Higher PSV and other aggregate properties

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ABSTRACT

PSV is a standard laboratory measurement of skid resistance. Many years of testing has shown that certain types of aggregate give higher values in relation to others. There is a general ranking of rock types e.g. gritstone has better PSV than basalt which is better than limestone. In the UK this natural ranking has resulted in the majority of higher trafficked roads to be surfaced using gritstone sources. However, within each of these general rock type groupings there is a tremendous possible range in PSV. PSV has been a key aspect of quarrying, specifications, aggregate selection and asphalt surfacing mixes development in the UK. However, the standard PSV method has remained relatively unchanged in contrast to the tremendous change in expectation to perform from modern highway surfacing materials. The paper considers whether the standard 6 hour test is still able to predict in-service skid resistance of asphalt surfacing materials. The effect of variables such as extended polishing, sideways polishing, freeze thaw and bitumen coatings during testing are discussed. The research suggests that the standard PSV test is a ranking tool for a given set of laboratory conditions. Aggregates skid resistance is dependant on test conditions that in turn related to in-service conditions. The authors have developed a suite of test methods using the basic PSV test apparatus that offer an alternative to skid resistance prediction. The skid data presented is compared with other properties for a range of rock types measured using standard and non-standard test methods. The paper concludes that aggregate skid resistance is gained at the other aggregate properties such as strength, abrasion and durability. This is particularly important for countries that either currently do not have higher PSV aggregate sources, who are looking for higher PSV sources, or who are interested in using or specifying higher PSV aggregates.

KEY WORDS

PSV, aggregate, performance, prediction.

1. INTRODUCTION

Aggregate form's the bulk of every generic type of surfacing material. Geologically different types are used in many different ways. The testing of aggregate for use in asphalt mixtures for highway construction has remained relatively unchanged for many years. Compared to developments over the last few decades in the assessment of bitumen and bituminous mixtures most countries around the world continue to rely on simplistic methods that date from the middle or early 20^{th} century.

The in-service performance of surfacing aggregate in asphalt mixes is affected by many factors. When attempting to explain just those involved at the tyre / surface interface, Williams et al. (1972) proposed 47 variables grouped under the four headings of the tyre, pavement, lubricant and operating conditions. As an indication of their recognition of the complexity of the phenomena which occur at this location, they refer to their model of 47 variables as being simplified. However, the tyre / surface interface is just one of a wide range of factors which contribute towards either successful performance or premature failure.

Woodward (1995) identified the factors shown in Figure 1 as contributing towards successful performance or premature failure of surfacing mixes. It was recognised that this was an over-simplification as many factors are inter-related while others are not shown. This example also highlights some of the factors that subsequently limit the present effectiveness of laboratory testing. Figure 1 widens the range of factors which contribute to the prediction and understanding of performance risk.

