Basic oxygen steel slag as surface course aggregate: An investigation of skid resistance

Prepared for Viridis Ltd.

P G Roe

TRL Report TRL566

First Published 2003
ISSN 0968-4107

CONTENTS

Executive Summary

In the Autumn of 1999 Viridis (an ENTRUST Approved Environmental Body), instigated Project 001, Research And Specification Of Steel Slag As Wearing Course. This three-year project was carried out by TRL and was funded through the Landfill Tax Credit scheme. The work had the overall objective of providing a research base that would encourage the future use of steel slag in road surface courses.

Steel Slag is a solidified mixture of the residues from the high-temperature processes used to refine iron during steel production. The main type produced in the UK is a by-product of the Basic Oxygen Steel (BOS) process. About one million tonnes of BOS slag are produced annually at three steelworks, with about 4M tonnes stockpiled. Some material is used in various ways but there is scope to increase its use, particularly as an aggregate in road surfacings. Increasing use of BOS in this context has potential environmental benefits by simultaneously reducing the demand for tipping space and for quarried premium aggregate.

BOS slag has been used in road surface courses (previously called ‘wearing courses’) for many years. However, its use has been mainly in counties along the North East coast of England, usually on roads within the steelworks complexes or on local roads in their immediate vicinity. Several factors have limited more widespread use, including its higher density (which increases transport costs) and concerns over possible expansion *in situ*. Further, a lack of experience with its use may have discouraged engineers from accepting the material.

Aggregates for use in surface courses must have good resistance to polishing, as measured in the Polished Stone Value (PSV) test, so that designers can provide in-service skidding resistance appropriate to the type of site and traffic level. Experience on small-scale trials has suggested that BOS slag can deliver skidding resistance that is better than that indicated by its performance in the PSV test. However, the limited use of BOS slag in surface courses means that most information on its performance is anecdotal and independent systematic studies of the skid resistance performance of the material have been limited.

The present study included an initial literature review and some laboratory studies, but the main emphasis was to assess the skid resistance performance of the material in the road. This was achieved by monitoring seven different sites already laid with BOS slag aggregate in the surface course, together with a purpose-laid trial that directly compared two BOS sources with a 65PSV natural aggregate under heavier traffic.

The literature review revealed very little regarding skid resistance performance of BOS slag, reinforcing the need for this research. The laboratory studies, which included petrographic analysis and standard Polished Stone Value tests, showed that the main UK sources of BOS slag were generally consistent and similar to one another. It is thought that this is achieved by the homogenising effect of the various processes that the material passes through after initial tipping in the slag pits at the steelworks before being sold as a road aggregate.

The main finding of the laboratory investigations was that the standard PSV test is inappropriate for assessing the likely in-service skidding resistance performance of BOS slag. Values of PSV across the full practical range can be obtained, even from one source, that depend as much upon the test laboratory and procedures followed as on the underlying properties of the material. Also, the nature of the material has itself the potential to lead to varying results in the laboratory test that are not reflected in the road. Alternative test procedures could be developed, but these would then be unique to BOS slag, not necessarily comparable with the equivalent test for natural aggregates, and with no certainty of greater reliability in assessing in-service performance.

It was therefore concluded that where BOS slag is to be considered for use as a surface course aggregate, the decision should be based on known in-service performance in comparable situations rather than on the results of a PSV test. This principle is already permitted locally for natural aggregates.

Monitoring in-service skidding resistance with SCRIM has demonstrated that:

- On lightly trafficked roads, Mean Summer SCRIM Coefficient (MSSC) values well above the investigatory level can be achieved and maintained for many years.
- Levels of MSSC are consistent over long distances where traffic levels do not change.
- Under medium and heavy traffic, and in high-stress situations, MSSC levels vary, depending upon traffic action and the nature of the site (as occurs with natural aggregates).
- A direct comparison of two sources of BOS slag with a 65PSV natural aggregate under traffic of about 3000 CVD has shown very similar MSSC from the three types of material (0.45-0.50) after two full years in service.
- On one site, where the BOS slag was used in a surface dressing, unusually low values of MSSC were found, although they were still acceptable in that location. This may have been due to a combination of circumstances unique to that site.

A comparison with the requirements set out in the Design Manual for Roads and Bridges has shown that, overall, BOS slag provides MSSC values that would be expected from natural aggregates with PSV = 60. It is therefore concluded that BOS slag should be permitted for use on Trunk Roads and Principal Roads in situations where this level of PSV would normally be required. This would allow BOS slag to be used more widely in large-volume applications such as moderately heavily trafficked motorways and most dual carriageways, as well as many single-carriageway roads, with consequent environmental benefits.

Further work is now in hand to establish whether the material can be considered for use in an even wider range of circumstances.

1 Introduction

Steel Slag is a solidified mixture of the residues from the high-temperature processes used to refine iron during steel production. The main type of steel slag produced in the UK is Basic Oxygen Steel (BOS) slag. The existing stockpile, both at currently working and recently active steelworks, amounts to about four million tonnes; annual arisings, from three steelworks (Port Talbot, Scunthorpe and Teesport) are currently about 1M tonnes. In the UK, Blast Furnace Slag (BFS), a co-product of iron production has been used in road construction for many years and, for this reason, disposal of the material is not a major problem. Relatively small quantities (300,000 tonnes per annum) of slag are produced by Electric Arc Furnaces and most of this is used in roads.

Few large new road schemes are being built at present in the UK and those that are, are being designed for longer life. The bulk of material in the construction will remain in place for many years, but the surface course layer may be overlaid or replaced periodically during the life of a road in order to maintain adequate skid resistance. Many of today’s roads are laid with surfacings that use higher-quality aggregate throughout the surface course layer (sometimes referred to as the ‘wearing course’). This contrasts with the use of a thin layer of chippings spread on to a hot rolled asphalt surface (or in a surface dressing) that was commonplace on major roads during the last quarter of the last century. Therefore, a significant requirement for aggregates in this sector in future is likely to be in the surface course.

Basic Oxygen Steel (BOS) slag – sometimes called Basic Oxygen Furnace (BOF) slag – has been used in surface courses for many years. However, its use has been confined, limited mainly to roads within the steelworks complexes or on local roads in their immediate vicinity, particularly in counties along the North East coast of England. Several factors have limited the more widespread use of BOS slag in the UK. These include its higher density (which increases transport costs because a smaller volume can be carried in a single load) and concerns over possible expansion *in situ*. Further, a lack of experience with its use may discourage engineers from accepting the material.

A critical requirement of aggregates for use in surface courses is that they should have good resistance to polishing, as measured in the Polished Stone Value (PSV) test (BSI, 1989). This requirement exists to help designers to provide in-service skidding resistance appropriate to the type of site and traffic level. A result of the limited use of BOS slag in surface courses is that, hitherto, most information on its performance has been anecdotal. Independent systematic studies of the skid resistance performance of the material have been limited but experience on small-scale trials suggests that BOS slag can deliver skidding resistance that is better than that indicated by its performance in the PSV test.

If the use of BOS slag could be increased, there would clearly be a contribution to sustainable development. Apart from the obvious reduction in material tipped or put to landfill, if it could find widespread use as a surface course aggregate then there would be a corresponding reduction in the quantity of aggregate that would otherwise be quarried. Therefore, Tarmac Limited, with responsibility for disposal of all the BOS slag produced in the UK, has used the Landfill Tax Credit Scheme to fund a research project into the use of BOS steel slag in road surface courses.

The project was arranged through Viridis, (an ENTRUST Approved Environmental Body) and work began in the autumn of 1999, funded through the Landfill Tax Credit scheme. The project had the overall objective of providing a research base that would encourage the future use of BOS slag in surface courses. To achieve this, the project had two main components:

a An examination of the performance of BOS slag in the Polished Stone Value test, with a view to the possibility of developing improved test procedures and specifications that might facilitate its greater use.

b An evaluation of the skid-resistance performance on in-service roads of surfacing materials using BOS slag as the main aggregate.

The work was carried out in two main phases. The first of these provided an initial assessment of the material. This included:

- A review of current published knowledge of the use of BOS slags in surface courses.
- Some initial laboratory studies.
- The first results from a programme of skid resistance measurements on selected roads where BOS slag had been used.

The second phase of work involved some additional laboratory studies to further examine the material and test procedures. However, the primary focus was on extended monitoring of skid resistance performance. At this stage, a site that incorporated both natural aggregate and BOS slag from two sources was laid and added to the monitoring programme. This is the final report for the project.

2 Background review

As a precursor to the main practical work, a review was made of the published literature covering the use of steel slag in roads around the world. The literature review was supplemented by visits to two of the UK steelworks sites and discussions with the UK slag-handling contractor. It was found that at that date (autumn 1999) the bulk of the published work related either to Electric Arc Furnace (EAF) slag or to uses other than in the surface course. This section therefore summarises the findings of potential relevance to this project.

2.1 Production and general properties of BOS slag

The BOS process consists of placing scrap steel into a vessel and adding molten iron, from the blast furnace. Oxygen is then blown into the vessel through a lance until the correct temperature and correct properties are achieved. Through this process, unwanted elements are oxidised and these combine with a lime-based flux that is added to the vessel, to form steel slag. The steel slag is then separated from the molten steel.

In the UK, steel slag is received from the steel making process at temperatures exceeding 1300°C. It is then poured into pits where it is allowed to cool, with water sprays to accelerate the cooling. The solidified slag is dug out from the pits and transferred to a plant where residual ferrous material is removed for recycling. Material from the de-metalling plant is then passed to the slag-handling contractor.

Because it has a relatively high content of unspent lime (up to 8%), the finest material may be sieved out and used for agricultural purposes. Some is also utilised in rock wool insulation and in cement production. The remaining bulk material is essentially agglomerations or mixtures of the molten ore and limestone residues. The free lime in the material is deliberately hydrated before the product is sold as roadstone aggregate by subjecting the crushed and screened BOS slag to 12 months of natural weathering in managed stockpiles.

The literature suggests that the chemistry of the slag produced is likely to vary between sites of production, even where the source materials are similar. If this were true for UK sources, it might be expected that the expansion and skid resistance characteristics could also vary. Therefore, all major sources of UK BOS slag were included at some stage within the laboratory test programme and at least two were included in the road monitoring.

2.2 Skid resistance properties

There was very little information in the literature on the use of BOS slag in surface courses and in relation to its in-service skid resistance. There are some reports on the standard laboratory tests that relate to skid-resistance (such as polishing and abrasion).

Generally, Polished Stone Value (PSV) test results were reported as being in the range 55 – 65. Vesicular (often described as ‘honeycombed’) slag tended to have a better PSV than flat, glassy slag. Throughout the literature, BOS slag tended to have a low Aggregate Abrasion Value (AAV). This implies a lower rate of wear under traffic, potentially leading to a longer service life in surface courses than some other high-PSV materials. However, although resistant to wear, the literature suggests that slag with highest skid resistance tends to be weaker, with a low Los Angeles Abrasion Value and low crushing strength. An effect of this would be the possible crushing of the material under compaction.

Work in the UK by Ibberson *et al.* (1996) on EAF slag may also be applicable to BOS. That research team was particularly concerned with large variations in the PSV of EAF slag, within batch and over time. The variation within batch made characterisation of PSV difficult and the reduction of this variation was a target of the research. Among the areas of concern were variation in the particles sampled for the test and the effect of the operator selecting individual chippings from a 2kg sample to make the test specimens. It was found that a procedure that limited scope for ‘selective’ sampling led to an improvement in precision in the PSV test results for the EAF slag.

