The Skidding Resistance Potential of Steel Slag Aggregates

by

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PREFACE

The author graduated from Salford University in 1991. Since that time he has worked with Tarmac construction on the prestigious Trident submarine missile storage base at Coulport in Scotland and on an A30 road contract in Devon. After leaving Tarmac he spent a brief spell at Biffa Waste Services as a flow survey engineer before commencing on a Teaching Company Scheme between Sheffield Hallam University and The Slag Reduction Company.

The work presented in this thesis forms a part of a three year Teaching Company Scheme project between the Slag Reduction Company / Steelphalt of Rotherham and the School of Construction, Sheffield Hallam University. The project was jointly funded by the Slag Reduction Company and the Teaching Company Directorate and aims to enhance the knowledge and utilisation of steel slag within highway materials and surfaces.

The Authors involvement in the project relates to a two year Teaching Company Associate appointment to investigate the PSV and on-road skid-resistance potential of steel slag aggregate. The intention is that this work will form the initial stage of an on-going development to be undertaken by Slag Reduction Co. Ltd, which in years to come will considerably enhance the engineering in-service performance knowledge of steel slag in UK highways.

THE SKIDDING RESISTANCE POTENTIAL OF STEEL SLAG AGGREGATES

ABSTRACT

Steel slag, a by-product of the steel industry, has been used in road construction in South Yorkshire and the surrounding areas for the past 60 years. There is anecdotal evidence of good performance from these materials which is supported by the fact that they continue to be used today to the satisfaction of the user. The work undertaken resulted from the need to quantify performance characteristics and develop confidence in the use of steel slag aggregates.

The work reported here relates to the skidding resistance potential of steel slag aggregate for use in highway surfaces. Results are presented for both the laboratory determination of the properties of steel slag and for the in-service behaviour of steel slag aggregate road surfaces.

The results are analysed and reviewed and conclusions drawn. Recommendations are made for further work, as it is intended the work initiated here should continue in future years to build up a detailed and extensive data bank of knowledge on the skidding resistance potential of steel slag.

The experimental work contained within this thesis is essentially presented in two sections :-

i) Investigations relating to the laboratory determination of the polishing resistance of steel slag aggregate and efforts to improve the consistency of test results on this aggregate.

ii) Investigations relating to the current on-road skid resistance of selected roads within the region, and using historic data to relate these findings to laboratory test and on-site service conditions..

Within section (i) other work is discussed related to assessing the variability of the processed aggregate from different parts of the processing plant and different supplying sites.

Additionally within section (i) the PSV characteristic of 3mm sized steel slag aggregate is determined and a polishing profile is suggested for steel slag aggregate during the course of a standard PSV test.

The discussion and analysis sections attempt to inter-relate the findings of areas (i) and (ii) above and use historic data, when available, to assess longer term trends.

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1.0 INTRODUCTION

Steel slag is a by-product of the steel industry and for the last 60 years, a limited quantity has been used as an aggregate source for traditional bituminous road materials. Until recently road design methods were semi-empirical, but modern approaches to design consider the road to be a multi-layer structure, capable of analysis. In general this results in the more technically demanding and more expensive materials being used in the upper and surface layers of the road. Engineering performance requirements are now being set at national and international level for these various layers. In the future, material suppliers will have to demonstrate that their products will meet these requirements, rather than simply mixing and supplying products in accordance with standard recipe based specifications.

The bituminous materials manufactured using Rotherham based steel slag aggregate are used mainly in wearing courses. This is due to a combination of two factors, (a) there is anecdotal evidence which suggests the aggregate performs well within wearing courses and contributes to the good skidding resistance and (b) due to the limited volume of steel slag produced in the South Yorkshire region the aggregate tends to be used in the most profitable layers of the road structure. Consequently the use of the aggregate as a bituminous bound base course has virtually ceased with attention to the performance of the material now being focussed at road surface level.

The Slag Reduction Company and Steelphalt haven't up to now systematically assessed the technical performance of it's loose aggregate and resultant bituminous mixtures. This lack of knowledge would have left the company in a poor position to meet the requirements of the approaching changes to the performance specification. To fulfil this need for information relating to the performance of it's bituminous materials and constituent aggregates, the Company embarked upon a Teaching Company Scheme in association with the School of Construction at Sheffield Hallam University. A three year scheme was arranged and structured into the following projects:-

Project A	The quantification of the skidding resistance potential of steel slag aggregates, thereby enabling the future on road skid resistance to be predicted.
Project B	Development of a new range of steel slag bituminous mixtures which will meet performance requirements, particularly in respect to rutting resistance.
Project C	Development of a technical data base of user friendly information for use within a quality assurance /monitoring scheme which, when established, will enable steel slag expertise to be marketed abroad.

This thesis details the work carried out in Project A. This area of work can be divided into two main sub-sections, namely :-

i) Laboratory determination of the polishing resistance of the aggregate

ii) The on-road skid resistance of the aggregate

This sub-division of the work is reflected in the presentation of the thesis, in that Section 2.0 covers the work performed within sub-section (i) and section 3.0 covers the work performed within sub-section (ii).

Little published work has been performed specifically on the polishing resistance of steel slag aggregates. Consequently the review of previous work presented in section 2.2 to 2.4 inclusive aims to detail the current requirements for the PSV of aggregates used in different road locations, detail the development of the polishing test procedure used during the investigation and to raise the awareness of the factors which can cause variations in the test results. This review will familiarise the reader with the limitations of the test procedure, and hence test results, and highlight the importance of obtaining consistent test results to enable confident use of the aggregate by the road engineer at specific site locations. A separate section outlining the limited information on steel slag PSV levels is contained within section 2.8. This section contains mainly company data obtained on the aggregate over a number of years, but also contains current PSV data on other aggregates, which are presented here to help place the steel slag aggregate results into context.

With respect to the on road skid resistance determination of steel slag aggregates, once again little work has been performed directly assessing the skidding resistance of steel slag aggregate. The only work which has been performed is ad-hoc in-company discrete test data, which was not part of a systematic assessment. Consequently, no conclusions have been drawn from this test data. The literature review which is contained within sections 3.3 to 3.5 inclusive, therefore aims to provide an insight to the mechanisms which provide, and factors which affect, the on-road skid resistance of surfaces and the current levels of skid resistance required for different road locations. The intention here is to set the scene against which the skid resistance performance of steel slag can be measured.

2.0 LABORATORY DETERMINATION OF RESISTANCE TO POLISHING

The resistance to polishing of aggregate has always been considered an important factor[1] in assessing an aggregates potential performance for on road skidding resistance. It is vital therefore that an aggregates resistance to polishing is accurately known if the aggregate is to be effectively used as a constituent of a road surfacing material. The level of polishing resistance has always been perceived to be good for steel slag but this has never been unequivocally quantified. Consequently the aggregate has never consolidated an exact position in the market place with regard to its resistance to polishing. The work reported in this chapter of the authors study aims to locate steel slag aggregate unequivocally within the polishing resistance scale, by analysis of a sufficiently large data base of laboratory polishing test results. Confidence limits placed on these results will further strengthen the position of the aggregate within the polishing resistance scale. A further aim of this section was to compare and contrast the polishing resistance of steel slag aggregate from various sources to identify and assess the importance of factors which may influence laboratory test results.

Within this chapter the author will highlight the test procedure used to identify the polishing characteristics of the aggregate and the historical development of the testing procedure from its conception. The scope and aims of the author's study and the methodology used to achieve those aims will be fully detailed. The results from the investigation will be discussed and compared against previous research within the subject area. The conclusions from the authors research will be detailed throughout the text and then summarised at the end.

2.1 Test Procedure Adopted

One of the main aims behind the research was to produce a significantly large number of polishing test results on steel slag standard production aggregate and other fractions of the aggregate. The only test currently used commercially within the UK for determining the polishing resistance of aggregates is the Polished Stone Value (PSV) test[2]. Consequently, this test procedure was used throughout the testing period. Further reasons for using this particular test were :-

i) The PSV test is currently used extensively within the UK to determine the polishing resistance of aggregates. PSV results have been produced in vast quantities by local authorities and private materials testing laboratories on natural aggregates, for which the test was originally set up for, and also on steel slag aggregates. Some of this data was available to the author and could be used to compare and contrast his findings against those proposed by other researchers.

ii) The recognition and interpretation of PSV results by the roadstone industry due to experience with previous test results and analyses.

iii) The PSV test method is in the process of being accepted as the European Standard test for determining the polishing resistance of aggregates. Once the procedure has been accepted as the European Standard this will ensure long term recognition and validity of the test results.

In some cases some modifications were made to the standard test in order to perform particular sub investigations. Where any such modifications were used they are detailed later in the text within the relevant section.

2.2 Development of the PSV Test

2.2.1 Accelerated Wear Machine

Following the Second World War, the large increase in motor vehicles and higher traffic speeds provided the impetus to study the relationship between road materials and skid resistance of roads(1).

The first accelerated polishing machine was constructed by the Road Research Laboratory in 1952. This machine was developed to study the different factors which cause wear on a surface dressing. Early results suggested that loose grit on the surface might be an important factor contributing to the abrasive wear of aggregates. The results confirmed that the machine could be used to emulate the polishing effect of traffic on the roads.

The accelerated polishing machine (figure 2.1) tested a surface formed from 12.5mm Chippings set in a sand-cement mortar around the rim of a steel wheel. Each specimen covered an area of 6 sq. ins. (3900 sq. mm.). A braking force could be applied to the tyre by means of a hydraulic mechanism. The "road" was kept wet by spraying with water . When the aggregates were only subject to a rolling action, little polishing occurred. When fine grit was fed between the aggregate and the tyre, then polishing did occur. The original grit was detritus collected from under the wings of cars but this was obviously uncontrolled and hence non-standard. Later, graded sand was incorporated into the test method which was subsequently replaced with coarse and fine emery abrasive, which is still in use today.

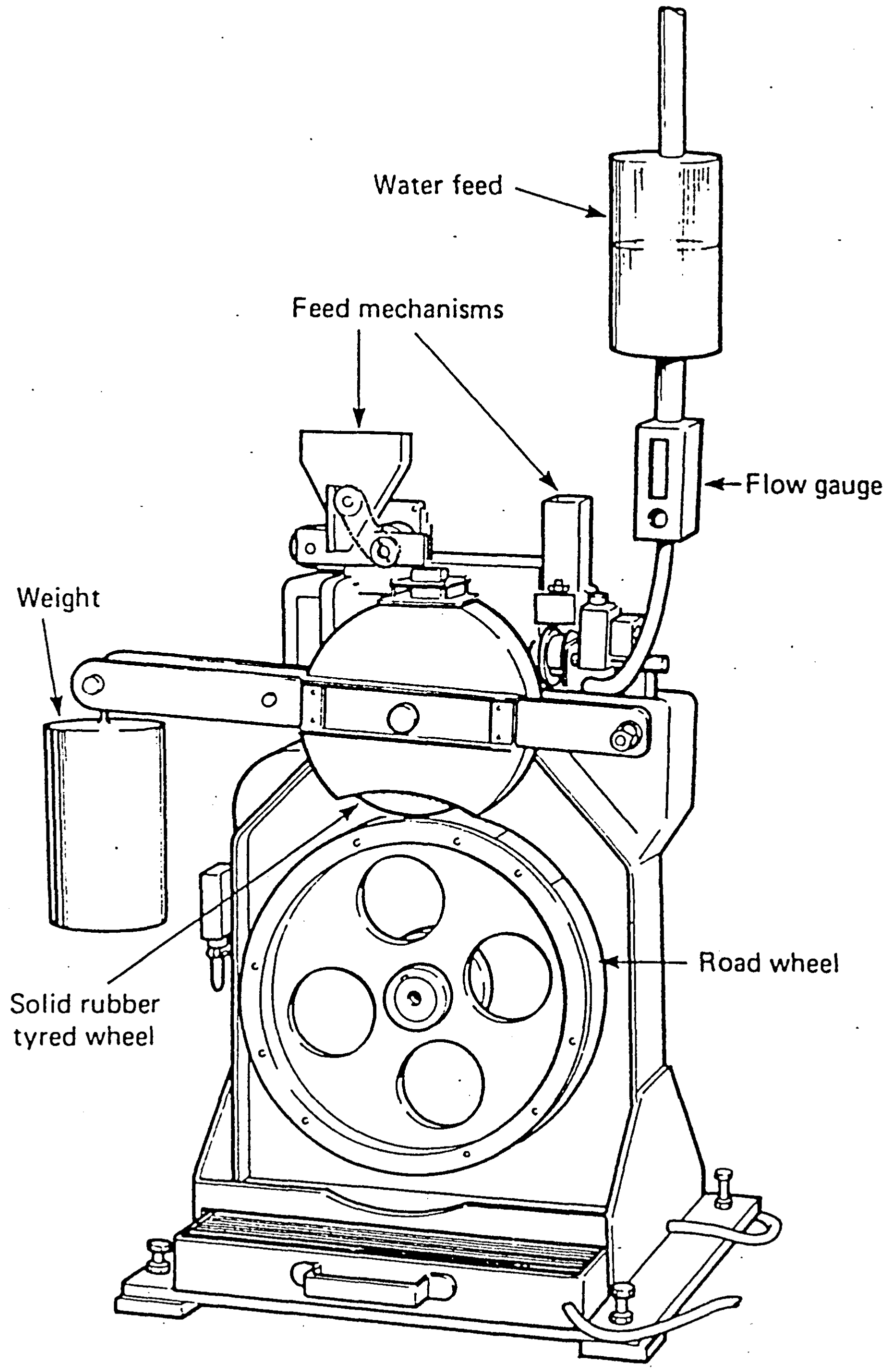


figure 2.1
Accelerated Polishing Machine

2.2.2 Roughness Number Test

By 1957 the accelerated polishing machine was being used as the basis for a test assessing the resistance to polishing of aggregates. The extent of the polishing was measured by the use of a modified version of the portable skid-resistance tester(3) which had originally been developed for on road skid resistance testing. The modifications to the pendulum tester were a narrower rubber slider and a differently calibrated clip on scale to measure the pendulum upswing (figure 3.4 later). The result was expressed as a "roughness number" which ranged from 0 for specimens that became highly polished and 10 for specimens that did not polish during the test. The significance of the results from the polishing tests were assessed by small scale road experiments(1) and showed a good correlation. This suggested that the method of polishing employed for the test reflected the actual polishing conditions on the road

2.2.3 Polished-Stone Coefficient (PSC) Test

In 1958 the "Polished-stone coefficient " replaced "roughness number" as the measure of polish resistance. The test procedure was the same as for the roughness number determination . Good correlation was found between test PSC's and on road skidding levels as detailed in figures 2.2 and 2.3.

2.2.4 Polished Stone Value Test

The PSV test was introduced by the British Standards Institution in 1960. The test was very similar to the PSC test but the result was multiplied by 100 to give a whole number rather than a coefficient. This was to avoid confusion with results from the on road skidding results (section 3.2.1). The test has been continually upgraded since 1960, some of the main developments being,

i) 1965 - use of a solid rubber tyre rather than a pneumatic tyre

ii) 1975 - use of control stone on test wheel to correct any variation of polishing between different tests or different laboratories.

iii) 1975 - use of calibration specimen to ensure constant performance of skid-tester from test to test.

iv) 1983 - change of control stone due to original stone going out of production.

v) 1989 - Introduction of "two wheel" test and new specimen arrangement on periphery of wheel to reduce reproducability and repeatability of test.

<u>Note</u>: For definition of control stone and callibration stone see glossary of terms (p.101)

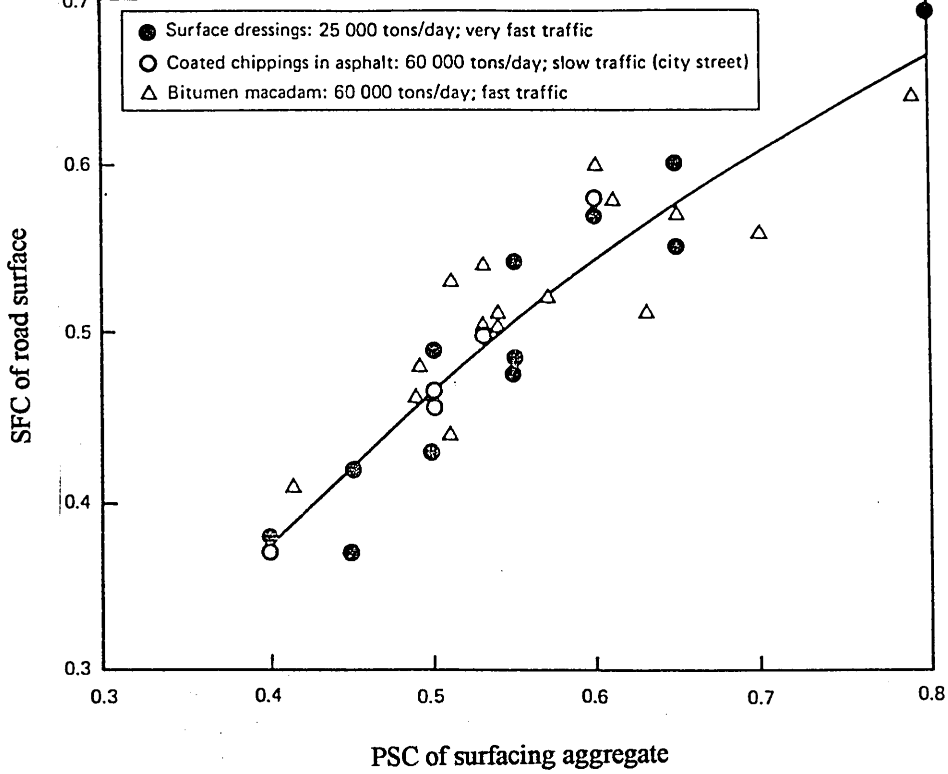


figure 2.2

Relationship between Sideway-force Coefficient and PSC(Ref 33)

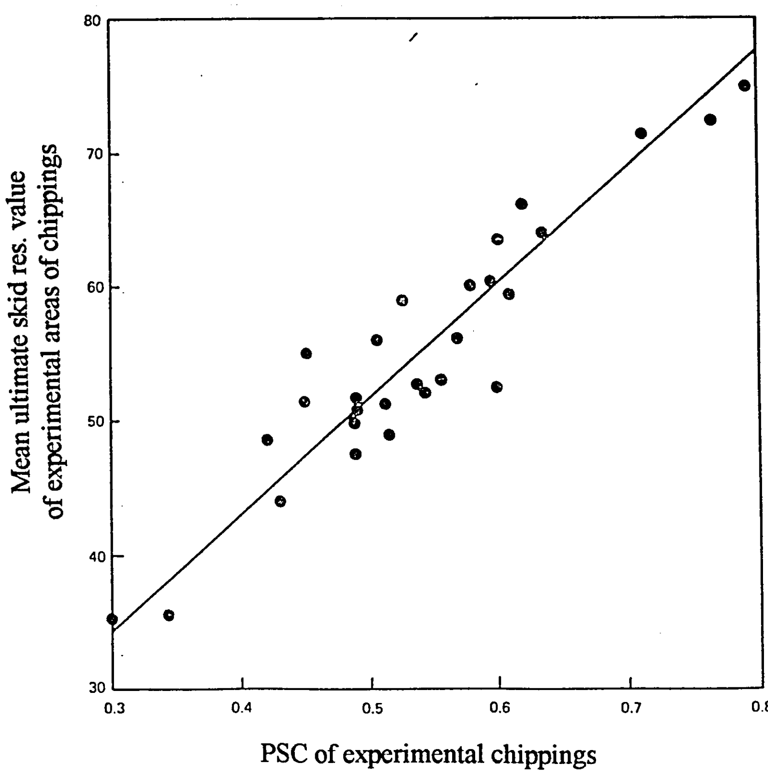


figure 2.3

Correlation between PSC and the ultimate state of polishing of road surface (Ref 33)

The alteration which had the biggest impact on the actual test result was the change from using a pneumatic tyre to using a solid rubber tyre in 1965. This brought about a 10% reduction in the PSV of an aggregate and consequently had an effect on the comparison of test results before and after the implementation of this change. The other changes were introduced specifically to reduce the repeatability and reproducibility of the test procedure.

2.3 Factors Affecting Polished Stone Values

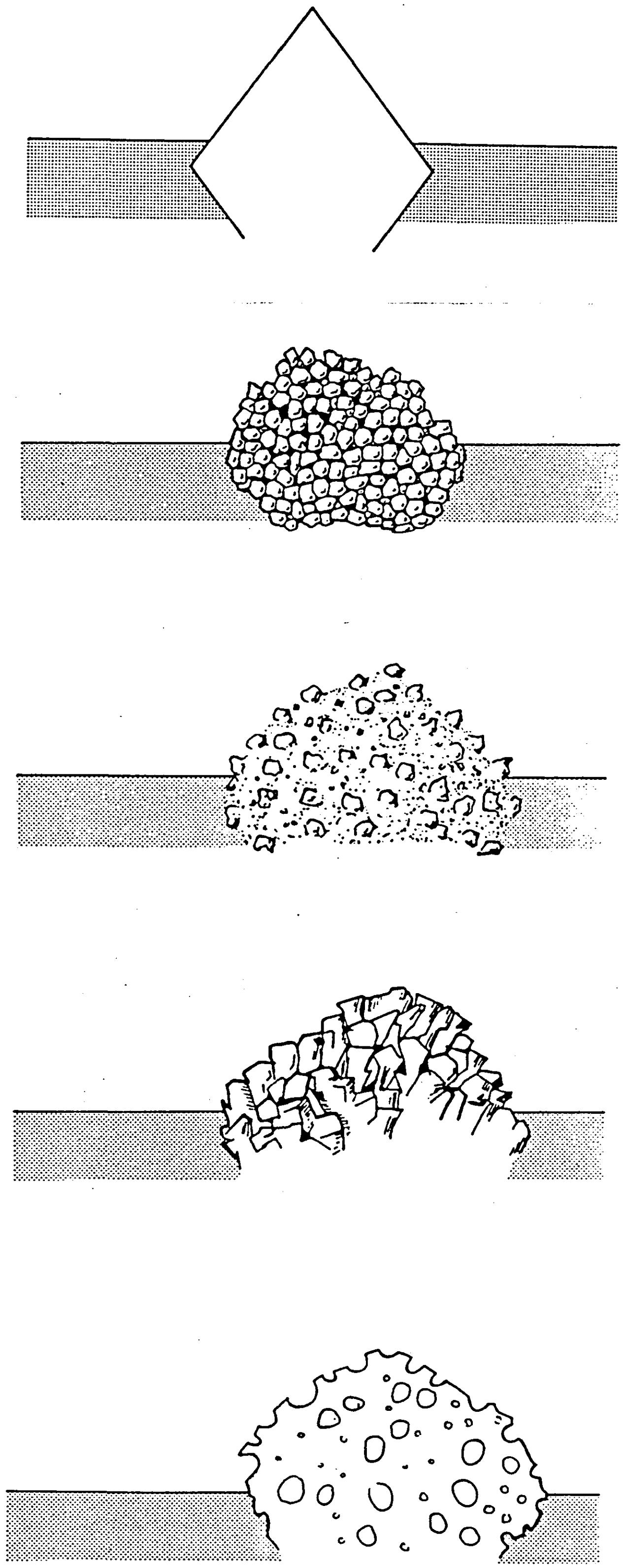
2.3.1 Factors Affecting the Resistance to Polishing of Aggregates

Different aggregates have traditionally shown large variations in PSV (section 2.8.2). In order to obtain a better understanding of this problem petrological examination studies were made[4] of samples from 76 different sources. The petrographic origins of aggregates with high and low resistance to polishing were found to differ for the various rock groups. Generally, it was found that rocks composed of minerals of widely different hardness, and rocks that wear by the pulling out of mineral grains from a relatively soft matrix, had relatively high resistance to polishing. Conversely aggregates consisting of minerals having nearly the same hardness wore uniformly and tended to have low resistance to polishing. Steel slag does not appear to fit into any of these categories but the open vesicular nature of the body of steel slag suggests that the aggregate will be in the former category where irregular wear of the contact surface ensues. Figure 2.4 details various types of aggregate which are thought to produce polish-resistant roadstones.

2.3.2 Factors Affecting the Results of PSV Tests

There are three factors[5] affecting the PSV result of an aggregate other than the petrological properties of the chippings. These are :-

i) testing techniques
ii) aggregate production
ii) sampling procedures



(i) Very hard materials

(ii) Conglomerations of small,hard particles

(iii) Dispersions of hard particles in a softer matrix

(iv) Materials which fracture in an irregular, angular manner

(v) Vesicular materials

figure 2.4
Various types of aggregate which produce polish - resistant roadstones(Ref 4)

2.3.2.1 Testing Techniques

Factors responsible for causing variance of results due to the operation of the PSV test are :-

- i) manufacture of test specimen
- ii) abrasives used for polishing
- iii) calibration of friction testing instrument and its use

Factors ii) and iii) above have almost been but eradicated from the test procedure due to standardised grading of abrasive and calibration controls on both the accelerated polishing and skid-testing procedures.

The manufacture of test specimens (figure 2.5) does cause a problem, particularly where steel slag aggregate is concerned. The British Standard for the PSV test has attempted to standardise production of the specimens by controlling the sampling, size and mass of sample from which the specimens are produced. Whilst these measures are all worthwhile, the final selection of the chippings is entirely dependant on the operator.

Manual selection of the chippings does not cause a problem with natural aggregates due to the homogeneous nature of the chipping's. Manual selection of steel slag chippings for a PSV specimen does cause a problem because the aggregate consists of a blend of various types of chipping (section 2.10.4). The as measured PSV of an aggregate can be directly affected by the choice of chippings. It could be that a PSV operative, experienced in the production of natural aggregate PSV specimens, may choose chippings from a steel slag aggregate PSV sample which resemble those of a natural aggregate. This could result in an unrepresentative specimen being produced as far as steel slag was concerned.

To combat this problem the author developed a procedure to randomise the selection of chippings, which is discussed later in section 2.9.

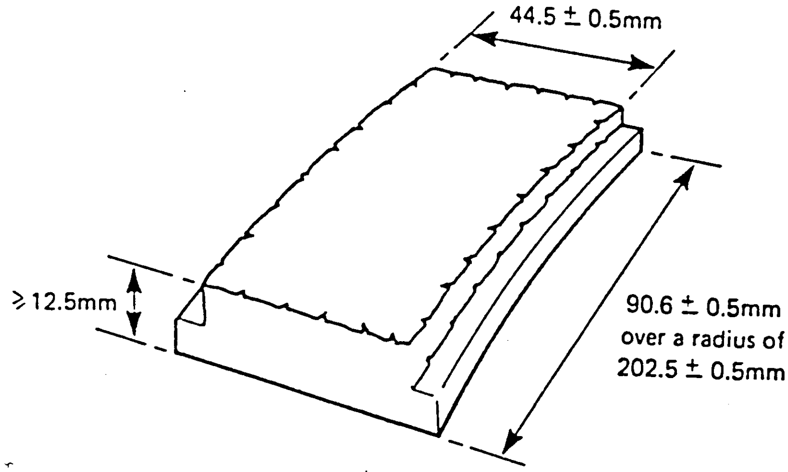


figure 2.5
PSV test specimen

2.3.2.2 Aggregate Production

Natural aggregate sources can show considerable variation within a particular quarry face. The consistency of the aggregate issued to the client over a period of time can be significantly increased by blending all the quarried aggregate together at the stockpile. If quarrying takes place in isolated sections of the quarry, with no blending of the aggregate, PSV results from that specific area of the quarry face will be very consistent. Should the mining activity move to a different face within the quarry, the PSV characteristics would be likely to change. This would increase the long term variability of the quarried aggregate. Consequently, natural aggregates are usually blended from all sections of the quarry face.

Steel slag aggregates face a similar problem. Material is supplied to a central processing area at Templeborough (figure 2.6) in Rotherham from steelworks at Stocksbridge, Aldwarke and Tinsley park. The steel slag produced at these sites can vary independently due to different furnace usage, slag handling and cooling methods. Raw steel slag is stockpiled and processed at Templeborough in site specific batches. Once processed, the resulting aggregates are stockpiled together to produce a blend. This reduces the long term variability of the issued aggregate.

2.3.2.3 Sampling Procedure

Shergold has shown[6] that use of a suitable sampling procedure can greatly increase the value of a single test on an aggregate. He devised a method whereby eight incremental samples of production were taken at regular intervals throughout a working day to provide a test sample.

A similar testing method is used in the present British Standard[7]. Ten samples are taken from a stockpile all at the same time. Sample points are equally spaced around the stockpile and at least 150mm below the surface. The resultant sample is then quartered by use of a riffle box to provide the test sample. This method is critical if an isolated PSV is to be performed on a single sample of aggregate and used as a representative figure for that aggregate. The author did not use this sampling method for some of the investigations due to the large numbers of tests involved.

Where British Standard sampling was not employed, aggregates were sampled directly from the plant silo's and "blended" to a ratio determined by the yield from the different plants.

2.4 Standards for On Road Resistance to Polishing

The PSV test is performed on aggregate prior to the aggregate having any involvement in on road service. Consequently, polishing resistance values can be quoted with greater confidence than "in-service" skid resistance values of an aggregate. This is due to the large number of variables which determine the skid resistance of an in service aggregate compared to those which determine the laboratory controlled PSV of an aggregate.

The confidence in PSV results has led to mandatory standards being set for polishing resistance levels ahead of any mandatory requirements for the "in-service" skid resistance of aggregates (see section 3.6). The various specification for the PSV requirements of aggregates used in different site categories are chronologically detailed in the following section.

2.4.1 Ministry of Transport's Technical Memorandum T2/67 (1967)

These limits were suggested by Giles[8] and were based on the results from full scale experiments together with data from skidding accident sites, with three categories of site being specified for on road skidding resistance. The initial proposals suggested category A - "Most difficult", B - "General requirement" and C - "Easy" sites required PSV's of 65, 60 and 45 respectively.

Subsequently a shortage of high PSV stone caused moderation of the category A and B sites to 62 and 59 respectively.

2.4.2 Transport and Road Research Laboratory (TRRL) Proposals (1973)

The earlier recommendations for minimum values of PSV for the three broadly defined categories of site had the advantage of simplicity but were not capable of fully reflecting the fact that a slippery surface is not the only contributing factor to the incidence of skidding. Other factors for consideration when setting acceptable skidding levels for road surfaces include alignment, number and type of intersections, traffic speed, superelevation and visibility. The TRRL proposals(9) stated the PSV of the surfacing aggregate required in order to meet these newly prescribed skid resistance levels. The proposals (table 2.1) were formulated from results detailed in an earlier investigation by the TRRL(10) relating to the effect of traffic and aggregate on the skidding resistance of bituminous surfacings. The proposals called for considerable usage of PSV 75 aggregate. This is not available in 20mm -6mm chipping form, however calcined-bauxite / epoxy-resin surfaces (section 2.7.2) were capable of achieving this level of polish resistance.

	PSV of aggregate necessary					
Required mean summer	***Traffic in commercial vehicles per lane per day***					
SFC at 50 km/h	**<250**	**1000**	**1750**	**2500**	**3250**	**4000**
0.30	30	35	40	45	50	55
0.35	35	40	45	50	55	60
0.40	40	45	50	55	60	65
0.45	45	50	55	60	65	70
0.50	50	55	60	65	70	75
0.55	55	60	65	70	75	
0.60	60	65	70	75		
0.65	65	70	75			
0.70	70	75				
.0.75	75					

Table 2.1
PSV of aggregate necessary to achieve the required skidding resistance in bituminous surfacings under different traffic conditions (Ref 9)

2.4.3 Department of Transport's Technical Memorandum H16/76 (1976)

This specification supplements the 1976 edition of the DoT's specification for Road and Bridge works. Table 2.2 shows the specification.

Site	Traffic in commercial vehicles per lane per day	Minimum PSV	Remarks
Straight & Low Risk	Less than 250	60	Values include +5 units for braking/turning Risk rating 6
	250 to 1000	65	
	1000 to 1750	70	
	greater than 1750	75	
Motorway	Less than 1750	60	Values include +5 units for braking/turning Risk rating 4
	1750 to 2500	65	
	2500 to 3250	70	
	greater than 3250	75	
Dual Carriageway	Less than 1750	55	Risk rating 2
	1750 to 4000	60	
	more than 4000	65	
Single Carriageway		45	No risk rating applied Local aggregates usually well above 45. These should be used.

Table 2.2
Minimum polished stone values for bituminous roads H16/76

2.4.4 Department of Transport Highways, Safety and Traffic Directorate[11](1992)

This specification was introduced at the end of 1992 and defines the specification requirements for PSV (table 2.3a and 2.3b) and AAV (table 2.4) for new bituminous surfacings, including resurfacing and surface dressing, on trunk roads and motorways. The standard gave PSV and AAV requirements for different categories of highway layout and different traffic flows in order to assure skidding performance of the resulting road surface above the investigatory levels of skidding resistance set in Departmental Standard HD 15/87. It included a greater number of PSV categories than its predecessor and generally had more stringent requirements.

2.4.5 Highways Agency Design Manual for Roads and Bridges[12](1994)

The current specifications detailing the PSV requirements of surfacing aggregate are shown in tables 2.3a and 2.3b. They are identical to the specifications detailed in section 2.4.4. The on road skidding resistance requirements (section 3.6.5) remained unaltered and consequently using the prescribed PSV aggregate for a particular site and traffic loading should result in a surface performing above its investigatory skidding level. AAV limits are prescribed within the specification, the limits being detailed in table 2.4.

	Site Category	Site definition	TRAFFIC (CV / lane / day) at DESIGN LIFE													
			0 - 100	101 250	251 500	501 750	751 1000	1001 1250	1251 1500	1501 1750	1751 2000	2001 2250	2251 2500	2501 2750	2751 3250	>3250
I	A B D	Motorway (main line) Dual carriageway (All purpose) non event junctions Dual carriageway (all purpose) minor junctions	**55**								**57**		**60**		**65**	**68**
II	C E	Single carriageway non-event sections Single carriageway minor junctions	**45**	**50**	**53**		**55**	**57**		**60**	**63**		**65**		**68**	
III	F G1 H1 L	Approaches to and across major junctions (all limbs) Gradient 5% to 10%, longer than 50m (Dual downhill single uphill and downhill) Bend (not subject to 40mph or lower speed limit) radius 100 - 200m Roundabout	**50**	**55**	**57**	**60**		**63**		**65**		**68**		**over 70**		

Table 2.3
Minimum PSV of chippings (or coarse aggregate for unchipped surfaces) for flexible surfacings on new or resurfaced roads (Ref 12)

	Site Category	Site definition	TRAFFIC (CV / lane / day) at DESIGN LIFE													
			0 - 100	101 250	251 500	501 750	751 1000	1001 1250	1251 1500	1501 1750	1751 2000	2001 2250	2251 2500	2501 2750	2751 3250	>3250
IV	G2	Gradient >10% longer than 50m (Dual downhill, single uphill and downhill)	**55**	**60**	**63**		**65**		**68**		**over 70**			–		
	H2	Bend (not subject to 40mph or lower speed limit) radius<100m														
V	J/K	Approach to roundabout, traffic signals, pedestrian crossing, railway level cossing etc.	**63**	**65**	**68**		**over 70**							–		

Table 2.3
Minimum PSV of chippings (or coarse aggregate for unchipped surfaces) for flexible surfacings on new or resurfaced roads

Traffic (CV / lane / day) at design life	< 250	251 - 1000	1001 - 1750	1751 - 2500	2501 - 3250	> 3250
Max AAV for chippings	14	12	12	10	10	10
Max AAV for aggregate in coated macadam wearing course	16	16	14	14	12	12

Table 2.4
Maximum AAV for flexible surfacings on new or resurfaced roads

2.5 Objectives of the PSV Investigation

The main objectives of the PSV investigation were:-

i) provide a PSV baseline of standard production steel slag aggregate. This could then be used as a baseline against which comparisons with other types of steel slag could be made.

ii) highlight the PSV's associated with steel slag aggregate derived from different parts of the processing plant and different sites and compare these with the baseline PSV determined in (i) above.

iii) Develop a greater understanding of steel slag properties and their relationship with polishing resistance.

iv) Highlight any other skid resistance applications steel slag could be used in.

2.6 Aggregates Tested During Routine PSV Determinations

2.6.1 An Overview of the Crushing Process

The processing plant at Templeborough works, Rotherham, consists of two inter-related plants. Aggregate is fed into the primary hopper (figure 2.6) from which naturally arising aggregate (smaller than 20mm diameter) is immediately separated from the larger steel slag. This oversize material is then passed through the "main plant" crushing and screening system. Here it passes through a jaw crusher and under a number of overband magnets to remove the steel from the slag. The material is then screened out with any standard sizes passing into the main plant storage silo's. Any oversize material is passed on to the "pan mills" processing plant.