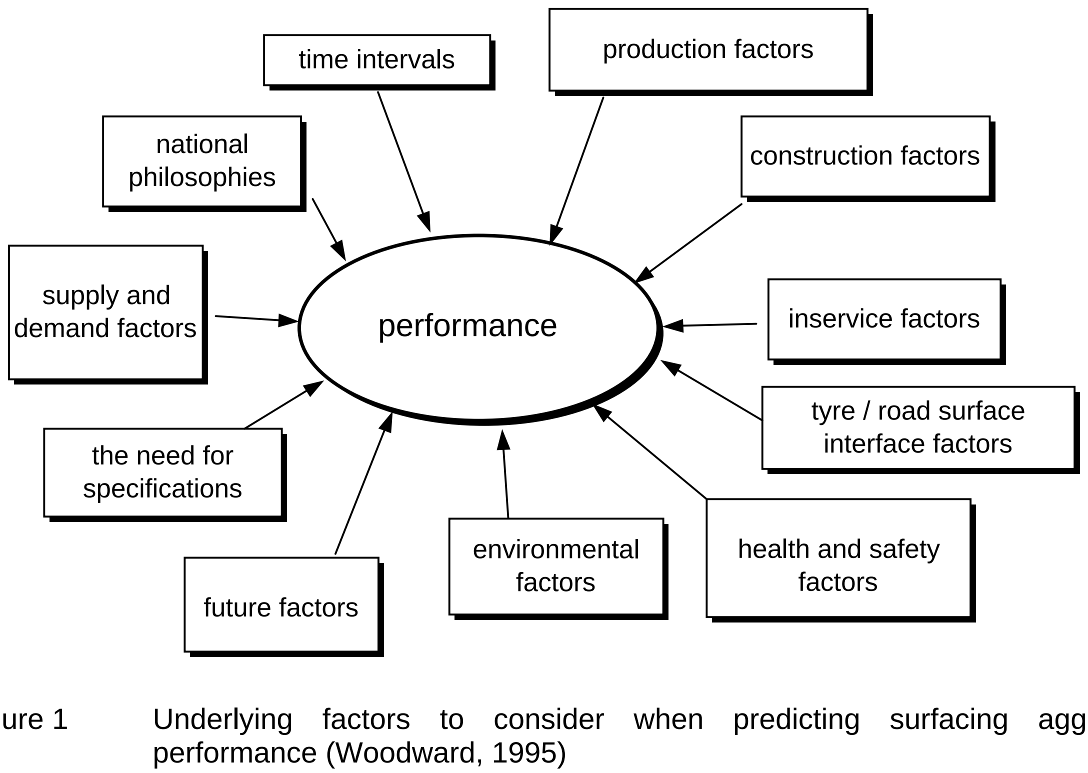

Figure 1 Underlying factors to consider when predicting surfacing aggregate performance (Woodward, 1995)

There is tremendous variability in the types of naturally occurring rock that may be used as aggregate. The simplest classification is based on whether they are of igneous, sedimentary or metamorphic. When considering their potential as aggregate, one must recognise the importance of differing time-scales. This ranges from the geological age of the rock to weathering processes prior to quarrying as aggregate. They may range from hundreds of millions of years in age to newly formed by volcanic eruption. They are made of many different types of minerals which can vary in properties such as hardness or stability in the presence of water or the atmosphere. Some have remained relatively unchanged over millions of years, others may have been effected by chemical / weathering processes whilst a few may undergo rapid change once quarried to produce aggregate.

Not all are suitable as aggregate for highway surfacing construction. Just like other construction materials, engineers must rely on testing to determine their suitability. However, compared to the testing of asphalt mixtures the methods available for surfacing aggregate have remained relatively unchanged from the middle or early 20th century. Few offer insight into performance with most simply ranking one aggregate in relation to another. More importantly, even fewer consider performance in terms of engineering time i.e. the ability to maintain fit for purpose during the design life of the highway pavement.

It has been the authors experience that many failures can be attributed to this fundamental matter i.e. the assumption that if the aggregate has remained in the ground for 100 million years then it will last another 10 to 40 years as part of an asphalt surfacing mix. Performance expectation continues to grow. There are natural limits to performance that can be expected from an aggregate before it suffers premature failure. In relation to skid resistance, nature balances short term in-service performance by premature failure caused a wide range of possible factors including loss of texture depth due to excessive wear, soundness problems due to environmental stressing conditions such as freeze / thaw, wetting and drying or asphalt mix fretting and ravelling due to failure of the aggregate / bitumen bond.

This paper considers the laboratory testing of surfacing aggregate where the same aggregate source may be used as fine aggregate in slurry mixes or as 14mm in a SMA. The ability of a selection of commonly used test methods to predict performance during engineering time is considered. This is particularly relevant given the importance now placed on sustainability where there is pressure to find better uses for both virgin, reused and recycled construction materials.

2. CURRENT UK AGGREGATE TESTING

In the United Kingdom, the testing of materials is in accordance with British Standards. The first British Standard to consider aggregate was BS 63 in 1913. This evolved into BS 812 which was first published in 1938 and subsequently revised. Since the mid 1980's it was revised to contain approximately 24 parts or sections each containing a particular test method (BS 812). The main test methods applicable to aggregate for use in asphalt mixes include grading, shape, fines content, mechanical strength, abrasion, polishing and soundness. Although BS 812 contains a range of aggregate test methods, it must be recognized that there has not been any major shift in their emphasis from the first draft in 1938. Test methods that originally used single pieces of stone were replaced by single-sized crushed rock aggregate. Until the inclusion of a soundness test in 1991, the only other notable addition was a polishing test in 1960.

In terms of actual use (in-service performance) most methods have particular limitations e.g. from assessing single sizes, the dry static assessment of strength, the dry assessment of abrasion resistance, the use of 10mm aggregate for skid-resistance to a 3 week test-duration for soundness. If one compares the laboratory to the road surface, then these are basic problems which must be addressed if one wishes to predict performance i.e. un-realistic stone sizes, presence of moisture, dynamic stressing, time and expense.