Work in Australia (Heaton, 1979) has suggested that steel slag has a surface which is chemically active, and that this may contribute to a skid resistance level in-service that is greater than that indicated by PSV results alone. Holliday (1998) said that, unlike natural aggregates, steel slag tends to maintain its characteristics with time, especially in wet conditions.

In the USA, the Missouri State Highway Department (Missouri State Highway Department, undated) constructed five ‘steel slag’ test sections on a road. These were tested for skid resistance over a period of between 2 and 4 years after laying, using an ASTM locked-wheel skid trailer (similar to the Pavement Friction Tester operated by TRL on behalf of the Highways Agency). It was concluded that steel slag gave ‘good results’ but there were insufficient appropriate data recorded to judge this performance in a way that could be related to UK BOS slag or road conditions.

2.3 Durability

As well as its polishing behaviour when used in surface courses, the literature includes some general coverage of the durability of steel slag used in roads. Durability of the slag is not a topic that was specifically included within the scope of this project. However, it is an aspect of the material that seems to have limited the use of the slag elsewhere and so it is covered briefly here.

A number of studies and various techniques have been used to investigate the chemical composition of steel slag. However, no reported work was found that linked this testing with the material’s skid resistance properties. Rather, the studies have been more focussed on investigating the causes of expansion in the steel slag.

In all the literature, free lime and magnesium oxide within the steel slag were identified as the sources of the expansion effects. Expansion can be limited by weathering of the steel slag in stockpiles after processing, as is the practice in the UK. Emery (1984) suggested expansion tests should be conducted on stockpiles before use. In contrast, Heaton (1996) found that expansion testing at elevated temperatures or pressures can cause expansion that will not occur under usual conditions. Therefore, testing associated with the disruption of individual particles was more indicative of a slag’s actual behaviour under normal environmental conditions.

Although expansion can be a concern where the larger particles of the material are used, such as fill or sub-bases, there were some papers indicating behaviours that could be a potential problem in surface courses. For example, Goldring and Jukes (1997) concluded that macro inclusions of lime were particularly liable to cause disruption. Dispersed free lime was gradually hydrated, but it was unclear whether this was a cause of instability; they suggested that the microstructure of the slag might be strong enough to contain this type of expansion. Alexandre, *et al.* (1993) agreed, blaming unassimilated free lime for expansion, and adding that magnesium-wusite with MgO contents above 70% in MgO rich slags were also a cause of instability.

Coomarasamy and Walzak (1995) found that free lime alone was not a good indicator of whether a slag was prone to excessive expansion, confirming the findings of Goldring and Jukes (1997) and Alexandre *et al.* (1993). They also found that calcium carbonate was deposited on the slag surface during exposure to humid conditions, forming a weak layer that would be disadvantageous for an asphalt aggregate interface, particularly if this occurred following mixing.

EAF steel slag was used in Canada for a number of years but, in 1991, a moratorium on its use was imposed following the premature deterioration of the surfacings (Hajek and Bradbury, 1995). The mode of deterioration was random cracking throughout the surface, some cracks extending deeper than the surface course. The cause of the cracking was identified as the expansion of the steel slag. Ravelling would then occur followed by the formation of potholes. The pavements needed to be rehabilitated at 7 to 10 years (cracking first being observed at around 4 years). The pavements would have been expected to last for 15 to 18 years if built from natural aggregates. Although records were not kept, it is possible the slag used in the original trials was weathered for a year or more. However, as demand grew the weathering period was reduced and may have been only ‘a few days’ for later works (Bradbury 2000).

2.4 Issues relevant to the project

Some important issues of potential relevance to this project emerged from the literature. They can be summarised as follows:

- Even when the raw materials entering the steel making process are similar, different plants can produce slags with different characteristics and the properties of material from one source might not necessarily be typical of another. Because of this, it cannot be assumed that the characteristics of UK BOS slags would be the same as foreign slags. Similarly, it was not assumed that slag from different UK sources would necessarily be the same as one another. Therefore, all the main UK sources of slag were included in the initial investigations.
- BOS slag has generally been reported as having a PSV in the range 55 to 65. There were claims in the literature that steel slag provides better skid resistance than its PSV would suggest, but these had little evidence supplied to back them. An important part of this project therefore, was the practical investigation of skid resistance performance of road surfacings containing steel slag from UK sources on in-service roads.
- Studies on testing EAF slag showed that PSV can vary within batch and over time. Also, variability in PSV could be caused by the operator being selective in choosing the particles to include in test specimens. Altering the method to remove some of the operator judgement in selecting material improved precision. It was thought possible that BOS slag would show similar effects and so this issue was considered in the programme of laboratory studies.
- The expansion problem is likely to be very small in surface courses. The bulk of the material is sealed in an asphalt layer and the weathering procedure adopted by the handling contractor should virtually eliminate any risk of surfacing failure from this cause. However, the formation of chemical layers on the surface of the particles could be a potential issue for laboratory tests and performance on the road.

Many countries have used steel slags in surface courses successfully over long periods but these do not necessarily have the same stringent requirements for skid resistance as the UK and there are no clear data on its skid resistance performance. Although Canadian experience found that expansion of steel slag caused premature deterioration of the surface course, this does not appear to have been an issue in other countries, such as Australia. Discussions with UK local authorities that have used BOS steel slag as a surface course aggregate have found no indication of this problem occurring in Britain.

Initially, it was envisaged that the laboratory work for this project would cover three aspects of BOS slag produced in the UK, namely: microscopy (to investigate potential for formation of microtexture), the behaviour of the material in the PSV test and chemical properties. However, following this review, and an assessment of comprehensive chemical data provided by the slag producers, it was decided that it would not be worthwhile pursuing this aspect of the investigation. Instead, the resources were allocated to allow more-extensive road tests later in the project and the laboratory work, described in the next section of the report, was concentrated on PSV testing and microscopy.

3 Initial site and laboratory investigations

3.1 Site visits and sampling

In recent years, production of BOS slag in the UK has been at four main centres: Llanwern[1] and Port Talbot in South Wales, Scunthorpe in North Lincolnshire and Teesport, near Middlesbrough on Teesside. Most of the BOS that has been utilised in surface courses on public roads has been from Scunthorpe and used in that general area.

As a precursor to the laboratory work, an assessment of the ways in which the slag is processed prior to sale for use in road surface courses was made. This helped to determine the pattern of tests that would be included in the study and hence the sampling programme required. For this purpose, both Llanwern and Scunthorpe were visited to view the production process and the weathering regimes employed.

a Slag handling at the sites

At both the sites visited, the slag is weathered for twelve months in open-air stockpiles before being deemed ‘ready

---

[1] *The plant at Llanwern was active when this project began but shortly after the laboratory studies phase of this work it was announced that, the works would be closing. Although Llanwern no longer produces BOS slag, a considerable stockpile remains at this location.*

for sale'. At Llanwern, each month's production was crushed and graded and stored in a separate stockpile, each up to 4-5m high. This allowed samples to be taken from material of a specific age. A similar arrangement was also in use at Port Talbot. At Scunthorpe, the size of the stockpiles was much greater, up to 10m high, and the age of the material was therefore not known exactly. However, the date of closing of each stockpile was recorded, so it was known that all material within a specific stockpile was of at least a certain age. It is understood that, since these visits, the stockpiling arrangements at Scunthorpe have also been modified to reflect the practice in Wales.

b Sampling regime

In the light of observations during the site visits, it was decided that the laboratory studies should take some account of the weathering process. At Llanwern, where the stockpiling arrangement made it possible, samples of different ages were taken to investigate possible changes over time. In all cases, samples were taken from different points in the stockpiles in order to observe whether the expected homogenisation during processing had occurred. Bulk samples were gathered according to the sampling schedule in Table 3.1. All 'ready for sale' material had been weathered for at least 12 months. Later in the project, samples from Teesport were also supplied.

Table 3.1 Samping schedule

Site	*Sample No.*	*Quantity*	*Material type*
Llanwern	1-3	3 x 200kg	Ready for sale
	4-6	3 x 60kg	Fresh material†
Llanwern	7	1 x 50kg	Ready for sale
	8	1 x 50kg	Weathered for 12 months (Before further processing)
	9	1 x 50kg	Weathered for 9 months
	10	1 x 50kg	Weathered for 6 months
	11	1 x 50kg	Weathered for 3 months
	12	1 x 50kg	Fresh (0 months) material†
	13	1 x 50kg	Weathered for 12 months (Before further processing)
Scunthorpe	14-19	6 x 200kg	Ready for sale
Port Talbot	20-22	3 x 60 kg	Ready for sale
Teesport	23-25	3 x 60 kg	Ready for sale

† *'Fresh material' was taken from stocks of newly delivered slag that had not been weathered. Samples 1-3 and 4-6 were taken from different points within the relevant stockpile. Sample 13 was taken from the middle of the stockpile at its base, the point furthest from the edge of the stockpile, to investigate whether weathering occurs throughout the stockpile. All other samples were taken from close to the edge of the stockpile, having removed the crust that forms on the stockpile surface.*

For the laboratory test programme, it was assumed that the ready-for-sale material had been fully weathered and that therefore no further significant changes would be expected following sampling. These samples were kept for further testing throughout the laboratory regime. However, samples of a specific age were tested close to the time of supply and were then disposed of, on the basis that the weathering regime in the laboratory was likely to be different from that within the stockpile.

3.2 Petrographic examination

A petrographic examination of particles from the various samples was made in order to identify any characteristics that might contribute to skidding resistance. In particular, the examination considered the likelihood of the material developing microtexture on the surface of the particles and the ability of the material to maintain that microtexture under polishing action.

A variety of particles from each of the main samples was examined to assess their general characteristics. A sample was taken from each bulk sample of the material, dried and encapsulated in resin for ease of handling. Thin sections for petrographic analysis were then cut from the resin block containing the slag particles. Most of the slag particles in the analysis were of nominal 10mm size. This size was chosen because it is the size used in the PSV test and is common in many asphaltic surfacings, particularly modern proprietary materials.

c General observations

The smaller (10mm) particles showed a variety of shapes and surface textures. However, it was clear that the particles could be divided broadly into two main groups; cubic particles with little surface texture and irregular, vesicular particles. Examples of both types were included in the thin-sectioning process. In addition, a very small number of smooth, almost spherical, particles were found. They resembled cooled droplets of metal and the thin sections proved to be completely opaque, suggesting that they were mostly metal. Examples of all these types of particles have also been observed in the road surfacings studied.

It was expected that particles of BOS slag would vary considerably in structure because of the nature of its production. Some large pieces of slag were cut through to reveal their internal structure. It was found that the structure could vary from a highly vesicular, frothy mix to a smooth homogenous mass over a distance of only millimetres within one piece. The same piece could contain inclusions of metallic iron ranging in size from microscopic to almost a centimetre in diameter. It is probable that this change in structure leads to the two main particle shapes observed in the smaller-sized material. The closest analogous natural material is the ejecta from volcanoes, where the external surfaces of the molten material are flash frozen while the internal material cools more slowly.

d Analysis of the thin-sections

The analysis focussed on three main areas:

- Component minerals of the steel slag.
- Textural determination including voids.
- Changes relating to age/weathering of the slag.

To a greater or lesser extent, all the particles had an overall red/orange appearance resulting from the large quantities of iron present in the material. Apart from some minor differences in particle distribution, all three slags appeared quite similar under the microscope. The slag particles generally fell into one of three categories.

The first group of slag particles had a crystalline texture that varied from coarse (0.3mm) crystals to a very fine texture in which individual crystals were so small as to be indistinguishable under the magnification used. Often, these particles showed a wide range of crystal sizes. This occurs where the crystals have formed slowly, developing out of the molten slag and allowing differentiation according to melting point for the minerals, with the interstitial regions filled with a very fine-grained sludge of mixed materials.