In the pan mills plant the oversize aggregate from the main plant is fed into a surge hopper. From here it is fed into an "autocone" rotary crusher and after crushing is further de-scrapped by overband magnets. The material is then re-screened with standard sizes passing into the pan mills storage silo's and oversize aggregate being recirculated through the above process until it is reduced to a standard size fraction.

The aggregate obtained from the main plant storage silo's is therfore either naturally arising, or crushed by a single pass through the jaw crusher. This aggregate consists of essentially rounded particles which usually have a coating of dust.

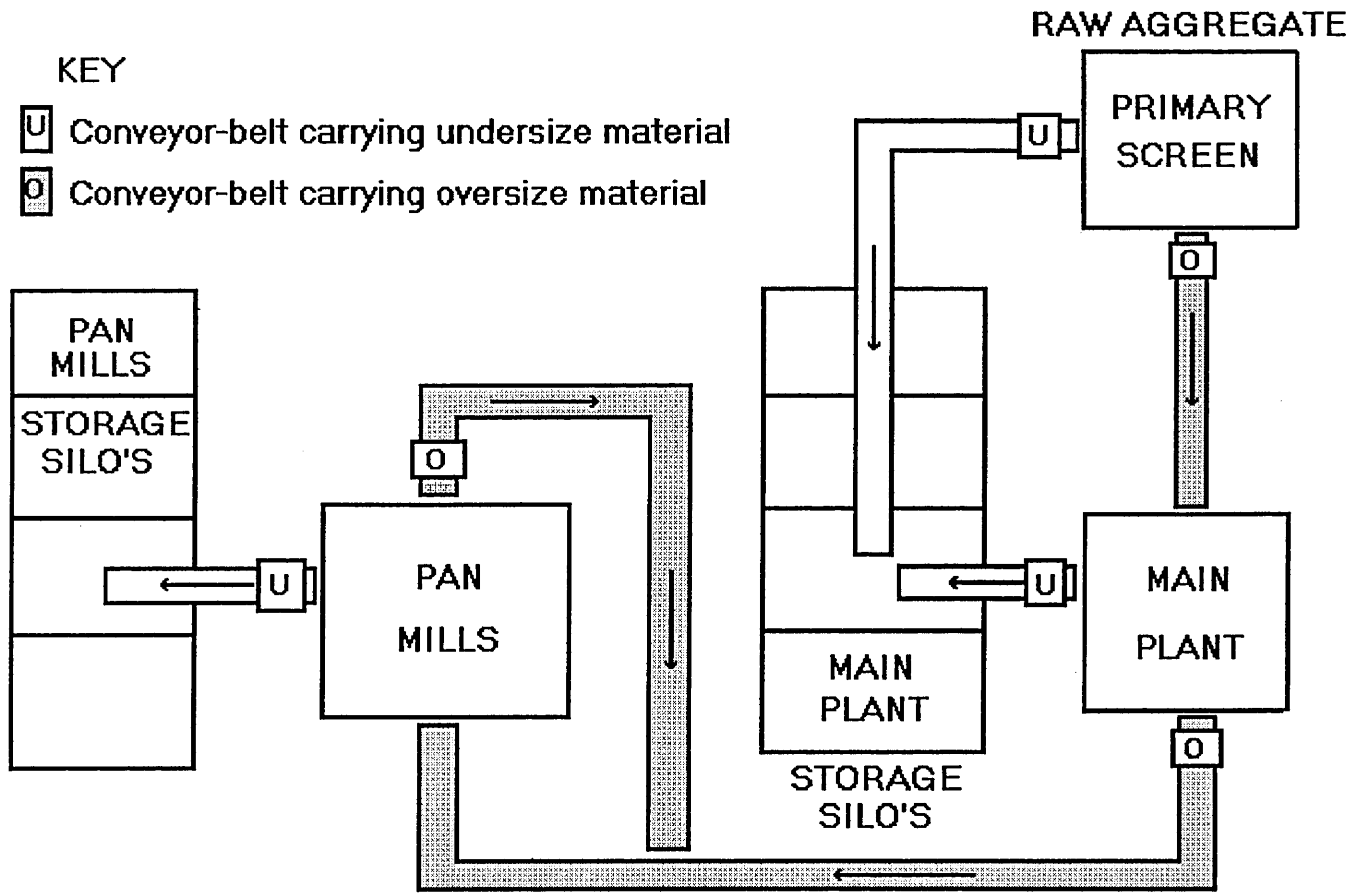


Figure 2.6

Schematic representation of the processing plant at Templeborough, Rotherham

The aggregate obtained from the pan mills storage silos has undergone crushing in both of the processing plants. None of this aggregate is naturally arising and consequently the Pan Mills aggregate tends to be cleaner and a bit more flaky than the main plant aggregate. The author suggests that this material is somewhat harder than the main plant aggregate due to the additional processing it has undergone.

2.6.2 Routine Production Aggregate

Steel slag is processed through the two plants detailed in section 2.6.1. A baseline routine production value was required for the reasons detailed in section 2.5. Samples for this determination were not taken to the relevant British Standard. The large number of samples taken over 17 months of testing were thought to be sufficient to provide a representative cross section of aggregate production. The actual sampling procedure adopted is detailed below.

Samples were obtained directly from the two plants. 10mm aggregate from one of the plant storage silos was emptied into a dump truck and a sample of approximately 15kg was taken. This was repeated for the other plant silo. The two samples were then sieved out to produce the required PSV size fraction. Each sample was then riffled down to approximately 1100 grammes for main plant and 900 grammes for pan mills. This corresponds to 55% and 45% of total production for main plant and pan mills respectively. The proportion of aggregates produced were obtained by averaging plant output records.

A further reason for not sampling the aggregate directly from the stockpile was that a representative sample of main plant and pan mills derived aggregates could not be guaranteed. Sampling direct from the particular processing plant was far more effective in guaranteeing the correct proportions of the two aggregate types.

Production of test specimen was initially as per the British Standard PSV procedure but later a non-standard production technique was used. This modified technique is detailed later in section 2.9.

2.6.3 Plant Specific Aggregate

An investigation was performed into the polishing resistance of aggregates obtained from the two processing systems, Pan Mills and Main Plant. Sampling for this investigation ran in conjunction with the sampling of the routine production aggregate. Both methods of specimen production were used during this investigation.

2.6.4 Site Specific Aggregates

Raw steel slag is generated at two principal sites in South Yorkshire, Stocksbridge and Aldwarke steelworks. The steel slag is brought in by road from these sites and crushed at Templeborough. An investigation was performed to determine if any difference was present in the polishing resistance of the steel slags from the different sites. A 2½ tonne sample of aggregate from the pan mills and main plant processing systems was stockpiled from Aldwarke and Stocksbridge sources. British Standard samples, as detailed in section 2.3.2.3, were taken from the stockpiles in order to gain representative samples of each aggregate type.

A further source of steel slag is Cardiff. The steel slag derived from Cardiff is not currently utilised as a highways surfacing materials and therefore an investigation was performed into the polishing resistance of Cardiff steel slag. The sampling techniques varied for this investigation due to the remoteness of the Cardiff site not allowing bulk samples to be transported and crushed through the plant at Templeborough. The exact sampling methods used will be detailed later in the text.

2.7 Other Investigations built into the PSV Program

2.7.1 The Effect of Steel Slag Aggregate Properties on PSV

Commercially produced steel slag aggregate is a blend of aggregates derived from two processing plants which in turn are fed by aggregates from two supplying steelworks. These factors, combined with the different rates of cooling of the steel slag during handling results in a blended aggregate consisting of chippings with very different physical appearances (figures 2.7(a) and 2.7(b)). A sub-investigation was undertaken to identify if any correlation existed between the quantified properties of visually different chipping's and their resultant PSV's.

2.7.2 Polishing Resistance of 3mm Steel Slag Aggregate

Sites requiring high skid resistant properties such as approaches to traffic lights and roundabouts (table 2.3a and 2.3b), require surfaces produced from aggregates having very good resistance to polishing[13]. PSV values of 70+ are often required for these sites but this level of polish resistance can not usually be achieved by chipping size aggregates. In the late 50's, a proprietary surface using 3mm calcined bauxite bonded to the road surface with an epoxy-resin was developed[14]. This is still used predominantly today at such difficult sites.

Due to the hard nature of steel slag, an investigation was performed to determine if a 3mm steel slag aggregate could be used in such a surfacing.

(i) vesicular structure

(ii) solid structure

figure 2.7 (a)
various types of steel slag chipping - Dark colour aggregate

(i) vesicular structure

(ii) solid structure

figure 2.7 (b)

Various types of steel slag chipping - Light colour aggregate

2.7.3 Polishing Profile of Steel Slag Aggregate

A further investigation was performed to assess the laboratory based polishing profile with time of steel slag compared to that of a natural aggregate.

2.8 Historic PSV Results

2.8.1 Steel Slag Aggregates

Sporadic PSV tests have been performed on steel slag derived from Templeborough works since 1961. The PSV test has undergone some major changes since then which have affected the results obtained by the test. Since 1965 however (see section 2.2.4), the test method has produced results which can be considered to be consistent and comparable between years. The results of the historic PSV's taken at recognised laboratories, are shown in Appendix 1.6.1. Averaging the results from the individual years produces the chart shown in figure 2.8.

Clearly the variation of historic PSV's has been considerable. This may be due to the variability of the steel slag itself. Another factor could be the variability of results between different testing houses. As discussed previously, PSV specimens are produced by manual selection of chippings from a large sample. The PSV specimen, and hence result, is directly affected by the operative. Operatives at different laboratories have their own production techniques and preferences in chipping selection. Consequently, PSV results, from different laboratories, taken on the same aggregate can vary significantly. This inconsistency is clearly displayed on the historic PSV data collected at Steelphalt.

2.8.2 Other Aggregates

PSC tests (see section 2.2.3) were performed on 292 samples of aggregate(15)(1) and showed wide ranges of values for different aggregates (figure 2.9). Results for the artificial group (slag) recorded PSC values between 0.35 and 0.60. This range of results represented various types of slag, with no details being available specifically for steel slag aggregates.

In 1992 a study was commissioned by the Department of the Environment to investigate the availability of "high specification aggregates for road surfacing materials". This study(16) currently defines the understood levels of polishing resistance associated with various UK aggregates at the present day. An extract from the published table of results is shown in appendix 1.6.3.

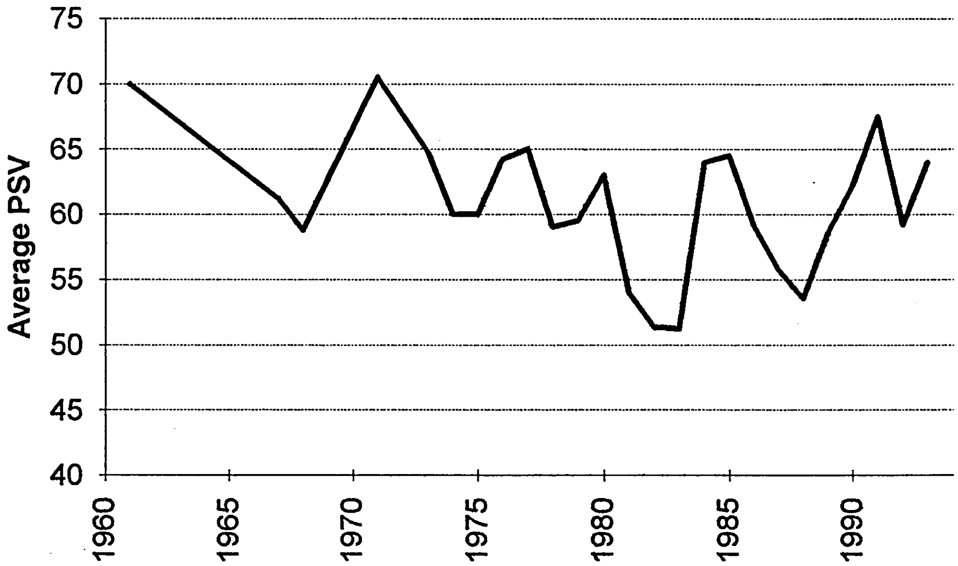


figure 2.8
Average yearly PSV results on steel slag aggregates from Templeborough

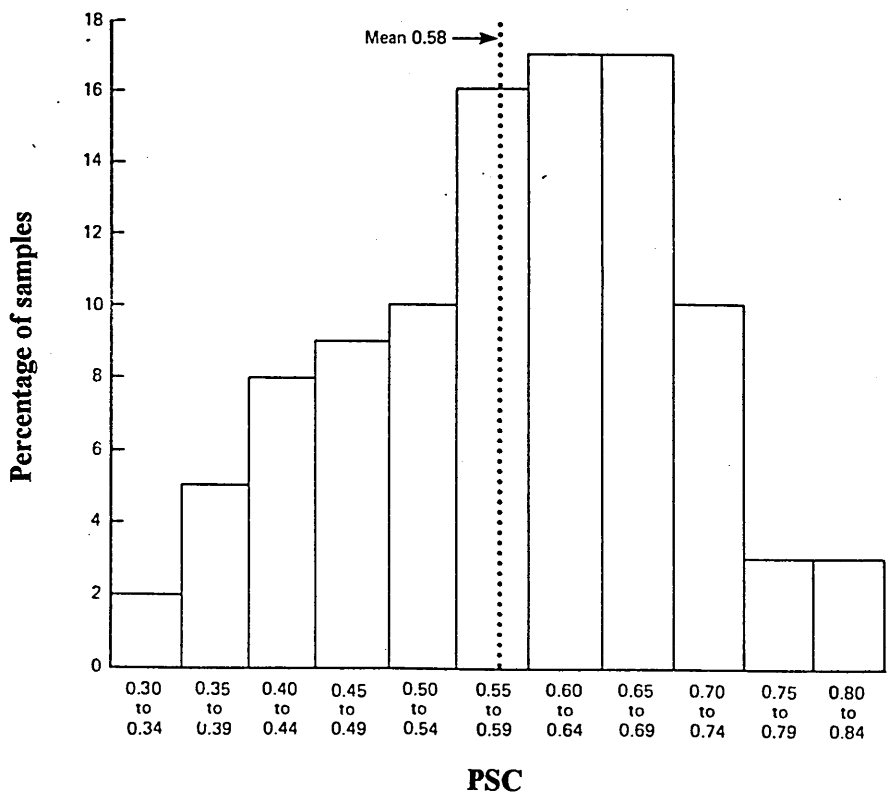


figure 2.9
Distribution of polished stone coefficients of roadstones (Ref 15)

It can be seen that a PSV level of 63.5 was quoted for steel slag aggregate from Templeborough works. Consequently, this is the current level of PSV associated with steel slag aggregate within the roadstone industry. The work detailed in sections 2.6.2 and 2.10.1 of this study will help to confirm or dispel this value of polishing resistance.

2.9 Development of Representative Specimen Production Technique

The production of the PSV specimen is critical to a PSV result. The selection of the chippings to be placed in the PSV specimen mould is even more critical for steel slag than for natural aggregates due to the variability of chippings within the steel slag blend. As detailed previously, the current British Standard requirement is for chippings to be manually chosen from a 2 kg sample to make up the test specimens. Each specimen uses approximately 60 grammes of aggregate. Consequently, the four specimens produced from a sample use about 250 grammes in total which represents about one eighth of the sample mass thereby allowing the operator a significant choice in the selection of chippings. To reduce the variability of PSV results of steel slag, this operator dependant element of the specimen production routine needed to be removed. This was achieved by using a riffle box to 'choose' the chippings to be used in the PSV mould, rather than relying on the operator. A 2kg sample was produced, as standard, and then quartered by use of the riffle box. Each quarter in turn was then riffled down until a sample of just sufficient size to produce a PSV specimen remained. This effectively eradicated the operator dependant element from the production of the specimens apart from the actual placing of the chippings in the mould. This method was used extensively during the testing program, the exact areas being detailed later in sections 2.9.1 to 2.9.3 inclusive.

2.10 PSV Results

2.10.1 Routine Production Steel Slag Aggregate

Weekly samples of the routine production aggregate were taken as detailed in section 2.6.2. Thirty two tests were conducted on steel slag specimens produced using the British Standard PSV test method. Thirty six tests were carried out on steel slag specimen produced using the riffle method detailed in section 2.9. Results for all the tests are detailed in appendix 1.1.

2.10.1.1 Traditionally Produced Specimen

Table 2.5 shows a summary of the results obtained from the PSV tests on steel slag aggregate specimens prepared using the traditional British Standard method. The average PSV of the tests was 63.0. The variability of the results was large however with a standard deviation of 3.16. This affected the confidence analyses and produced the large 95% confidence interval for the mean PSV and the low minimum PSV expected (to 95% confidence) from a single test. The above confidence limits still leave some doubt regarding the exact position of steel slag aggregate within the PSV scale.

Property	Value
No of tests	32
No. of specimens	128
$PSV_{average}$	63.0
Standard deviation	3.16
$PSV_{average}$ to 95% confidence	61.9 - 64.1
Single PSV to 95% confidence	57.8
repeatability (r)	4.93

Table 2.5
Summary of results obtained on traditionally prepared steel slag PSV specimens

2.10.1.2 Riffle Produced Specimen

Table 2.6 details the results obtained from the PSV tests on steel slag aggregate using specimen prepared with the use of a riffle box. The average PSV from the tests was 63.9. The standard deviation was 2.13, which resulted in a 95% confidence interval for the actual mean value of 63.2 - 64.6. The minimum PSV expected (to 95% confidence) of any single determination was found to be greater than 60 units of PSV. The above confidence analyses place the aggregate firmly into the 58 < PSV < 65 range.

Property	Value
No of tests	36
No. of specimens	144
$PSV_{average}$	63.9
Standard deviation	2.13
$PSV_{average}$ to 95% confidence	63.2 - 64.6
Single PSV to 95% confidence	60.4
repeatability	4.05

Table 2.6
Summary of results obtained on riffle prepared steel slag PSV specimens

2.10.1.3 Comparison of the Two Production Methods

The number of tests performed using the two methods of specimen production was approximately equal and of a significant number. This allowed a direct comparison to be made between the two methods.

The average PSV figure of all tests gave values of 63.0 and 63.9 for traditional and riffle methods respectively. This shows very little diffence between the PSV's obtained from the two methods. This suggests that the use of the riffle method did not produce a major difference in the basic level of PSV results and therefore was assumed to be a valid method for producing PSV specimens.

The standard deviation, and hence variability of the results was increased by 50% when the traditional method was used instead of the riffle method. This resulted in a much wider 95% confidence interval being placed on the mean value of the traditionally prepared specimen results than on the riffle prepared specimen results. A clearer picture of the position of steel slag within the PSV scale is provided by using the riffle specimen production technique.

The problem of high variability of results on confidence intervals is further shown by the 95% confidence levels for individual PSV determinations. The figures proposed represent PSV levels below which 5% of test results may lie. Once again, these figures show the increased interval between sample average and confidence interval values for the traditional production method due to its inherent variability.

The level of repeatability (r) set by BS 812 : part114 : 1990 is 3 units. This is lower than the figure derived[17] from either method of specimen production used during the testing. The level of repeatability may have been high for steel slag aggregates due to the following reasons :-

i) High degree of variability of Chippings contained within an individual sample

ii) Seasonal variation of steel slag

Point (i) can be present in natural aggregates, however the basic structure of a natural aggregate is usually very consistent. Steel slag aggregate consists of a blend of 4 very different types of chipping (section 2.10.4) and this blend can have a great effect on the variability of PSV's if the proportions of each type of chipping within the blend changes.

Point (ii) applies only to steel slag aggregates. Weather and temperature conditions may affect steel slag whilst cooling and cause seasonal variations in the polishing qualities of the aggregate (section 2.10.1.4). Consequently, the fact that the repeatability of the steel slag aggregate results was above that prescribed for natural aggregates in the British Standard was not too alarming. What was important was that the use of the riffle method had halved the margin by which the aggregate failed to meet the British Standard requirement.

2.10.1.4 Chronological variability of Steel Slag PSV

Due to the regular taking and testing of PSV samples throughout a period of 17 months, it was possible to plot the fluctuations in PSV of steel slag aggregate throughout this period. Figure 2.10 shows fluctuations in the value of all the steel slag PSV's taken during the investigation. Figure 2.11 shows the 5 point running averages of PSV results from testing using the two different specimen production techniques. The PSV results from specimens produced using the two production methods show fluctuations with time. Both plots show a higher level of PSV during the Winter months than during the summer months. These fluctuations are, however, much more pronounced for the results obtained from the British Standard produced specimen. This may have been due to the early results being part of a learning curve but more likely this was the effect of manual selection of chippings rather than randomised chipping selection . The fluctuation of PSV results obtained using the riffle method of specimen production does suggest that steel slag exhibits some amount of seasonal variation in PSV. These fluctuations may possibly be attributed to the following factors :-

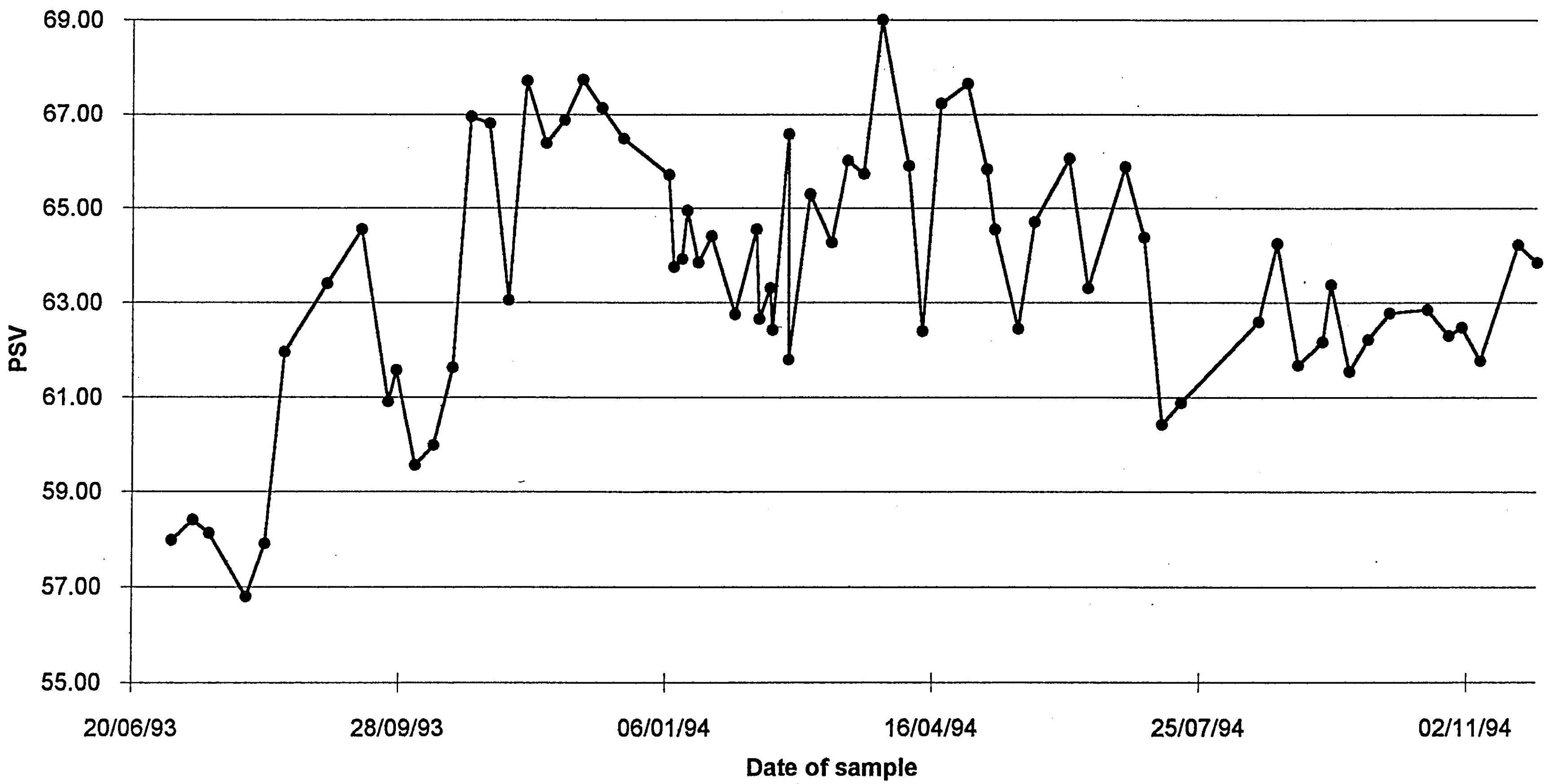
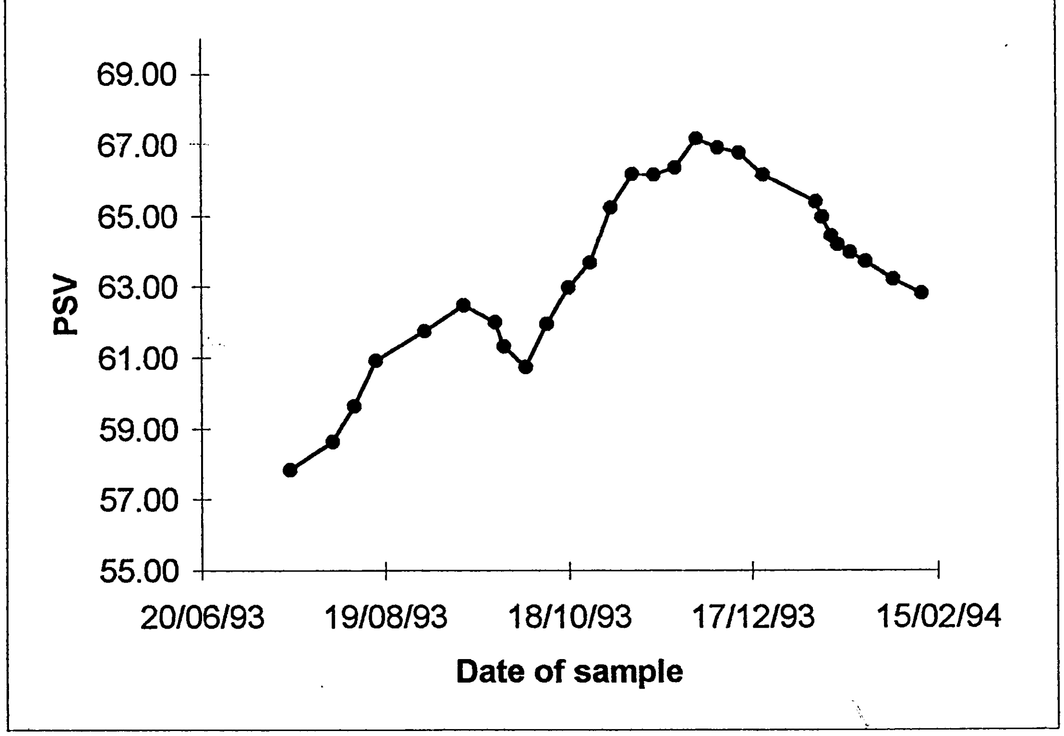
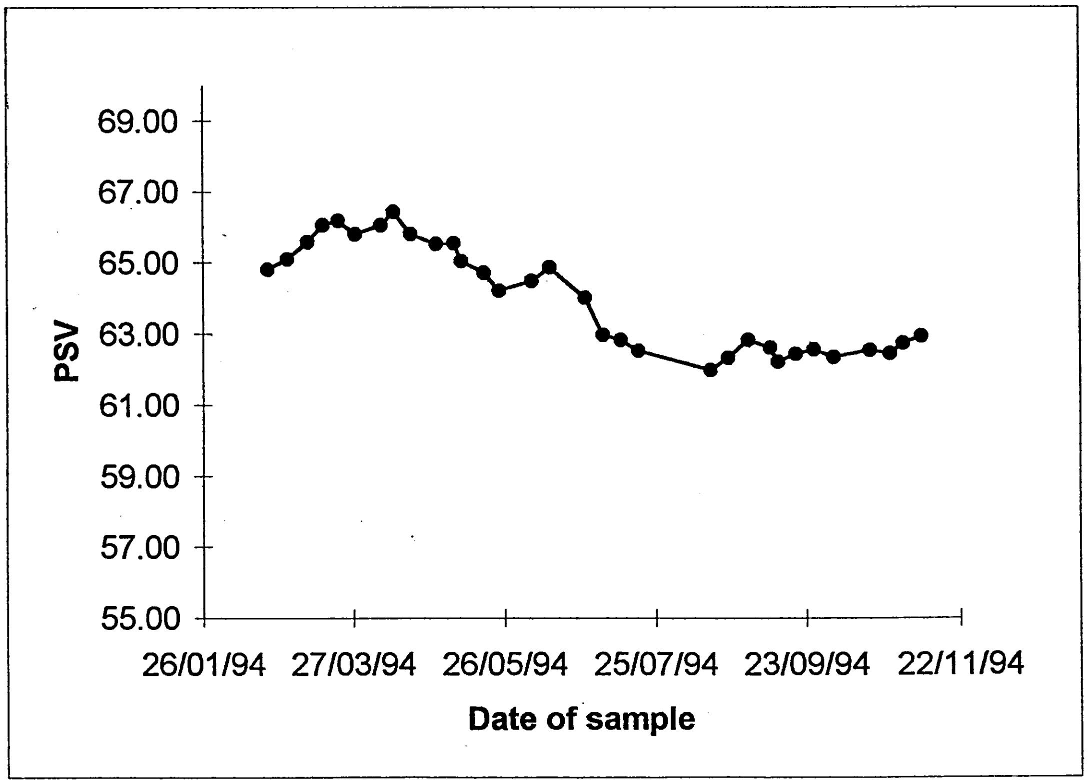


figure 2.10
Standard production aggregate PSV results



(i) "traditional" British Standard method



(ii) "riffle" method

figure 2.11

5 point running average plots on PSV results on standard production aggregate using the two specimen production techniques

i) Seasonal weather and temperature changes affect the cooling rates of the steel slag on site and hence the resultant PSV of the aggregate

ii) The steel slag produced is directly associated with properties of the steel produced within the furnace. Any change in steel production is reflected by a change in steel slag properties.

The seasonal fluctuations shown for the PSV results from the British Standard specimen production method (figure 2.11 (i)) relate much more closely to the fluctuations detailed on the historic PSV chart (figure 2.8) than do the fluctuations shown for the results using the riffle method (figure 2.11 (ii)). This reinforces the benefit of using a random specimen production technique to improve the consistency of PSV results on steel slag aggregate.

2.10.2 Variability of Aggregate from Different Parts of Templeborough Plant

The steel slag aggregate processed at Templeborough is obtained from the two plant storage silos detailed in section 2.6.1. An investigation into the difference in PSV between the aggregates obtained from the two plants was performed. Both riffle and traditionally produced specimen were used for the PSV tests. The results obtained are detailed in appendix 1.2.1

The Pan mills derived aggregate gave a lower PSV than the Main plant derived aggregate. 95% confidence intervals on the mean value of the PSV (appendix 1.2.2) showed that some overlap of the possible average PSV of the two aggregates existed. This overlap suggested that no significant difference existed between the aggregates.

Four tests were performed on riffle prepared specimen and 12 tests performed on traditionally prepared specimen. Despite the obvious limitations of comparing the results from the two production techniques, a comparison is shown in table 2.7.

	Pan Mill	Main Plant
Riffle (4 results)	64.3	66.1
Traditional(12 results)	64.2	65.9

table 2.7
Average PSV's for both plants using different production methods.

These results strengthen the findings from section 2.10.1.3 in comparing the two specimen production methods. Once again the mean PSV obtained from using the riffle method of specimen production is not significantly different to that from using the traditional production method. Analysis of standard deviations has not been performed because of the large difference in sample size.

2.10.3 Variability of Aggregates Derived from Various Supplying Sites

From section 2.6.4, the aggregate from three steel slag handling sites was investigated. The results from the three sites investigated are detailed in appendix 1.3. A summary of key values, detailed in table 2.8, show that from a practical point of view, no difference existed between the aggregates derived from the Sheffield and Rotherham supplying sites. The results do suggest that the resistance to polishing of Cardiff derived aggregate was superior to that of the South Yorkshire aggregates.

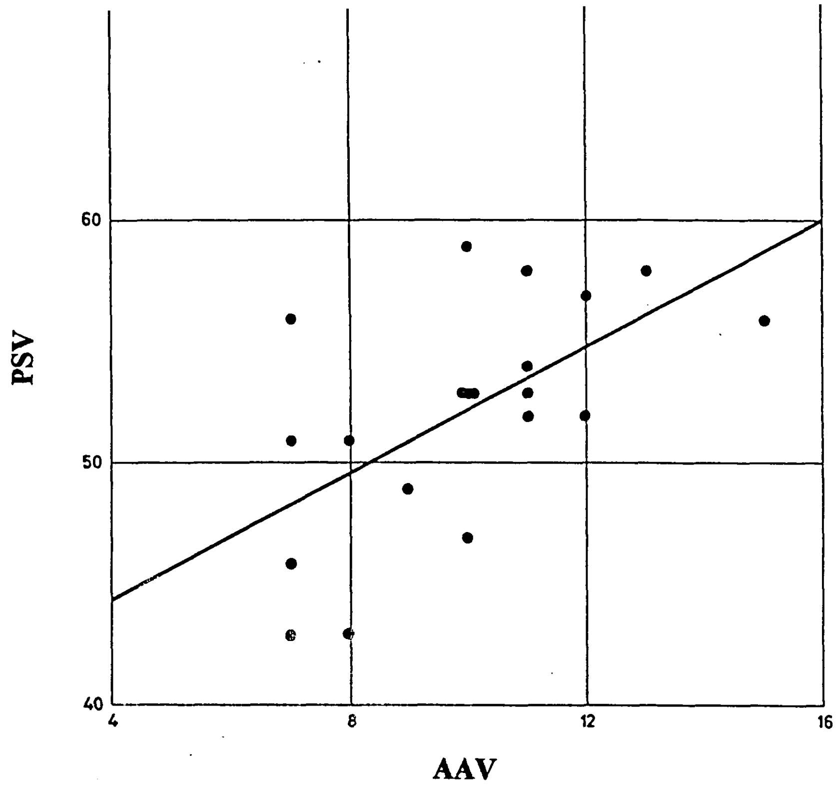
	Stocksbridge	Aldwarke	Cardiff
Average PSV	64.5	64.9	69.8
Standard deviation	2.46	2.18	2.01

Table 2.8
Summary of PSV results on various steel slag supplying sites

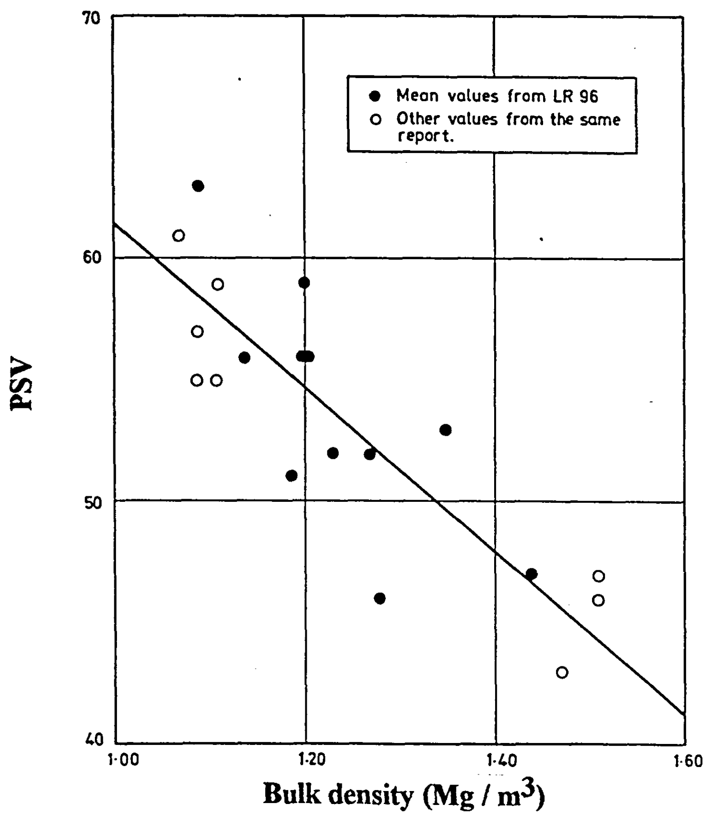
2.10.3.1 Additional Testing on Cardiff Derived Aggregate

The standard production PSV of steel slag aggregate in the Sheffield area was within the range 58 - 65 resulting from section 2.10.1 work. Aggregates with PSV's above 65 are rare and consequently command higher premiums than aggregates below 65. The marked difference in PSV shown in table 2.8 for steel slag derived from the Cardiff plant was a very significant result and consequently required further examination of the aggregates properties.