In 1998 the United Kingdom signed the Construction Products Directive. The aim of this European Directive was to remove barriers to trade between participating countries and the simplification of existing national technical requirements (QPA, 2003). This marked the start of work across Europe to develop common European Standards. Each member country was approached to put forward suggestions for suitable methods. On 1st January 2004 a series of product standards and supporting test methods were adopted with existing British Standards withdrawn in June 2004 (BS EN 13043, PD 6682-2, PD 6682-9, BS EN 932, BS EN 933, BS EN 1097, BS EN 1367, BS EN 1744).

A summary of the main test methods for aggregate that will be used in asphalt mixes is shown in Table 1. It must however be stressed that the methods selected in this process were not the result of a research project into developing improved predictive test methods. Rather, they are existing methods that in most cases have been in use for many years. In terms of predicting performance they are as limited / or as good as those found in most countries around the world. There is no guarantee that the prediction of in-service performance or the minimization / understanding of risk will be improved by their use.

Table 1 Summary of main European test methods for aggregate

Physical properties	Test method
Grading	Sieve analysis
Fines content	Wet sieving to determine %<0.063mm
Shape	Flakiness index
Resistance to fragmentation	Los Angeles test (reference method) German Schlagversuch impact test
Resistance to wear	French micro-Deval coefficient
Resistance to polishing	British polish stone value
Resistance to surface abrasion	British Aggregate abrasion value
Durability in terms of freeze-thaw resistance	Water absorption as a screening test for freeze/thaw resistance Freeze-thaw test or magnesium sulfate soundness where necessary
Bulk density	Bulk density
Thermal shock	Sonnebrand test – 36 hour boiling in water Soaked, surface dry aggregate heated at 700^{0}C for 3 minutes

3. SUSTAINABLE SKID RESISTANCE

Sustainable issues now affect most aspects of construction. Occupying at least 90 to 95% of an asphalt surfacing mix, this applies to the use of aggregate. Reliance on the use of reference tests carried out on single sizes of aggregate will not improve the risk of predicting performance. Neither will it ensure acceptance of the ideals of sustainability. Although properties such as size, shape and strength are important, there are additional factors which are equally if not more important to understand and predict how a specific aggregate is to perform as part of a modern highway pavement.

The underlying emphasis must recognize and understand risk. This will allow selection of the most appropriate aggregate for a specific use whether virgin, secondary or recycled i.e. optimum sustainable design. There are problems around the world with meeting the demand and supply of suitable sources. In many countries aggregates may be over or under-specified due to poor understanding of aggregate performance. Equally important is the ability to recognize whether an aggregate that is being proposed to be recycled has reached the end of its engineering design life.

In many developed and rapidly developing countries, the growth of traffic and in particular heavier and overweight goods vehicles is creating extreme stressing conditions that far exceed the traffic on which test methods and specification requirements were developed. Certain types of mix may protect weaker aggregates whilst others fail by exploiting weaker particles. Therefore, it may be possible to enhance the use of lower quality material by using it in ways different to what is done traditionally.

Stressing at the tyre / aggregate interface is much greater for positive texture depth (chip seals) than for negative texture depth (SMA, thin surfacings) and so positive textured mixes require aggregate with improved wear resistance than smooth negative textured mixes. Many countries are now trying to introduce skidding standards to promote safety requiring a different philosophy from what they consider to be good quality hard aggregate.

4. LABORATORY PREDICTION OF SKID RESISTANCE

Aggregate skid resistance is quantified in the laboratory using the PSV test. This has been a British Standard since 1960 and recently became the Euro Norm for measuring this property. PSV is typically the main property used when selecting surfacing aggregate in the UK. A range of test regimes based on the equipment used in the BS 812 PSV test method have been developed during a number of research projects including SKIDPREDICT (Roe and Woodward, 2004) and SKIDGRIP (Woodward, 2003).

These regimes considered conditions such as dry and wet unpolished aggregate, change in skid resistance each hour during the standard 6 hour test, extended polishing (3 hours rough emery + 30 hours fine emery), use of roughening cycles to renew skid resistance, use of freeze/ thaw cycles to renew skid resistance, fine emery on new moulds, effect of side ways polishing at 3, 6, 10 and 20^0. A coded abbreviation was developed to explain the test conditions carried out. For example, CE(3) means using coarse emery for 3 hours, CE(3)FE(22)CE(3)FE(3)SIDE(3) means the use of coarse emery for 3 hours, followed by fine emery for an extended period of 22 hours, followed by 3 hours of coarse emery, followed by fine emery for 3 hours, followed by sideways polishing for 3 hours. The purpose of the different test regimes was to expose test samples to differing stress conditions in the laboratory that could simulate combinations of polish and wear found on the road network.