The second group had a largely opaque base material, with small (0.05mm), discrete crystals of a mineral that was highly birefringent (ie, showing bright colours under polarised light). In these particles the crystallisation process was interrupted, with only the highest melting point minerals having time to crystallise out before the rest cooled to an amorphous mass. The third particle type was of a largely glassy material that may or may not have devitrified to give thin feathery structures.

The voids within the slag particles also varied, depending on the stage of the melting and cooling process in which they were formed. The size of the voids was not related to the texture of the slag; voids of all sizes occurred in all of the slag particles. However, the boundaries of these voids and their general shape were influenced by the crystalline texture of the slag. Fine-grained and glassy slag particles tended to have larger, discrete, circular voids with smooth boundaries; in some cases the thin zone around the boundary is even more fine-grained than the rest of the particle. Course-grained slag particles had voids that could be more irregular and their boundaries often followed the margins of crystals. Particle boundaries (ie, breaking surfaces) tended to follow crystal boundaries for the coarse-grained particles, but tended to be smooth for the fine-grained and glassy materials.

The slag particles had a distinct outer layer. This layer was thicker and more noticeable on the Llanwern particles than on those from Scunthorpe. It was also found on the Port Talbot material. Unlike the cores of the particles, this layer was not stained by iron, suggesting that it is a post-processing feature. This feature was also found filling voids and cracks that had been open to the atmosphere.

A likely explanation of this is carbonation, where free lime within the slag reacts with the carbon dioxide in the atmosphere to produce calcium carbonate (the possibility of this occurring had been noted in the literature review). The carbonation was seen filling cracks within slag particles but it is unclear whether this was an expansive reaction leading to breaking open of the slag particles. The carbonation was thickest on the oldest of the slags and, on the material sampled from the base of the stockpile, was up to 0.2mm thick. Virtually no carbonation was evident on the fresh material but the slags of intermediate age did not show a clear succession. The appearance of this layer on the sample from the base of the stockpile would suggest that weathering is having an effect through the entire depth of the stockpile.

The material from Llanwern that was examined was uncrushed or graded and therefore was likely to have laid undisturbed after stockpiling. On the other hand, the Scunthorpe material had been crushed and graded following weathering, and so the carbonation layer may have been removed during the processing. This could explain the difference in the thickness of the layer noticed between the two sources.

e Possible influences of petrography on polishing or skid resistance

The examination of the BOS slag under the microscope showed some variation in the crystallographic textures available. However, the generally fine crystals and the lack of robust silicate minerals suggest that its behaviour under polishing is likely to be comparable to a similar basaltic or porphyritic material. This suggestion is borne out by the range of measurements of PSV obtained from the various samples and particle types (see Section 3.3). These fell between the values expected for a porphyry (PSV 47) and a trachyte rock (PSV 57).

Particles of the two main types of shape (regular cubic and the irregular particles) were observed to have different structures, the regular particles having a larger grain size than the irregular. This may affect the *in situ* microtexture and hence, the friction properties of the particles.

A secondary observation may also indicate a possible issue for longer-term durability of slag particles in surface courses. During one of the early PSV test runs, as occasionally occurs, the resin base of one specimen cracked so that it broke loose from the test wheel. This caused additional stresses on the remaining specimens, which happened to have been made from the Llanwern slag. The carbonated layer on the surface of that material failed under stress resulting in almost total chipping loss from the PSV specimens. It might be that this layer causes adhesion difficulties in the upper layers of asphalt materials. However, the processes of preparing the slag aggregate and mixing the asphalt may well reduce any risk by removing the carbonation. This appears to been the case with the grading of the Scunthorpe material.

3.3 Measuring the PSV of BOS slag

a Standard PSV tests

The PSV test has been in use for many years as a means of assessing the suitability of aggregates for use in surface courses. The test precision is generally understood and specifications that utilise PSV have been in place since 1976. The test and associated specifications were based primarily on research using natural aggregates. However, experience has shown that aggregates do not always achieve in practice the skidding resistance that their PSV test results would suggest (Roe and Hartshorne, 1998). Recent changes to the Highways Agency requirements (HD36/99, DMRB, Vol 7 Section 5) have reflected this. They also include a provision that allows an aggregate to be used even if the PSV is lower than the minimum advised, providing that there is evidence of satisfactory performance in a comparable situation. (Specifications used by UK Local Authorities are largely derived from HA recommendations).

Materials such as BOS slag are still governed by the requirements of these specifications. A wide range of results has been reported in the literature and the PSV of BOS slag has been viewed as being more variable than that of a natural aggregate. If use of the material is to be increased, engineers must be confident in selecting it. For this reason, it is important to understand both how the material behaves in the test and how it performs as a surfacing aggregate in providing in-service skidding resistance.

Therefore, an initial investigation was made of the PSV of samples obtained from three of the main sources of BOS slag. A series of standard PSV tests examined the PSV of slag at different ages and from the three sources; the results are given in Table 3.2, rounded to the nearest integer.

Table 3.2 Standard PSV results

Source	*Sample*	*PSV*	*Average*
Llanwern	1. Ready for sale	49	50
	2. Ready for sale	52	
	3. Ready for sale	48	
	4. Fresh	50	49
	5. Fresh	48	
	6. Fresh	50	
Scunthorpe	14. Ready for sale	47	49
	15. Ready for sale	47	
	16. Ready for sale	48	
	17. Ready for sale	53	
	18. Ready for sale	48	
	19. Ready for sale	49	
Port Talbot	20. Ready for sale	53	51
	21. Ready for sale	51	
	22. Ready for sale	50	

The results are remarkably consistent, with the variation between individual samples being of a similar order to the repeatability of the PSV test. In particular:

- The results from different sampling points in the stockpiles were very similar, supporting the argument that processing homogenises the different batches of slag.
- There was no apparent difference in PSV between the weathered and unweathered material at Llanwern.
- There was no measurable difference in PSV between the three sources, although they are in different parts of the country.

Some workers have reported that soaking the specimens can affect results, particularly with EAF slag. In order to explore this, after the standard test measurements had been made, all specimens from Llanwern and Scunthorpe were soaked overnight and re-tested with the pendulum tester. No significant changes in results were found.

b Further testing

The results from the standard PSV tests, although consistent, were at the low end of the range that is usually expected from BOS slag. Although the test procedure on the British Standard had been followed, it was noted that there was nonetheless scope for interpretation in practice that might affect the results obtained.

In this case, the operator was faced with the distinct particle types, as described earlier. For consistency, he decided that the intentions of the specification could best be achieved by selecting the regular cubic particles for the PSV test specimens. However, this meant that no ‘irregular’ or metallic particles were tested. In order to assess whether this was a possible factor for further attention, a particle count was conducted to establish the relative proportions of the two types of particle in the material.

Two samples, each approximately 1kg in mass, were taken from the 10mm sized material from Llanwern and Scunthorpe and separated into the two particle types (by visual judgement). The resulting groups were weighed and the proportion of the ‘irregular’ shaped particles calculated, as given in Table 3.3.

Table 3.3 Proportion of ‘irregular’ particles in the samples

Source		*% by mass*
Scunthorpe	A	19
	B	15
Llanwern	A	26
	B	13
Average		18

It was decided that further PSV tests were necessary to investigate the effect of the presence of irregular shaped particles on the PSV result. Therefore, from the remaining ready-for-sale material from Llanwern and Scunthorpe, sets of PSV specimens were prepared containing proportions of particles as follows:

- Irregular particles only.
- A 4:1 mixture of regular to irregular particles (in an attempt to reproduce the proportions estimated from the particle counts).
- A random selection from a riffled-down sample of all-in material.

Subsequently, specimens from Port Talbot were prepared using random selection.

The results of these tests are given in Table 3.4, which includes the corresponding results from Table 3.2 for ease of comparison.

Table 3.4 PSV results with different proportions of particle type

Specimen particle type	*Llanwern*	*Scunthorpe*	*Port Talbot*
Regular only (results of original tests included for comparison)	50	49	51
Irregular only	54	57	Not tested
4:1 regular to irregular	54	53	Not tested
Random selection	56	54	53

Because there had been a time lapse between the two groups of tests for Llanwern and Scunthorpe, selected specimens of both types were re-tested with the pendulum tester at a later date; these tests confirmed the original assessment.

The results from the three sources were again similar but, significantly, specimens containing ‘irregular’ particles showed an increase in the PSV result. Although it was not investigated further in this project, there may be a number of explanations for this effect. Differences in the granular structure of the material may contribute to different responses to the polishing processes. Alternatively, the different particle shapes could influence the response of the pendulum slider as it passes over the specimens during the measurement stage of the PSV test and thence give rise to different friction values. The presence of irregular particles may also influence skid resistance found on the road.

c Examination of commercial PSV test specimens

It is clear from the TRL tests that widely varying PSV results can result simply from the operator’s choice of particles for the test specimens. This finding had been foreshadowed by the work on EAF slag found in the literature review.

In discussion with the slag handling company, it emerged that they suspected that something similar was occurring in commercial testing. They were able to provide TRL with examples of PSV specimens taken from an exercise in which samples from the same batch of slag had been sent to four test houses for simultaneous PSV tests. Some of the test specimens had been returned and all of them had been pendulum tested by the supplier’s own in-house laboratory. TRL examined these specimens and, after soaking overnight, tested them with a pendulum tester for further comparison.

Table 3.5 summarises the various measurements, including those reported by the test houses that made the specimens. The test houses have been given the code letters A-D; laboratory S is the slag handler’s facility. The individual control-stone specimens that were associated with each test were not available so, for comparison purposes, the uncorrected pendulum results have been used. However, it can be seen that the reported PSV result (i.e. corrected for control stone) for each of the four test houses is within the range of the uncorrected specimens, indicating that the correction effect would have been small.

The range of PSV results reported by the four test houses is very large, from 53 to 66. This exceeds the reproducibility of the test by a significant margin (BS812 Part 114 gives the reproducibility of the test as 5 units). The results from S and TRL are lower than those obtained by the test houses, and TRL was lower than S (these differences would be reduced by application of the control stone correction). No attempt has been made to address this matter here since this kind of testing is not normal practice and may simply reflect a change in the character of the specimens after some time in storage. However, the important point is that *the repeat pendulum tests by both Laboratory S and TRL confirmed a wide range between the four test houses.*

Table 3.5 Comparison of commercially-produced PSV test specimens of BOS slag

Test house	*Reported PSV*	*Range of individual specimens (uncorrected)*	*Specimen identifier*	*Uncorrected pendulum results*	
				Laboratory S	*TRL*
A	65	64.7 – 65.7	10a	60	57.7
B	53	49 – 52.5	1	51	50.7
			2	59.3	54.3
C	66	63.3 – 67.3	1	57.3	55.7
			2	56	55
			3	58.7	54
			4	60	55
D	58	58.3 – 59.3	9	54	50.7
			9a	53.7	50.3
			10	56.3	52.3
			10a	52	48.3

So great a difference between results could imply that the material was very variable within the bulk sample. However, the earlier TRL tests have shown that this is unlikely and the range of individual results for each laboratory was reasonable. A much more likely explanation is that the variation results from differences in the ways in which the specimens had been made up.

On close examination of the individual PSV specimens, it was clear that they had been produced in different ways by each laboratory, albeit consistently within each laboratory. The differences were in the way in which particles had been chosen and arranged within the mould. Laboratories B and C had both produced samples that were similar to TRL’s original ‘regular particle’ PSV specimens. The specimens from laboratory C, however, were made with more definitely cuboid particles than those chosen by the operator at laboratory B. Laboratory D had chosen ‘irregular’ particles only for their specimens. Laboratory A had been meticulous in selecting very cubical stones, and had arranged them in ordered rows; further, they appeared to have been cleaned. The samples are illustrated (approximately actual size) in the following photographs.

