CURRENT PRACTICE IN THE LABORATORY TESTING OF AGGREGATES WITH REFERENCE TO THE WHIN SILL DOLERITE OF NORTHUMBERLAND

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Current Practice in the Laboratory Testing of Aggregates with Reference to the Whin Sill Dolerite of Northumberland.

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by

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SUMMARY

Although petrological work has been undertaken by numerous authors on the Whin Sill complex, the advent of tighter standards in aggregate testing and also the introduction of European and International standards, have brought about the suggestion of a re-examination of both the fresh, altered and weathered dolerite. The description, classification and, in particular, the testing of aggregates in a manner appropriate to their use in the construction industry has long posed problems, not only of a scientific nature but also from practical and commercial points of view.

The occurrence, outcrops and quarries of the Whin Sill in the North-East of England are described along with stratigraphy and age, and the method of emplacement of the complex. A brief petrological description of the Whin Sill is given along with geochemical and mineralogical analyses made by a number of authors.

A description, classification and characterisation of the dolerite is given according to British, American, European and International Standards, ISRM, NIRR and CADAM systems. The effects of alteration and weathering, leading to the production of a rock of poor quality are mentioned along with its unsuitability as a construction material.

Previous work on Whin Sill aggregate testing undertaken at the University of Newcastle-upon-Tyne is correlated and reviewed along with other published values of data from numerous sources.

A thorough description of current laboratory testing techniques has been made using Whin Sill material for undertaking tests. Physical test for classification including aggregate grading, shape, angularity, sphericity, roundness, surface texture, relative density, bulk density, unit weight, water absorption, elongation index, flakiness index, quick absorption, porosity and Weinert tests. Mechanical tests for classification include aggregate impact and crushing values, 10% fines values, point load test, Schmidt rebound number, unconfined compressive strength and ultrasonic velocities. The Los Angeles abrasion value and polished stone value tests are described for use as

determination of aggregate durability. Chemical disintegration tests are also mentioned for their use in determining the ability of an aggregate to resist changes in the physical environment.

1 INTRODUCTION

1.1 General Description

The Whin Sill, which is essentially composed of quartz dolerite, underlies much of the North-East of England covering an area of *c.* 4000 – 5000 km^2. It extends eastwards below the North Sea and can be found extensively from Yorkshire to the south and as far as Northumberland to the north. It is the dramatic views of the Roman Wall (Hadrian's Wall), Northumberland, where a considerable length of the wall to the west of the North Tyne River runs along the crest of the sill scarp, and High Force waterfall, Middleton-in-Teesdale which feature in most tourist literature. The outcrops of the Whin Sill in the geology of the North-East of England can be seen in Figure 1.1, overleaf. It has been the subject of voluminous geological, geophysical, petrological and chemical studies and the literature is exhaustive. However, the alteration and weathering aspects of the Whin rock, although sparingly considered in the earlier works has only been the main subject of several localised studies during the last two decades. Even less attention has been attributed to the engineering properties of the rock. The only published paper on this aspect is by Dearman *et al* (1984).

The objectives of this project are to describe, test and classify Whin Sill material using current laboratory techniques as we move towards the introduction of European and International standards.

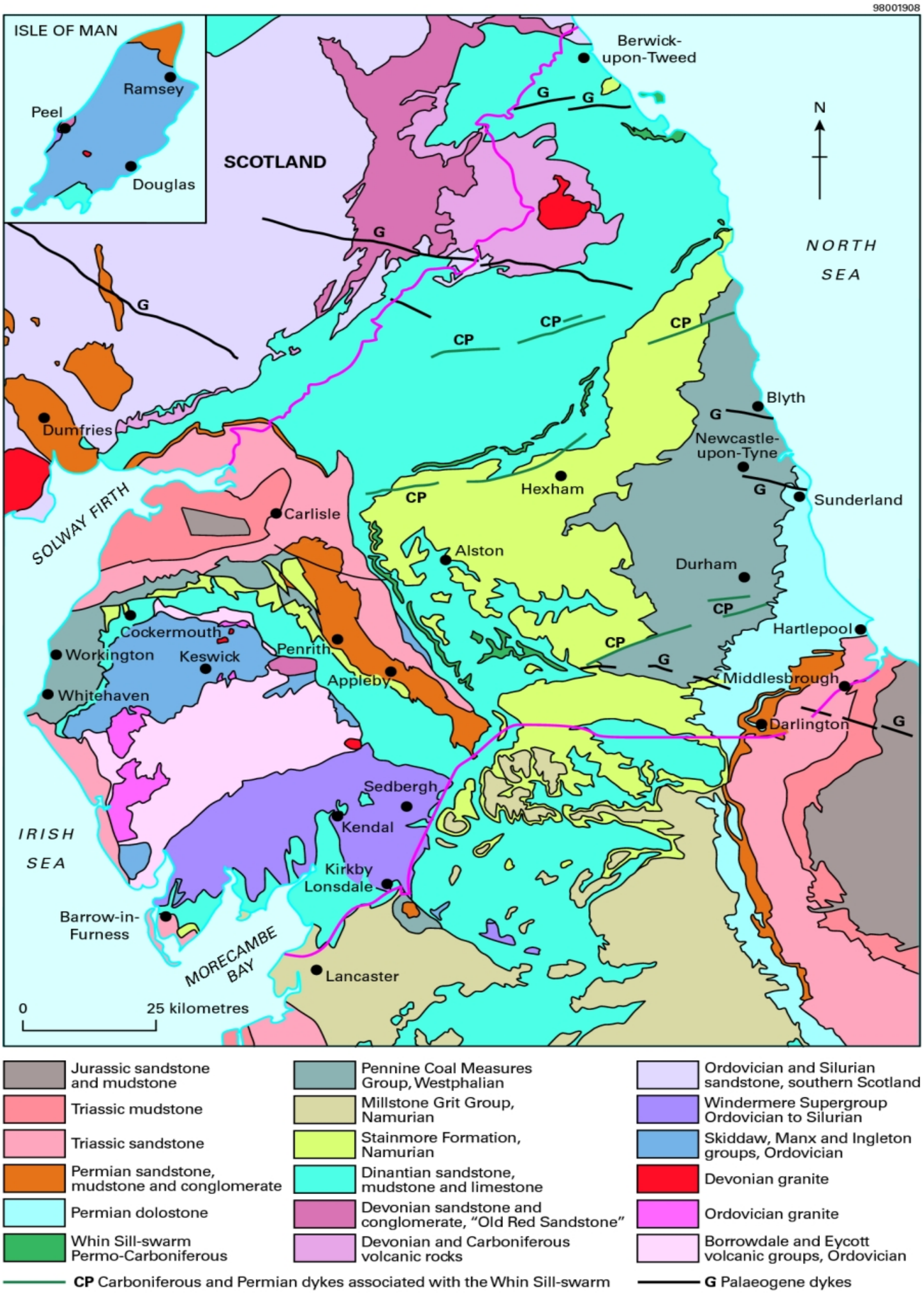


Figure 1.1. Geological map showing outcrops of the Whin Sill in the North-East of England.

1.2 Emplacement

The emplacement and occurrence of the Whin Sill complex has been discussed by a number of people. The magma which produced the Whin Sill complex was most likely generated in the mantle from tholeiitic magma. It is said by some that the complex consists of a series of sills of varying thicknesses, presumably linked at depth, although there is no obvious feeder for the sill. However, Dunham (1970) has stated that "The combination of the greatest thickness and lowest stratigraphic horizon for the sill in Upper Teesdale suggests that a feeder might be in the vicinity." In contrast, Randall (1989) assumes that the magma was intruded from a south-east to north-west direction to be emplaced in one episode forming a single cooling unit.

The sill began to crystallize at approximately 1100 to 1150°C and already contained microphenocrysts of plagioclase and pyroxene which began crystallizing at depth. By approximately 1025°C the main part of the sill had completely solidified and the increased concentration of volatiles in the central and upper parts of the sill allowed the pegmatites to crystallise. Crystallization terminated in the final residual melt at approximately 750°C and upon reaching 500°C certain vertical joints and parts of the upper contact were mineralised with quartz, calcite and pectolite. (After Randall, 1989). The crystallisation and post-crystallisation events in the Whin Sill at Barrasford are represented in table 1.1.

Approximate Temperature (°C)	Event
1150	Emplacement of Whin Magma – to form single cooling unit – magma contains phenocrysts of Orthopyroxene and Plagioclase.
1130	Volatiles concentrate in the upper part of the sill allowing development of pegmatites.
1125	Most of the dolerite has solidified.
750 - 715	Final solidification of normal pegmatite and intrusive pegmatite. Contractual joints develop. Emplacement of tachylyte intrusive basalt.
590	Solidification of alpite veins.
570	Final solidification of quartz pegmatite and pectolite. Hydrothermal vesicles filling and veining by quartz, calcite and minor iron sulphides.
460	Metasomatism of quartz pegmatite and pectolite.
400	Replacement of pectolite by stevensite. Veining by calcite, quartz, barite, Pb, Zn and Fe sulphides related to Alston Block.

Table 1.1. Crystallisation and post-crystallisation events in the Whin Sill at Barrasford. (After Randall, 1989).

1.3 Stratigraphy and Age

K-Ar determinations undertaken by Fitch and Miller (1967) suggest an age of 295±6 Ma for the sill which intrudes Upper Carboniferous (Westphalian) rocks at its lowest stratigraphic level, but does not penetrate into Permian strata, where weathered pebbles of the Whin Sill dolerite, known locally as brockram, occur.

1.4 Petrology

The main mass of the Whin Sill is a dark greenish grey, medium grained, sparse phenocrystic QUARTZ-DOLERITE, very strong, with large columnar jointing. “It is typically composed of 55.3% plagioclase (zoned from An_{68} to An_{25}), 31.7% clinopyroxene (augite, subcalcic augite and pigeonite), 3.5% orthopyroxene, 6.5% Fe-Ti oxides, 1.5% quartz, 1.3% biotite and a small amount of secondary carbonates, pegmatite, apatite and horneblende.” (Clark, 1992).

Five major lithologies have been determined within the Whin Sill (Fitch and Miller, 1967);

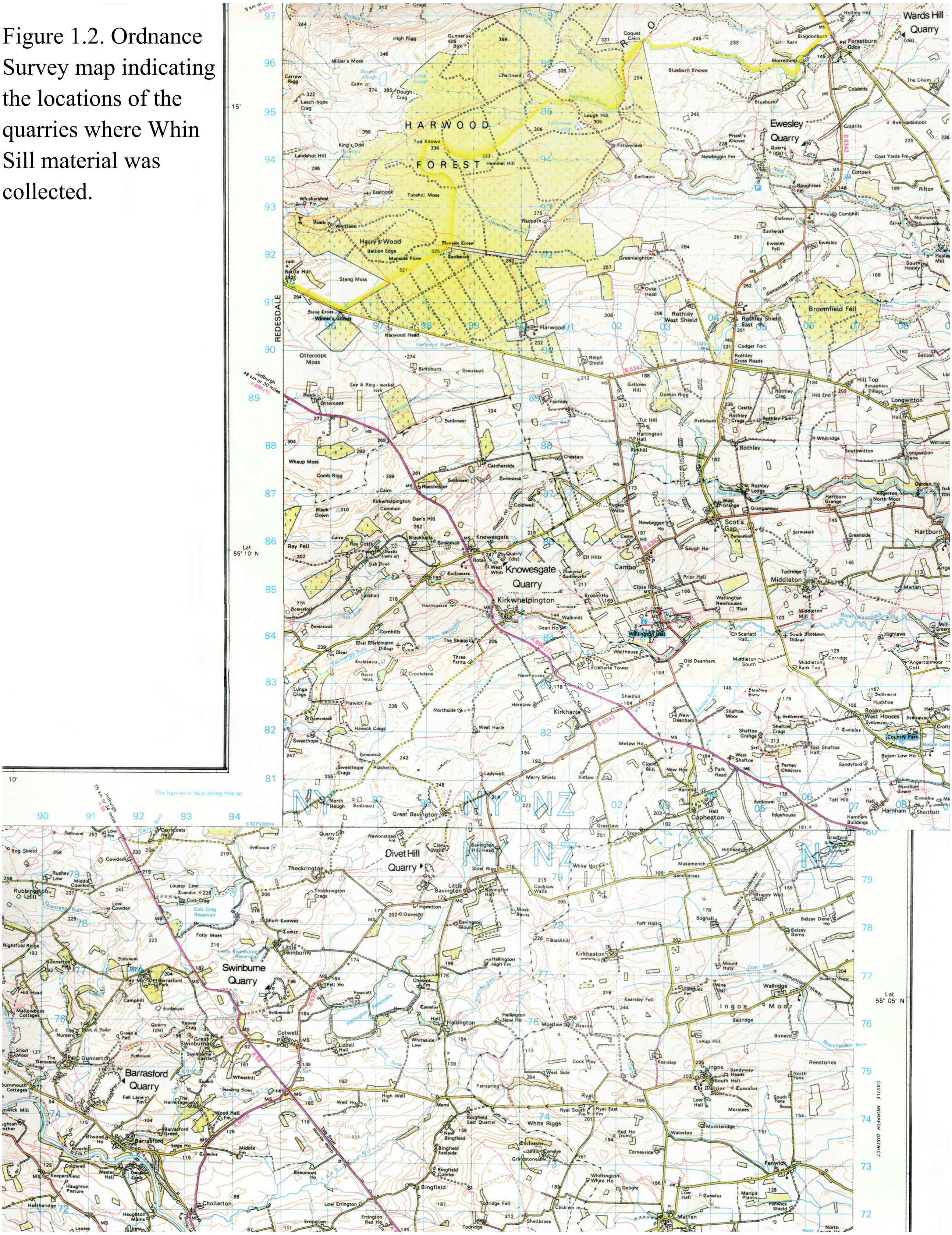
- Tachylitic chilled margin facies – Black, very fine grained rock in which the constituent minerals cannot be distinguished by the naked eye.
- Fine-grained quartz-dolerite – Fine-grained, grey or greenish rock in which ferromagnesian minerals and feldspars are seen using a hand lens.
- Medium-grained quartz-dolerite – This is typical Whin Sill dolerite in which the constituent minerals are visible to the naked eye.
- Dark greenish or grey dolerite pegmatite, rich in large pyroxenes up to 20mm in length.
- Pink granophyric pegmatite with an average grain size of 2mm to 3mm.