The data obtained suggests that standard PSV test is simply a ranking tool that offers limited prediction of the complex development of skid resistance during the life of modern asphalt materials. Consider the data shown in Figure 2 for three different aggregates assessed using the standard PSV test and 5 alternative variations using the same equipment. These variations include use of coarse emery only, fine emery only, extended duration of polishing, sideways polishing and use of freeze / thaw cycles. The data highlights the unpredictability of each aggregate in relation to the variation in test method i.e. skid resistance is dependant on the test conditions used suggesting that the same is to be expected in-service.

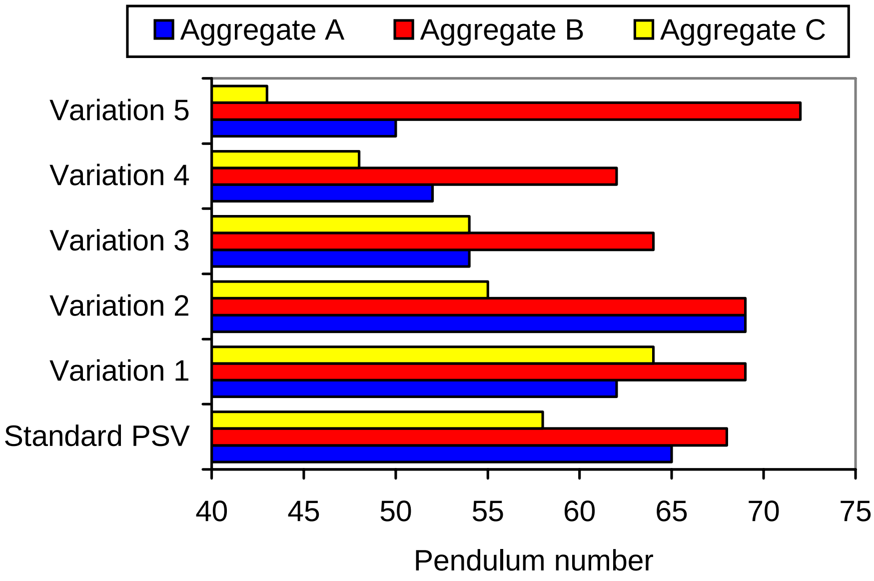

Figure 2 Varying test conditions during accelerated polishing for 3 aggregates

This research has shown that the standard PSV test should not be considered as a measure of an ultimate state of polish, nor should it be the sole basis of surfacing aggregate selection. Rather, testing aggregate using these alternative methods could result in better sustainability and prediction of in-service performance i.e. a lower PSV aggregate when used as a smaller size may offer better levels of skid resistance than the standard test suggests.

Figure 3 shows the variation in pendulum value with offset angled polishing for 5 aggregate sources. This is a method developed where the tyre is off-set at a fixed angle to induce differing levels of stress at the tyre / aggregate interface. The data shows that an of 6^0 gives the greatest amount of polishing. At the 10^0 angle, higher shear stress causes the weaker aggregate to wear away at a greater rate, there-by exposing new unpolished surface i.e. the classic theory of plucking as proposed by Knill (1960). This is particularly evident with gritstone sources C, D and E that showed a marked increase in pendulum value at this angle. At the lower angles the amount of polishing increased with increase in shear stress being applied by the angle. In contrast, the two igneous sources A and B continued to polish.

