0.387	0.425	0.564
B-6-(A)	B	0/10	Y	5.7	6.00	0.566	0.51	0.458	0.433	0.395	0.371	N/A
B-6-(B)	B	0/10	Y	5.7	6.00	0.599	0.548	0.487	0.457	0.411	0.382	N/A
J-0-(A)	J	0/10	Y	Master specimen		0.423	0.326	0.346	0.373	0.354	0.386	0.855
J-0-(B)	J	0/10	Y	Master specimen		0.321	0.216	0.252	0.281	0.35	0.374	0.784
J-0-(C)	J	0/10	Y	Master specimen		0.414	0.389	0.394	0.42	0.438	0.451	0.771
J-0-(D)	J	0/10	Y	Master specimen		0.38	0.347	0.350	0.351	0.365	0.341	0.799
J-1.54-(A)	J	0/10	Y	4.5	1.54	0.513	0.493	0.476	0.467	0.449	0.445	N/A
J-1.54-(B)	J	0/10	Y	4.5	1.54	0.49	0.474	0.452	0.435	0.421	0.410	N/A
C-0-(A)	C	0/10	Y	Master specimen		0.391	0.334	0.340	0.341	0.341	0.332	0.756
C-0-(B)	C	0/10	Y	Master specimen		0.455	0.388	0.413	0.418	0.421	0.414	0.777

Unique identifier	Mix			Age and trafficking		$\mu_{PWS(60)}$ at roll overs:						$\mu_{PWS(17)}$ at 0 roll overs:
	Code	Aggregate size	Gritted	Age (yrs)	Cumulative CV (millions)	0	1,500	12,000	30,000	90,000	180,000	
C-0-(C)	C	0/10	Y	Master specimen		0.394	0.357	0.357	0.347	0.343	0.331	0.840
C-0-(D)	C	0/10	Y	Master specimen		0.521	0.477	0.462	0.456	0.433	0.409	0.800
C-1.62-(A)	C	0/10	Y	6.5	1.62	0.472	0.429	0.394	0.375	0.342	0.32	N/A
C-1.62-(B)	C	0/10	Y	6.5	1.62	0.457	0.422	0.389	0.366	0.336	0.314	N/A
C-7.56-(A)	C	0/10	Y	5.3	7.56	0.429	0.418	0.380	0.362	0.325	0.305	N/A
C-7.56-(B)	C	0/10	Y	5.3	7.56	0.437	0.416	0.395	0.368	0.329	0.307	N/A
D-0-(A)	D	0/10	N	Master specimen		0.320	0.376	0.412	0.413	0.363	0.352	0.623
D-0-(B)	D	0/10	N	Master specimen		0.306	0.377	0.417	0.4102	0.3633	0.355	0.643
D-0-(A)	D	0/10	Y	Master specimen		0.482	0.483	0.474	0.4751	0.445	0.420	0.636
D-0-(B)	D	0/10	Y	Master specimen		0.487	0.497	0.505	0.4722	0.444	0.41774	0.675
D-2.08-(A)	D	0/10	Y	6.4	2.08	0.452	0.444	0.422	0.399	0.373	0.362	N/A
D-2.08-(B)	D	0/10	Y	6.4	2.08	0.429	0.423	0.419	0.404	0.378	0.365	N/A
E-3.09-(A)	E	0/14	Y	5.6	3.09	0.442	0.429	0.432	0.422	0.398	0.384	N/A
E-3.09-(B)	E	0/14	Y	5.6	3.09	0.668	0.599	0.623	0.586	0.552	0.544	N/A
F-0-(A)	F	0/10	Y	Master specimen		0.323	0.324	0.318	0.326	0.336	0.325	0.855
F-0-(B)	F	0/10	Y	Master specimen		0.354	0.311	0.293	0.302	0.288	0.265	0.885
F-0-(C)	F	0/10	Y	Master specimen		0.380	0.314	0.294	0.306	0.294	0.305	0.789
F-0-(D)	F	0/10	Y	Master specimen		0.332	0.355	0.336	0.331	0.333	0.309	0.761
F-2.98-(A)	F	0/10	Y	5.6	2.98	0.537	0.532	0.518	0.497	0.473	0.453	N/A
F-2.98-(B)	F	0/10	Y	5.6	2.98	0.468	0.456	0.452	0.438	0.406	0.395	N/A
G-1.1-(A)	G	0/10	Y	3.4	1.10	0.537	0.528	0.504	0.473	0.430	0.406	N/A
G-1.1-(B)	G	0/10	Y	3.4	1.10	0.510	0.502	0.470	0.450	0.413	0.388	N/A