1.5 Whinstone Quarries

Quarries in the sill provide the bulk of the crushed rock aggregates suitable for roadstone in the North of England. In recent years a number of the smaller quarries, particularly those with poor access, geological conditions and limited reserves have closed and production is now concentrated in a few remaining large quarries, such as Barrasford Quarry, Northumberland (NY 913 743) and Force Garth Quarry, Middleton-in-Teesdale (NY 872 282). The quartz dolerite is generally of high strength and only slightly affected by weathering, thus leading to high quality aggregates. The most common geological problems in the quarrying have been abrupt transgressions of the sill to different levels in the country rock, the occurrence of large rafts of limestone within the sill and faulting. At some quarries, however, dolerite locally known as “Woodhead” differs from the typical dolerite in having a distinctive paler colour, coarser texture and lower strength. The origin of woodhead from normal fresh quartz-dolerite can be attributed to one of the following processes;

- During the solidification of the magma, micas and chlorite are crystallised at the later stages of formation due to the magma being enriched in volatiles.
- Rapid crystallisation and escaping gases account for corrosion and micro fracturing in previously formed phenocrysts which are later infilled with mica and chlorite.
- Hydrothermal alteration due to residual magma solution moving through the sill producing veining and replacement of earlier formed minerals, with members of the chlorite group, mica and amphiboles.
- Alteration and weathering of pyroxenes and feldspars due to a change in environmental conditions (climate and stress). The important processes being solution, oxidation, reduction, hydration and carbonation.

Figure 1.2. Ordnance Survey map indicating the locations of the quarries where Whin Sill material was collected.



This woodhead material is particularly abundant at two quarries in Mid-Northumberland, Knowesgate (NY 995 867), and Ewesley (NZ 061 942). Inclusion of woodhead material in aggregates from Knowesgate quarry lead to their rejection by the local authority and, as it proved impossible to separate the poorer material, due to its unpredictable and patchy distribution, the quarry closed. Ewesley quarry is also abandoned for the same reason.

The effect of weathering along joint planes often leads to the production of corestones, which are spherical in nature and consist of a core of fresh dolerite surrounded by a mantle of weathered material, often up to 20mm in thickness. This material can easily be mistaken for woodhead which is distinguished by its “woody” sound when struck with a hammer blow, unlike fresh dolerite which produces a typical “ringing” sound.

Figure 1.2, shows the locations of all the quarries visited and where samples of Whin Sill dolerite were collected. Samples were collected from stockpiles of 10mm to 14mm aggregate in working quarries, care being taken to obtain representative samples. In top loaded stockpiles coarser fragments concentrate towards the base of the slope, therefore aggregate was collected from the middle of pile faces. Ideally, crushed rock aggregate should be samples whilst in motion eg, from conveyor belts or at discharge from bins, but this is not always feasible. Block samples were collected from all of the quarries visited, care being taken to ensure that the samples reflected the rock types present. Direct sampling from the working quarry face allowed rock lumps of fresh dolerite to be collected, whereas in abandoned quarries, altered woodhead material was sought.

1.5.1 Barrasford Quarry

Barrasford quarry (NY 913 743) (Figure 1.4 & Plate 1.1), owned by Tarmac Roadstone Ltd., is situated in the North Tyne valley approximately seven miles to the North of Hexham, Figure 1.3. The Whin Sill is notable in this region for its unusual intrusive relations. The sill transgresses the Oxford Limestone; to the North-East the Limestone lies below whereas in the South-West it lies above the sill. For an outcrop distance of approximately 2km the full thickness of the limestone can be found both above and below the sill and large rafts of shale and limestone occur within it. In addition, the dip slope to the main escarpment (dip to the SE) is modified by west facing escarpments due to offshoots from the upper surface of the sill which have been emplaced along low angle fractures that dip ESE in the overlying sediments (Randall, 1959). The maximum measured thickness of the sill is 40m but thickness in this region is variable. Barrasford quarry has revealed almost all varieties of Whin Sill that have been described as special occurrences elsewhere (Randall, 1989). The production of aggregates at Barrasford quarry can be represented by the process flow chart shown in figure 1.6. All of the processes involved allow the production of a high quality aggregate with low variability in such features as grading, shape, distribution and cleanness, ie, Presence of coating.

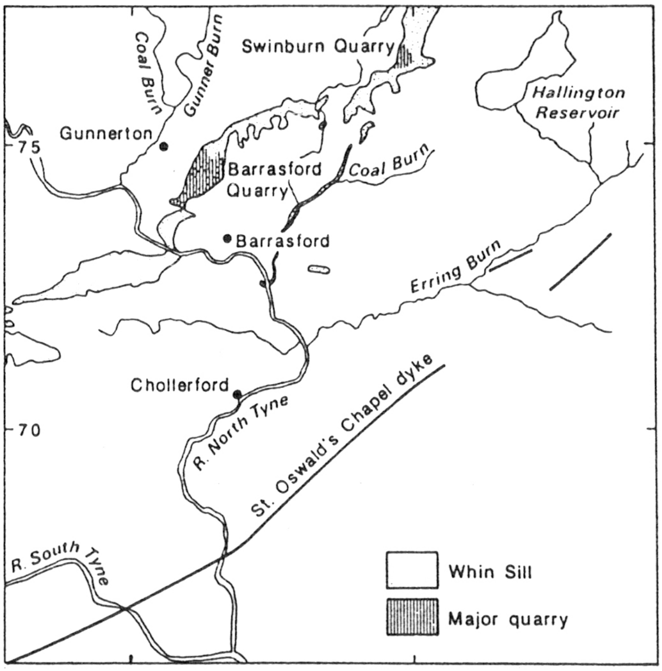


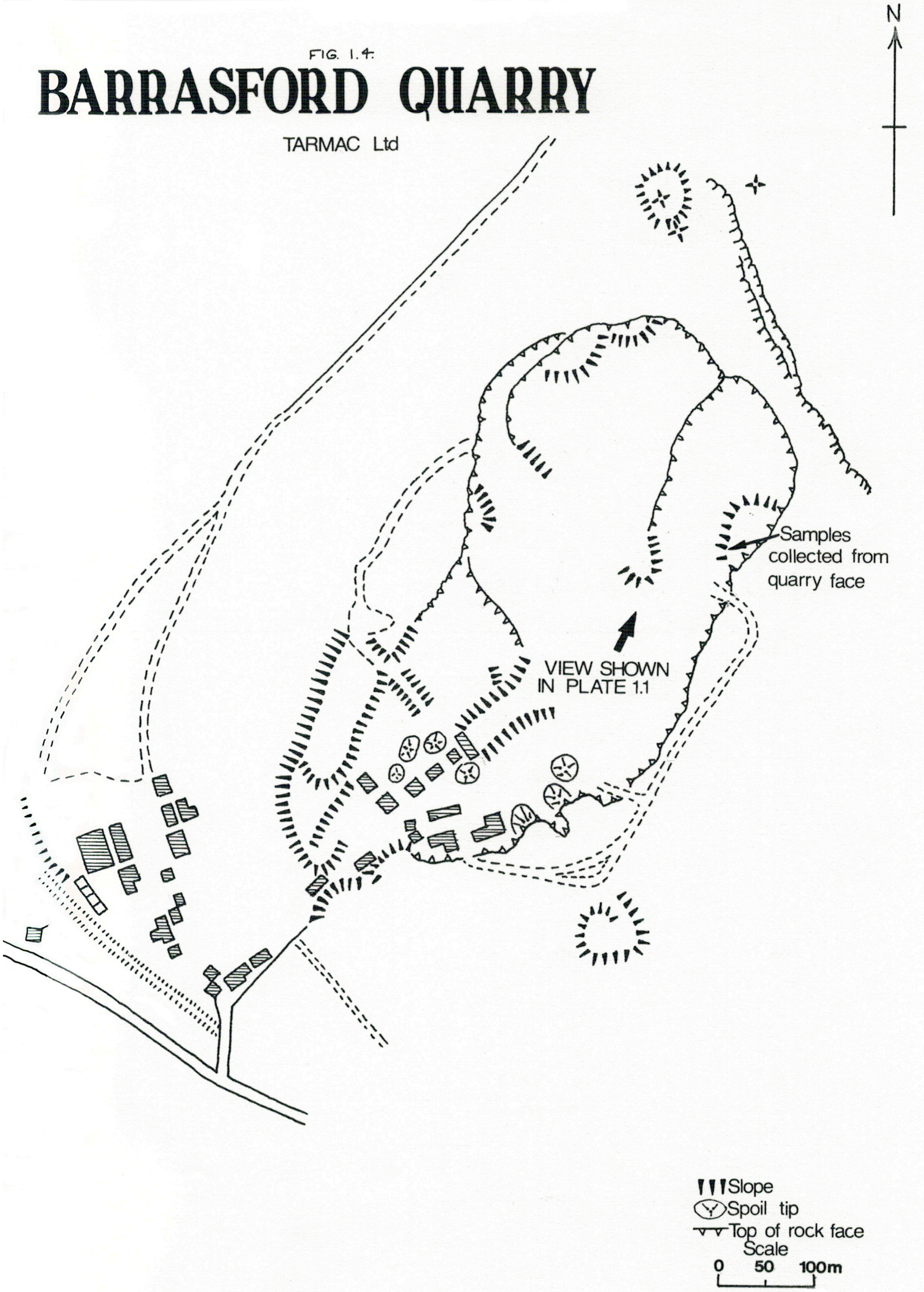
Figure 1.3. Location map of Barrasford Quarry, Northumberland. (Randall, 1989).

Plate 1.1. Photograph of Barrasford Quarry. (29th June 1993).

FIG. 1.4.

