Scottish Road Research Board

PROVIDING APPROPRIATE LEVELS OF SKID RESISTANCE

70058173
JULY 2020

PUBLIC

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TYPE OF DOCUMENT (VERSION) PUBLIC

PROJECT NO. TS/TRBO/SER/2017/04/02
OUR REF. NO. 70058173

DATE: JULY 2020

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PROVIDING APPROPRIATE LEVELS OF SKID RESISTANCE

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PUBLIC

QUALITY CONTROL

Issue/revision	**First issue**	**Revision 1**	**Revision 2**	**Revision 3**
Remarks	001			
Date	3/03/2020	03/04/2020	08/04/2020	08/07/2020
Prepared by	Michael McHale Alan Ferguson Luke Martin	MM	MM	MM
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Project number	70058173			
Report number	70058173-002			
File reference	Skid resistance report			

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EXECUTIVE SUMMARY

Transport Scotland commissioned WSP to undertake a study to gain a better understanding of the relationship between TS2010 surface course materials and the skid resistance provided by the materials. The overall aim of the study was to evaluate the current procedure for providing appropriate levels of skid resistance on the trunk road network, and to assess whether any changes were required.

It is generally acknowledged that low skidding resistance on roads is rarely the direct cause of an accident, but it becomes important when other factors create a demand for friction to permit rapid, controlled braking or manoeuvring. Historically, the aim of skidding standards has been to equalise accident risk across the network by providing higher levels of friction in situations where accidents are more likely to occur. Providing the most appropriate level of skid resistance is challenging for several reasons such as changes in road materials, driving behaviour, car technology and the nature of the road environment at each location.

This study attempts to gain a better understanding of the relationship between Transport Scotland's preferred surface course (TS2010), the in-service skid resistance using the characteristic skid coefficient (CSC), recent crash history data and the influence of weather, such as rainfall. With the aid of a business intelligence (BI) tool, data was collected and processed to provide information such as scheme location, site class, material type, age and in-service skid resistance. The data was used to determine the performance of TS2010 on different site classes; how friction changes with time; an assessment of Transport Scotland's current approval system; and whether friction performance is influenced by location, or environmental effects. In addition, a review of wet crash rates against skid resistance for different site categories was undertaken to explore whether there is scope to amend existing investigatory levels (ILs).

Based on an analysis of the collected information, various conclusions were made, including:

- no significant difference was observed in skid resistance performance of individual TS2010 mixtures when laid on different Site Classes;
- there is a general trend for the in-service friction to reduce slightly with time and that around half of the overall loss occurs between year one and year two;
- the current approval system for classifying TS2010 in terms of friction performance is working well;
- the relationship between aggregate PSV and CSC is complex, with some lower PSV aggregates outperforming higher PSV aggregates;
- there appears to be little benefit in specifying natural aggregates with a PSV 68+, as they do not perform any better than aggregates in the PSV 65-67 range.
- there is some evidence that some TS2010 mixtures provide higher in-service friction in the wetter parts of the country;
- for certain site categories, the data suggests that the wet crash rate is not influenced by the CSC value, i.e. higher CSC does not equate to a lower wet crash rate; and
- the overall CSC performance of TS2010 shows that the top performing mixtures will broadly achieve 0.5 IL.

Based on an examination of wet crash rate versus CSC for TS2010 mixtures some amendments to the current ILs (CS 228) have been proposed. Each site category was examined to determine whether

any patterns or trends existed. In some instances, a relationship did not appear to exist and it is likely that the occurrence of accidents are influenced by other factors, such as human error. Where a reasonable or strong relationship existed then a revised default IL has been proposed. The amendments are contained within Table 6-1 in Section 6 of this report.

In addition, the report makes several other recommendations associated with approving and improving TS2010, including:

- Consider approving certain TS2010 mixtures for use on higher site classes where good performance has been achieved on Site Class 1.
- Monitoring the general trend for overall CSC to reduce with time to determine whether this tendency continues or stabilises.
- Continue to classify TS2010 use based on CSC rather than aggregate PSV.
- Study the influence of rainfall on TS2010 performance with a view to reclassifying mixtures based on their location on the network.
- Consider trialling the use of TS2010 mixtures that utilise calcined bauxite grit.

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INTRODUCTION

1 INTRODUCTION

1.1 BACKGROUND

Currently in the UK the skid resistance for most surface course mixtures is controlled by specifying the Polished Stone Value (PSV) of the coarse aggregate or chipping. An exception to this exists in Scotland where the skid resistance of TS2010 surface course is controlled by a performance-based specification (TSIA No 35, 2018). The latter involves measuring the early-life skid resistance of new materials using a braked-wheel fixed slip device, known as the GripTester. Similar to the rest of the UK, the longer-term in-service skid resistance is measured using the sideway-force coefficient routine investigation machine (SCRIM).

The current PSV requirements and their relationship with in-service skid resistance has been developed over many years based on data collected in England. In Scotland, anecdotal evidence suggests that the expected or predicted levels of in-service skid resistance utilising PSV has generally not been achieved. The aim of this study is to review the current situation in Scotland with a view to improving the provision and management of skid resistance on Scottish trunk roads.

1.2 SCOPE

Transport Scotland commissioned WSP to undertake a study to gain a better understanding of the relationship between TS2010 surface course materials and the provision of skid resistance on the trunk road network. The study aims examine the link between road surface material properties, annual in-service skid resistance measurements made with SCRIM, and recent crash history data. The overall aim of the study is to appraise the current UK skidding resistance standard and guidelines (CS 228) and to determine whether the most appropriate materials and levels of skid resistance are being provided on the trunk road network in Scotland, and to assess whether any changes are required.

The project was split into two parts:

- a review of available literature relating to the provision and management of skid resistance on roads, embracing current specifications, standards and research papers, including a review of a recently completed study on the Friction After Polishing (FAP) test; and
- an examination of skid resistance data held on Transport Scotland's Integrated Roads Information System (IRIS), including measurements of the underlying skid resistance, material properties, age, location, weather effects and recent crash history data.

The aim of the literature review was to establish the current situation and to inform the subsequent analysis of available data relating to skid resistance. This report describes the study, including: the results of the literature review; the data analysis undertaken, including the approach and a discussion of the findings; main conclusions; and finally, the report makes proposals to improve the current systems and processes associated with the provision and management of skid resistance on Scottish trunk roads.

2

LITERATURE REVIEW

2 LITERATURE REVIEW

A review of literature relating to the development and specification of skid resistance was carried out and has been split into four sections: early research and specifications (1920 to 1980s); recent research (1990s to present); current standards; and summary.

2.1 EARLY RESEARCH & SPECIFICATIONS (1920-1980s)

In the 1920s, the numbers of both commercial and private vehicles were seen to increase at a remarkable rate. As the traffic increased, the number of accidents increased, and these were mainly attributed to a lack of adhesion between tyre and road, especially in the wet. Concerns about increasing accidents led to significant research into the skidding resistance of roads.

2.1.1. Road Research Laboratory

Ground-breaking research was carried out by the Road Research Laboratory to try and understand the processes that influence the skid resistance of road surfaces. Studies were undertaken to develop tests that could measure the friction of surfaces and simulate the effect of traffic polishing aggregates present in the surfacing of a road. By the 1950s, three forms of apparatus had come in to use: the portable skid resistance tester (pendulum tester); braking force machines and the sideway-force machine (pre-cursor to SCRIM). Figure 2-1 shows an early braking-force trailer attached to a test car which was used for measuring the skidding resistance of airfield runways (1953). Figure 2-2 shows a skidding-test car with the rear door open to show a test wheel and mounting designed to measure the sideway-force coefficient (CFC). In parallel to this work, two standardised tests were developed to assess the Polished Stone Value (PSV) and the Aggregate Abrasion Value (AAV).

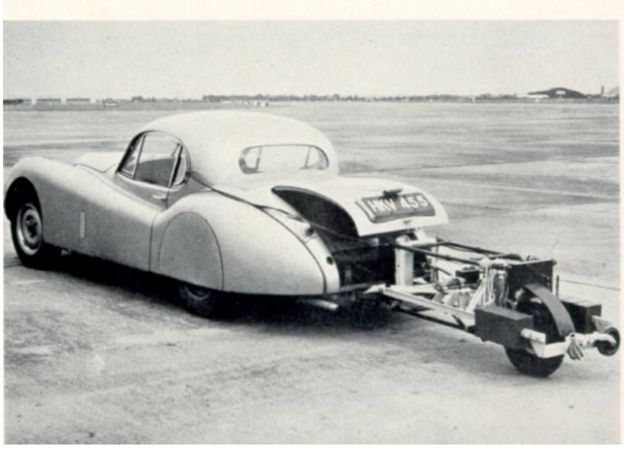


Figure 2-1 - Braking-force trailer

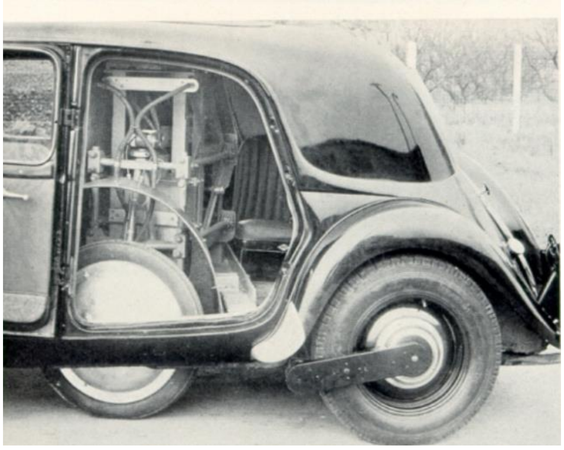


Figure 2-2 - Early sideway-force coefficient

Research findings from this period were reported by McLean and Shergold (1958), namely:

- Aggregate testing showed that resistance to polishing was dependent on the source of the aggregate.
- Gritstones provided high values after testing; basalt, gabbro, granite, porphyry and quartzite groups produced intermediate values; and flint, hornfel and limestone groups were observed to polish significantly.

- Polishing was related to traffic intensity and road geometry.
- Seasonal changes in skid resistance were related to detritus being present on the road surface, and aggregates were expected to be less polished in the winter than summer, and less polished in wetter areas of the country.

Further work by Neville (1974) and Hosking *et al* (1976) showed that the difference between summer and winter conditions was related to changes in aggregate microtexture. During dry summer conditions, road detritus ground to a fine powder acts as a polishing medium and reduces SFC values. The opposite effect results in the winter months when, under wet conditions, the surface rainwater washes away the dust and facilitates larger particles, such as salt and grit, to scratch the polished surface and increase the skid resistance.

2.1.2. Relationship between PSV & heavy commercial vehicles

A trial in England on skid resistance was designed by Szatkowski and Hosking (1972) to derive a relationship between side force coefficient (SFC), traffic and PSV. The work was based on 139 sections of roadway that carried different amounts of commercial vehicles per day (CVD) and contained different coarse aggregate PSVs. It subsequently became the basis for the standard for the construction of new roads in 1976. It was presented in the form of a table that gave the minimum PSV for given levels of traffic on different categories of site.

2.1.3. Identifying high PSV aggregates

Work by Hosking (1976) describes how polishing processes are related to material properties. He noted that the resistance to polishing is influenced by the way aggregates wear owing to fracture and crushing. The behaviour of the aggregate is related to its mineral composition and factors such as the degree of agglomeration of the constituents, and the presence of minerals susceptible to weathering.

2.1.4. Texture Depth

Work using the braking-force trailer highlighted the need for macrotexture. High speed tests using the braking-force trailer showed that wet skidding resistance fell with speed and that surfacing with higher texture depth showed less loss of skidding resistance. It was suggested that the texture depth was needed to assist the rapid removal of water from the interface between the tyre and the road, allowing the tyre to make intimate contact with the microtexture provided by the aggregate.

Braking force machines were particularly valuable in investigating the skidding resistance of airfield surfaces and the effect of texture depth on high speed roads. This type of apparatus also assisted major tyre manufacturers to develop tread patterns which contributed to improving tyre/road friction, particularly when braking from high speeds.

2.1.5. Standard for surface courses

As a result of the research described above, the Department of Transport introduced standards for the properties of aggregates used in newly-constructed roads in 1976. Dependant on site categories and traffic flows, the specification included a minimum PSV and AAV, together with a requirement for an initial texture depth, i.e. 1.5mm, which was measured using a sand patch test.

2.1.6. In-service Skidding Resistance (1988)

During the same period, it became clear that wet-road skidding accidents occurred in clusters and that common factors included alignment, topography, surfacing regularity and surfacing smoothness. Maintenance treatments were effective in reducing accidents, but a methodology was required which could be used for preventative purposes. It was recognised that low skidding resistance is rarely the direct cause of an accident. Rather, it becomes important when other factors create a demand for friction to permit rapid, controlled braking or manoeuvring.

Continuing the theme that the level of friction required was related to the risk of an accident, skidding and accident data from a wide range of sites were collected in the 1970s. This allowed the risk of wet skidding accidents at a site to be related to SFC measured at 50 km/h. These data provided the basis of the current UK skidding standards which define “Investigatory Levels” for the skidding resistance of different categories of site. The chief objective was to equalise accident risk across the network. The first standard for in-service skidding resistance of UK Trunk Roads was introduced in 1988, based on regular monitoring with the Sideway-force Coefficient Routine Investigation Machine (SCRIM).

2.2 RECENT RESEARCH (1990s - PRESENT)

2.2.1. Review of PSV requirements (1990s)

Owing to the growth in traffic levels in the 1990s it was decided to review the relationship derived in 1970s by Szatkowski and Hosking (1972). Research by Roe & Hartshorne (1998) highlighted that large variations in skid performance could be obtained from a single source of aggregate. Importantly, the work showed that the existing 1970s relationship underestimated skid resistance for sites carrying high traffic levels, i.e. above the range of the original study. In particular, the study showed that aggregates do not necessarily continue to polish as traffic levels increase. The work provided evidence that some materials were over specified and that a limited number of types of aggregate were used. Attempts were made to modify the PSV test regime to see if it could improve the prediction of in-service performance but this proved to be unsuccessful. The study recommended that further research was required to explain the variations found in service, and to enable the performance of a wider range of aggregates and their properties to be assessed.

2.2.2. Introduction of negatively textured surfacing

The research and development of standards described above was based on traditional surfacing, such as HRA and surface dressing. The mid-90s saw the introduction of proprietary materials that were developed in mainland Europe. Known generically as Thin Surfacing Course Systems (TSCS), the materials presented a significant step change in that they utilised different coarse aggregate sizes and possessed a negative rather than a positive texture.

Initially, following the introduction of TSCS, the PSV requirements for coarse aggregate remained the same. However, several studies were carried out in the noughties to explore the differences in performance of negatively textured materials. One study (Roe & Dunford 2012) monitored a range of TSCSs with different PSVs and aggregate size. The study showed that the trends with PSV were complex with some lower PSV aggregates outperforming higher PSV aggregates. The study highlighted that the frictional properties of thin surface courses systems incorporating aggregates with a nominal size of 10mm or less, were better than those for larger sized aggregates. The smallest aggregate size (0/6 mm) was found to provide a higher skid resistance, particularly on sites carrying higher traffic volumes. It was thought that this might be associated with lower contact pressures in the tyre-road interface, and a reduction in the amount of polishing imposed by traffic.

The study also looked at the texture depth and the high-speed friction of TSCS and noted that 0/6mm materials produced friction levels markedly above what might be expected for surfacing that possess a low texture. Various mechanisms for this were suggested at the time, namely:

- texture measurement techniques may not adequately characterise the road surface;
- a higher proportion of aggregate in the tyre/road interface allows for greater grip;
- Smaller-sized particles lead to a different pressure distribution in the contact patch, also affecting the way in which the tyre and road interact; and
- different contact areas or pressure distributions affect the polishing mechanism and the equilibrium skid resistance developed.

As a result of the above study, the minimum PSV (IAN 156/12) and texture depth (IAN 154/12) requirements for negatively textured TSCS were revised in 2012 and these can be found in the latest UK standard for surface course materials (CD 236).

2.2.3. TS2010 Surface Course

Following repeated examples of shorter than anticipated service life from various TSCSs in Scotland, research was undertaken to reconfigure surface courses in 2008 (McHale et al, 2011). One of the main objectives was to reduce the open texture appearance of surfacing by specifying the use of denser mixes using smaller stone sizes to enhance durability. As part of a road trial, several mixtures were laid that contained different aggregate sizes and compositions, including the application of grit (see Figure 2-3).

A range of measurements were taken to assess the surface characteristics and to allow comparisons with conventional materials. The study showed that gritting is shown to have an influence on increasing early-life skidding resistance. It significantly improves friction at intermediate and high speeds initially, but dependant on grit retention the effect can reduce with traffic. It was considered that the benefits of gritting could be short lived on motorways, but likely to be of value in reducing the skid risk on roads where traffic is lighter, particularly when the bitumen coating of surface aggregates is present for longer.

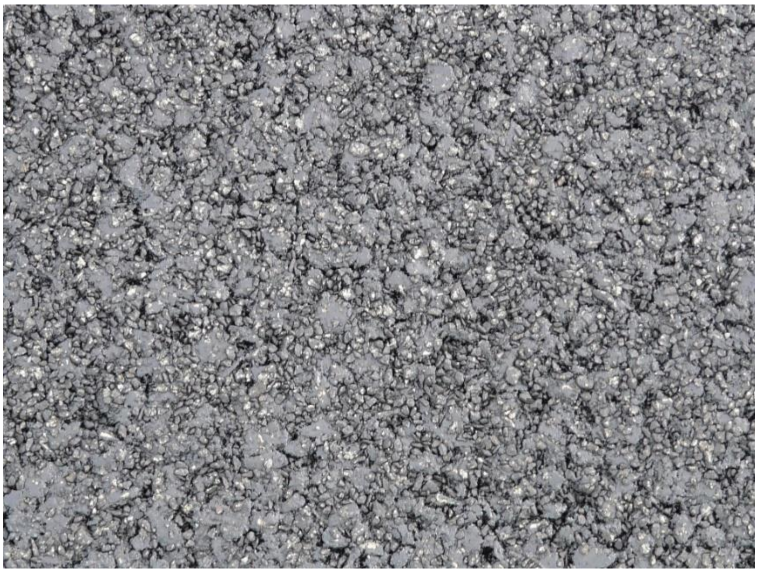


Figure 2-3 - New TS2010 surface course after gritting (TRL670)

2.2.4. Performance-based skid resistance specification

The TS2010 specification breaks with convention (McHale, 2015) by not specifying a minimum texture depth. Trials of TS2010 had consistently shown that the strict grading requirements inherently provide adequate surface texture. However, to ensure a satisfactory level of skid resistance was being provided, an early-life skid resistance requirement was introduced and measured using a braked-wheel fixed slip device, known as the GripTester (Figure 2-4).

Figure 2-4 - GripTester measuring early-life skid resistance

Data collected by the GripTester, since the introduction of the TS2010 specification, has added weight to the growing evidence that aggregate PSV and a minimum texture depth cannot be reliably used to predict skid performance for some modern negatively textured surface courses.

2.2.5. Wehner-Schulze or Friction After polishing (FAP) test

The Highways Agency (now Highways England) purchased a Wehner-Schulze machine in 2005 to evaluate its ability to simulate the polishing action of traffic on aggregates and asphalts and its potential use as a specification tool for surface course materials.

Figure 2-5 - FAP testing equipment

The Wehner-Schulze (W-S) machine was in developed in the 1960s and its use is becoming more widespread in Europe, where it is seen to have the potential to become a tool for specifying “Friction after Polishing” or FAP (see Figure 2-5). A three-year study by Dunford and Roe (2012) compared the polishing applied to the pavement surface course by real traffic with the polishing that can be applied in the laboratory using the W-S machine.

Asphalt slabs were prepared in the laboratory, cored into discs, and embedded in the surface course in three separate sites to sample a range of traffic conditions. Identical asphalt slabs were prepared for testing in the Wehner-Schulze machine and to two different test regimes, one using grit blasting and one without, were used. Friction tests on cores extracted from the trial sites showed that W-S friction measurements (prior to polishing) correspond reasonably well to friction measurements carried out by SCRIM, i.e. SC. (see Figure 2-6).

Test results demonstrated that friction measurements from samples subjected to artificial polishing broadly correlate with those from samples subjected to light traffic but there was considerable unexplained variation in the data.

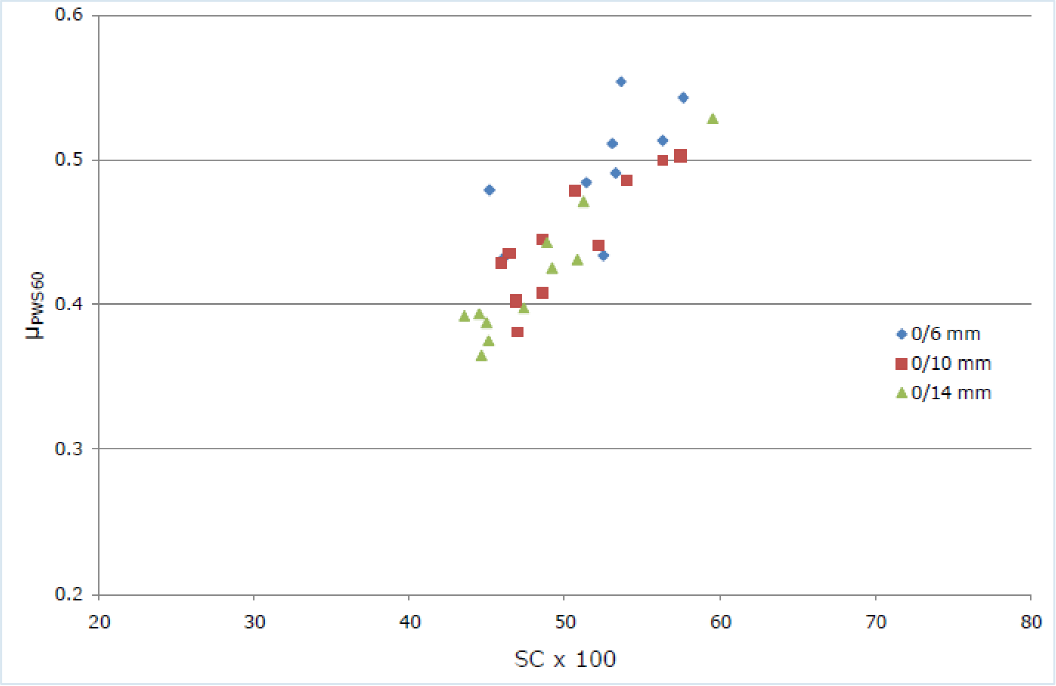


Figure 2-6 - Relationship between SCRIM and W-S test results (Roe & Dunford, 2012)

The repeatability of the machine was thought to be satisfactory, but the reproducibility, as measured in a pan-European cooperative study, required improvement. It was concluded that individual machines were suitable for research purposes and asphalt design, but further work was required if it was to be used for specification purposes.

A study by Friel *et al* (2013) describes the first assessment of asphalt mixtures used in Ireland using the Wehner-Schultze machine. All mixtures were made with a greywacke aggregate (PSV 62) and included: 0/10mm SMA, 0/14mm SMA and Hot Rolled Asphalt (HRA) with 20mm pre-coated chippings. Testing was carried out at the IFSTTAR laboratory in Nantes, France. The 0/10mm SMA was found to have the highest W-S friction coefficient closely followed by the 14mm SMA. The HRA was significantly lower. The results showed that different friction coefficients are possible for the same aggregate if used in different types or aggregate mix configurations. The paper concludes that if the W-S test is to be adapted as a European Standard test method, it must be able to realistically assess a varied menu of differing asphalt mix types. The paper suggested that more research was required to better understand its ability and operating limitations.

2.2.6. Blending aggregate sources

A study by Dunford (2014) investigated various combinations of 6/14mm and 4/10mm sources from different PSV groups: low (49-53), medium (54-63) and high (63-68). A particularly interesting conclusion from this study was that the smaller aggregate sizes had a disproportionate influence on the combined friction level, even when considering the lower proportion, by mass, of the 4/10mm source in the mixture. It was speculated that this was related to the higher surface area, per unit mass, of the smaller aggregates, and could be an important factor when considering the sustainability or cost savings associated with using a scarcer or more expensive aggregate source.

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

A study by TRL (Sanders *et al*, 2018) was undertaken with the aim of determining whether the Friction After Polishing (FAP) test could be used as an alternative to the PSV test to predict the in-service levels of skid-resistance produced by TS2010 materials. Both trafficked and untrafficked specimens of TS2010 materials were tested as part of the study. FAP measurements were compared with measurements such as SCRIM and traffic levels, and other factors such as road site categories, material age and texture depth. Analysis of these results found that it was not possible to generate a model based on the data that could predict the in-service skid performance of TS2010 materials. Other conclusions included:

- 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 of TS2010 specimens.
- Due to the inconsistent presence of grit, large variations in performance were recorded with the FAP test, even within a 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 FAP test simulates the polishing effect of vehicles but it does not necessarily replicate the combined effects of weathering and vehicle polishing experienced on the Scottish network.

A visual examination of the test specimens used in the TRL study permitted some additional observations to be made:

- Grit retention was high on untrafficked cores after W-S testing.
- Trafficked cores showed the effects of real-life trafficking, which was not replicated by the FAP test polishing regime after 180,000 passes (see Figure 2-7).
- Polished aggregate could be clearly seen on trafficked cores, but no significant polishing could be seen on untrafficked specimens following FAP testing.
- Some of the differences in results could be explained by the different appearance of trafficked and untrafficked cores, but not all.
- Laboratory prepared specimens appeared to produce more consistent results.

Figure 2-7 - Trafficked (left) and untrafficked (right)

The FAP study provided an important insight into the friction provided by gritted TS2010 surface course materials. However, the presence, spread rate and retention of grit (particularly in service) produced large variations in the FAP results. Weathering and polishing on in-service roads is not replicated in the FAP test, and as such, the test cannot be regarded as a realistic predictor of ultimate SCRIM. Assuming a method could be introduced to control the influence of the grit, it is possible that the FAP test could be used for ranking the skid resistance performance of different surface course mixtures.

2.2.8. Justifying the use of low PSV aggregates based on performance

The Design Manual for Roads and Bridges (DMRB) advises designers on the minimum polished stone value (PSV) that is required for a particular road, but states that where knowledge exists that a local aggregate will give the required skid resistance in service then that aggregate may be used irrespective of the PSV. This clause acknowledges the fact that the in-service skid performance is not wholly predicted by the PSV test. It is worth noting that the overall position has shifted under CD 236. Using an alternative PSV now requires a departure from standard, whereas HD36 permitted this as the default stance, stating that the prescribed table values were only to be used if no other information was available.

Based on a study carried out on the Isle of Skye, Transport Scotland have approved two methods for evaluating the in-situ skid performance of a local aggregate (McHale *et al.*, 2017). The methods include using either SCRIM or GripTester surveys to collect road friction data. The collection of in-service skid performance data on the Isle of Skye demonstrated that aggregates do not always polish to the extent typically shown in design charts, particularly where relatively low levels of traffic and harsher weather conditions prevail.

2.2.9. Skidding measurements and Environment Effects

The skid resistance of road surfaces can fluctuate within a year and between successive years, while maintaining a similar general level over a long period of time. There are a number of different methods to normalise this variation and one method is to use benchmark sites which have three surveys in the year (early, mid and late season). These three surveys are used to indicate seasonal variation and provide a Seasonal Correction (SC). However, several studies have shown that not only is there within year variation, but there is also between year variation depending on whether summers are wetter or drier than average and how harsh the winter period. The current UK standard (CS 228) permits a method that uses measurements from the preceding three years to characterise the long-term skid resistance of the network.