Unique identifier	Mix			Age and trafficking		$\mu_{PWS(60)}$ at roll overs:						$\mu_{PWS(17)}$ at 0 roll overs:
	Code	Aggregate size	Gritted	Age (yrs)	Cumulative CV (millions)	0	1,500	12,000	30,000	90,000	180,000	
H-0-(A)	H	0/10	Y	Master specimen		0.432	0.345	0.31	0.317	0.315	0.314	0.840
H-0-(B)	H	0/10	Y	Master specimen		0.389	0.318	0.311	0.316	0.311	0.304	0.866
H-0-(C)	H	0/10	Y	Master specimen		0.467	0.406	0.373	0.372	0.368	0.366	0.733
H-0-(D)	H	0/10	Y	Master specimen		0.492	0.369	0.337	0.352	0.351	0.36	0.728
I-0-(A)	I	0/6	N	Master specimen		0.264	0.232	0.253	0.282	0.3116	0.30687	0.516
I-0-(B)	I	0/6	N	Master specimen		0.242	0.194	0.242	0.275	0.2846	0.27634	0.607
I-0-(A)	I	0/6	Y	Master specimen		0.574	0.487	0.457	0.451	0.4422	0.43084	0.669
I-0-(B)	I	0/6	Y	Master specimen		0.488	0.492	0.477	0.458	0.4316	0.41318	0.586
I-2.73-(A)	I	0/6	Y	3.1	2.73	0.506	0.494	0.492	0.483	0.448	0.426	N/A
I-2.73-(B)	I	0/6	Y	3.1	2.73	0.475	0.466	0.474	0.467	0.437	0.418	N/A
K-0-(A)	K	0/10	N	Master specimen		0.275	0.262	0.310	0.305	0.296	0.283	0.606
K-0-(B)	K	0/10	N	Master specimen		0.25	0.254	0.286	0.285	0.286	0.279	0.630
K-1.71-(A)	K	0/10	Y	4.7	1.71	0.489	0.463	0.430	0.403	0.372	0.355	N/A
K-1.71-(B)	K	0/10	Y	4.7	1.71	0.465	0.452	0.434	0.417	0.381	0.364	N/A
L-0-(A)	L	0/6	N	Master specimen		0.277	0.291	0.336	0.337	0.322	0.323	0.725
L-0-(B)	L	0/6	N	Master specimen		0.285	0.291	0.319	0.351	0.325	0.309	0.724
L-1.71-(A)	L	0/6	Y	4.7	1.71	0.49	0.473	0.447	0.426	0.393	0.376	N/A
L-1.71-(B)	L	0/6	Y	4.7	1.71	0.473	0.459	0.436	0.409	0.376	0.356	N/A
M-0-(A)	M	0/10	N	Master specimen		0.267	0.27	0.312	0.324	0.311	0.322	0.624
M-0-(B)	M	0/10	N	Master specimen		0.280	0.243	0.266	0.282	0.249	0.250	0.702
M-0-(C)	M	0/10	N	Master specimen		0.303	0.307	0.381	0.390	0.375	0.349	0.704
M-0-(D)	M	0/10	N	Master specimen		0.276	0.328	0.325	0.360	0.332	0.315	0.773

Unique identifier	Mix			Age and trafficking		$\mu_{PWS(60)}$ at roll overs:						$\mu_{PWS(17)}$ at 0 roll overs:
	Code	Aggregate size	Gritted	Age (yrs)	Cumulative CV (millions)	0	1,500	12,000	30,000	90,000	180,000	
M-6.95-(A)	M	0/10	Y	6.0	6.95	0.490	0.466	0.413	0.377	0.333	0.305	N/A
M-6.95-(B)	M	0/10	Y	6.0	6.95	0.444	0.422	0.381	0.347	0.302	0.272	N/A