BARRASFORD QUARRY

TARMAC Ltd



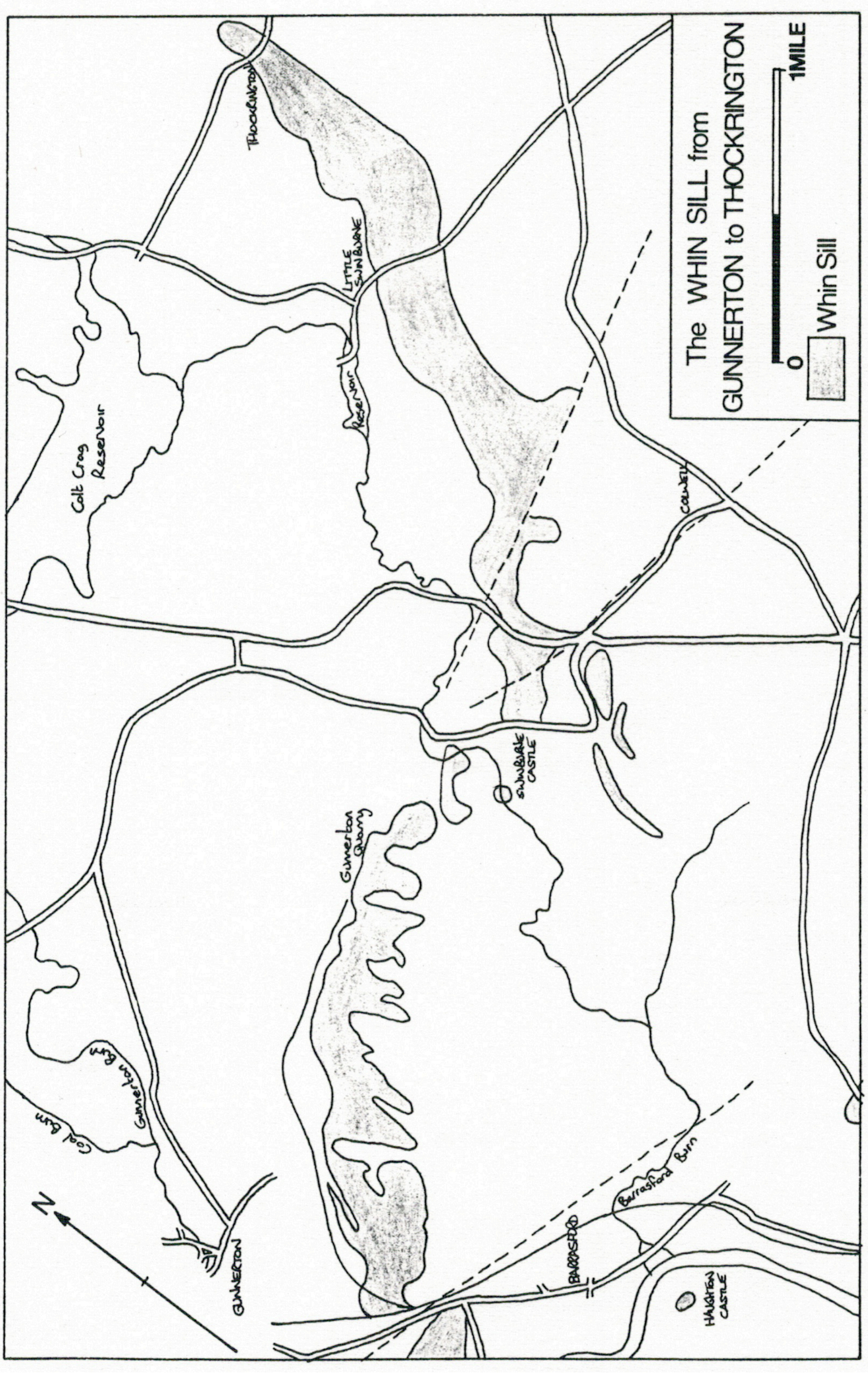
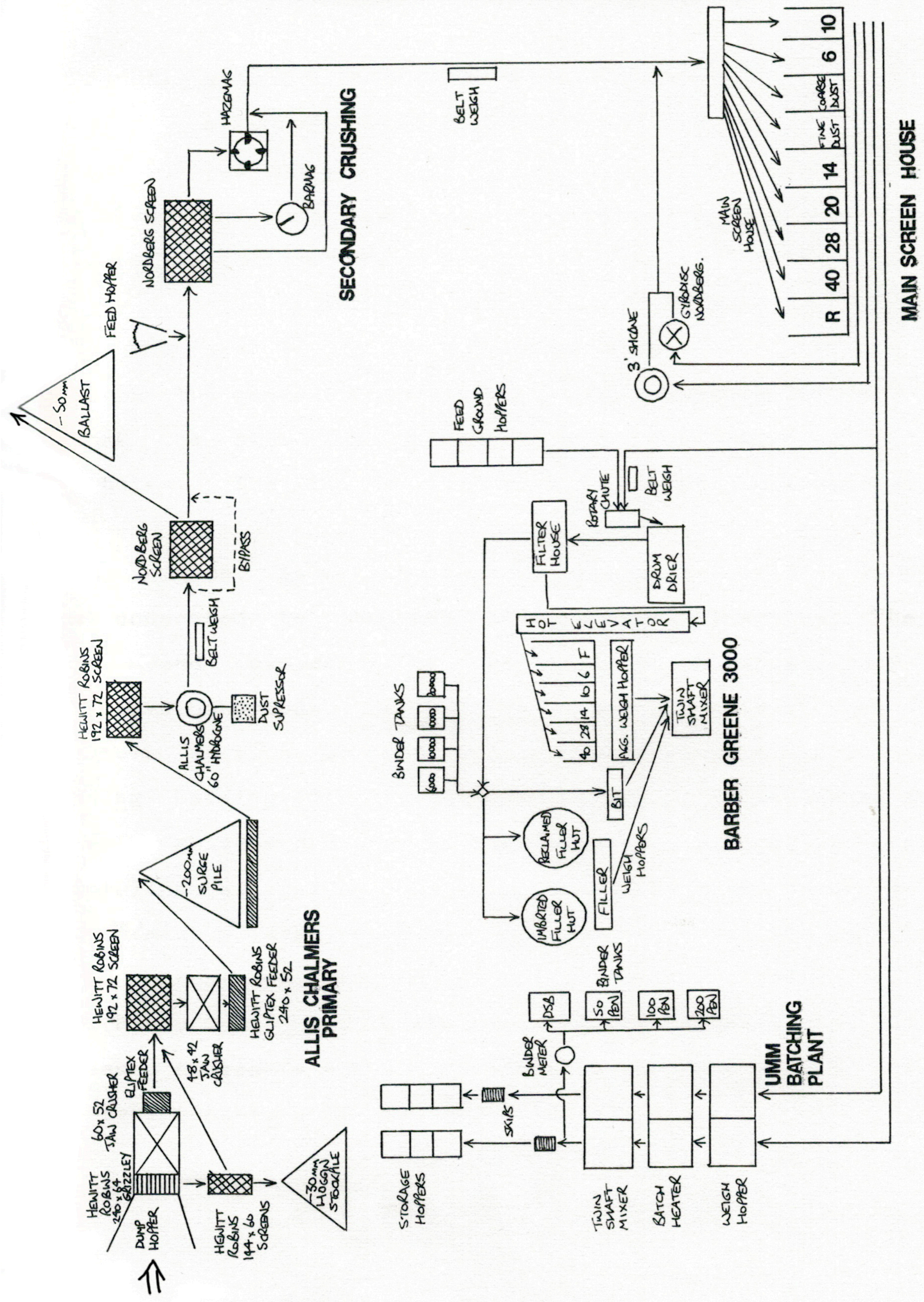


Figure 1.5. Outcrop of the Whin Sill in the Barrasford region between Gunnerton and Throckrington, after Randall (1959).

Figure 1.6. Process flow chart for the production
of aggregates at Barrasford Quarry.



1.5.2 Ewesley Quarry

Ewesley quarry (NZ 061 942), owned by Tilcon (Northern) Ltd., has been disused for a number of years, and up until mid 1988 use of the coating plant continued using imported stone from other Whin quarries as well as the well known red Porphyrite from the Cheviot Hills. The quarry is located some 6km North-West of Netherwitton, North-East England. The first Geological Survey map showed no outcrop of the Whin Sill at the present quarry site, shown in figure 1.7, and it is said that the sill was discovered here from fragments seen around rabbit holes. The sill was uncovered in the area during excavations for the nearby Font Dam, constructed for Tynemouth Waterworks and completed in 1908. As with Barrasford, the quarry originally had rail sidings connected to the LNER (North British) system. The quarry provides good exposures of the sill which shows very little transgressive behaviour, the upper and lower contact of the sill in the eastern section of the quarry conforming closely to the surrounding bedding (Plate 1.2). The effect of the columnar jointing on slope stability can also be seen, especially along the north face where toppling failures can commonly be seen to have occurred. This quarry contains a large proportion of altered woodhead material and weathered corestones, and is the reason for its closure as explained earlier (Plate 1.3). Due to the closure of this quarry the collection of processed aggregate was not possible, although a number of block samples representative of woodhead material were collected from the quarry face to allow for laboratory testing to be undertaken.

FIG. 1.7.
EWESLEY QUARRY
TILCON Ltd
N
Samples collected from this location
VIEW SHOWN IN PLATE 1.2
Slope
Spoil tip
Top of rock face
Scale
0
50
100m

Plate 1.2. Outcrop of the Whin Sill in Ewesley Quarry (26th October 1993).

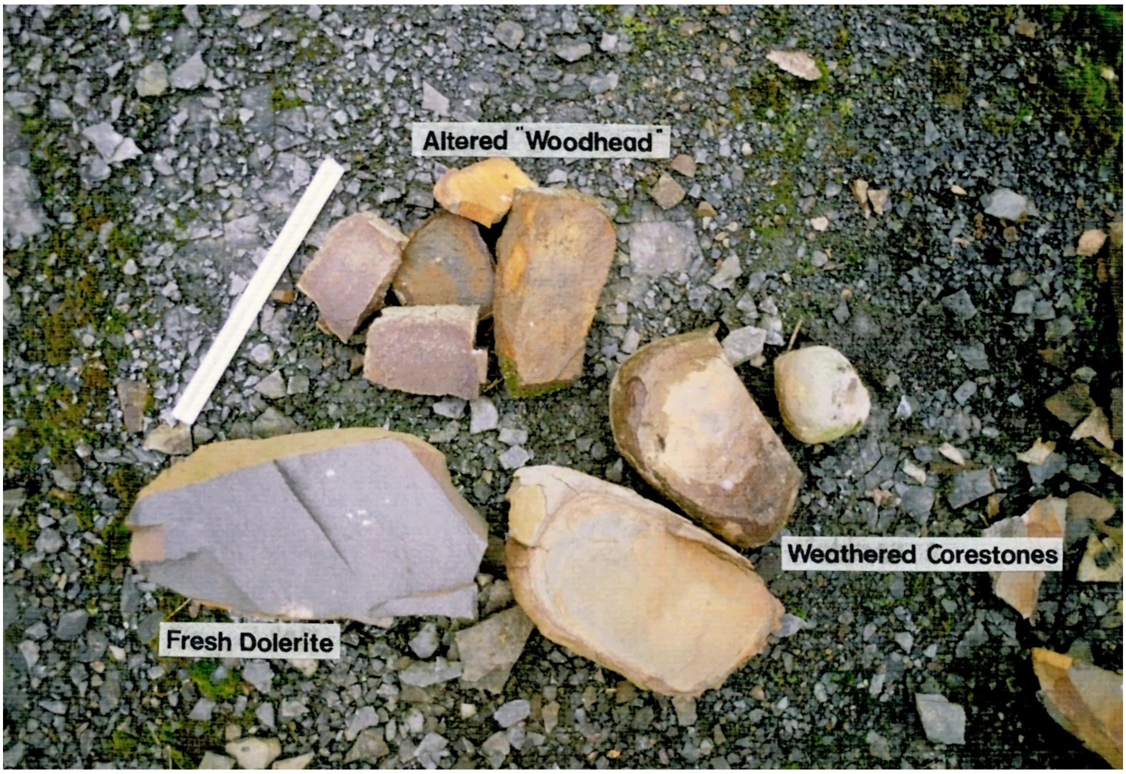


Plate 1.3. Types of Whin Sill dolerite found in Ewesley Quarry (26th October 1993).

1.5.3 Knowesgate Quarry

Knowesgate quarry (NY 995 867) (Figure 1.9), some 32km North-West of Newcastle-upon-Tyne, and approximately 1.5km North-West of Kirkwhelpington, is also owned by Tarmac Roadstone Ltd., and has been closed for a number of years due to poor sill quality. The gentle inclined sill is approximately 10m thick at the location of the quarry, and although the base is not exposed the chilled upper margin of the sill is in contact with the limestone. An ill-defined columnar jointing is crossed extensively by vertical master joints in two directions and both of these have associated calcite veins. Joint bounded blocks can be found that are entirely fresh or altered dolerite (Dearman *et al,* 1984). Figure 1.8, shows the geological and topographic setting of the Knowesgate area (Hussen, 1971). The quarry has been backfilled with landfill and therefore limited access to the quarry face is available (Plate 1.4). As with Ewesley representative block samples of woodhead material were collected for description, laboratory testing and classification.

1.5.4 Swinburne Quarry

Swinburne quarry (NY 946 765) is a moderately sized working quarry owned by ARC (Figure 1.10), situated approximately four miles to the North-East of Barrasford quarry, just off the A68 (Jedburgh) road. Plate 1.5, shows the current working face and collection of fresh aggregate and block samples was undertaken from stockpiles.

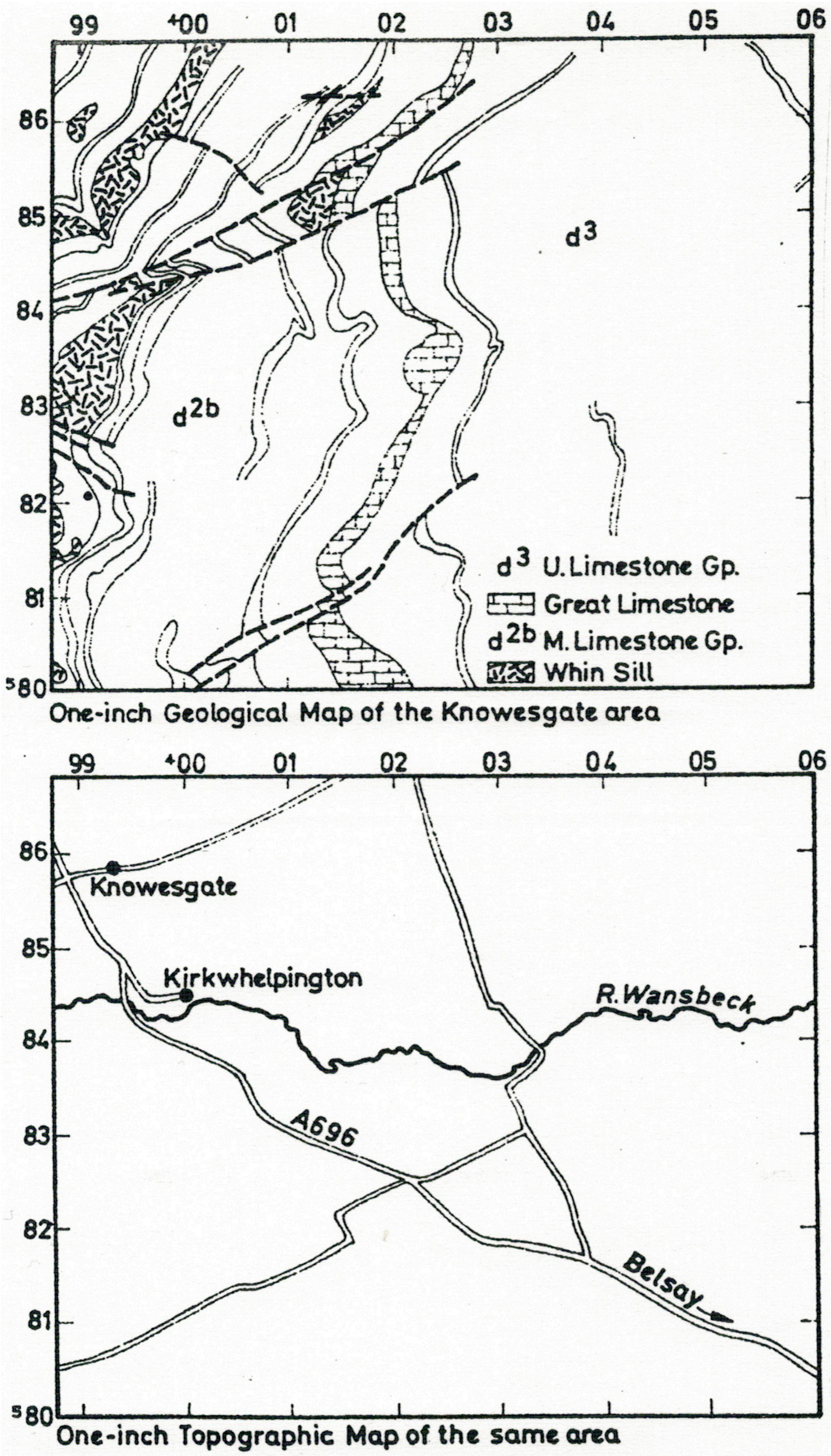


Figure 1.8. The geological and topographic setting
of the Knowesgate area (Hussen, 1971).