General road debris such as particulates, dust and road salt, that are present on the road surface prior to skid resistance testing can influence the measurements made. It is likely that the interval between periods of heavy rainfall will also restrict the amount of polishing of road surfacing by vehicular traffic. A study by McHale *et al* (2017) provided evidence that sites that share a similar geography, climate and traffic levels can influence the degree of polishing that occurs. The study showed that relatively high rainfall and short periods between rainfall, even during summer, restrict the amount of polishing of road surfacing by vehicular traffic.

A study in Ireland (Mulry *et al*, 2012) discusses the impact of climate change and contends that there is no longer a simple cyclical pattern of warm dry summers followed by cold wet winters. In general, the paper suggests that there are increasingly wetter summers and drier winter periods, and significant changes in weather patterns with greater variation of rainfall and temperature occurring from year to year. The study uses SCRIM data collected over a five-year period to look at the effect of seasonal variation between years and during each year, and develops a model to correct for seasonal variation based on surface type, temperature and accumulated rainfall rather than the calendar time of year. The study indicated that temperature may be a major factor affecting seasonal variation of skid resistance and it might be beneficial to record surface temperature at the time of measurement.

2.2.10. Road accidents and skid resistance

As mentioned earlier, road accidents in the 1980s were seen to be related to wet-road skidding that occurred in clusters and that common factors included alignment, topography, surfacing regularity and surfacing smoothness. A publication (DfT, 2016) relating to the number of GB personal-injury road traffic accidents in 2015, summarises some of the factors that affect road casualty numbers. The document stresses that there is no single underlying factor that drives road casualties, but major influences, include:

- The distance people travel
- The mix of transport modes used
- Behaviour of drivers, riders and pedestrians
- Mix of groups of people using the road (e.g. changes in the number of newly qualified or older drivers)
- External effects such as the weather, which can influence behaviour such as encouraging or discouraging travel, or by making the road surface more slippery.

The last bullet point relates directly to road friction, however the document goes on to say that good weather (higher temperatures and lower precipitation) tends to increase casualties and bad weather tends to decrease casualties. It appears that all accidents have a cause and that the cause is often someone making a mistake or exhibiting dangerous or thoughtless road behaviour, but when and where fatalities occur appears to be becoming more random. It is also likely that developments in vehicle technology have made an impact on reducing accidents. Safety features which are becoming increasingly standard include electronic stability control (ESC), tyre-pressure monitoring systems (TPMS) and autonomous emergency braking (AEB).

2.2.11. Texture depth and accidents

A small study was undertaken by WDM for Transport Scotland in 2002 to determine whether there was a relationship between texture depth and accidents (Transport Scotland, 2002). The study was based on accident and friction data collected over a three-year period between 1999 and 2001.

In general, there seemed to be no connection between the texture depth and accident rate for most of the site categories described in HD 28/94. This was thought to reflect the fact that only a small length of network contained materials with very low textures. However, data associated with major junctions did appear to have a correlation between the texture and wet and dry accidents, i.e. the accident rates reduced as the texture increased. When major junctions from the urban and rural environment were separated, the rural junctions maintained the correlation, but there was no correlation for the urban junctions. It was highlighted that the major urban junction category represented a small number of junctions on the Scottish trunk road network.

The study concluded that with the exception of rural major junctions there appeared to be no evidence that texture is related to accidents occurring, providing that a minimum texture depth is provided. The report recommended that a more detailed study that investigated sites that have low textures should be considered.

2.2.12. Collisions and skid resistance on strategic roads

A study based on data from Highway England’s Strategic Network examined the relationship between collisions, skid resistance and other characteristics (Wallbank *et al*, 2016). Building on a previous survey undertaken in 2004 (Parry & Viner, 2005), the study found that although the general trend for collision risk to decrease with increasing skid resistance still existed, the trends were less pronounced.

A multivariate regression technique was used to investigate the relationship between collisions and a number of variables (where available) including skid resistance, rut depth, texture depth, curvature, gradient and crossfall. The results provided an indication of the direction of the relationship between the significant variables and collision numbers but was not able to predict the actual number of collisions expected on a given section.

The study showed that, with the exception of the gradients category, texture depth appeared in all the models for all collisions and did not seem to be only associated with preventing vehicles skidding on wet roads, i.e. it appeared to be associated with an increased road surface friction in all conditions.

The study made several recommendations highlighting that for bends and gradients the skid resistance exhibits a significant influence on collision risk and treatments to these sites should consider enhanced skid resistance, or other options for reducing risk. A similar situation exists for roundabouts. No change was recommended to the ILs for non-event categories A-C, and no change was recommended to the ILs for junctions (category Q) and pedestrian crossings (K).

2.2.13. SCRIM Investigatory Level Review

The Scottish Roads Research Board (SRRB) commissioned Atkins to review the appropriateness of the current Investigatory Levels (ILs) used on the Scottish trunk road network (Atkins, 2018). The study found that approximately 28% of the NW trunk road network is below the IL. The report makes several recommendations to improve the situation. One suggestion is to carry out a data cleansing exercise of the crash data by reviewing the causality factors, ensuring that an incident is attributable to the road surface and/or skidding issue before applying it. The report also contends that skidding resistance strategies developed by UK Local Authorities (LAs) may be appropriate for some Scottish trunk roads owing to lower volumes of traffic and the fact that many rural roads that are not designed to current UK standards. It notes that some LAs have developed their own bespoke SCRIM Category and IL tables following research into crash rates. The report also highlights that traffic speed data is becoming more accessible, and road authorities are able to undertake a risk-based approach to managing the skidding resistance of the road network, particularly on high speed bends. Based on an analysis of CSC vs. wet crash rate, the report recommends that TS consider merging ‘Gradient 5%-10%’ and ‘Gradient >10%’ into a unified ‘Gradient ≥ 5%’ site category; review the impact of reducing the Single and Dual Bend radius from 500m to 250m; further investigation into Single Bends < 100m radius, to establish the factors that influence the wet crash rate; and examining wet injury crash rates for ‘Approach to Junction’ site categories.

2.2.14. Transport Scotland HD28 review

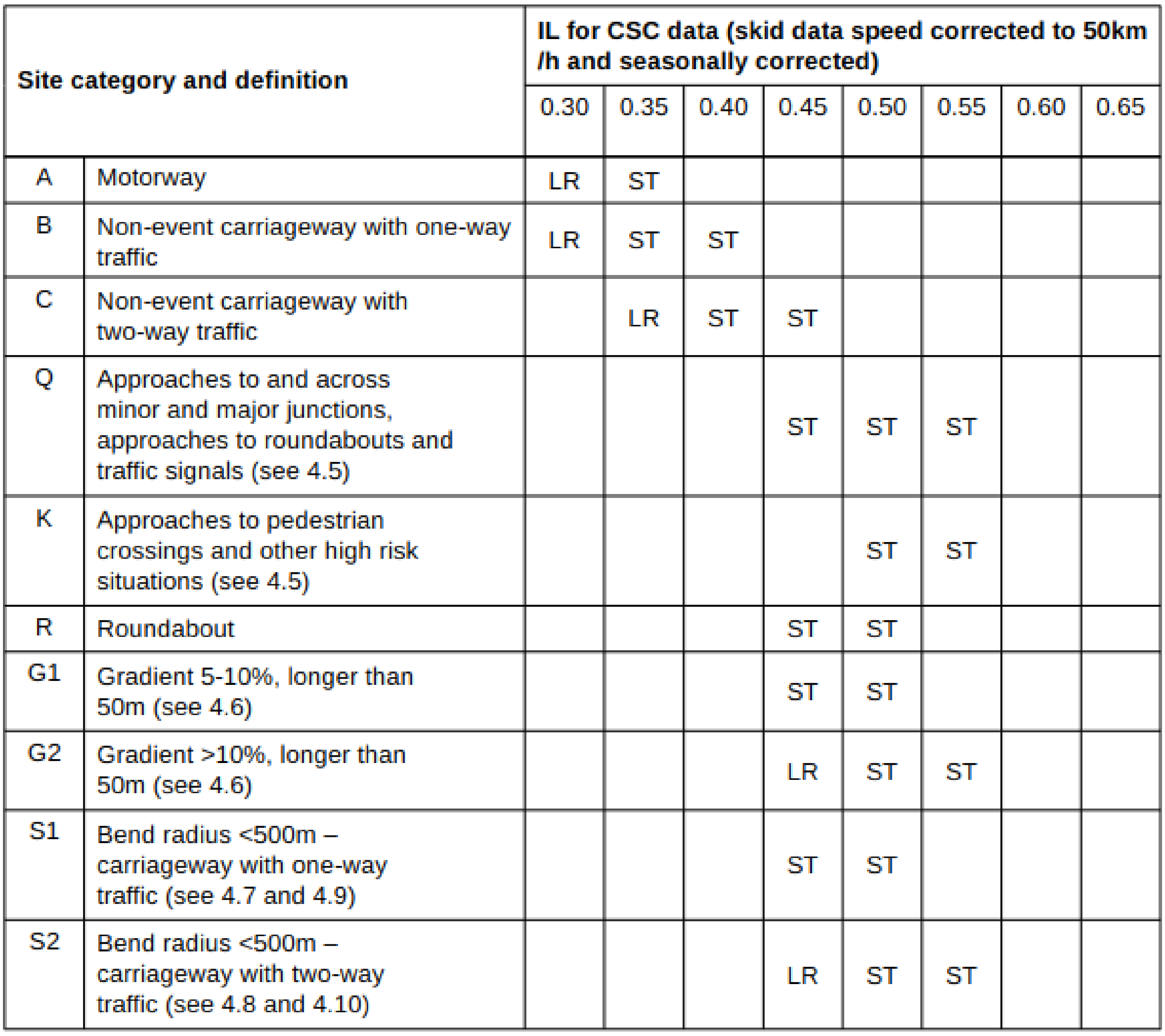
Transport Scotland commissioned W.D.M. Limited (Stephenson and Blackmore, 2019) to review relationships between wet crash rates and investigatory levels from 2015 to 2018. The work followed on from research published in 2005 by TRL (Parry & Viner, 2005) and a previous review by W.D.M. Limited in 2015. The report highlighted that crash records for 2015 to 2018 showed a reduction in wet crashes per day. However, the analysis also showed that the overall skid resistance levels provided on the network had reduced over this period, i.e. the percentage below Investigatory Level (IL). It is likely that some of the factors described in 2.2.10 above could explain why some of the in-service skid resistance measurements below IL criteria do not necessarily lead to increased accidents occurring. The report found that in general wet crash rates for sites surfaced with TS2010 were lower than sites surfaced with thin surfacing course systems (TSCS). The report recommended that changes to the IL be considered for certain categories, e.g. dual and single carriageway bends where the radius is 250 to 500m.

2.3 CURRENT STANDARDS

2.3.1. CS 228 - Measurement and interpretation of skid resistance

The current UK standard used to determine appropriate levels of skid resistance on the strategic road network is known as CS 228. The document provides the procedure for measuring skid resistance and provides a methodology to assess the requirement for maintenance work where the measured skid resistance falls below a predetermined level.

Measurements of skid resistance are made using sideway-force coefficient routine investigation machines and the data is processed to derive Characteristic Skid Coefficient (CSC) values. CSC is an estimate of the underlying skid resistance once the effect of seasonal variation has been taken into account. Processed CSC values are compared with pre-determined Investigatory Levels (ILs), to identify lengths of road where skid resistance is at or below a limit. The limit is where a road is judged to require an investigation of the skid resistance requirements. This depends on the site category which is assigned based on broad features of the road type and geometry plus specific features of the individual site. Guidance on assigning site categories and ILs is provided in Table 4.2 of the standard (Figure 2-8).



Site category and definition		IL for CSC data (skid data speed corrected to 50km /h and seasonally corrected)							
		0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
A	Motorway	LR	ST						
B	Non-event carriageway with one-way traffic	LR	ST	ST					
C	Non-event carriageway with two-way traffic		LR	ST	ST				
Q	Approaches to and across minor and major junctions, approaches to roundabouts and traffic signals (see 4.5)				ST	ST	ST		
K	Approaches to pedestrian crossings and other high risk situations (see 4.5)					ST	ST		
R	Roundabout				ST	ST			
G1	Gradient 5-10%, longer than 50m (see 4.6)				ST	ST			
G2	Gradient >10%, longer than 50m (see 4.6)				LR	ST	ST		
S1	Bend radius <500m – carriageway with one-way traffic (see 4.7 and 4.9)				ST	ST			
S2	Bend radius <500m – carriageway with two-way traffic (see 4.8 and 4.10)				LR	ST	ST		

Figure 2-8 - Site categories and investigatory level (CS 228)

Key: 'ST' indicates the range of ILs that should generally be used for roads carrying significant levels of traffic.

'LR' indicates a lower IL that may be appropriate in lower risk situations, such as low traffic levels or where the risks present are mitigated by other means, providing this has been confirmed by the crash history.

The decision on whether maintenance treatment is required is unlikely to be clear cut and requires professional engineering judgement, which needs to take into account local experience, the nature of the site, the condition of the road surfacing and recent crash history.

The way in which surveys are planned and how seasonal variation is accounted for is provided in the National Application Annexes (NAA) for each UK Overseeing Organisation. For example, Transport Scotland's specific requirements, based on their network geometry and road alignment, are stated in their NAA.

2.3.2. CD 236 - Surface course materials

Surface course materials for new and maintenance construction on both flexible and rigid pavements must comply with CD 236. The standard provides requirements for aggregates in surface course materials, which aim to ensure that appropriate skidding resistance is provided on roads.

Coarse aggregates or chippings must undergo polished stone value (PSV) testing in accordance with BS EN 1097-8 (BSI, 2009) to determine the resistance to polishing under the action of traffic, and the appropriate PSV for the coarse aggregate shall be selected from Tables 3.2a and 3.2b, based on the relevant site categories and traffic levels. The standard does provide scope to use an aggregate with a lower PSV than indicated in the tables if it can be demonstrated that the proposed lower PSV aggregate has achieved the required life, skid resistance and skidding accident rate on a road of similar geometry, traffic volume and meteorological conditions. This information is captured and controlled through the Departure from Standard process under CD 236.

An amendment to CD 236 is contained within Transport Scotland's NAA when using TS2010 (TSIA No 35, 2018). It states that aggregate with a PSV other than those contained in the CD 236 Tables shall be permitted providing it has been demonstrated that the aggregate is able to provide the required skid resistance based on previous use of the aggregate. An example of one methodology for supporting a case to use a lower PSV aggregate with adequate skid resistance is presented in TRL report PPR820 (McHale *et al*, 2017).

2.3.3. PSV test

The current European Standard for determining the PSV of an aggregate is BS EN 1097-8 (2009). The test is carried out on a 10mm nominal aggregate size, i.e. passing a 10mm sieve and retained on a 7.2mm. Aggregate particles are arranged randomly in a single layer within a standard mould. Voids are then filled with sand and resin is applied to harden the specimen ready for testing; the exposed surfaces of the specimens sit proud of the backing resin. A water/corn emery mix is applied to surface of test specimens just prior to contact with a test wheel (to simulate detritus). Once the sample has undergone polishing action in the accelerated polishing machine, the state of friction reached is measured by means of a friction test (pendulum test).

The PSV test has had its critics, for example, Woodward *et al* (2005) highlighted that the PSV test at best presents an idealised view of performance, i.e. it simply ranks one aggregate source against another and the aggregate size may only represent a small part of the actual surfacing mixture.

Issues with sourcing a control stone used for calibrating the PSV test were reported by Dunford (2013). The supply of a control stone ran out in 2008 and problems were encountered with a new source when laboratories reported that they had difficulty obtaining test results within the required range.

2.3.4. FAP test

A European Standard, BS EN 12697-49 was introduced in 2014 to determine the friction after polishing of asphalt mixtures (BSI, 2014). The standard describes the equipment; operation; preparation of specimens for testing (both laboratory-produced and from site); and measurement and reporting of friction measurement.

The FAP test has several potential advantages over the PSV test in that test specimens can be formed from disks of asphalt prepared in the laboratory or cored from the road surface. The latter options remove the subjectivity associated with sample preparation (as in the PSV test), where careful alignment of the particles of coarse aggregate in mosaics can influence the friction results. The method also enables asphalt surfacing to be tested as a whole in addition to the coarse aggregate component.

2.4 SUMMARY

2.4.1. Early research

Early research (1920-1980) focussed on understanding the processes that influenced the skid resistance of traditional surfacing materials, such as HRA and surface dressing. Owing to the method of construction or installation, these materials possessed a positive texture: stone chippings were pressed (compacted) onto a level datum or asphalt layer. Tests and method were developed to measure friction and simulate the effect of traffic polishing on these types of surfacing. Major advances during the period included:

- Creation of devices to measure low and high-speed wet skidding resistance.
- The development of a routine monitoring machine (SCRIM) to assess in-service pavements.
- Recognising the effect of seasonal changes on road surfaces.
- The development of laboratory tests to ensure aggregates provide some provision for skid resistance (PSV) and wear (AAV) at the design stage of materials.
- Developing a relationship between SFC, traffic, and PSV.
- Establishment of investigatory levels (ILs) with the objective of equalising accident risk across the network.

It is noteworthy that the measurement of PSV was - and arguably still is - the driving force behind managing skid resistance since its implementation in the 1960s.

2.4.2. Recent research and standards

Since the 1990s attempts have been made to broaden the knowledge base to allow for changes that have occurred on the road network. These include increased traffic flows and the introduction of modern materials, known generically as Thin Surfacing Course Systems (TSCS). The latter introduced a new surface profile termed negative texture, which owing to new mixture compositions and methods of construction, comprise a flat surface that is criss-crossed by indentations. The surface that makes contact with the tyre comprises a composite or range of aggregate sizes, i.e. coarse aggregate, fine aggregate and binder, rather than individual coarse aggregate pieces. Modern TSCS provide a running surface that is smooth and noticeably quieter, particularly when smaller aggregate sizes are employed. In Scotland, a negatively textured SMA-based surface course material (TS2010) further alters the surface of a typical TSCS through the application of a lightly coated grit. The latter has been demonstrated to increase both the early-life and longer-term skid resistance dependent on grit retention.

In summary, the tyre-road contact which includes a distribution of contact pressures depending on the shape of aggregate, and aggregate sizes and their arrangement, has changed. Consequently, several studies have shown that the PSV test is not a true or fair indication of the in-service skid resistance that can be expected from a TSCS mixture. It has become clear that the test does not adequately reflect in-service performance for skidding resistance under present-day conditions. Reasons surround the fact that only a single (10mm) size aggregate is tested (BS EN1097-8, 2009). Furthermore, a study into blending aggregate sources showed that smaller aggregate sizes have a disproportionate influence on the combined friction level, even when considering the lower proportion, by mass, in the mixture. It is speculated that this might be related to the higher surface area, per unit mass, of the smaller aggregates. In summary, it appears that the PSV test is not suitable for assessing negatively textured mixtures.

The W-S or FAP test offers some benefits over the PSV test, particularly in facilitating tests on asphalt samples and enabling the effects of bitumen and fines to be considered. However, available publications suggest that more research is required to better understand its ability and operating limitations.

In terms of aggregate testing, the use of negative textured materials, different aggregate sizes (including the application of grit) and their corresponding skid performance means there is scope to improve the specification of aggregate sources.

Current skid policy, including the research reviewed here, relies on equalisation of accident risk by direct measurement of low speed skid resistance (SCRIM) and measurement of texture depth as some protection against reduction of skid resistance at speed. One recent study used a multivariate regression technique to investigate the relationship between collisions and a number of variables such as skid resistance, rut depth, texture depth, curvature, gradient and crossfall. The results provided an indication of the direction of the relationship between the significant variables and collision numbers but was not able to predict the actual number of collisions expected on a given section.

Based on this literature review, there appears to be no single underlying factor that drives road casualties. Other factors such as driver behaviour and advances in vehicle technology mean that the setting of Investigatory Level (IL) criteria is challenging. One approach is to carry out data cleansing exercises, e.g. crash data should be reviewed to determine causality factors, thus ensuring that an incident is attributable to the road surface and/or skidding issue before applying it. In addition, traffic speed data is becoming more accessible, and road authorities are able to undertake a risk-based approach to managing the skidding resistance of their network. Through the collection of appropriate data, it is possible to develop bespoke SCRIM Category and IL tables, and this has been done by various LAs. It is possible that the impact of climate change may also mean that adjustments to the way low speed skid resistance (SCRIM) measurements are collected may be required to accommodate the effects of weather or seasonal variation.

3

METHODOLOGY

3 METHODOLOGY

In order to the examine the link between TS2010 surface course, annual in-service skid resistance measurements and recent crash history data, the study was split into two parts, viz.: Review of TS2010 friction performance; and Review of wet crash rate against SCRIM Site category (CSC).

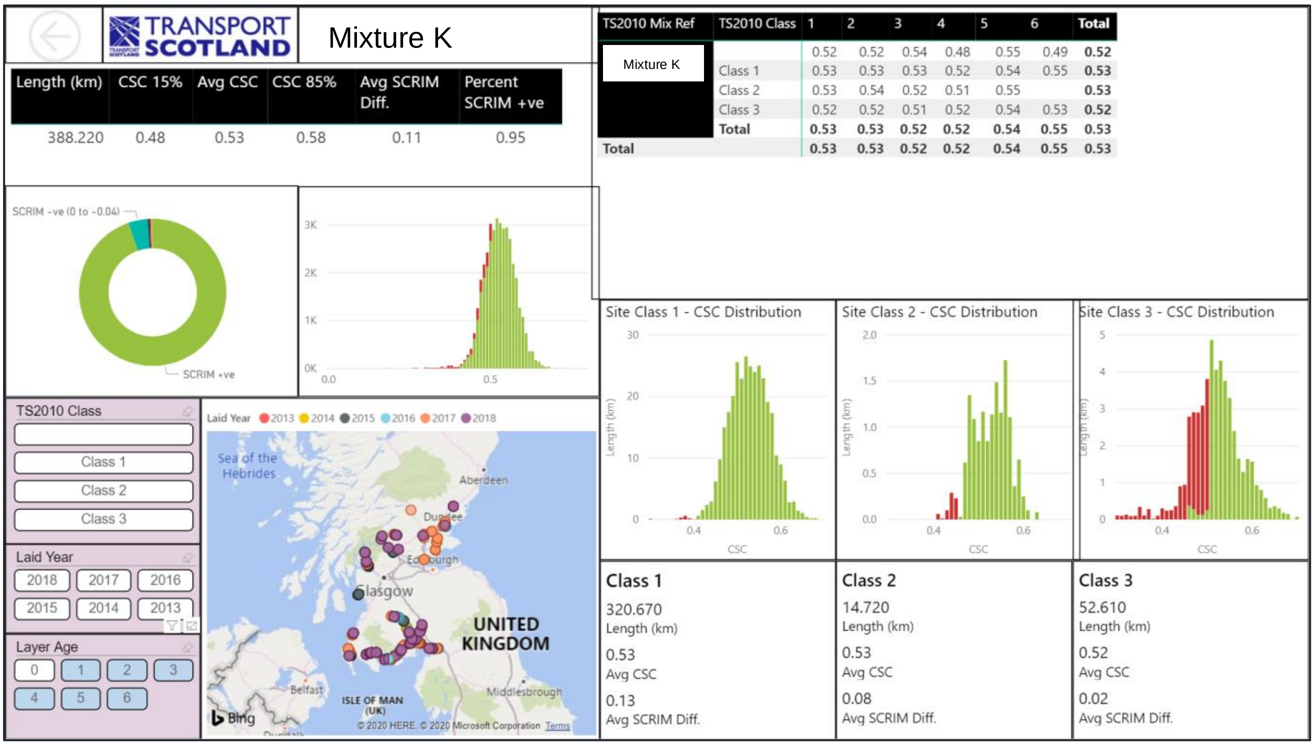
3.1 REVIEW OF TS2010 FRICTION PERFORMANCE

As the friction performance of TS2010 mixtures is not specified by PSV and minimum texture, it was decided to review available data to determine the following:

- The friction performance of TS2010 mixtures on different Site Classes i.e. where different road categories are deemed to require low, medium and high levels of friction.
- Changes in the friction provided by TS2010 mixtures over time.
- Appraisal of Transport Scotland's existing approval certificates - are materials that produce the highest friction used on sites that require a higher demand for friction.
- Assessment of weather effects - is friction performance influenced by location or region.

3.1.1. TS2010 Data

Annual skid resistance data is held on Transport Scotland's Integrated Road Information System (IRIS). A business intelligence (BI) tool, Microsoft Power BI, was used to collect and process the skid resistance data (CSC) along with other data such as scheme location, material type and age. The BI tool was used to conduct ad-hoc analysis and provide interactive visualisations, such as summary graphs, charts and map-based material location. An example of an output from the BI tool is shown in Figure 3-1.



Mixture K

Length (km)	CSC 15%	Avg CSC	CSC 85%	Avg SCRIM Diff.	Percent SCRIM +ve
388.220	0.48	0.53	0.58	0.11	0.95

TS2010 Mix Ref	TS2010 Class	1	2	3	4	5	6	Total
Mixture K		0.52	0.52	0.54	0.48	0.55	0.49	**0.52**
	Class 1	0.53	0.53	0.53	0.52	0.54	0.55	**0.53**
	Class 2	0.53	0.54	0.52	0.51	0.55		**0.53**
	Class 3	0.52	0.52	0.51	0.52	0.54	0.53	**0.52**
	Total	**0.53**	**0.53**	**0.52**	**0.52**	**0.54**	**0.55**	**0.53**
Total		**0.53**	**0.53**	**0.52**	**0.52**	**0.54**	**0.55**	**0.53**

Class 1	Class 2	Class 3
320.670 Length (km)	14.720 Length (km)	52.610 Length (km)
0.53 Avg CSC	0.53 Avg CSC	0.52 Avg CSC
0.13 Avg SCRIM Diff.	0.08 Avg SCRIM Diff.	0.02 Avg SCRIM Diff.

Figure 3-1 - Example of BI display for TS2010 mixture

3.2 REVIEW OF WET CRASH RATE AGAINST SCRIM SITE CATEGORY

Building on conclusions and recommendations from the literature review, this part of the study explores whether low wet crash rates can be used to justify a bespoke SCRIM Category and IL table for Scotland.

3.2.1. Skidding data

Wet crash rates and CSC values were taken from the Transport Scotland HD28 Review report (Stephenson and Blackmore, 2019). Four years of 100m summary SCRIM Coefficient and traffic count data from 2015 to 2018 were used. The data includes all surfacing types used across the network, i.e. TSCS, TS2010, HRA, HFS, etc. The CSC values were linked to each of the wet crashes by survey year. In total 1612 wet crashes were linked to an associated CSC value over the four years of analysis. To compare the CSC values against wet crash rates the CSC values were grouped into bands of width 0.04, i.e. a mid-point skid resistance of 0.42 represents the range of data with values greater than or equal to 0.40 and less than 0.44.

The volume of traffic is an important factor when comparing the accidents with skid resistance levels from different locations. As the number of accidents at a heavily trafficked intersection may be compared to another category with low traffic, the accidents are converted to accident rates, which are accidents/one hundred million vehicles per km (Acc/100Mvkm).