Appendix C CSC, Texture and PSV data

Material code	Site class	CSC at average age (years)							SMTD at average age (years)							Aggregate PSV
		0.5	1.5	2.5	3.5	4.5	5.5	6.5	0.5	1.5	2.5	3.5	4.5	5.5	6.5	
A	1	0.498	0.491	0.471	0.465	0.433	0.446	0.507	0.673	0.587	0.659	0.620	0.696	0.619		62
A	3	0.539	0.520	0.520					0.716							62
B	1	0.524	0.511	0.529	0.534	0.531			0.648	0.629	0.681	0.639	0.653			68
B	2	0.528	0.541	0.476		0.492			0.637	0.654	0.612		0.632			68
B	3	0.529	0.519	0.517	0.520				0.746	0.642	0.658					68
C	1	0.496	0.476	0.480	0.471	0.507	0.400	0.391	0.840	0.791	0.785	0.783	0.616	0.789	0.777	60
C	2	0.454	0.438	0.406	0.424				0.778		0.900	0.926				60
C	3	0.506	0.440	0.451	0.455				0.840	0.698	0.782					60
D	1	0.523	0.494	0.494	0.476			0.405	0.824	0.838	0.812	0.959	0.916		0.948	55
D	3	0.538	0.507	0.484	0.497				0.774	0.779	0.777	0.823				55
F	1	0.487	0.465	0.454	0.441	0.446		0.423	0.884	0.823	0.857	0.854		0.762		60
F	3	0.499	0.445	0.422	0.405				0.748	0.812	0.842	0.822				60
G	1	0.510	0.466	0.455	0.465	0.474			0.843	0.748	0.791	0.775				55

Material code	Site class	CSC at average age (years)							SMTD at average age (years)							Aggregate PSV
		0.5	1.5	2.5	3.5	4.5	5.5	6.5	0.5	1.5	2.5	3.5	4.5	5.5	6.5	
G	2	0.482							0.842							55
G	3	0.499	0.469	0.504	0.524				0.851		0.750					55
H	1	0.467	0.448	0.458	0.451				0.862	1.241	0.666					55
I	1	0.578	0.573						0.637	0.659						55
I	2	0.513	0.521						0.736	0.486						55
J	1	0.529	0.537	0.528	0.528	0.533			0.638	0.592	0.559	0.630				65
J	2	0.561	0.537	0.543	0.530	0.534			0.763	0.651		0.700				65
J	3	0.536	0.518	0.518	0.488	0.531			0.658	0.580	0.549	0.662				65
K	1		0.488	0.517		0.601	0.510		0.634		0.632		0.663			55
M	1	0.517	0.477	0.467	0.473				0.738	0.699	0.699	0.688				55
M	2	0.510	0.473	0.478	0.421				0.627	0.681	0.663	0.754				55
M	3	0.523	0.487	0.491	0.454				0.854	0.655	0.766					55