FIG. 1.9.

KNOWESGATE QUARRY

TARMAC Ltd

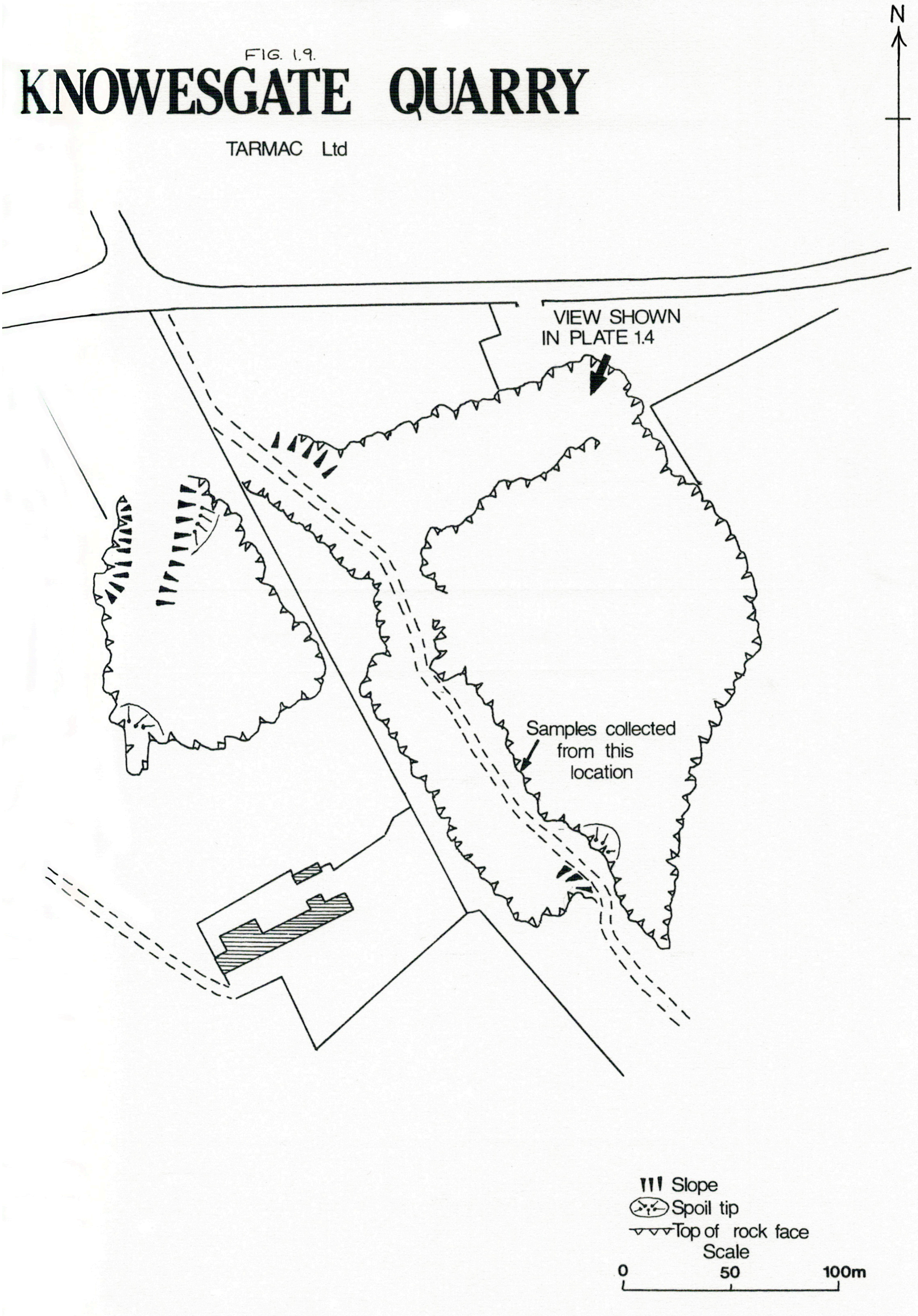
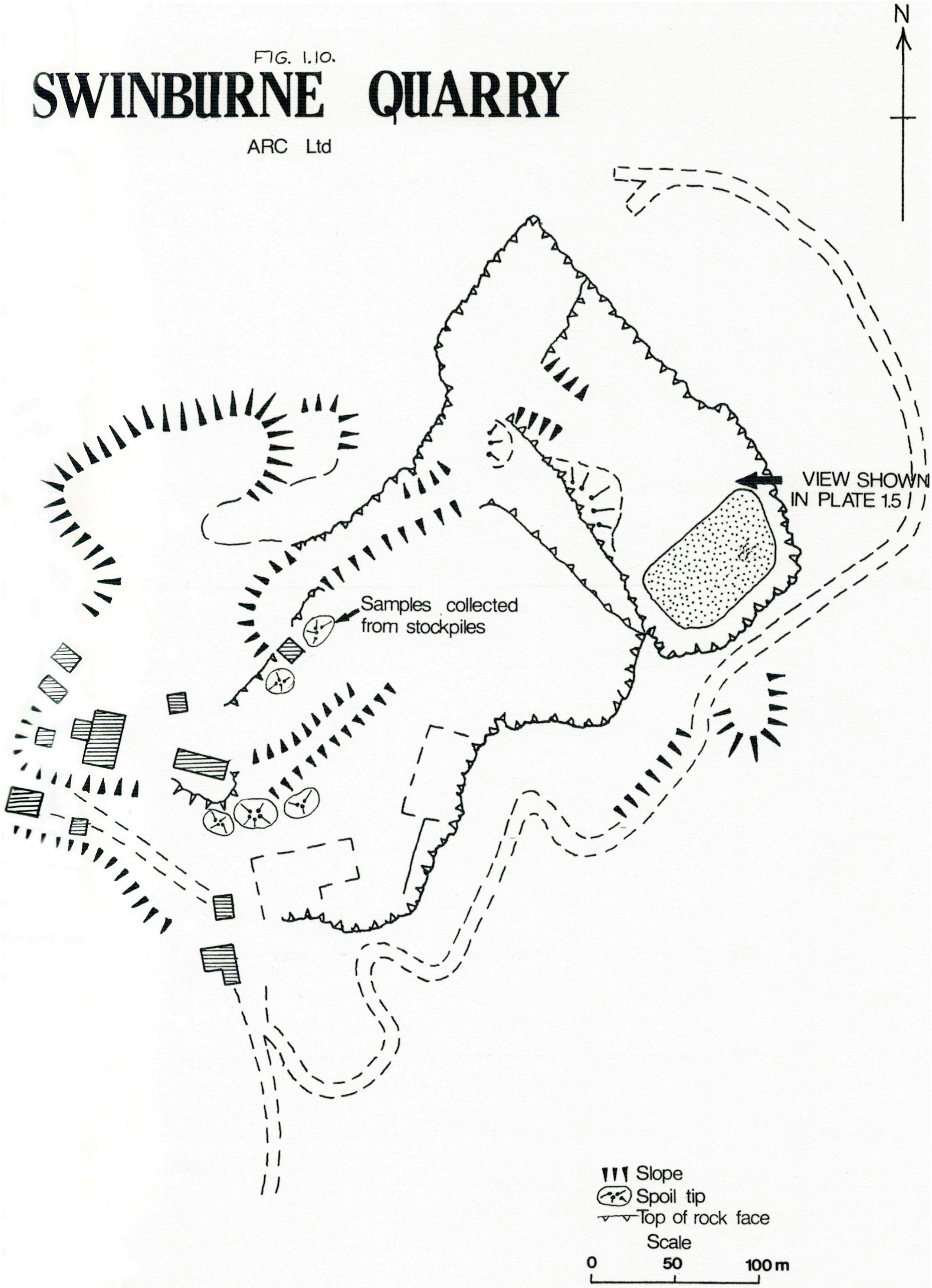


Plate 1.4. Knowesgate Quarry rock face and landfill site (26th October 1993).

Plate 1.5. The working face of Swinburne Quarry (26th October 1993).


N
FIG. 1.10.
SWINBURNE QUARRY
ARC Ltd
VIEW SHOWN
IN PLATE 1.5
Samples collected
from stockpiles
Slope
Spoil tip
Top of rock face
Scale
0
50
100 m

1.5.5 Divet Hill Quarry

Divet hill quarry (NY 980 790), owned by RMC is a small operational Whin Sill quarry located approximately four miles to the South of the village of Kirkwhelpington, just off the B6342 secondary road at the village of Little Bavington (Plate 1.6). Samples of 10-14mm processed aggregate were collected from stockpiles along with a number of block samples of fresh dolerite from the quarry floor. Samples could not be collected directly from the quarry face as blasting was being undertaken.

Plate 1.6. Divet Hill Quarry
(26th October 1993).

1.5.6 Wards Hill Quarry

The disused Wards Hill quarry (NZ 079 965) owned by Alnwick Estates, occurs approximately 1500m East of the B6342 and is situated in the first reappearance of the Whin Sill beyond the River Coquest. The transgression of the sill is very evident in the quarry (Plate 1.7), the sill changes horizon abruptly at several points on the faces and the quarry must have been difficult to work, although the lack of spoil rather suggests that most of the material was used. In the North-Western quarry face limestone and shale dipping to the South-East at approximately 15-20° is overlain by the dolerite and on the South-East face of the quarry the sill is overlain by limestone strata dipping at the same angle. Figure 1.11 is a detailed plan of the quarry site and as can be seen, the quarry was worked at two levels. This exposed both the top and base of the sill where it intrudes the horizon of the Great Limestone. It is probably that there are further reserves to the west, but the plant had been sited on this side, thus restricting the development in this direction. Block samples of fresh Whin dolerite were collected from the quarry faces for laboratory testing.

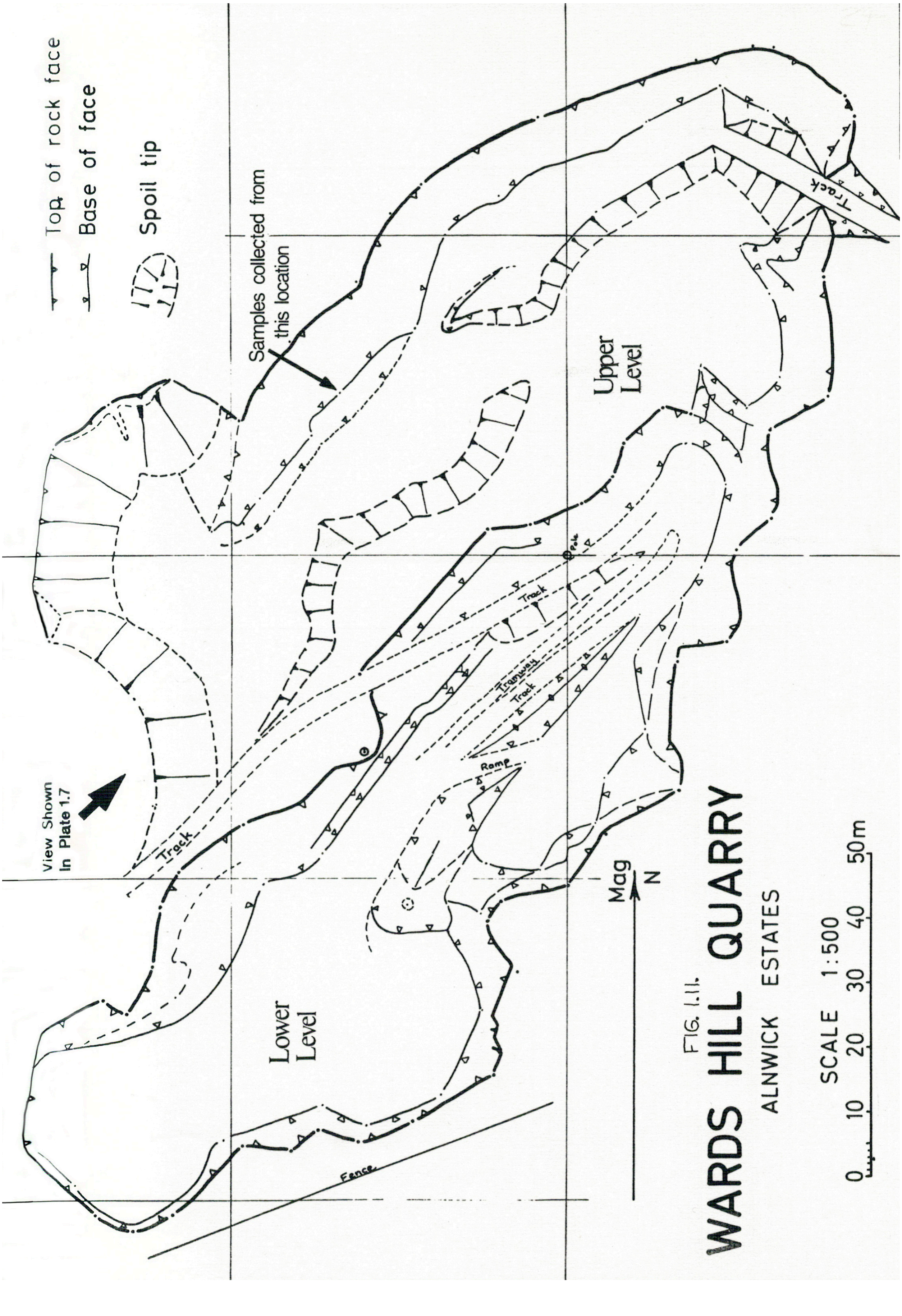

Top of rock face
Base of face
Spoil tip
Samples collected from this location
View Shown In Plate 1.7
Track
Tramway
Ramp
Pole
Fence
Upper Level
Lower Level
Mag N
FIG. 1.11.
WARDS HILL QUARRY
ALNWICK ESTATES
SCALE 1:500
0 10 20 30 40 50m

Plate 1.7. Photograph showing the outcrop of Whin Sill material in Wards Hill Quarry (29th June 1993).