4

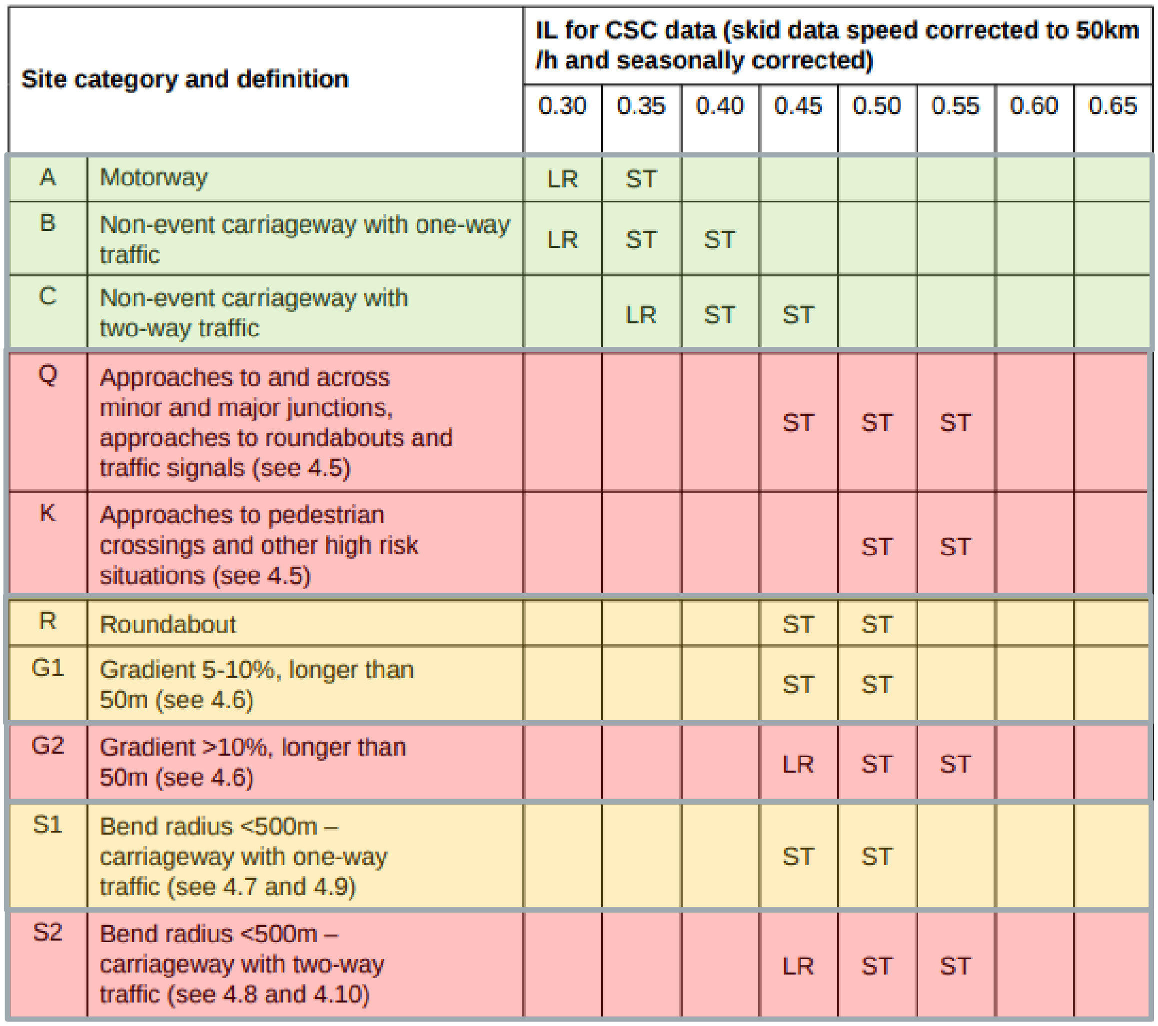
REVIEW OF TS2010 FRICTION PERFORMANCE

4 REVIEW OF TS2010 FRICTION PERFORMANCE

4.1 SKIDDING RESISTANCE REQUIREMENTS

Transport Scotland broadly classifies the trunk road network according to the risk of skidding by allocating site categories in accordance with the requirements and guidance contained in the UK Standard (CS 228). Site categories are assigned based on broad features of the road type and geometry plus specific features of the individual site. For each site category, an IL is assigned according to the perceived level of risk within each site category. These ILs represent a limit, above which the skid resistance is considered to be satisfactory. If a site is at or below the IL it is judged to require an investigation to be undertaken. Recommended site categories and investigatory levels from CS 228 are reproduced in Table 4-1. For skid resistance compliance purposes, the Specification for Surface Course TS2010 (TSIA 35, 2018) pools the site categories into three site classes and these are highlighted below.

Table 4-1 - Site categories and investigatory levels



Site category and definition		**IL for CSC data (skid data speed corrected to 50km /h and seasonally corrected)**							
		0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
A	Motorway	LR	ST						
B	Non-event carriageway with one-way traffic	LR	ST	ST					
C	Non-event carriageway with two-way traffic		LR	ST	ST				
Q	Approaches to and across minor and major junctions, approaches to roundabouts and traffic signals (see 4.5)				ST	ST	ST		
K	Approaches to pedestrian crossings and other high risk situations (see 4.5)					ST	ST		
R	Roundabout				ST	ST			
G1	Gradient 5-10%, longer than 50m (see 4.6)				ST	ST			
G2	Gradient >10%, longer than 50m (see 4.6)				LR	ST	ST		
S1	Bend radius <500m – carriageway with one-way traffic (see 4.7 and 4.9)				ST	ST			
S2	Bend radius <500m – carriageway with two-way traffic (see 4.8 and 4.10)				LR	ST	ST		

Key: Site Class 1 Site Class 2 Site Class 3

LR – Lower risk situation, ST – Significant levels of traffic

4.2 INDIVIDUAL TS2010 MIX PERFORMANCE

With the aid of the BI tool, CSC data was collected on individual TS2010 mixtures. For each TS2010 mix, bespoke boxplots were produced and these can be found in Appendix A. An example of the boxplots for one of the mixtures (Mixture K) is shown in Figure 4-1. The boxplots provide a good indication of how CSC values vary or are spread out, e.g. 70% of the data collected lies within the area shaded green. In addition, the boxes show the minimum, maximum, mean average (dot), 15th percentile and 85th percentile value for each survey year, which approximates to the material age. No attempt was made to remove outliers and this explains the depth or height of some of the boxes. The graphs show the underlying friction results for the three site classes and a weighted average of all site classes. Numbers in brackets below each survey year show the aggregated survey length that the data is based on.

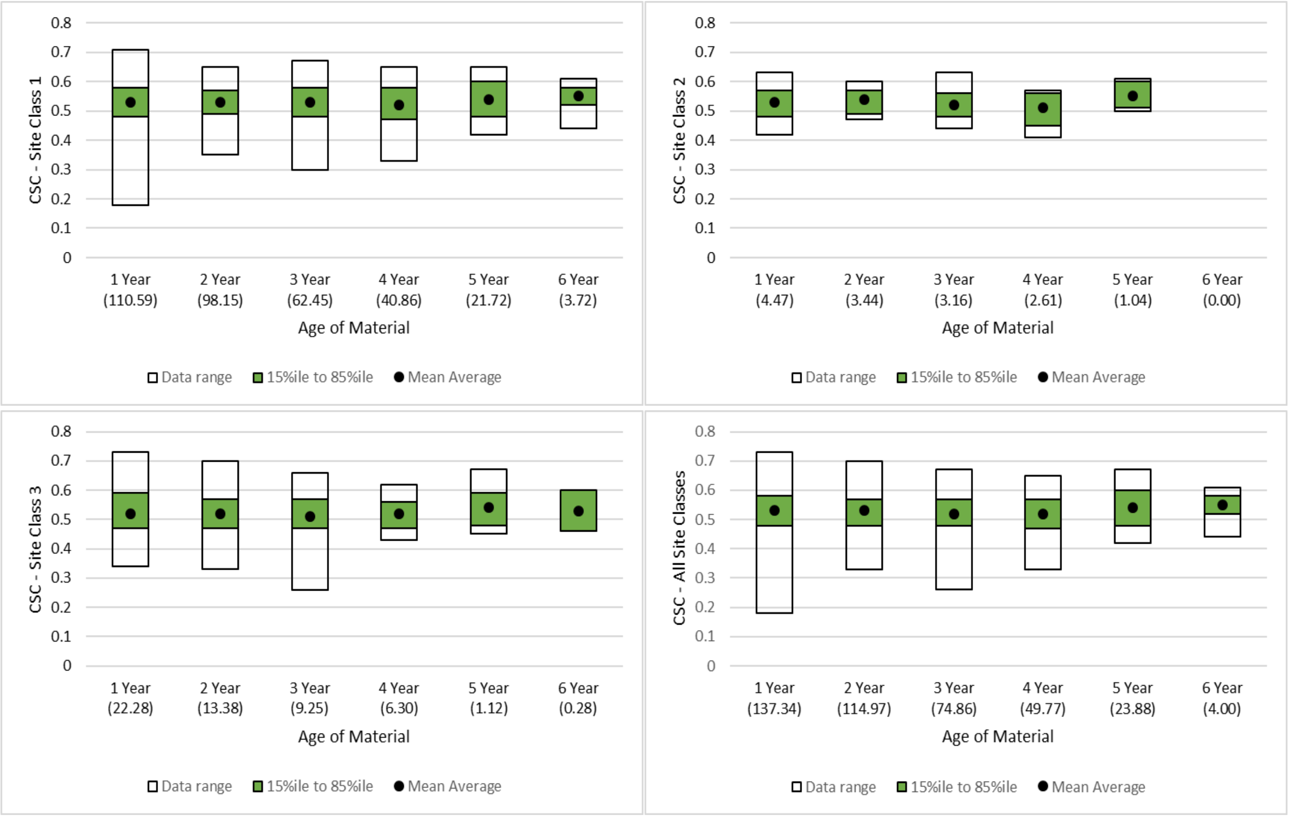


Figure 4-1 - Boxplots for Mixture K

4.3 SITE CLASS PERFORMANCE

The data was examined to determine whether the underlying friction provided by each mix varied between site classes. Figure 4-2 shows the overall averages for individual materials laid on Site Class 1 versus Site Class 2 and 3, and Site Class 2 versus Site Class 3. It can be seen that when the average CSC from different sites is compared, the data points lie close or are spread evenly across the line of equivalence (x=y). An important point is that there is much more data for Site Class 1 in terms of measurements and the length of time that it has been in service. If individual mixtures performed less well when used on class 2 and 3, then you would expect the data points to be below the line of equivalence. In summary, there appears to be no significant difference in performance when an individual material is laid on a different site class.

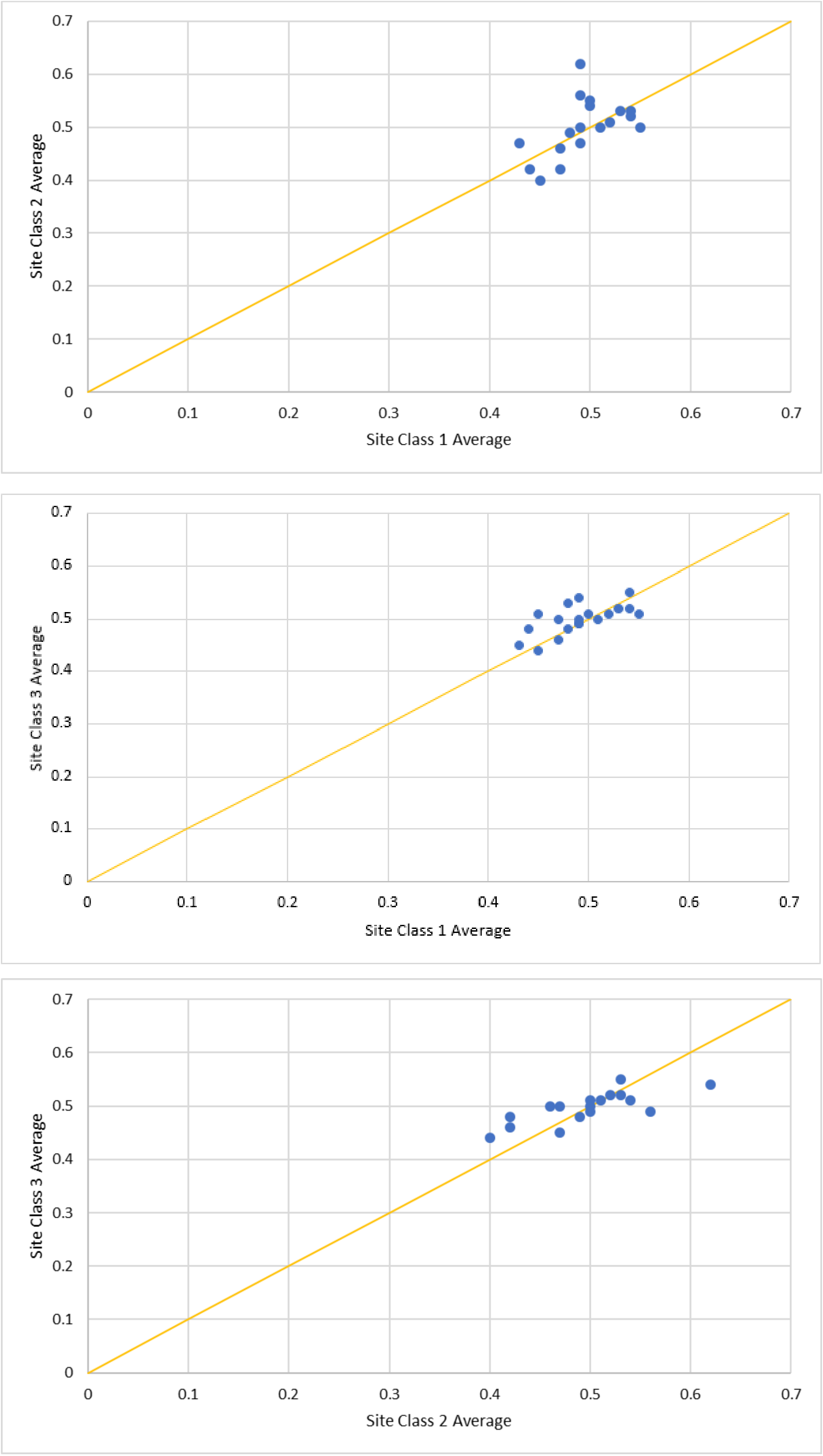


Figure 4-2 - Individual mix performance on different site classes

4.4 CHANGES IN CSC WITH AGE

In order to examine whether the underlying friction of TS2010 mixtures reduces with time or accumulative trafficking, mean average CSC values were plotted against age in years. In order to avoid sites with limited data skewing results a minimum length of survey data was set at 5km. The results are shown in Figure 4-3 and it is seen that over a five-year period the average CSC appears to remain reasonably stable with a slight tendency to reduce over time.

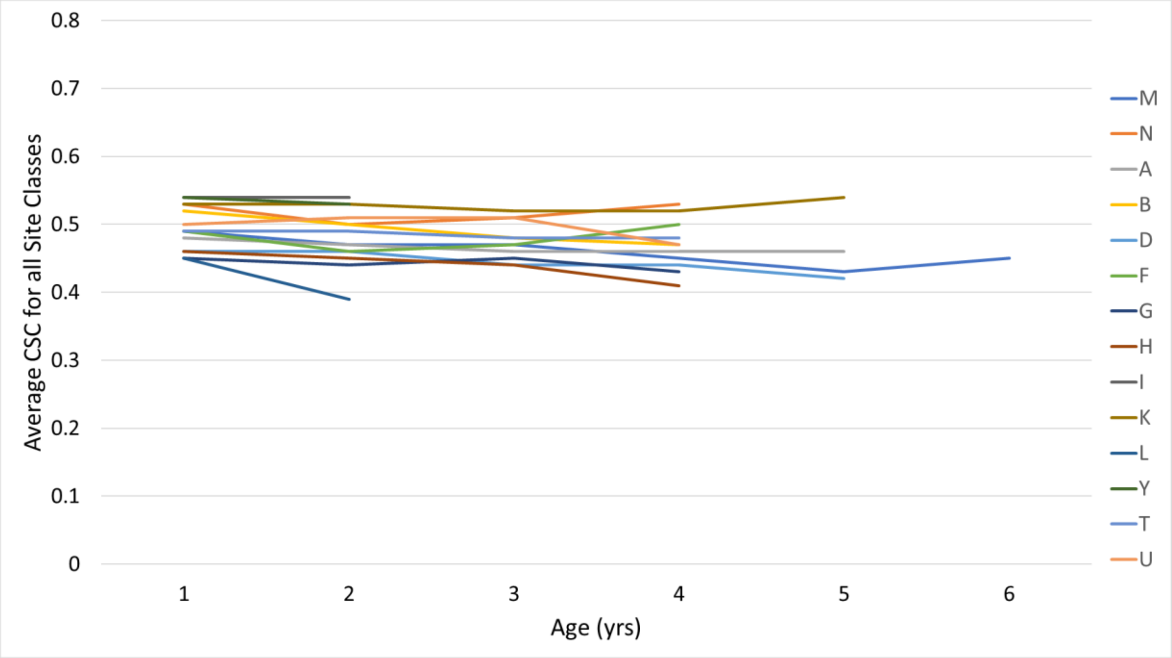


Figure 4-3 - Evolution of average CSC with age

A more detailed analysis shows that the average difference or reduction in CSC is small and highlights that most of the reduction occurs in the early years, i.e. year 1 to year 2.

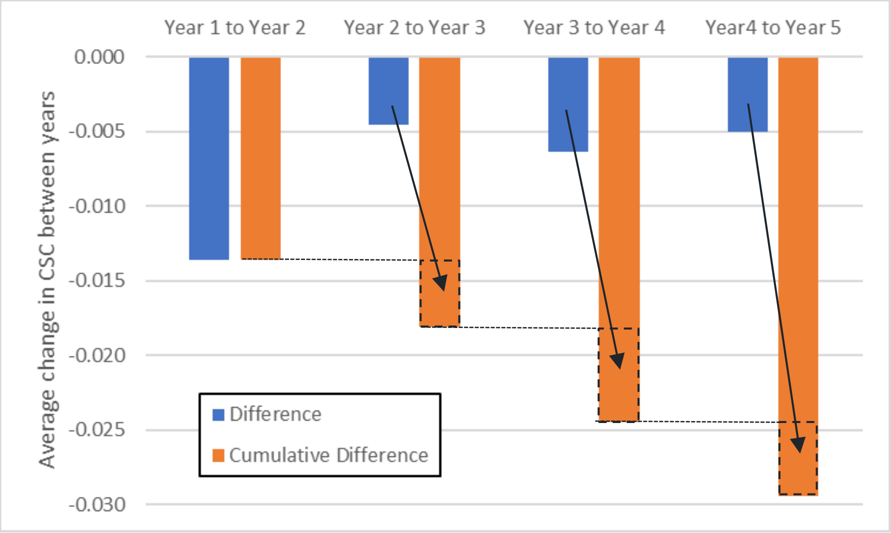


Figure 4-4 - Reduction in average CSC with time

4.5 PERFORMANCE VERSUS APPROVAL

Currently TS2010 mixtures are given Site Class approval based on a combination of GripTester and CSC measurements. The former is used in the material's early life, which can be up to one year, thereafter the approval is based on CSC performance. The performance of TS2010 materials on different site classes (see Table 4-1) is reviewed on an annual basis. Depending on the in-service performance of each material, authorisation for use on site classes is reviewed, i.e. a higher or lower Site Class can be approved based on CSC performance.

Figure 4-5 shows the overall weighted averages of CSC for TS2010 mixtures and their current approval for use on the network. The different mixture identifiers are shown on the x-axis along with the nominal age of the material, i.e. how long it has been in service. The figure excludes the first year of collected data so that early-life effects can be discounted. The box plots provide an indication of how the CSC values vary for each material, i.e. how the performance of some mixtures is more consistent than others. The materials have been arranged by the mean average CSC (black dot) and the current site class approval for each mix is highlighted. The CSC mean averages range from 0.42 to 0.54.

4.5.1. Performance based on PSV

With the exception of TS2010 surface course, the normal convention when specifying road surfacing is to use aggregates with an appropriate resistance to polishing, known as the polished stone value (PSV). Aggregate PSVs are selected for a particular site category and traffic loading in accordance with CD 236 and are expected to provide wet skidding resistance above the appropriate IL.

Figure 4-6 shows the overall weighted averages of CSC for TS2010 mixtures grouped by PSV. The figure is a good illustration of how PSV does not adequately reflect in-service performance. The data shows that the relationship between PSV and CSC is complex, with some lower PSV aggregates outperforming higher PSV aggregates. The survey lane length of each material is included in the label.

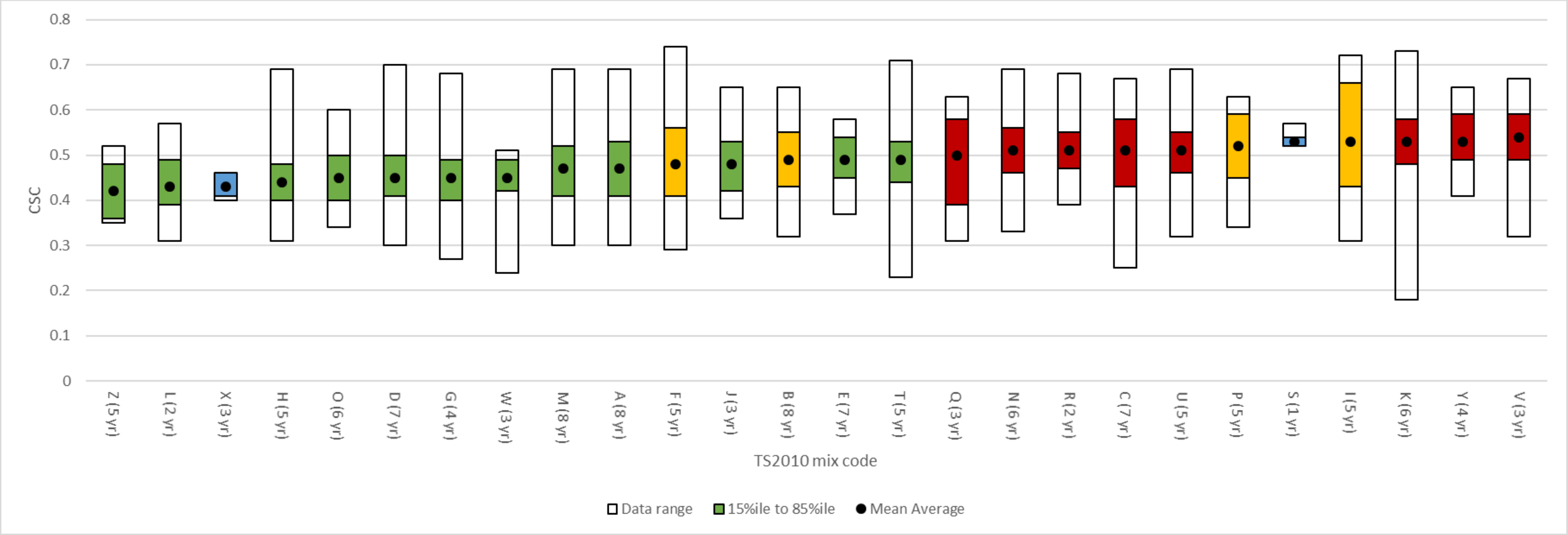


Figure 4-5 - Overall TS2010 performance based on weighted average CSC

Key:

🟩 Site Class 1 approval 🟨 Site Class 2 approval 🟥 Site Class 3 approval 🟦 Approval pending

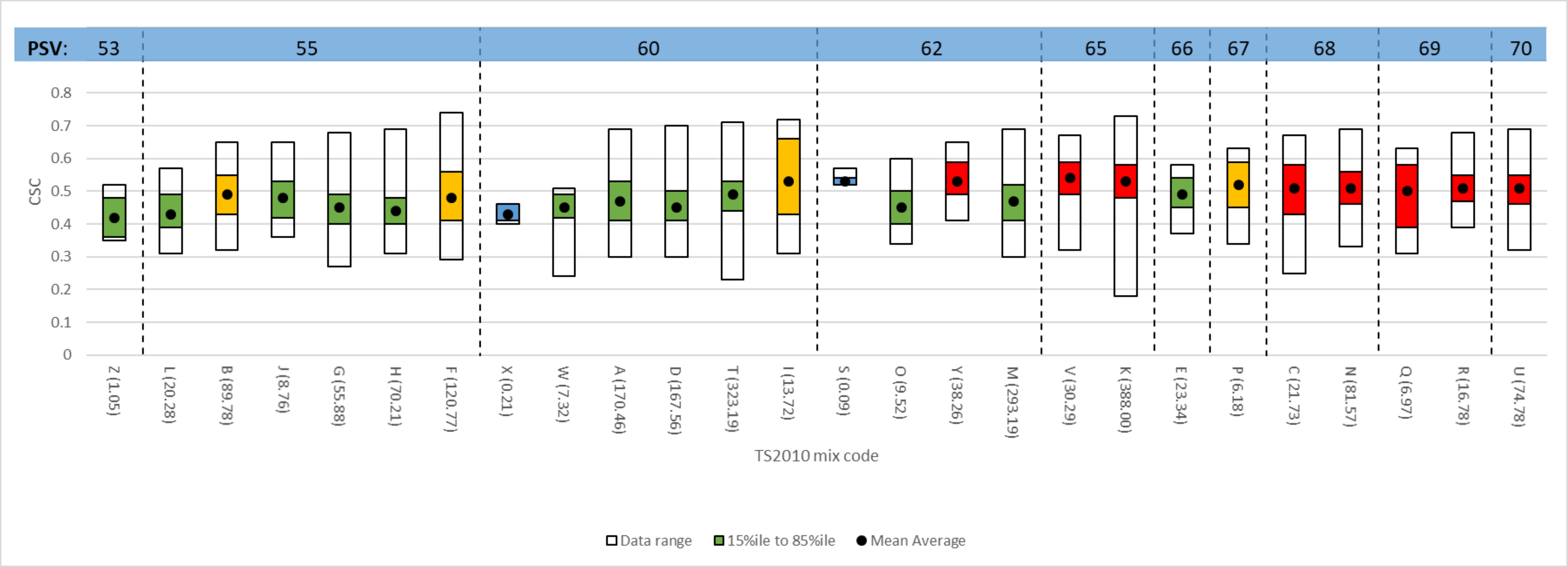


Figure 4-6 – Relationship between TS2010 friction performance and aggregate PSV

Key:

🟩 Site Class 1 approval 🟨 Site Class 2 approval 🟥 Site Class 3 approval 🟦 Approval pending

4.6 INFLUENCE OF LOCATION

Predicting the weather is complex, but in broad terms, the Scottish climate can be divided into a comparatively dry east and wet west. Figure 4-7 shows 30-year monthly average rainfall data for Winter but a similar, although less severe, trend is seen over the remaining seasons.