Appendix D Graphical results of modelling exercise

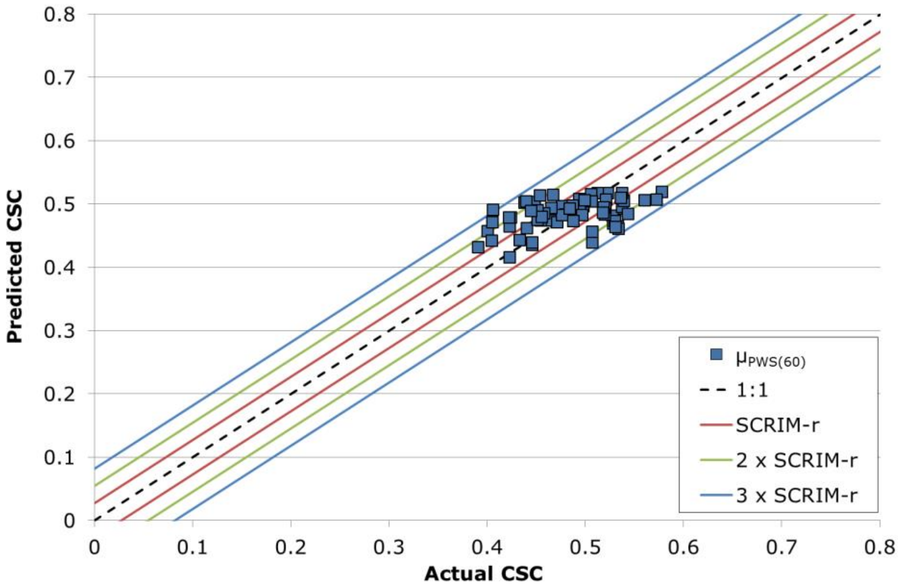

Figure 8-1 Predicted Vs. Actual CSC values using $\mu_{PWS(60)}$

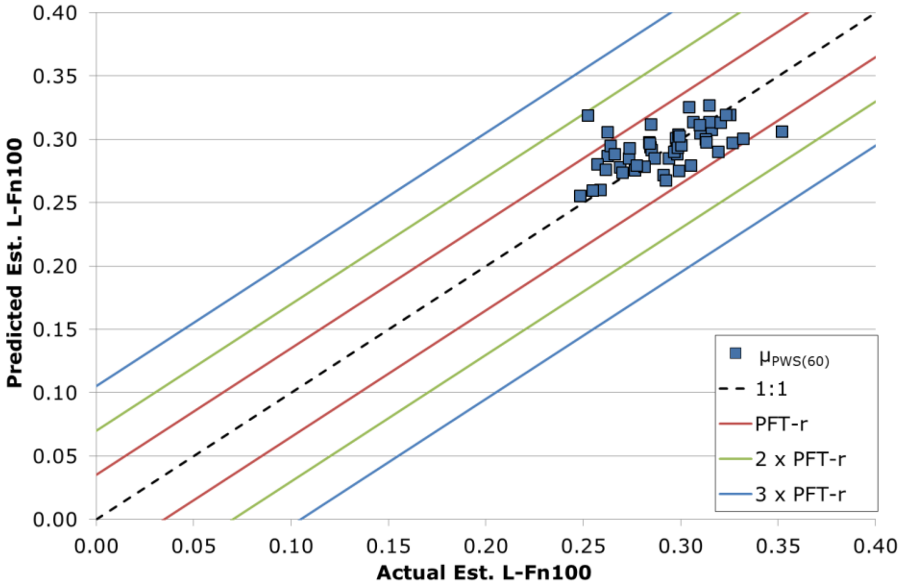

Figure 8-2 Predicted Vs. Actual Est. L-Fn100 values using $\mu_{PWS(60)}$

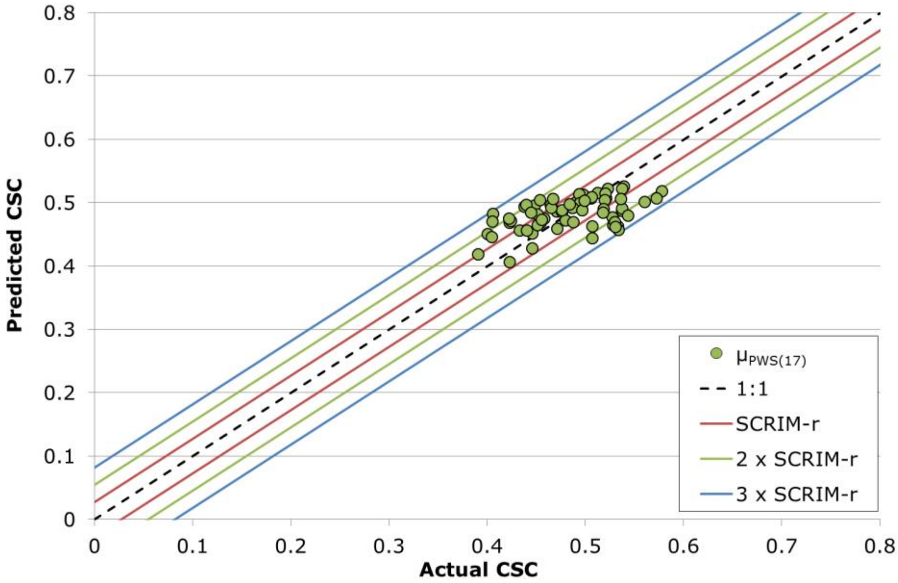

Figure 8-3 Predicted Vs. Actual CSC values using $\mu_{PWS(17)}$