2 PREVIOUS WORK AND LITERATURE REVIEW OF WHIN SILL AGGREGATES

2.1 Testing in Engineering Geology Coursework Programme

Aggregate testing of Whin Sill dolerite is undertaken every December as an academic teaching exercise, both in the field and in the laboratories of the Department of Civil Engineering, The University of Newcastle-upon-Tyne. This is undertaken by final year geotechnical option undergraduates and Master of Science students from the Engineering Geology, Soil Mechanics and Rock Mechanics courses. It has continued for a number of years and presented here is a correlation of five years work.

The material was collected from a total of three quarries by the students; Barrasford, Knowesgate and Ewesley. The material from Barrasford was regarded as typical of fresh unaltered dolerite, and combined material from Knowesgate and Ewesley representative of the altered dolerite known as woodhead. The dolerite was sampled in block form from all of the quarries allowing cores to be produced for testing of the rock mass as a whole. 10mm – 14mm crushed rock aggregate product was collected from stockpiles at Barrasford quarry, and due to the closure of Ewesley and Knowesgate quarries a number of years ago aggregate material is no longer available in the quarry, therefore aggregate was produced in the laboratory by crushing woodhead samples and sieving to the correct nominal size.

Two groups of tests were carried out on both the fresh dolerite and the altered woodhead material;

- Standard tests on aggregates; Aggregate crushing value (ACV), Aggregate impact value (AIV), Flakiness index, Elongation index, Quick absorption tests, Point load strength and Weinert classification.

- Standard tests on rock cores; Dry density, Saturated density, Porosity, Dry and saturated ultrasonic velocities and finally the unconfined compressive strength.

All of the tests were carried out using the relevant standards as indicated below;

Tests on Aggregates:

• Aggregate Crushing Value	BS812: 1975 BS812: 1989
• Aggregate Impact Value	BS812: 1975 BS812: 1989
• Flakiness Index	BS812: 1975 BS812: 1989
• Elongation Index	BS812: 1975 BS812: 1989
• Quick Absorption Test	BS812: 1975 BS812: 1989 Hamrol (1961)
• Point Load Strength	Franklin (1970)
• Weinert Classification	Weinert (1964)

Tests on rock Cores:

• Dry Density & Saturated Density	BS812: 1975 BS812: 1989
• Porosity	BS812: 1975 BS812: 1989
• Ultrasonic Velocity	BS812: 1975 BS812: 1989
• Unconfined Compressive Strength	BS812: 1975 BS812: 1989

The overall average results obtained, representative of both the fresh and altered Whin Sill dolerite are shown in Tables 2.1 and 2.2. The individual results obtained in 1986, 1990, 1991, 1992 and 1993 are shown in Appendices 2, 3, 4, 5 and 6 respectively. It is worthwhile noting at this point that there appears to be a number of anomalies in some of the data (indicated with an asterix) and these are more likely due to sample preparation and testing than unusual properties of the material.

Quarry	Rock Description	Year of Sampling	Aggregate Crushing Value (%)	Aggregate Impact Value (%)	Flakiness Index (%)	Elongation Index (%)	Quick Absorption Test (%)	Weinert Number	Point Load Strength (MN/m^2)
Barrasford	Fresh Dolerite	1986	27	27	27	20	1.00	6	3.02
Barrasford	Fresh Dolerite	1990	12	14	46	22	1.05	4	7.43
Barrasford	Fresh Dolerite	1991	26	11	22	19	0.85	6	6.08
Barrasford	Fresh Dolerite	1992	13	3	18	22	0.82	5	5.78
Barrasford	Fresh Dolerite	1993	19	6	24	33	2.00	6	5.13
Overall Mean for Fresh Dolerite			19	12	27	23	1.14	5	5.49
Ewesley &	Woodhead	1986	37	29	23	27	1.90	6	2.97
Knowesgate	Woodhead	1990	38	29	68*	80*	1.28	7	3.38
Ewesley &	Woodhead	1991	22	18	24	19	0.50	8	2.85
Knowesgate	Woodhead	1992	26	15	22	31	0.39	5	5.00
" "	Woodhead	1993	22	10	19	13	2.00	9	--
Overall Mean for Woodhead			19	20	31	34	1.21	7	5.05

Notes: * These values for Flakiness Index and Elongation Index appear unusually high and are most likely to be 32 and 20 respectively.
-- Indicates that there was no data available for this test.

Table 2.1. Averages taken from standard tests on aggregates 1986, 90, 91, 92 & 93.

Quarry	Rock Description	Year of Sampling	Dry Density (Mg/m^3)	Saturated Density (Mg/m^3)	Porosity (%)	Ultrasonic Velocity (Dry) (Km/s)	Ultrasonic Velocity (Sat) (Km/s)	Unconfined Compressive Strength (MN/m^2)
Barrasford	Fresh Dolerite	1986	2.900	--	0.400	4.960	--	259
Barrasford	Fresh Dolerite	1990	2.888	2.880	<1	5.596	5.417	169
Barrasford	Fresh Dolerite	1991	2.780	2.790	0.930	5.620	5.320	313
Barrasford	Fresh Dolerite	1992	2.990	3.020	0.180	7.010	5.010	312
Barrasford	Fresh Dolerite	1993	3.030	3.030	0.727	4.400	4.500	217
Overall Mean for Fresh Dolerite			2.920	2.930	<1	5.517	5.062	254
Ewesley &	Woodhead	1986	2.730	2.770	0.429	3.740	5.470	59
Knowesgate	Woodhead	1990	2.756	2.640	2.630	3.050	3.959	47
Ewesley &	Woodhead	1991	2.920	2.920	0.470	5.860	5.640	275*
Knowesgate	Woodhead	1992	2.810	2.820	0.510	2.000	2.400	75
" "	Woodhead	1993	2.930	2.920	1.200	5.600	5.600	159*
Overall Mean for Woodhead			2.829	2.814	1.048	4.050	4.541	123

Notes: * These values for U.C.S. appear rather high for woodhead material, and are more likely the result of weathered fresh dolerite than altered woodhead.
-- Indicates that there was no data available for this test.

Table 2.2. Averages taken from standard tests on rock cores 1986, 90, 91, 92 & 93.

2.2 Published Data

Dearman *et al* (1984) presented some of the early data obtained at the University of Newcastle-upon-Tyne in 1984 at the Paris International Association of Engineering Geology (IAEG) Meeting. The specimens studied for this work were collected from the disused Knowesgate quarry as described earlier. The results published for physical tests on rock material, aggregate and weathering simulation tests are shown in tables 2.3, 2.4 & 2.5 respectively.

	Fresh Dolerite (Whin Sill)	Altered Dolerite (Woodhead)
Bulk Density, dry g/cm^3, saturated	2.92 2.95	2.69 2.74
Porosity %	2.7	4.2
Quick Absorption Index (I_{QAT}) %	0.26	1.4
Schmidt Hammer Value (SHV)	54	43
Point Load Strength, I_{50}, MN/m^2	13.6	2.6
Brazilian Tensile Strength, MN/m^2	19.3	4.4
Uniaxial Compressive Strength (σ_c) (38 x 76 mm cylinders) Dry, MN/m2	276	94
Tangent Young's Modulus (at ½ σ_c) GN/m^2	42.7	11.9
Poisson's Ratio	0.29	0.15
Ultrasonic Wave Velocity Km/sec - Dry - Sat	5.41 5.56	3.26 3.98

Table 2.3. Physical tests on rock material, Dearman *et al* (1984).

	Fresh Dolerite (Whin Sill)	Altered Dolerite (Woodhead)
Aggregate Crushing Value (ACV) %	14	25
Aggregate Impact Value (AIV) %	12	29
10% Fines, KN	310	130
Elongation Index (I_E) %	30	19
Flakiness Index (I_F) %	45	21
Weinert Number	3	6

Table 2.4. Physical tests on $^1/_2$" – $^3/_8$"
(12.7mm to 9.5mm) aggregate, Dearman *et al* (1984).

	Fresh Dolerite (Whin Sill)	Altered Dolerite (Woodhead)
Na_2SO_4 Soundness %	0.6	28.9
$MgSO_4$ Soundness %	0.0	10.5

Table 2.5. Weathering simulation tests,
Dearman et al (1984)

Test	Test Value
Bulk Density, g/cm3	More than 2.6
Water absorption (porosity) %	Less than 3
Aggregate Crushing Value (ACV) %	Maximum 30
Aggregate Impact Value (AIV) %	Maximum 45$^+$ Maximum 30*
10% Fines (kN)	Minimum 50

Notes : $^+$general use, *for wearing surfaces.

Table 2.6. British standard and other acceptance
values for tests on roadstone aggregates
after Dearman *et al* (1984).

The paper by Dearman *et al* (1984) illustrates the variation in physical properties between fresh dolerite and woodhead by means of the standard range of physical tests. Comparison between the test results obtained by Dearman *et al* (1984) and the suitable acceptance limits for roadstone aggregates, shown in Table 2.8, reveals that "The test values for woodhead are generally much closer to the limiting acceptance values than fresh dolerite, but they are, with the single exception of porosity, within the acceptance limits." Dearman *et al* (1984).

Table 2.7, shows typical properties of fresh Whin Sill dolerite based on data from eight quarries (Tarmac Roadstone Holdings Ltd.).

	Average	Range
Crushing Strength MN/m2	322	300 – 375
Aggregate Crushing Value	11.4	9 – 13
10% Fines Value kN	373	328 – 488
Aggregate Abrasion Value	4.2	3.0 – 5.0
Aggregate Impact Value	9.8	7 – 12
Polished Stone Value	57	54 – 61
Specific Gravity	2.9	2.84 – 2.94
Water Absorption %	0.61	0.2 – 1.0

Table 2.7. Properties of aggregates from the Whin Sill dolerite based on data from eight quarries (Tarmac Roadstone Holdings Ltd.).

3 PETROLOGY OF THE WHIN SILL

3.1 Petrological Analysis

Typical Whin Sill dolerite can be described as a dark grey, medium grained quartz-dolerite. Essential minerals consist of around 50 percent feldspar, 38 percent pyroxene, and in very small amounts, Fe-Ti oxides around 7 percent, quartz 1.5 percent and biotite 1.3 percent. There are a number of common secondary minerals including carbonates, chlorite and horneblende. Accessory minerals are apatite with very small amounts of pyrite being detectable in some cases. Olivine has been detected in some studies (eg, Dunham and Kaye, 1965) but is very infrequently found, although olivine pseudomorphs are present in most samples of the sill. Table 3.1, shows the characteristic petrographic analyses of Whin Sill dolerite obtained from a number of sources.

%	Fresh Knowesgate[1]	Altered Knowesgate[1]	Wards Hill[2]	Force Garth[3]	High Force[3]	Crossthwaite[3]
Unaltered Feldspar	53.9	40.2	49.15	55.0	53.4	53.4
Altered Feldspar	1.1	1.7	23.17	--	--	--
Altered Pyroxene, Olivine, Chlorite and Biotite	25.4	19.0	16.02	32.1	31.8	31.8
Fe-Ti Oxides	8.7	6.7	10.32	6.5	5.7	5.7
Carbonate	1.1	1.3	--	--	--	--
Quartz	0.7	1.8	--	1.1	1.9	1.9
Micro-Fractures	0.2	2.8	--	--	--	--

Table 3.1. Petrographic analysis of Whin Sill dolerite. From [1]Dearman *et al* (1984), [2]Bastekin (1980) and [3]Clark (1992).