The test samples used to produce the above Cardiff results were manufactured using a naturally occurring i.e. uncrushed aggregate which had been hand sieved to provide the standard PSV size fraction. The naturally occurring aggregate was used because there was not a full scale crushing and screening plant at Cardiff. The test results were intended to be an initial indication of the polishing resistance of Cardiff aggregate. The author suggests that the above results could be misleading because of the weak nature of the unprocessed aggregate. The aggregate was weak because the very honeycombed sections of the aggregate (refer to section 2.10.4) had not been reduced to dust by the action of a crushing process. A weak aggregate can have a high Aggregate Abrasion Value (AAV), and from earlier work by Hosking [17] the greater the AAV of the aggregate, the higher the PSV(figure 2.12). Hence, the weaker "naturally occurring" fraction of the Cardiff steel slag tested could have had an inherently improved PSV which would be unrepresentative of the polishing resistance of the processed aggregate



(i) Aggregate Abrasion Value - PSV relationship



(ii) Bulk density - PSV relationship

figure 2.12

Proposed relationships between blastfurnace slag properties and PSV (Ref 17)

It was decided to obtain further samples of Cardiff aggregate and to crush them in small scale rotary and jaw crushers to analyse the effect on the aggregate of different crushing methods. The aggregate sampled for this part of the investigation was partially processed by the small plant present at the Cardiff site and had passed a 50mm automated screen. It was decided to use this aggregate to determine if the weaker element of the steel slag mix had been removed by the light crushing it was subjected to, and any effect of this on the PSV of the resultant aggregate. Three types of aggregate were prepared for PSV testing :-

i) "As sampled" partially processed Cardiff steel slag aggregate

ii) Partially processed aggregate given one pass through a small scale rotary crusher contained within the main plant at Templeborough

iii) Partially processed aggregate passed repeatedly through a laboratory jaw crusher until all the aggregate passed the 20mm sieve

This provided three samples of aggregate at different levels of crushing (i.e. (i)light, (ii)medium, (iii)severe) from the same original sample. PSV and 10% fines[18] strength tests were performed on each of the samples to provide some indication of the effect that different regimes of crushing had on the polishing and strength characteristics of Cardiff aggregate. The results from the investigation are shown below :-

Aggregate	Level of processing	PSV	10% fines (strength)
Part processed	LOW	**68**	110 kN
Part processed, rotary crushed (single pass)	MEDIUM	**67**	180 kN
Part processed, jaw crushed (multiple passes)	HIGH	**64**	210 kN

Table 2.9
PSV and 10% fines test results on partially processed Cardiff aggregate.

This clearly showed that increased processing of the aggregate resulted in higher strength but lower PSV results. The results still did not contain any data on the PSV and strength level of any Cardiff steel slag placed through a full scale plant crusher. To obtain this data a crushing trial was organised to pass a sample of oversize (i.e. 75mm+) raw Cardiff steel slag through the "Autocone" rotary crusher within the "Pan Mills" (see section 2.6.1) part of the plant. This crushing unit was chosen because:-

i) this was the likely type of crusher to be used if a plant was set up in Cardiff to utilise the higher PSV aggregate apparently produced there.

ii) Contamination of the small sample being used was less likely using the "Autocone" than a jaw crusher

ii) Loading the "Autocone " crusher with a small sample was much easier than loading a jaw crusher.

The PSV and 10% fines test results of the full scale "Autocone" test are shown in Table 2.10. Clearly the results indicate that this sample of Cardiff slag processed through a full scale rotary crusher has excellent resistance to polishing and sufficient strength to be used as a 65+ PSV road surfacing aggregate.

Date sampled	sample type	Individual specimen SRV				PSV	10% fines (kN)	
							Wet	Dry
30/11/94	Raw slag, 75mm+	74.6	72.3	75	76.6	72	160	180

Table 2.10
Test results on "Autoconed" Cardiff raw slag

Further work is currently being performed at Templeborough into the polishing characteristics and strength of Cardiff steel slag with a view to installing a commercial crushing, screening and coating plant at the site to supply high specification road aggregates.

2.10.4 Relationship of Steel Slag Aggregate Properties with PSV

Steel slag aggregate can be visually separated into four different types of chipping. A sample of steel slag consists of a blend of varying proportions of these constituent particles. The majority of chippings fall under the following categories :-

i) **Dark vesicular** (fig 2.7a (i)) - chippings are dark grey in colour and have a closed, vesicular nature caused by entrainment of air within the body of the chipping during rapid cooling. The closed nature of the vesicles appears to make the interior of the Chippings impenetrable by water.

ii) **Dark solid** (fig 2.7a (ii)) - chippings are again dark grey in colour. The body of the chipping is solid with very little visual evidence of porosity.

iii) **Light vesicular** (fig 2.7b (i)) - chippings are light grey in colour and have large vesicles present on the surface of the chipping.

iv) **Light solid** (fig 2.7b (ii)) - Light grey colour chippings with a solid body. Visual evidence of constant small scale porosity throughout the body of the chipping.

A minority of other miscellaneous types of chipping include :-

a) black glassy appearing chippings which are a result of the molten slag splashing against the side of the slag pot and cooling to the ambient temperature very rapidly. These chippings resist processing and consequently are present in the end product.

b) black, very vesicular, very brittle chippings resembling coal. These are formed when water is sprayed onto the cooling slag when it is still very hot. The rapid cooling caused by the water causes the slag to 'pop' and to cool in a very expanded, light-weight form. This type of chipping is normally reduced to dust during processing.

It was proposed to investigate the relationship between the polishing resistance of the four main categories of chippings and their respective properties. Previous work(17) on blast furnace slag suggests that the PSV was proportional to the aggregate abrasion value (AAV) but inversely proportional to the bulk density (figure 2.12).

2.10.4.1 Methodology

The properties of the constituent parts of the steel slag blend were determined by a vacuum soaking method. The apparatus is shown in figure 2.13. Four samples of approximately 60g were prepared for each type of chipping. All the chippings were derived from a single PSV sample used in section 2.10.1 in order to eliminate as many variables as possible. Prior to testing the dry weight of each individual sample was taken. One set of chippings was placed into individual containers and into the empty vacuum chamber. The air was removed down to a pressure of 20mm Hg. This effectively removed any air present within the body of the chippings. The top valve was closed off and the vacuum pump disconnected from the vacuum chamber. The top valve was attached to a reservoir of water via a length of pipe which was full of water to prevent the inflow of air. The top valve was reopened allowing the water to flow into the depressurised chamber. Once the level of water in the vacuum chamber had reached above the level of the chippings, the top valve was closed and the chippings left to soak under the remaining vacuum for 10 minutes.

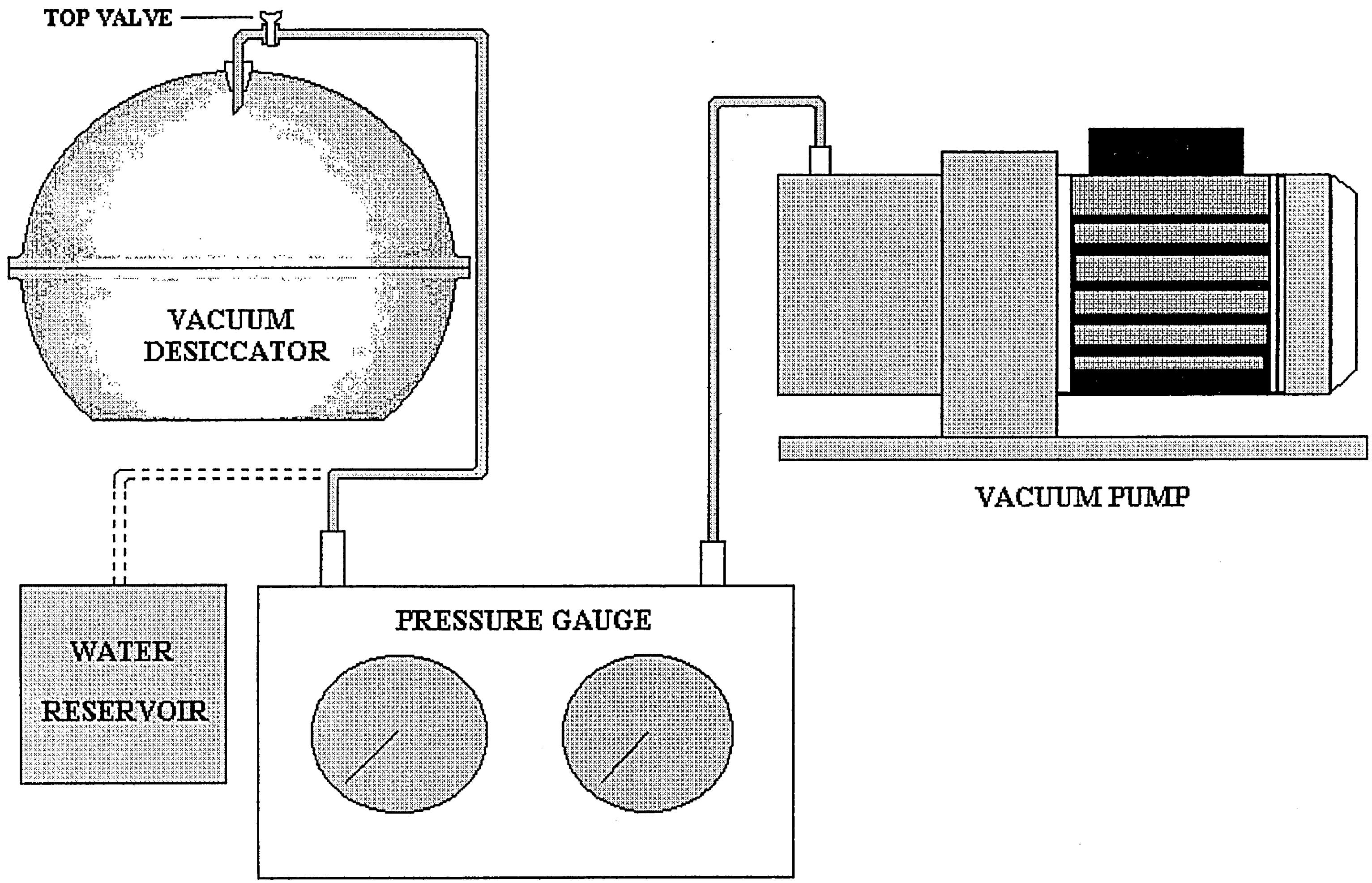


Figure 2.13
Schematic representation of vacuum test apparatus

After the soaking period the following measurements were taken :-

i) The weight of chippings and basket in water (resting on the bottom of the reservoir)

ii) The weight of chippings and basket suspended in water

The above methodology and measurements were repeated for the other chipping types under test. The dry weight, weight in water and weight suspended in water of the basket was taken before and after the testing of the chippings so the respective weights could be subtracted from the weights taken in (i) and (ii) above.

Following the determination of the physical properties of the individual samples, a PSV specimen was produced from each of the individual samples. The resulting specimens (4 for each chipping type) were then subjected to a British Standard PSV test. Skid Resistance Values (SRV) were taken for each specimen and corrected by use of the PSV control stone values. This allowed a direct comparison to be made between corrected SRV and chipping properties.

The measurements from the above investigations and subsequent further calculations are detailed fully in appendix 1.4.

2.10.4.2 Results

Figure 2.14 shows the relationship between specific density of the chipping and the Skid Resistance Value (SRV) of the various steel slag fractions. This agrees with the relationship suggested by Hosking(fig 2.12) between bulk density and PSV for blast furnace slag. The SRV is seen to decrease as the Specific density increases. The equation for the linear regression shown in figure 2.14 is :-

$$SRV = 119 - (0.017 \times \text{Specific Density})$$

This relationship is expected because an increased particle density suggests that a chipping contains fewer air vesicles and therefore is more prone to polishing and losing it's skid resistance (figure 2.16). Chipping's containing fewer air vesicles will lose their skid resistance more readily because as they are worn down under testing/traffic, fewer fresh vesicles are broken into resulting in a much smoother surface.

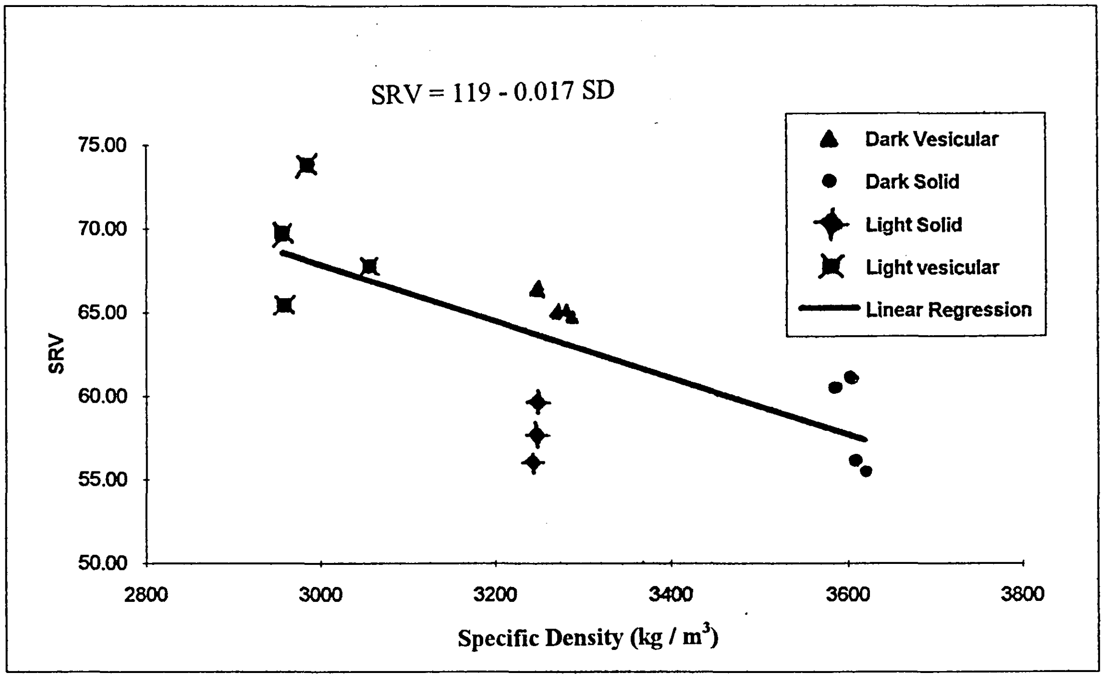


figure 2.14

Relationship between specific gravity and Skid Resistance Value for steel slag aggregate

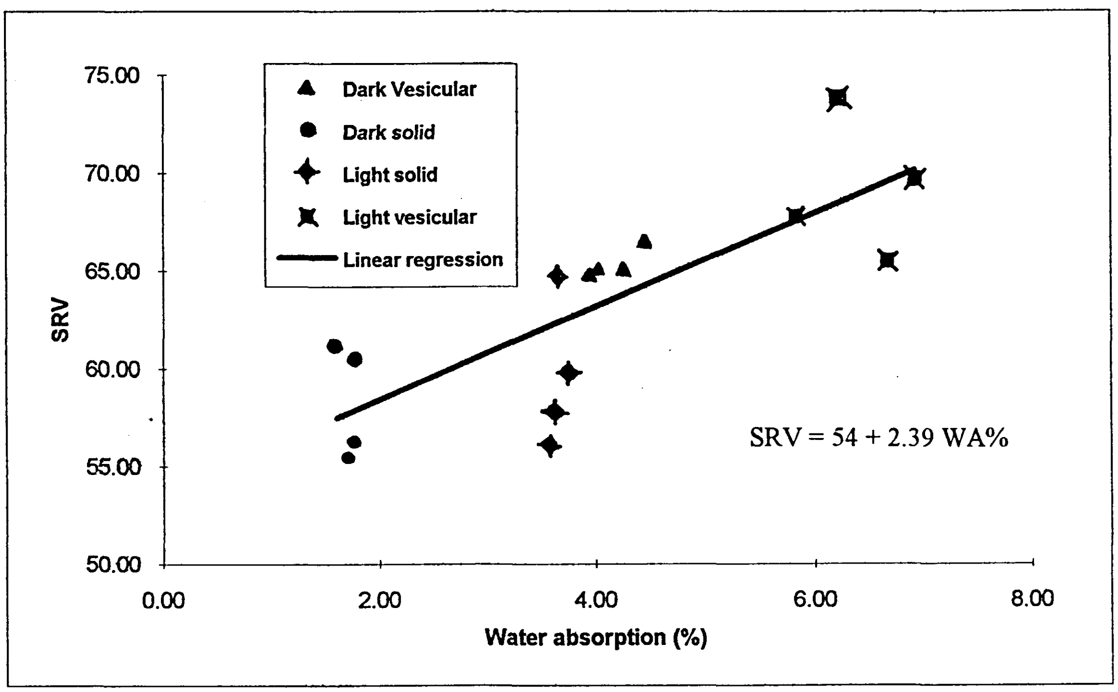


figure 2.15

Relationship between water absorption and Skid Resistance Value for steel slag aggregate

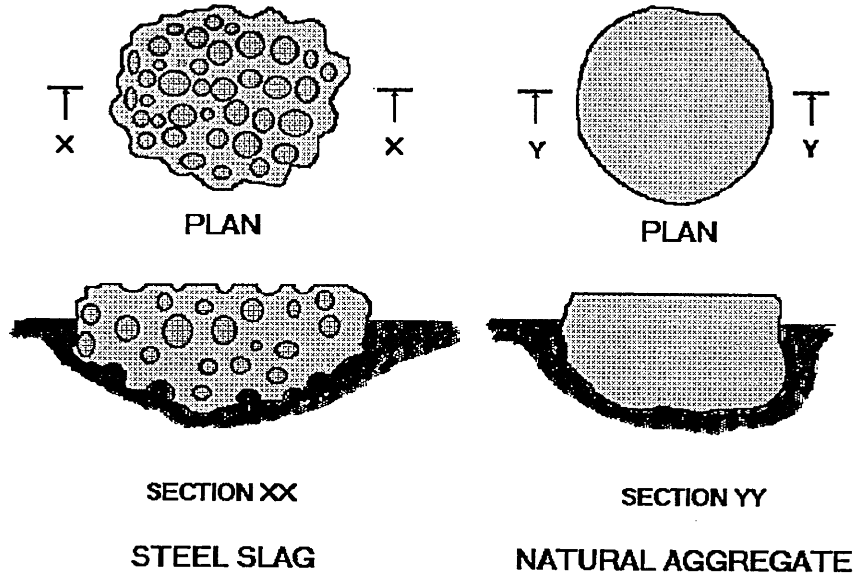


figure 2.16
Authors suggested comparison of surface textures
after the polishing of steel slag and a homogeneous natural aggregate.

Figure 2.15 shows the reverse relationship between Water absorption(%) and SRV. The equation for the linear regression shown in figure 2.15 is:-

SRV = 54 + (2.39 x Water Absorbtion)

This is an expected relationship once more. The highly vesicular chippings are represented by the higher water absorption figures which produce increased SRV's.

Table 2.11 shows the average results for each chipping type. The range of PSV's obtained from the different chipping types was 58.5 to 69. From the table it is clear that segregation of chippings from the steel slag blend could produce aggregates of distinct levels of polishing resistance. The practicalities of achieving this segregation would be very complex and are beyond the scope of this thesis.

Chipping type	PSV	Standard deviation
Dark vesicular	65.5	0.76
Dark solid	58.5	2.91
Light vesicular	69	3.52
Light solid	59.5	3.77

Table 2.11
PSV's of distinct steel slag chipping "types" (extract from app. 1. 4.1)

However the author and his colleagues had some concern regarding the validity of the vacuum test procedure. The "closed porosity" nature of steel slag may not have allowed air to be extracted from, or water absorbed into the body of the Chippings. If this was the case, the only available method for determining the true specific gravity of closed porosity bodies was a destructive grinding method which breaks down the chipping and vesicles before measurement, thus ensuring no entrapped air. Use of this method would prevent any direct correlation being achieved between the chipping properties and the SRV.

The values quoted from the investigation can certainly be assumed to be characteristic of surface properties of the four chipping types. The values can only be assumed to be characteristic for the size of chipping tested due to the non-constant relationship between surface area and volume of bodies. The investigation was therefore deemed to be valid for the aggregate size tested and relates only to the surface properties of the aggregate. The author believes that the investigation was valid within the scope of the project because :-

i) the investigation was intended to be a comparison of the performance of different elements of the steel slag blend. The same size fraction chippings were used throughout the investigation and consequently any relationship between size of chipping and test result is not relevant.

ii) the performance of the chippings was assessed by their skidding resistance. The fact that the test results obtained from the vacuum determination method may reflect only the surface properties of the chippings is not significant because it is the surface of the chippings where the resistance to skidding is actually mobilised.

2.10.5 3mm Aggregate Investigation

Section 2.7.2 details the usage of 3mm aggregates on UK roads at the present day. Calcined Bauxite is a very hard, artificially manufactured aggregate[18] which has excellent skid resistance properties when used as a 3mm aggregate bonded to the road surface with an Epoxy Resin.[14] The price of calcined bauxite varies depending on which country the aggregate is sourced from. All command a premium price however. This price is justified by high mining, heat treating, and transportation costs, combined with small yield and good performance of the aggregate.

The hard nature of steel slag aggregate, indicated by it's very low AAV figure (from company records and appendix 1.6.3), suggests that steel slag 3mm aggregate might, in certain cases, be a possible alternative to the expensive calcined bauxite[15].

2.10.5.1 Methodology

The aim of the investigation was to directly compare the skidding resistance of a sample of 3mm calcined bauxite with various steel slag aggregate fractions. Once the various elements of steel slag production had been tested and ranked in order of skid resistance, further testing would be executed on any promising steel slag fractions. Determination of skidding resistance levels was through the use of a modified version of the British Standard PSV test.

The author observed a problem with the operation of the polishing test in that the level of the surface of the 3mm test specimens (section 2.10.5.2) when placed on the machine was higher than that of the 10mm chipping control specimens. This resulted in the wheel jumping off the preceding 3mm specimen and landing on the 10mm control specimen some distance in from the leading edge. This resulted in some length of the control specimen being left unpolished and the whole specimen having a higher SRV than normally associated with the control stone under standard test conditions. Consistency of the polishing regime enacted on the aggregate for each test could not be verified by the SRV results for the control specimen because of the above inconsistency in polishing. This problem was eradicated by introducing "direct comparison" tests whereby the two aggregates being tested were polished on the same wheel, thus ensuring similar polishing regimes for each aggregate.

In order to ensure consistency of results from the pendulum skid tester, calibration checks were performed throughout the test period using criggion specimens, as detailed in the British Standard PSV test procedure.

2.10.5.2 Specimen Production using 3mm Aggregate

One difficulty faced within the investigation, was the production of PSV specimen using 3mm aggregate in moulds designed for use with 10mm Chipping's. To convert the standard moulds for use with the 3mm aggregate, a blanking plate 3mm thick was placed in the curved bottom of the mould. This allowed a "blank" specimen to be cast using crystic resin which was 3mm short of the required profile. A system of adhering 3mm aggregate to these blank specimen plates was required and initially a commercially available epoxy resin adhesive was used.

Observations made during production and after testing of the specimens showed poor performance of the epoxy resin in holding the Chipping's on the face of the specimen blank. A new adhesive system was tried which made use of crystic resin as used in the specimen blank production. The surface of the blank specimen to which the 3mm grit was to be adhered to was scarified prior to application of the resin and visual inspection of the specimens before and after testing showed excellent performance of this adhesion system. This method of attaching 3mm aggregate was used on the remainder of the testing. The 3mm aggregate was positioned onto the specimen by sprinkling the grit over the resined area and then adjusting the adhered grains to give an even running surface, free from any resin.

2.10.5.3 Aggregate Grading under Test

To limit the number of variables present in the program, it was decided to test a specific grading of the aggregate. The grading tested in the British Standard PSV(2) test is that passing a 10mm sieve and retained on a 14/10 flakiness index sieve. Applying this to the 3mm test it was decided that the test aggregate would be that passing a 3.35mm British Standard test sieve and retained on a 6.3/3.35 flakiness index sieve.

2.10.5.4 Aggregate Sources Tested

Steel slag aggregate is derived from 2 connected processing plant silo's (section 2.6.1). Samples of the 3mm - dust size fraction were taken direct from each plant silo and screened out to the grading specified in the last section.

Another source of steel slag utilised at Templeborough is the slag produced by a Basic Oxygen furnace and is referred to as Basic Oxygen Steel slag (BOS slag). Routine testing of BOS slag is outside the scope of this thesis because the routine production aggregate at Templeborough is steel slag. BOS slag has lower skidding resistance than steel slag, is less vesicular, has lower density and a matt brown appearance. The aggregate is sometimes used at Templeborough when the stocks from the Sheffield steel works are reduced. A more profitable use for the aggregate might be in use as a 3mm aggregate. The skidding properties of the specified 3mm grading of BOS slag were therefore investigated within this section of the work.

The calcined bauxite (Guyana) was screened out to provide the same grading as for the steel slag.

2.10.5.5 Results

The results for all the 3mm aggregate investigations are detailed in appendix 1.5 (pages 1(xi)-1(xv)). The following section will detail the investigations as they progressed, detailing the aggregates tested and the reasons for performing the tests.

The initial stage of the investigation was to quantify the skidding resistance potential of all the different fractions of steel slag currently produced at Templeborough and the skidding potential of the Guyana calcined bauxite against which the steel slag's performance was to be measured. Manufacture of the initial steel slag specimens was with the epoxy resin adhesive as detailed in section 2.10.5.2. The chippings appeared to be poorly bonded to the surface of the specimen blank and subsequent testing proved this. The Guyana bauxite and BOS specimens were produced using the crystic resin system and testing of these resulted in no chipping loss. These results were therefore considered to be representative of the aggregate.

The results from the initial comparison test (appendix 1.5.1, page 1(xi)) were affected by significant chipping losses from the steel slag samples. The calcined bauxite results, which were unaffected by chipping losses, gave an average Skid Resistance Value (SRV) on the pendulum skid resistance tester of 74. One of the steel slag "Pan mills" derived aggregates gave a SRV in excess of 71. This specimen was relatively unaffected by chipping loss and therefore appears to be a representative result for this fraction of the aggregate, but this would need confirmation by further testing of the aggregate The "main plant" derived aggregate gave SRV results around 65-66. These specimen had been significantly affected by chipping loss and were possibly not representative of the aggregate. The results of the BOS slag aggregate showed a low average SRV (60-63) which made this material unsuitable for use in this application.

The conclusions from the initial test were :-

i) The calcined bauxite results could be relied on as representative results for comparing the skidding performance of the various steel slag aggregates against.

ii) The steel slag aggregates derived from the "Pan mills" and "Main Plant" storage silo's showed promising results despite significant chipping losses on some specimens. It was proposed to re-test the aggregate with new specimens using the crystic resin adhesion system.

iii) The BOS slag aggregate showed poor SRV performance without any chipping loss and it was decided to eliminate this from the investigation.

The aim of the second test was to reliably quantify the skid resistance properties of the two remaining fractions of steel slag and to compare their performance against that of a natural aggregate of known PSV(55). All specimens were produced using the crystic resin adhesive and no problems with chipping loss were encountered. The results from this test are detailed fully in

Appendix 1.5.2 (page 1(xii)). The pendulum skid tester was shown to be working incorrectly at this point by the results achieved on the "Criggion" calibration specimens. The usual adjustments to amend the operation of the skid tester had no effect on the results being obtained. Rather than discard the results (which had to be taken within 1 hour of completing the polishing run) the calibration values were used to correct the results obtained. The correction was the sum of the typical historic SRV of the calibration specimen minus the SRV obtained on that specimen during the test. For this test, measured SRV's were reduced by 4 units.

The "Pan mills" derived aggregate gave a corrected SRV performance of 70. This is equal to the required SRV performance of 70 for this type of surfacing. The "Main plant" derived aggregate gave a corrected SRV performance of 65, which agreed with the performance suggested in the initial investigation. The natural aggregate had a corrected SRV performance of 62, the lowest level of SRV, but this was expected from the lower PSV figure of this aggregate compared to that of the steel slag. Conclusions from this section of the investigation were :-

i) The "Pan mills" derived aggregate showed a level of performance just equal to that required for this type of surfacing. This fraction of the aggregate was identified as the one with the greatest potential for use in a 3mm epoxy-resin surfacing.

ii) The "Main plant" derived aggregate showed low levels of SRV once again and it was decided to eliminate this fraction of steel slag from the investigation.

The final test of the investigation was aimed at providing a direct comparison between the performance of steel slag "Pan mills" derived aggregate and Guyana calcined bauxite. The skid resistance of the steel slag compared to the calcined bauxite was to be monitored after a standard six hours of polishing on the accelerated polishing machine (APM) and then after a second six hours polishing. To carry out the test, six steel slag and six calcined bauxite specimen were produced using crystic resin adhesive. The results from the testing are detailed fully in Appendices 1.5.3, 1.5.4 (pages 1 (xiii) and 1 (xiv)). Figure 2.17 shows :-

i) After the standard 6hrs polishing, steel slag retained an average SRV of 70. This was at the level required by current specifications (section 2.4.5). This represented 94% of the SRV retained by the calcined bauxite
(average SRV = 74.5).

ii) After the extended 12 hrs polishing, the average SRV of steel slag had been reduced to 64.5 compared to a SRV performance by the calcined bauxite of 71. Ninety one percent of the SRV of the calcined bauxite was retained by the steel slag. More important was that the skid resistance value of the steel slag had fallen below the level of SRV prescribed for this type of surfacing.

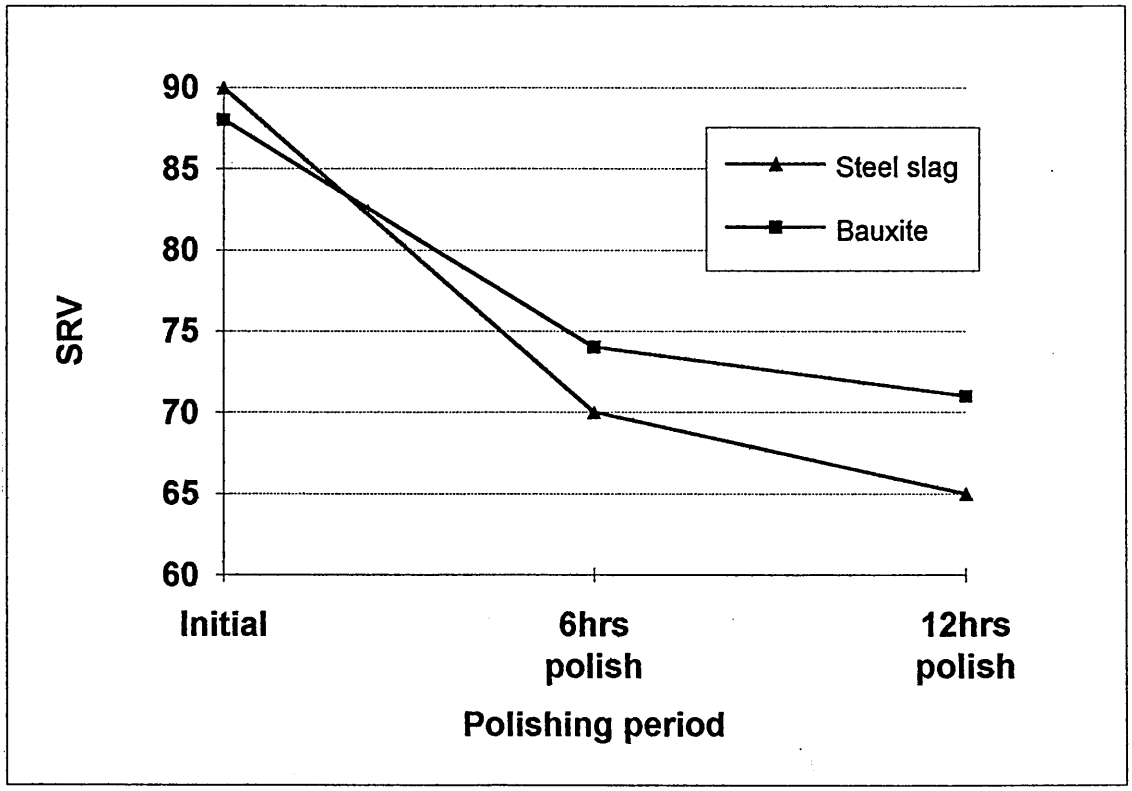


figure 2.17

Polishing profile of 3mm steel slag and Guyana bauxite aggregate

The above findings suggest that the "Pan mills" derived steel slag 3mm aggregate can be used as an alternative to the traditionally used calcined bauxite, based on the testing method used above. Performance of the aggregate is not as good as that of the calcined bauxite and does not have as good resistance to polishing over extended periods. It does however merit further consideration being given to the performance of an aggregate which could conceivably be used at a lower cost to both the client and the environment.

2.10.6 Comparison of Steel Slag and Natural Aggregate Polishing Profiles

Roadstone aggregates are tested for polishing resistance characteristics by the Polished Stone Value test (PSV) detailed earlier. In this test the specimens are polished for a period of 6 hrs in total, a skid resistance value taken at the end of this period and then correction factors added/subtracted from the measured SRV to give a PSV result. Within the test structure, there is no mechanism for assessing the polishing profile of the aggregate during the test period. In order to investigate the polishing profile of steel slag, the following test procedure was performed.

2.10.6.1 Methodology

Steel slag specimens were produced according to the "riffle" PSV test procedure. These specimens were then skid tested prior to any polishing and also skid tested every hour during the test. There was no other alteration to the standard PSV test other than this and therefore the end PSV was considered by the author to be a British Standard result.

A major concern during the investigation was to ensure comparable results between successive hourly tests. This was achieved by taking calibration readings before each group of tests using a Criggion calibration specimen of known value. Any fluctuation in the resultant SRV of the Criggion calibration specimen was reflected in a correction factor on the recorded SRV's of the test specimens. This procedure accounted for any fluctuations in performance of the skid tester throughout the test.

2.10.6.2 Analysis of Results

To assess the relationship of polishing of steel slag aggregate with time, the analysis of the results needed to compare the state of polishing of the specimens throughout the polishing time against the initial unpolished state. Further requirements were to provide a profile representative of a cross section of steel slag aggregate and also to compare steel slag against the performance of the natural aggregate. To provide these comparisons the following analysis was performed on the results.

With reference to appendix 1.7 (page 1 (xix)), SRV results were produced for each of the individual specimen prior to any polishing and for every subsequent 1 hours polishing upto the standard test run of 6 hours. To provide an analysis to the above requirements, the average of the 12 steel slag specimens prior to polishing was calculated and taken as 100% skid resistance value. The results after 1 hours polishing of the steel slag specimens were then averaged similarly, the resultant being expressed as a percentage of the zero polish average. This procedure was repeated for the results on natural aggregate specimens, providing an average percentage drop in skid resistance for each aggregate type after 1 hour of polishing. This calculation was repeated for each hour of polishing to produce a polishing profile in terms of percentage of retained skid resistance against time.

2.10.6.3 Results

The test results are detailed fully in Appendix 1.7 (page 1(xix). Figure 2.18 shows the relationship of SRV for steel slag throughout the six hour period and compares it to the polishing profile of a natural aggregate (i.e. the PSV control stone).