Figure 3.1 shows a normal specimen of control stone and Figure 3.2 shows a BOS sample made from ‘regular’ particles (as used in the TRL ‘standard’ tests). Figure 3.3 shows a specimen with a mixture of regular and irregular BOS particles from the TRL tests. Figure 3.4 shows a specimen from one of the commercial laboratories with ‘regular’ particles, while Figure 3.5 illustrates a sample with a high proportion of ‘irregular’ particles. Lastly, Figure 3.6 shows the regimented arrangement of particles from Laboratory A.

All of these specimens had been made in accordance with the same written standard and complied with the written requirements. However, they differed considerably in the way in which the words were interpreted (especially laboratory A) and, in the process, features were introduced into the specimens that could affect the pendulum measurements. For example, tighter packing of individual stones reduces the number of exposed edges that can catch

Figure 3.1 PSV specimen – control stone (TRL)

Figure 3.4 PSV specimen – (Laboratory B, reported PSV=53)

Figure 3.2 PSV specimen – BOS ‘regular’ particles (TRL, reported PSV=50)

Figure 3.5 PSV specimen – (Laboratory D, reported PSV=58)

Figure 3.3 PSV specimen – BOS ‘random’ particles (TRL, reported PSV=56)

Figure 3.6 PSV specimen – (Laboratory A, reported PSV=65)

the pendulum slider whereas aligning particles increases this possibility.

These test results, together with other factors, suggest that the standard PSV test may not be an appropriate tool for assessing the polishing characteristics of BOS slag in relation to its performance on the road. This matter is discussed further in Section 6.1.

4 Skidding resistance measurements – sites and programme

In the past, the use of some aggregates could stand or fall on their PSV test results because this was the main criterion by which they were judged in relation to skidding resistance. However, the introduction of the UK Skidding Standards in 1988 and the changes to the DMRB in 1999 have led to a focus on in-service performance rather than relying entirely on expectations based upon laboratory testing. This has given engineers greater freedom, in principle, to use an aggregate that is known to provide satisfactory performance in a particular situation although its PSV may be lower than the 'default' advice suggests.

However, if engineers are to be encouraged to make wider use of BOS slag, they must be confident that the surfacing will deliver the skid resistance that they need. Therefore, it is essential to understand what levels of skidding resistance can be provided by BOS slag in surface courses on the road network.

The purpose of this stage of the project was to make an objective assessment of the performance of BOS slag on in-service roads. To do this, a number of sites were identified where BOS slag was already in use in surface courses and the skid resistance was measured, initially as a 'snapshot' and then with a more extended monitoring programme.

4.1 Sites included in the SCRIM monitoring programme

Seven sites were chosen for initial inclusion in the programme of skid resistance measurements. They were selected from a number of locations suggested by Tarmac and all were in the North East of England. (This was an inevitable constraint because there had been no history of use of BOS slag for road surfacings elsewhere in the UK, even near to the main production points in South Wales.)

Sites within the steelworks complexes were deliberately omitted. These could have offered surfacings of some considerable age but the type of traffic, together with unusual quantities of dust and other detritus in these areas, would make comparison with conditions on the public road network inappropriate. Although some minor roads were considered, these were also excluded because the traffic on such sites, and hence the aggregate requirements, are relatively undemanding. In such situations, steel slag would not necessarily be in direct competition with higher-performance natural aggregates.

The sites were chosen to provide a range of surfacings and conditions, subject to the practical limitations imposed by the scale and timing of the testing programme. They comprised a mixture of short sections of trial surfacings, routine resurfacing and newly constructed roads. The surfacings ranged from very recently laid material through to a section that had been in service on a principal road for some twenty years.

These surfacings had been laid, or were planned, well before the project started. Most were on relatively lightly trafficked roads and the BOS slag used came from the same source. Useful though they would be in the assessment process, it would also be important to assess the relative performance of BOS slag from different sources, ideally under the same conditions, and under heavier traffic. Therefore, in order to assist with this, two trial sections were laid on the A66 in Middlesbrough (which was already being resurfaced) in August 2000, with the assistance of Tarmac and Middlesbrough Borough Council.

This section of the A66 is a relatively heavily trafficked all-purpose dual carriageway that takes traffic out of Middlesbrough westwards towards the A19 and Darlington. The road at this point has three lanes, with lane 1 formed by the on-slip from the A1085 which then becomes the off-slip for the A19. Through and overtaking traffic on the A66 uses lanes 2 and 3.

Sections of a proprietary surfacing using BOS slag coarse aggregate were laid adjacent to each other on the westbound carriageway. Two mixes were used: one containing Llanwern BOS slag coarse aggregate and the other using BOS slag from Scunthorpe. Control sections, using the same gritstone coarse aggregate that had been used on an adjacent section of the A66, were laid upstream and downstream of the steel slag sections. For technical reasons blast furnace slag (BFS) fines were used in these mixes. For the Llanwern section, Llanwern BFS fines were used but the Scunthorpe BOS and crushed rock sections used BFS fines from Redcar which, it is understood, is usual practice for material of this type laid in the North East.

Laying parallel lengths of the same materials across all three lanes enabled simultaneous comparisons of performance of the materials under different traffic levels. The control sections at each end of the site formed part of the general resurfacing of this stretch of the A66 and used a PSV 65 natural aggregate. This provided a general check on the behaviour of the steel slag in comparison with a high-PSV aggregate known to give acceptable performance on this type of road.

Table 4.1 contains a brief description of the eight sites included in the SCRIM monitoring programme. Where possible, an indication of the traffic level, expressed as commercial vehicles per day (CVD), is given, based either on data from the local authority or the author's estimate.

4.2 Measurement programme

The skidding resistance on each site was measured using SCRIM (Sideway-force Coefficient Routine Investigation Machine). SCRIM is the standard device used to monitor skidding resistance on the Trunk Road network throughout the UK for comparison with the national Skidding Standards. It measures skidding resistance in terms of the ratio between the sideways-force developed on an angled test wheel and the vertical load acting on the wheel, the measurements being known as 'SCRIM Coefficients'). Results always refer to wet roads: SCRIM carries its own

Table 4.1 Summary description of sites included in SCRIM monitoring programme

Site code	*Location*	*Description*
A	A46 Nettleham Heath	A lightly-trafficked (<400 CVD) rural principal road, just north of Lincoln. Single carriageway with minor junctions and easy bends. The surface is a ‘temporary’ basecourse using BOS slag coarse aggregate that was laid in 1980 and never overlaid. Measured in both directions.
B	A46 Welton Hill	On the same road as Site F, a few miles further north with rather less traffic (<200 CVD). The site is located in a series of bends, with a minor junction at its southern end. This was laid as a trial in November 1996. Three experimental sections using BOS slag coarse aggregate (120m ‘Steelmac’ with 10mm aggregate; 100m ‘Steelmac’ with 20mm aggregate and 130m of 20mm basecourse) plus 250m of HRA with 62 PSV natural aggregate chippings laid at the same time. Measured in both directions.
C	A156 Drinsey Nook	A very-lightly trafficked (<150 CVD) single carriageway Class A road linking the A57 with the A1 to the west of Lincoln. A 1.7km length of racked-in surface dressings laid in the summer of 1997, experimenting with different combinations of BOS slag or granite as coarse aggregate and/or racking chips. Measured in both directions, together with an adjacent section of hot rolled asphalt.
D	A1031, Humberston Road, Cleethorpes	A single-carriageway, gently curving, 40mph suburban A-road. 900m of BOS slag Stone Mastic Asphalt (SMA) laid late summer 1998, together with an adjacent 400m of conventional rolled asphalt. Traffic level estimated as <250 CVD.
E	A15 Barnetby to Barton on Humber	A lightly trafficked (estimated as <750 CVD) rural dual carriageway A-road. 11km of continuous proprietary surfacing using BOS slag coarse aggregate, laid in January/February 1999. Measured northbound in Lane 1 only.
F	A689 Wynyard, west of Hartlepool	A lightly trafficked (approx. 750 CVD) rural dual carriageway A road. 1.2km of BOS surfacing laid in September 1999, approx. 2 km of adjacent older surfacings. Measured westbound in both lanes.
G	A16 Peaks Parkway, Grimsby	A single carriageway urban distributor road built on the line of a former railway, carrying medium levels of heavy traffic (approx. 1000-1250 CVD). Completed in late spring 1998. Straight, with both de-restricted and 30mph limit sections. The 30mph stretch has 3 traffic-light controlled junctions and a railway underpass section. Approximately 4km of proprietary surfacing with BOS coarse aggregate; the junction approaches were inlaid with sections using a >65 PSV gritstone aggregate instead of BOS slag. 1.6km of adjacent old road. Measured in both directions.
H	A66 Middlesborough	A heavily trafficked (>3000 CVD) 3-lane dual carriageway. Proprietary surfacing with sections using BOS coarse aggregate from two sources, laid across all three lanes in late summer 2000. 350m Scunthorpe BOS, 250m Llanwern BOS. 65 PSV natural aggregate control sections (200m and 100m), also newly laid, at each end. Measured in all lanes.

water supply to wet the road just in front of the test wheel (Hosking and Woodford, 1976, British Standards Institution, 1999).

Skidding resistance varies with the time of year and is generally lowest in the summer and early autumn, when the roads are dry and the aggregates have been polished by traffic. During the winter, when roads are wetter and the action of frost and grit has a coarsening effect, there is generally an increase in measured skidding resistance. For this reason, when results are to be compared with the requirements of the skidding standards, a mean summer SCRIM Coefficient (MSSC) is currently used. This is the average of three measurements spread out over the period May–September, when skidding resistance is usually at its lowest. Over time, the road gradually polishes to an equilibrium level of skidding resistance that depends upon the amount of heavy traffic using the road.

Initially, a ‘snapshot’ of the SCRIM Coefficient of the ‘existing’ sites (that is, all sites except Site H) was made during the first two weeks of November 1999 in order to verify their suitability for future study. This was followed by a measurement of MSSC with three visits to each site during the summer of 2000, together with an initial measurement at Site E, the A66 trial site, two weeks after it had been laid.

It was decided not to continue monitoring on sites A, B and C beyond the summer of 2000 because these were very lightly trafficked and had been laid for long enough to have reached their equilibrium skidding resistance level. On the remaining sites, monitoring was continued with MSSC measurements and an autumn ‘snapshot’ in 2001, followed by a further MSSC measurement in 2002.

All the measurements were carried out at the standard test speed for SCRIM, 50km/h. The average SCRIM Coefficient (SC) was recorded for each ten-metre length of road along the site. On shorter sites, duplicate passes were made in order to give improved precision for comparing sections. On longer runs, a single pass only was made. The single-carriageway roads were measured in both directions.

5 Skidding resistance measurements – results

5.1 Initial assessment on the lightly-trafficked sites

a Sites A and B

Site A was by far the oldest surfacing studied; it was about 20 years old at the time that the MSSC measurements were made. Clearly, assuming that traffic levels had been generally consistent from year to year, skidding resistance on this surfacing would have been at its equilibrium level. Site B was also approaching 4 years old at that stage and so the surfacings there would be expected to have reached equilibrium skidding resistance, too.

The results for these two sites are summarised in Table 5.1. The table gives the average SCRIM Coefficient (SC) for the November 1999 'snapshot' and the Mean Summer SCRIM Coefficient (MSSC) for the following summer for each of the sections. The values are overall averages for both sides of the road on the corresponding sections of surfacing (at both sites the two sides of the roads gave very similar results). The variation along the road within these averages was small and typical of that normally found with most surfacing materials on stretches of road that have similar surfacing and the same traffic conditions.