- Plagioclase Feldspar – This is the most abundant mineral in the Whin Sill and occurs throughout the sill both as lath-shaped phenocrysts, commonly 2mm or more in length and in the groundmass, similarly lath shaped but only attaining a length of up to 1mm. Petrographical evidence indicates that only the plagioclase crystallised throughout almost the entire crystallization of the rock with compositional zoning extinction from cores of An_{68} to rims of An_{25} ($NaAlSi_3O_8$ (Albite) – $CaAl_2Si_2O_8$ (Anorthite)). This compositional zoning of the plagioclase suggests that the crystals were not in equilibrium with the liquid during its crystallization due to either the co-precipitation of clinopyroxene or to the cooling rate (Dunham and Strasser-King, 1981).
- Clinopyroxene – Clinopyroxene is the second most abundant mineral and occurs both as phenocrysts up to 2mm long and in the groundmass as pale brown to pale green, subhedral to euhedral individuals. Three groups of clinopyroxene phases can be recognised, pigeonite ($Ca(Mg,Fe)Si_2O_6$), augite ($Ca(Mg,Fe^{2+})(Al,Fe^{3+}Ti)(Al,Si)_2O_6$) and subcalcic augite which is thought to be a metastable phase consisting of unmixed augite – pigeonite grains.
- Orthopyroxene – Orthopyroxene occurs only as phenocrysts up to 3mm long and is not recognised in the groundmass. The grains are elongate, poikolitically enclosing plagioclase laths and are rimmed with clinopyroxene. Twinning in the crystals is not common and the crystals are frequently bent or broken.
- Iron-Titanium Oxides – These occur as minute grains towards the margins of the sill, but towards the centre of the sill they occur as phenocrysts, commonly enclosing silicates in the groundmass.
- Quartz – Quartz occurs throughout the sill as discrete grains and as graphic intergrowth's with alkali feldspar in the dolerite pegmatite.

- Sulphides – Minor amounts of sulphides occur in the Whin Sill. The most common sulphide is pyrrhotite occurring generally with small amounts of chalcopyrite, pyrite and chalcopyrrhotite.
- Other Minerals – Carbonate minerals are dispersed throughout the sill, along with elongate apatite minerals up to 0.3mm long. Secondary biotite and haematite are also found in small quantities throughout the sill.

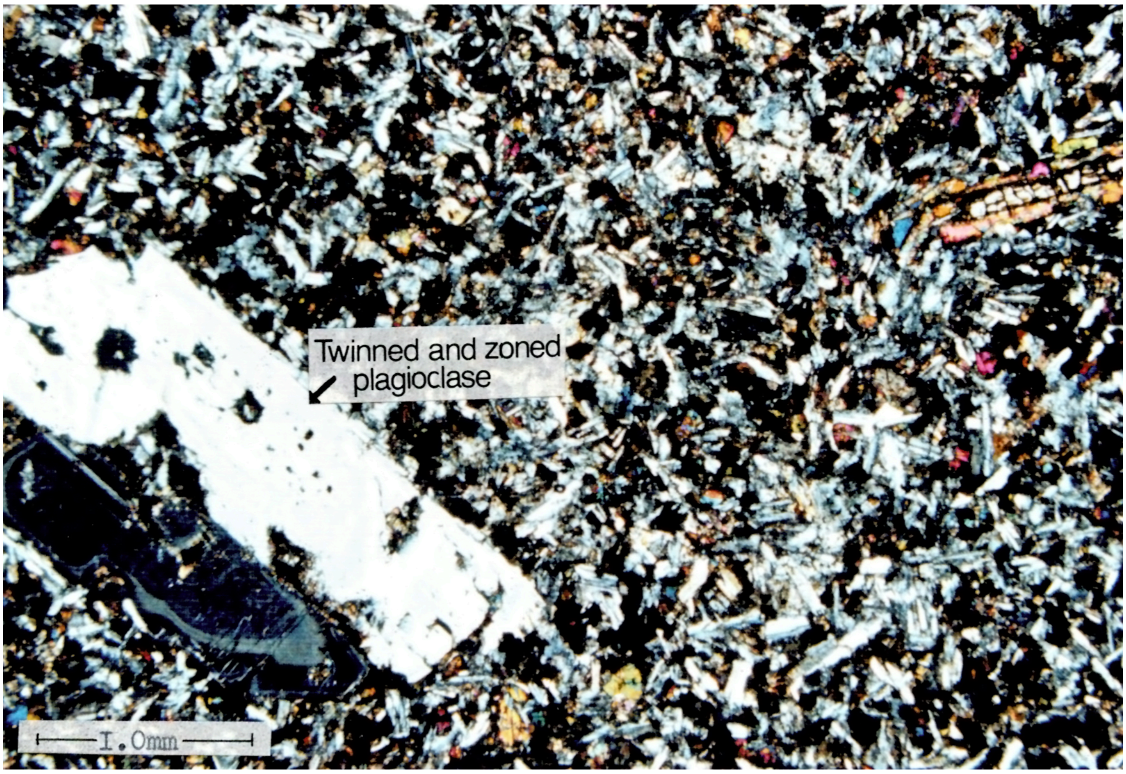


Plate 3.1. Compositionally zoned plagioclase
in fresh Whin Sill dolerite (XPL) (Clark, 1992).

Typical fresh samples of Whin Sill dolerite show intergranular, interstitial and subophitic textures with plagioclase laths forming an interlocking mesh around subhedral and granular pyroxenes. Occasional microphenocrysts of compositionally zoned plagioclase may be visible in cross polarised light (Plate 3.1) and occur due to the nature of cooling of the magma. Carbonate is invariably present in dolerite samples from Knowesgate quarry and increases in amount near the calcite veins and some primary joint surfaces. Plates 3.2 (PPL) and 3.3 (XPL) show typical thin sections of fresh Whin Sill dolerite.

Altered samples of dolerite known as woodhead show alteration of feldspars to sericite, chlorite and iron oxide, and in some cases uralisation of the pyroxene minerals to fibrous amphibole has occurred, due to the pneumatolitic action of hydrous magmatic liquids. Some pyroxene grains are completely altered to very fine grained secondary minerals, chlorite and opaque iron oxides. Altered pyroxenes make up approximately 26.5% of the rock and the carbonate content is relatively high at 1.3%. Microfracturing is much more abundant within the rock mass and are probably original, primary fractures formed before and/or penecontemporaneously with the hydrothermal alteration. They range between 1mm and 2mm in width, are rather irregular in outline; carbonate content, chlorite and iron oxides increasing around these microfractures.

The origin of woodhead material was discussed in section 1.5 with hydrothermal alteration of magma being the most likely explanation for its occurrence. Weathering can be regarded as the last agency affecting the Whin Sill. “It is perhaps a moot point how far the small departure from freshness, which so much of the rock exhibits, is due to weathering or to antecedent attack by hydrothermal solutions.” (Smythe, 1930). The picture becomes more complicated when considering that there are several sub varieties of altered dolerite due to the gradational nature of alteration processes, and that both fresh and altered dolerite can be found to different degrees (Dearman *et al*, 1984). The effect of alteration and weathering are similar in that both tend to increase the secondary

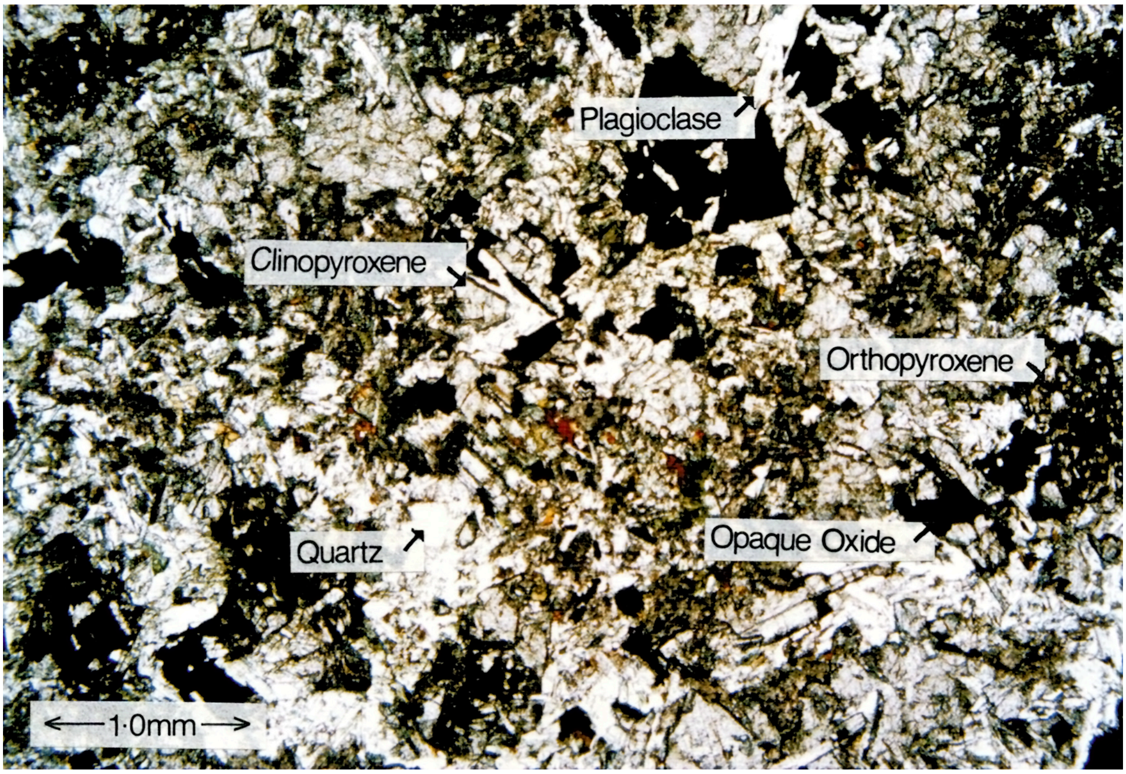


Plate 3.2. Photomicrograph of fresh Whin Sill dolerite in plain polarised light (PPL). (Clark, 1992).

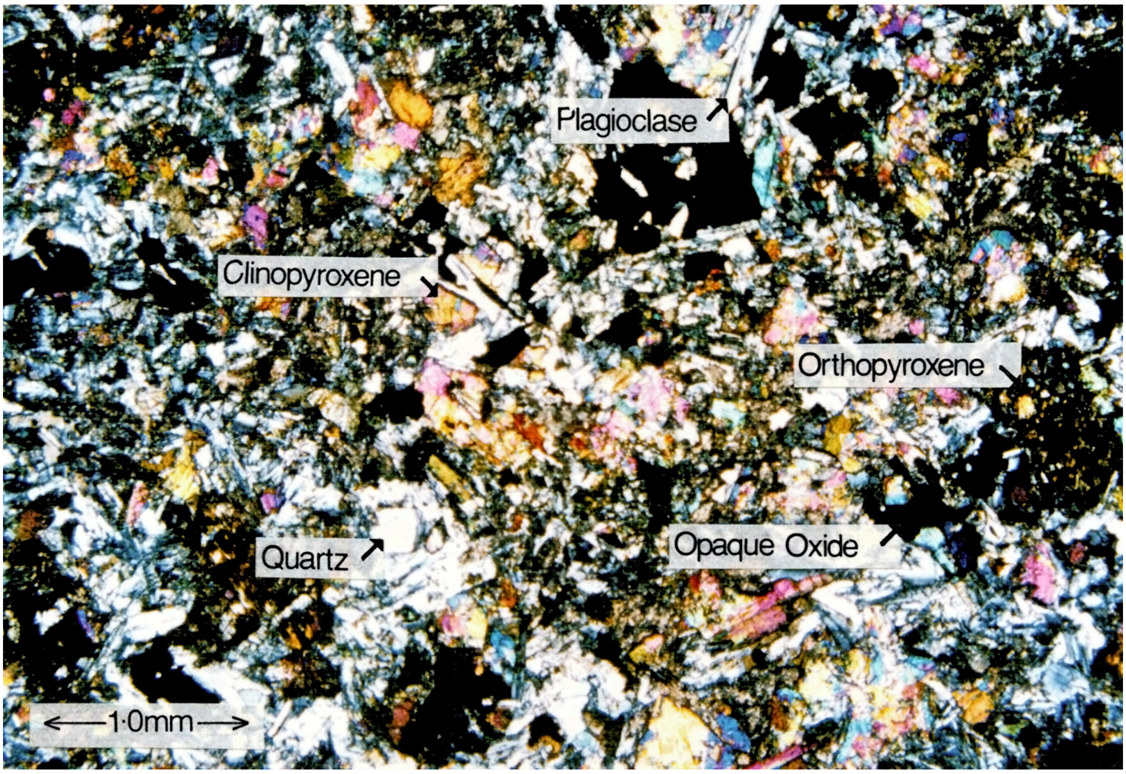


Plate 3.3. Photomicrograph of fresh Whin Sill dolerite in cross polarised light. (Clark, 1992).

mineral content of the rock (ie, carbonate, chlorite and opaque iron oxides), and also porosity and intensity of microfracturing.

The micropetrographic index (Mendes *et al*, 1966) has been determined by Dearman *et al* (1984) for both fresh and altered dolerite and the proportions of sound and unsound constituents between the two rock types can clearly be seen.

Description	Sound Minerals %	Unsound Constituents %	Micropetrographic index
Fresh dolerite	88.7	11.7	7.8
Altered dolerite	67.7	32.3	2.1

Table 3.2. Micropetrographic indices
for fresh and altered dolerite
after Dearman *et al* (1984).

3.2 Geochemical Analysis

Extensive geochemical analysis of the Whin Sill dolerite have been carried out by numerous authors, and they have shown that there is no significant regional variation in the composition of the sill, Table 3.3, shows the results of major element geochemical analyses made by various authors on material from the Whin Sill throughout the region. Table 3.4, shows typical trace element analyses again made by various authors on material from the Whin Sill throughout the region.