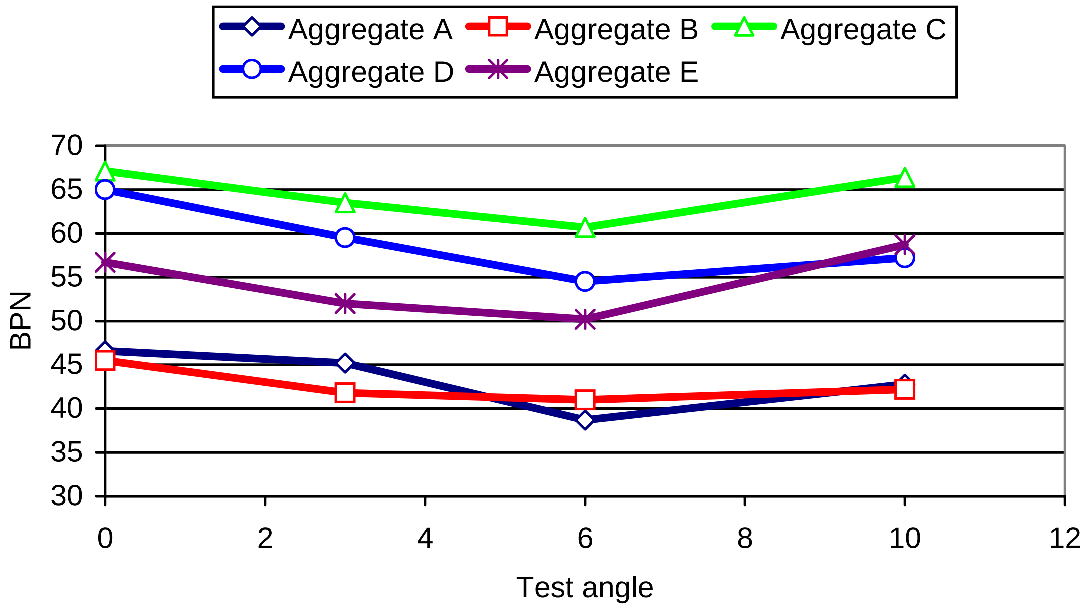

Figure 3 Effect of test angle on the polishing of different rock types

This difference in polish and wear characteristics between the aggregate sources may be attributed to their basic petrology. The hard, crystalline nature of the igneous sources dictates their low pendulum value and good abrasion resistance. The sedimentary sources are essentially composed of sand grains bound together with clay rich cement. This encourages a plucking effect at higher shear stress, which abrades the surface but renews micro-texture. Aggregate E is a greywacke formed by a higher grade of metamorphism than aggregate D. This has strengthened the clay cement binding the rock and made the aggregate harder and less resistant to wear but reduced resistance to polishing except at high tracking angles when shear stress is sufficient to remove the strongly bonded grains.

5. SKID RESISTANCE AND STONE SIZE

The standard PSV test is carried out on 10mm aggregate. However, this is not the main aggregate size in most asphalt mixes. For example, the UK skidding standards are predominately based on the SCRIM measurement of 20mm high PSV gritstone chippings applied to hot rolled asphalt. Do the found relationships apply to modern thin surfacings or micro-asphalts incorporating 10 or 6mm aggregate?

Figure 4 is a simple example showing skid resistance data at different sizes for 4 aggregate types. The 6.3/10mm is the standard size. It also plots the skid resistance obtained after 3 and 6 hours for the four aggregates and four sizes. Coarse emery abrasive was used for the first 3 hours followed by 3 hours of fine emery as in the standard test. This shows a general increase in skid resistance with reducing particle size. However, the effect of additional time and polishing media has a significant effect adding to the uncertainty of prediction.