Table 5.1 Summary skidding resistance measurements, Sites A and B

Site	*Surfacing (section length in brackets)*	*SC*[†] *November 1999*	*MSSC*[†] *Summer 2000*
A	20mm BOS slag basecourse, (2 x 1920m)	0.50	0.48
B	10mm 'Steelmac' (2 x 120m)	0.55	0.51
	20mm 'Steelmac' (2 x 100m)	0.55	0.52
	20mm basecourse (2 x 130m)	0.56	0.54
	HRA with natural aggregate chippings (2 x 250m)	0.60	0.58

[†] *Overall average for section, including both directions*

It can be seen that all the surfaces showed the expected slight seasonal reduction in skidding resistance between the autumn and the following summer.

The specific skidding resistance requirements for these sites is not known, but it is likely that they would have been categorised as 'Category C: single carriageway non-event' (Site F) and 'Category E: single carriageway minor junctions' (Site G). This would have implied investigatory levels for MSSC of 0.40 and 0.45 respectively.[2]

In both cases, the year 2000 MSSC is well above these levels. In the case of Site A, this level of skidding resistance was being maintained after some 20 years in service. At site B, the BOS slag surfaces were also performing well in comparison with the natural aggregate section. It is understood that the reported PSV of the aggregate used in the pre-coated chippings was 62.

b Site C

Site C was unusual because it incorporated BOS aggregate in a surface dressing whereas, elsewhere, BOS had always been used in asphalt mixes. It was also unusual because, experimentally, different combinations of a granite aggregate and BOS slag had been used for the main aggregate and the smaller 'racking' chips.

As with sites A and B, this site showed the expected lower summer values than in the autumn test. The summer 2000 MSSC values are illustrated graphically in Figure 5.1.

This graph shows clear differences between some of the sections. In particular, the sections with the BOS slag as the main chippings (shown in Figure 5.1 by the triangle markers and more heavily weighted lines) give noticeably lower MSSC than the sections where the granite is the main chipping.

The surface dressing lengths are on a continuous straight section of road, whereas the HRA section approaches and runs through a bend. On the HRA section, although the natural aggregate used does not change, there is a clear drop in the skidding resistance through the bend, due to the increased polishing action of the cornering vehicles. It is not known what type of rock was used for the pre-coated chippings here.

This site is on a quiet County road, and consequently the Authority had applied low risk ratings and investigatory levels. On some sections, the skidding resistance was approaching the IL. However, it is understood that there had been no recorded accidents on the site and so it was not considered a problem.

The relatively low values of MSSC on the sections with BOS as the main aggregate were unexpected, especially for such a lightly trafficked road and in the light of experience on the other sites. This is discussed further in Section 6.2.

5.2 Sites with longer-term monitoring

Table 5.2 summarises the SCRIM measurements on the five sites that were monitored until 2002. The results in the table are the average values for the sections concerned. The non-BOS slag sections are shown in italic script.

The results in Table 5.2 show that there was a general tendency for the MSSC to increase by a small amount from year to year. There have been anecdotal suggestions that the skidding resistance of BOS slag can improve with time.

---

[2] *The concepts of Site Category and the term 'Investigatory Level' (IL) are fully explained in HD 28/94 in Section 3 of Volume 7 of the Design Manual for Roads and Bridges (DMRB, Vol 7). If the MSSC falls below the IL for a particular site, the maintaining authority should investigate the site for possible problems and consider whether surface treatment might be necessary. Different categories of site are assigned different levels of wet skidding accident risk and hence different IL values. The DMRB applies to UK Trunk Roads. Some local authorities have their own standards, usually based on the DMRB but with some variations to reflect different levels of risk on some parts of the network. At any individual site, the IL set may vary from the default level depending on local circumstances. The levels suggested here are those that would be assigned by default to trunk road sites of this type.*

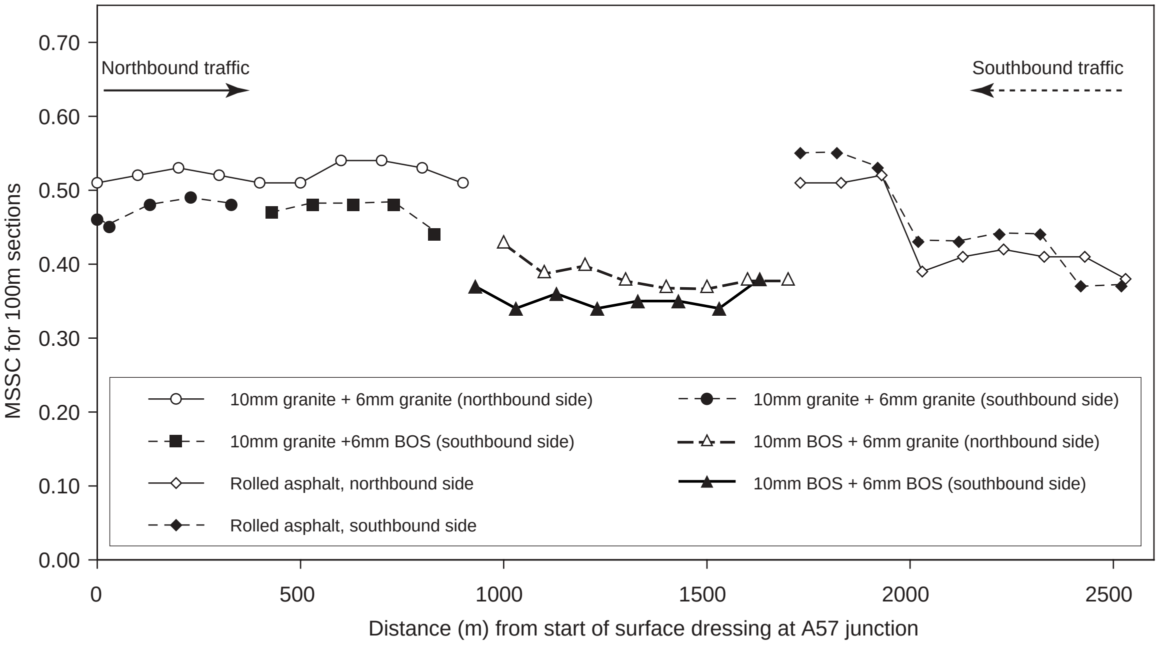

Figure 5.1 Summer 2000 MSSC on Site C

Table 5.2 Summary of measurements from the main monitoring programme

			*Overall length**	*Measured skidding resistance†*				
Site code	*Section*		*(km)*	*SC Nov 99*	*MSSC 2000*	*MSSC 2001*	*SC Nov 01*	*MSSC 2002*
D	BOS slag section		1.8	0.48	0.42	0.44	0.45	0.48
	'old' surfacing (HRA)		*1.2*	*0.48*	*0.39*	*0.40*	*0.45*	*0.42*
E	Lane 1 BOS slag		10.8	0.48	0.43	0.45	0.51	0.50
F	Lane 1 BOS section		1.25	0.67	0.46	0.51	0.50	0.53
	'Old road' approach		*1.6*	*0.51*	*0.46*	*0.50*	*0.53*	*0.51*
	'Old road' follow-on		*0.4*	*0.59*	*0.47*	*0.50*	*0.52*	*0.53*
	Lane 2 BOS section		1.25	–	0.60	0.65	0.63	0.64
	'Old road' approach		*1.6*	–	*0.53*	*0.54*	*0.57*	*0.56*
	'Old road' follow-on		*0.4*	–	*0.56*	*0.59*	*0.61*	*0.62*
G	BOS derestricted section		2.8	0.46	0.43	0.45	0.46	0.48
	BOS main 30mph sections		2.2	0.48	0.42	0.44	0.48	0.45
	BOS underpass section		0.7	0.46	0.38	0.40	0.46	0.41
	Inlaid junction approaches		1.0	0.54	0.46	0.49	0.49	0.49
	Old town road		*1.6*	*0.48*	*0.41*	*0.46*	*0.50*	*0.46*
H	Scunthorpe BOS	Lane 1	0.37	–	0.60‡	0.48	0.51	0.48
		Lane 2	0.37	–	0.60‡	0.42	0.44	0.45
		Lane 3	0.37	–	0.58‡	0.46	0.48	0.47
	Llanwern BOS	Lane 1	0.14	–	0.61‡	0.44	0.48	0.48
		Lane 2	0.22	–	0.59‡	0.42	0.45	0.47
		Lane 3	0.22	–	0.58‡	0.47	0.51	0.46
	Nat. agg. control	*Lane 1*	*0.32*	–	*0.57‡*	*0.48*	*0.53*	*0.50*
		Lane 2	*0.32*	–	*0.54‡*	*0.45*	*0.52*	*0.50*
		Lane 3	*0.32*	–	*0.56‡*	*0.47*	*0.53*	*0.49*

** Includes both sides of road on single carriageways.*

† SCRIM Coefficient (SC) or Mean Summer SCRIM Coefficient (MSSC) averaged over the whole test section.

‡ One measurement only (Sep 00) approximately two weeks after laying.

However, a similar trend can also be seen in the in the non-BOS sites. This indicates that there was probably an underlying seasonal component, in any effects observed here.

More detailed comment on the results from the individual sites is made in sections a-e.

a Site D

Site D (Figure 5.2) is a typical outer-suburban principal road, with occasional side turnings and entrances but no major junctions. It is a gently curving road and is subject to a 40mph speed limit. The route generally carries free-flowing local light traffic, with the occasional bus or delivery vehicle, but little heavy traffic. Figure 5.3 shows the surfacings where the old chipped rolled asphalt (right) and the SMA with BOS slag coarse aggregate meet on the southbound side.

Figure 5.2 Site D looking towards the BOS slag section

Figure 5.3 The surfacings on site D (BOS slag SMA to the left)

The level of skid resistance along the two parts of the sites was generally uniform and above any likely investigatory level. It is interesting to observe that the BOS slag appeared to have been polished less by the traffic than was the natural aggregate during the summers. In both the November measurements (1999 and 2001) the two types of surfacing gave the same average SC (0.48 and 0.45 respectively). During the summer periods, however, the BOS slag gave slightly higher average MSSC values than the old road surface.

The rolled asphalt section had been in place for many years and so would have reached its equilibrium value. This surface shows generally similar levels for the three summers (0.39, 0.40 and 0.42), reflecting local seasonal variation. The BOS surfacing, however, was laid in the summer of 1998 and so would not have been expected to have reached its equilibrium level when monitoring began. In normal circumstances, it would be expected that the level of skid resistance would gradually fall over the three years of the monitoring period as a result of a certain amount of polishing by traffic. In fact, the MSSC increased in this period (0.42, 0.44, and 0.48), to a greater extent than is suggested by the seasonal variation shown by the old surfacing.

b Site E

Site E was chosen to assess how consistently BOS slag could perform over a long length of route. The site was laid in the late winter of 1999 and was therefore about 10months old when the first ‘snapshot’ measurements were made. Figure 5.4 shows the variation in skidding resistance along the site and compares the measurements made in November 1999 with the MSSC for the following summer. Each point represents the average SC or MSSC for a 200m section.

The last 400m stretch was resurfaced between November 1999 and the following summer and so the surfacing at this point was new at the time of the measurements in the first summer season. This part of the site is on a slip road that carries much less traffic than the main carriageway.

The autumn SC values vary, from about 0.4 to around 0.55, with a trend to increase along the site for about 8.5km before tending to fall again. For a large part of the site, they are markedly higher than the MSSC (reflected in the overall average values in Table 5.2). It is likely that this difference occurred because, at that stage, the surfacing was still settling to a more general level in response to traffic action.