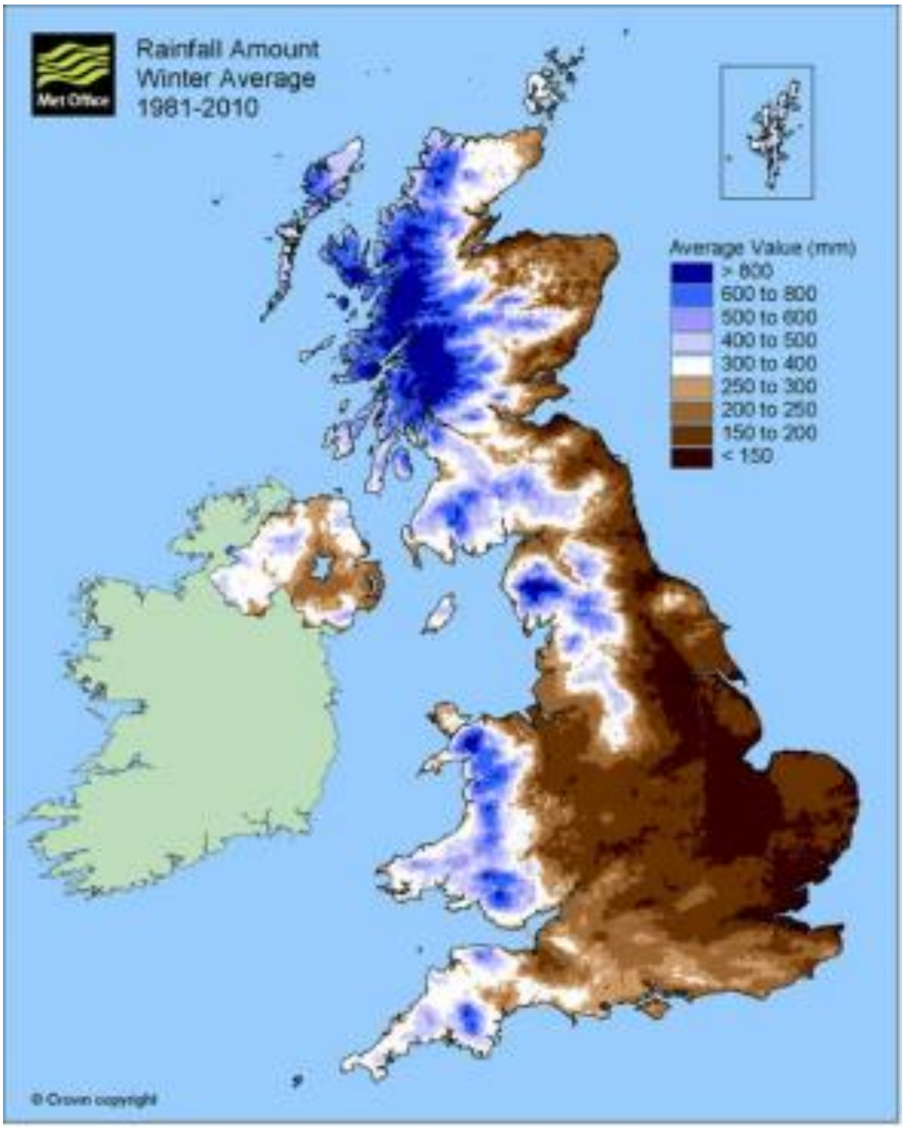


Figure 4-7 - Example of average rainfall data for the UK (image courtesy of the Met Office)

From a review of the CSC data it was noted that Mixture K has been used in different locations across Scotland. It was therefore decided to compare the performance of Mixture K material based on the average rainfall data and the locations were split into three zones: SW, W & E. These zones are highlighted with black dotted circles in Figure 4-8. The material is predominantly used in the SW but is also used in both the western and eastern parts of the Central Lowlands. For the latter areas, the aggregate used in the manufacture of Mixture K is transported to asphalt plants located in the Central Lowlands.

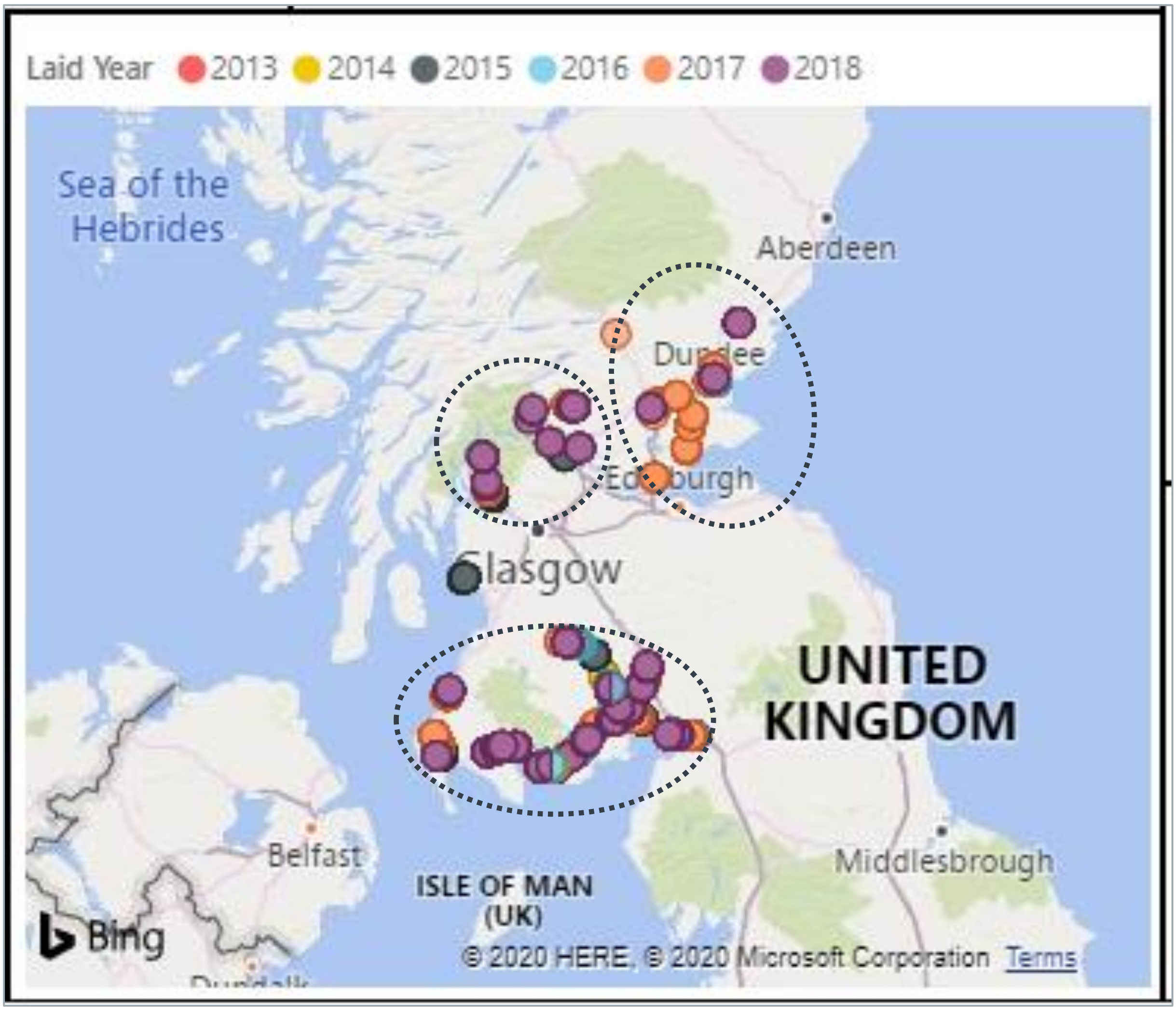


Figure 4-8 – Selected locations where Mixture K has been used

Data from the two west and east rainfall zones were analysed using the BI tool and the results are shown in Figure 4-9. The average CSC is given below the site class categories for the three rainfall zones. It should be noted that the lengths quoted in the figures are survey lengths rather that physical material lengths, i.e. higher survey lengths are associated with older material which has been tested more times. The east rainfall zone contains predominantly young materials (< 3 years old), whereas south west zone contains many materials that are six years old.

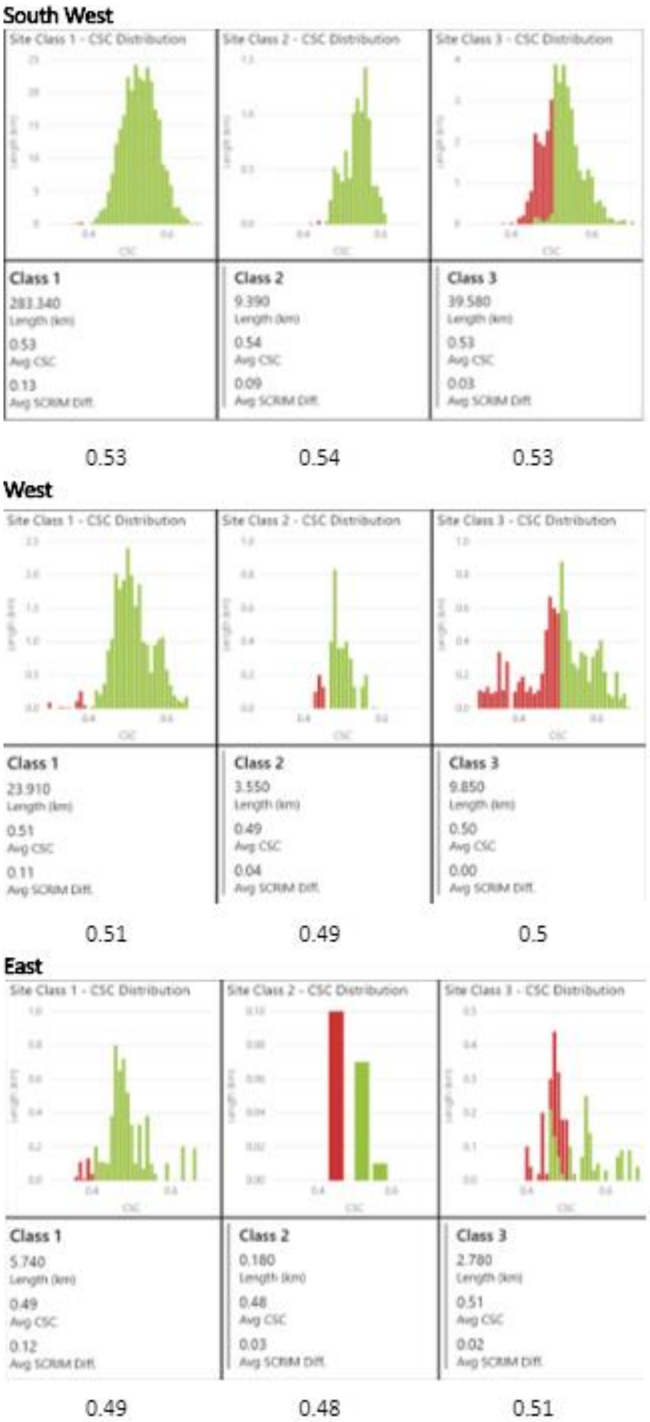
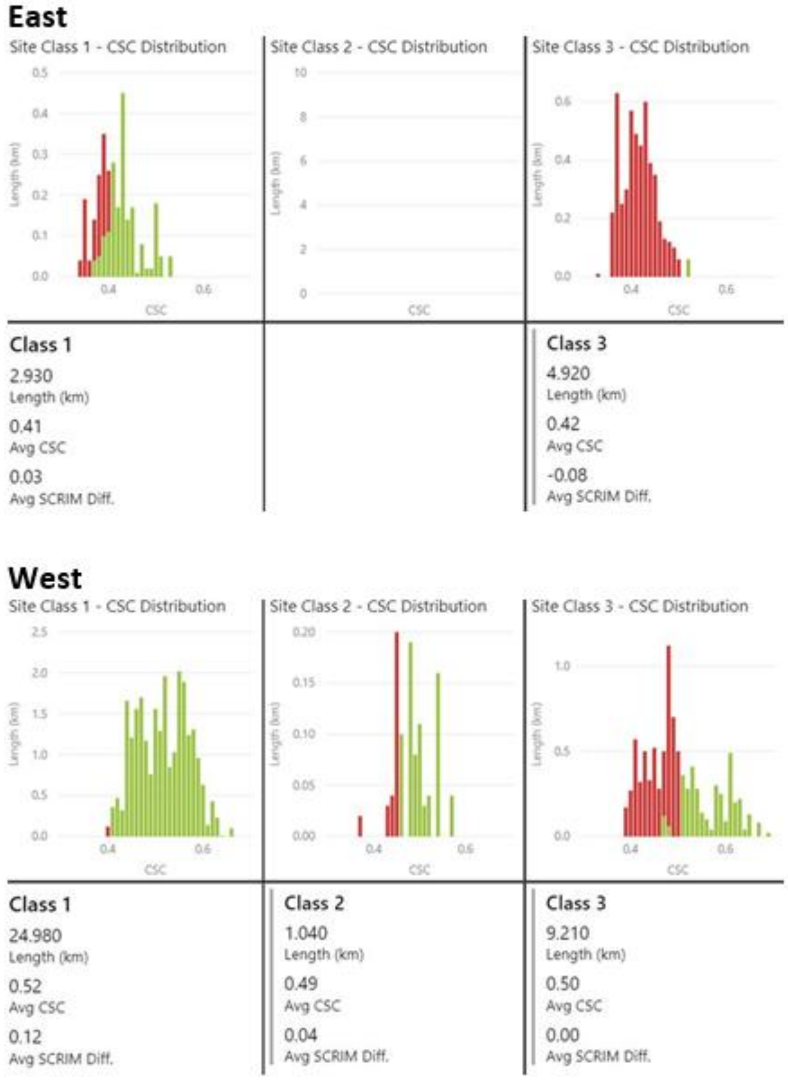


Figure 4-9 - Performance of Mixture K in different rainfall zones

The results indicate that the average underlying friction provided by Mixture K is higher in the SW than in the east of the country, i.e. 0.53 versus 0.49 (Class 1).

A similar exercise was carried out for Mixture F. Two zones located in the NE and NW were selected for comparison and these are shown in Figure 4-10. Friction data on materials laid in the east (dry) and west (wet) zones are shown in Figure 4-11. The results indicate that the average underlying friction provided by Mixture F is notably higher in the NW than in the NE, i.e. 0.52 versus 0.41 (Class 1).

Figure 4-10 - Selected locations where Mixture F has been used



East

Class 1
2.930
Length (km)
0.41
Avg CSC
0.03
Avg SCRIM Diff.

Class 3
4.920
Length (km)
0.42
Avg CSC
-0.08
Avg SCRIM Diff.

West

Class 1
24.980
Length (km)
0.52
Avg CSC
0.12
Avg SCRIM Diff.

Class 2
1.040
Length (km)
0.49
Avg CSC
0.04
Avg SCRIM Diff.

Class 3
9.210
Length (km)
0.50
Avg CSC
0.00
Avg SCRIM Diff.

Figure 4-11 - Performance of Mixture F in different rainfall zones

5

REVIEW OF WET CRASH RISK AND SKID RESISTANCE

5 REVIEW OF WET CRASH RISK AND SKID RESISTANCE

A recent study titled, Transport Scotland HD28 Review (Stephenson and Blackmore, 2019), examined the link between wet crash rates and IL. The report highlighted that crash records for 2015 to 2018 showed a reduction in wet crashes per day. Between 2009 and 2013 there were between 2.7 and 3.5 wet crashes per day, this range reduced to 2.0 to 2.6 between 2015 and 2018. It is noteworthy that over the same period the number of dry crashes per day remained largely the same, around 4 per day. This reinforces the findings of other studies that there is no single underlying factor that drives road casualties.

The same review showed that the percentage of the network below IL had increased from around 20% in 2013 to 25% in 2018. This suggests that there may be scope to revise some of the ILs where there is evidence that a higher IL may not be appropriate based on the wet crash rate. This would have the benefit of reducing the length of the network reported below IL, and the costs associated with carrying out investigations, and the environmental impact of importing scarce resources from long distances to meet these IL requirements. However, any change to IL needs to be carefully considered to ensure that the underlying friction available to road users is appropriate.

In the HD28 Review report, power trendlines were often used as a line of best fit to represent the behaviour of the data for each site category. It is understood that this approach was adopted to keep parity with previous work carried out for Transport Scotland, titled ‘Implementing a Skid Policy into Scotland’ (Morrison *et al*, 2008).

For this current review, the 2019 HD28 Review report data was used. However, it was concluded that the power trendlines used previously did not always describe the relationship between wet crash rate and CSC. A different approach was taken using piecewise linear functions for the different site categories, i.e. the data was split into straight-line segments. This permitted the identification of a CSC threshold where no significant improvements in accident rates were achieved through increasing CSC. For certain categories, near horizontal linear functions (or flat line relationships) were observed showing that there was very little benefit in increasing the levels of CSC. The aim of the analysis was to prevent the over specification of limited resources of high PSV aggregate, particularly in light of the marginal benefits yielded as shown in the earlier part of this report.

5.1 CATEGORY A: MOTORWAY

The ‘Motorway’ site category results are shown in Figure 5-1. On initial inspection, the figure could be regarded as a flat line with low wet crash rates, i.e. <5. However, the lowest mid-point CSC band of 0.27, which contains the CSC values between 0.25 and 0.29, does show an elevated wet crash rate. Using piecewise linear functions, the data has been split into two groups with associated best fit lines. The band shaded yellow highlights the current IL range from Table 4.1 of CS 228. i.e. 0.30 to 0.35. Based on the data contained in the figure it appears that an investigatory level of 0.35 CSC appears appropriate as it lies to the right of the intersection of the two groups of data. This value is easily achieved with current TS2010 materials.

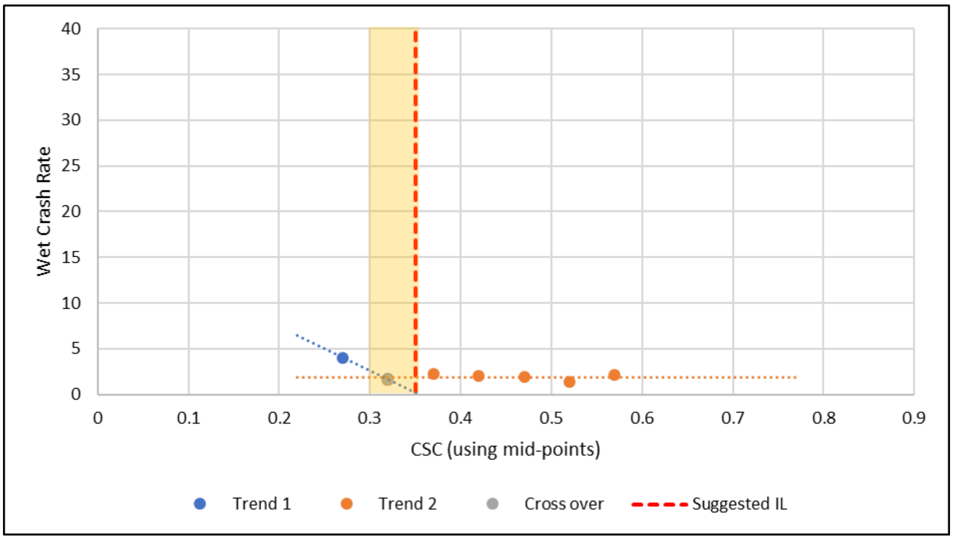


Figure 5-1 - Motorway - CSC band vs. Wet Crash Rate

5.2 CATEGORY B: NON-EVENT CARRIAGEWAY WITH ONE-WAY TRAFFIC

The ‘Non-event carriageway with one-way traffic’ (Dual carriageway) site category results are shown in Figure 5-2. Similar to the Motorway category, the figure could be regarded as showing a relatively flat line, but again it shows signs of higher wet crash rates corresponding to the lower friction bands. The data has been split into two groups with associated best fit lines. The band shaded yellow highlights the current recommended IL range of 0.30 to 0.40. Based on this approach it appears that an investigatory level of 0.35 CSC is appropriate.

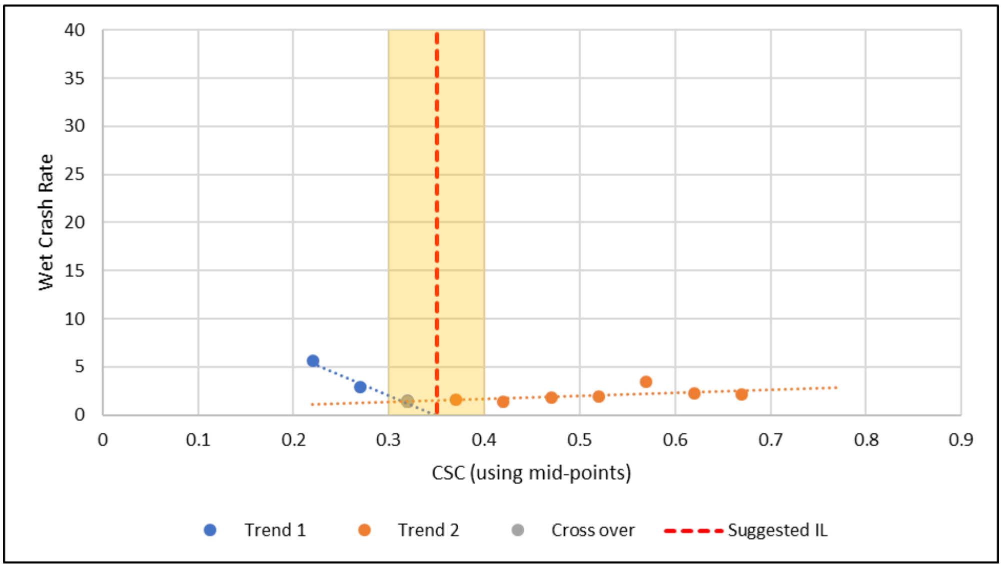


Figure 5-2 - Dual Non-event - CSC band vs. Wet Crash Rate

5.3 CATEGORY C: NON-EVENT CARRIAGEWAY WITH TWO-WAY TRAFFIC

The ‘Non-event carriageway with two-way traffic’ (Single carriageway) site category results are shown in Figure 5-3. This figure shows more marked signs of higher wet crash rates corresponding to the lower friction bands. The data has been split into two groups with associated best fit lines. The band shaded yellow highlights the current recommended IL range of 0.35 to 0.45. Based on this approach it appears that an investigatory level of 0.40 CSC is an appropriate value.

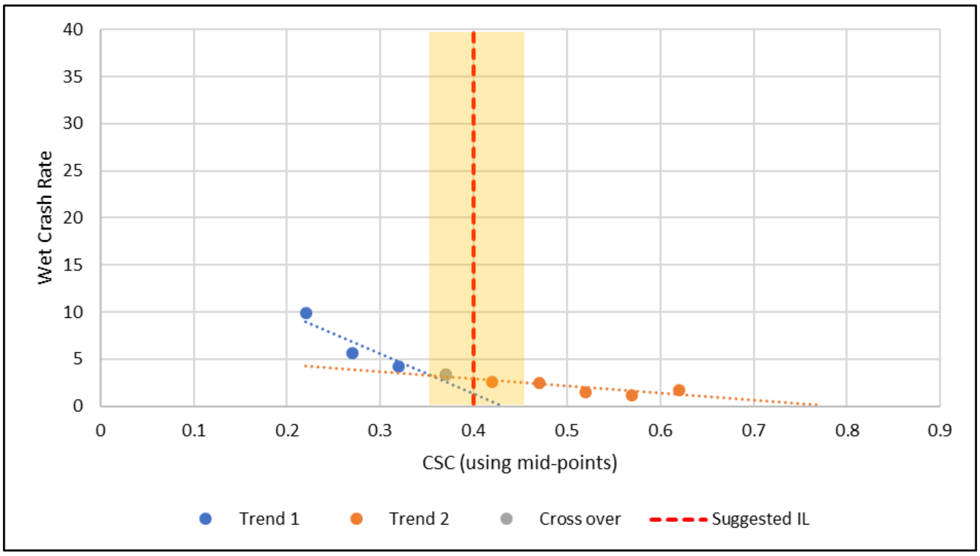


Figure 5-3 - Single Non-event - CSC band vs. Wet Crash Rate

5.4 CATEGORY Q: APPROACHES TO AND ACROSS MINOR AND MAJOR JUNCTIONS, APPROACHES TO ROUNDABOUTS AND TRAFFIC SIGNALS

The ‘Approach to junction or roundabout’ site category results are shown in Figure 5-4. This figure does not display a strong relationship for wet crash rates to decrease with higher friction and it suggests that other factors are influencing the Wet Crash Rate, the most obvious being increased vehicle interactions. As a result, the Wet Crash Rates are much higher than the non-event categories discussed above.

The data has been split into two groups with associated best fit lines. The band shaded yellow highlights the current recommended IL range of 0.45 to 0.55. Based on the adopted approach it appears that an investigatory level of 0.45 CSC would be an appropriate default value. It should be noted that CSC values in excess of 0.65 (high-friction surfacing) do not reduce Wet Crash Rates to an acceptable level. It is likely that other engineering measures such as speed reducing measures may be required.

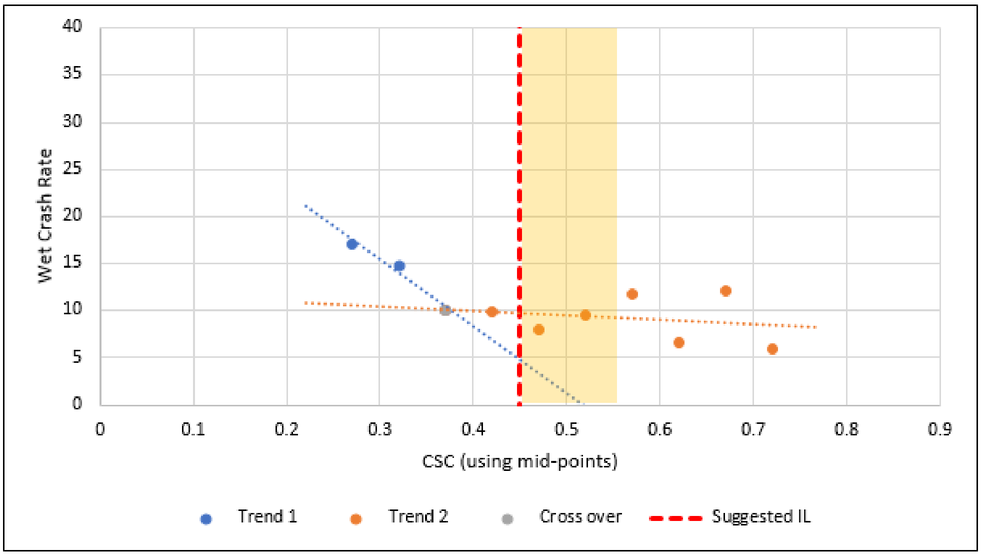


Figure 5-4 - Approach to junction or roundabout site category versus crash rate

5.5 CATEGORY K: APPROACHES TO PEDESTRIAN CROSSINGS AND OTHER HIGH RISK SITUATIONS

The ‘Approach to pedestrian crossings…’ site category results are shown in Figure 5-5. This figure does not show any meaningful relationship. In total, 11 wet crashes occurred on this site category. Based on the limited amount of data available no change to the existing IL recommendations (band shaded yellow) is made.

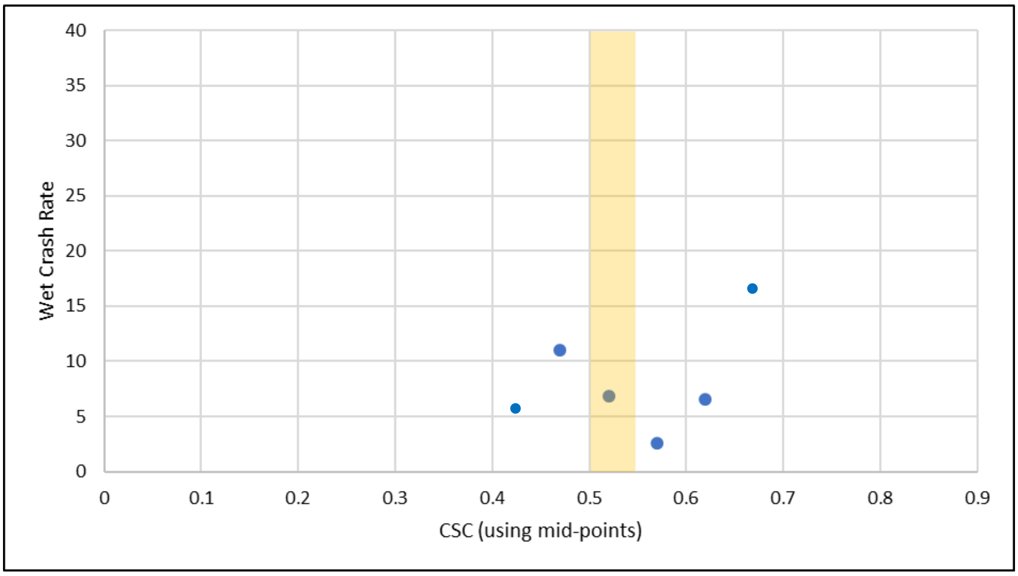


Figure 5-5 - Approach to crossings - CSC band vs. Wet Crash Rate

As most of the incidents have occurred on surfaces with relatively high CSC, it is likely that other factors such as human error relating to both pedestrians and drivers has contributed to the events recorded.