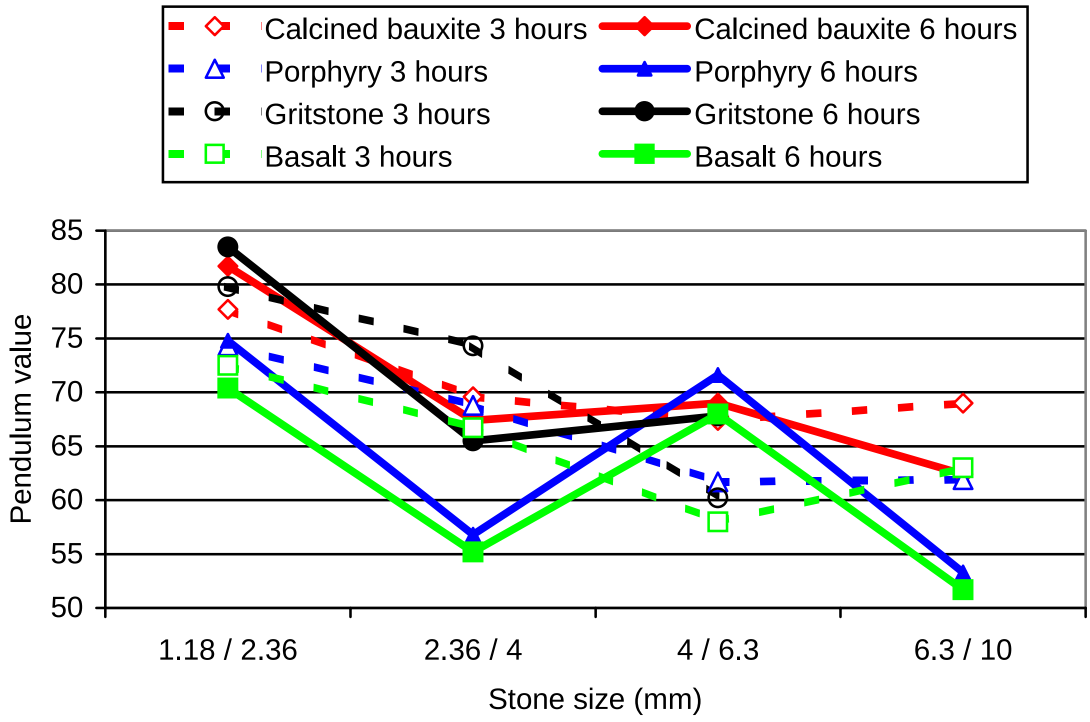

Figure 4 Effect of stone size on the polishing of different rock types

6. SKID RESISTANCE AND STRENGTH

The simple examples shown in Figure 3 and 4 highlight that skid resistance performance characteristics of surfacing aggregate are related to other properties. Whilst the expectation to perform continues to increase, the amount and type of stressing from a wider range of factors may now be affecting surface aggregate to levels not experienced before. Overstressing will lead to premature failure. In terms of skid resistance, what is already a natural limit is being stretched with aggregates expected to perform under increased trafficking conditions or in applications where the aggregate may not have a proven record. By increasing the expectation for an aggregate to provide skid resistance, nature may balance in-service performance by premature failure e.g. loss of skid-resistance due to aggregate polishing, aggregate wear or failure of the aggregate / bitumen bond, aggregate soundness problems due to environmental stressing such as freeze / thaw, wetting and drying, fretting and ravelling due to failure of the aggregate / bitumen mix.

Specification requirements typically have single limits with little provision for differences in performance due to rock type, dry test methods are used to predict strength, with there being little consideration of basic environmental conditions such as wetting to change in properties with time. Woodward found that higher PSV is gained at the expense of properties such as strength, wear and durability. A typical asphalt material used in road construction contains at least 90 to 95% aggregate. Whilst the effect of moisture is quite well documented in the literature a simple improvement in considering the in-service performance in terms of strength or abrasion of a surfacing aggregate would be to consider what happens to the aggregate when it get wet e.g. due to a shower of rain.

For example, a few raindrops on the windscreen results in approximately a 10% reduction in skid resistance. A wet surface equates to further reductions ranging from 20 to 70%. Tyre / road noise is affected and surfaces that may have been designed to be quiet when dry become noisier when wet. Aggregate properties change every time it rains with certain aggregate types loosing more than 50% of their dry strength. For example, Figure 5 shows possible test data for three aggregates using the British Standard Ten Percent fines Value test method. This wet test simply involves soaking the aggregate in water for 24 hours prior to testing. Most simple strength test methods could be improved by assessing both dry and wet aggregate. In terms of optimising the sustainable use of aggregate, this simple example illustrates that a performance or risk-based specification could consider this fundamental property i.e. it could simply ask for both values and a percentage change.