However, by the summer of 2000 the level of skid resistance was broadly uniform along the site with long stretches at similar levels. This continued to be so throughout the monitoring period. This is illustrated in Figure 5.5, which shows, for the three seasons, the variation in MSSC along the site. The likely investigatory level for this type of site, 0.35 is also included in Figure 5.5 for comparison. In each season, skid resistance was maintained above the investigatory level, with only minor variations, along the whole site.

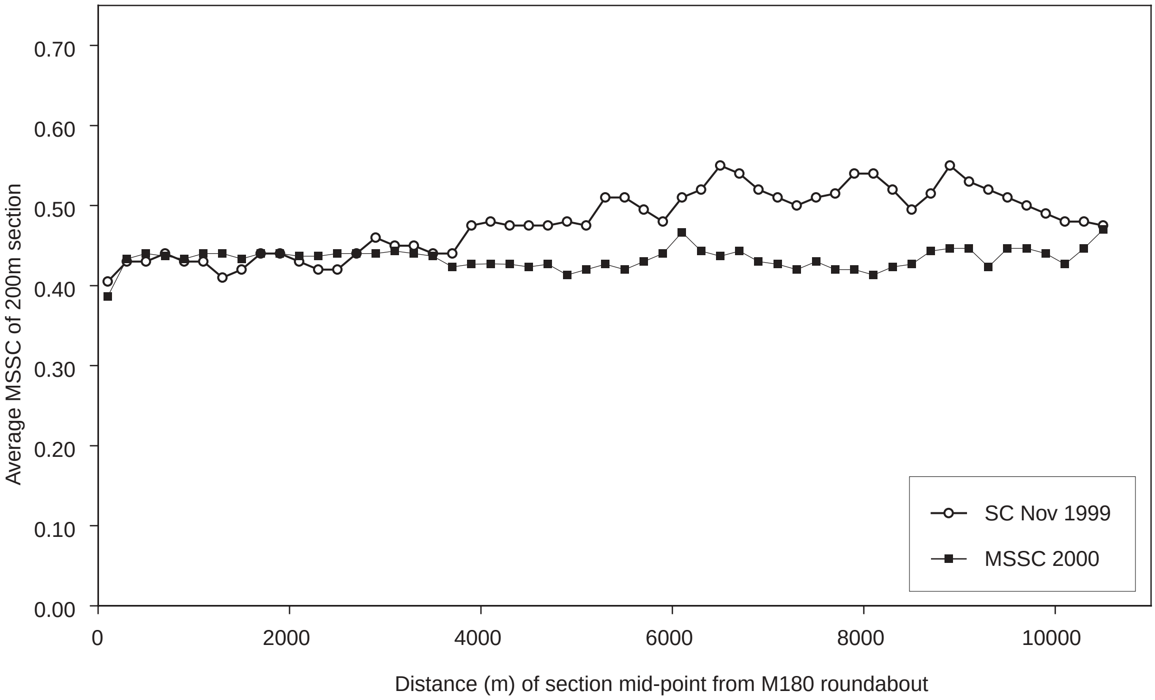

Figure 5.4 Variation along site E between autumn 1999 and summer 2000

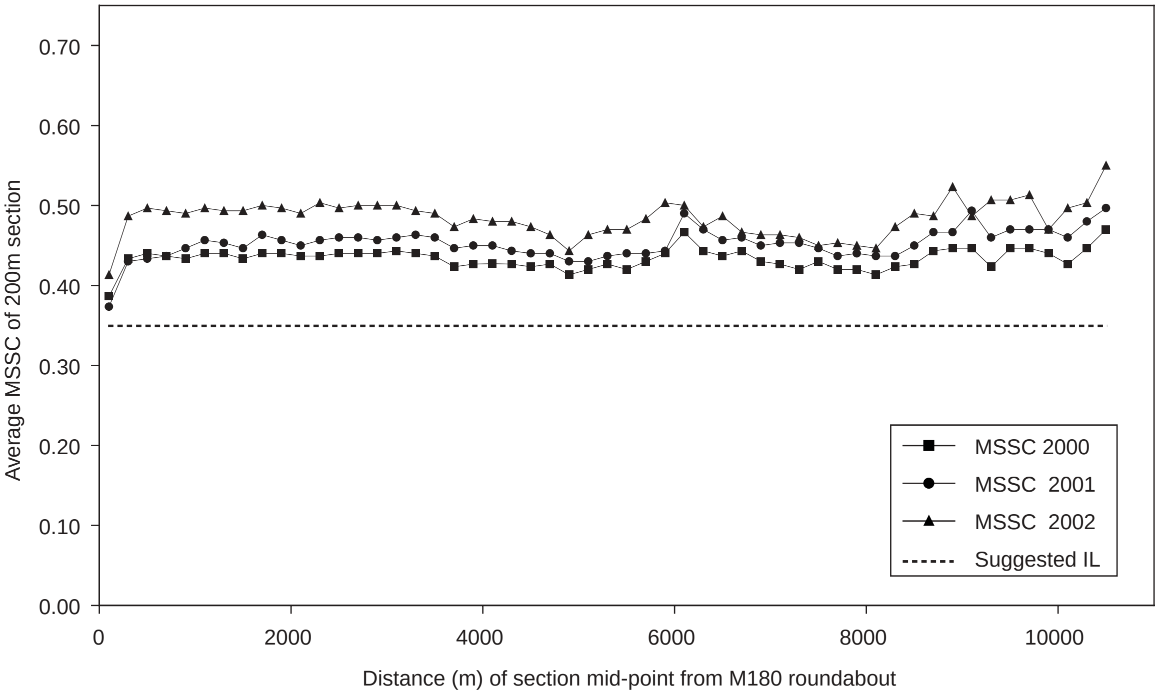

Figure 5.5 Variation in skid resistance along Site E over three summers

The first 200m section of this site includes the exit bend from an interchange roundabout, and traffic is both cornering and accelerating as it enters the section. The greater stresses cause greater polishing action and hence a lower average skidding resistance for a short distance (an effect also observed with natural rocks: see Section 6.2b).

c Site F

Site F is another rural dual carriageway. In this case, the site provides comparative measurements on the same surfacing materials with two traffic levels in the two traffic lanes. Lane 1 carries approximately 750CVD, whereas Lane 2 carries only light traffic, with the occasional heavy vehicle for short distances when overtaking. Two ‘control’ lengths of well-established surfacings were available for comparison with the steel slag, one at each end of the resurfaced length. It can be seen from the summary results in Table 5.2 that there is a marked difference between the two lanes for all three sections, with Lane 1, as would be expected, showing much lower MSSCs than Lane 2.

As with other sites, there is a tendency for MSSC to increase over the three years. At this site, the change on the BOS slag section in Lane 1 is very similar to that on the older surfacings. In Lane 2 the BOS slag was about the same in 2002 compared with 2001 whereas the old surfaces showed a similar pattern to Lane 1. This apparent difference in behaviour may relate to the process by which the skidding resistance of this very lightly trafficked section is approaching its equilibrium level.

Importantly, the MSSC in Lane 1 for the BOS slag is well above any investigatory level for this site (which would probably be 0.35) and compares well with that of the natural aggregates previously chosen.

d Site G

Site G (Figure 5.6, Figure 5.7 and Figure 5.8) is a more complex site. It provides evidence of the performance of the BOS slag under the same general traffic level but in different circumstances, comparing free moving, de-restricted traffic with urban braking and acceleration. The traffic level on this site is also much heavier (at 1000-1250 CVD) than on the sites considered so far.

As can be seen in Table 5.2, the de-restricted section had the highest average MSSC (0.49 in 2002). The 30mph section, with more braking or acceleration and slower-moving traffic, had a lower average value (0.45 in 2002). The MSSC on the underpass section was lower still (0.41 in 2002). As with the other sites, the MSSC on the BOS sections increased slightly over the three summers, more noticeably on the de-restricted section. However, the ‘old’ road section also showed an increase, although not between 2001 and 2002. This site is only a little over a kilometre to the west of Site D, so it is likely that ‘seasonal’ influences would be similar.

Unlike the other sites, where the skidding resistance was generally uniform along the test lengths, because of the different traffic behaviour, there was far more variation here. This is illustrated in Figure 5.9, which shows the SC for July 2002 for the northbound lane. In this figure, each point represents a single 10m measurement.

Figure 5.6 Site G: de-restricted section looking south

Figure 5.7 Site G: 30mph section, traffic light approach

Figure 5.8 Site G: underpass section looking north

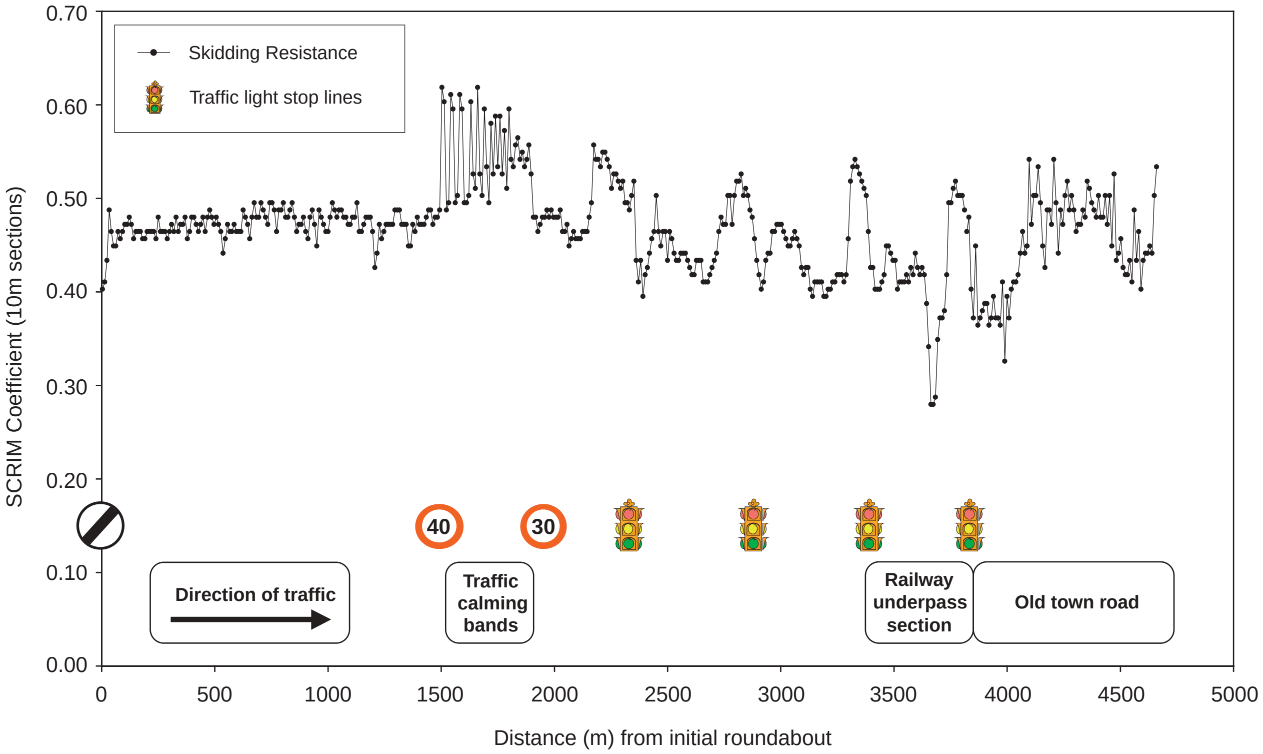

Figure 5.9 Variation of SC along Site G in September 2000

Looking at Figure 5.9 from left to right (in the direction of traffic), a number of features can be seen in the SC measurements, described as follows. All these effects were mirrored on the corresponding parts of the southbound lane:

- *Chainage 0-20m*: The SC of the BOS slag was relatively low on the roundabout exit when compared with the bulk of the de-restricted section (also BOS slag).
- *Chainage 20m-1500m:* On the rest of the de-restricted section, the SC is generally uniform, as has been seen on the other longer sites studied.
- *Chainage 1500-2000:* This section has been designed to slow traffic down on the otherwise fast, straight road on the approach to the 30mph limit. In addition to the 40mph speed limit, bands of red-coloured high-friction surfacing have been laid across the full width of the road. These lead to the wide fluctuations in skid resistance on this part of the site.
- *Chainage 2000-2500:* This section is the approach to the first traffic light controlled junction. The first 200m or so are a continuation of the general BOS slag material. The SC here starts at a similar level to the de-restricted section but then begins to decrease. This probably reflects increased stresses from traffic braking behind queues at the traffic lights. The second part of this section is the high-PSV natural aggregate (PSV >65 Gritstone) that was inlaid at the time of construction in this higher-risk area (and at other similar locations on the site). There is a sudden increase in the SC at the start of this material. It is interesting to note that the natural aggregate material shows a decrease in SC on the approach to the traffic light stop line, presumably also a result of braking stresses. Where the BOS surfacing restarts at the junction, with stresses from turning and accelerating traffic, the SC falls sharply again, then increases towards the level achieved on the free-rolling section at around 2500m.
- *Chainage 2500-3500:* A similar pattern to that described in the previous paragraph can be seen on the approaches to, and through, the next two signal-controlled junctions. The lengths of high-PSV natural aggregate inlay are shorter at these two junctions.
- *Chainage 3500-3900:* This is the ‘underpass’ section, laid with BOS slag up to the approach to the traffic lights at the end of Peaks Parkway. There is a sharp drop in SC in the middle of the section. This corresponds to the lowest point of the underpass. The low SC here was not due to a deficiency in the BOS slag surfacing, but to the presence of contaminating materials. The road on this section drained to this point and mud and detritus accumulated in the dip, both contaminating the surface and, possibly, acting as an additional polishing medium. (This effect was even more marked on the southbound side).
- *Chainage 3900 onwards:* This is the ‘old road’ section and the variable nature of the skidding resistance on this section reflected conditions on the road. This had a mixture of surfacings and substantial patched areas along its length, as well as entrances to retail sites, a bus garage and a further set of traffic lights.

e Site H

Site H (Figure 5.10) provides a comparison of the performance of two sources of BOS slag and a natural aggregate, all laid at the same time and subject to the same traffic conditions. At the time of the final measurements in

Figure 5.10 Site H (the left carriageway) BOS slag sections

the programme, the surfacings on this site were just two years (25 months) old. It is therefore too soon at the time of writing to conclude whether the equilibrium skidding resistance level had been reached in all lanes.

However, by July 2002, the bitumen originally on the upper surfaces of the coarse aggregate had largely worn away from all of the most heavily trafficked sections. Some was still visible on the edges where vehicle tyres do not normally make contact. This condition indicates that, while equilibrium skidding resistance may not have been reached during 2002, it is likely that the MSSC measured then would have been nearing the equilibrium level. The MSSC values along each of the short sections were consistent.

6 Discussion

6.1 The suitability of the PSV test for assessing BOS slag

Based on the tests and observations described in Section 3.3 above, the standard PSV test is unlikely to provide a consistent assessment of BOS slag. It is possible to obtain almost any result within the practical range for the test, even from one sample of material.

The uncertainty derives not only from the test procedure and the way in which it can be interpreted, but also from the nature of BOS slag itself. It is likely that the surface of the slag material is chemically active and that, therefore, the specimen surfaces could change in character at the microscopic level because of material changes as well the polishing processes. This is why some workers have suggested additional soaking phases between periods on the accelerated polishing machine and testing with the pendulum.

Alternative test strategies could be considered that would focus on the sampling and specimen preparation stages of the test. These could include limiting the scope for particle selection by reducing the sample size by further riffling, as has been suggested by workers with EAF slag, or by including ‘soaking’ stages. Clearly, controlling the preparation of test specimens more carefully could have an effect. However, any such approach would lead to a test process that is unique to BOS slag, without any confidence that the results would provide a useful guide to in-service performance. Thus, there would inevitably need to be specific requirements for this particular material, so the test would be of limited value.

Variation in PSV test results can occur with natural aggregates and some may well be due to differences in techniques such as is illustrated by Figure 3.6. However, the scope for ‘selecting’ material when preparing test specimens is much less with natural aggregates. Most of the variation tends to occur between samples taken from the quarry at different times (which is to be expected) and tends not to cover so wide a range as has been seen here in relation to BOS slag.

All of these arguments lead to the conclusion that the PSV test is unsuitable as a means of determining whether BOS slag should be used as a surfacing aggregate in a particular situation. It is therefore considered that a better approach for the time being is to base a decision on whether or not to use BOS slag on the known actual performance of the material in the road in a comparable situation.

6.2 In-service performance

This work has demonstrated that the skidding resistance of surfacings using BOS slag coarse aggregate can vary widely, depending upon the particular circumstances of its use. While this general observation is also true of natural aggregates, the PSV test does provide some indication of likely behaviour for them. If PSV is considered inappropriate for BOS slag and in-service performance is to be used as a criterion for judging its suitability, it is necessary to discuss further what the present study indicates in that context.

a Site C, the surface dressing site

Most of the surfacings covered by this study were SMA-derivative or dense asphalt mixes in which the coarse aggregate was BOS slag. On one site (Site C), however, the BOS aggregate had been used as a surface dressing chipping, in various combinations with a granite aggregate. This site, which was straight, with no junctions and light traffic, would normally be expected to maintain a good level of skidding resistance since there should be relatively little aggregate polishing.

While this was true of the granite sections, the skid resistance on the sections where BOS slag formed the main chipping size was much lower than values observed on any other sites in this study.

There was no obvious reason why this should be the case. Close inspection of the surface indicated that this was a surface dressing in good condition. There was no significant fatting-up of the binder (the most common reason for unusually low skid resistance on this type of surface). The aggregate appeared clean, with no contamination from external sources visible.

The main difference between this site and the others studied, apart from the surfacing type, was that it was on a sheltered road, lined with trees on both sides and close to a canal. It has been commented that BOS slag can be chemically active, with exposed surfaces reacting with air and water on the surface or in the atmosphere as the material wears. It is possible, therefore, that in this particular location there may have been localised conditions that favoured the build-up of some kind of chemical film (probably lime) on the surface that was not removed by frequent passage of vehicles. This may not have been enough to be visible but may have been enough to influence the skidding resistance measurements.

However, although the measured skid resistance at this site was low, it met the requirements at that location. There is not enough evidence to conclude that BOS slag is inappropriate for use either in surface dressings or in such locations. Further investigation both of surface dressings at different types of location and of other types of surfacing at similar locations is needed to clarify these points.

b Behaviour in high-stress situations

There is evidence from several of the sites included in this study that BOS slag tends to give much lower skid resistance in high-stress situations than on normal main-line runs. This, however, is also known to occur with natural aggregates especially in situations such as the approaches to traffic lights and roundabouts. There are indications on Site G, for example, that the high PSV natural aggregate used on the traffic light approaches was tending to polish to a greater extent closer to the traffic lights where, presumably, more frequent braking occurs.

However, as well as these well-known situations, the measurements have shown reduced skidding resistance on roundabout exits and in acceleration areas. Examples are the start of Site E, the northbound start of Site G and on the areas where vehicles accelerate away from the traffic lights on the latter site.

It might be expected that natural aggregates would show similar effects, although they are not normally investigated. In order to confirm this, some limited measurements were made using SCRIM on local principal roads near TRL. Figure 6.1 illustrates some results from these tests, showing the SCRIM Coefficient at 10m intervals for lane 1 of a three-kilometre length of dual carriageway with an intermediate roundabout and an off-slip road. The intermediate roundabout serves an industrial area and the road forms part of an important link between two motorways. The traffic levels are not known, but Lane 1 is probably in a similar category to Site G. The surfacing on the first two sections was a surface dressing (several years old). The slip road (from distance point 7650m) was surfaced with HRA. The intermediate roundabout and its approach had been treated with a high-friction surfacing, as had the approach to the final roundabout at the end of the slip road.

This graph clearly shows a tendency for skid resistance to be lower in acceleration areas such as roundabout exits, although the aggregate does not change. Thus, it is concluded that the lower levels of skidding resistance exhibited by the BOS slag in higher stress areas are not unique to this material.

c General performance of BOS slag aggregate on in-service roads

The evidence presented here suggests that BOS slag aggregate will deliver an MSSC of 0.40 or better over a range of road types and traffic levels where the traffic is generally flowing freely. On the most lightly trafficked sites, such as the overtaking lanes of rural dual carriageways, relatively high values of over 0.60 can be achieved, whereas values around 0.45 are more likely on more heavily trafficked sections.

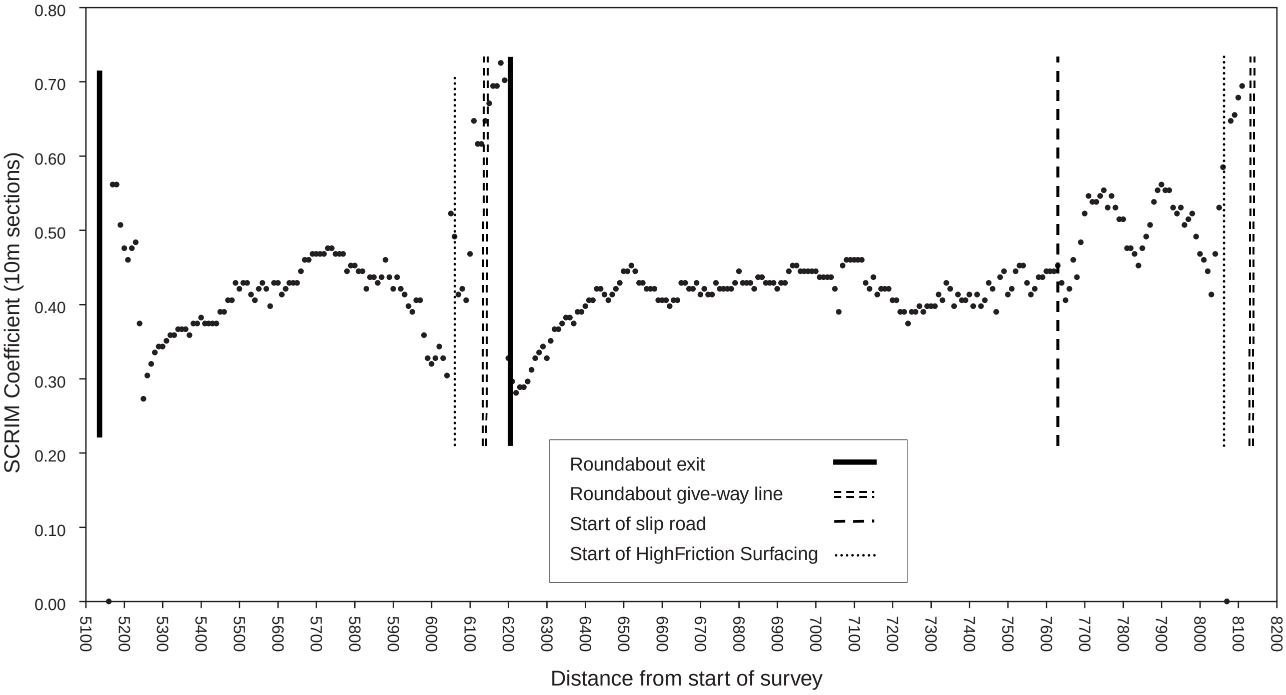

Figure 6.1 Variation in skidding resistance on a ‘principal road’ with acceleration and deceleration areas

To demonstrate how the performance of the roads studied in this project can justify the use of BOS, the various sites studied have been compared with the current Highways Agency requirements. Table 6.1 is based upon part of Table 3.1 of HD36, which defines the minimum PSV requirements for aggregates to be used in new surface courses. To this table, the sites from this study have been added, inserted in the box that they would most closely represent if they were trunk roads. This shows how the MSSC provided by the BOS slag for the various sites compares with the default investigatory level and the PSV that would normally be specified in comparable situations.