	Force Garth[1]	Crossthwaite[1]	Fresh Knowesgate[2]	Altered Knowesgate[2]	Barrasford[3]	Barrasford[3]	Throckley[4]	Woodland[4]	Rookhope[5]
SiO_2	49.91	50.75	50.63	50.83	49.50	0.20	49.72	50.01	47.73
Al_2O_3	14.45	14.06	13.54	13.64	14.43	13.90	13.75	12.53	15.73
Fe_2O_3	4.23	4.60	1.45	3.64	3.82	4.79	3.39	3.25	3.36
FeO	8.60	8.20	8.99	8.09	8.51	7.99	9.46	9,70	9.87
MgO	6.04	5.43	5.51	5.80	6.12	5.90	4.89	5.60	5.05
CaO	8.32	7.74	9.34	10.01	9.36	9.30	9,41	9.11	9.15
Na_2O	2.52	2.60	2.44	2.38	2.42	2.41	2.97	2.37	2.55
K_2O	1.25	1.89	0.94	0.81	0.95	0.90	0.91	0.85	0.62
TiO2	2.57	2.55	2.28	2.29	2.36	2.20	2.68	2.57	2.57
MnO	0.15	0.15	0.20	0.18	0.19	0.17	0.17	0.20	-
P_2O_5	0.29	0.29	0.30	0.28	0.29	0.26	0.63	0.32	0.28
Total Loss On Ignition	1.81	2.31	3.40	2.51	1.33	1.28	2.44	2.07	3.04

Table 3.3. Major chemical analyses (%) of Whin Sill dolerite after [1]Clark (1992), [2]Hussen (1971), [3]Randall (1989), [4]Dunham and Strasser-King (1981) and [5]Dunham and Kaye (1965).

	Force Garth[1]	Crossthwaite[1]	Barrasford[2]	Barrasford[2]	Throckley[3]	Woodland[3]	Rookhope[4]
Cr	67	56	81	85	43	30	-
Ni	58	58	58	62	44	40	54
Zn	122	121	127	131	109	-	109
Cu	56	60	63	80	45	45	59
Pb	7	7	7	-	-	-	-
Sr	420	428	369	378	126	220	-
Rb	68	48	23	25	403	370	409
Ba	276	306	-	-	126	220	-
Y	20	23	25	-	38	-	-
Zr	116	143	190	-	175	200	203
Nb	12	25	17	-	-	-	-
V	388	410	360	-	334	300	-
Sc	25	24	25	-	-	-	-
S	1155	1377	-	1000	-	-	-

Table 3.4. Trace element analyses (ppm) of Whin Sill dolerite after [1]Clark (1992), [2]Hussen (1971), [3]Randall (1989), [4]Dunham and Strasser-King (1981) and [5]Dunham and Kaye (1965).

Further petrographical, mineralogical and geochemical analyses are not dealt with here as they have been covered before, and are beyond the scope of this project. Attention should be drawn to authors such as Dunham and Kaye (1965), Dunham and Strasser-King (1981), Randall (1989) and Clark (1992) for further insight into these topics.

4 THE DESCRIPTION AND CLASSIFICATION OF WHIN SILL AGGREGATES

4.1 Introduction

"The description and, in particular, the classification of aggregates in a manner appropriate to their use in the construction industry has long posed problems, not only of a scientific nature but also from practical and commercial points of view." (Collis and Fox, 1993). Some aggregate classification schemes are based entirely on geological information, namely mode of formation, mineralogy and texture. Others attempt to classify rock materials from both an engineering and a geological point of view, and are based on the petrography of the material, rock parameters derived from tests and field condition of the rock mass as a whole. The British Standard Code of Practice for Site Investigation (BS5930. 1981) requires that rocks in natural outcrops, cores or excavations be described in the following sequence;

- Colour.
- Grain size.
- Texture and structure.
- State of weathering.
- ROCK NAME.
- Strength.
- Other characteristics and properties.

Examples of Whin Sill dolerite can be described ranging from;

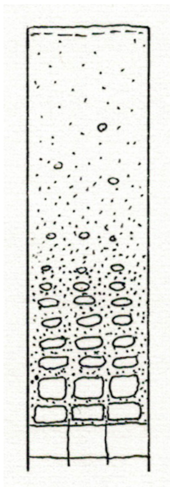
Dark grey, fine-medium grained, crystalline, fresh QUARTZ DOLERITE of extremely high strength, for fresh dolerite, to;

Yellowish-brown, fine grained, highly weathered QUARTZ DOLERITE, moderately strong "Woodhead", for altered and weathered woodhead material.

Whilst this descriptive scheme is not directly applicable to processed aggregates, it is suitable for the description of unprocessed rock in existing quarries, rock outcrops or drilled cores.

4.2 Weathering and Alteration

Attention must be drawn to the state of weathering in the above classification, as the degree of weathering and alteration of a rock mass must play a vital role in the potential performance of aggregate material. A state of weathering scheme was proposed by the Geological Society Working Party Report (1977) and is shown in Table 4.1. From this proposal material of grades IA and IB are generally satisfactory for aggregates, whilst those classed as grade III or higher are usually unsuitable. Figure 4.1 is a schematic representation of the weathering zones.



Zone	Description
VI	Residual Debris / Soil
V	Residual Debris with Corestones
IV	> 50% Corestones
III	Corestones with Residual Debris
II	Partially Weathered Rock
IB	Jointed Rock
IA	Fresh Jointed Rock

Figure 4.1. Schematic representation of weathering zones through a jointed igneous rock.

Term	Description	Grade
Fresh	No visible sign of rock material weathering.	IA
Faintly Weathered	Discolouration on major discontinuity surfaces.	IB
Slightly Weathered	Discolouration indicates weathering of rock material and discontinuity surfaces. All the rock material may be discoloured by weathering and may be somewhat weaker than in its fresh state.	II
Moderately Weathered	Less than 50% of the rock material is decomposed and/or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework or as corestones.	III
Highly Weathered	More than 50% of the rock material is decomposed and/or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework or as corestones.	IV
Completely Weathered	All rock material is decomposed and/or disintegrated to a soil. The original mass structure is largely intact.	V
Residual Soil	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly sorted.	VI

Table 4.1. Weathering and alteration grades,
after the Geological Society (1977).

Weinert (1964) has studied the performance of basic igneous rocks in southern Africa for road construction, and his work has relevance to basic igneous rocks in temperate climates as well. An outline of classification of the weathered state of aggregate by the National Institute for Road Research South Africa is given in section 5.1.112, including laboratory values determined for the Whin Sill dolerite. Weinert found aggregate performance to be related to the degree of alteration (the secondary mineral content) and climatic environment. “In the UK basalts and dolerites are commonly used as a crushed rock aggregate, but have a reputation for high drying shrinkage in concrete. This drying shrinkage can be shown to be related to the degree of weathering and alteration of the rock as determined by the visual mass weathering grade and percentage of alteration secondary minerals.” (Collis and Fox, 1993).

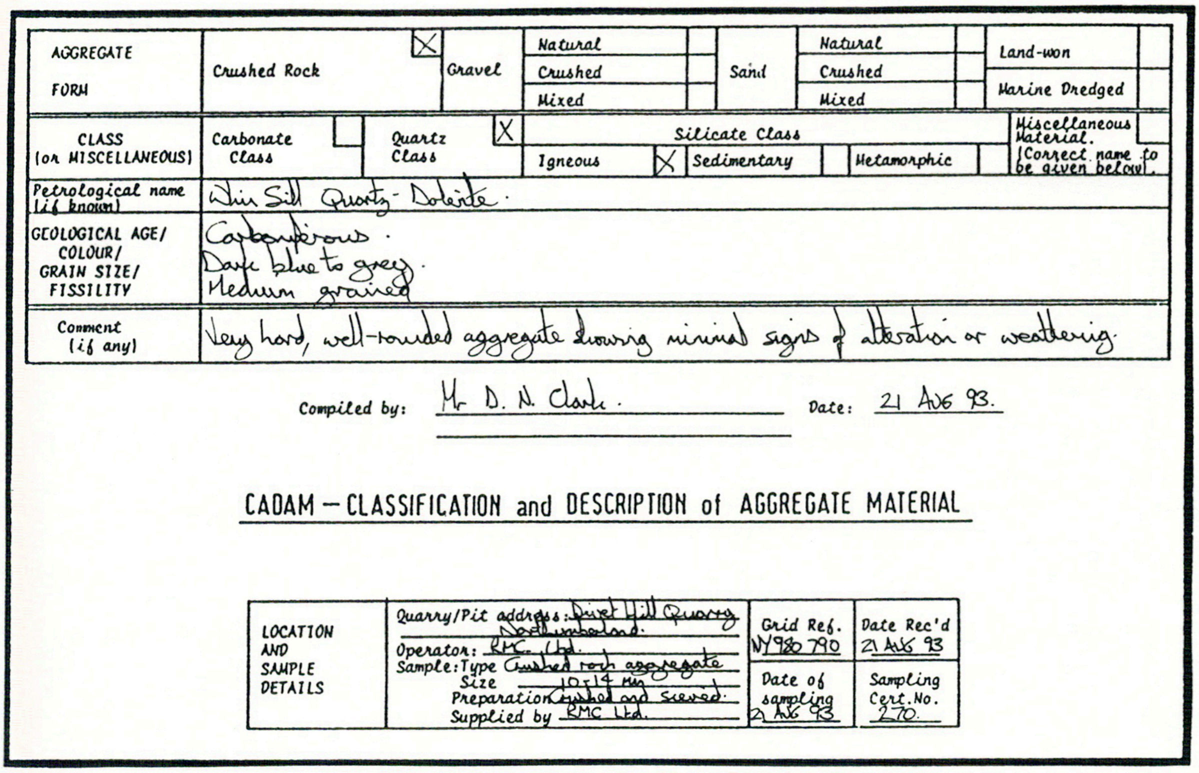
4.3 The CADAM System for Classification

The Geological Society Working Party proposed a system for the classification and description of aggregate material, known by the acronym CADAM. The system provided a simple, rational and descriptive classification which could be easily understood and followed several basic requirements. The system should;

- Be simple in concept and yet at the same time use only terms which have a precise meaning.
- Use properties relevant to aggregate materials as the basis for grouping them into classes.
- Have no bias except that which may reflect on the importance of the material as an aggregate.
- Be capable of being further expanded, as necessary, by the use of supplementary information relating to particular material or its intended use.

Then, data should be assembled on the standard form shown in figure 4.2.

Although this system is simple and easy to understand, it has not been widely adopted in practice and reflects a reluctance by the industry to use a scheme which is at variance to current British Standards. This system is not recommended by the second Engineering Geology Working Party Report on Aggregates (Collis and Fox, 1993), who have proposed an updated scheme (Section 4.8).



AGGREGATE FORM	Crushed Rock [X]	Gravel	Natural / Crushed / Mixed	Sand	Natural / Crushed / Mixed	Land-won / Marine Dredged
CLASS (or MISCELLANEOUS)	Carbonate Class [ ]	Quartz Class [X]	Silicate Class: Igneous [X] / Sedimentary [ ] / Metamorphic [ ]			Miscellaneous Material. (Correct name to be given below).
Petrological name (if known)	Whin Sill Quartz-Dolerite.					
GEOLOGICAL AGE/ COLOUR/ GRAIN SIZE/ FISSILITY	Carboniferous. Dark blue to grey. Medium grained					
Comment (if any)	Very hard, well-rounded aggregate showing minimal signs of alteration or weathering.					

Compiled by: Mr D. N. Clarke. Date: 21 AUG 93.

CADAM – CLASSIFICATION and DESCRIPTION of AGGREGATE MATERIAL

LOCATION AND SAMPLE DETAILS	Quarry/Pit address: Divet Hill Quarry Northumberland. Operator: RMC. Ltd. Sample: Type Crushed rock aggregate Size 10-14 mm Preparation crushed and sieved. Supplied by RMC Ltd.	Grid Ref. NY980 790	Date Rec'd 21 AUG 93
		Date of sampling 21 AUG 93	Sampling Cert. No. 270.

Figure 4.2. Suggested form for use of the CADAM system. (Collis and Fox, 1993).

4.4 The British Standard Classification

The current version of BS812 (1989), Methods of Sampling and Testing of Mineral Aggregates for Fillers, states that the description of an aggregate should include information such as the type of aggregate, be it crushed rock, sand, gravel or artificial in origin, the nominal aggregate size and any other extraneous information referring to the aggregate sample. It also requires that the aggregate is identified using a relevant petrographical name and geological age.