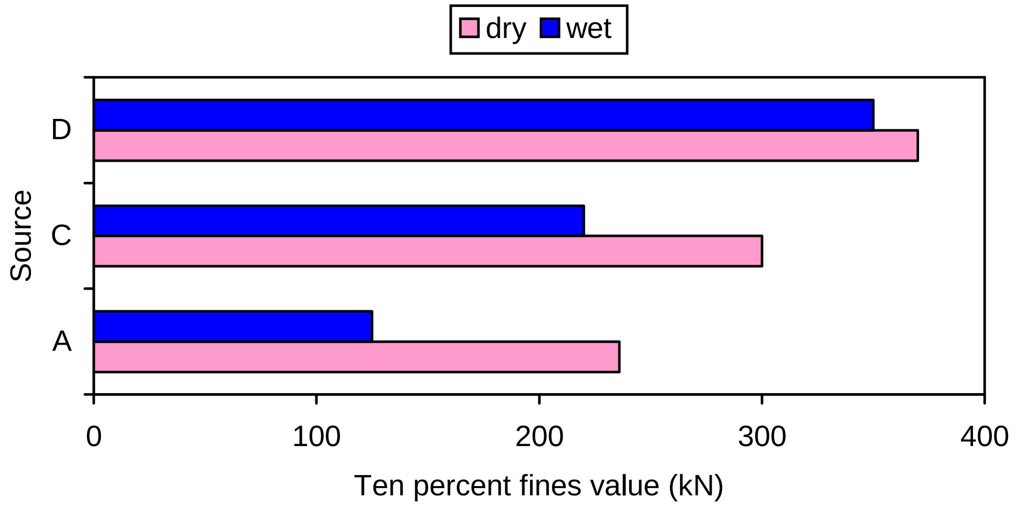

Figure 5 Comparison of dry and wet strength data for three aggregates

7. SKID RESISTANCE AND COMPOSITIONAL VARIABILITY

Knowing both dry and wet strength would allow better prediction of an aggregates contribution to overall performance of the asphalt mix. This is relatively straight forward if the aggregate source is homogenous in composition and behaves in a predictable manner. However, many aggregate sources are heterogeneous and consist of different constituents each with different response to water. For example, each part of single basalt flow may be different depending on how it has been affected by weathering processes. The quarried aggregate may contain differing amounts of expansive clay minerals. Trafficking will differentially wear the weaker aggregate particles in preference to the more resistant particles. Whilst this differential in wear properties may be exploited to maintain texture depth and wet skid resistance, the integrity of the mix will ultimately be affected by the on-set of premature ravelling and accelerated stone loss.

This simple example illustrates that it is important to identify whether there will be differential performance in mix properties due to a homogenous or heterogeneous aggregate being used. Figure 6 shows the range of PSV values obtained from crushed lump samples from 4 greywacke quarries. The distribution of results varied from 6 points for Quarry A to 10 points for Quarry B. The plots also show another issue, i.e. there may be one or two values that are much higher than the remainder. This degree of variability in skid resistance was also found to occur for all of the other common test properties.

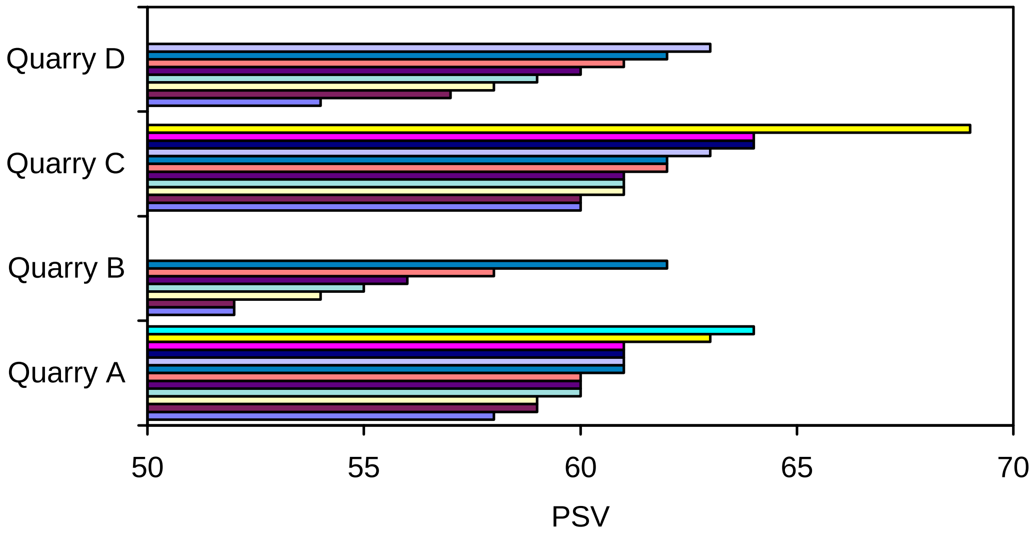

Figure 6 Range of PSV from lump samples collected at four greywacke quarries

8. SKID RESISTANCE AND AGGREGATE MINERALOGY

Aggregate performance depends on its mineralogy i.e. the types, distribution, size, degree of alteration etc give an aggregate its ability to cope during engineering life. Like many countries around the world, basalt is an important surfacing aggregate in Northern Ireland. A number of basic quarry types have been identified (Woodward, 1995). A Type 1 quarry represents what may be termed the classical weathered basalt flow. This consists of a distinctive vertical sequence of 5 differing grades of basalt quality as summarized in Table 2.