5.6 CATEGORY R: ROUNDABOUT

The ‘Roundabout’ site category results are shown in Figure 5-6. Similar to the figure above, the data shows no meaningful relationship. It is likely that other factors such as increased vehicle interaction and human error have a strong influence on whether a collision occurs. It is therefore not possible to comment on the appropriateness of the existing ILs shade in yellow, based on purely CSC and Wet Crash Rate. No change to the existing IL recommendations (band shaded yellow) is made.

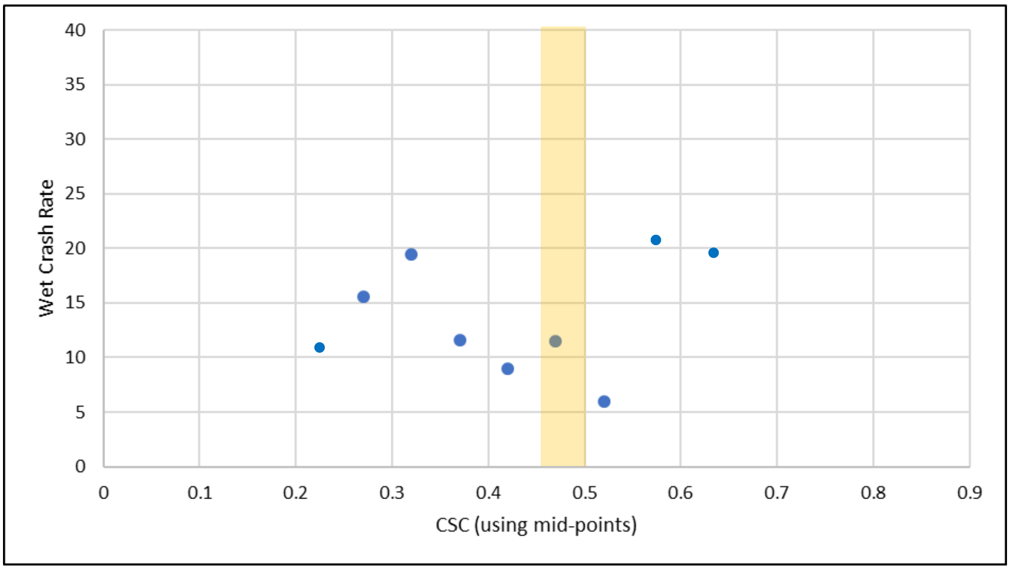


Figure 5-6 - Roundabout - CSC band vs. Wet Crash Rate

5.7 CATEGORY G1: GRADIENT 5-10%, LONGER THAN 50M

The ‘Gradient 5-10%, longer than 50m’ site category results are shown in Figure 5-7. The range of CSC band mid-points are quite narrow for this site category, i.e. 0.32 to 0.52. However, the figure does indicate that higher wet crash rates correspond to the lower friction bands. Although based on limited information, the data points have been split into two groups with associated best fit lines. The band shaded yellow highlights the current recommended IL range of 0.45 to 0.50. Based on this approach it appears that an investigatory level of 0.45 CSC is an appropriate value.

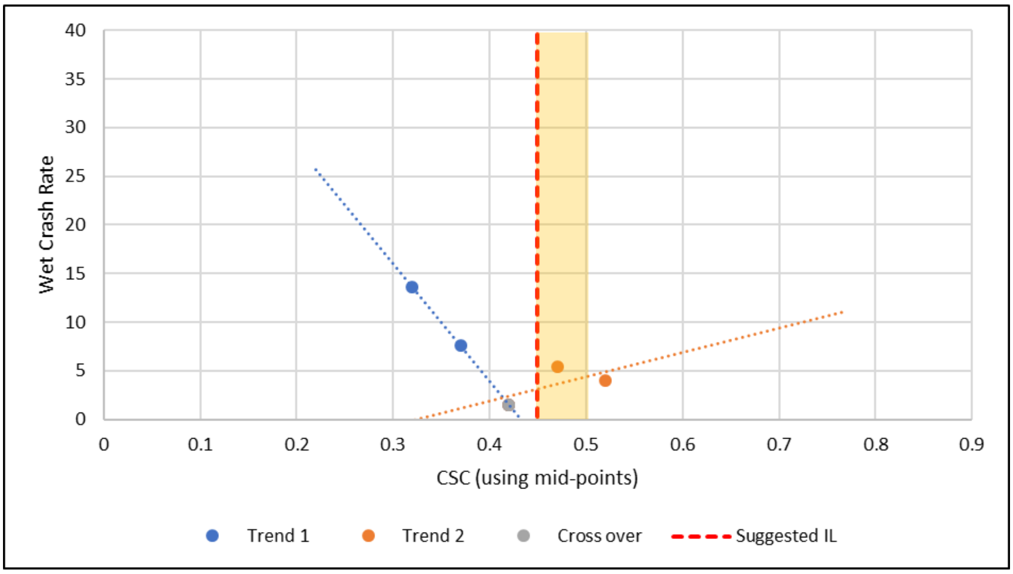


Figure 5-7 - Gradient 5-10% - CSC band vs. Wet Crash Rate

5.8 CATEGORY G2: GRADIENT >10%, LONGER THAN 50M

There were no wet crash data points available for the ‘Gradient >10%, longer than 50m’ site category.

5.9 CATEGORY S1: BEND RADIUS <500M – CARRIAGEWAY WITH ONE-WAY TRAFFIC

Following on from the HD28 Review report, Category S1 has been sub-divided into separate <100m, 100 - 250m and 250 - 500m bend types.

5.9.1. Dual carriageway bends < 100m

The ‘Bend radius <100m – carriageway with one-way traffic (dual carriageway) site category results are shown in Figure 5-8. Similar to category K and R, the data shows no meaningful relationship. Wet Crash Rates appear to be high even with high friction and it is likely that other factors such as vehicle speed and human error have a strong influence on whether a collision occurs. It is therefore not possible to comment on the appropriateness of the existing ILs shade in yellow, based on purely CSC and Wet Crash Rate.

5.9.2. Dual carriageway bends 100 – 250m

The bend radius 100-200m for dual carriageway category results are shown in Figure 5-9. Based on the limited amount of data available no change to the existing IL is recommended.

5.9.3. Dual carriageway bends 250 – 500m

The bend radius 250 – 500m for dual carriageway category results are shown in Figure 5-10. The data is very flat with relatively low wet crash rates. There is a strong case to reclassify bend radius 250 – 500m to Category B with an IL of 0.35.

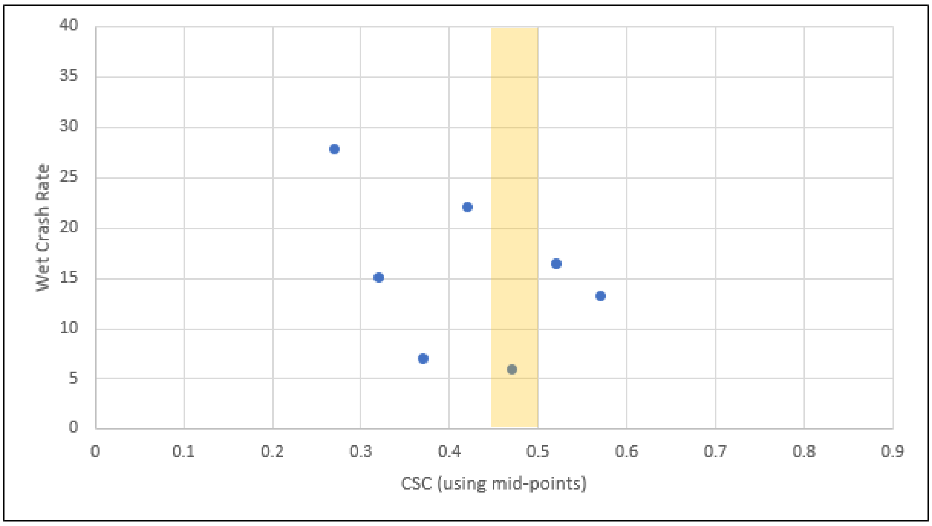


Figure 5-8 - Dual Bends <100m - CSC bands vs. Wet Crash Rate

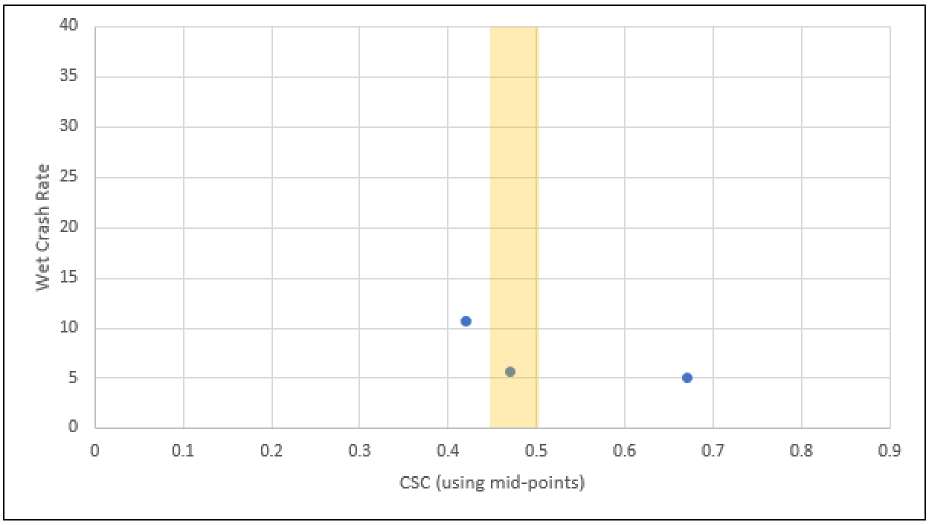


Figure 5-9 - Dual Bends 100-250m - CSC band vs. Wet Crash Rate

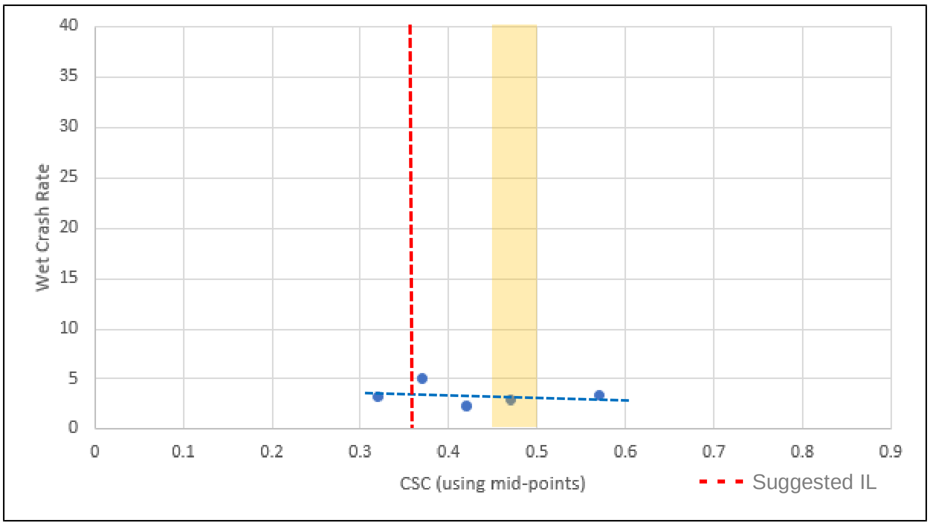


Figure 5-10 - Dual Bends 250-500m - CSC bands vs. Wet Crash Rate

5.10 CATEGORY S2: BEND RADIUS <500M – CARRIAGEWAY WITH TWO-WAY TRAFFIC

Similar to Category S1 above, Category S2 has been sub-divided into separate <100m, 100 - 250m and 250 - 500m bends.

5.10.1. Single carriageway bends < 100m

The 'Bend radius <100m – carriageway with two-way traffic (single carriageway) site category results are shown in Figure 5-11. The data shows a general reduction in wet crash rate for higher CSC values, although there is considerable scatter. In this instance the existing IL guidance seems appropriate if the mid-range point is selected (0.50) although the data scatter suggests that other measures such as speed reduction should be considered.

5.10.2. Single carriageway bends 100 – 250m

The bend radius 100-200m for single carriageway category results are shown in Figure 5-12. The data has been split into two groups with associated best fit lines and shows a general reduction in wet crash rate for higher CSC values. Based on the data the mid-point of the existing IL range appears appropriate.

5.10.3. Single carriageway bends 250 – 500m

The bend radius 250 – 500m for dual carriageway category results are shown in Figure 5-13. The data is very flat with low wet crash rates. There is a strong case to consider reclassifying single bend radius 250 – 500m to Category C with an IL of 0.40.

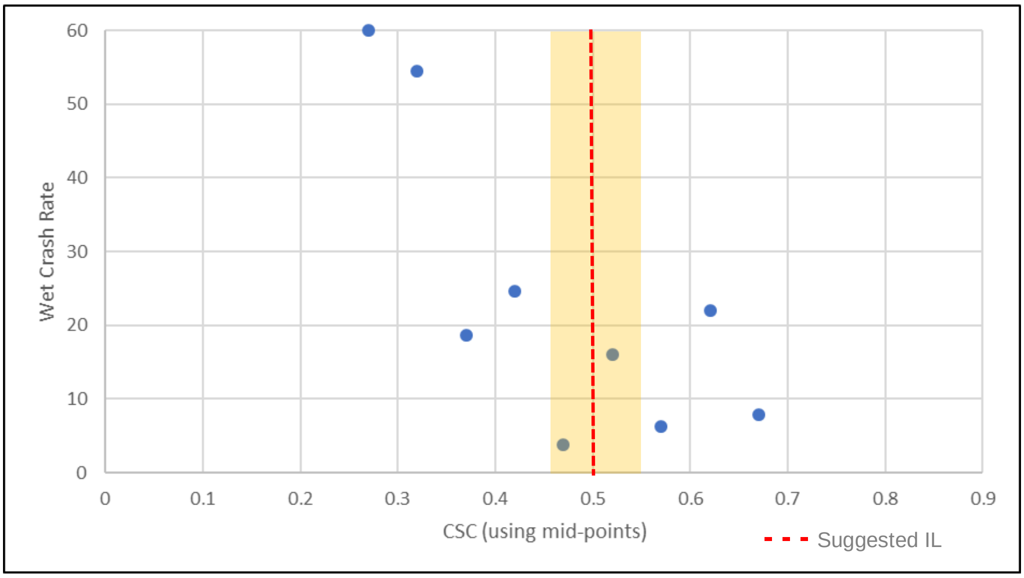


Figure 5-11 - Single Bends <100m - CSC bands vs. Wet Crash Rate

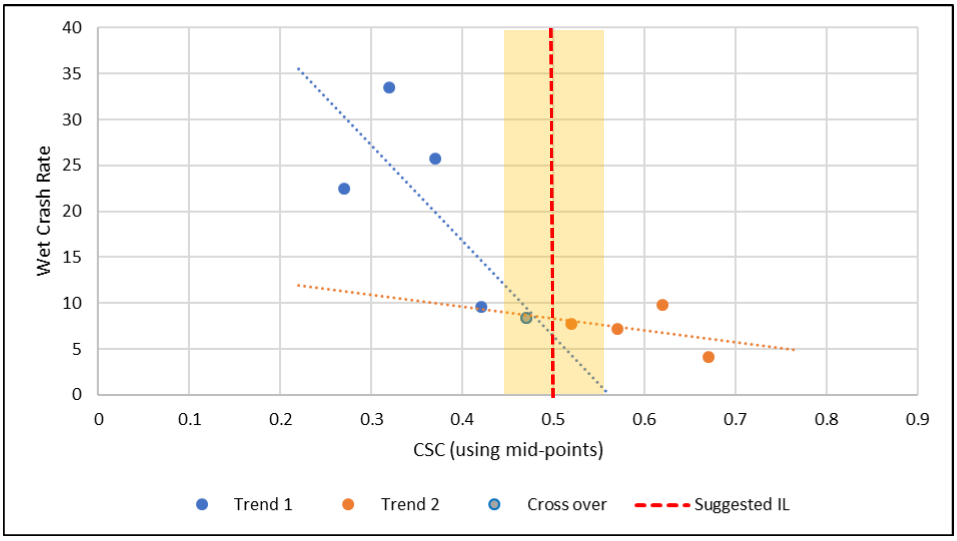


Figure 5-12 - Single Bends 100-250m - CSC bands vs. Wet Crash Rate

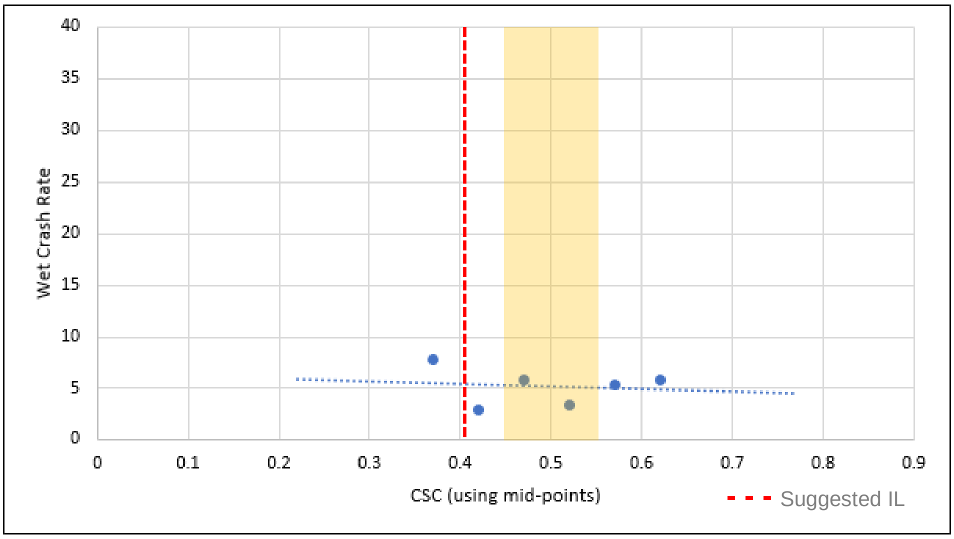


Figure 5-13 - Single Bends 250-500m - CSC bands vs. Wet Crash Rate

6

DISCUSSION

6 DISCUSSION

6.1 FRICTION PERFORMANCE OF TS2010

6.1.1. Performance of TS2010 on different site classes

The overall average CSC of TS2010 materials was compared in Section 4, Figure 4-2. From these figures it appears that there is no significant difference in performance when the same material is laid on a different site class. As the overall average data points can be based on different amounts of data, i.e. ranging between one and eight years, a separate exercise was conducted to compare only those results from year one to eight individually where available. The results were no different from using the overall averages, i.e. no significant difference. Based on the analysis of the data available in this study, it suggests that if an individual material provides a level of friction on site class 1, it will maintain this performance on site class 2 and 3. Currently approval for site class 2 and 3 is only permitted if data is collected directly from a site class 2 or 3 trial, this finding suggests that this is not necessary.

6.1.2. Changes in friction with time

Figure 4-3 shows how the average CSC for individual TS2010 mixtures changes between year one and year five; data from year zero to year one was discounted owing to early-life effects. The general trend over this period shows a tendency for the underling friction to reduce with time. The average drop in friction between year one and year five is 0.03 CSC. Figure 4-4 highlights that around half of this overall loss in friction occurs between year one and year two. It will be interesting to see whether the trend for friction continues to reduce over time or whether the level of friction stabilises.

6.1.3. Review of TS2010 site class approval

The overall weighted averages of CSC for TS2010 mixtures and their current approval for use on the network are shown in Figure 4-5. The underlying friction produced by the individual TS2010 mixtures is ranked in ascending order of overall average CSC from left to right. The figure shows that the current approval system is working well, i.e. in general materials that produce the highest underlying friction are approved for the most demanding site class (coded red), and vice versa (coded green).

Figure 4-5 contrasts well with Figure 4-6 where the materials are ranked by ascending aggregate PSV. There appears to be a relationship with PSV and the level of underlying friction produced for high PSV aggregates, but there is considerable scatter in average CSC for low and mid-range PSV aggregates. Figure 6-1 shows the mean average performance of aggregates when they are combined into four PSV groups: <60, 60-64, 65-67 and 68+. The figure shows that on average PSV group 65-67 provides a slightly higher average CSC than the PSV 68+ group. These results agree with other research that highlights that the PSV test simply ranks one aggregate size and source against another and that the single aggregate size tested only represents a small part of surfacing mixture. The figure also highlights that there appears to be no benefit in specifying TS2010 mixtures with a PSV68+ in terms of enhancing in-service friction.

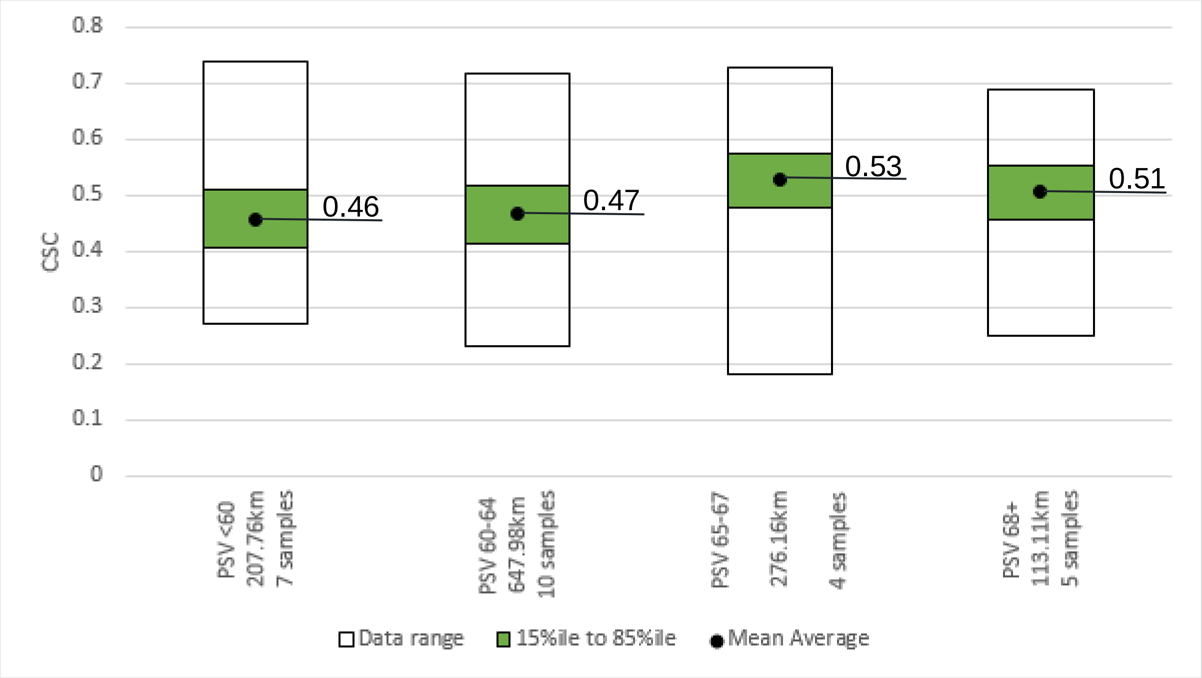


Figure 6-1 - Performance of combined PSV groups

6.1.4. Influence of weather conditions

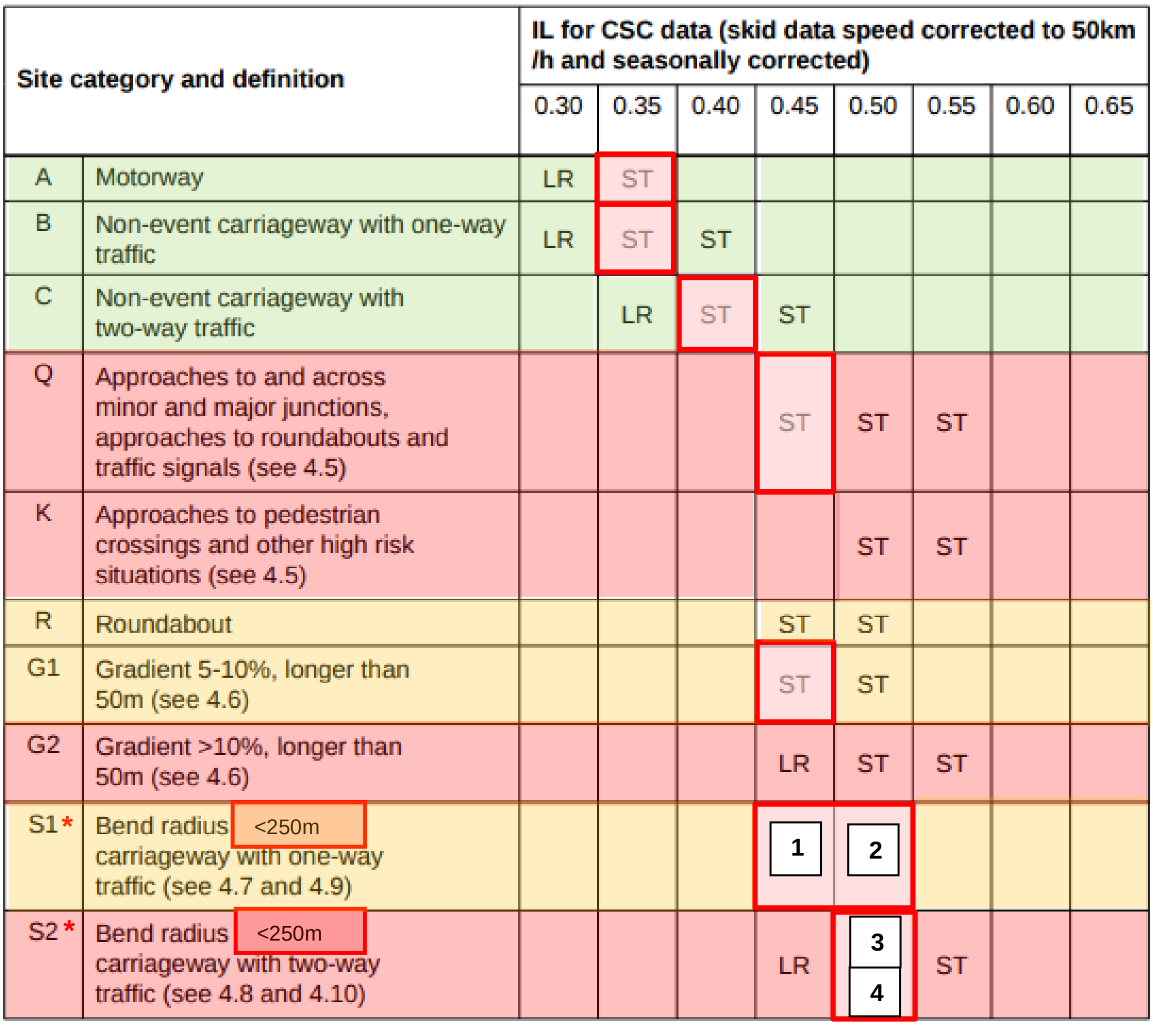
The influence of rainfall on a mixture's ability to provide or maintain friction levels was observed in a study undertaken on the Isle of Skye (McHale *et al.*, 2017). The climate in Skye can be characterised by relatively high rainfall and short periods between rainfall, even during summer, which restricts the amount of polishing of road surfacing by vehicular traffic. It is likely that rainfall cleans the surface by removing the normal build-up of detritus which is known to act as a polishing medium.