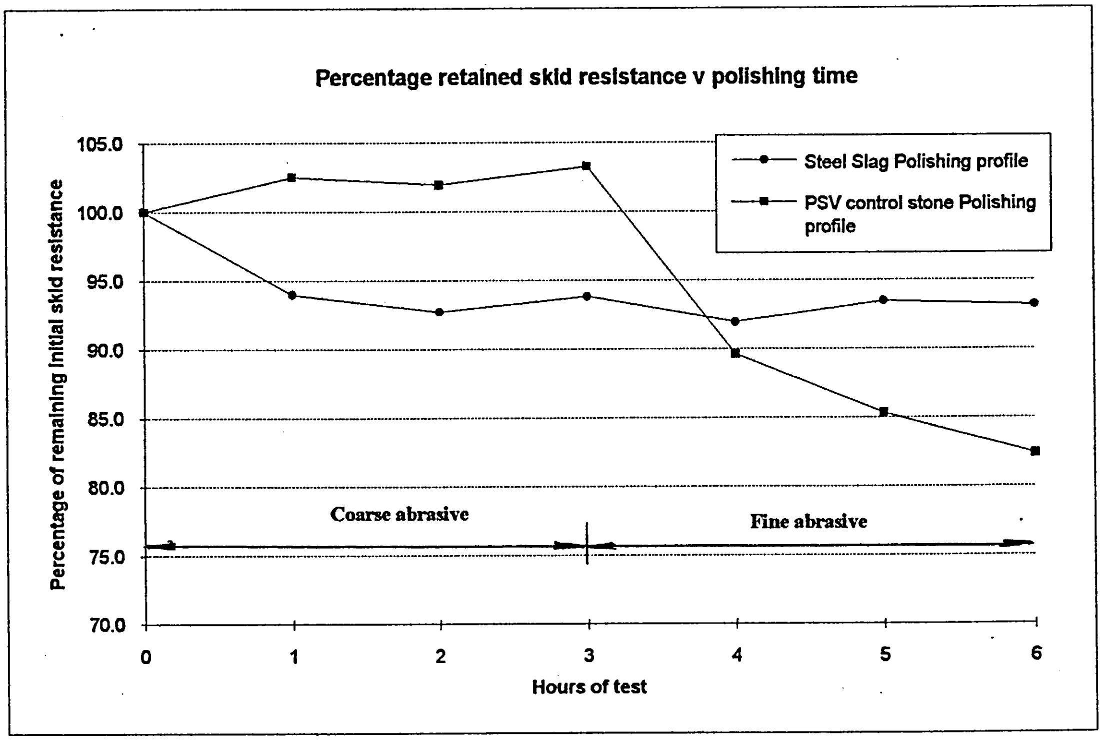


figure 2.18

Polishing profiles of steel slag and a natural aggregate

The graph shows a six hour polishing period on the accelerated polishing machine. The first three hours of the polishing are performed using a coarse "corn emery" abrasive. This period of polishing emulates the "abrasion" effect of traffic on a road surface which usually occurs during the Winter months when wet grit and large particles of detritus cause the roadstone to be scarified and worn down (see section 3.4.1). This condition leaves the micro-texture of the chippings intact due to the scarification by the coarse grit. The second three hours of polishing are performed using a fine "emery flour" abrasive. This is intended to simulate the action on a road surface during dry summer periods when finer, dry particles of grit polish the road surface reducing the micro-texture to a minimum.

The two profiles derived from the two aggregates show very different polishing characteristics. The steel slag polishing profile shows immediate reduction of SRV over the initial 1 hour "coarse abrasive" polishing. This suggests much of the initial skid resistance of steel slag is supplied by sharp, angular projections on the surface of the chipping which can easily be removed by coarse polishing regimes. Once the initial roughness of the surface has been removed, very little reduction in skid resistance takes place beyond this point. The application of a fine abrasive also results in little reduction in skidding resistance. The author feels this may be due to the presence of vesicles within the surface of the chipping. The flat surfaces between the vesicles (figure 2.16) will achieve a high degree of polishing. The resistance to skidding may however be maintained by the sharp edges where the vesicle wall meets the surface of the chipping. This sharp edge encourages interlock between the rubber and the chipping, thus maintaining the skid resistance of the aggregate during fine polishing.

In marked contrast to the polishing profile of steel slag aggregate is the polishing profile of the natural aggregate. This shows a very slight increase in skidding resistance over the initial "coarse abrasion" period. This relationship was also observed on type "A" stone during similar testing by Maclean and Shergold(1), detailed in figure 2.19. The author feels this may be due to a lack of any sharp angular projections being present on the surface of the natural aggregate prior to polishing. Without any such angular projections the significant reduction in skid resistance seen for the steel slag within the first hour of polishing cannot occur with the natural aggregate. The surface texture that was present on the natural aggregate prior to polishing was not diminished by the coarse polishing action. It is more likely that the surface was scarified by the action of the coarse abrasive and consequently it's skidding resistance was improved.

The behaviour of the natural aggregate under the fine polishing regime was entirely different to that under the coarse polishing regime. An immediate reduction in skid resistance retention to a level below that of steel slag was recorded within the first hour of fine polishing. The level of retained skid resistance continued to deteriorate throughout the three hours of fine polishing, with no indication of achieving a residual value. Once again, the author feels this is due to the solid, relatively smooth surface of this particular natural aggregate becoming finely polished under the fine polishing regime. Unlike the steel slag aggregate, no undulations were present in the surface of the natural aggregate and therefore the friction between the rubber and the chipping is entirely dependant on micro-texture. The micro-texture of the natural aggregate was constantly being reduced by the fine polishing and therefore the polishing effect was cumulative rather than concentrated around any particular period.

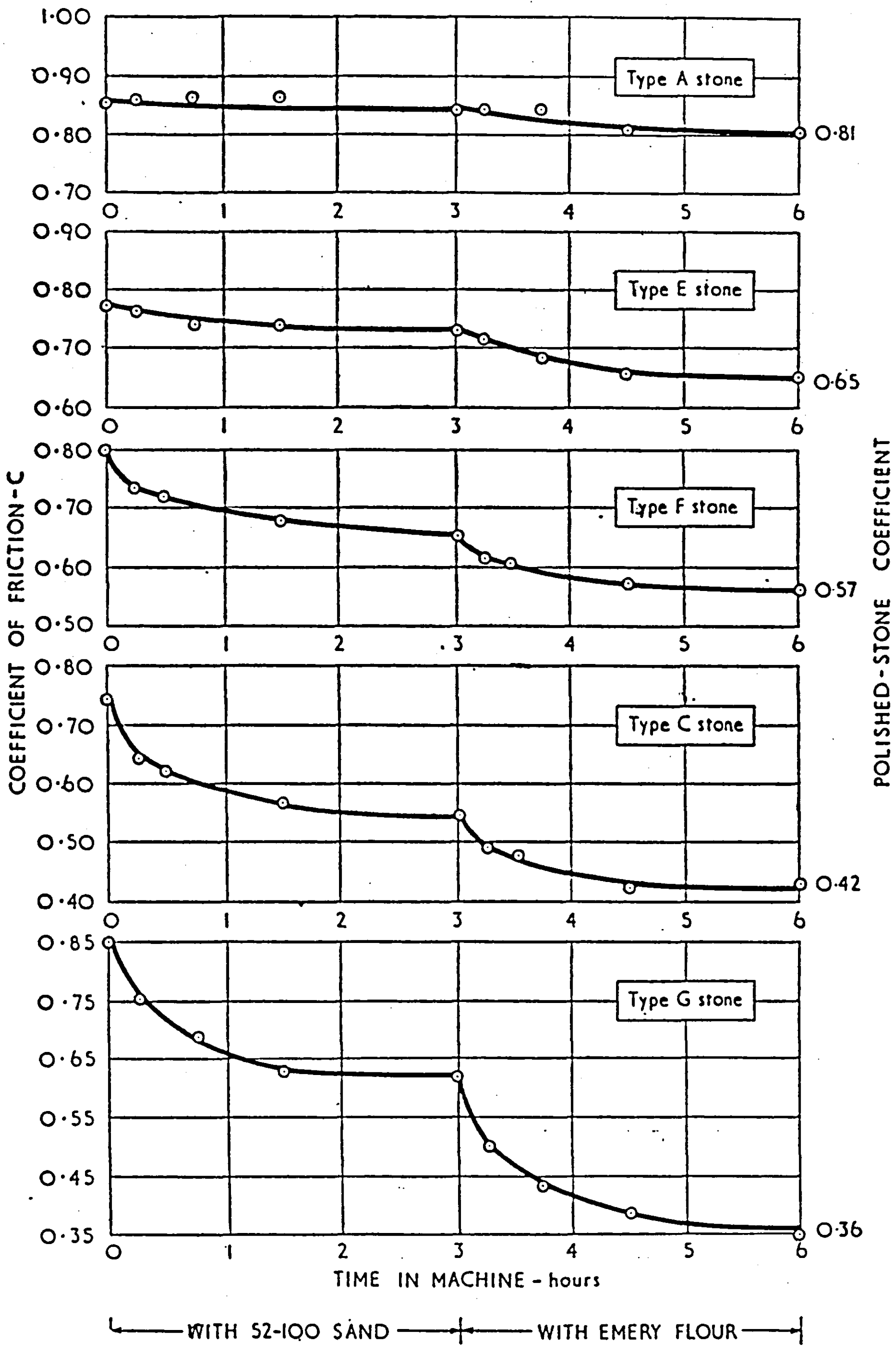


figure 2.19

Polishing profiles on other aggregates (Ref 1)

2.11 Main Conclusions from the Laboratory PSV investigation

The conclusions from the various investigations undertaken in this chapter are :-

i) The experimental results using the PSV test on samples of standard production steel slag aggregate gave an average value of 63.5. Confidence intervals placed on the results show the average PSV for steel slag aggregate is 95% certain to lie within the range $58 < PSV < 65$.

ii) A method of steel slag specimen production involving the use of a riffle box was proposed and shown to reduce the variability of PSV test results on steel slag.

iii) No difference existed between the polishing characteristics of steel slag aggregates obtained from the two main supplying sites in Sheffield and Rotherham based on the limited testing carried out in this project. A significant difference did exist between the steel slag derived from the above sites and that derived from a site at Cardiff.

iv) No significant difference was found to exist between the aggregates derived from different parts of the processing plant.

v) A relationship between the skid resistance and different physical properties of the aggregate was derived. The relationships derived were as follows:-

a) Specific density v skid resistance

SRV - 119 - (0.017 x Specific Density)

b) Water absorption v skid resistance

SRV = 54 + (2.39 x Water Absorption)

vi) 3mm steel slag "Pan mills" derived aggregate has acceptable skid resistance performance compared to that of a currently used, good quality 3mm calcined bauxite. This suggests that the steel slag aggregate tested has a possible application for high skid resistant epoxy resin bonded surfacings, although further testing is required to confirm this position.

vii) The polishing profile of steel slag aggregate during a standard test on an accelerated polishing machine, shows marked differences to that of a natural aggregate during the same polishing regime.

3.0 On Road Skid Resistance Determination

In 1906 a Parliamentary Select Committee was set up to investigate the cause and control of skidding. Actual research on Britain's roads did not commence until 1927 at the National Physical Laboratory at Teddington. Work later transferred to the newly formed Road Research Laboratory (RRL) at Harmondsworth in the early 1930's. Work at the RRL (latterly known as the Transport and Roads Research Laboratory, Crowthorne) has continued until the present day where a considerable fund of knowledge on the in-service skidding resistance of roads and the reasons for the different levels of skid resistance has been collected. The relevant areas of this fund of knowledge will be discussed later in this section

In order to collect skidding resistance data a consistent method of measurement was required. Various methods of achieving the measurement of skid resistance of road surfaces have been used throughout the years by the TRRL and local authorities. Currently, the accepted form of on road skid testing is the Sideway-force Coefficient Routine Investigation Machine (SCRIM). This apparatus is widely used by most local authorities for the routine skid resistance testing of trunk roads and also by the TRRL for research purposes. The SCRIM machine was chosen to perform the on road skidding resistance testing due to the familiarity and acceptance of results and their interpretation within the highways industry.

A main consideration during the earlier work undertaken into skidding resistance was the provision of skidding resistance standards for different road surfaces. These standards were intended to ensure that different road sites did not create a higher risk of skidding accidents than other road sites. The principle behind this ideal was not to produce a uniform high skid resistance surface for all road sites but rather tailoring a sites skid resistance to the risk of that site having a skidding accident. This, it was hoped, would achieve the aim that the risk of skidding accidents occurring at all sites should be the same.

The on road skidding resistance performance of steel slag aggregates has traditionally been perceived to be better than the PSV of the aggregate suggested. This relationship has been perceived by Local Authority Engineers through experience of working with the aggregate. A further property associated with the aggregate, once more through experience of working with it, was the apparent retention of skid resistance over long periods of time. Both of the above relationships are unproven and therefore require quantification of the skidding resistances of steel slag road surfaces. This was the aim of the work contained in this chapter, where on road skidding resistance has been compared against the age of surfaces and the volume of traffic passing over them.

3.1 UK Methods of On Road Skid Resistance Determination

3.1.1 The Sideway-force Coefficient Routine Investigation Machine (SCRIM)

The SCRIM method of measurement was designed by the Transport and Road Research Laboratory (TRRL)[21] with the first machine being built by WDM Ltd of Bristol in 1968. It is currently the standard skid testing apparatus for Local Authorities and is also widely used by research organisations. The format and relevance of results are widely recognised throughout the industry and therefore this machine was used for the skid testing during this investigation.

The machine consists of a lorry chassis onto which is mounted a water tank of approximately 3000 litres capacity (figure 3.1). The test wheel is mounted mid-machine, in line with the nearside wheel of the truck and is angled at 20° to the direction of travel. Water from the tank is fed onto the road surface 400mm in front of the test wheel at a rate of 0.95 litres/sec ± 20% under normal testing speeds. When the vehicle moves forward the test wheel slides in the direction of travel whilst rotating freely in its own plane. Electronic load cells measure the normal and vertical forces exerted on the wheel (figure 3.2), the data being collected by a micro-processor located in the cab. The sideway-force coefficient is defined[21] as the ratio of the normal force to the plane of the wheel (the side-way force) to the load on the wheel.

Target speeds are generally 50 km/h for routine carriageway testing and 20km/h for testing roundabouts. SCRIM is capable of testing at speeds of up to 80 km/h but a higher water delivery rate of 1.20 litres/sec ± 20% must be used at these speeds.

3.1.2 Braking-Force Coefficient (BFC) machines

3.1.2.1 Braking Force Trailers

A towed-wheel BFC machine (figure 3.3) was developed by the TRRL for studying BFC's at high speeds on roads and runways. In this test the trailer tyre is locked for approximately 2 seconds. The brake torque is measured and the force between tyre and road surface deduced. The braking-force coefficient is defined as the ratio of the force between the tyre and road to the vertical load on the wheel

The test method produces results of a very intermittent nature and for safety reasons, require surfaces to be free of other traffic. This makes the test of little use for routine highway monitoring and is currently used on the road for research purposes only. This test method was not acceptable for this project due to the safety implications associated with its use, unfamiliarity

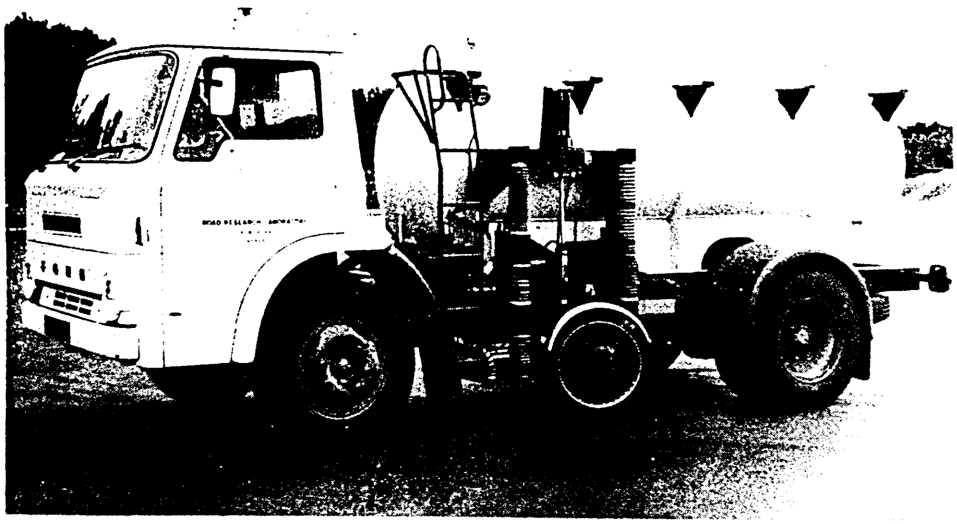


figure 3.1
The Sideway - force Coefficient Routine Investigation Machine (SCRIM)

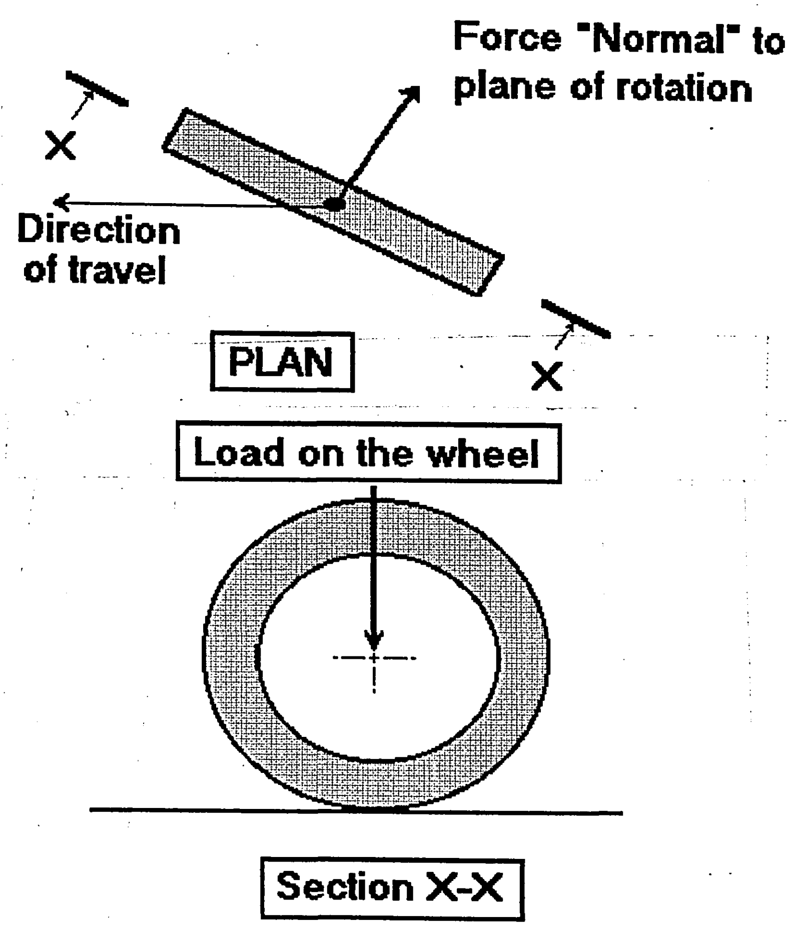


figure 3.2
Forces acting on SCRIM test wheel.

of results with local engineers and the only test trailer is not commercially available, being operated by the TRRL.

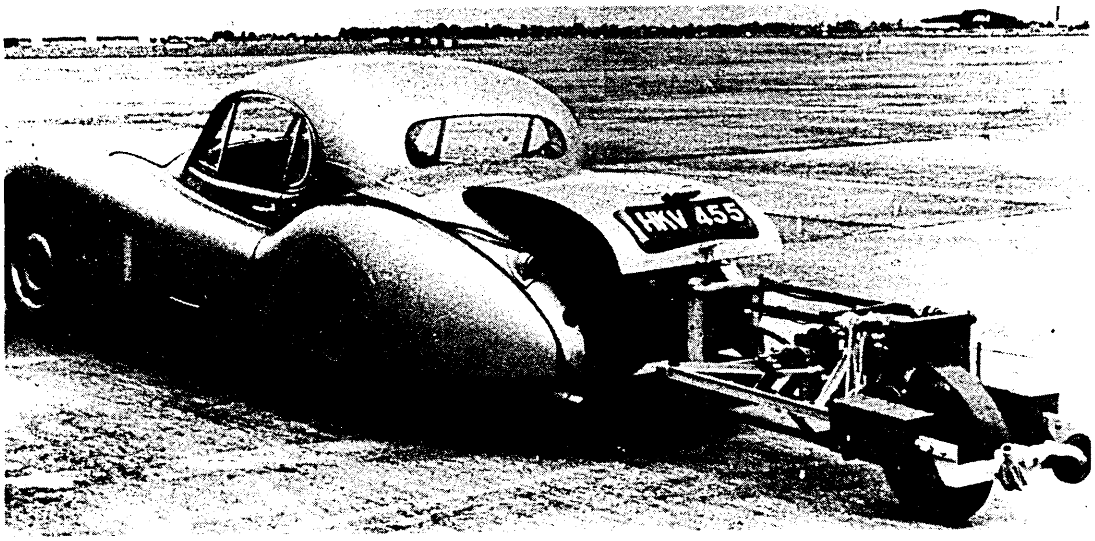


figure 3.3
Trailer for measurement of BFC

3.1.2.2 Deceleration of a Skidding Car

A decelerometer fitted to a car[22] can be used to measure the deceleration from 50km/h of the car when all four tyres are locked in a skid. It's main application was in comparing the performance of various tread patterns. The practical problems of ensuring simultaneous locking of all four wheels and the effect of tyres and suspension on the results produced unreliable test data and limited its wider usage.

A further problem with the four wheel locking system was that directional stability was completely lost during skidding. To combat this problem a car was developed where only the front wheels locked[23]. This maintained directional stability at all test speeds but still did not allow the equipment to test bends.

3.1.3 Izod Pendulum Principal (Stanley Portable Skid Resistance Tester)[3][24][25]

The above equipment was developed in the early 1950's at the TRRL to provide an inexpensive and portable means of quickly assessing the skid-resistance of a road surface. A pad of tyre-tread rubber of a standard composition is mounted on the end of a pendulum arm (figure 3.4) and is allowed to swing from a standard height over a length of road between 125 and 127 mm in length. The skid resistance of the surface is measured by the loss in upswing of the pendulum arm after passing the road surface. The test conditions have been chosen to give values which correspond to the Skid Resistance Value (SRV) of a patterned tyre at 50 km/h. Due to the relatively small area of road surface tested, the SRV does not necessarily correlate closely with SFC or BFC measurements.

Present day traffic speed and volumes have greatly increased the dangers associated with this test procedure. It is therefore imperative that adequate precautions are taken when carrying out this test. The area of road surface tested using this apparatus is very small and consequently the results can be severely affected if the actual area of road tested is unrepresentative. The small area tested also makes the test procedure very time consuming for testing long stretches of road. The implications the above factors would have had on the testing program during this project excluded the test procedure from being used during the investigations.

The portable skid tester has been modified for use in the laboratory based Polished Stone Value determination of aggregates (section 2.4).

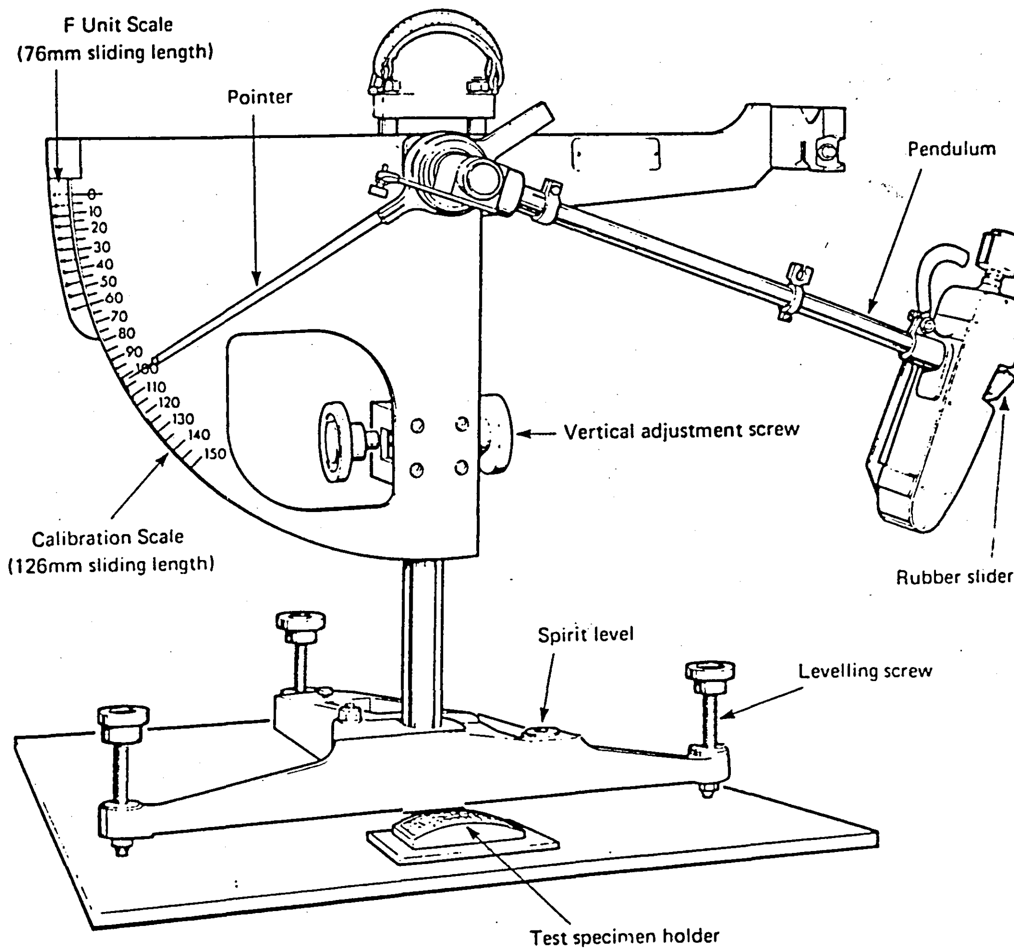


figure 3.4
Pendulum skid resistance tester

3.2 Historical Development of SCRIM

3.2.1 Motorcycle and Side-car (1929)[26][27]

The first method of measuring the Sideway Force Coefficient (SFC) was through the use of a motorcycle and sidecar (figure 3.5). The wheel of the sidecar could be angled at 20° to the direction of travel during the test. Similar to the modern day SCRIM vehicle, SFC was defined as the ratio of the force normal to the plane of the test wheel to the load on the wheel (figure 3.2). The forces were transmitted by a link mechanism to give a single track on a moving pen chart. This provided a continuous record of the skid resistance of the road. The virtues of the apparatus were quickly realised and more robust versions were designed in the mid-1930's.

figure 3.5
Early motorcycle and sidecar for measurement of SFC

3.2.2 Installation into a Suitable Car

Following the second world war, the motorcycle skid test apparatus was installed into a suitable front wheel drive car. This involved incorporating a fifth wheel, the test wheel, inside the body of the car. The first suitable cars available were Citroens and the first test machines were fitted to these. In the early 1960's the Austin 1800 became commercially available and three were converted for SFC measurement (figure 3.6)

figure 3.6
Installation of SFC test equipment into an Austin 1800

3.2.3 SCRIM

The above cars were only suitable for research purposes because they required a water bowser to wet the road surface ahead of them and the processing of results was very time consuming. A special vehicle was therefore designed at TRRL in the late 1960's to overcome these shortcomings and has become known as the SCRIM machine. The latter computes the average SFC over successive 5, 10 and 20 metre sub-lengths of road. The results were originally recorded on Punched paper-tape, but are now stored on magnetic tape. Details concerning location, direction of study and speed of vehicle are also recorded.

In order to ensure compatible results throughout the country, correction factors are applied to the results to correct for actual SCRIM vehicle speeds(28) different from the standard test speed, and for day to day variation in machine characteristics. On modern SCRIM machines corrections to the results due to the above effects are automatically included in the printout.

Calibration corrections are constant for any one days SCRIM and are relative to the results from the daily calibration of the SCRIM. Corrections for speed of SCRIM are continuously variable and are applied by reducing the measured SFC by 0.01 units for each 4 km/h the speed falls below the target 50km/h[28]. This estimate becomes less accurate the more the actual speed deviates from the target speed. Hence a lower speed limit of 30km/h is set, below which any results are discarded. Test speeds below the target speed are unlikely to occur on motorways but are likely to occur on almost all other roads due to congestion.

For test results taken above 50 km/h the reverse applies whereby the measured SFC must be increased by 0.01 units for every 4 km/h above the target speed. Testing at a higher than target speed very rarely occurs because this would purely be down to driver error.

3.3 The Components of Skidding Resistance of Road Pavements.

Skidding tends to occur when a road surface is wet[29]. Consequently research into the skidding resistance of road surfaces has concentrated on wet road conditions[30].

The friction coefficient between two sliding surfaces is thought to be the sum of the following two components :-

i) Adhesion from points where the surfaces are in contact. This suggests the water barrier between the two surfaces has been penetrated. Drainage channels in the form of road macro-texture and tyre tread pattern remove the majority of water. Ultimate penetration of the water film can only be achieved by the presence of fine scale sharp edges on the road surface (figure 3.7). These many sharp edges are referred to as micro-texture.

ii) The second component arises if the irregularities in the road surface produce appreciable distortion of the tyre. This distortion can occur in the presence of a lubricant without any contact between the surfaces. These irregularities are referred to as macro-texture.

For vehicles travelling at speeds below 50 km/h the micro-texture is dominant when determining skid resistance. The smooth finish surfacings such as Close Graded Wearing Courses and Hot Rolled Asphalt perform best in this speed range due to their low surface texture and hence strong reliance on the adhesive component.

At increased speeds, where penetration of the water film becomes increasingly difficult due to the reduction in time available, the above mentioned surfacings suffer drastically reduced skid resistant values. At higher speeds skid resistance of a wet road becomes almost entirely dependant on the distortion of the tyre by the macro-texture of the road surface. Ideal surfaces for use on high speed roads are therefore hot rolled asphalt's with pre-coated Chipping's and surface dressings. These surfaces present a continuous mosaic of projecting aggregate to the tyre, resulting in good surface texture and hence good tyre/surface interlock.

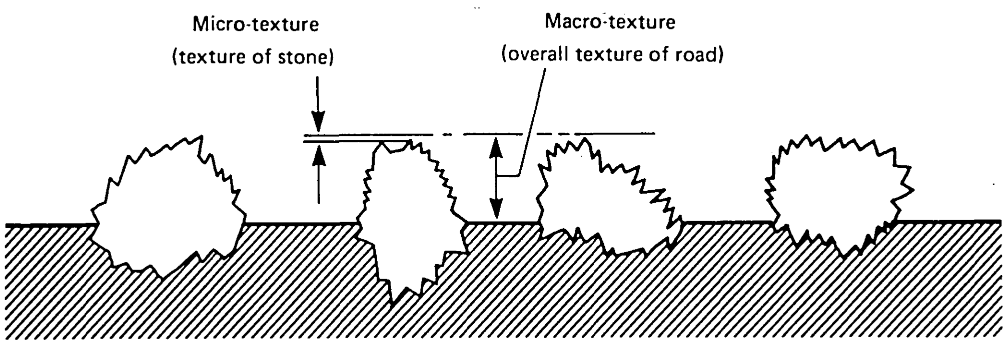


figure 3.7

Micro and macro-texture of a road surface

3.4 Factors Affecting the Skidding Resistance of Road Surfaces

3.4.1 Seasonal Variations

In dry conditions, all clean and surfaced roads have a high resistance to skidding with SFC values of about 0.90(29). This level of skidding resistance is well above any prescribed levels of skid resistance required, as detailed later in section 3.5.5. During the Summer months, dry conditions account for the state of UK roads for about 85% of the time (12). During dry periods, deposits of rubber and dust can build up on the road surface and clog up the micro and macro texture of the surface. It is when a road is in this condition that its wet skidding resistance is at a minimum. If a road in this condition is subject to a short period of rainfall, this results in an extremely slippery and dangerous surface. If rainfall were to persist on a road in this condition, skidding resistance would be restored by a combination of washing away the rubbery lubricants and the action of traffic cleaning out the macro and micro texture. As a result of this, wet skidding resistance is at its greatest over the Winter months(31) provided ice is not present because these are the wettest months and grit (detritus) and salt on the roads help to scour and thus regenerate the road surface.

The above mechanisms produce seasonal variations(29) in the skid resistance of the road surface as demonstrated in figure 3.8. It has been the practice of the TRRL to measure SFC in the Summer months (May to September incl.) when the values are at their lowest. The mean of such measurements is termed the "Mean Summer SFC"(21) and is based on three measurements taken during the SCRIM season of May to September.

3.4.2 Aggregate PSV and Traffic Densities

The polishing characteristics of the aggregate used in a bituminous road surface and the amount and weight of traffic passing over that road are important factors in determining its skid resistance. Research by Szatkowski and Hosking(10) in 1972 produced direct correlation between traffic density and SFC, which varied consistently with the PSV of the aggregate (figure 3.9). The proposed relationship showed a general reduction in expected SFC of a road if the PSV of the surfacing stone was reduced or the traffic densities travelling on it were increased. The proposed relationship was valid for hot rolled asphalt with pre-coated chippings and surface dressings

The effect of traffic densities on SFC is less clear at low densities. If a road is only lightly trafficked, the cleansing action of traffic (particularly in wet weather) is significantly reduced. This may result in the macro and micro texture of that surface becoming clogged and hence reducing the SFC. It is possible that as the traffic density increases, the cleansing action increases and improves the SFC. At the same time, the wear on the roadstone lowers the potential SFC. At some traffic density, the rejuvenating effect of the traffic and the potential SFC of the road produce a maximum skid resistance. Following this point, SFC is reduced relative to traffic density only. A possible relationship for skid resistance of road surfaces at low traffic densities was suggested by the author and is shown in figure 3.10. There is however no research at present to support the hypothesis because most research is concerned with the effects of high traffic densities on the skid resistance of road surfaces.