From this exercise, it was concluded that it would be reasonable to allow the use of BOS slag in situations where a minimum PSV of 60 would normally be specified. There are other site categories, investigatory levels, and heavier traffic levels, included in HD36, but these are more demanding and require much higher PSV aggregates. It is considered that BOS slag is unlikely to be an appropriate choice for them.

There have been suggestions that BOS slag might maintain its skid resistance properties or they might improve with time. Although there is some suggestion in the results from this study that this could occur, seasonal factors over the monitoring period appear to have caused skid resistance to increase on the non-BOS materials as well. It is therefore impossible to assess from the presently available data whether there is any real effect being demonstrated by the BOS slag.

6.3 Further work

This work has shown that BOS slag has the potential to be used widely, and with confidence, in situations where natural aggregates with a minimum PSV of 60 would normally be used. Most dual carriageways and less heavily trafficked stretches of motorway, together with many single-carriageway principal roads, would be included and this would open the market for potentially large volumes of material to be used. This would have the environmental benefit of reducing the quantity of natural aggregates used for this purpose.

However, some questions have been raised that require further work to provide even greater confidence in the material and to possibly extend the scope for its use. In particular:

- The performance of the material over longer periods under the heaviest traffic has yet to be demonstrated.
- The question of whether skidding resistance of BOS slag actually improves with time has not been answered.

It is therefore suggested that monitoring of the sites in this study should continue for at least a further two seasons. Also, if the opportunity arises, a study should be made of the behaviour of the material under the heaviest levels of traffic that occur on some motorways and sections of trunk road.

The mechanisms by which BOS slag maintains its performance could also be studied, perhaps by extracting samples from road surfaces for microscopic investigation in the laboratory.

Table 6.1 Comparison of study site performance with HD36 requirements

		Required PSV at different traffic levels (cv/lane/day) at design life							
		(Equivalent study site from this project and average MSSC achieved)							
IL band *Default IL*	*Site categories and definitions (as in Table 3.1 of HD36/99)*	*0-250*	*251 -500*	*501 -750*	*751 -1000*	*1001 -2000*	*2001 -3000*	*3001 -4000*	*4001 -5000*
I 0.35	A,B: Motorway, (mainline), Dual carriageways non-event	50 ***F(L2)*** ***>0.60***	50	50 ***E,*** ***F(L1)*** ***>0.50***	50	50	55	60 ***H*** ***>0.45***	60
Ia 0.35	A1: Motorway mainline 300m approach to off-slip roads	50	50	50	55	55	60	60	
II 0.40	C,D: Single carriageways (non-event), dual carriageways approaches to minor junctions	50 ***A,B*** ***>0.45***	50	50 ***E*** ***>0.50***	55	60 ***G (a)*** ***>0.45***			
III 0.45	E,F,G1,H1: Single carriageways minor junctions, approaches to and across major junctions, gradients (5-10% >50m (dual downhill only), bends <250m radius>40mph	55 ***D*** ***>0.45***	60	60	65	65 ***G (b)*** ***0.45****			

* *This is the result for the BOS slag leading up to the traffic light approaches (ie 100-200m from the stop line depending on the junction) and may therefore be optimistic. For the main junction approaches a 65 PSV natural aggregate was used on these parts of the site, with an average MSSC of 0.49*

Another aspect to investigate further is the performance of the material in situations such as that found on Site H in this study, where the skid resistance was unusually low. This would clarify whether the material is more generally suitable for use in surface dressings or lightly trafficked, sheltered situations with higher skidding accident risk than was the case at this site.

7 Conclusions

This study of Basic Oxygen Steel Slag has shown that the material can be used successfully, and with confidence, in road surface courses in a wide range of situations.

Laboratory studies, including petrographic analysis and standard Polished Stone Value tests, have shown that the main UK sources of BOS slag are generally consistent and similar to one another. This is achieved by a combination of the processes by which the material from the slag pits is homogenised through the initial de-metalling and the subsequent crushing and weathering carried out by the slag-handling contractor prior to sale.

Laboratory investigations have also shown that the standard PSV test is inappropriate for assessing the likely in-service skidding resistance performance of BOS slag. Values of PSV covering the full practical range obtained with natural aggregates commonly used in UK roads can be obtained in the test. Much of this wide variation arises from the test laboratory and the procedures followed; the scope for differences in test technique is much greater than for a natural aggregate. Also, unlike natural aggregates, the nature of the material itself has the potential to lead to varying results in the laboratory test that are not reflected in the road. Alternative test procedures could be developed, but these would then be unique to BOS slag, not necessarily comparable with the equivalent test for natural aggregates, and with no certainty of greater reliability in assessing in-service performance.

It is therefore concluded that where BOS slag is to be considered for use as a surface course aggregate, the decision should be based on known in-service performance in comparable situations rather than on the results of a PSV test. Highways Agency requirements already allow a similar approach for natural aggregates, for local situations.

In-service skidding resistance has been monitored using SCRIM on a number of sites where BOS slag had been used as the main aggregate in the surface course. This has demonstrated that:

- On lightly trafficked roads, MSSC well above the investigatory level can be achieved and maintained for many years.
- Levels of MSSC are consistent over long distances where traffic levels do not change.
- Under medium and heavy traffic, and in high-stress situations, MSSC levels vary, depending upon traffic action and the nature of the site, as occurs with natural aggregates.
- A direct comparison of two sources of BOS slag with a 65PSV natural aggregate under traffic of over 3000 CVD has shown very similar MSSC from the three types of material (0.45-0.50) after two years in service.
- On one site, where the BOS slag was used in a surface dressing, unusually low values of MSSC were found, although they were still acceptable in that location. This may have been due to a combination of circumstances unique to that site.

A comparison with the requirements set out in the Design Manual for Roads and Bridges has shown that, overall, BOS slag provides MSSC values that would be expected from natural aggregates with a PSV of 60. It is concluded that BOS slag should be permitted for use on Trunk Roads and Principal Roads where a minimum PSV of 60 would normally be required, except at the heaviest traffic levels, where the material has not yet been tested. This would allow BOS slag to be used more widely in large-volume applications such as moderately heavily trafficked motorways and most dual carriageways, as well as many single-carriageway roads, with consequent reduction in the demand for natural aggregates.

Further work is recommended in order to establish whether the material can be considered for use in an even wider range of circumstances.

8 Acknowledgements

This report was produced in the Infrastructure Division of TRL, for Viridis Ltd. The author wishes to acknowledge the assistance provided by the Tarmac Group and the various local authorities on whose roads the study sites lie. The Project Manager was Mr P G Roe and the Quality Audit Review Officer was Dr A R Parry.

9 References

Alexandre J, Beisser R, Geiseler J, Kuhn M, Motz H, Jukes L, Koller W and Priet J (1993). Utilization of BOS slag in Europe meets high standards. *European Oxygen Steelmaking Congress 1993.*

Bradbury A (2000). Personal communication with regard to the Canadian moratorium on the use of steel slag in surface courses.

British Standards Institution (1989). *Testing aggregates: Method for determination of the polished stone value.* BS 812 (1989) Part 114. London: British Standards Institution.

British Standards Institution (1999). *Methods for measuring the skid resistance of pavement surfaces – Part 1: Side-way force coefficient routine investigation machine.* BS 7491-1:1999. London: British Standards Institution.

Coomarasamy A, Walzak T L (1995). *Effects of moisture on surface chemistry of steel slags and steel slag-asphalt paving mixes*. Transportation Research Record, No 1492, 1995.

Design Manual for Roads and Bridges. Volume 7, Section 3, Part 1, HD28/94: Skidding Resistance. London: The Stationery Office.

Design Manual for Roads and Bridges. Volume 7, Section 5, Part 1, HD36/99: Surfacing Materials for new and maintenance construction. London: The Stationery Office.

Emery J (1984). Steel slag utilization in asphalt mixes. *Canadian Technical Asphalt Association Proceedings, 1984.*

Goldring D C and Jukes L M (1997). *Petrology and stability of steel slags*. Ironmaking and Steelmaking, Vol.24, No 6, 1997.

Hajek J and Bradbury A (1995). Deterioration of asphaltic concrete surfaces containing steel slag. *TAC Annual Conference, 1995.*

Heaton B S (1979). Steel furnace slag as an aggregate in asphaltic concrete. *The Australian I.M.M. Utilisation of Steelplant Slags Symposium, 1979.*

Heaton B S, Francis C L, James W and Cao T (1996). The use of BOS steel slags in road pavements. *Combined 18th ARRB Transport Research Conference and Transit NZ Land Transport Symposium, 1996.*

Holliday K A (1998). *Steel slag. The high performance industrial aggregate*. The Asphalt Year Book 1998.

Ibberson C M, Sytock A F and Taylor I F (1996). *The performance of steel slag aggregates: Skidding resistance*. The Asphalt Year Book 1996.

Missouri State Highway Department. *An investigation of skid resistant asphaltic mix designs.*

Roe P G and S Hartshorne S A (1998). *The polished Stone Value of aggregates and in-service skid resistance*. TRL Report TRL322. Crowthorne: TRL Limited.

Hosking J R and Woodford G C (1976). *Measurement of skiding resistance: Part I. Guide to the use of SCRIM*. Laboratory Report LR737. Crowthorne: TRL Limited.

Abstract

Around 1M tonnes of Basic Oxygen Steel (BOS) slag are produced as a by-product of steel making in the UK each year. Increasing its use as an aggregate in road surfacings has potential environmental benefits of reducing demand for both tipping space and quarried premium aggregate. TRL has carried out a three-year research project for Viridis (an ENTRUST Approved Environmental Body), directed at providing a research base that would encourage the future use of BOS slag in road surface courses. The work combined studies to assess the performance of the material in laboratory polishing tests with an assessment of its skidding resistance on the road. Skid resistance monitoring with SCRIM covered a number of sites where BOS had been used, including a purpose-laid trial.

Related publications

TRL408	*Enabling the use of secondary aggregates and binders in pavement foundations* by V M Atkinson, B C Chaddock and A R Dawson. 1999 (price £35, code H)
TRL322	*The Polished Stone Value of aggregates and in-service skidding resistance* by P G Roe and S A Hartshorne. 1998 (price £25, code E)
CR358	*A review of the use of waste materials and by-products in road construction* by P T Sherwood. 1994 (price £50, code N)
CT89.2	Aggregates in road construction update (1999-2001) *Current Topics in Transport: selected abstracts from TRL Library's database* (price £20)
CT136.1	Road surfacing treatments update (1999-2001) *Current Topics in Transport: selected abstracts from TRL Library's database* (price £20)

Prices current at April 2003

For further details of these and all other TRL publications, telephone Publication Sales on 01344 770783, or visit TRL on the Internet at www.trl.co.uk.