Utilising the BI tool, it was possible to extract average CSC data for two TS2010 mixtures that are used in parts of Scotland that have different weather conditions in terms of rainfall. Figure 4-9 and Figure 4-11 show that the mixtures provide higher friction in the relatively wetter western parts of the country compared to the drier eastern coastline. In particular, for Mixture F provides 0.52 CSC in the west as opposed to 0.41 in the east, this equates to around a 25% increase. It is possible that the difference is related to other factors such as trafficking levels.

6.2 CRASH HISTORY VERSUS SURFACE FRICTION

In Section 5, the CS 228 site categories were examined to see if the current recommended ILs were appropriate based on the Wet Crash Rate and CSC bands. Each figure was examined to determine whether any patterns or trends existed. In some instances, a relationship did not appear to exist and it is likely that the occurrence of an accident was influenced by factors other than wet crash rate and underlying friction. Where a reasonable or strong relationship existed, a revised default IL has been recommended. The findings and potential implications of the data analysis have been summarised and highlighted in pink in Table 6-1.

Table 6-1 - Suggested IL amendments to site categories based on data analysis



Site category and definition		IL for CSC data (skid data speed corrected to 50km /h and seasonally corrected)							
		0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
A	Motorway	LR	ST						
B	Non-event carriageway with one-way traffic	LR	ST	ST					
C	Non-event carriageway with two-way traffic		LR	ST	ST				
Q	Approaches to and across minor and major junctions, approaches to roundabouts and traffic signals (see 4.5)				ST	ST	ST		
K	Approaches to pedestrian crossings and other high risk situations (see 4.5)					ST	ST		
R	Roundabout				ST	ST			
G1	Gradient 5-10%, longer than 50m (see 4.6)				ST	ST			
G2	Gradient >10%, longer than 50m (see 4.6)				LR	ST	ST		
S1*	Bend radius <250m carriageway with one-way traffic (see 4.7 and 4.9)				1	2			
S2*	Bend radius <250m carriageway with two-way traffic (see 4.8 and 4.10)				LR	3 4	ST		

Key: New proposed default IL, based on analysis ☐

TS2010 site classes: 🟩 Site Class 1 🟨 Site Class 2 🟥 Site Class 3

Notes: 1 = Dual bends 100-250m; 2 = Dual bend <100m

3 = Single bends 100-250m; 4 = Single bends <100m

S1* bends >250m should be treated as Cat B(0.35) and S2* bends as Cat C(0.40)

6.3 PROVIDING THE FRICTION REQUIRED

Owing to its low noise and proven durability characteristics, in most instances TS2010 will be the preferred surfacing choice for the Scottish network. The overall CSC performance of TS2010 (Figure 4-5) shows that the top performing mixtures, that utilise natural aggregates, will broadly achieve 0.5 IL. However, the box plots in Figure 4-5 highlight that each mix provides a range of friction values and that no TS2010 mixture will consistently provide a CSC of 0.55 at the 15th percentile level, i.e. provide this level of friction 85% of the time.

High friction surfacing materials will provide higher levels of friction but they are problematic owing to their low life expectancy. There is therefore a gap in the market to develop a TS2010 mixture that can provide enhanced friction. As TS2010 mixtures utilise the use of grit there is a possibility that the application of calcined bauxite as a replacement for grit may elevate the in-service friction provided. Trials would be required to ensure that an adequate proportion of grit is retained and that the elevated friction levels are not short lived.

7

CONCLUSIONS & RECOMMENDATIONS

7 CONCLUSIONS & RECOMMENDATIONS

7.1 ANALYSIS OF TS2010 SKID RESISTANCE DATA

Based on the analysis of the skid resistance data collected annually on the Scottish trunk road network the following conclusions can be made:

- There appears to be no significant difference in skid resistance performance of individual TS2010 mixtures when laid on different site classes.
- There is a general trend for the underling friction to reduce slightly with time on all TS2010 sites. The average drop in friction between year one and year five is 0.03 CSC, but around half of this overall loss in friction occurs between year one and year two.
- The current approval system for TS2010 appears to be working well in that mixtures that produce the highest in-service skid resistance are used on sites that are perceived to require a higher level of friction.
- The relationship between PSV and CSC is complex, with some lower PSV aggregates outperforming higher PSV aggregates.
- There appears to be little benefit in specifying natural aggregates with a PSV 68+, as they do not perform any better than aggregates in the PSV 65-67 range.
- There is some evidence that some TS2010 mixtures provide higher friction in the relatively wetter western parts of the country compared to the drier eastern coastline.
- The overall CSC performance of TS2010 shows that the top performing mixtures will broadly achieve 0.5 IL.

Following on from the above conclusions the following recommendations are made:

- Consider approving certain TS2010 mixtures for use on higher site classes where good performance has been achieved on Site Class 1.
- Monitor the general trend for overall CSC values to reduce with time in order to determine whether this tendency continues or stabilises.
- Continue to classify TS2010 use based on CSC rather than aggregate PSV.
- Study the influence of rainfall on TS2010 performance with a view to reclassifying mixtures based on their location on the network.

7.2 ANALYSIS OF CRASH HISTORY AND CSC

Based on an examination of wet crash rate versus CSC for TS2010 mixtures some amendments to the current ILs (CS 228) have been proposed. Each figure was examined to determine whether any patterns or trends existed. In some instances, a relationship did not appear to exist and it is likely that the occurrence of accidents are influenced by other factors, such as human error. Where a reasonable or strong relationship existed then a revised default IL has been proposed. The amendments are contained within Table 6-1 in Section 6 of this report.

8 ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the input of Andrew Ferguson, Jacobs, who developed the business intelligence (BI) tool that enabled the collection and processing of the skid resistance data used in this report.

9 REFERENCES

Atkins (2018). *SCRIM Investigatory Level Review.* Scottish Roads Research Board (SRRB).

British Standards Institution (2009). *BS-EN 1097-8:2009. Tests for mechanical and physical properties of aggregates. Part 8: Determination of the polished stone value.* London: BSI.

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

Department for Transport (2016). *Reported road casualties in Great Britain: main results 2015.* London: The Stationery Office.

Dunford, A., & Roe, P. (2012). *PPR604. Use of the Wehner-Schulze machine to explore better use of aggregates with low polish resistance. 1. Capabilities of the Wehner-Schulze machine.* Wokingham, Berkshire: TRL Ltd.

Dunford. A (2013). *PPR603*. *Establishing a new supply of UK PSV control stone*. Crowthorne: TRL Limited.

Dunford, A. (2014). *PPR710. Laboratory studies investigating the use of blended PSV aggregates*. Wokingham, Berkshire: TRL Ltd.

Friel et al (2013). *Use of Wehner Schulze to predict skid resistance of Irish surfacing materials*. Airfield and Highway Pavement Conference 2013, Los Angeles.

Highways England, Transport Scotland, Welsh Assembly Government and the Department for Regional Development Northern Ireland (2012). *Interim Advice note 156/12* Revision of Aggregate Specification for Pavement Surfacing.

Highways England, Transport Scotland, Welsh Assembly Government and the Department for Regional Development Northern Ireland (2012). *Interim Advice note 154/12* Revision of SHW Clause 903, Clause 921 and Clause 942.

Highways England. *CD 236,* Surfacing materials for new and maintenance construction. https://www.standardsforhighways.co.uk/dmrb/

Highways England. *CS 228,* Skidding resistance*.* https://www.standardsforhighways.co.uk/dmrb/

Hosking, J. (1976). *LR693. Aggregates for skid resistant roads*. Crowthorne, Berkshire: Transport and Road Research Laboratory.

Hosking, J., & Woodford, G. (1976). *LR738. Measurement of skidding resistance Part II.* Factors affecting the slipperiness of a road surface. Crowthorne, Berkshire: Transport and Road Research Laboratory.

Maclean, D., & Shergold, F. (1958). *Road Research Technical Paper No.43. The Polishing of Roadstone in Relation to the Resistance to Skidding of Bituminous Road Surfacings*. London: Her Majesty's Stationery Office.

McHale, M. J., Carswell, I., & Roe, P. (2011). *TRL 670. New surface course specification for Scotland*. Wokingham, Berkshire: Transport Research Laboratory.

McHale M J and McLaughlin M (2015). *A durable and sustainable surface course*. CAPSA' 15, Sun City, SA.

McHale M J, Martin L A and Scott J (BEAR Scotland) (2017). *PPR820. A procedure for justifying aggregate use based on in-service skid performance.* Wokingham, Berkshire: Transport Research Laboratory.

Morrison D, Grant W and Donbavand J (2008). *Implementing a Revised Skid Policy into Scotland*, Safer Roads International Conference.

Mulry B, Brennan M J and Sheahan J N (2012). *A model for adjusting SCRIM skid resistance data to reflect seasonal variation.* 5th Eurasphalt & Eurobitume Congress, 13-15th June 2012, Istanbul.

Neville, G. (1974) *LR621. A Study of the Mechanism of Polishing of Roadstones by Traffic*. Department of the Environment, Transport and Road Research Laboratory, Crowthorne.

Parry AR and Viner H E (2005). *TRL622. Accidents and skidding resistance standard for strategic roads in England.* Crowthorne: TRL Limited.

Roe & Hartshorne (1998) *TRL322. The Polished Stone Value of aggregates and in-service skidding resistance.* Crowthorne: TRL Limited.

Roe, P., & Dunford, A. (2012). *PPR564. The skid resistance behaviour of thin surface course systems*. Wokingham, Berkshire: Transport Research Laboratory.

Saunders P D, Martin L A and Gravanis J (2018). PPR924. Evaluating the friction after polishing as an in-service skid resistance prediction tool for TS2010 materials. Wokingham, Berkshire: Transport Research Laboratory.

Stephenson M and Blackmore M (2019). *Transport Scotland HD28 Review*. Transport Scotland, Buchanan Street, Glasgow.

Szatkowski, W., & Hosking, J. (1972). *LR504. The Effect of Traffic and Aggregate on the Skidding Resistance of Bituminous Surfacings*. Crowthorne, Berkshire: Transport and Road Research Laboratory.

Transport Scotland (2002). *Correlation between Texture Depth and accidents.* Unpublished Internal Report. Glasgow: Buchanan House.

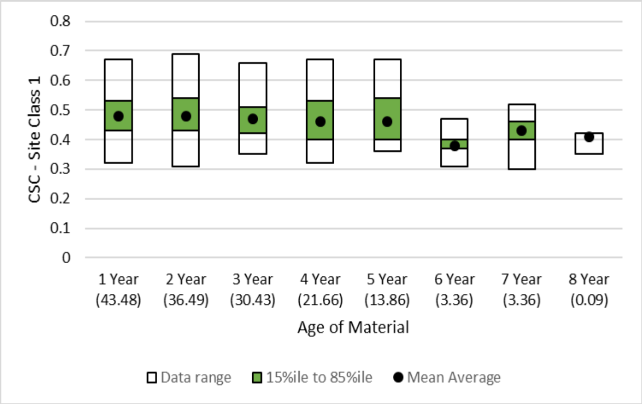
TSIA No. 35 (2018). *Transport Scotland Interim Amendment No. 35, TS2010 Surface Course Specification and Guidance.* Glasgow: Buchanan House.

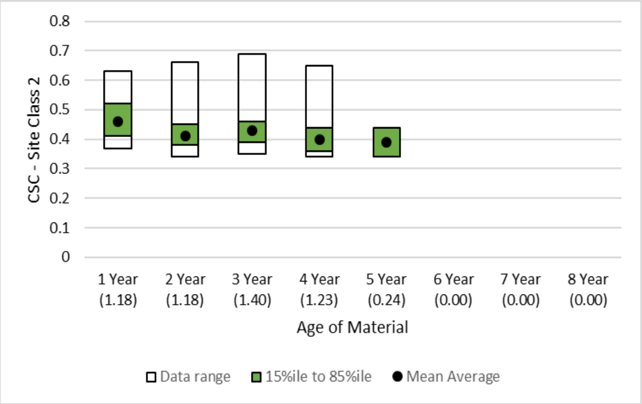
Woodward, WDH, Woodside, AR and Jellie, J.H. (2005). *Higher PSV and other aggregate properties*. International Surface Friction Conference - Roads and Runways, Christchurch, New Zealand.