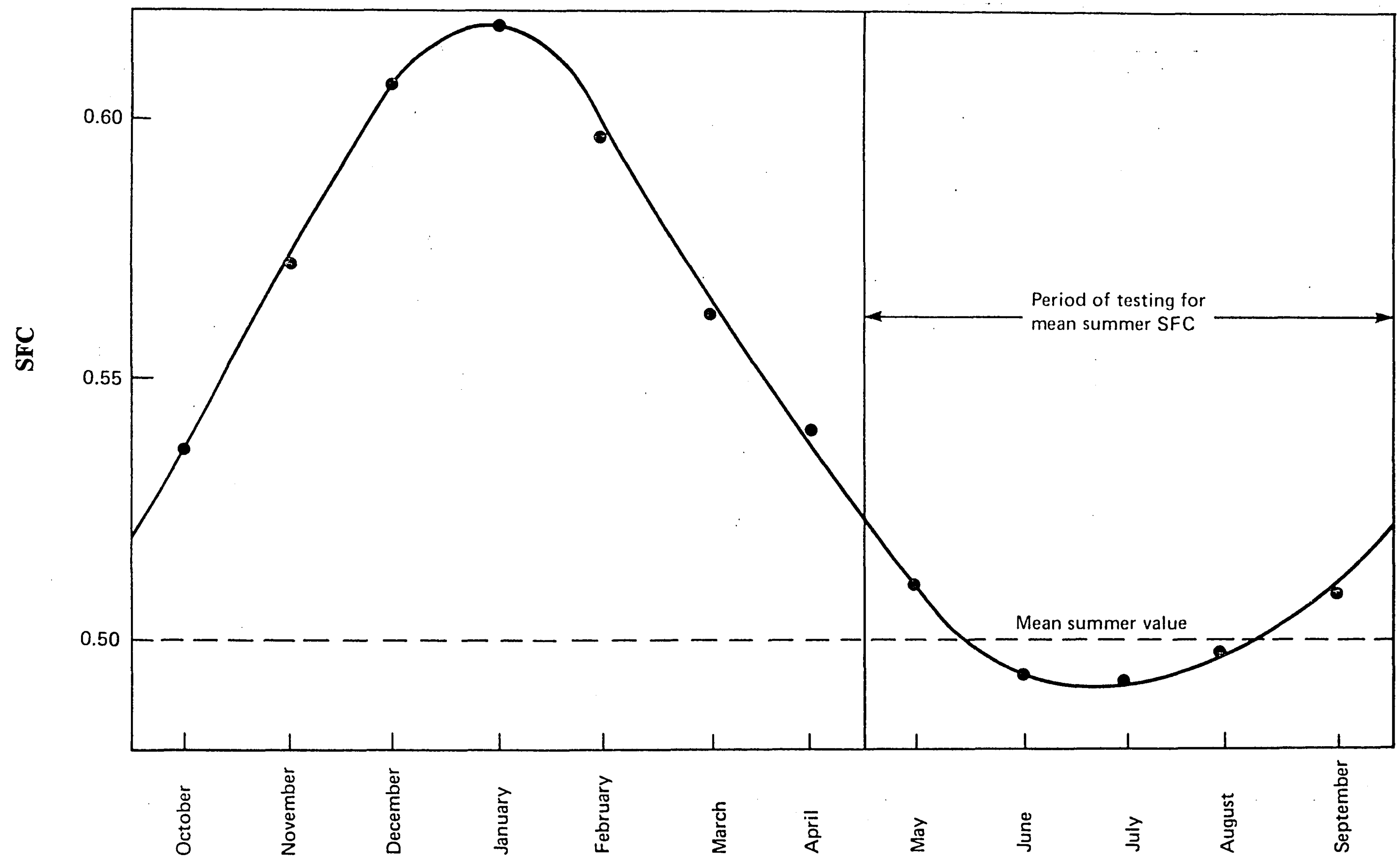


figure 3.8
Estimate of the seasonal variation of SFC of a site with a mean summer SFC of 0.50 (Ref 29)

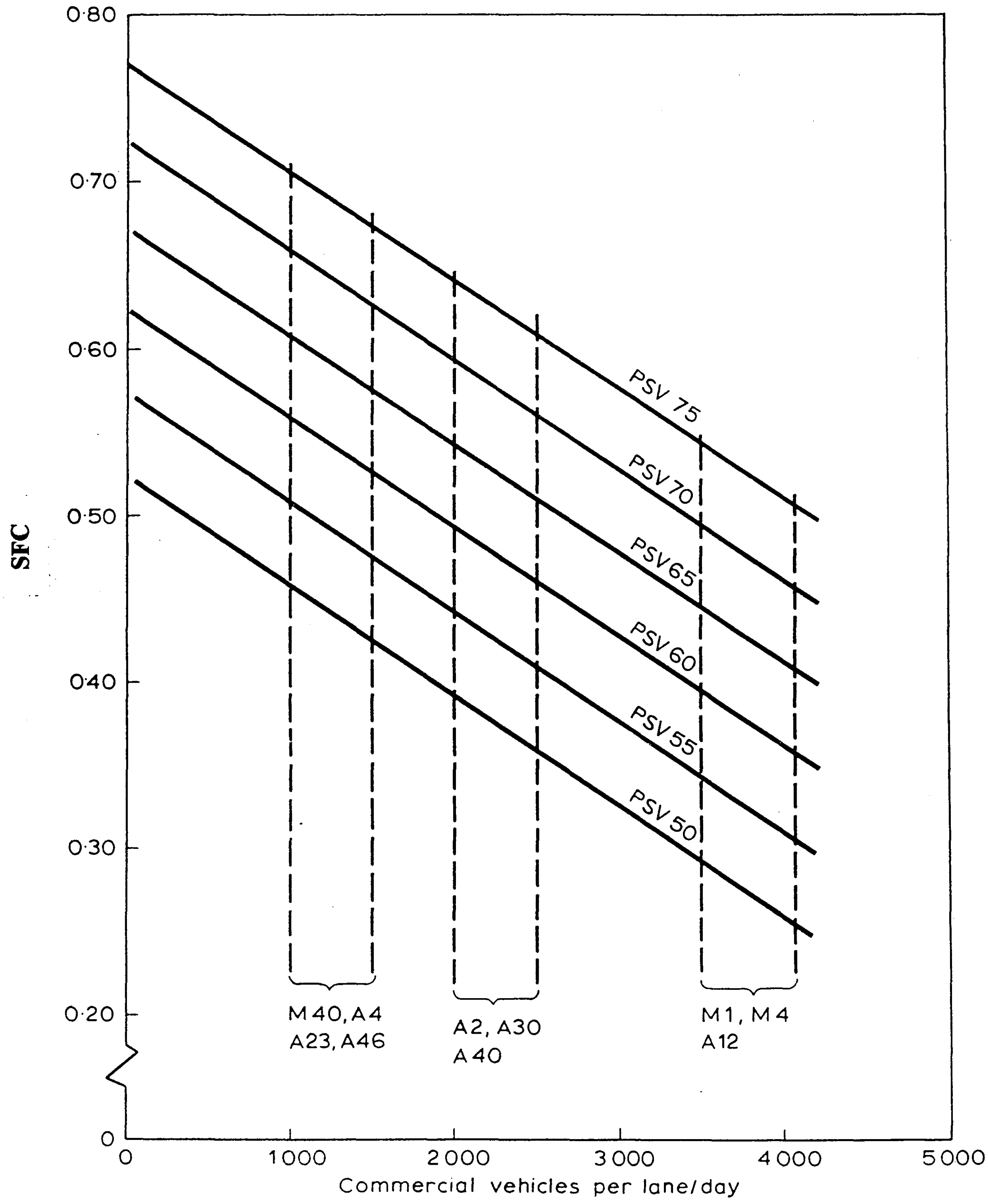


figure 3.9

Skidding resistance achievable on bituminous surfacings (Surface dressing or rolled asphalt with chippings of given PSV) under different traffic conditions. (Ref 10)

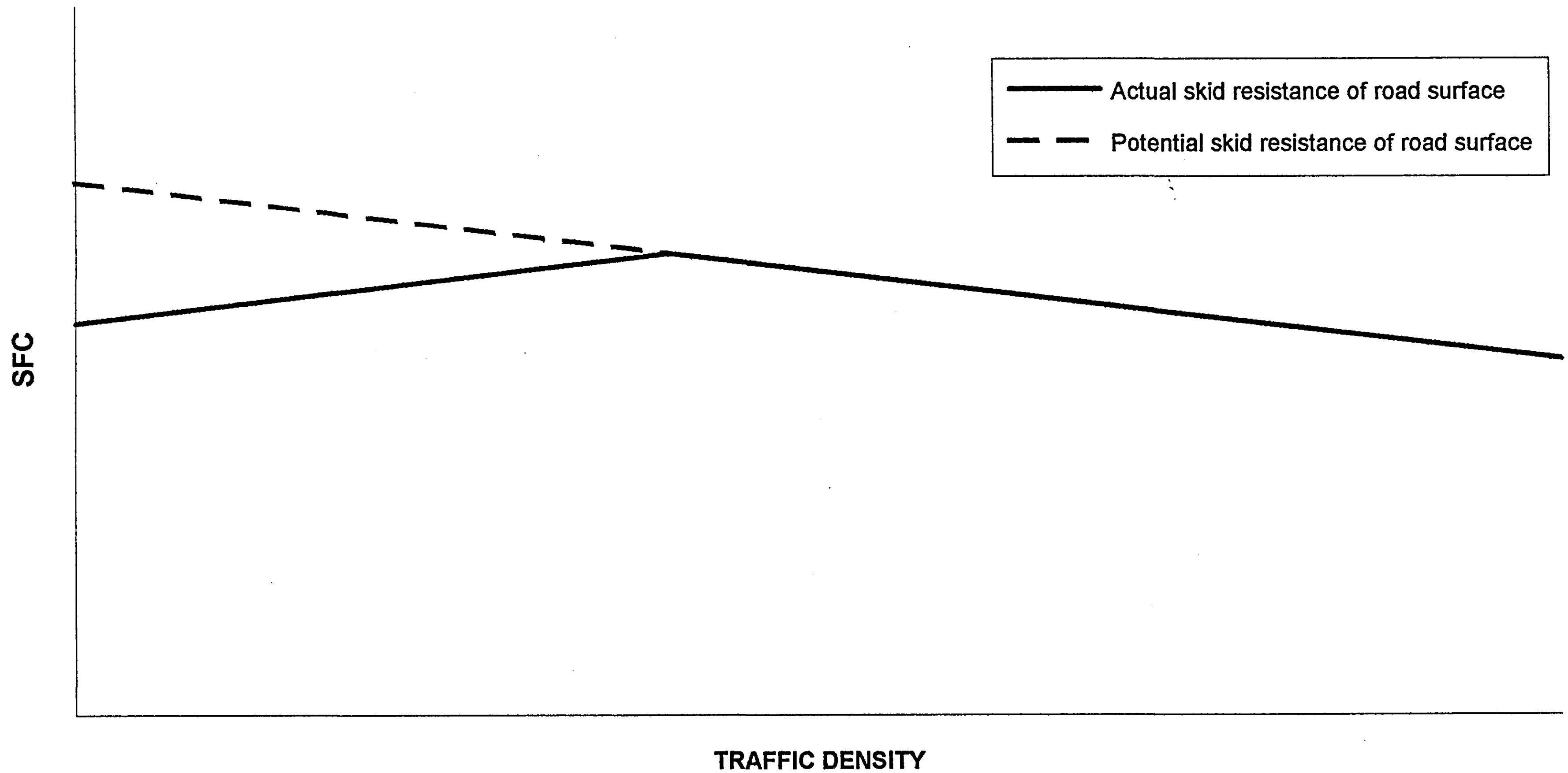


figure 3.10
Authors possible relationship between low traffic densities and SFC

3.4.3 Age of Surfacing

Szatkowski and Hosking(10) suggested that the age of a surface has very little effect on the skid resistance of that surface. The level of skid resistance of a road surface is determined by the amount and weight of traffic passing over it and the PSV of the chippings used in the surface layer.

The effect of traffic on SFC is not cumulative from year to year. Apart from variation between seasons (see section 3.4.1) the level of mean summer SFC is maintained throughout consecutive years until either the surface chippings wear away or traffic densities change. The above work by Szatkowski and Hosking provided examples of this relationship, and these are detailed in figures 3.11 and 3.12.

A high PSV aggregate used on a road surface will still polish with time but the residual or "equilibrium" level of skidding resistance will be greater than that for a road surface constructed using chippings with a lower PSV. Figure 3.13 taken from Szatkowski and Hoskings work clearly shows the effect of traffic on aggregates with different PSV's.

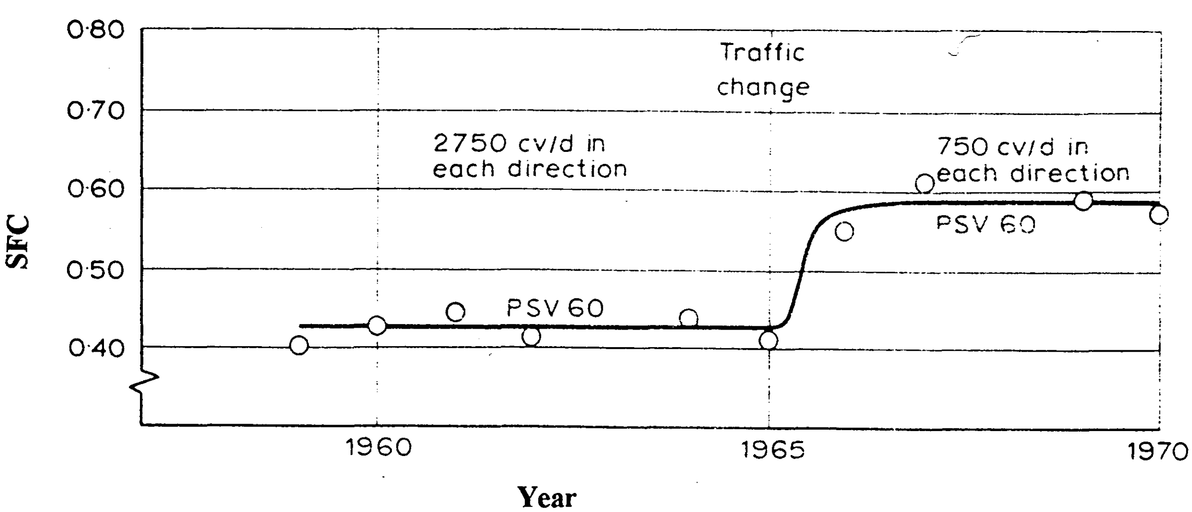


figure 3.11

Skid resistance of a road surface due to reduced traffic density (Ref 10)

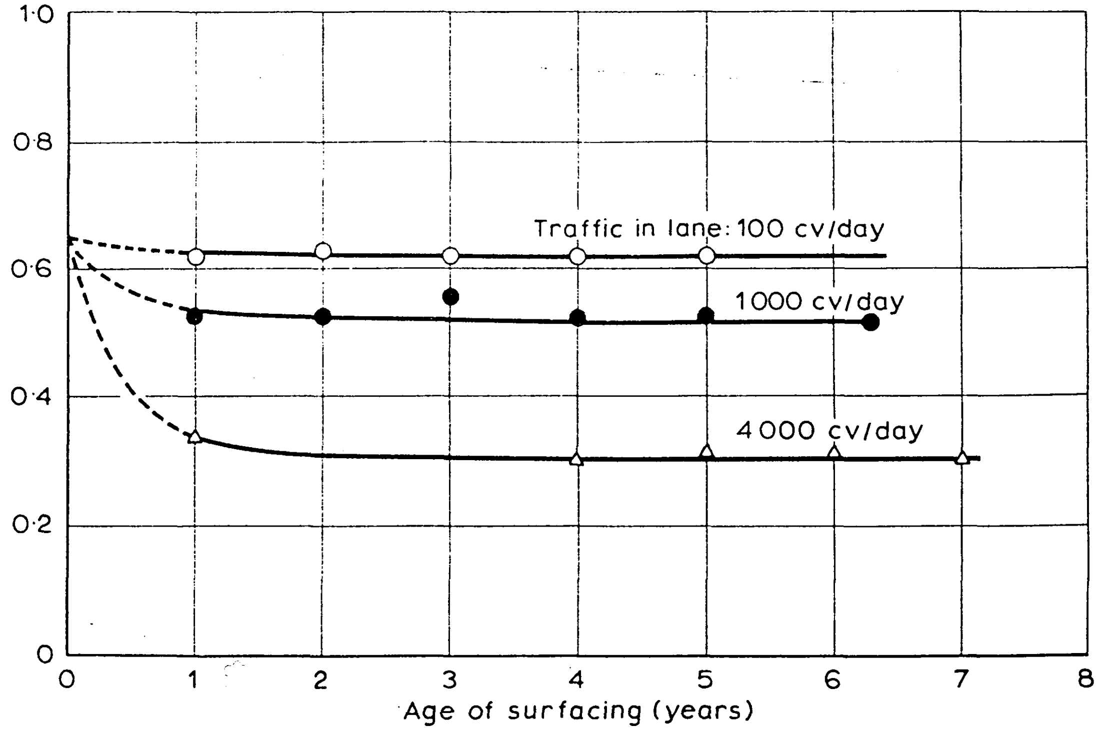


figure 3.12
Effect of traffic on skidding resistance of a typical motorway standard surfacing (Rolled asphalt with precoated chippings of PSV 58-60)(Ref 10)

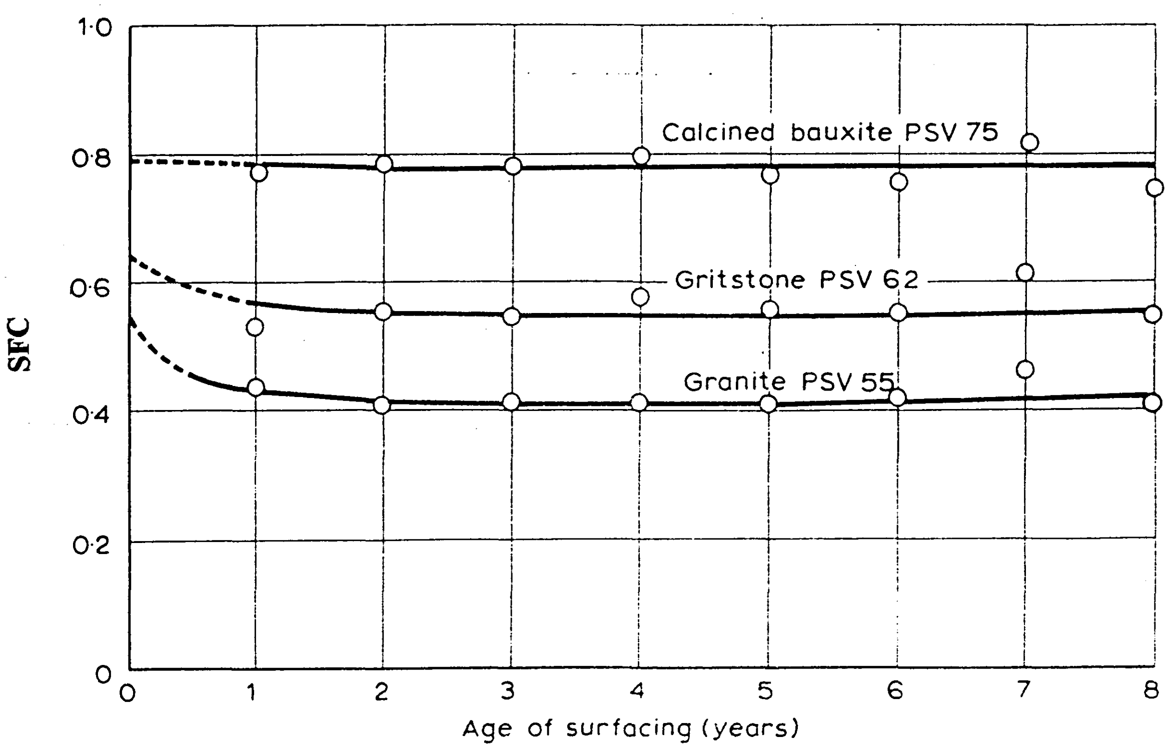


figure 3.13
Levels of skidding resistance recorded on different sections of the same road (Surface dressing using 13mm chippings. Traffic in lane : 2100 CV / day)(Ref 10)

3.4.4 Physical Parameters of Site

The physical layout of a site has a direct effect on the skid resistance of a surface[32]. On roads where vehicles generally follow a straight path at constant speed, skidding requirements are at their lowest and skidding levels are maintained due to relatively low stresses between road and tyres.

At locations where severe braking, cornering or acceleration occur, the polishing action of the tyres is at a maximum thus reducing the skidding resistance of the surface relative to other sites. The skidding resistance requirement is therefore greatest at such sites. Consequently, obtaining and maintaining performance at such sites is difficult.

3.5 On Road Specification of SCRIM Results

Since the instigation of research into the skidding resistance of road surfaces, it has been a primary aim to establish, from accident records, acceptable limits of slipperiness for different sites. Identification of such limits has always taken into account the high cost of motor accidents and the increased cost of providing high skid resistant surfacings. It wasn't until the mid-1950's that any such criteria were created. These and subsequent criteria are detailed in the following section.

3.5.1 Giles' Proposals(1957)[8]

Giles developed skid resistance criteria for different types of road based on the detailed testing of sites from which the Police had reported wet-weather skidding accidents (table 3.1). He found fairly well-established thresholds of SFC below which skidding accidents were likely to occur for different categories of road.

3.5.2 Marshall Committee Recommendations (1970)[33][34]

Giles criteria were modified by Sabey in 1968. Her recommendations were accepted by the Marshall Committee in 1970 as target values for skid resistance used in the preparation of maintenance schedules. The main differences between Marshall recommendations and Giles' proposals were the omission of category D sites, clearer definition of category B sites and the reduction of required SFC for the category A sites from 0.60 to 0.55.

Category	Type of site on wet surface	SFC at 30 mile/h
A	"Most difficult sites" such as : 1. roundabouts 2. bends with radius less than 500 ft on fast de-restricted roads 3. gradients 1 in 20 or steeper of length greater than 100 yards 4. approaches to traffic lights on de-restricted roads	**above 0.6**
B	"General requirements" such as : roads and conditions not covered by categories A & C	**above 0.5**
C	"Easy sites" such as : mainly straight roads with easy gradients and curves and without junctions and free from any features such as mixed traffic especially liable to create conditions of emergency	**above 0.4**
D	"Proved sites" such as : roads with coefficients below 0.4 which because of factors such as very slow or infrequent traffic cannot be shown by accident studies to be above normal danger	**no requirement**

table 3.1

Giles' recommendations for on road skidding resistance levels (Ref 8)

3.5.3 Transport and Road Research Laboratory's Proposals (1973)

In 1970 the TRRL set out to produce a scheme, again based on Giles proposals, which would be cost acceptable to all parties[35]. Improvements were made based on further research. Risk ratings were built in for the various categories determined by local accident figures. This helped to make the criteria more flexible and reflect the actual requirements for an individual site.

The effect of macro-texture on change in SFC with speed was also included in the proposal. This gave a comprehensive policy on surfacings. Minimum texture depth limits were determined from a number of experimental sites. These limits were intended to prevent high speed SFC falling below 80% of low speed SFC.

3.5.4 Department of Transport's Standard (1988)

To have maximum effect in improving road surfaces, any standard needs to have mandatory backing. A major deterrent in adopting mandatory standards has however been the legal implications of such actions. The first mandatory requirements for in-service trunk roads[36][37] in Great Britain were published in 1988 by the DoT. This was Departmental Standard HD 15/87 and advice note HA 36/87. Its introduction was made possible following the large scale National Skidding Resistance Survey (NSRS) completed by the DoT. Information on accident risk versus SFC for around 5000 sites allowed the DoT to select maintainable, cost effective, accident saving "investigatory levels" for each category

The resulting standards required one third of the trunk road network to be tested each year, the full network being tested over a three year period. Investigatory levels are prescribed (table 3.2) and if the SFC is at or below that level, warning signs should be erected, the maintaining agent notified and the site investigated. Should it be confirmed that there is a skidding problem, a cost and economic appraisal must be undertaken. Such sites are then short listed in order of priority thereby enabling the allocation of funds.

3.5.5 Highways Agency Specification (1994)

The current on road skidding resistant criteria[12] for all sites are contained in the Highways Agency specification. It has retained the exact criteria as detailed for the DoT's standard (table 3.2)

Site Category	Site definition	(i) Investigatory Levels MSSC (at 50 km/h) (ii) Corresponding risk rating							
	(i)	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
	(ii)	1	2	3	4	5	6	7	8
A	Motorway - mainline								
B	Dual carriageway (all purpose) Non event sections								
C	Single carriageway non event sections								
D	Dual carriageway (all purpose) minor junctions								
E	Single carriageway minor junctions								
F	Approaches to and across major junctions (all limbs)								
G1	Gradient 5% to 10% longer than 50m Dual (downhill only) Single (uphill and downhill)								
G2	Gradient steeper than 10% longer than 50m Dual (downhill only) Single (uphill and downhill)								
H1	Bend (not subject to 40 mph or lower speed limit) radius < 250m								
J	Approach to roundabout								
K	Approach to traffic signals, pedestrian crossings, railway level crossings or similar.								
	Investigatory levels MSSC (at 20km/h)	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75
		1	2	3	4	5	6	7	8
H2	Bend (not subject to 40mph or lower speed limit) Radius < 100m								
L	Roundabout								

Table 3.2

Highways agency specification (1994) for on road skidding resistance requirements for different traffic densities and risk rating of sites. (Ref 12)

3.6 Objectives of the SCRIM Investigation in this Project

Within the programme of work being undertaken by the author, the objectives of the SCRIM investigation were to :-

(i) assess the on road skidding resistance performance of various steel slag bituminous mixtures and surface dressings under varying
- Traffic densities
- Ages of surfacing

(ii) assess the performance of Steel Slag mixes with that of comparable Natural aggregate mixes.

3.7 SCRIM Program Details

3.7.1 SCRIM Program Contractor

A SCRIM machine was hired from West Yorkshire's Highways, Engineering and Technical Services (HETS) Laboratory based at Horbury Road, Ossett, Nr Wakefield. This was hired for three days on each of three separate occasions during the months of May, August and September 1994. On road measurements of the skid resistance of various types of surfacing within the region were performed with the author in attendance for each days testing.

3.7.2 Sites Investigated

Test site locations, lengths and materials are detailed fully in appendix 2.1(pages 2(ii) and 2(iii)). Location maps have not been provided but sites can be located on town plans.

3.7.3 Correction Factors Applied

Calibration and speed correction factors were applied to the raw SFC results. The data processing software automatically incorporated any required correction factors into the SFC's reported on the printout. Calibration correction factors are constant on any one days testing proportional to the static calibration results obtained before and after the days testing.Speed correction factors are applied depending on the speed of the test vehicle. Correction values are as detailed in section 3.2.3.

3.7.4 Analysis of SCRIM Data

In its purest form, the use of the SCRIM machine and resulting data is as a routine investigation test procedure which aids the allocation of funding within a Local Authority's highway maintenance program. It is from the SCRIM results that an engineer can decide whether a road surface needs immediate replacement or predict the time when it may need replacement. Local Authorities analyse SCRIM test results, as outlined below, in order to assess the perceived state of the existing road-surface (refer to table 3.2).

i) For category A, B and C sites, analysis is based on the average SFC over a 100m stretch

ii) For category D,E,F,J and K sites, analysis is based on the average SFC over a 50m approach to the feature

iii) For category G and H sites, analysis is based on the average SFC over a 50m stretch

iv) For category L sites, analysis is based on the SFC for each 10m interval

The aim therefore is for the Engineer to determine a maintenance program which maintains skidding resistance compliance.

The authors use of SCRIM results was intended for research work, in particular the relationship between SFC and various ages and traffic densities on various types of surfacings. Consequently, the authors analysis has been carried out on a "whole site" basis rather than individual 50m or 100m lengths.

The full SCRIM printouts are stored at Steelphalt and may be viewed with permission from the Slag Reduction Company Ltd.

3.7.5 Generation of 1994 Mean Summer SFC's

A typical SCRIM printout is shown in table 3.3. One result is generated every 10m along the length of the survey i.e. for run 1 values of 63, 62 and 62 were recorded consecutively along the road surface . Once three runs have been performed on the site, each particular 10m section then has three results. The mean of the 3 results for each individual 10m section are then reported in the final column as MSSC (Mean Summer SCRIM Coefficient). The 1994 mean summer SFC for the whole site is the average of all the MSSC results contained within the site boundaries. Where there are short changes in surface within the site boundaries, such as approaches to pedestrian crossings, these values have been omitted from the average.

RUN 1		RUN 2		RUN 3		Chainage		
SC	km/h	SC	km/h	SC	km/h	km	MSSC	Event
63	50	61	49	62	50	0.040	62	
62	50	61	50	62	49	0.050	62	1 Ash Rd (R)
62	50	60	50	61	49	0.060	61	

Table 3.3

Typical extract from SCRIM printout

3.7.6 Comparison of 1994 Mean Summer SFC with Existing Single Run Company Data

Steelphalt had previously obtained SCRIM data from single runs performed in September 1989,1990,1992 and November 1991. To compare 1994 mean summer SFC results to previous data it was necessary to standardise the test data available. The recognised SCRIM season is May to September with results obtained outside these months being deemed to be non standard results. As previously mentioned, the 1994 tests consisted of three runs performed in May, August and September. To standardise the results it was decided to omit the November 1991 test results from the analysis and use only the September values from the 1994 test runs. This left September SFC results from 1989,'90,'92 and '94 on a good range of sites. An overall September SFC for the site was calculated by taking the average of all the individual 10m section values.

3.8 Analysis of Results

The 1994 and previous Steelphalt SCRIM surveys produced data for five different categories of surfacing. The vast majority of road surfaces tested were stretches of road where constant speed and linearity appertained. The resultant SFC's of these surfaces can be assumed to be the skidding resistance of road surfaces which have been subjected to relatively low polishing conditions. From table 3.2 the sites tested can all be assumed to have risk ratings somewhere between 3 and 4. Sites with risk ratings of 3 and 4 have corresponding SFC investigatory levels of 0.4 and 0.45 respectively. Consequently all of the sites tested during the authors SCRIM investigation can be assumed to have investigatory levels imposed upon them which are within the range suggested above. Performance of individual sites against the investigatory levels for those sites can therefore be determined from the 1994 SCRIM results.

The above assumption of consistency of risk rating for all the sites tested isolated the main factor for the reduction of skidding resistance of one site compared to another to be the amount and weight of the traffic passing over that surface. Traditionally, skidding resistance to traffic density analyses have been performed using commercial traffic densities because the deterioration of a road surface caused by cars is thought to be insignificant compared to that of heavy goods vehicles. This approach was adopted for the authors skidding / traffic relationships to allow direct comparison between the previous research and the authors findings.

Each category of surfacing material will be detailed separately in this section, comparing relationships for on road skidding resistance values (SFC's) to commercial traffic densities, age of surfacing and performance with time.

Given the level of data available, the author has tried to produce relationships to predict the on road skidding performance of slag aggregates from a knowledge of the aggregates PSV. However, factors such as the varying agres of surfaces, road layout, road conditions and other factors detailed in section 3.4, have not been accounted for.

3.8.1 10mm Close Graded Wearing Course (10mm CGWC)

A summary of the results obtained on this type of surfacing during the 1994 SCRIM program is given in appendix 2.2 (page 2(iv) along with all relevant traffic data.

3.8.1.1 Skid Resistance Performance under Varying Traffic Densities

From section 3.5 a primary objective of the SCRIM investigation was to determine the performance of Steel Slag aggregate under varying traffic densities. For 10mm CGWC figure 3.14 shows the distribution of 1994 mean summer SFC against 1994 traffic density figures for a series of sites in the South Yorkshire and North Midlands area. No account for age of surface was taken into consideration for this relationship due to the phenomena expressed in section 3.4.3.

This type of surfacing is not used on the higher speed roads because of its smooth surface texture and hence almost entire reliance on the adhesion mechanism in order to provide its skid resistance (see section 3.3). This surfacing is only specified for lower speed roads and consequently lower traffic density roads. For this reason the range of commercial vehicle densities plotted in figure 3.14 are likely to represent the full range of densities expected on this type of surface.

The gradient of the regression is 3×10^{-5} .
The intersect of the regression and the Y-axis is at SFC = 0.58

The linear regression of the results has an equation of the form :-

$y = mx + c$ where c = constant (Y intersect)
m = gradient of line

hence the equation reads :-

$$SFC = 0.58 - 3 \times 10^{-5} \text{ cv/lane/day}$$

The regression line shows reducing skid resistance of the road surface with increased commercial vehicle densities. This is the expected form of the relationship from earlier research[10].

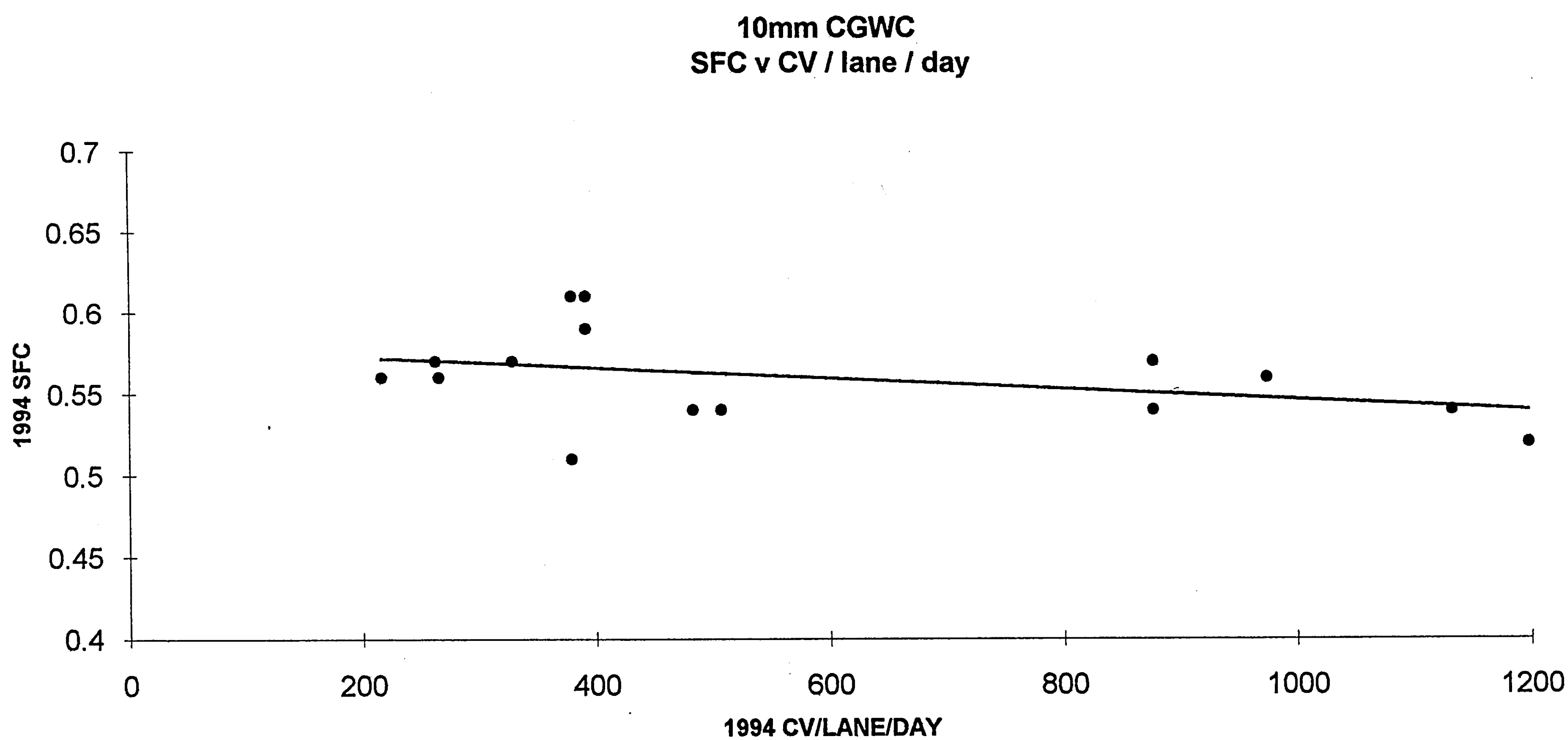
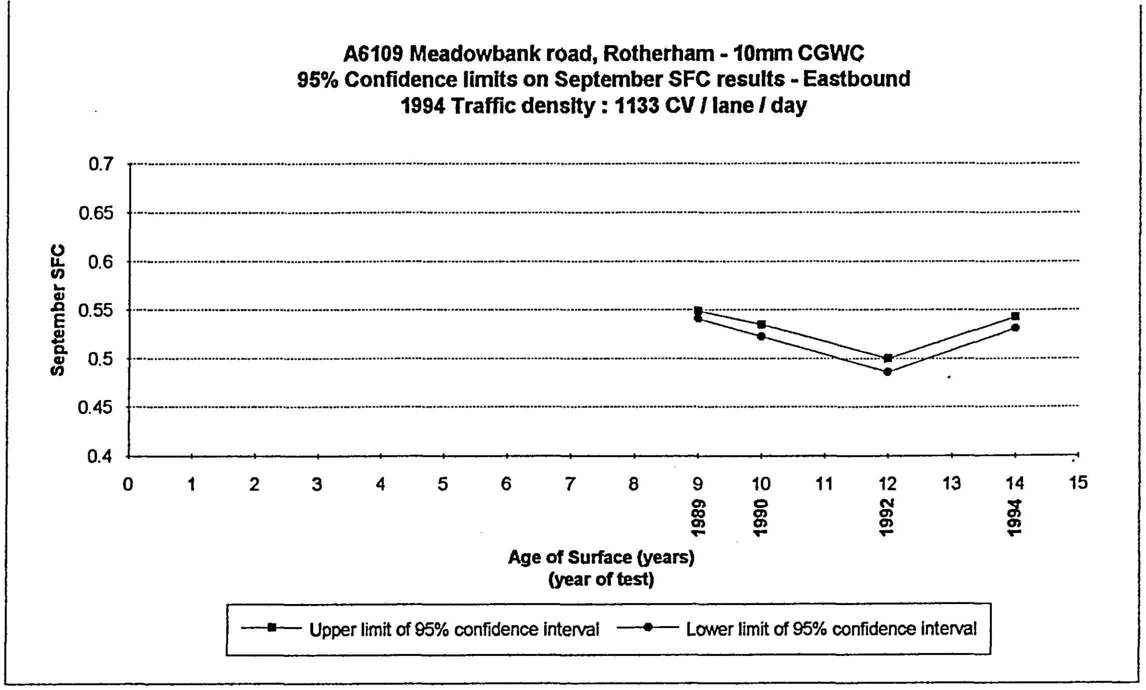


figure 3.14
Skidding resistance of different sites under different traffic densities for 10mm Close Graded Wearing Course
(10 CGWC)

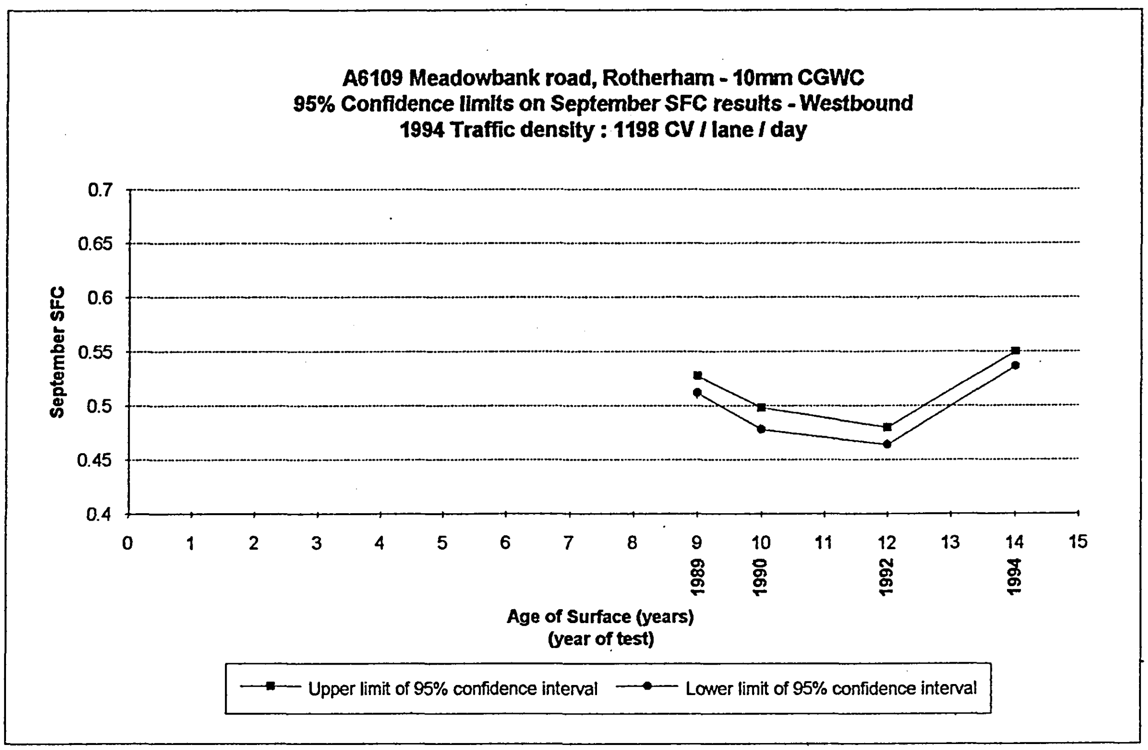
3.8.1.2 Skid Resistance Performance over Time

Research to date suggests that freshly laid road surfaces have high skid resistance. When the road begins to be trafficked, the skid resistance reduces to a lower equilibrium level . This usually occurs within the first year of trafficking. Once this equilibrium level is attained, the skid resistance of the road will maintain this level provided their is no change in traffic volumes passing over it. Eventually the surface chippings will either be worn away or embedded into the surface causing a need for renewal of the road surface.