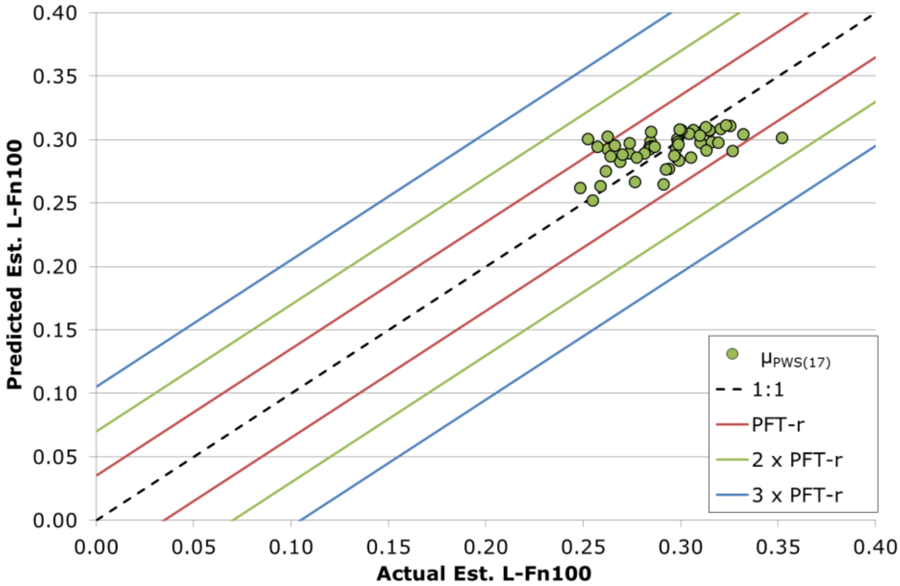

Figure 8-4 Predicted Vs. Actual Est. L-Fn100 values using $\mu_{PWS(17)}$

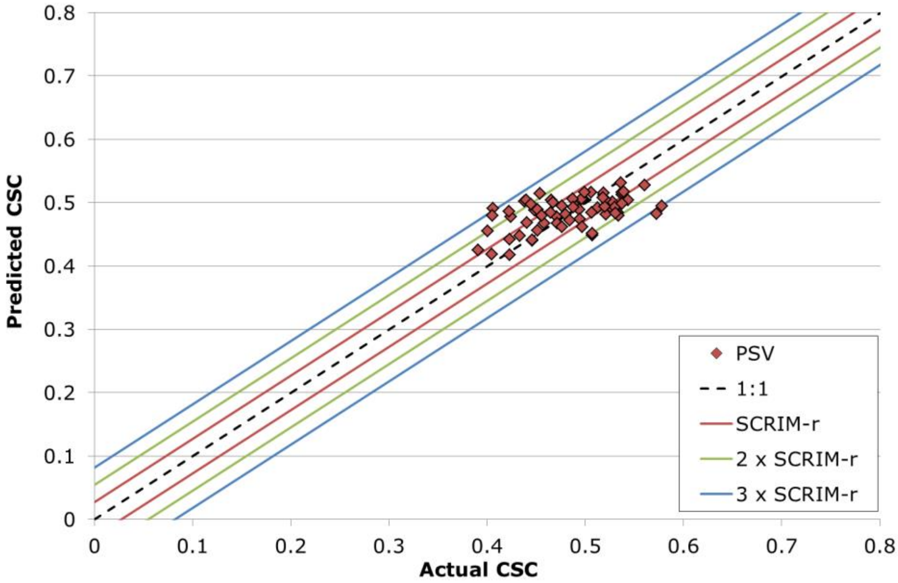

Figure 8-5 Predicted Vs. Actual CSC values using PSV

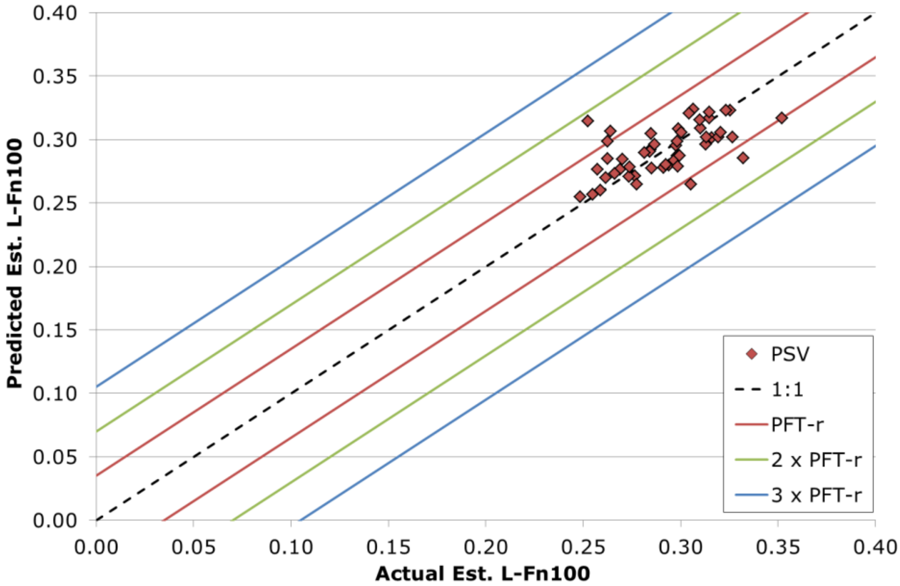

Figure 8-6 Predicted Vs. Actual Est. L-Fn100 values using PSV

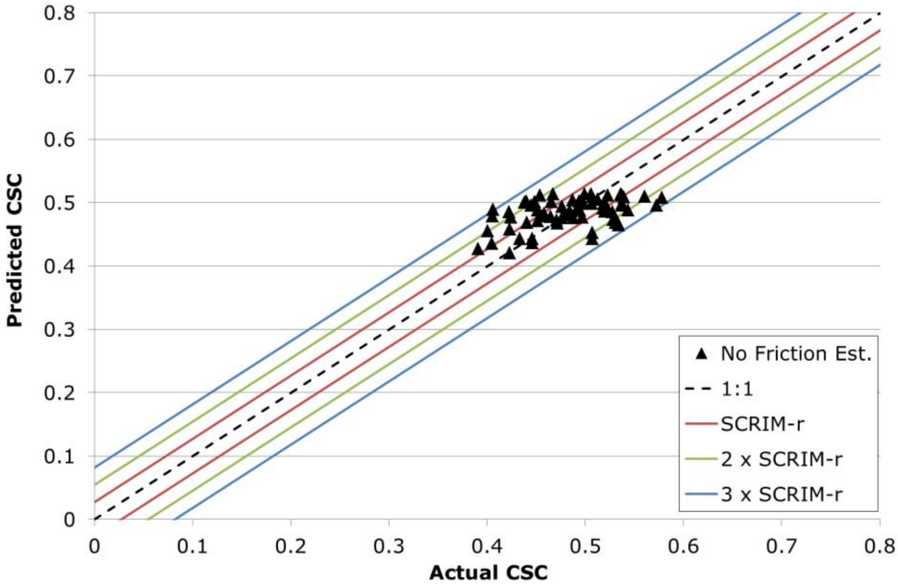