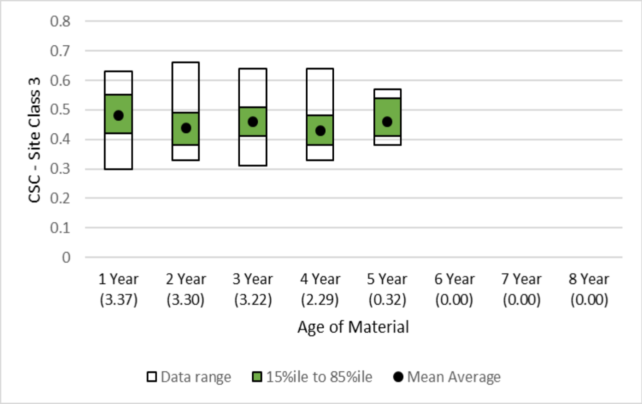
Appendix A

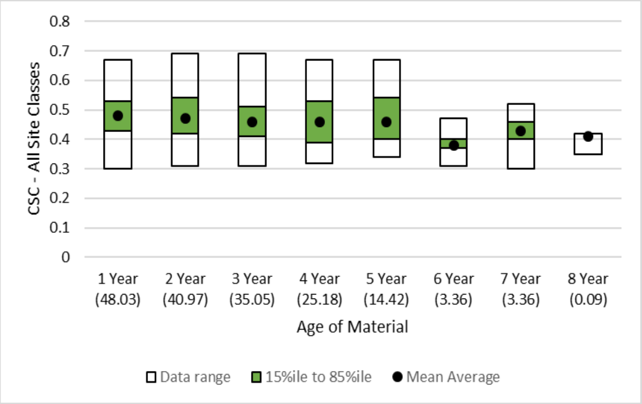
BOX PLOTS FOR TS2010 MIXTURES

Mixture A

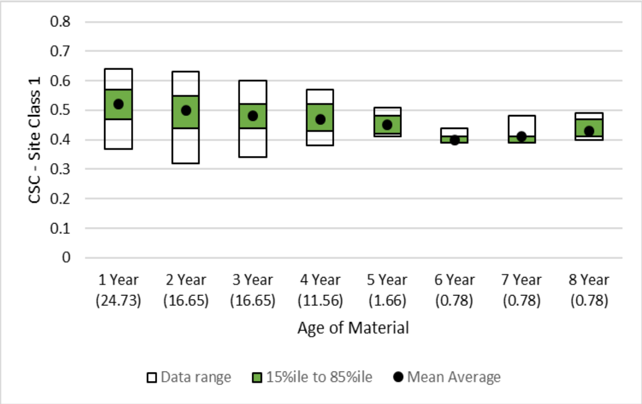


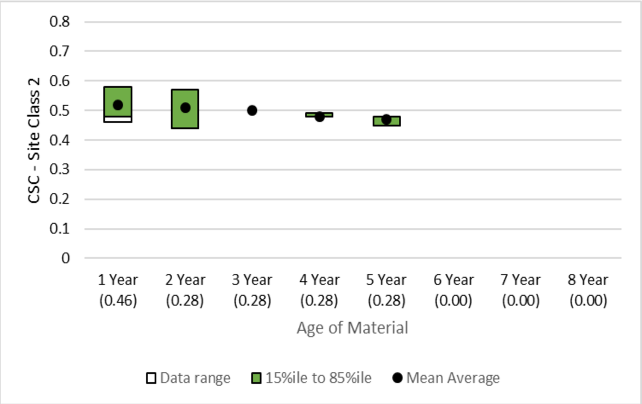


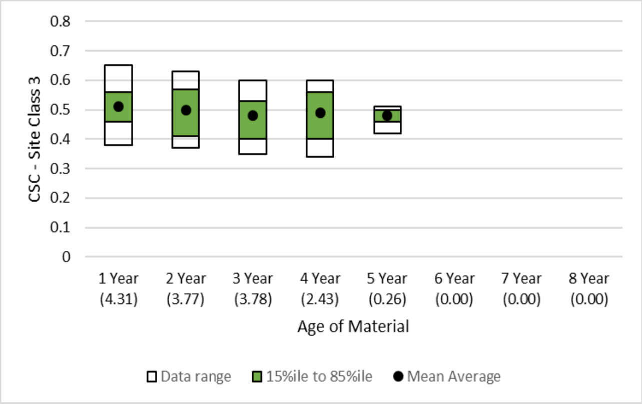


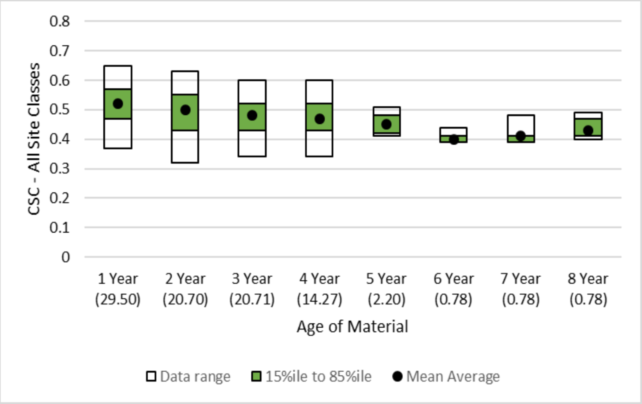


Mixture B

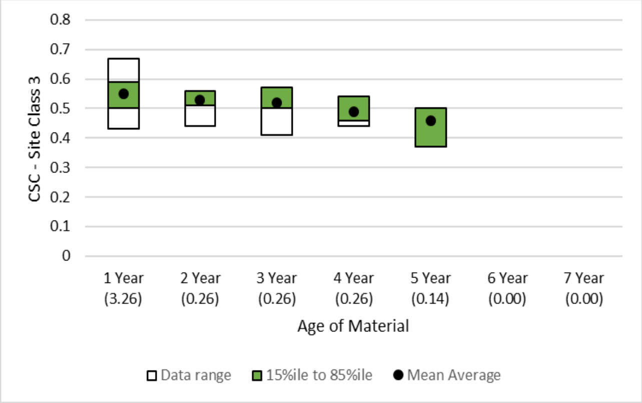


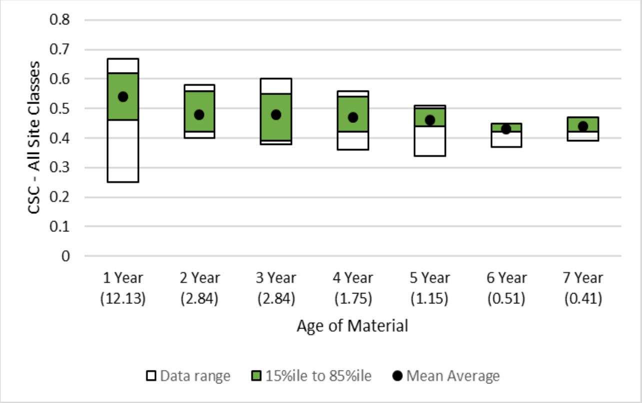




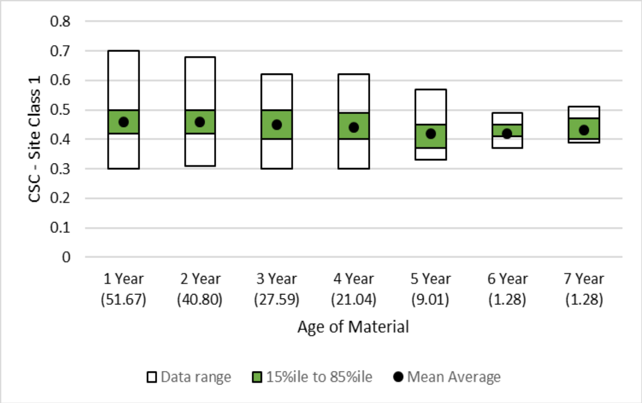


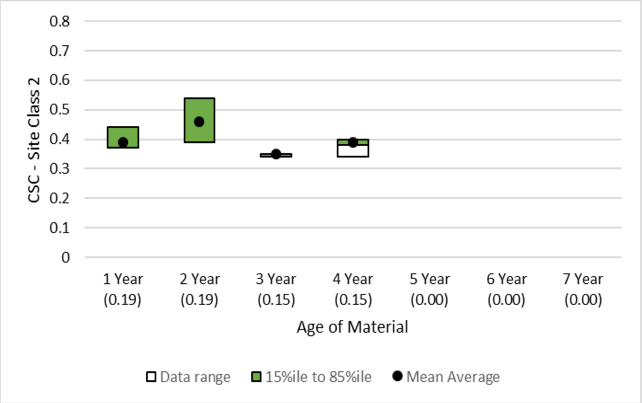
Mixture C

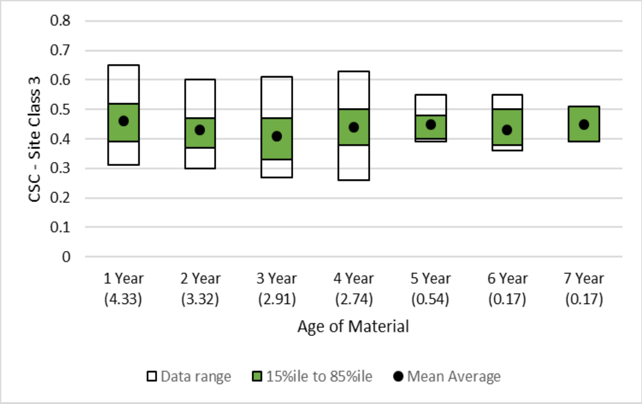


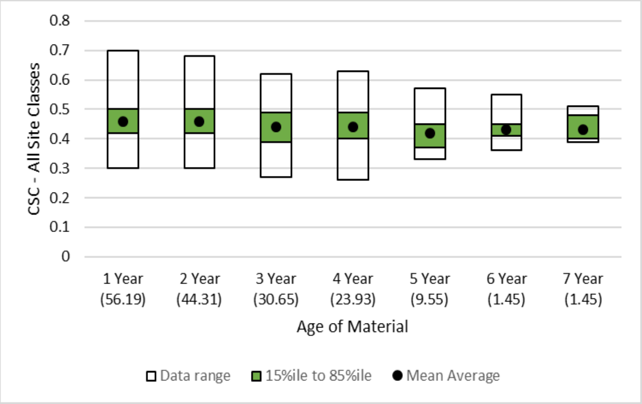


Mixture D





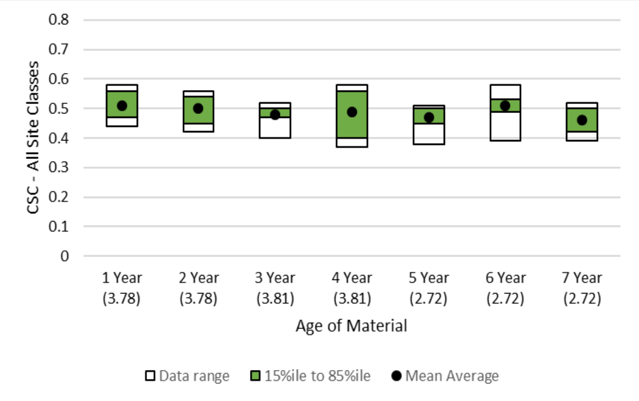




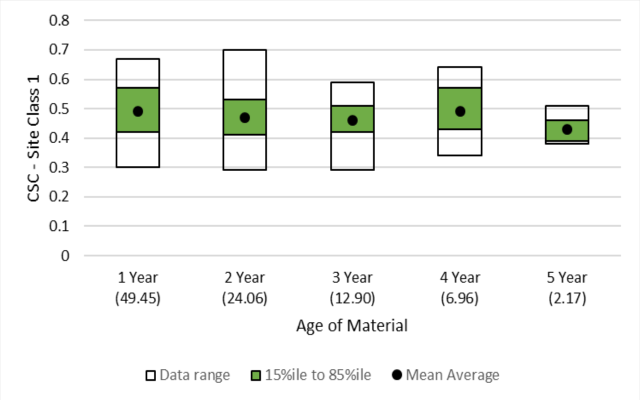
Mixture E

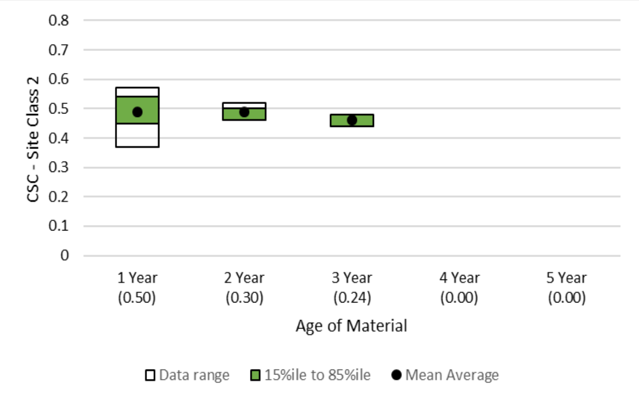
No data on Site Class 2

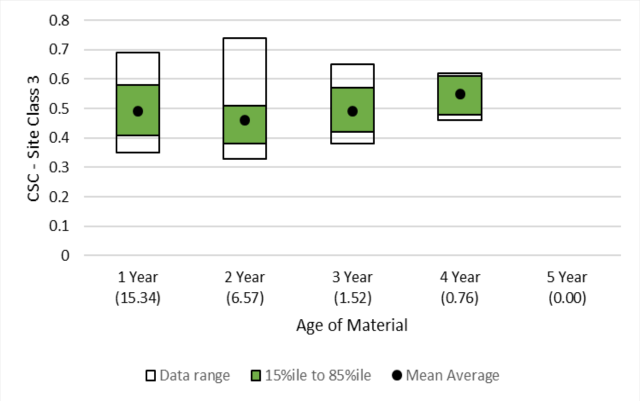
No data on Site Class 3

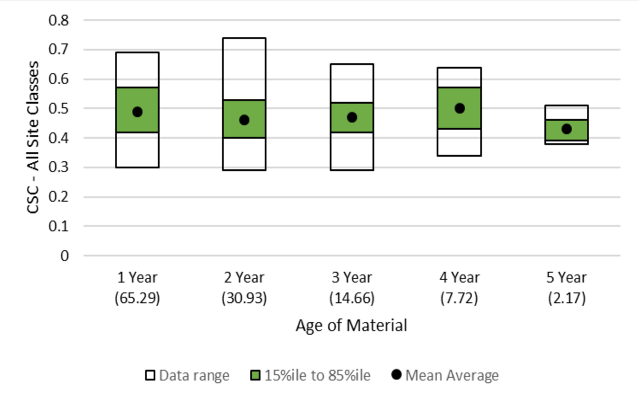


Mixture F

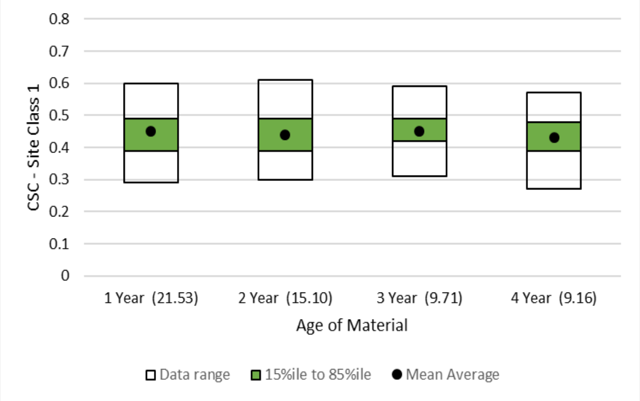








Mixture G



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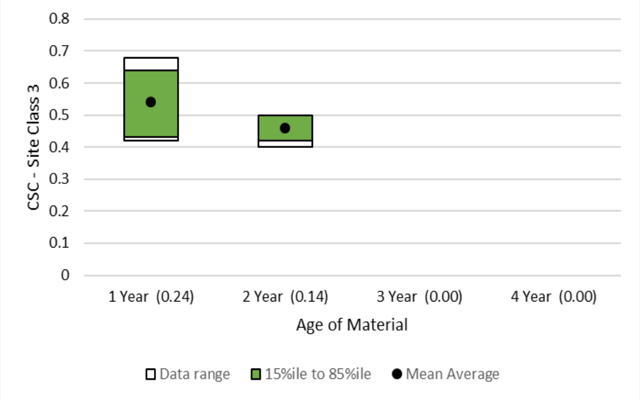
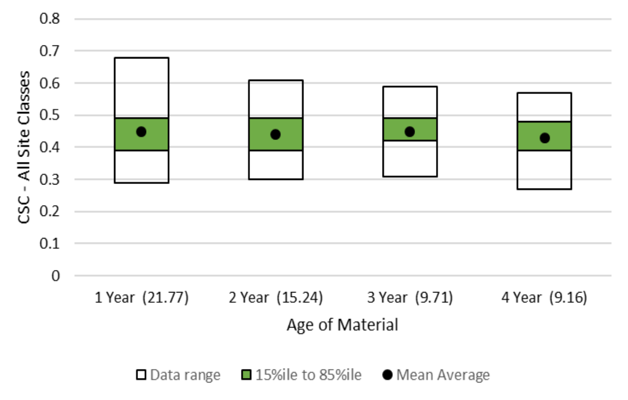
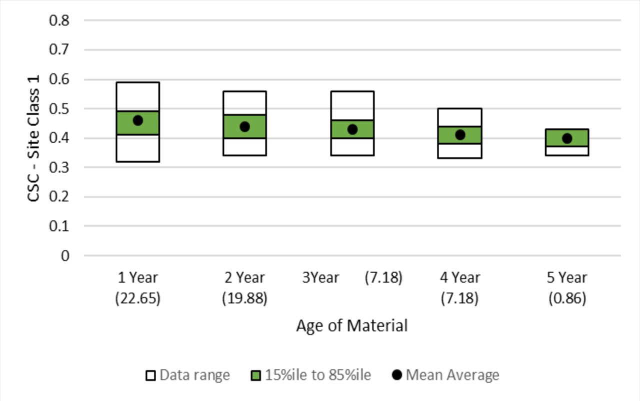
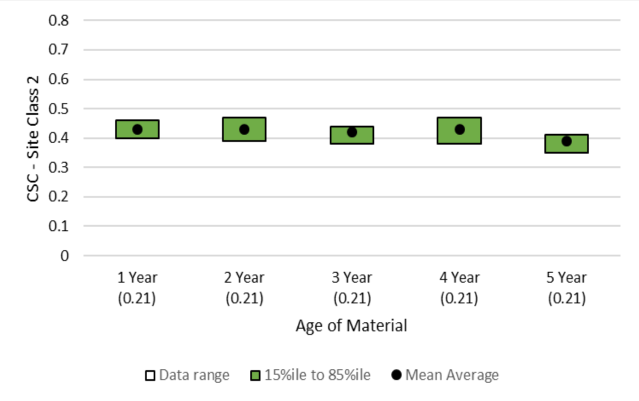
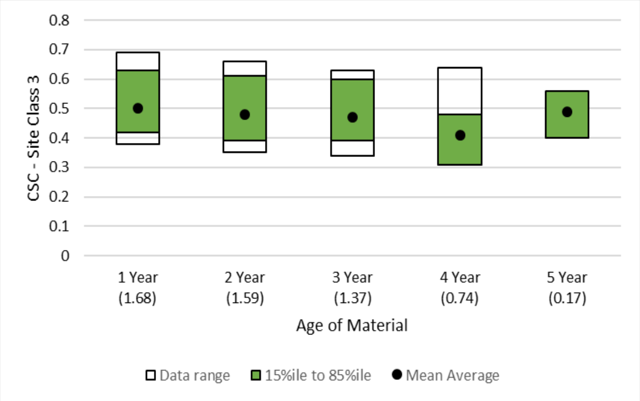


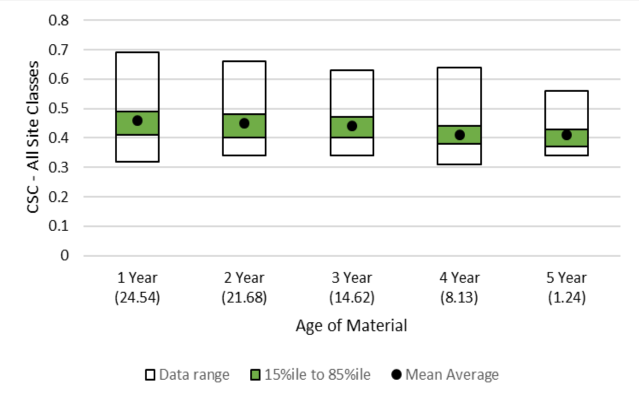


Mixture H

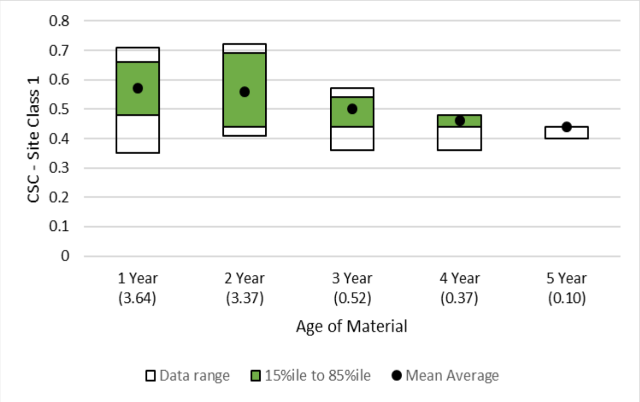


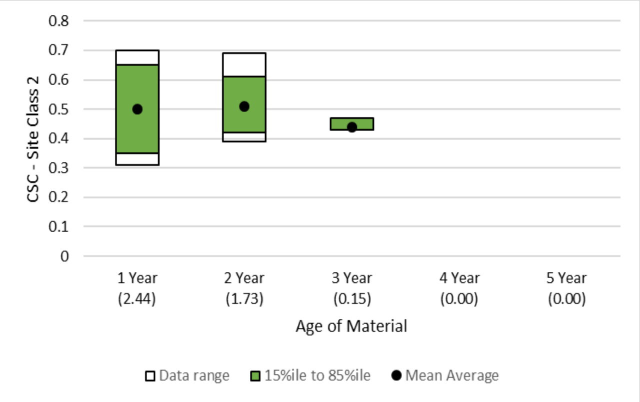


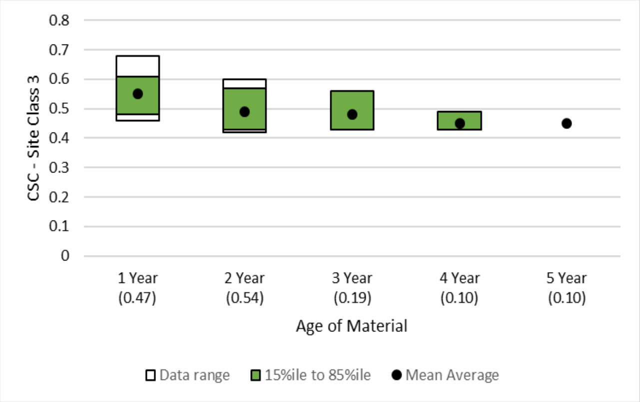


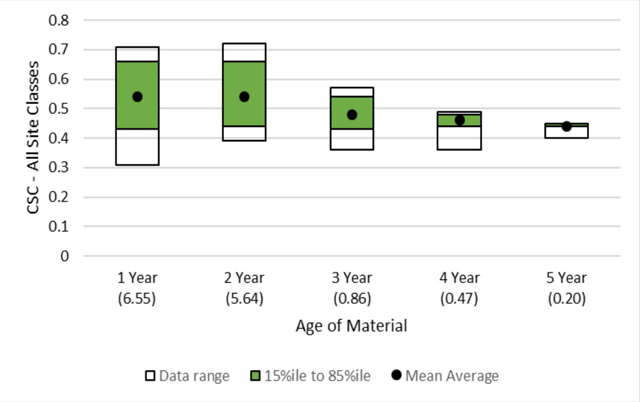


Mixture I

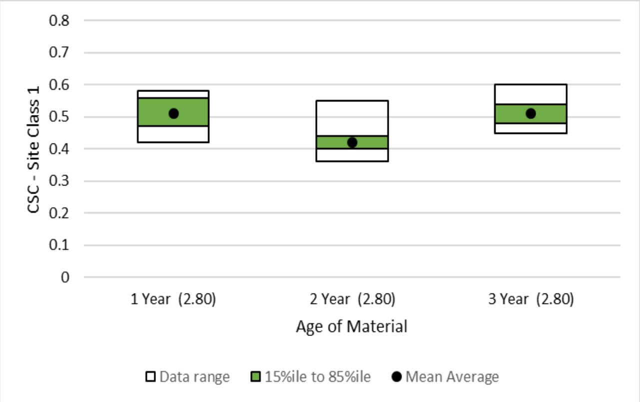








Mixture J



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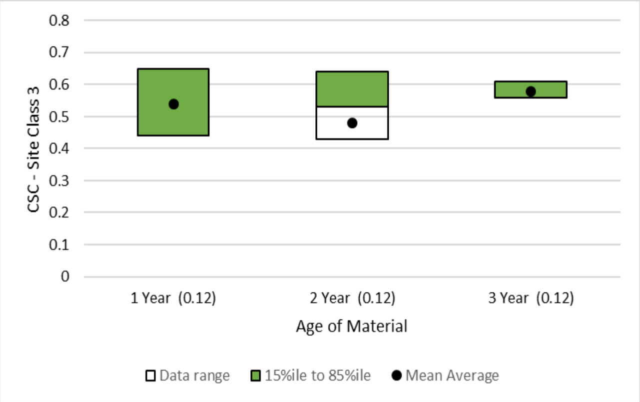
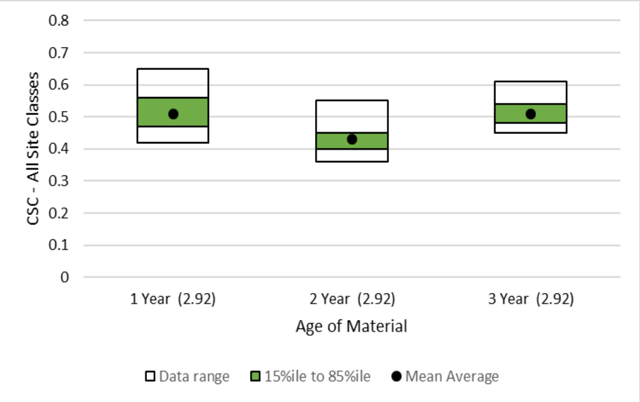
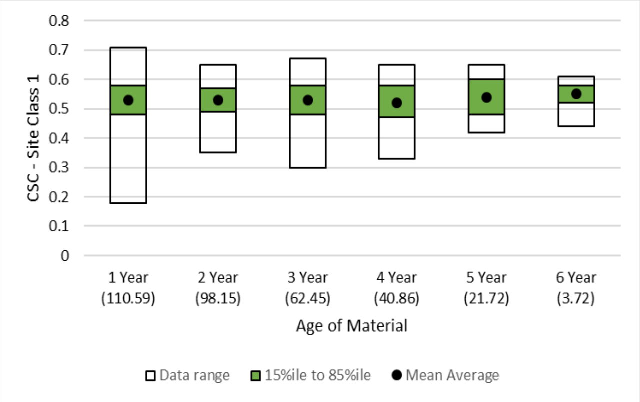
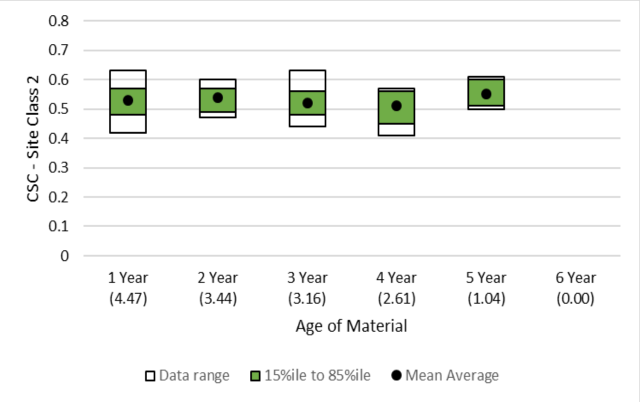
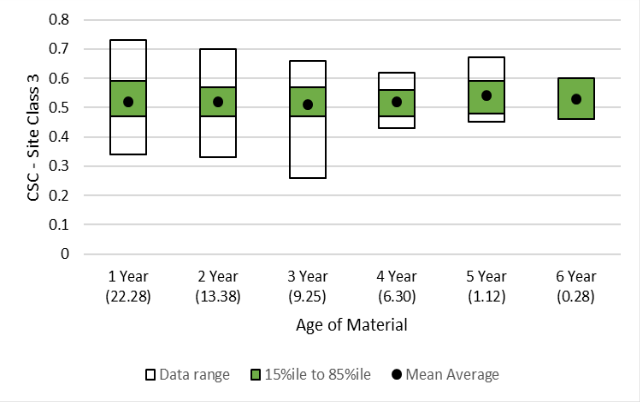


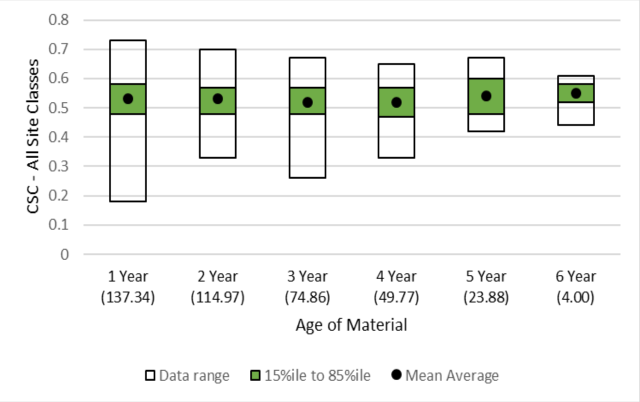


Mixture K

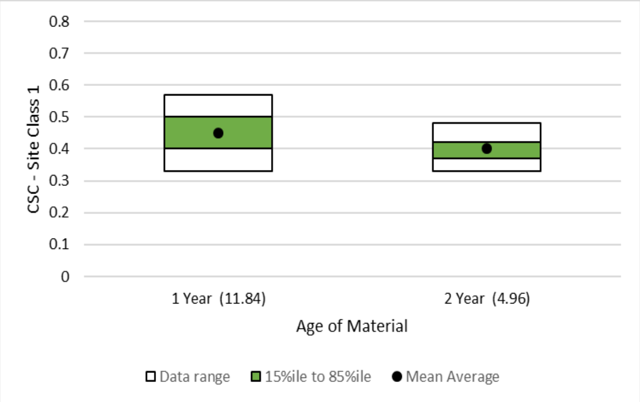


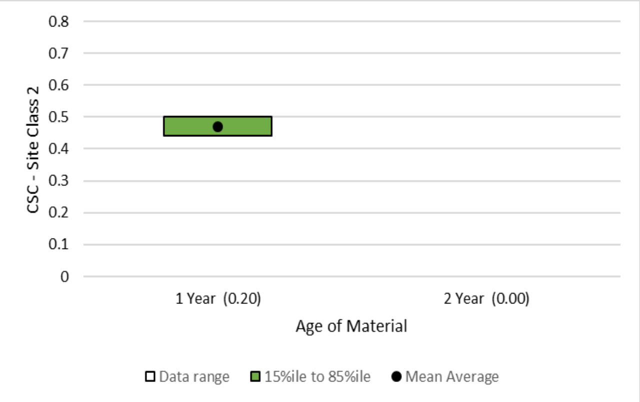


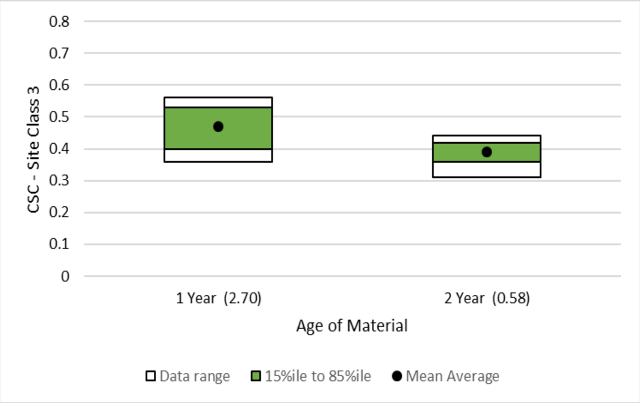


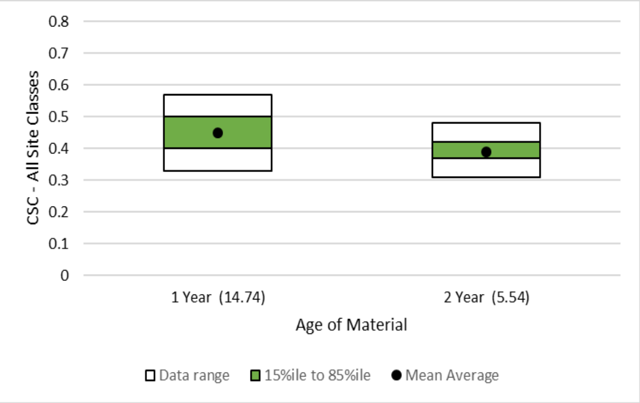


Mixture L

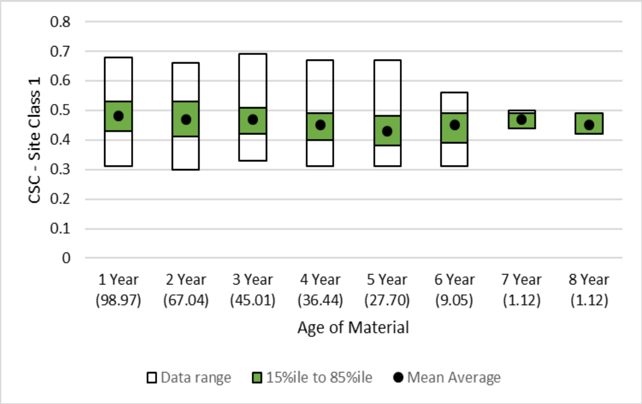


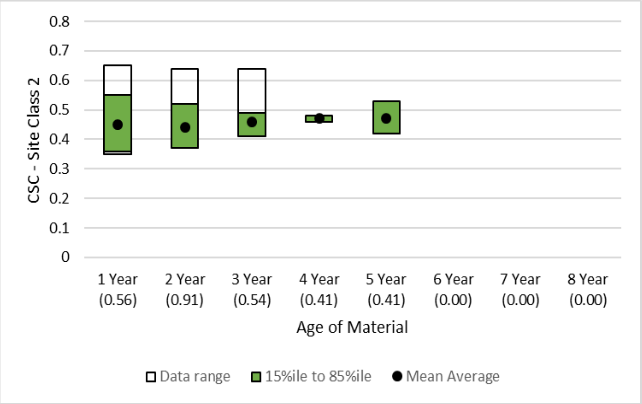


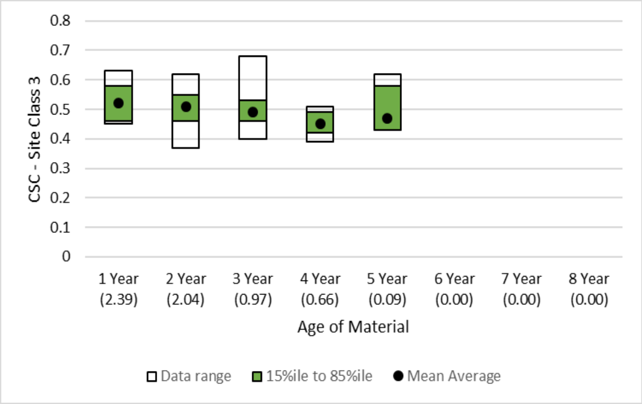


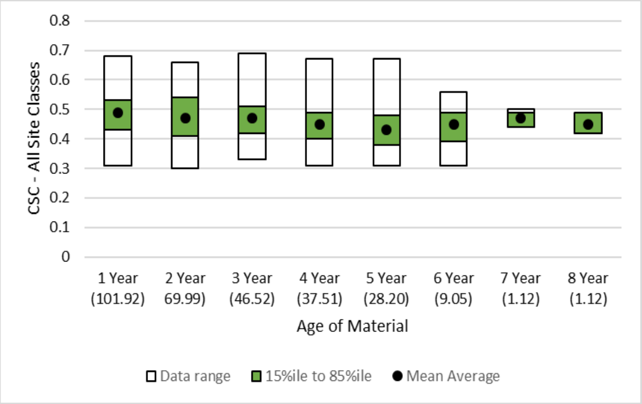


Mixture M

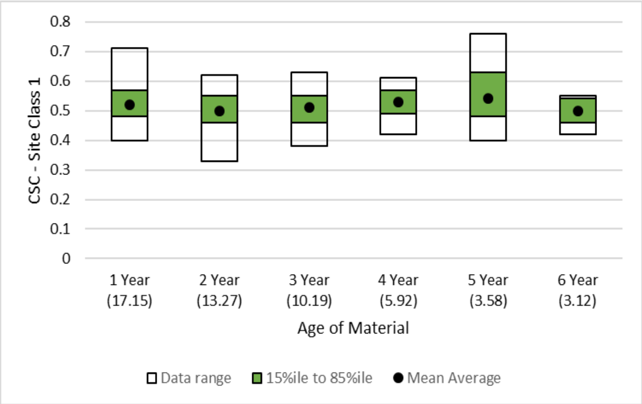


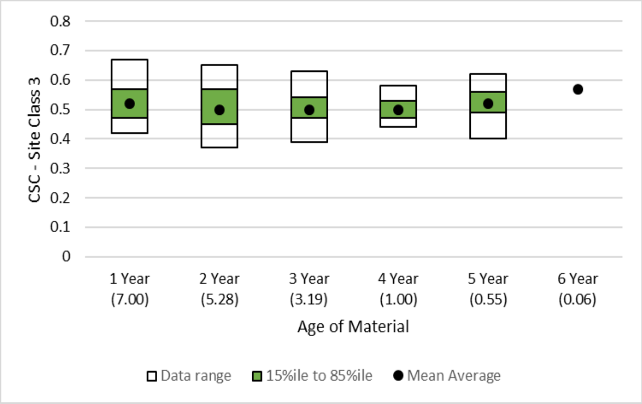


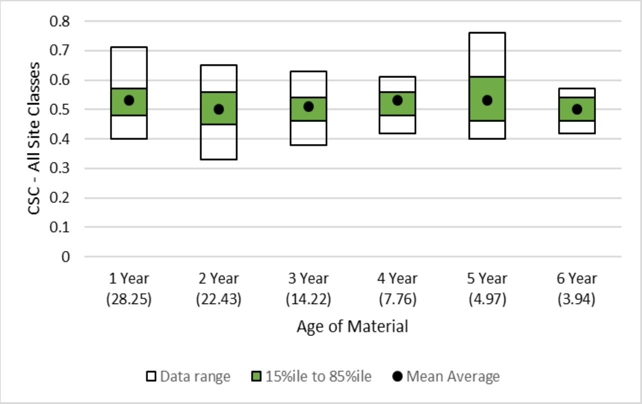




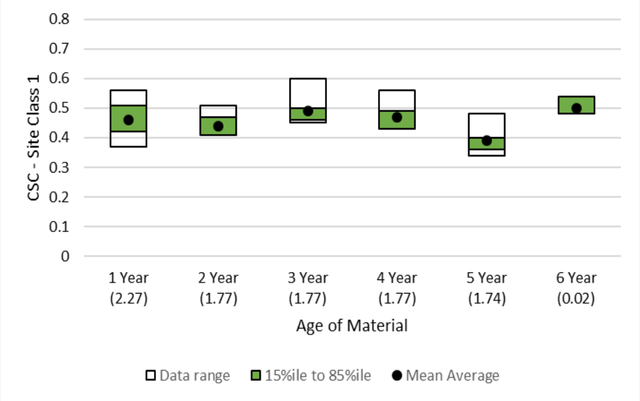
Mixture N







Mixture O



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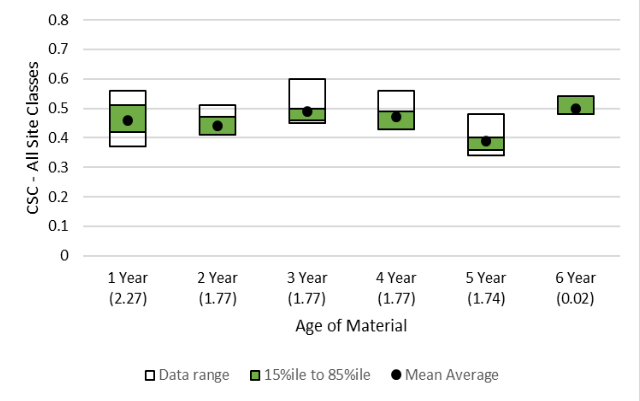
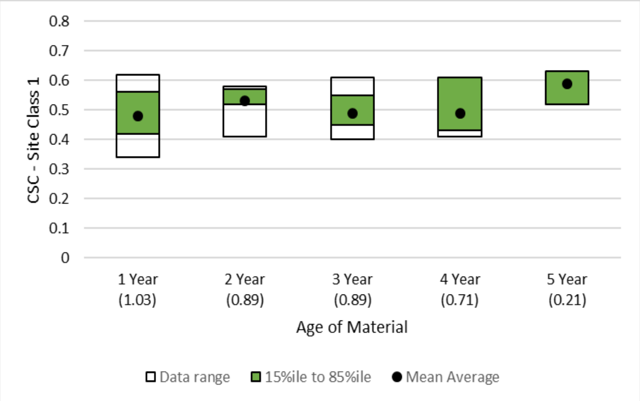
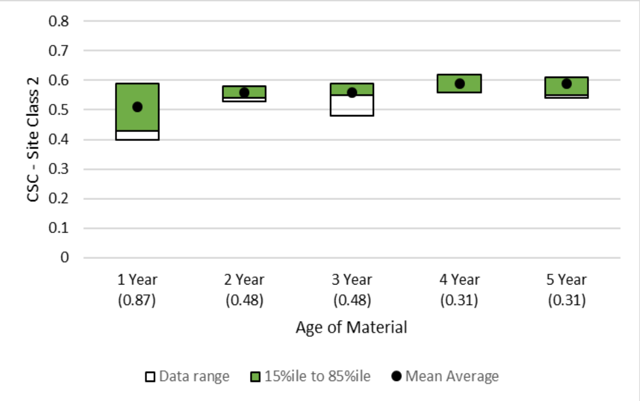
No data on Site Class 3