Meadowbank road in Rotherham is constructed from 10mm CGWC which was laid in 1980. 1994 mean summer SFC results were taken on this surface along with previous September SFC determinations commissioned by Steelphalt in 1989, 1990 and 1992. Analysis of all the above results, undertaken as detailed in section 3.7, yields the resulting profiles of September SFC against age of surface as shown in Figure 3.15. Clearly the 14 year old road surface is still complying with the minimum skidding levels required for the site (section 3.8). A summary of the September SFC's measured on the above site is provided in Appendix 2.7 (page 2(ix))



(i) Eastbound



(ii) West bound

figure 3.15
Skid resistance performance with time for 10mm Close Graded Wearing Courses

3.8.2 10mm Surface Dressing Chippings (10mm SDC)

Surface dressing chippings were produced at Steelphalt until 1992. A summary of the results obtained on this type of surfacing during the 1994 SCRIM program is given in appendix 2.3 (page 2(v)) along with all relevant traffic data.

3.8.2.1 Skid Resistance Performance under Varying Traffic Densities

In 1972 Hosking and Szatkowski proposed a relationship between Sideway force Coefficient and Traffic densities as discussed in section 3.4.2. Figure 3.16 shows the 1994 SCRIM survey results plotted in the form of Hosking and Szatkowski's proposed relationship.

Current work by the author has determined that the average PSV of 1994 steel slag production is 63.5 (section 2.10.1.2), with a 95% certainty that any one test is greater than 60 (by riffle method). All of the 10mm SDC sites are quite old. With reference to the earlier work by the author into historic PSV results on steel slag, the results of PSV tests on fresh steel slag at the time of laying these 10mm SDC sites was about 59. A linear regression analysis of the 1994 SFC results yields a trend line equivalent to that expected from an aggregate with a PSV of 57. Clearly, the authors laboratory determined and the apparent PSV from figure 3.16 do not correlate. However, a better correlation is achieved between the historic PSV and apparent PSV indicated in figure 3.16.

The author is of the view that over the long time periods these surfaces have been trafficked, the surface texture will have been significantly reduced. This will have reduced the SFC of the surface (as discussed in section 3.2) hence reducing the apparent PSV deduced from figure 3.16.

The results lead to two conclusions about the SFC/traffic density relationship of 10mm steel slag surface dressings on this graph:-

i) The aggregate tested by the author in the laboratory PSV tests has different skid resistant properties to the on road aggregate tested during the SCRIM program. The aggregate tested on the road is assumed to have a PSV = 59 from historic PSV data.

ii) 16 year old steel slag surface dressing chippings with an approximate original PSV of 59 produces the same performance of on road skidding resistance as that expected from an aggregate with a PSV of 57. The reduction between laboratory PSV and apparent PSV from the on road skidding chart is possibly due to the loss of surface texture due to the age of the surfacing.

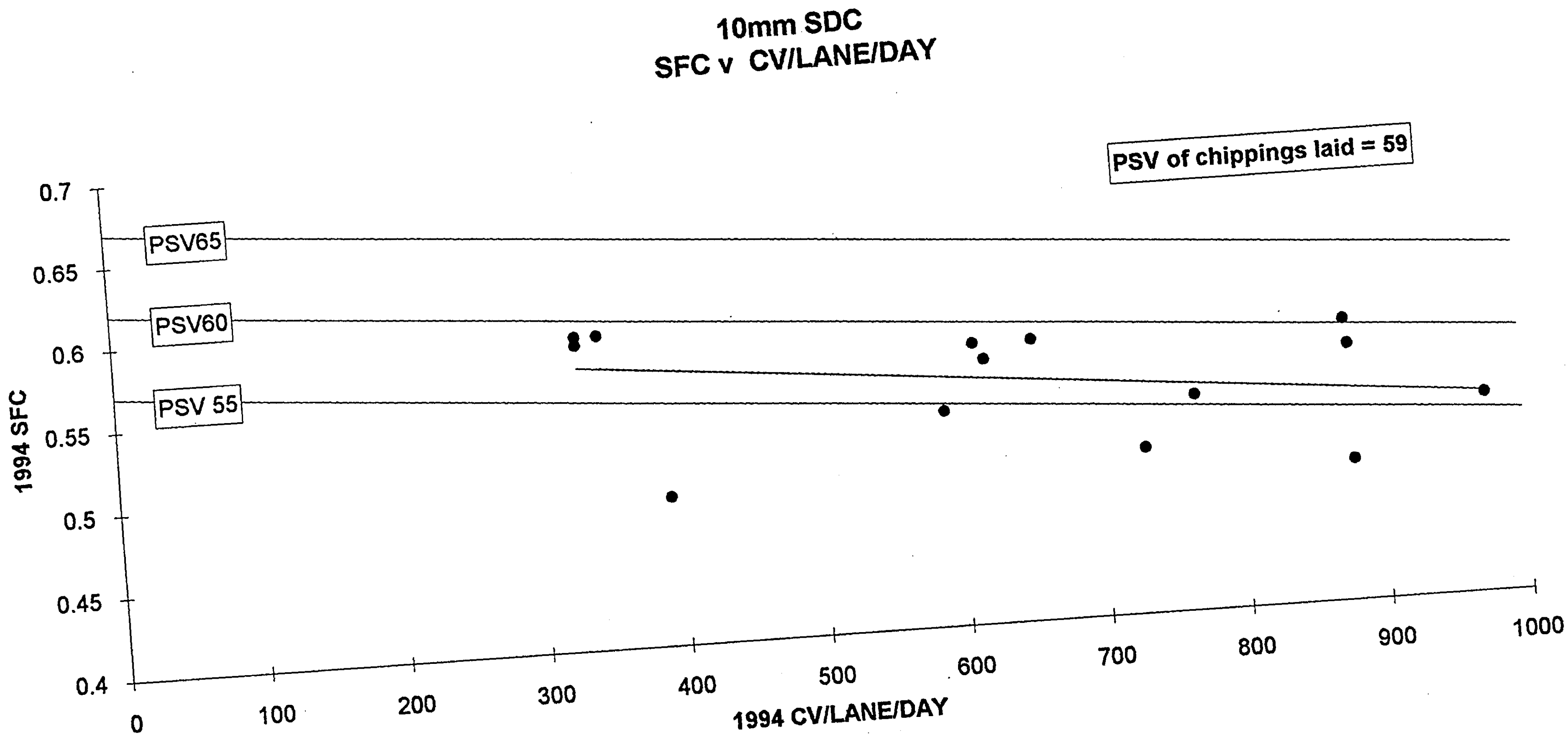


figure 3.16
Skidding resistance of different sites under different traffic densities for 10mm Surface Dressing Chippings.
(Shown overlaying Szatkowski and Hosking relationship (Ref. 12))

The conclusions above suggest that steel slag aggregates skid resistance to commercial vehicle density relationship is almost as good as that expected from a natural aggregate within its skid resistance design life. This was despite the age of the steel slag surfacings tested.

3.8.2.2 Steel Slag and Natural Aggregate Skid Resistance Performance over Time

1994 mean summer SFC values and 1992 and 1990 Steelphalt single run SFC results were available on steel slag and natural 10mm SDC sites on the A629 Wortley road. The sites were surface dressed at similar times. September SFC values were determined in accordance with section 3.7.7. Results for both carriageways were then averaged for each aggregate type.

Figure 3.17 shows that steel slag has a higher combined skid resistance for all of the years tested which suggests better performance of the steel slag aggregate than the natural aggregate. The plotted values show an apparent increase in SFC with increased age of road surface, however this is likely to be a scatter of results about an equilibrium skidding resistance level brought about by varying weather conditions during the individual test days. A summary of the September SFC's measured on the above surfaces is provided in appendix 2.7 (page 2(ix)).

3.8.2.3 Performance of 16 year old Steel Slag Surface Dressing

Appendix 2.3 (page 2(v)) shows a concentration of data available on 10mm SDC sites laid in 1978. Statistical analysis of these results provides a valuable insight to the skid resistance retention of very old steel slag aggregate. The 95% confidence interval for the average of the 1978 results was as follows :-

$$0.537 < \text{ave SFC}_{95\%\ \text{confidence}} < 0.583$$

The SFC level below which only 5% of tests on road surfaces would occur was :-

$$\text{Individual SFC}_{95\%\ \text{confidence}} > 0.49$$

Hence for a sixteen year old steel slag 10mm SDC surface, carrying traffic densities of between 330 and 879 vehicles, a mean summer SFC value will be greater than 0.49 (to 95% confidence). From section 3.8 a direct comparison can be achieved between the performance of steel slag 10mm SDC after 16 years and the mandatory requirements for this surface.

Mandatory requirements = 0.45

Performance after 16 years > 0.49 to 95% confidence

From this it is clear that Steel slag 10mm surface dressings with an original PSV of 59 are still performing to prescribed criteria after 16 years.

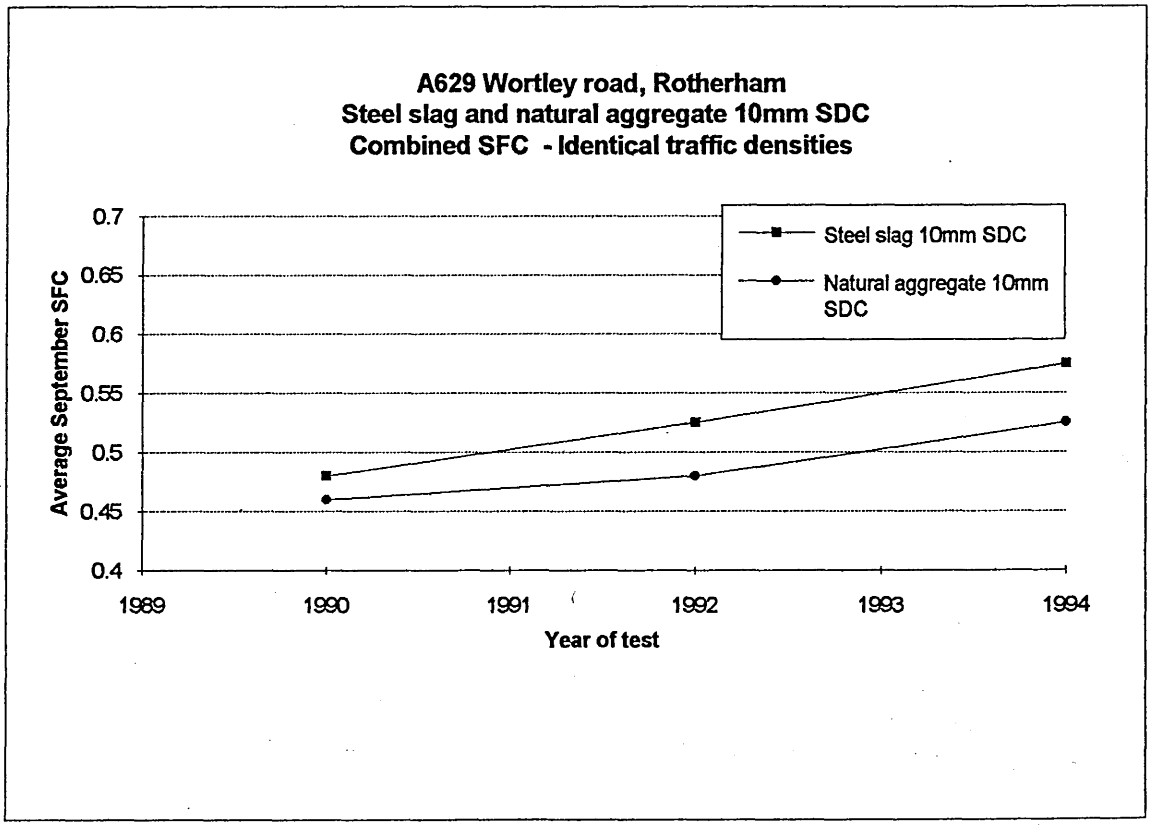


figure 3.17

Performance comparison of steel slag and natural aggregate 10mm surface dressings

3.8.3 14mm Close Graded Wearing Course (14mm CGWC)

A summary of the results obtained on this type of surfacing during the 1994 SCRIM program is given in appendix 2.4 (page 2(vi) along with all relevant traffic data. Risk rating and investigatory level assumptions are as detailed in section 3.8

3.8.3.1 Skid Resistance Performance under Varying Traffic Densities

Figure 3.18 shows the relationship between 1994 mean summer SFC's and 1994 commercial vehicle densities for steel slag 14mm CGWC surfaces. No consideration for age of surfacing has been given on the results in the relationship (section 3.4.3).

The range of commercial vehicle densities covered in figure 3.18 are likely to eclipse the full range of densities expected on this type of surface for the reasons expressed in section 3.8.1.1. A linear regression of the results shows a downward trend of skidding resistance with increasing traffic density. This is similar to the relationship obtained for 10mm CGWC surfaces. The gradient of the regression is 4.55×10^{-5}. The intersect of the regression and the Y-axis is at SFC = 0.595

The equation of the regression takes the form :-

$$y = mx + c \qquad \text{where} \quad c = \text{constant (Y intersect)}, \quad m = \text{gradient of line}$$

hence the equation reads :-

$$SFC = 0.595 - 4.55 \times 10^{-5} \text{ cv/lane/day}$$

The gradient of the reduction of skid resistance with increased traffic density is greater for 14mm CGWC surfaces than for 10mm CGWC surfaces.

The theoretical zero traffic skid resistance is however greater for 14mm surfaces than for 10mm surfaces. In the authors opinion, this is expected due to the more rugous surface texture of 14mm CGWC. The zero traffic skid resistance is theoretical because the low traffic effects discussed in section 3.4.2 could result in lower zero traffic skid resistance values than interpolation of the linear regression would suggest.

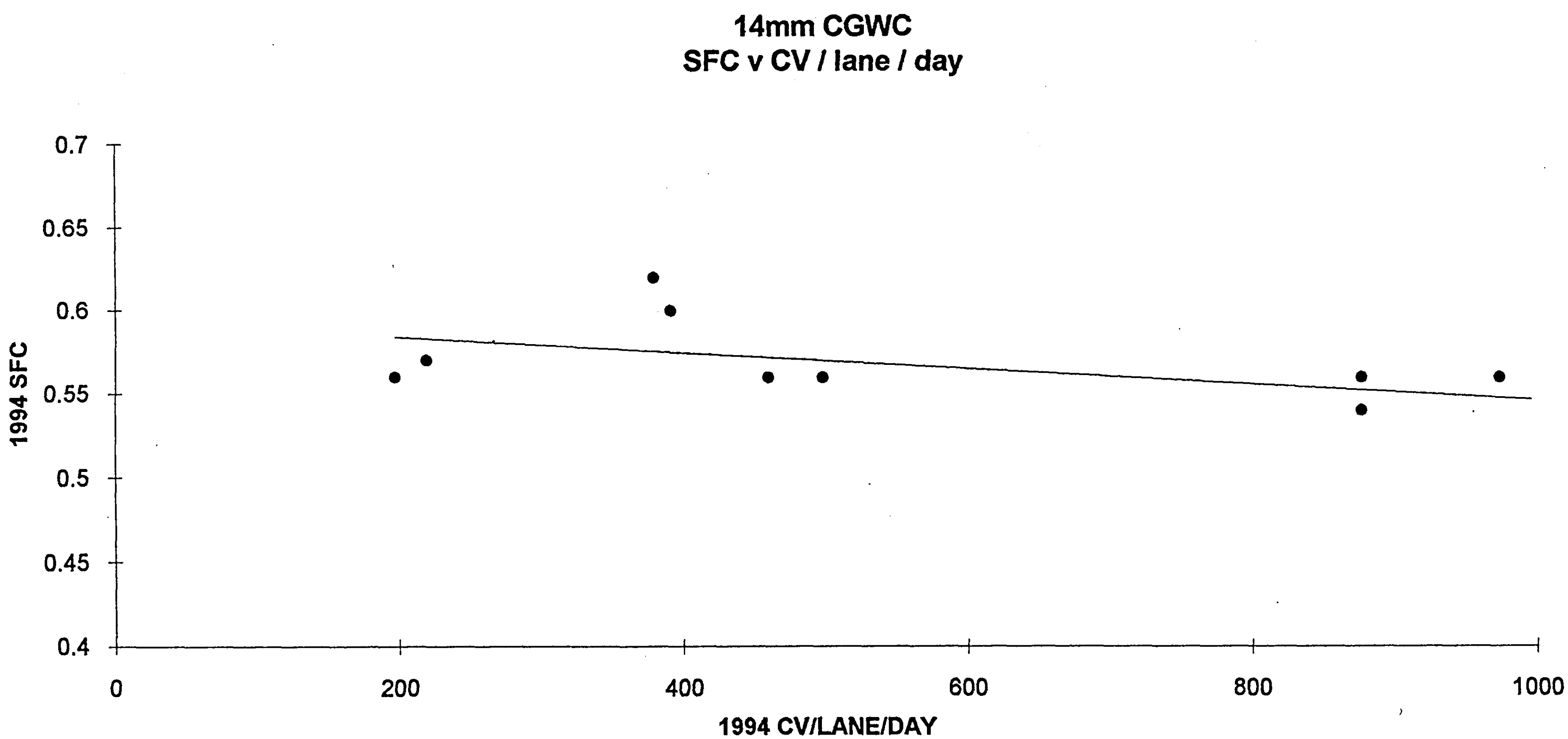


figure 3.18
Skidding resistance of different sites under different traffic densities for 14 mm Close Graded Wearing Course (14CGWC)

3.8.3.2 Comparison of Steel Slag and Natural Aggregate Skid Resistance Performance over Time.

September SFC data from 1994, 1992 and 1990 is available on stretches of 14mm CGWC constructed using steel slag and natural aggregate. The surfaces are both sited on the A629 Wortley road between Rotherham town centre and the M1 Motorway. SFC results for each carriageway were averaged. A comparison of these averaged results for each aggregate type is shown in figure 3.19. A summary of the September SFC's measured on the above surfaces is provided in appendix 2.7 (page 2(ix)).

Steel slag displayed higher Skid resistance in 1990 than the natural aggregate. Latterly the performance of the two aggregates was virtually identical. This suggests that the performance of steel slag is at least as good as that of an equivalent surface constructed using a natural aggregate 14mm CGWC.

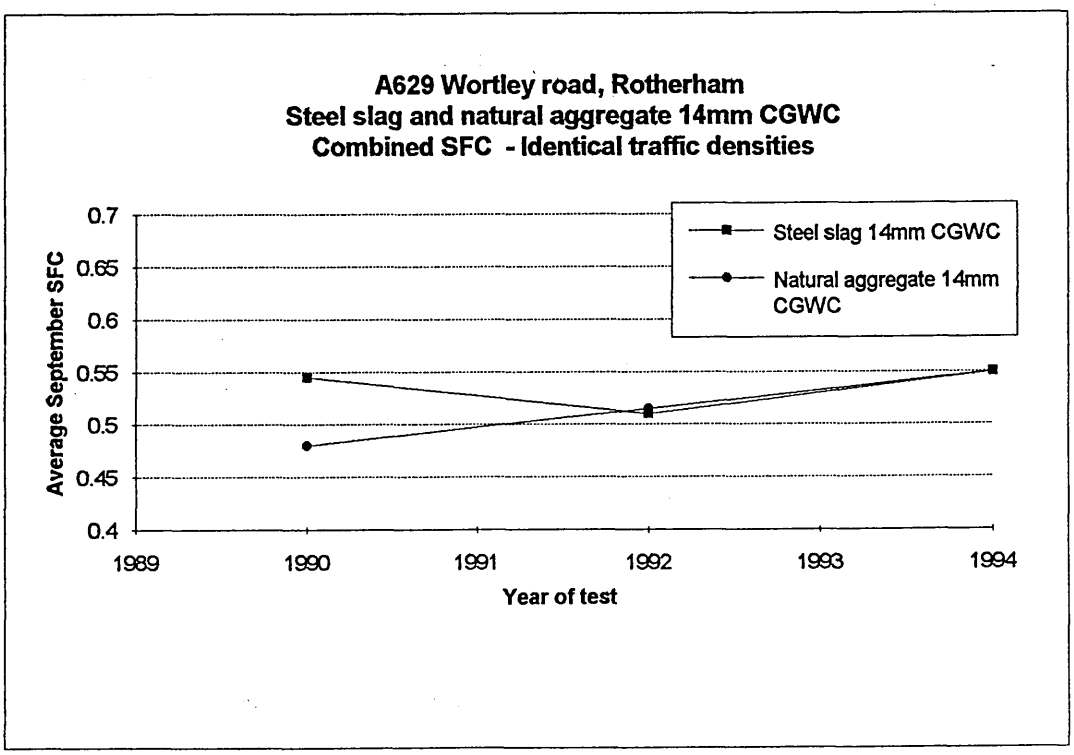


figure 3.19

Performance comparison of steel slag and natural aggregate for 14mm Close Graded Wearing Courses (14mm CGWC)

3.8.4 14mm Surface Dressing Chipping

A summary of the results obtained on this type of surfacing during the 1994 SCRIM program is given in appendix 2.5 (page 2(vii)) along with relevant traffic data. Similar to 10mm SDC, all the surfaces tested are within risk categories 3 and 4.

3.8.4.1 Skid Resistance Performance under Varying Traffic Densities

As previously discussed Hosking and Szatkowski proposed a relationship between SFC and traffic densities for surface dressed roads. Figure 3.20 shows the 1994 SCRIM survey results plotted in the form of Hosking and Szatkowski's proposed relationship.

The 14mm SDC sites under investigation were laid in 1988. The PSV of steel slag produced in 1988 was about 54 from the data on historic steel slag PSV's. The linear regression in figure 3.20 gives a trend line equivalent to that expected from an aggregate with PSV 55 - 57. The following conclusion can be made from this observation :-

i) Steel slag with an approximate PSV of 54 performs on the road with a skidding resistance equal to that expected from an aggregate with a PSV of 55-57.

Unlike the 10mm SDC surfaces, the 14mm surfaces investigated are considered to be within their design life (≈7 years). It is unlikely therefore that surface texture will have been reduced to such a level as to have a significant detrimental effect on skidding levels.

The results contained within this project lead to the following conclusion about the SFC / traffic density relationship for 14mm surface dressings :-

> within their expected skid resistance design life, 14mm steel slag surface dressings have a better on road skid resistance performance than their PSV would suggest. This is based on an analysis against the relationship proposed by Hosking and Szatkowski.

3.8.4.2 Skid Resistance Performance over Time

West Bawtry road in Rotherham was resurfaced with 14mm SDC in 1988. The stretches of 14mm SDC were from Canklow roundabout to Rotherway roundabout and Rotherway roundabout to the junction with Moorgate.

The most reliable results were obtained on the Rotherway roundabout to Moorgate

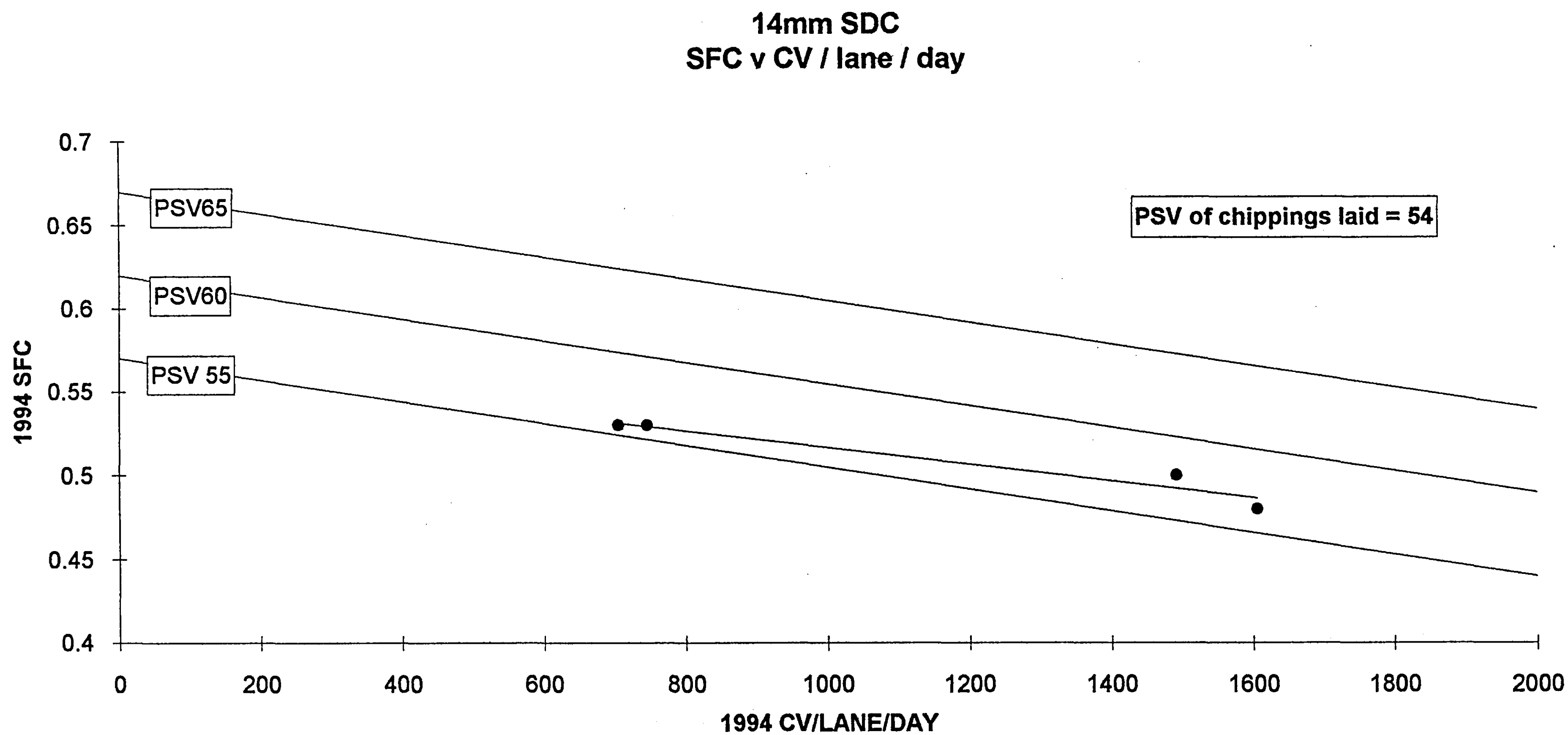
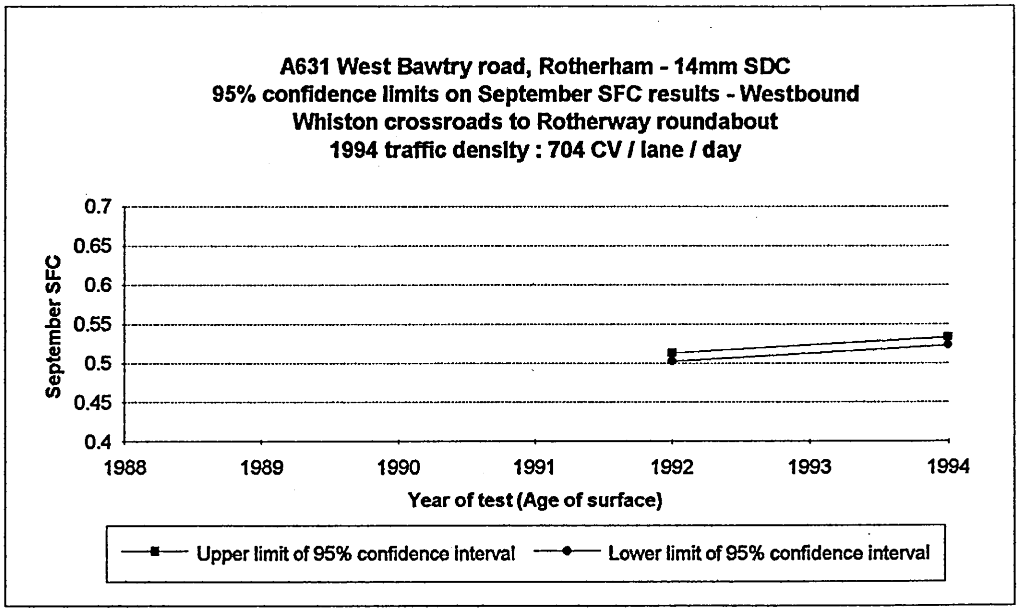


figure 3.20
Skidding resistance of different sites under different traffic densities for 14mm Surface Dressing Chippings.
(Shown overlaying Szatkowski and Hosking relationship (Ref. 12))

junction stretch due to roadworks on the other surface. 1994 commercial vehicle traffic densities of 745 Eastbound and 704 Westbound were present on the site. Figure 3.21 shows the September SFC to age of surface relationship for the site. The level of September SFC for both carriageways is above the investigatory level (0.45) required for the sites, once again providing evidence of the long term retention of the skid resistant properties of steel slag. A summary of the September SFC's measured on this type of surfaces is provided in appendix 2.7.



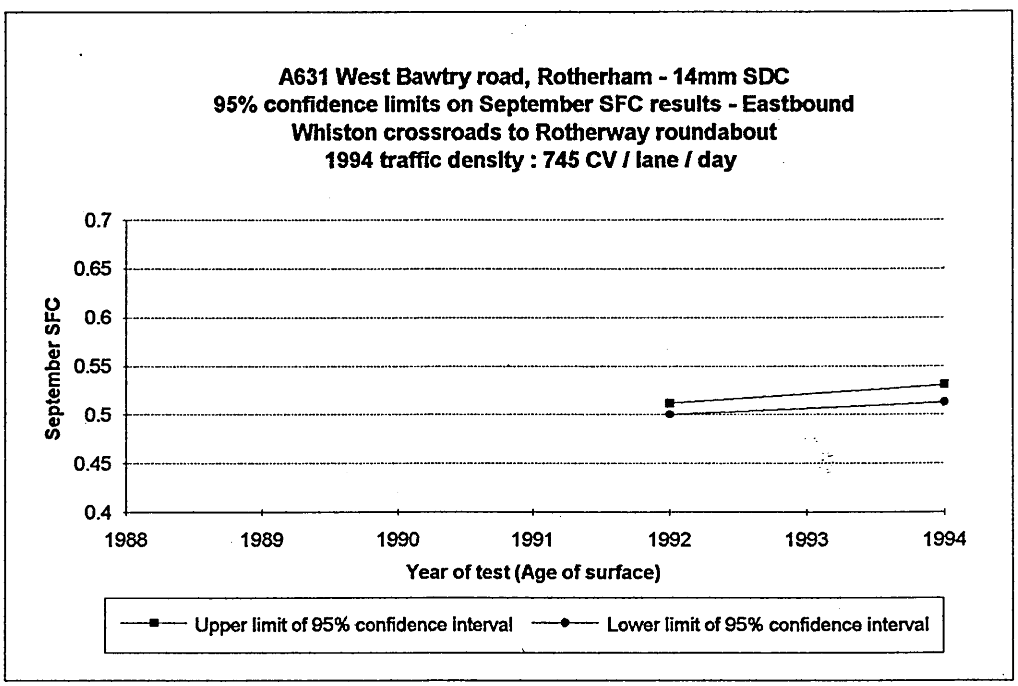


figure 3.21

Performance of 14mm surface dressing with age of surface

3.8.5 20mm Pre-Coated Chipping's (PCC) in Hot Rolled Asphalt (HRA)

A summary of the results obtained on this type of surfacing during the 1994 SCRIM program is given in appendix 2.6 (page 2(viii)) along with the relevant traffic data.

3.8.5.1 Skid Resistance Performance under Varying Traffic Densities

20mm PCC in HRA surfaces are within the scope of Szatkowski and Hoskings recommendations for skid resistance of road surfaces under different commercial vehicle traffic volumes. Figure 3.22 shows the authors relationship between commercial vehicle traffic densities and on road skidding levels for steel slag 20mm PCC in HRA. The overall trend of SFC v traffic density is decreasing, but at a lower rate than that proposed from the recommendations. In comparison to Szatkowski and Hoskings proposed relationship we can observe a skid resistance performance equivalent to a chipping of PSV 55 at about 400 cv/lane/day and a skid resistance performance equivalent to a chipping of PSV 61 at about 2000 cv/lane/day.

This increase in relative performance may be due to 3 effects:-

i) The cleansing effect of the increased traffic densities discussed in section 3.5.2. This effect can be assumed to occur for Natural aggregates as well as steel slag and therefore cannot account for the difference between the two types of aggregate.

ii) The vesicular nature of some of the chippings within the steel slag blend can result in the surface texture of the chippings being maintained. The maintenance of skid resistance is achieved by the action of the traffic wearing down the surface of the chipping and breaking into new, previously sealed vesicles (figure 2.14). This mechanism does account for the difference between steel slag and natural aggregates because natural chippings tend to polish without being able to open up fresh areas of surface texture.

iii) The proposed relationship suggested by Szatkowski and Hosking does not truly reflect the on road skidding performance of 20mm PCC in HRA made from steel slag aggregate.

This suggests that the skid resistance relationship proposed for natural aggregate 20mm PCC in HRA (figure 3.9) is not applicable to steel slag 20mm PCC in HRA because steel slag retains it's skid resistance much more effectively under increased traffic densities than natural aggregate.