Figure 8-7 Predicted Vs. Actual CSC values using no friction estimations

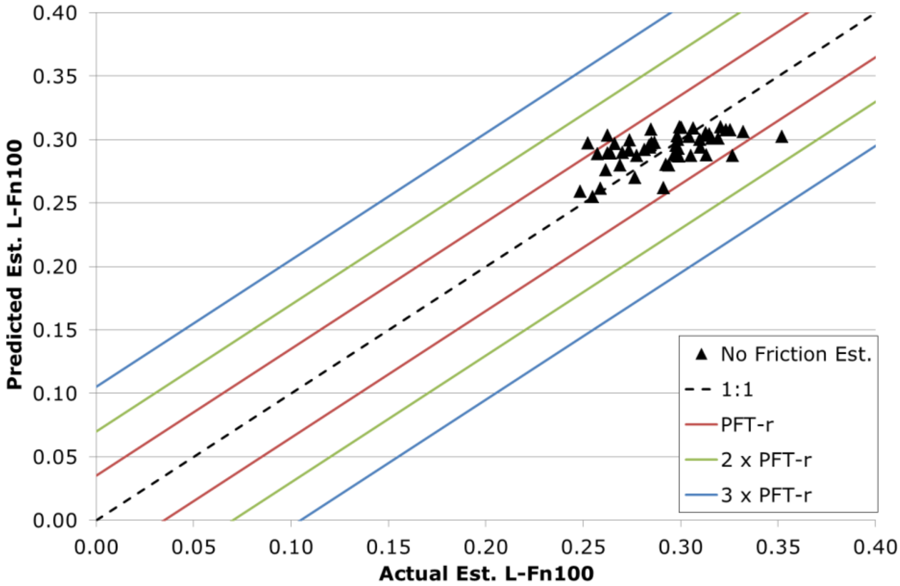

Figure 8-8 Predicted Vs. Actual Est. L-Fn100 values using no friction estimations

Evaluating friction after polishing as an in-service skid resistance prediction tool for TS2010 materials

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