Mixture P





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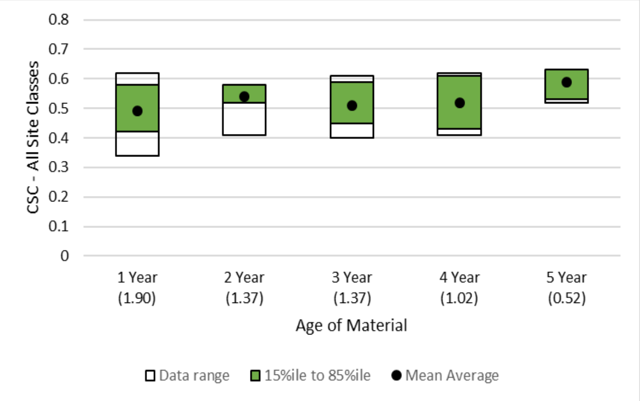
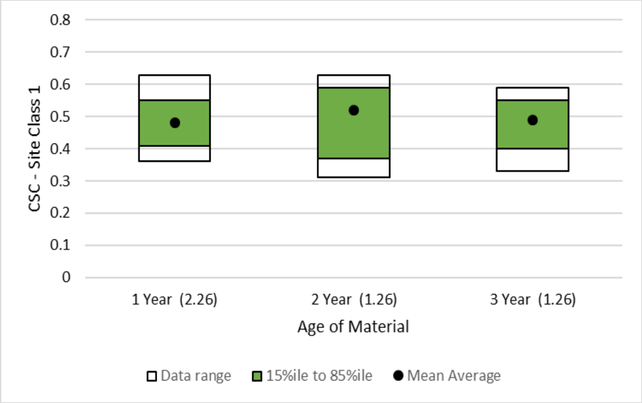
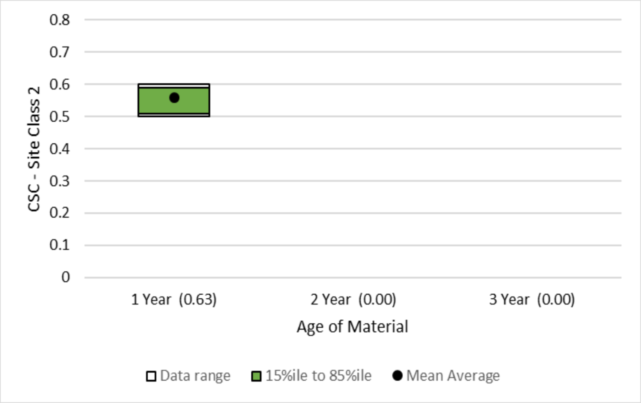
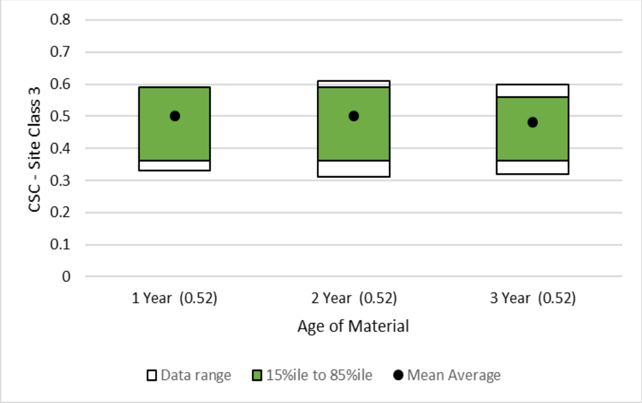
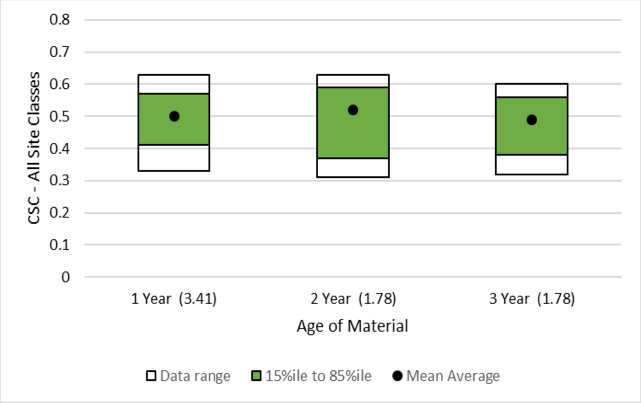


Mixture Q

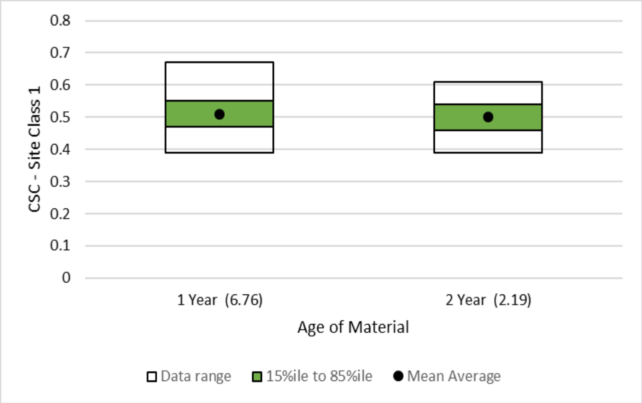


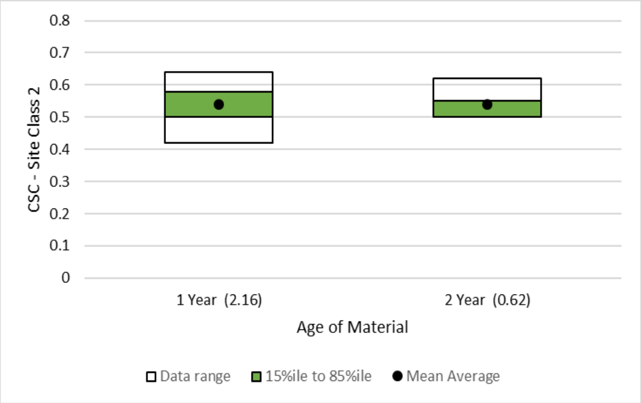


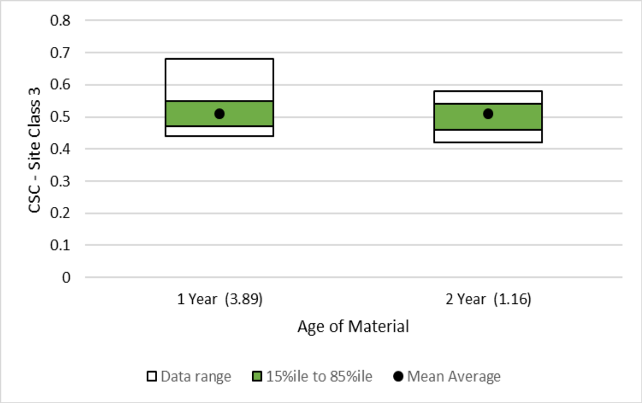


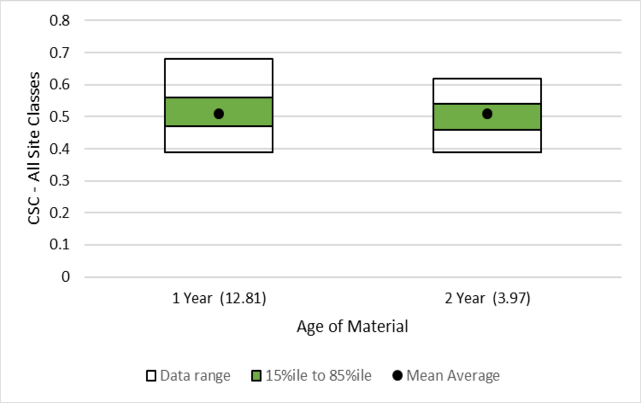


Mixture R

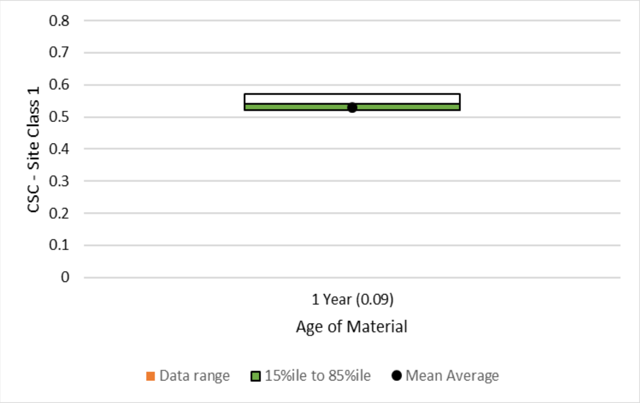






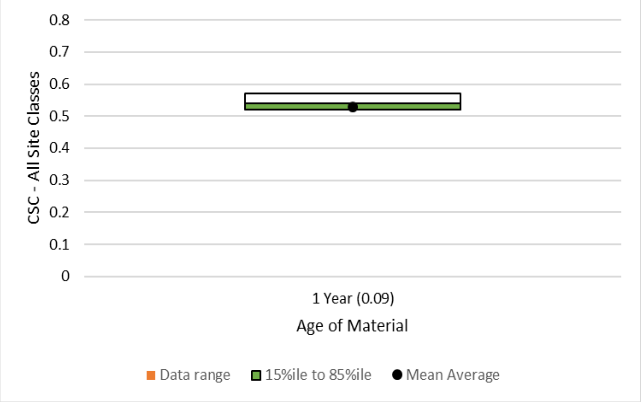


Mixture S

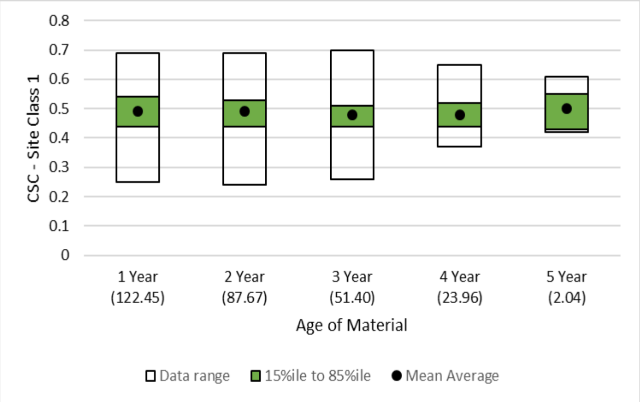


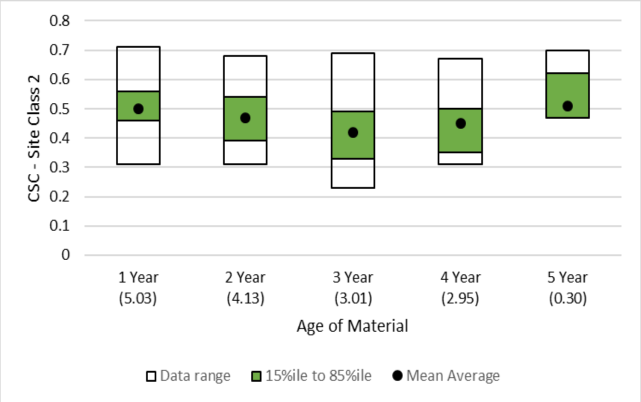
No data on Site Class 2

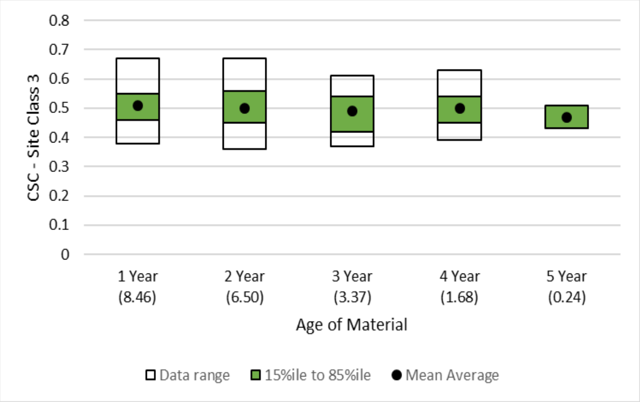
No data on Site Class 3

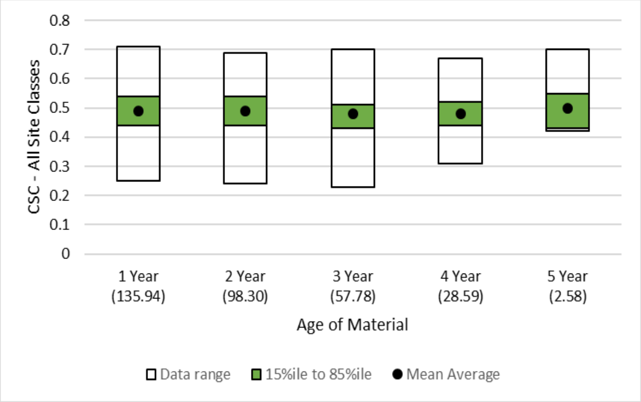


Mixture T

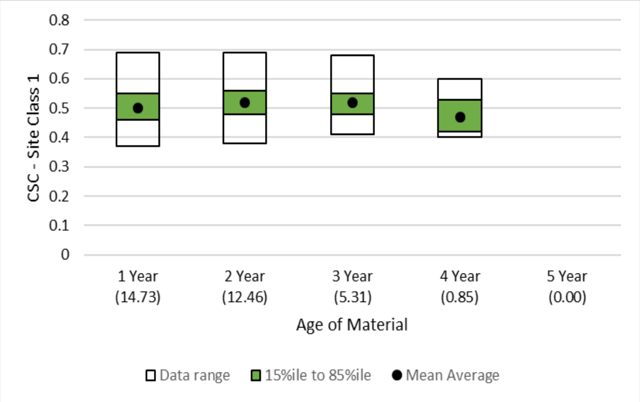


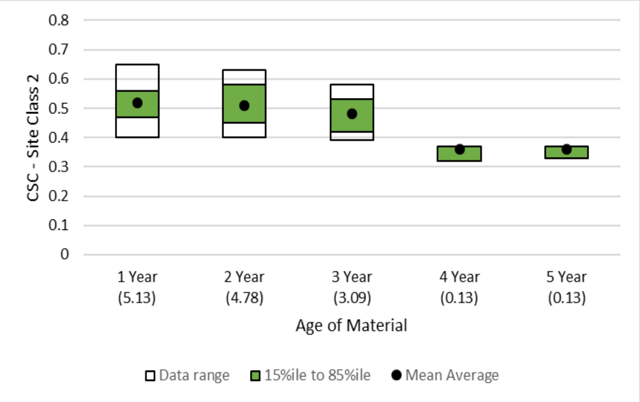


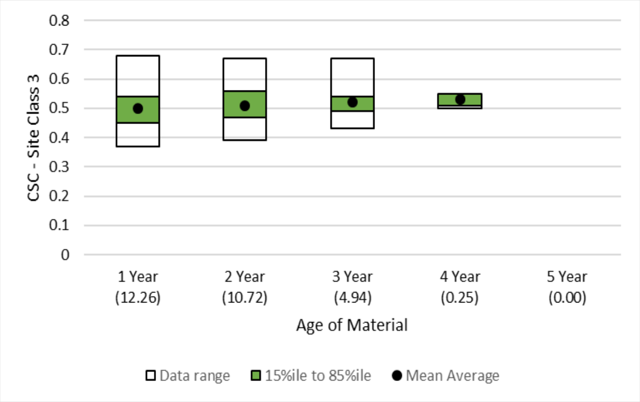


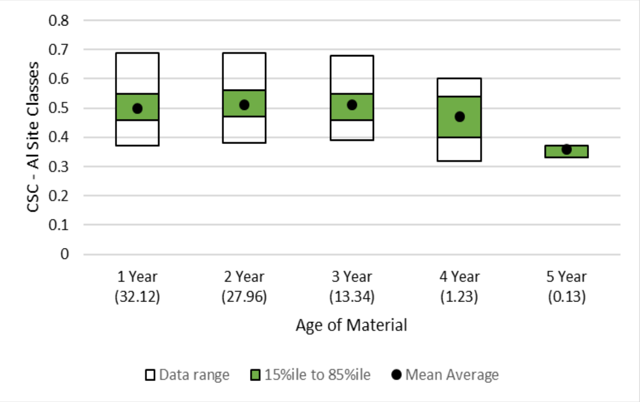


Mixture U

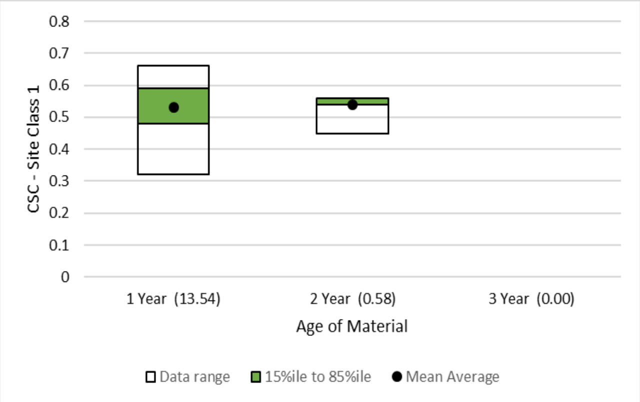


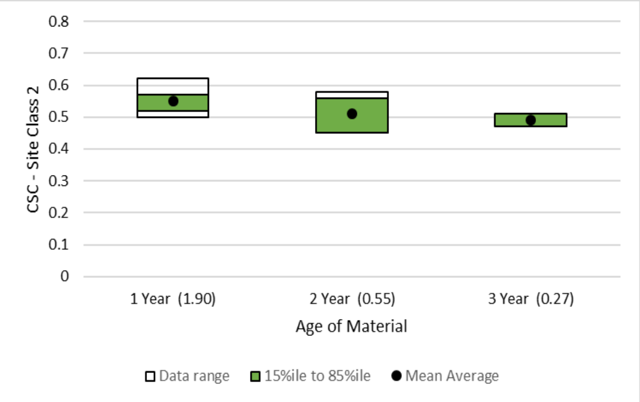


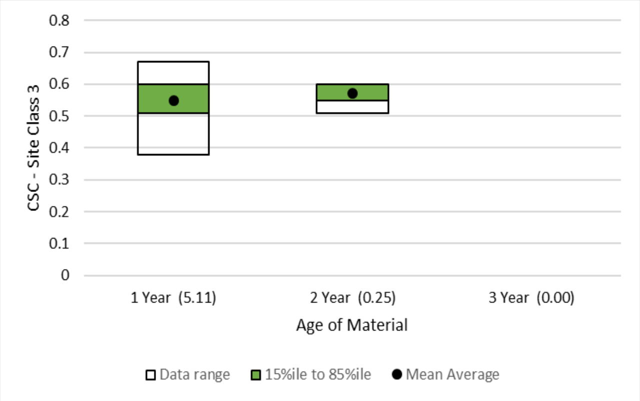


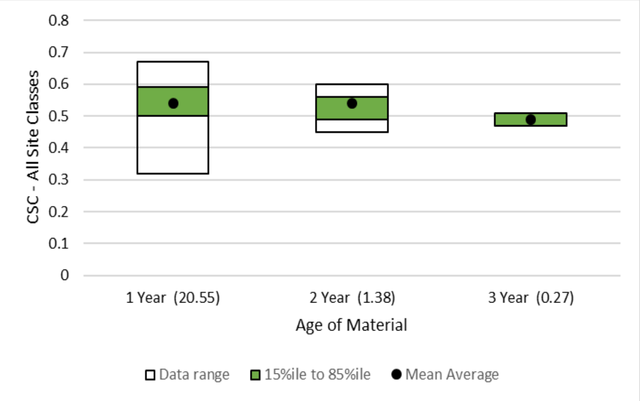


Mixture V

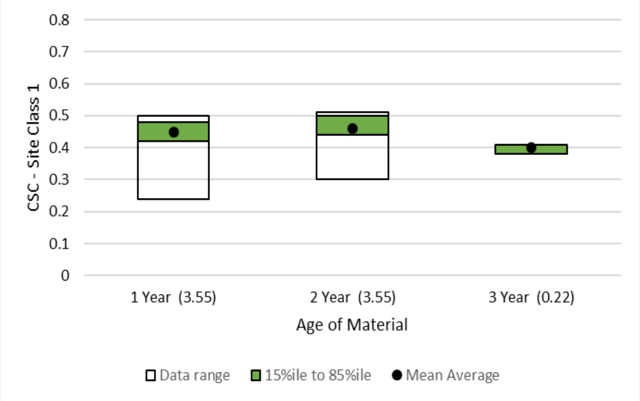








Mixture W



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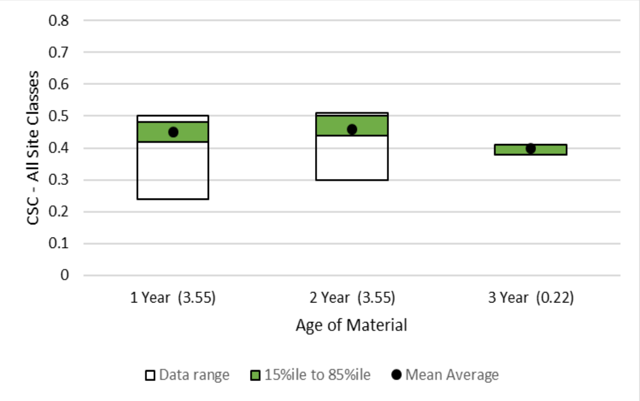

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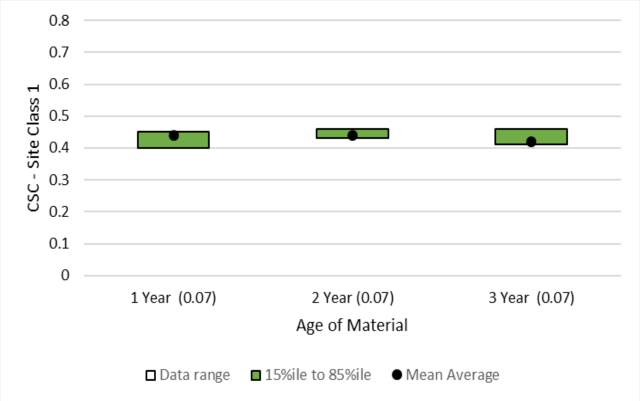

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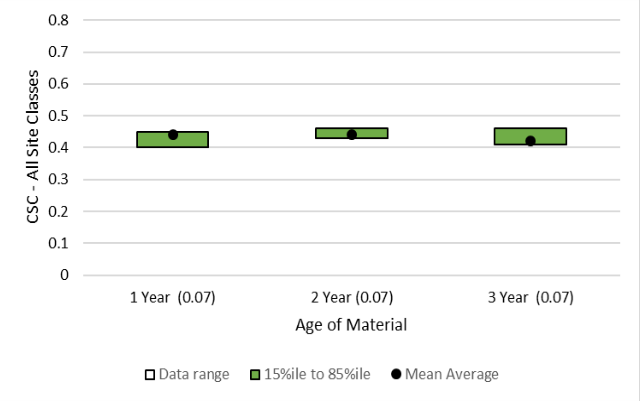

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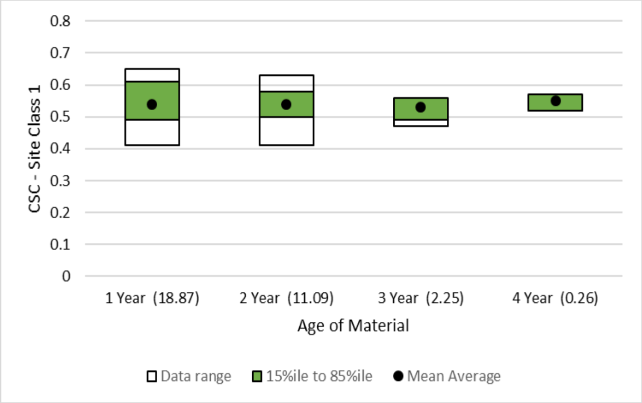

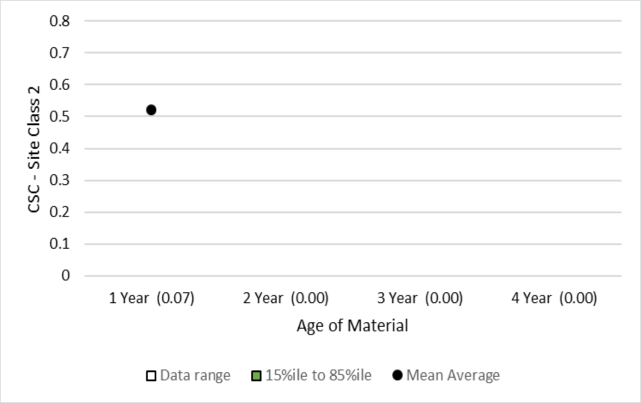

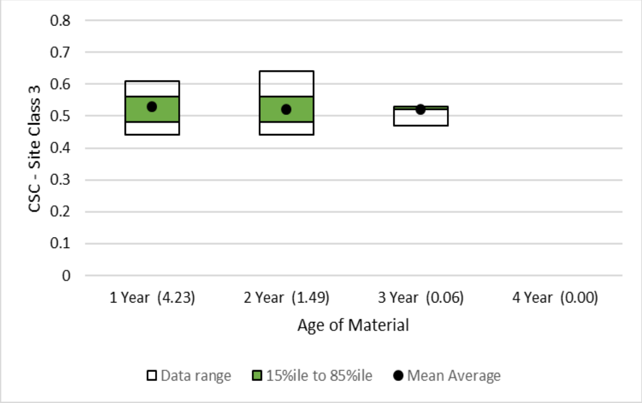

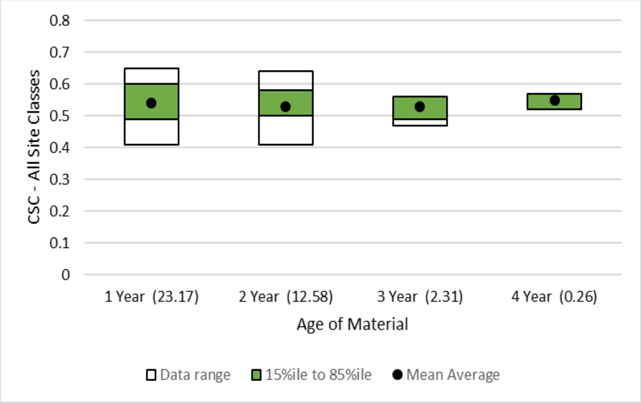

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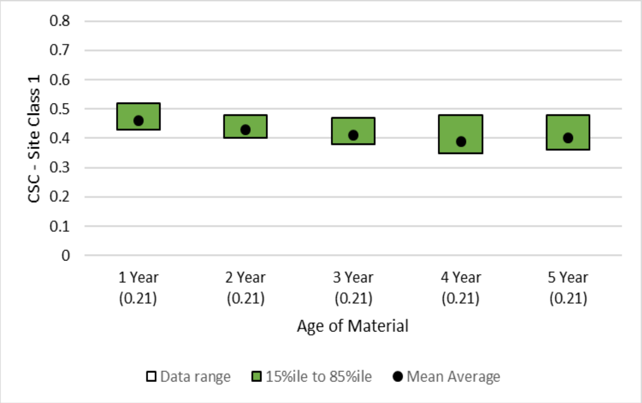

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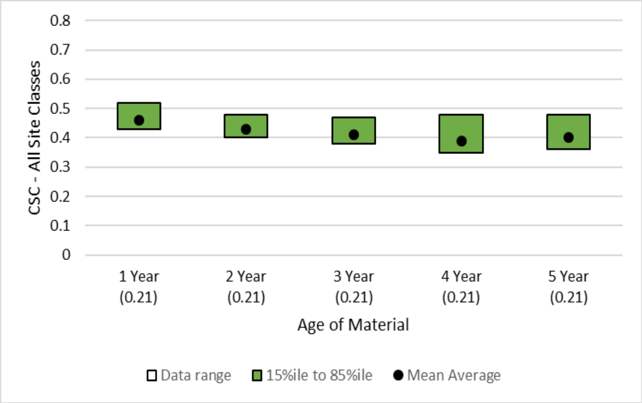

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