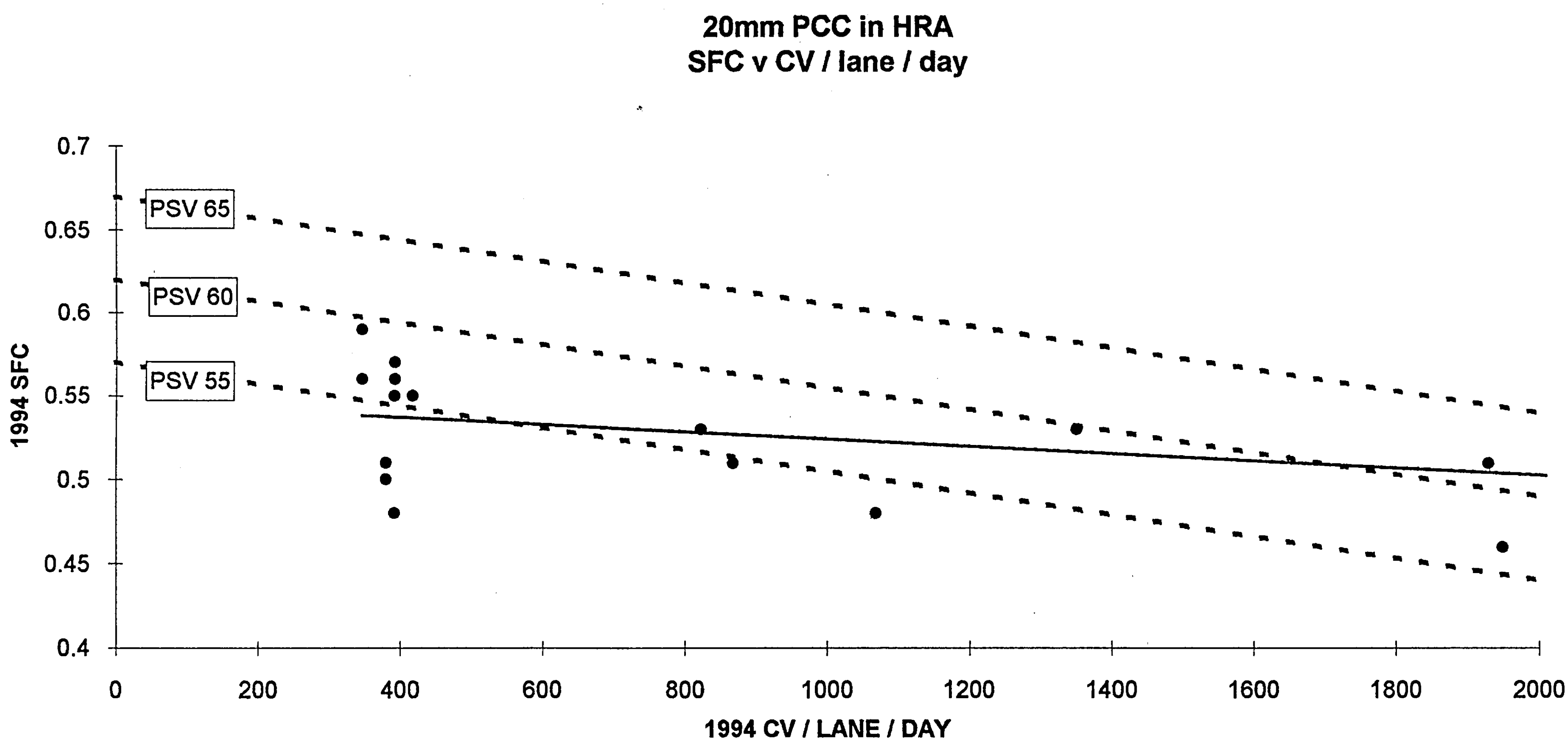


figure 3.22
Skidding resistance of different sites under different traffic densities for 20mm Pre-Coated Chippings in Hot Rolled Asphalt. (Shown overlaying Szatkowski and Hosking relationship (Ref. 12))

3.8.5.2 Comparison of SFC to Traffic Density Relationship for Steel Slag and Natural Aggregate

On road skid resistance test results are supplied in TRRL report LR 504 for 20mm PCC in HRA surfaces constructed using natural aggregate. The test results are obtained from a variety of sites under different commercial vehicle densities using chippings of PSV 58 - 60. A comparison of steel slag and the above field data is given in figure 3.23. The comparison shows the improved skid resistance retention of steel slag with higher traffic densities than that of the natural aggregate. The reason for this phenomena is probably due to the reasons discussed in section 3.8.5.1.(ii) above

3.8.5.3 Skid Resistance Performance over Time

Sheffield road between M1 Jcn 34 and Rotherham town centre was surfaced with 20mm PCC in HRA in 1974. The original wearing course is still present and figure 3.24 shows the results of September SFC values taken since 1989 (see also appendix 2.7). The investigatory level for this road is somewhere between 0.4 and 0.45 (on average) and therefore this surface may be approaching the end of it's skid resistant life. 1994 mean summer SFC results however, indicate that the surface is still performing to the required skid levels after a period of 20 years. Once again this suggests the long term skid resistance retention of steel slag aggregate surfaces however this is only based on evidence of three test points.

There needs to be a continuing monitoring of a road surface over a long period of time using SCRIM before a definite commentary on skid resistance performance with time can be produced for steel slag aggregate.

20mm PCC in HRA (natural & steel slag aggregate)
SFC v CV / lane / day

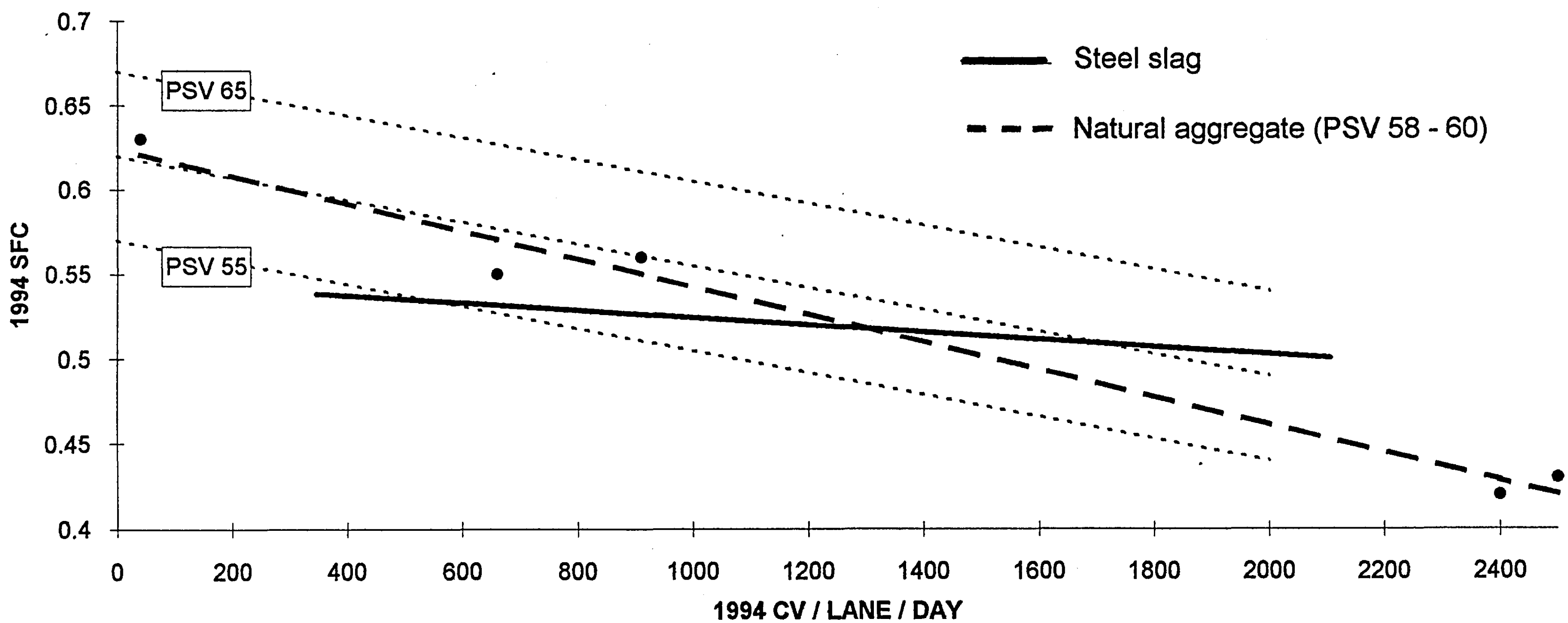
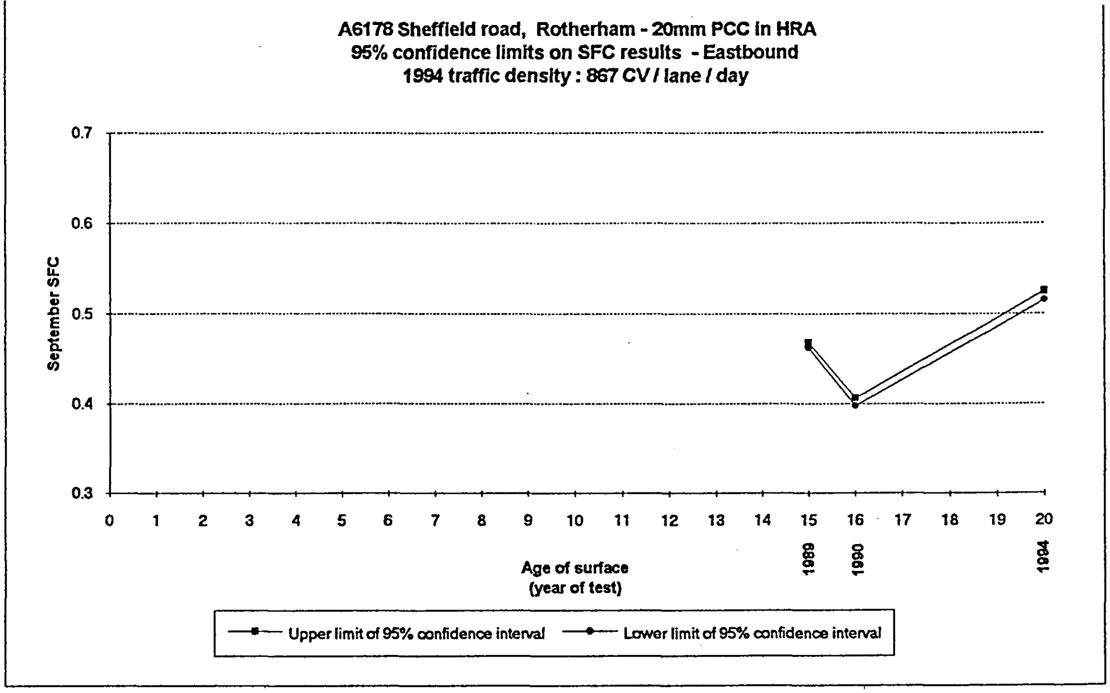
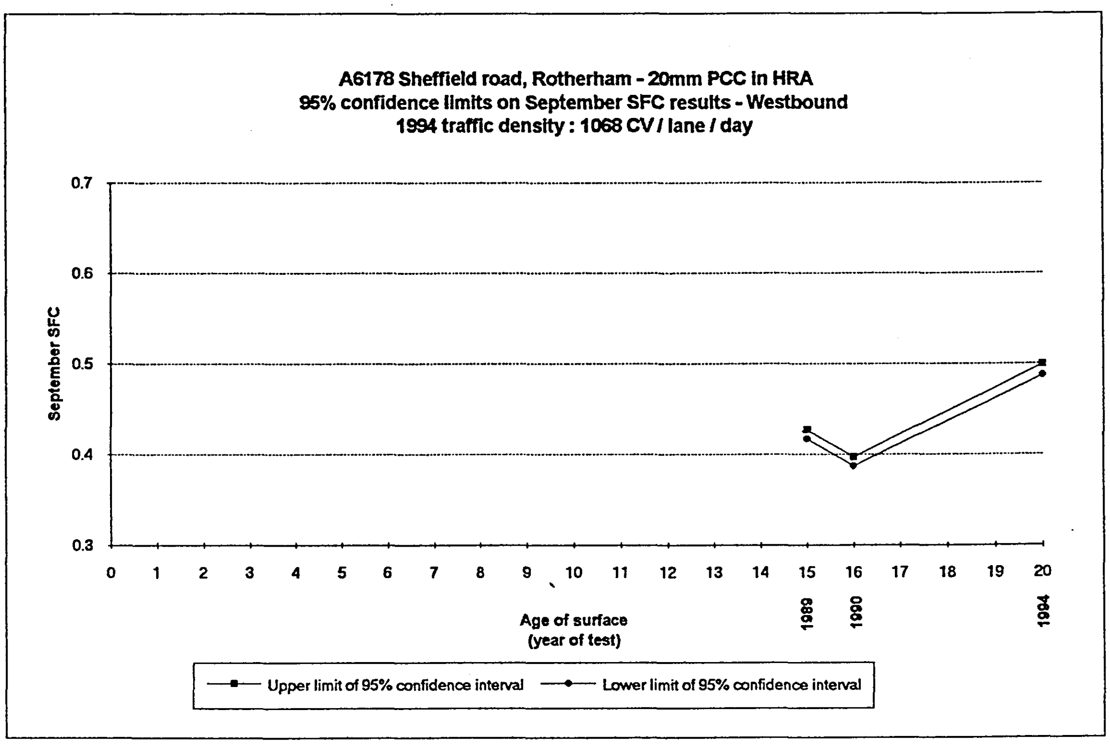


figure 3.23
Performance comparison of steel slag and natural aggregates when used in 20mm Precoated Chippings in hot rolled Asphalt surfaces (Shown overlaying Szatkowski and Hosking relationship (Ref. 12))



(i) Eastbound



(ii) West bound

figure 3.24
Skid resistance performance with time for 20mm Precoated Chippings in Hot Rolled Asphalt

3.9 Main Conclusions from On Road Skid Resistance Investigation

i) All of the surfaces tested during the project show reduced skid resistance with increased traffic density. This agrees with the relationship proposed by earlier researchers.

ii) 14mm surface dressed roads, within their skid resistance design life, appear to perform better than their original PSV result suggests.

iii) 16 year old 10mm surface dressed roads perform almost as well as their initial PSV result suggests despite being well outside the skid resistance design life normally associated with these surfaces.

iv) Steel slag 20mm Pre-Coated Chipping in Hot Rolled Asphalt surfaces show a lower deterioration of skid resistance with increased traffic density compared to that obtained from a similar material produced from natural aggregate.

v) All steel slag aggregate surfaces tested retained their skidding resistance over very long periods.

4.0 OVERALL CONCLUSIONS

The following conclusions arise from conditions only relating to the actual roads and laboratory testing conditions and the assumptions used in this project. They may not apply to other roads and materials in other situations, and therefore are not at this stage proposed as generic conclusions.

i) The average PSV of steel slag aggregate based on 70 results is 63.5. The author is 95% confident that the actual average PSV value for steel slag aggregate is within the PSV range $58 < PSV < 65$.

ii) A method of steel slag specimen production involving the use of a riffle box has been devised and this was found to reduce the variability of PSV test results.

iii) No difference existed between the polishing characteristics of steel slag aggregates obtained from the two main supplying sites in Sheffield and Rotherham. A significant difference did exist between the steel slag derived from the above sites and that derived from a site at Cardiff.

iv) No significant difference was found to exist between the aggregates derived from different parts of the processing plant.

v) A relationship between the skid resistance and the different physical properties of the aggregate was derived. The relationships derived were as follows:-

a) Specific Density v Skid Resistance

SRV = 119 - (0.017 x Specific Density)

b) Water Absorption v Skid Resistance

SRV = 54 + (2.39 x Water Absorption)

vi) The polishing profile of steel slag aggregate during a standard test on an accelerated polishing machine, shows marked differences to that of a natural aggregate under the same polishing regime.

vii) All of the road surfaces tested during the project show reduced skid resistance with increased traffic density. This agrees with the relationship proposed by earlier researchers.

viii) All steel slag aggregate surfaces tested retained their skidding resistance for up to 20 years, which is greater than the expected skid resistance life of most aggregates.

5.0 FURTHER DISCUSSION OF CONCLUSIONS

The original need for the research was to supply quantified evidence of the skidding resistance potential of steel slag aggregate. This was to be achieved by two parallel programs investigating the laboratory polishing resistance, and on road skidding resistance of steel slag aggregate. The two programs of work have addressed these two requirements as fully as possible during the time scale available.

The laboratory polishing resistance of standard production steel slag has been fully assessed and shown to be within the industry PSV classification of 58 - 63. Measures have been suggested, implemented and verified which help to reduce the variability of PSV test results on steel slag aggregate. Further work has shown that different crushing plants do not have a significant effect on the PSV of the aggregate passing through them. The PSV of aggregates supplied from different sites within South Yorkshire have also been shown to display no difference in their PSV's. A source of high PSV aggregate was highlighted from a slag handling site in South Wales.

The determination of on road skidding resistance of steel slag aggregate has achieved an excellent start. The large volume of results on steel slag surfaces have already gone a long way to achieving the need of quantifying the perceived good performance of the aggregate in service. The relationships suggested between the PSV and on road skidding resistance can only be a best estimate relationship. This is because the "actual" PSV of the aggregate laid can only be estimated from the available historic PSV data on steel slag aggregate. In order to obtain a definite link between the PSV of the aggregate and the skid resistance of the in-service aggregate, sites constructed from aggregate produced during the intensive PSV investigation need to be tested using SCRIM. A direct correlation can then be achieved between PSV, SFC and commercial traffic densities. The current aggregate PSV lies, on average, between 63.2 and 64.6 (using riffle method). The two predicted PSV levels used in this thesis during assessment of the performance of surface dressings, suggested PSV levels of 54 and 59. If the relationships shown for these sites are true, then much higher SFC's can be expected from the current production aggregate under the same traffic densities. This relationship may be determined if the company continues to perform SCRIM programs on selected road surfaces.

5.1 Further discussion of work in general

The following areas of work produced some apparent trends or patterns in the data, however, due to the amount of data available, the conclusions drawn cannot be considered to be definite but a best interpretation.

i) 3mm investigation - 3mm steel slag 'Pan Mills" derived aggregate appeared to have acceptable levels of skid resistance performance compared to that of a currently userd 3mm calcined bauxite. This suggested that the material tested had a possible use as an alternative aggregate for high skid resistant requirement sites such as approaches to traffic lights and roundabouts

ii) The 14mm surface dressed roads tested during the SCRIM program appeared to perform better in on road skidding than their original original PSV result suggested. This was for 14mm SDC road surfaces within their expected design life and based on an assumed original PSV of 54.

iii) The 10mm surface dressed roads tested during the SCRIM program appeared to perform marginally below that suggested by their original PSV result. This was, however, on road surfaces twice the age of the expected skid resistance design life of aggregates. The assumed original PSV was 59

iv) Hot Rolled Asphalt with 20mm pre-coated chipping surfaces appeared to show a reduced rate of deterioration of skid resistance with increased traffic density compared to that obtained from a similar material produced using natural aggregate. This relationship did not, however, take into account the various ages of the surfaces involved.

6.0 RECOMMENDATIONS FOR FURTHER WORK

1 Further SCRIM testing to be performed on steel slag surfaces constructed from aggregate processed within the period July 1993 - December 1995. A direct comparison may then be achieved between the skid resistance levels of steel slag road surfaces and the known PSV of the constituent steel slag aggregate.

2 Further investigate the link between polishing resistance and the different types of chipping within the steel slag blend. The aim of the work would be to allow an estimate of the PSV of a sample of aggregate to be taken from a knowledge of the physical properties of the particular sample.

3 Results from full scale road trials are required to determine whether or not the 3mm "Pan mills" derived aggregate can be used as an acceptably performing aggregate within an epoxy-resin bonded surfacing.

4 Continued testing of steel slag standard production aggregate using the riffle test method to further show the consistency of PSV results from using the new test method compared to those using the British Standard test method.

5 Work contained within this thesis detailing the PSV of steel slag aggregate after various degrees of crushing showed a possible relationship between 10% fines value and the PSV. Further work into pinpointing a relationship between 10% fines and PSV would be useful for predicting the PSV of aggregates from their 10% fines values.

ACKNOWLEDGEMENTS

Many thanks are due to the guidance of Dr. I.F.Taylor and Professor A.F.Stock during the course of both the Teaching Company Scheme and the production of this thesis. Equal gratitude is given to the Slag Reduction Company, in particular their Technical Manager Mr. Nick Jones.

Further thanks are due to Mr. Alan Taylor-Firth, whose input towards randomising chipping selection for PSV specimen production was invaluable. and to Mr. Alan Morton for guidance relating to the conduct of PSV tests and ensuring PSV testing consisitency.

Finally, the biggest thankyou has to go to my future wife, Kate, for having to go without company, humour and holidays whilst I was writing up this thesis.

GLOSSARY OF TERMS

PSV Polished Stone Value. Provides an index of resistance to polishing of different aggregates relative to a control aggregate. The PSV of an aggregate is the corrected mean SRV (see below) of 4 specimens of that aggregate following polishing on an accelerated polishing machine

SRV Skid Resistance Value as determined by the avarage of the last 3 from 5 swings of the pendulum skid resistance tester over either a PSV specimen or an area of road surface.

SFC Sideway - Force Coefficient. Skidding resistance of a stretch of road surface as determined with the use of a SCRIM machine.

SCRIM Sideway-force Coefficient Routine Investigation Machine. Designed by the Transport and Road Research Laboratory for quick and efficient routine determination of the skidding resistance of major trunk roads and motorways.

AAV Aggregate Abrasion Value. Provides an index of the abrasion resistance of various aggregates.

Calibration Specimen - specimen produced using aggregate from Criggion quarry. Specimen have undergone one standard PSV polishing run and the SRV of the specimen after polishing noted. The SRV of that particular callibration specimen may then be used to compare the performance of the portable skid resistance tester with time by re-testing the callibration specimen (without further polishing) prior to commencing each batch of testing.

Control Stone - aggregate from a particular quarry with a known and consistent PSV

Control Stone Specimen - 4 No. specimen are produced from Control Stone aggregate for each British Standard PSV run. The SRV of the specimens must fall within a pre-determined range for the test to be considered valid.

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Appendix 1.0 - Full results from PSV investigation

Contents **1i**

Glossary of tems used in appendix 1

5/7/93 SPA(T)	denotes date of sample, type of steel slag and specimen production method used.
SPA	Standard Production aggregate
BOS	Basic Oxygen process Steel slag
SEC	Secondary steel slag
(T)	"Traditional" British Standard specimen production method used.
(R)	"Riffle" specimen production method used.
MP	Main Plant derived aggregate
PM	Pan Mills derived aggregate

KEY

SPA - denotes Standard Production Aggregate

BOS - denotes Basic Oxygen Steel lsag

SEC - denotes Secondary steel slag

(56) - denotes result omitted due to chipping loss from specimen

shading - results omitted from analysis

Sample number	Date and type of sample	Specimen number	Wheel I	Wheel II	Average	**PSV**
1	5/7/93SPA(T)	1 & 2	60, 57.6	62, 58.3	59.5	**58**
2	13/7/93SPA(T)	3 & 4	58, 62	59.6, 60	59.9	**58**
3	19/7/93SPA(T)	5 & 6	56.3, 58.3	59.6, 64.3	59.6	**58**
4	29/7/93SPA(T)	7 & 8	56.6, 49.6*	59.3, 56.6	55.5	**(56)**
5	2/8/93SPA(T)	9 & 10	56.6, 59.6	58, 59	58.3	**57**
6	9/8/93SPA(T)	11 & 12	60.3,59.3	58, 60	59.4	**58**
7	16/8/93SPA(T)	1 & 2	62.3, 64.6	64.6, 62.3	63.5	**62**
8	23/8/93SPA(T)	3 & 4	58*, 63.3	63.3, 62.6	63.0	**(61.5)**
9	1/9/93SPA(T)	5 & 6	62, 64.3	66.3, 67	64.9	**63.5**
10	14/9/93SPA(T)	7 & 8	68.3, 66.3	66, 63.6	66.0	**64.5**
11	24/9/93SPA(T)	9 & 10	62.6, 66	60, 61	62.4	**61**
12	27/9/93SPA(T)	11 & 12	63, 65	63, 61.3	63.0	**61.5**
13	4/10/93SPA(T)	1 & 2	63.6, 61	59, 55	59.7	**60**
14	11/10/93SPA(T)	3 & 4	60, 58	61, 61.3	60	**60**
15	18/10/93SPA(T)	5 & 6	63.3, 61.3	58, 64.3	61.7	**62**
16	25/10/93SPA(T)	7 & 8	68.6, 67.6	67, 65	67	**67**
17	1/11/93SPA(T)	9 & 10	68, 65	65, 69.6	66.9	**67**
18	8/11/93SPA(T)	11 & 12	65.3, 61.3	62, 64	63.1	**63**
19	15/11/93SPA(T)	1 & 2	65, 67.6	63, 67.6	65.8	**67.5**
20	22/11/93SPA(T)	3 & 4	66, 62	65.3, 64.6	64.5	**66.5**
21	29/11/93SPA(T)	5 & 6	66.3, 66	63.3, 64.3	65.0	**67**
22	6/12/93SPA(T)	7 & 8	65.3, 67	64, 67	65.8	**67.5**
23	13/12/93SPA(T)	9 & 10	63.3, 65.3	68, 64.3	65.2	**67**
24	21/12/93SPA(T)	11 & 12	63.3, 64	66, 65	64.6	**66.5**
25	7/1/94SPA(T)	1 & 2	65, 67	65,65	65.5	**65.5**
26	12/1/94SPA(T)	3 & 4	64, 63.3	67.3, 60.3	63.7	**64**
27	12/1/94SPA(T)	5 & 6	65, 66	65, 63	64.8	**65**
28	18/1/94SPA(T)	7 & 8	64, 63.3	62.3, 65	63.7	**64**
29	23/1/94SPA(T)	9 & 10	63.3, 64.3	60.6, 68.6	64.2	**64.5**
30	7/1/94SPA(T)	11 & 12	63.3, 65.3	60.3, 65.3	63.5	**63.5**
31	1/2/94SPA(T)	1 & 2	59, 64.3	62.3, 65	62.6	**62.5**
32	9/2/94SPA(R)	3 & 4	62.6, 68.3	67.3, 59.6	64.5	**64.5**
33	9/2/94SPA(T)	5 & 6	63.3, 66.3	61, 59.6	62.5	**62.5**
34	14/2/94SPA(R)	7 & 8	64.3, 60.6	66.6, 61.3	63.2	**63.5**
35	14/2/94SPA(T)	9 & 10	64, 65	60, 60.3	62.3	**62.5**
36	2/2/94(SEC)	11 & 12	62.6, 60	60, 60.6	60.8	**61**
37	21/2/94SPA(R)	1 & 2	70, 66.7	64.6, 67	67	**66.5**

Sample number	Date and type of sample	Specimen number	Wheel I	Wheel II	Average	**PSV**
38	21/2/94SPA(T)	3 & 4	65, 60.6	65, 58.6	62.3	**62**
39	1/3/94SPA(R)	5 & 6	67.3, 66.6	68, 61.3	65.8	**65**
40	9/3/94SPA(R)	7 & 8	66.6, 64.6	63.6, 64.3	64.8	**64**
41	15/3/94SPA(R)	9 & 10	72, 65	65, 64	66.5	**66**
42	21/3/94SPA(R)	11 & 12	65.3, 68	68.3, 63.3	66.2	**65.5**
43	28/3/94SPA(R)	1 & 2	66, 70.3	65, 64.3	66.4	**69**
44	7/4/94SPA(R)	3 & 4	66.3, 60.6	65, 61.3	63.3	**66**
45	12/4/94SPA(R)	5 & 6	59.3, 59.6	60, 60.3	59.8	**62.5**
46	19/4/94(Lab)(R)	7 & 8	66, 64.6	62.6, 65.3	64.6	**67**
47	29/4/94SPA(R)	9 & 10	66.3, 67.6	61.3, 65	65	**67.5**
48	6/5/94SPA(R)	11 & 12	65.3, 63.3	64.3, 60	63.2	**66**
49	9/5/94SPA(R)	1 & 2	65, 63.6	60, 62	62.6	**64.5**
50	18/5/94SPA(R)	3 & 4	60, 60	60.6, 61.6	60.5	**62.5**
51	24/5/94SPA(R)	5 & 6	61.3, 64.3	63, 62.6	62.8	**64.5**
52	2/6/94BOS(R)	1 & 2	59.6, 63	60, 60.3	60.7	**62**
53	6/6/94SPA(R)	3 & 4	66.6, 59	68, 65	64.6	**66**
54	13/6/94SPA(R)	5 & 6	65, 62.6	60, 60	61.9	**63.5**
55	27/6/94SPA(R)	1 & 2	70, 63.6	68.3, 59.6	65.4	**66**
56	4/7/94SPA(R)	3 & 4	64, 66.3	61.6, 63.6	63.9	**64.5**
57	11/7/94SPA(R)	1 & 2	64.2, 57.6	60.3, 57.6	59.9	**60.5**
58	18/7/94SPA(R)	3 & 4	60.3, 64	64.6, 52.6	60.4	**61**
59	25/7/94BOS(R)	5 & 6	57.6, 55	55, 54.3	55.5	**56**
60	2/8/94BOS(R)	1 & 2	58, 58.6	60, 57.6	58.5	**58.5**
61	8/8/94BOS(R)	3 & 4	65, 63	59.6, 64	62.9	**63**
62	16/8/94SPA(R)	5 & 6	60, 65	64.3, 60.3	62.4	**62.5**
63	23/8/94SPA(R)	7 & 8	65.6, 67	61, 62.6	64.0	**64**
64	31/8/94SPA(R)	9 & 10	60.3, 65	60.3, 60.3	61.5	**61.5**
65	9/9/94SPA(R)	11 & 12	60.3, 60	64.6, 61	61.5	**62**
66	12/9/94SPA(R)	3 & 4	65.6, 66.3	67.3, 64.3	65.9	**63.5**
67	19/9/94SPA(R)	5 & 6	67.6, 61	63, 64.6	64	**61.5**
68	26/9/94SPA(R)	7 & 8	63.3, 66	64.6, 65	64.7	**62**
69	4/10/94SPA(R)	9 & 10	63.6, 66.6	64.6, 66.3	65.3	**63**
70	10/10/94BOS(R)	11 & 12	60.3, 65	60, 62	61.8	**59.5**
71	18/10/94SPA(R)	1 & 2	61.6, 67	65, 62.2	64	**63**
72	26/10/94SPA(R)	3 & 4	62.3, 67.3	60, 64	63.4	**62.5**
73	31/10/94SPA(R)	5 & 6	72.3, 64	60, 58	63.6	**62.5**
74	7/11/94SPA(R)	7 & 8	67.3, 56	64.6, 63.6	62.9	**62**
75	21/11/94SPA(R)	9 & 10	65, 70	61.3, 65	65.3	**64**
76	28/11/94SPA(R)	11 & 12	60.6, 70.3	65.3, 63.6	65	**64**

Appendix 1.1.2 - Analysis of PSV results performed on standard production aggregate

Calculation of 95% confidence interval for mean of PSV results

from normal distribution theory we know :-

Confidence limits = ave. $\pm t_f(\alpha) \cdot (s / \sqrt{n})$ when the standard deviation is unknown
where
ave. = average result
$t_f(\alpha)$ = student's t - percentile (dependent on No. of deg. of freedom and confidence level required)
s = standard deviation of results
n = number of results

British Standard test results

Average result	=	63.0	
Standard deviation(s)	=	3.16	
$t_f(\alpha)$ - from tables	=	2.04	No. deg. freedom = 31 confidence level = 95%
n	=	32	

Placing these values into the above equation gives:-

X max = 64.1 X min = 61.9

"Riffle" test results

Average result	=	63.9	
Standard deviation(s)	=	2.13	
$t_f(\alpha)$ - from tables	=	2.029	No. deg. freedom = 35 confidence level = 95%
n	=	36	

Placing these values into the above equation gives :-

X max = 64.6 X min = 63.2

Appendix 1.1.2 - Analysis of PSV results performed on standard production aggregate

Calculation of PSV level below which only 5% of results are likely to occur

from normal theory we know:-

95% of area of normal curve lies above the value,

$$x = ave. - \sigma . Z$$

where : x = the level of result
ave.= the average of the sample
σ = standard deviation
Z = percentile

British Standard test results

ave. = 63.0
σ = 3.16
Z = 1.65 (from tables)

Hence, level below which 5% of results may occur is :-

$$63.0 - 3.16*1.65 = 57.8$$

"Riffle" test results

ave. = 63.9
σ = 2.13
Z = 1.65 (from tables)

Hence, level below which 5% of results may occur is :-

$$63.9 - 2.13*1.65 = 60.4$$

	Pan Mills				Main Plant			
Date of sample	Wheel I	Wheel II	average	corrected average	Wheel I	Wheel II	average	corrected average
5/7/93(T)	66.6	65.6	66.1	**66**	61.3	60.6	60.6	**60**
13/7/93(T)	65.3	59	62.1	**62**	63.3	61	62.1	**62**
19/7/93(T)	65	61.6	63.3	**63**	62	64.3	63.1	**63**
2/8/93(T)	64	65.3	64.6	**64**	68.3	66.3	67.3	**67**
9/8/93(T)	66	62.6	64.3	**64**	69.3	67.6	68.4	**68**
16/8/93(T)	69	66.6	67.8	**67**	71.3	70	70.6	**70**
23/8/93(T)	60.6	64	62.3	**62.5**	65	65	65	**65**
1/9/93(T)	65	67.3	66.2	**66.5**	70	63	66.5	**66.5**
24/9/93(T)	62.3	65	63.7	**64**	66.3	65	65.7	**66**
27/9/93(T)	56.3	63	59.7	**60**	71.6	70	70.8	**71**
4/10/93(T)	64	67	65.5	**65.5**	65	65	65	**65**
11/10/93(T)	65	67	66	**66**	65.3	68.3	66.8	**67**
9/3/94(R)	65,69.6	63.6,66	66	**64.5**	75,69	67,62	68.3	**66.5**
15/3/94(R)	64.3	63	63.7	**65**	69	66.3	67.7	**69**
21/3/9(R)	62.3	65	63.65	**64.5**	68.3	60	64.15	**65**
18/5/94(R)	60	64	62	**63.5**	62.6	63	62.8	**64**
			average	**64.2**			average	**65.9**
			S.D	**1.82**			S.D	**2.88**

Appendix 1.2.1 - Summary of polishing tests performed on aggregate derived from the two processing plant silo's

Appendix 1.2.2 - Analysis of PSV results performed on aggregate derived from the two processing plant silo's

Calculation of confidence interval for mean of PSV results

from normal distribution theory we know :-

Confidence limits = ave. $\pm t_f(\alpha) \cdot (s / \sqrt{n})$ when the standard deviation is unknown

where

ave. = average result

$t_f(\alpha)$ = student's t - percentile (dependent on No. of deg. of freedom and confidence level required)

s = standard deviation of results

n = number of results

Pan Mills derived aggregate

Average result =	64.2	
Standard deviation(s) =	1.82	
$t_f(\alpha)$ - from tables =	2.132	No. deg. freedom = 15 confidence level = 95%
n =	16	

Placing these values into the above equation gives:-

X max = 65.2 X min = 63.2

Main Plant derived aggregates

Average result =	65.9
Standard deviation(s) =	2.88
$t_f(\alpha)$ - from tables =	2.132 (as above)
n =	16

Placing these values into the above equation gives :-

X max = 67.4 X min = 64.4

A large overlap of the possible actual mean value of the aggregates existed which suggested that no significant difference was present between the aggregates.