Table 2 The main zones of a thick basalt flow

Zone	Typical depths for a 20m flow	Description of aggregate quality	Quality
1	0.5 to 1m	Red flow top, heavily altered, will disintegrate in presence of water	Unsound
2	3 to 4m	Purple vesicular zone, heavily weathered, susceptible to rapid break-down	Unsound
3	3 to 4m	Vesicular zone, vesicles prone to rapid degradation leaving sponge-type structure	Unsound
4	10 to 13m	Massive columnar zone of hard basalt	Sound
5	0.5 to 1m	Blocky vesicular base, vesicles prone to degradation	Unsound

To illustrate this vertical variation in quality, Table 3 shows the results obtained from a sequence of lump samples taken vertically from a single 24m thick basalt flow. Also indicated is the depth at which the samples are representative and the zone which they belong to. At this quarry a layer of boulder clay was stripped prior to blasting. However, the practical problem was deciding how much of the underlying weathered profile should also be stripped. It was easy to distinguish the red flow-top which may either be a weathered blocky lava top or the remains of a weathered ash-fall. Underneath this, weathering may progress to quite considerable depths. In the example shown for a 24m flow, the top 0 to 1.5m was red bole and being removed during stripping. Below this was a noticeably purple coloured 3m zone of heavily weathered vesicular basalt. Heavily weathered vesicular basalt occurred for another 4 to 5m.

Table 3 Variation in test data from a single thick basalt flow

Depth (m)	Zone	ssdRD	WA	TFV	AAV	PSV	MSSV	LA
0 - 1.5	1	2.53	7.56	98	31.1	63	0.0	49.8
1.5 - 3.5	2	2.59	5.76	158	29.5	68	3.5	40.7
3.5 - 5.5	3	2.60	7.66	125	20.7	66	11.1	30.9
5.5 - 7.5	3	2.66	4.36	195	17.8	64	40.3	16.2
7.5 - 10.5	3 / 4	2.69	3.24	183	16.0	58	63.4	20.7
10.5 - 16.5	4	2.84	1.43	246	5.23	52	92.4	16.1
16.5 - 20.5	4	2.74	1.94	210	10.8	56	91.0	17.9
20.5 - 22.5	4	2.78	2.35	215	8.8	55	81.4	15.3
22.5 - 24.0	5	2.66	4.36	195	17.8	60	40.1	16.0
0 - 3	1	2.45	9.64	73	33.7	62	0.0	39.3

However, in this example, only the top red layer was being removed prior to blasting. The crushed aggregate was being contaminated by the underlying unsound basalt and had been causing bituminous mixes to fret and break-up within a short period of time. It was only by taking lump samples vertically from the face that the extent of the problem was realised. Based on the results obtained the vertical sequence in quality is evident. This is particularly well seen in the MSSV results were very low values extend to a depth of about 10.5m - almost half of the total flow. Another important set of data are the PSV values. This shows that higher values are obtained at the expense of soundness. It could be possible for this quarry to quote a PSV 68 rather than the mid 50's obtained for the sound basalt. The results of the investigation indicated that a much greater depth of weathered basalt had to be stripped prior to blasting so that it did not end up in the quarried product.

9. CONCLUSIONS

This paper concludes by drawing attention to the need to consider the holistic role of aggregate as part of the asphalt surfacing mix. It is easy to consider aggregate as an inert material with constant engineering properties. There is a complex interaction between factors such as differences in rock-type, change in properties such as strength, soundness and skid resistance during engineering life, variation in the contribution of properties such as strength depending on mix type, variation in traffic induced stressing on properties such as load transfer or polish resistance, adhesion to bitumen and the presence of moisture at the aggregate / bitumen interface, or the ability to cope with unexpected in-service conditions. These are what constitute in-service performance. Reducing risk necessitates understanding these processes and quantifying their contribution to overall performance. Few test methods offer insight into performance. Most simply ranking one aggregate in relation to another. Most assess standard aggregate sizes that may not be used in the mix or which form only a small part of the total mix. These are fundamental problems if one wants to predict performance of aggregate, particularly in the consideration of risk.

However, despite the considerable change within the highways industry, there appears to be little interest in improving the prediction of aggregate performance. The common UK aggregate test methods give a simple empirical laboratory measurement that at best suggests an idealised view of performance. It may be argued that the introduction of European Standards to assess aggregate offers limited further improvement. Few consider performance. Their choice reflects the original aim of European Standards were each member country was asked to nominate what they thought was their best test methods. The resulting Euro Norms are not based on research but rather national interests.

This paper has considered some aspects relating to the performance testing of surfacing aggregate for use in asphalt mixes. Understanding and being able to quantify risk will become the key area towards ensuring sustainable future highways. This requires improved understanding of underlying factors i.e. of thinking outside the box. Methods of aggregate testing need to exist that determine those factors that cause an aggregate to fail prematurely, particularly with the ideals of sustainable construction and the need to improve safety.

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