Stocksbridge derived steel slag				Aldwarke derived steel slag				Cardiff derived steel slag			
Wheel I	Wheel II	average	PSV	Wheel I	Wheel II	average	PSV	Wheel I	Wheel II	average	PSV
70, 65	64, 65	66	**64.5**	64, 66.6	66.3, 66	65.7	**64**	68, 70	70, 71.6	69.9	**69.5**
64.3, 63.6	62, 62.6	63.1	**61.5**	60, 61.3	65, 65	62.8	**61.5**	70, 70.6	70, 72.3	70.7	**70**
63, 63.3	64, 69	64.8	**63.5**	67.3, 65.6	63.6, 66.3	65.7	**64**	65.3, 62.3	65.3, 69.3	65.5	**67**
58.6, 67	66.3, 64	64	**63.5**	63.6, 61	67, 66.6	64.5	**64**	69.6, 66.6	65, 65.3	66.6	**67**
64, 63.6	66.3, 65	64.7	**64**	65, 67	64, 67.6	65.9	**65.5**	74.3, 74.6	69.3, 68.3	71.6	**72**
		average	**64.5**			average	**64.9**	73.3, 74	67.6, 70	71.2	**71.5**
		S.D.	**2.18**			S.D.	**2.18**	72.6, 74.3	70, 66.3	70.8	**71.5**
										average	**69.8**
										S.D.	**2.01**

Summary of initial PSV results on site specific aggregates

CRUSHING PROCESS	RUN 2	RUN 2	AVE	PSV	10% fines (strength) results
as sampled	66.3, 66.6	66.3, 71	67.5	**68**	110 kn
small scale rotary crusher	66.6, 65	67.3, 65.6	66.1	**67**	180 kn
repeatedly crushed through a jaw crusher	65, 61.3	62.6, 66.3	63.8	**64.5**	210 kn

Summary of PSV and 10% fines test results on part processed Cardiff aggregate

Appendix 1.3 - Summary of PSV test results on site specific aggregates

TYPE	Wa	Ww (incl. bskt)	Ws (incl. bskt.)	Ww (basket)	Ws (basket)	Ww	Ws	Spec. gravity	WA%	AP	ASD	SRV(Corrected)
DV1	59.567	77.93	24.05	16.01	5.93	61.92	18.12	3287	3.95	0.13	3777.95	64.80
DV2	62.046	80.82	25.03			64.81	19.1	3248	4.45	0.14	3798.11	66.50
DV3	61.043	79.65	24.53			63.64	18.6	3282	4.25	0.14	3814.47	65.10
DV5	62.323	80.83	24.98			64.82	19.05	3272	4.01	0.13	3765.06	65.10
DS1	62.442	79.56	23.35			63.55	17.42	3585	1.77	0.06	3827.98	60.50
DS2	61.059	78.05	22.88			62.04	16.95	3602	1.61	0.06	3823.60	61.10
DS4	60.478	77.52	22.64			61.51	16.71	3619	1.71	0.06	3857.51	55.50
DS5	63.284	80.41	23.47			64.40	17.54	3608	1.76	0.06	3853.14	56.10
LV1	60.833	80.39	25.84			64.38	19.91	3055	5.83	0.18	3717.72	67.80
LV2	60.658	80.44	26.25			64.43	20.32	2985	6.22	0.19	3665.58	73.80
LV4	60.841	80.91	26.50			64.90	20.57	2958	6.67	0.20	3684.88	65.50
LV5	61.223	81.47	26.64			65.46	20.71	2956	6.92	0.20	3716.57	69.80
LS1	60.969	79.2	24.58			63.19	18.65	3269	3.64	0.12	3711.06	64.80
LS2	60.286	78.45	24.53			62.44	18.6	3241	3.57	0.12	3665.69	56.10
LS3	60.451	78.72	24.54			62.71	18.61	3248	3.74	0.12	3697.08	59.80
LS5	59.931	78.11	24.39			62.10	18.46	3247	3.62	0.12	3678.78	57.80

Full details of chipping property measurements and corresponding skidding resistance values

	Specific gravity		Water absorption%		Apparent porosity		Apparent solid density		corrected PSV	
Sample	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
DV	3272	17.19	4.17	0.23	0.14	0.01	3788.90	21.81	65.5	0.763
DS	3604	14.51	1.71	0.08	0.06	0.00	3840.56	17.24	58.5	2.907
LV	2989	46.46	6.41	0.48	0.19	0.01	3696.18	25.45	69	3.519
LS	3251	12.27	3.64	0.07	0.12	0.00	3688.15	19.97	59.5	3.766

Summary of chipping property averages and standard deviations

DV = Dark Vesicular DS = Dark Solid LV = Light Vesicular LS = Light Solid

Appendix 1. 4 . 1 Measurements and further calculations to determine the properties and skid resistance of various fractions of steel slag aggregate

Appendix 1. 4. 2 Details of calculations for appendix 1.4.2

Glossary of terms

Wa - Dry weight of aggregate
Ww (with basket) - weight of aggregate and basket resting on bottom of reservoir
Ws (with basket) - weight of aggregate and basket suspended in reservoir
Ww (basket) - weight of basket resting on bottom of reservoir
Ws (basket) - weight of basket suspended in reservoir
Ww - weight of aggregate resting on bottom of reservoir
Ws - weight of aggregate suspended
γ_W - density of water (1000 kg/m^3)

Calculations

Specific Gravity = $(Wa / Ws) . \gamma_W$

Water absorption (%) = ((Ww - Wa) / Wa) . 100%

Apparent porosity (%) = ((Ww - Wa) / Ws) . 100%

Apparent solid density = Wa / (Ws - Ww + Wa)

Appendix 1. 5. 1 - 3mm aggregate polishing test results
TEST NUMBER 23

3mm aggregate comparison test number 1
Skid Resistance Values (SRV)
Wheel 1 of 1 :- tested 27/9/94
comprising specimen 1- 3 "Pan Mills" steel slag
specimen 4 - 6 "Main Plant" derived steel slag
specimen 7 - 9 Basic Oxygen Steel slag
specimen 10 - 12 Guyana bauxite
specimen 13 - 14 control stone (10mm)

13	1	10	3	5	12	8	specimen number
64	68	77	67	69	75	62	
60	68	75	65	68	73	60	
60	67	75	65	67	73	60	
60	67	75	65	65	72	60	
60	66	75	65	65	72	60	
60	66.6	75	65	65.6	72.3	60	average SRV

7	11	6	4	9	2	14	specimen number
65	75	68	68	65	75	59	
65	74	68	66	60	73	56	
64	73	68	66	61	72	55	
63	72	66	65	61	71	55	
62	72	66	65	60	71	55	
63	72.3	66.6	65.3	60.6	71.3	55	average SRV

comments

"Main plant" and "Pan mills" derived steel slag aggregates suffered loss of grit from surface of specimen due to poor performance of adhesive. Results may be unrepresentative of aggregates therefore test will be repeated for these aggregate types.

BOS and bauxite specimens suffered no chipping loss due to a different and successful adhesive system being used. The results obtained for these aggregates are thought to be representative of the aggregates.

Appendix 1. 5 .2 - 3mm aggregate polishing test results
TEST NUMBER 24

Calibration test	Last test
65	64
65	62
65	62
65	61
65	60
65	61

3mm aggregate test number 2
Skid Resistance Values (SRV)
Wheel 1 of 1 :- tested 4/11/94

comprising specimen 1 - 4 "Pan Mills" derived aggregate
specimen 5 - 8 "Main plant" derived aggregate
specimen 9 - 12 Natural aggregate
specimen 13 - 14 Control stone (10mm)

13	1	10	3	5	12	8	specimen number
65	78	67	75	75	68	72	
64	75	65	73	72	65	71	
63	75	65	72	71	66	70	
63	75	65	71	70	65	70	
63	75	65	71	70	65	70	
63	**75**	**65**	**71.3**	**70.3**	**65.3**	**70**	average SRV

7	11	6	4	9	2	14	specimen number
71	70	74	75	70	80	70	
70	70	70	73	69	80	67	
70	70	70	74	67	79	66	
68	69	70	71	68	78	66	
68	69	70	70	67	77	66	
68.6	**69.3**	**70**	**71.6**	**67.3**	**78**	**66**	average SRV

comments

Some problem encountered with pendulum measuring above previous levels (determined from calibration specimen). Pendulum measurements are approximately 4 units higher than previously. Readings taken on the calibration specimen throughout the testing period showed constant over reading. Resultant SRV to have 4 units subtracted from their values for better indication of actual value.

Appendix 1. 5. 3 - 3mm aggregate polishing test results
TEST NUMBER 25

3mm aggregate test number 3
Skid Resistance Values (SRV)
Wheel 1 of 1 :- tested 24/11/94
comprising specimen 1 - 6 Bauxite aggregate
specimen 7 - 12 "Pan mills" derived aggregate
specimen 13 - 14 Control stone (10mm)

13	**1**	**7**	**2**	**8**	**3**	**9**	specimen number
60	73	70	75	72	75	75	
60	73	69	74	72	72	73	
60	73	68	73	71	73	73	
60	73	68	73	72	73	72	
60	73	67	72	71	73	72	
60	**73**	**67.6**	**72.6**	**71.6**	**73**	**72.3**	average SRV

4	**10**	**5**	**11**	**6**	**12**	**14**	specimen number
79	72	78	72	77	74	60	
78	70	76	70	76	72	59	
78	70	76	70	76	71	59	
77	70	75	70	76	71	59	
77	70	75	70	76	71	58	
77.3	**70**	**75.3**	**70**	**76**	**71**	**58.6**	average SRV

comments

Pendulum tester working to expected level once more. No problems encountered with any aggregate loss therefore results can be considered as an accurate comparison of performance.

Appendix 1. 5. 4 - 3mm aggregate polishing test results
TEST NUMBER 26

3mm aggregate test number 3 - additional 6 hrs of polishing
Skid Resistance Values (SRV)
Wheel 1 of 1 :- tested 25/11/94
comprising specimen 1 - 6 Bauxite aggregate
specimen 7 - 12 "Pan mills" derived aggregate
specimen 13 - 14 Control stone (10mm)

13	**1**	**7**	**2**	**8**	**3**	**9**	specimen number
	65	73	64	70	66	74	
	64	71	62	70	66	71	
	64	71	61	70	65	71	
	63	70	61	70	65	71	
	63	70	60	70	65	70	
	63.3	**70.3**	**60.6**	**70**	**65**	**70**	average SRV

4	**10**	**5**	**11**	**6**	**12**	**14**	specimen number
65	75	70	75	70	73		
65	75	68	72	69	72		
65	74	68	71	67	71		
65	74	67	71	67	71		
64	74	67	71	67	70		
64.6	**74**	**67.3**	**71**	**67**	**70.6**		average SRV

comments

Appendix 1. 5. 5 - 3mm aggregate polishing test results

Unpolished SRV of specimens

Unpolished results					
Pan mills aggregate 1		Pan mills aggregate 2		Guyana bauxite	
Direction 1	Direction 2	Direction 1	Direction 2	Direction 1	Direction 2
90	93	92	92	91	90
94	94	91	91	90	87
90	94	91	90	89	87
90	93	90	90	89	87
88	94	90	90	88	86
89.2	**93.6**	**90.3**	**90**	**88.6**	**86.6**
Average	**Average**				
90	**88**				

Notes.

Direction 1/2 - relates to skid testing the unpolished specimens with the pendulum slider passing first one way along the specimen surface and then, after remounting of the specimen, passing the other way along the specimen surface.

Testing laboratory	Date of test	Individual specimen test values	Corrected PSV	Testing laboratory	Date of test	Individual specimen test values	Corrected PSV
HARRY STANGER	07/06/61	not supplied	71	CUMBRIA LABS.	04/08/77	63/62/64/62	65
HARRY STANGER	07/06/61	not supplied	69	CUMBRIA LABS.	11/10/78	not supplied	59
HARRY STANGER	26/10/67	64/63/63/60	62	NICHOLLS COLTON & PRTNS	07/11/78	55/58/56/57	59
HARRY STANGER	26/10/67	63/62/60/59	61	NICHOLLS COLTON & PRTNS.	07/11/78	51/56/53/55	56
MESSRS. SANDBERG	03/11/67	60/59/59/60	60	NICHOLLS COLTON & PRTNS.	07/11/78	60/64/59/64	63
MESSRS. SANDBERG	03/11/67	60/59/60/60	60	NICHOLLS COLTON & PRTNS.	07/11/78	51/55/56/51	53
MESSRS. SANDBERG	03/11/67	63/62/64/63	63	CUMBRIA LABS.	16/11/78	not supplied	58
HARRY STANGER	05/04/68	64/62/61/60	62	CUMBRIA LABS.	16/11/78	not supplied	62
HARRY STANGER	05/04/68	54/51/51/47	51	NICHOLLS COLTON & PRTNS	23/11/78	55/57/60/60	58
WEST RIDING COUNCIL	11/11/68	62/63/61/61	62	NICHOLLS COLTON & PRTNS.	23/11/78	64/60/60/63	62
GLOUCESTERSHIRE C. C.	12/11/68	not supplied	60	NICHOLLS COLTON & PRTNS	20/02/79	not supplied	55
WEST RIDING COUNCIL	21/01/71	61/59/60/61	60	TESTING SERVICES LTD.	02/03/79	57/57/56/57	56
NICHOLLS COLTON & PRTNS.	13/02/71	68/67/68/68	68	TESTING SERVICES LTD.	02/03/79	57/58/58/58	58
NICHOLLS COLTON & PRTNS.	02/12/71	not supplied	73	HARRY STANGER	25/05/79	62/63/62/61	65
NICHOLLS COLTON & PRTNS.	02/12/71	not supplied	81	NICHOLLS COLTON PRTNS.	11/06/79	52/51/48/51	53
NICHOLLS COLTON & PRTNS.	19/01/73	59/69/71/72	68	ARC TECHNICAL	19/11/79	69/66/67/67	70
NICHOLLS COLTON & PRTNS.	19/01/73	68/64/66/68	67	HARRY STANGER.	10/03/80	60/59/64/61	65
NICHOLLS COLTON & PRTNS.	19/01/73	75/69/76/68	72	HARRY STANGER.	10/03/80	62/65/64	67
NICHOLLS COLTON & PRTNS.	06/06/73	63/61/62/62	62	HARRY STANGER.	29/12/80	55/53/61/65	60
NICHOLLS COLTON & PRTNS.	30/08/73	65/66/65/66	66	HARRY STANGER.	29/12/80	46/45/65/61	55
NICHOLLS COLTON & PRTNS.	30/08/73	66/66/66/65	66	NICHOLLS COLTON PRTNS.	29/12/80	65/66/70/67	68
NICHOLLS COLTON & PRTNS.	30/08/73	64/64/64/64	64	HARRY STANGER.	14/12/81	50/50/55/52	54
NICHOLLS COLTON & PRTNS.	19/09/73	53/54/52/53	53	NICHOLLS COLTON & PRTNS.	28/01/82	58/56/61/59	63
MESSRS. SANDBERG	07/06/74	59/60/60/61	60	NICHOLLS COLTON & PRTNS.	28/01/82	56/55/54/52	57
NICHOLLS COLTON & PRTNS.	21/01/75	63/61/64/64	63	HARRY STANGER	30/07/82	50/49/50/50	52
NASHMEAD ENG. SERVICES	11/11/75	59/61/63/62	61	TESTING SERVICES LIMITED	11/10/82	40/45/42/43	43
NASHMEAD ENG. SERVICES	11/11/75	55/57/56/58	56	MESSERS SANDBERG	19/11/82	48/48/48/44	46
CUMBRIA LABS.	14/12/76	64/64/62/64	63	NICHOLLS COLTON & PRTNS.	30/12/82	46/44/45/44	47
CUMBRIA LABS.	14/12/76	65/67/65/64	65	NICHOLLS COLTON & PRTNS.	05/01/83	48/52/48/48	52
CUMBRIA LABS.	14/12/76	65/66/67/67	66	HARRY STANGER LTD.	02/02/83	60/55/59/58	62
CUMBRIA LABS.	21/12/76	61/64/63/63	63	MESSERS SANDBERG	01/10/83	45/47/44/44	46

Appendix 1.6.1 - Historic PSV data collected at Templeborough on steel slag aggregate

Testing laboratory	Date of test	Individual specimen test values	Corrected PSV	Testing laboratory	Date of test	Individual specimen test values	Corrected PSV
CONSTRUCTION MAT. TESTG.	19/10/83	not supplied	49	HARRY STANGER LTD.	14/09/88	51/53/52/51	48
MESSRS SANDBERG	12/12/83	50/50/50/51	47	NICHOLLS COLTON & PRTNS.	15/06/89	57/56/57/58	58
NICHOLLS COLTON & PRTNS.	06/12/84	65/65/70/66	64	NICHOLLS COLTON & PRTNS.	03/07/89	64/63/60/60	61
NICHOLLS COLTON & PRTNS.	16/05/85	72/69/73/72	73	NICHOLLS COLTON & PRTNS.	28/07/89	61/59/64/62	62
NICHOLLS COLTON & PRTNS.	13/09/85	67/67/70/67	68	SUFFOLK COUNTY LAB.	25/10/89	69/65/67/65	63
NICHOLLS COLTON & PRTNS.	13/09/85	57/57/58/58	58	NICHOLLS COLTON & PRTNS.	26/10/89	51/54/52/52	53
NICHOLLS COLTON & PRTNS.	13/09/85	67/67/70/67	68	NICHOLLS COLTON & PRTNS.	26/10/89	49/50/48/48	50
NICHOLLS COLTON & PRTNS.	17/10/85	56/58/58/57	58	SUFFOLK COUNTY LAB.	22/11/89	60/62/63/62	63
NICHOLLS COLTON & PRTNS.	17/10/85	60/64/59/59	62	SUFFOLK COUNTY LAB.	10/01/90	63/62/61/62	63
NICHOLLS COLTON & PRTNS.	10/04/86	62/58/62/61	57	SUFFOLK COUNTY LAB.	17/01/90	61/61/59/63	62
NICHOLLS COLTON & PRTNS.	30/06/86	66/61/64/65	65	SUFFOLK COUNTY LAB.	27/04/90	not supplied	61
NICHOLLS COLTON & PRTNS.	30/06/86	not supplied	65	SUFFOLK COUNTY LAB.	24/09/90	not supplied	64
NICHOLLS COLTON & PRTNS.	26/09/86	65/63/59/60	60	NICHOLLS COLTON & PRTN's	10/10/90	64/64/62/62	61
HARRY STANGER LTD.	29/11/86	50/50/53/50	49	SUFFOLK COUNTY LAB.	06/06/91	not supplied	65
NICHOLLS COLTON & PRTNS.	15/01/87	59/55/56/57	56	SUFFOLK COUNTY LAB.	09/08/91	69/67/68/66	70
HETS MATERIALS LABS.	19/05/87	60/64/65/62	62	SUFFOLK COUNTY LAB.	03/01/92	66/69/65/66	69
TESTING SERVICES LTD.	04/06/87	not supplied	47	HETS MATERIALS LAB.	13/01/92	62/64/63/60	62
MACARTHY HUGHES LTD.	04/11/87	58/59/58/58	58	SUFFOLK COUNTY LAB.	16/01/92	not supplied	65
HETS MATERIALS LABS.	21/01/88	56/57/57/57	56	HETS MATERIALS LAB.	10/07/92	64/62/64/64	66
HETS MATERIALS LABS.	14/03/88	61/61/62/61	60	SUFFOLK COUNTY LAB	11/08/92	58/56/57/59	61
MACARTHY HUGHES LTD.	09/05/88	56/56/57/56	56	HETS MATERIALS LAB.	14/08/92	61/61/59/61	60
SOUTH YORKS. LABS.	12/05/88	48/46/47/47	49	HETS MATERIALS LAB.	28/10/92	63/65/64/66	64
HETS MATERIALS LABS.	06/07/88	59/62/57/59	55	SUFFOLK COUNTY LAB.	19/05/93	58/59/63/55	61
NICHOLLS COLTON & PRTNS.	28/07/88	52/51/48/53	51	CELTEST Ltd.	30/06/93	67/68/68/66	67

Appendix 1.6.1 (continued) - Historic PSV data collected at Templeborough on steel slag aggregate

Year	1961	1967	1968	1971	1973	1974	1975	1976	1977	1978	1979	1980	1981
Average PSV	70	61	59	71	65	60	60	64	65	59	60	63	54
Year	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	
Average PSV	51	51	64	65	59	56	54	59	62	68	59	64	

Appendix 1.6.2 - Yearly averages of PSV tests performed on ex. Templeborough steel slag aggregate

SITE DETAILS		PSV		AAV	
QUARRY	OPERATOR	Mean	No	Mean	No
Arcow	Tarmac	62.0	21	6.0	11
Bardon Hill	Evered -Bardon	57.0	46	2.5	10
Barton Wood	Devon CC	59.0	4	5.0	4
Bayston Hill	Tarmac	65.0	78	4.5	17
Bray Valley	A Nott & Co.	60.0	6	5.0	5
Callow Hill	Tarmac	68.5	28	7.9	25
Dry Rigg	Redland	63.0	36	8.0	21
Ghyll Scaur	Evered-Bardon	67.0	38	7.0	19
Griff	Pioneer	63.0	11	7.0	6
Haughmond Hill	Tarmac	63.5	8	4.5	6
Holmescales	Robinson Rock	60.5	9	6.5	10
Ingleton	ARC	61.0	28	5.0	18
Judkins	ARC	58.5	28	4.0	10
Lean	Roseland Aggregates	59.0	4	6.0	3
Mancetter	Tilcon	62.0	14	7.0	6
Quartzite	RMC	62.5	31	5.5	13
Roan Edge	RMC	62.5	11	8.5	6
Templeborough	Steelphalt	63.5	12	3.0	2
Triscombe	Tarmac	60.0	50	4.5	11
Venn	ECC Quarries	64.5	20	5.5	7
Whitwick	ARC	57.5	60	3.0	18

Appendix 1.6.3 - Extract of High Specification Aggregate quarries in England

Readings taken during test number 15, wheel 1.

Time of test	Specimen number															Corrected averages	
	13	1	10	3	5	12	8	7	11	6	4	9	2	14	Correction Factor (to be added)	Steel slag average	Control stone average
Pre-test	67	72.6	74.6	75.3	72	70.6	70	74	74.3	73.3	73.3	72.6	71	65.3	0.0	72.8	66.15
1 hour	66.6	65	66.6	68	66.3	65.6	64.6	68	68.3	66	66.3	66.6	65.6	65	2.0	68.4	65.8
2 hour	65.6	63.6	66.3	68.3	62.6	63	62.6	65.3	65.6	63.3	64.3	65.6	63.3	63.3	3.0	67.5	67.45
3 hour	64.6	62	68	68.2	63.3	64	62	66	65.6	63.3	64.3	63.6	61.6	64	4.0	68.3	68.3
4 hour	56.6	61.6	64.3	65.3	59	64	60.6	68	64	58.6	61	64.6	64	54	4.0	66.9	59.3
5 hour	52.6	64	66.6	67.6	58	64	62.6	68	65	58.3	62.3	64.3	67.6	52.3	4.0	68.0	56.45
6 hour	52	64	66.3	69	58	64.6	63	64.6	64.6	58	61.3	64.6	67.6	49	4.0	67.8	54.5

Uncorrected SRV results of individual PSV specimens

Time of test	Specimen number															Corrected averages	
	13	1	10	3	5	12	8	7	11	6	4	9	2	14	Time of test (hours)	Steel slag average	Control stone average
Pre-test	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0	100.0	100.0
1 hour	102.4	92.3	92.0	93.0	94.9	95.8	95.1	94.6	94.6	92.8	93.2	94.5	95.2	102.6	1	94	102.5
2 hour	102.4	91.7	92.9	94.7	91.1	93.5	93.7	92.3	92.3	90.5	91.8	94.5	93.4	101.5	2	92.7	102.0
3 hour	102.4	90.9	96.5	95.9	93.5	96.3	94.3	94.6	93.7	91.8	93.2	93.1	92.4	104.1	3	93.8	103.3
4 hour	90.4	90.4	91.6	92.0	87.5	96.3	92.3	97.3	91.5	85.4	88.7	94.5	95.8	88.8	4	91.9	89.6
5 hour	84.5	93.7	94.6	95.1	86.1	96.3	95.1	97.3	92.9	85.0	90.5	94.1	100.8	86.2	5	93.5	85.3
6 hour	83.6	93.7	94.2	96.9	86.1	97.2	95.7	92.7	92.3	84.6	89.1	94.5	100.8	81.2	6	93.2	82.4

Correceted percentages of retained skid resistance for individual specimen

Appendix 1.7 - Experimental results and further calculations for polishing profile investigation

Appendix 2.0 - Full results from the SCRIM investigations

Contents 2i

Glossary of terms used in appendix 2

COS	Change of surface
R/B	Roundabout
T.L.	Traffic Lights
10mm CGWC	10mm Close Graded Wearing Course
14mm CGWC	14mm Close Graded Wearing Course
10mm SDC	10mm Surface Dressing Chippings
14mm SDC	14mm Surface Dressing Chippings
20mm PCC in HRA	20mm Pre-Coated Chippings in Hot Rolled Asphalt

Site	Site location	Length of site (km)	Material
1	Kighill lane, Ravenshead	0.48	14mm CGWC
2	Chapel lane, Ravenshead	1.81	10mm CGWC
3	Church Hill rd, Mansfield Woodhouse	0.21	10mm CGWC
4	St. Edmunds Ave, Mansfield Woodhouse	0.18	10mm CGWC
5	A61 Chesterfield Ring Road	2.26	20mm PCC in HRA
6	A625 Hunters bar to Psalter lane - SHEFFIELD	9.68	10mm SDC
7	A625 Weetwood drive to Wheatsheaf PH		10mm SDC
8	A625 Limb lane to Sheephill road		10mm SDC
9	A625 COS after Whitelow lane to COS to Natural aggregate		10mm SDC
10	COS to Fox house PH		10mm SDC
11	A624 Chapel-on-le-Frith	0.43	14mm SDC
12	A621 Abbeydale road, Bannerdale rd to Sterndale road	5.74	10mm SDC
13	A621 T.L. at Glover road to Hillfoot road		10mm SDC
14	Norton lane, from R/B with Ring rd to Norton Ave R/B	1.27	10mm SDC
15	A57 Worksop road toward Anston	0.37	20mm PCC in HRA
16	Crowgate, from West st to bottom of Dog Kennels lane , Sth. Anston	1.58	14mm CGWC
17	A618 Guilthwaite Hill from Lights with A631 M1 motorway bridge	3.64	20mm PCC in HRA
18	A618 M1 motorway bridge to Ulley Country Club		20mm PCC in HRA
19	A618 Ulley Country Club to Ulley lane		10mm SDC
20	A631 West Bawtry road , Worrygoose to Rotherway R/B's	6.1	14mm SDC
21	A631 West Bawtry road, Rotherway to Canklow rd R/B's		14mm SDC
22	A631 Bawtry road, M1 to Canklow rd R/B's		14mm CGWC
23	A6178 Sheffield Rd, Centenary way R/B to M1 R/B	2.9	20mm PCC in HRA
24	Fenton Road, from Bradgate R/B to change of surface	1.85	14mm CGWC
25	A6109 Meadowbank Rd, Psalter lane to M1 R/B (W/Bound)	1.98	10mm CGWC
26	A629 Bradgate R/B to COS with new 14mm CGWC	4.97	10mm CGWC
27	A629 COS above to Droppingwell road		14mm CGWC
28	A629 Droppingwell road to Admirals Crest		10mm CGWC
29	A629 Newtons place to Eldertree road		14mm CGWC
30	A629 COS to M1 Junction 35		10mm SDC
31	B6089 Greasborough Rd, COS before Barbot road to 30mph signs	1.58	20mm PCC in HRA
32	B6089 Greasbrough road, Firth street to COS beyond Lowfield Avenue		10mm CGWC
33	B1396 Cantley lane, Lights with A638 to Green Boulevard roundabout	1.28	10mm CGWC
34	B1220 Carcroft, A19 to Dalecroft Road	2.27	10mm CGWC

Appendix 2.1 - Location of sites tested

Site	Site location	Length of site (km)	Material
35	B6411 Thurnscoe, Shepherds lane to Clayton lane	1.08	10mm CGWC
36	High Street Billingley, from Back lane to A635	1.01	10mm CGWC
37	A635 Darfield, from R/B with B6273 to Cliff road.	0.81	20mm PCC in HRA
38	Engine lane, Grimethorpe, from lights with A628 to railway bridge	2.68	20mm PCC in HRA
39	Engine lane, railway bridge to COS at colliery entrance		10mm CGWC
40	Engine lane, COS at Colliery entrance to 40mph signs		14mm CGWC
41	Engine lane, 40mph signs to King street		10mm CGWC
42	Engine lane, King street to Elizabeth street		20mm PCC in HRA
43	A6135 Ecclesfield road, from roundabout with A629 to Lights at Nether lane	1.85	10mm SDC
	Total length of road surface tested	54.5 km	

Appendix 2.1
Location of sites tested (in order of testing)

1994 SCRIM results and traffic count data for 10mm CGWC macadam									
1994 SCRIM results						Traffic Count data			1994 Equivalents
Site	Road	Date Laid	Site boundaries	Direction	1994 mean summer SFC	Date of survey	24hr total traffic	HGV's	HGV's
33	B1396 Cantley Road	25,26/3/93	A638 - Green Boulevarde R/B	SouthEast NorthWest	0.54 0.54	09/12/94	6673 8344	483 507	483 507
34	B1220	10/06/93	A19 - Dalecroft Rd, Carcroft	West East	0.56 0.57	May-90	2252 2318	188 228	216 262
35	B6411 Houghton Road		Shepherds lane - Clayton lane	West East	0.57 0.56	1993	4209 3538	317 256	328 265
36	High St, Billingley	15,16/3/94	Back lane - COS	South North	0.56 0.55	No traffic data available			
41	Engine lane, Grimethorpe	2-8/12/93	King St - 40mph signs	NorthWest SouthEast	0.59 0.61	1993	2318 2562	378 366	391 379
39	Engine lane, Grimethorpe	2-8/12/93	COS by Colliery entrance - COS on Railway bridge	NorthWest SouthEast	0.61 0.51	1993	2318 2562	378 366	391 379
2	Chapel lane	20-22/1/93	Chapel lane, Ravenshead	North South	0.55 0.55	1993	2250	23	23.8
3	Church hill rd.		Church Hill rd, Mansfield Woodhouse	SouthWest NorthEast	0.66 0.61	No traffic data available			
4	St. Edmunds Ave.		St. Edmunds Ave, Mansfield Woodhouse	NorthWest SouthEast	0.58 0.62				
25	A6109 Meadowbank Road	1980	M1 Jcn 34 - COS @ Derestriction signs	West East	0.52 0.54	5/10/94	9015 7993	1198 1133	1198 1133
32	Greasbrough road		COS before Firth St - COS	North South	0.55 0.58	28/02/89	4523	362	430
26	A629 Wortley road	1984	Bradgate R/B - COS to New 14mm	NorthWest SouthEast	0.54 0.56	13/10/94	7879 8517	877 974	877 974
28	A629 Wortley road	1984	Droppingwell road - Admirals crest	Northwest Southeast	0.57 0.56	13/10/94	7879 8517	877 974	877 974

Appendix 2.2

1994 SCRIM survey results and relevant traffic data for sites surfaced with 10mm Close Graded Wearing Course macadam

1994 SCRIM results and traffic count data for 10mm Surface Dressing Chippings.									
1994 SCRIM results						Traffic count data			1994 Equivalents
Site	Road	Year laid	Site boundaries	Direction	1994 mean summer SFC	Date of survey	24hr total traffic	HGV's	HGV's
6	A625	1978	Hunters Bar - Psalter Lane	SouthWest NorthEast	0.52 0.45	09/07/89	33796	946	879
7	A625		Weetwood Dr - Wheatsheaf PH	SouthWest NorthEast	0.55 0.56	09/07/89	33796	946	879
8	A625		Limb Lane - Sheephill Road	SouthWest NorthEast	0.61 0.56	09/06/90	5312	356	330
9	A625		COS after bend after Whitelow lane - COS to Natural Aggregate	SouthWest NorthEast	0.61 0.57	09/06/90	5312	356	330
10	A625		Fox House PH - COS at top of hill	SouthWest NorthEast	0.59 0.58	09/06/90	5312	356	330
12	A621 Abbeydale Rd	1978	Bannerdale Road - Sterndale Rd	Southwest NorthEast	0.57 0.53	24/10/90	7014 7194	534 514	613 590
13	A621 Abbeydale rd	1978	T.L. at Glover Rd - Hillfoot Rd	SouthWest NorthEast	0.57 0.56		8851 8813	571 540	655 620
14	Norton Lane	1977	A6102 - Norton Avenue Roundabout	NorthEast SouthWest	0.53 0.53	No traffic data available			
43	A6135	1979	COS to T.L's at Nether Lane (going Sth)	South North	0.53 0.5	09/05/90	8328 7890	669 637	768 731
19	A618		Ulley lane - Ulley Country club	North South	0.49 0.59	22/2/94	6621 6082	392 346	392 346
30	A629 Wortley Rd		COS to M1 Junction 35 Roundabout	NorthWest SouthEast	0.57 0.52	13/10/94	7879 8517	877 974	877 974

Appendix 2.3
1994 SCRIM survey results and relevant traffic data for sites surfaced with 10mm Surface Dressing Chippings

1994 SCRIM results and traffic count data for 14mm CGWC material									
1994 SCRIM results						Traffic count data			1994 Equivalents
Site	Road	Date laid	Site boundaries	Direction	1994 mean summer SFC	Date of survey	24hr total traffic	HGV's	HGV's
16	Crowgate - South Anston		Sheffield Road - COS at Bottom of Dog Kennels Lane	South North	0.56 0.57	25/8/92	2137 2285	184 204	197 219
1	**Kighill lane, Ravenshead**	15/12/93	Kighill lane, Ravenshead	SouthWest NorthEast	0.66 0.61	No traffic data available			
22	**A631**	1980	Bonet Lane - COS towards Canklow Roundabout	East West	0.53 0.54	13/7/92	9820 9797	930 855	996 916
24	**Fenton road, Rotherham**	1988	Fenton rd, A629 (Bradgate) R/B - COS	North South	0.56 0.56	17/1/90	5239 5491	401 434	460 498
27	**A629**	1988	COS to Droppingwell Rd	NorthWest SouthEast	0.56 0.56	13/10/94	7879 8517	877 974	877 974
29	**A629**	1988	Newtons Place - Eldertree Rd	NorthWest SouthEast	0.54 0.56	13/10/94	7879 8517	877 974	877 974
40	**Engine lane, Grimethorpe**		COS at Colliery entrance to 40mph sign	NorthWest SouthEast	0.6 0.62	1993	2318 2562	378 366	391 379

Appendix 2.4
1994 SCRIM survey results and relevant traffic data for sites surfaced with 14mm Close Graded Wearing Course macadam

1994 SCRIM resultsand traffic count data for 14mm SDC surfaces									
1994 SCRIM results						Traffic count data			1994 Equivalents
Site	Road	Date laid	Site boundaries	Direction	1994 mean summer SFC	Date of survey	24hr total traffic	HGV's	HGV's
20	**A631**	1988	Moorgate - Rotherway R/B	East West	0.53 0.53	22/2/94	12642 13268	745 704	745 704
21	**A631**	1988	Rotherway R/B - Canklow R/B	East West	0.48 0.5	13/7/92	11977 11658	1499 1393	1606 1492
11	**A624 (T)**	1990	COS with Jcn on Left to COS before over bridge Chapel-en-le-frith	South North	0.53	20/10/94	4117	427	427

Appendix 2.5
1994 SCRIM survey results and relevant traffic data for sites surfaced with 14mm Surface Dressing Chippings

1994 SCRIM results and traffic data for 20mm Pre-coated Chippings in Hot Rolled Asphalt									
1994 SCRIM results						Traffic count data			1994 Equivalents
Site	Road	Year laid	Site boundaries	Direction	1994 mean summer SFC	Date of survey	24hr total traffic	HGV's	HGV's
15	**A57**	1975	M1 Junction 31 - C.O.S. Anston bound	Eastbound Westbound	0.46 0.55	03/03/94	12395 12124	1948 2106	1948 2106
5	**A 61 (T)** Chesterfield by-pass	1984	Tesco Roundabout to M1 linkroad R/B	North South	0.53 0.51	09/07/94	14442 22583	1350 1928	1350 1928
17	**A618**	1975	A631 T.L.'s - Start of Motorway Bridge deck	North South	0.56 0.56	22/2/94	6621 6082	392 346	392 346
18		1977	End of M/way bridge deck - Ulley lane Country Club	North South	0.57 0.59		6621 6082	392 346	392 346
23	**A6178** **Sheffield Road**	1974	M1 Jcn 34 - A630 R/B	East West	0.51 0.48	10/06/94	5533 6349	867 1068	867 1068
31	**B6089** Greasbrough rd	1973	COS before Barbot Rd to 30mph signs	North South	0.53	28/2/89	4523	362	430
42	**Engine lane, Grimethorpe**		Elizabeth St - King St	NorthWest SouthEast	0.48 0.5	1993	2318 2562	378 366	391 379
38	**Engine lane, Grimethorpe**		T.L.'s with A628 to COS on Railway bridge	NorthWest SouthEast	0.55 0.51		2318 2562	378 366	391 379
37	**A 635**		COS to COS just off R/B with B6273	West East	0.55 0.53	1993	5856 5612	403 793	417 821

Appendix 2.6
1994 SCRIM survey results and relevant traffic data for sites surfaced with 20mm Precoated Chippings in Hot Rolled Asphalt.

Steel slag						Natural aggregate		
Site	Material	year of test	Direction		Combined SFC (If applicable)	Direction		Combined SFC
25	10mm CGWC		Eastbound SFC	West bound SFC				
		1989	0.537	0.543				
		1990	0.493	0.472				
		1992	0.528	0.488				
		1994	0.545	0.519				
30	10mm SDC		Northwest SFC	Southeast SFC		Northwest SFC	Southeast SFC	
		1990	0.481	0.48	0.48	0.47	0.45	0.46
		1992	0.54	0.508	0.525	0.47	0.49	0.48
		1994	0.586	0.561	0.574	0.53	0.52	0.525
27	14mm CGWC		Northwest SFC	Southeast SFC		Northwest SFC	Southeast SFC	
		1990	0.545	0.538	0.54	0.5	0.46	0.48
		1992	0.528	0.492	0.51	0.52	0.51	0.515
		1994	0.549	0.551	0.55	0.55	0.55	0.55
20	14mm SDC		East bound SFC	Westbound SFC				
		1992	0.506	0.508				
		1994	0.522	0.528				
23	20mm PCC in HRA		Eastbound SFC	Westbound SFC				
		1989	0.465	0.422				
		1990	0.402	0.392				
		1994	0.52	0.493				

Appendix 2.7
September SFC values calculated for steel slag and natural aggregate surfaces