4.5 American Standards for Classification

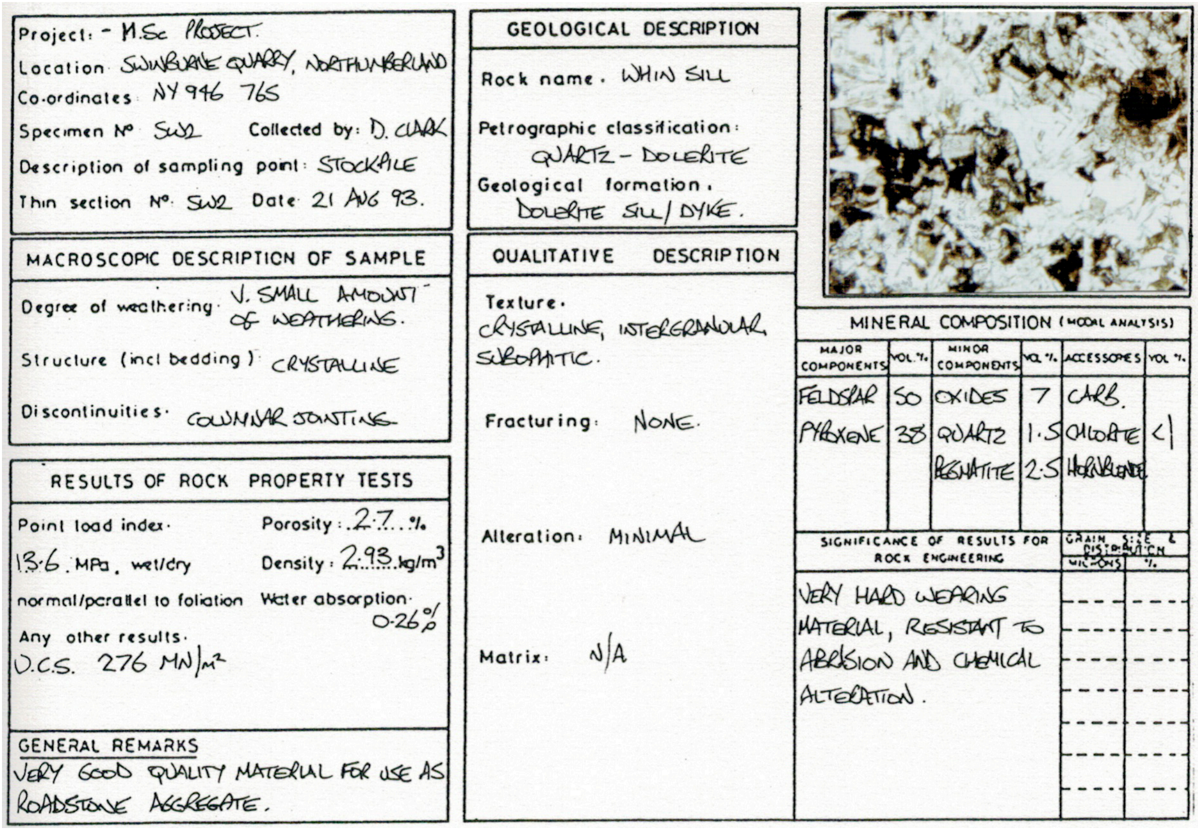
The American Society for Testing and Materials (ASTM) provides comprehensive requirements regarding the classification of aggregates. ASTM standard C294-86, *Standard Descriptive Nomenclature of Constituents of Natural Mineral Aggregates*, is for use in the description of mineral aggregates for use in concrete. Both aim to facilitate the description and classification of rock minerals in a geological manner although a detailed petrological examination is not mandatory, but usually necessary in most cases. The standards state that "the specific procedures employed in the petrographic examination of any sample will depend to a large extent on the purpose of the examination and the nature of the sample."

4.6 International Society for Rock Mechanics Classification

It was in 1981 that the International Society for Rock Mechanics (ISRM) issued two categories of laboratory and field tests requiring standardisation.

- Index Tests – Classification and characterisation of rock material, including mineral composition and texture along with fabric and mineral analyses, weathering, alteration, grain size, micro fracturing and porosity.
- Design Tests – Qualitative material characteristics, including tests thought to be necessary in order to appraise the likely engineering performance of the materials.

The ISRM issued the following form for the description of rock samples.



Project: - M.Sc PROJECT
Location SWINBURNE QUARRY, NORTHUMBERLAND
Co-ordinates NY 946 765
Specimen Nº SW2 Collected by: D. CLARK
Description of sampling point: STOCKPILE
Thin section Nº: SW2 Date 21 AUG 93.

MACROSCOPIC DESCRIPTION OF SAMPLE
Degree of weathering: V. SMALL AMOUNT OF WEATHERING.
Structure (incl bedding): CRYSTALLINE
Discontinuities: COLUMNAR JOINTING

RESULTS OF ROCK PROPERTY TESTS
Point load index: 13.6 MPa, wet/dry
normal/parallel to foliation
Porosity: 2.7 %
Density: 2.93 kg/m³
Water absorption: 0.26%
Any other results: U.C.S. 276 MN/m²

GENERAL REMARKS
VERY GOOD QUALITY MATERIAL FOR USE AS ROADSTONE AGGREGATE.

GEOLOGICAL DESCRIPTION
Rock name: WHIN SILL
Petrographic classification: QUARTZ - DOLERITE
Geological formation: DOLERITE SILL / DYKE.

QUALITATIVE DESCRIPTION
Texture: CRYSTALLINE, INTERGRANULAR SUBOPHITIC.
Fracturing: NONE.
Alteration: MINIMAL
Matrix: N/A

MINERAL COMPOSITION (MODAL ANALYSIS)

MAJOR COMPONENTS	VOL %	MINOR COMPONENTS	VOL %	ACCESSORIES	VOL %
FELDSPAR	50	OXIDES	7	CARB.	
PYROXENE	38	QUARTZ	1.5	CHLORITE	<1
		PEGMATITE	2.5	HORNBLENDE	

SIGNIFICANCE OF RESULTS FOR ROCK ENGINEERING: VERY HARD WEARING MATERIAL, RESISTANT TO ABRASION AND CHEMICAL ALTERATION.

GRAIN SIZE & DISTRIBUTION: microns / %

Figure 4.3. Form suggested by ISRM (1981) for the petrographic description of rock samples.

4.7 European and International Standards

There have been indications for a number of years that British Standards for aggregates will be replaced by European Standards. At the beginning of 1987 it became clear that the United Kingdom would have to take more notice of European and International Standards for aggregates. As a result of the determination by the member states of teh EEC to have an internal market, European legislation on several aspects of building materials is in preparation. These European Standards are being introduced by the Committee for European Standardisation (CEN) as part of the new approach to harmonization of standards in Europe to coincide with the revision of BS812 *Methods of Sampling and Testing of Mineral Aggregates for Fillers*, which is currently incomplete, and with the introduction of recognised European Standards. CEN members are the national standards bodies of Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxemburg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the UK.

A CEN Technical Committee has been working for several years to produce a draft CEN standard, but there would be no point in bringing out European Standards for aggregates that would cause technical problems, or increase cost unnecessarily for producers and users. The board decided, therefore, to set up a full Technical Committee for aggregates of all purposes. Its scope is "standardisation in the field of natural and synthetic aggregates, performance requirements, sampling, and methods of tests, with the aim of providing harmonised standards afterwards." (Pike, 1990). The work has been split amongst a number of sub-committees;

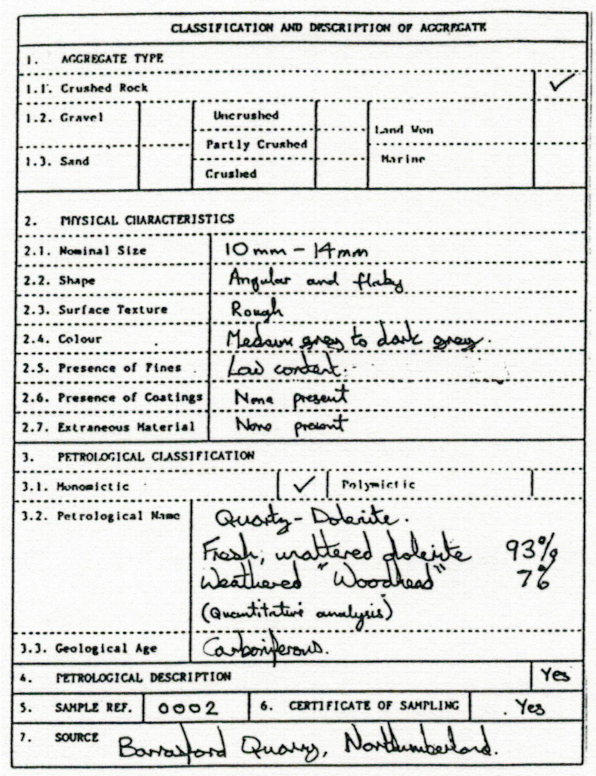
- Requirements for aggregates for masonry. (Netherlands)
- Requirements for aggregates for concrete. (United Kingdom)
- Requirements for aggregates for bituminous mixtures. (France, Belgium and Ireland)
- Requirements for unbound aggregates. (France)
- Requirements for lightweight aggregates. (Denmark)
- Aggregate test methods. (United Kingdom)

Little progress towards full harmonization can be achieved until the test methods decided upon are acceptable by member states, and thus, this program requires a large number of tests to be written over a short period of time.

Apart from CEN Standards, considerations must be given to the publications of the International Standards Organisation (ISO). It is CEN's policy to accept existing ISO Standards. If this is not possible, the drafters of CEN Standards should try to proceed by small amendments to existing ISO documents. There is no ISO committee for aggregates, but the United Kingdom has contributed to the work, and supports the principal of using ISO documents as a basis for drafts to be considered by the CEN. Although the United Kingdom considers that the existing ISO documents are flawed, they provide at least a first step towards documents that could be accepted widely. The United Kingdom is seeking ways to draw the activities of the ISO and CEN closer together. (Pike, 1990).

4.8 Proposed Engineering Group Classification Scheme

Due to the rejection of the CADAM system by the industry in favour of the current British Standards, the Engineering Group Working Party of the Geological Society have proposed an updated scheme which attempts to formalise the classification and description of an aggregate, whilst permitting flexibility in the detail of the information depending upon the circumstances. This simpler system is based primarily on the petrology of the source rock, combined with descriptions of aggregate type and physical characteristics such as nominal size, shape and surface texture. The proposed updated form for the classification of aggregates is shown in figure 4.4.



CLASSIFICATION AND DESCRIPTION OF AGGREGATE	
1. AGGREGATE TYPE	
1.1. Crushed Rock	✓
1.2. Gravel / 1.3. Sand	Uncrushed / Partly Crushed / Crushed — Land Won / Marine
2. PHYSICAL CHARACTERISTICS	
2.1. Nominal Size	10mm – 14mm
2.2. Shape	Angular and flaky
2.3. Surface Texture	Rough
2.4. Colour	Medium grey to dark grey.
2.5. Presence of Fines	Low content.
2.6. Presence of Coatings	None present
2.7. Extraneous Material	None present
3. PETROLOGICAL CLASSIFICATION	
3.1. Monomictic	✓ Polymictic
3.2. Petrological Name	Quartz-Dolerite. Fresh, unaltered dolerite 93% Weathered "Woodhead" 7% (Quantitative analysis)
3.3. Geological Age	Carboniferous.
4. PETROLOGICAL DESCRIPTION	Yes
5. SAMPLE REF. 0002	6. CERTIFICATE OF SAMPLING Yes
7. SOURCE	Barrasford Quarry, Northumberland.

Figure 4.4. Geological Society proposed form for the classification of aggregates. (Collis and Fox, 1993).

5 TESTS FOR THE CLASSIFICATION OF AGGREGATES

5.1 Physical Tests for Classification

5.1.1 Aggregate Grading and Particle Size

The particle size distribution or grading of an aggregate by sieving is determined by sieving the sample through square hole test sieves complying with BS410: 1986, in accordance with the methods specified in BS812: Section 103.1. Both crushed rock and natural aggregate is differentiated at the 5mm size range into coarse and fine aggregates (BS812: 1985). The sieves used in the United Kingdom for the grading of aggregate for bituminous mixtures and surface dressing are usually selected from;

450mm or 300mm diameter perforated plate:
63.0, 50.0, 37,5, 28.0, 20.0, 14.0, 10.0, 6.3 and 5.0mm
300mm or 200mm diameter wire cloth:
3.35, 2.36, 1.7 and 1.18mm, and 600, 425, 300, 212, 150 and 75µm.

"In Europe at present, there is no universally accepted single series of sieve aperture sizes in use for aggregate, but it is an aim of the European Committee for Standardisation (CEN) to reach an agreement on a single unified series by 1992. The International Standard, ISO 6274 *Concrete – Sieve analysis of aggregates* already specifies a preferred Series A that comprises a selection of preferred aperture sizes. Series A is a geometrical progression, based on 1mm, with a common ratio of 2;

63.0, 31.5, 16.0, 8.09, 4.0, 2.0, 1.0, 0.500, 0.250, 0.125, 0.063mm.

It has the benefit of simplicity, and it could provide an acceptable basis for compromise in CEN for the grading of aggregates used in both concrete and bituminous materials... Which ever single unified series is eventually adopted, most European countries will, as a consequence, have to make some changes to screen sizes used in the aggregate processing and sieve sizes for laboratory analysis." (Pike, 1990).

In sieving an aggregate sample the product is influenced by the shape of the constituents. The volume and size of the particles retained on a particular sieve are conditioned by shape eg, elongate fragments in any one size approximate in size to the flaky fragments of the next coarser size (Lees, 1964). Sieves, therefore, do not rigorously size the fragments where the shapes are very different. This implies that in aggregate with a high proportion of elongate grains the particle size would be coarser than one which is rich in flakes (Collis and Fox, 1985).

The draft European Standard (prEN 933-1, 1992) has been circulated for public comment and is concerned with the determination of aggregate particle size distribution – granulometric analysis (sieving method), although the European Standard for sieve apertures referred to in the text is not available for comment.

5.1.2 Aggregate Particle Size

In crushed rock aggregates, such as those of the Whin Sill, the constituent particles within a particular size fraction may display a wide range of shapes. The shape of an aggregate particle is a function of the petrology of the rock and the quarrying and aggregate production process. "Although the particle shape of crushed aggregates is affected to some extent by the nature of the rock and the type of crusher used, it is largely determined by the reduction ratio in the final stage of crushing, and this should not exceed 4:1. Shape is therefore predominantly a function of process control and the selection of the right type of crushing plant for the particular rock." (Pike, 1990).

BS812: Part 102 groups these shapes into six categories as shown in figure 5.1, these being rounded, irregular, angular, flaky and elongate.

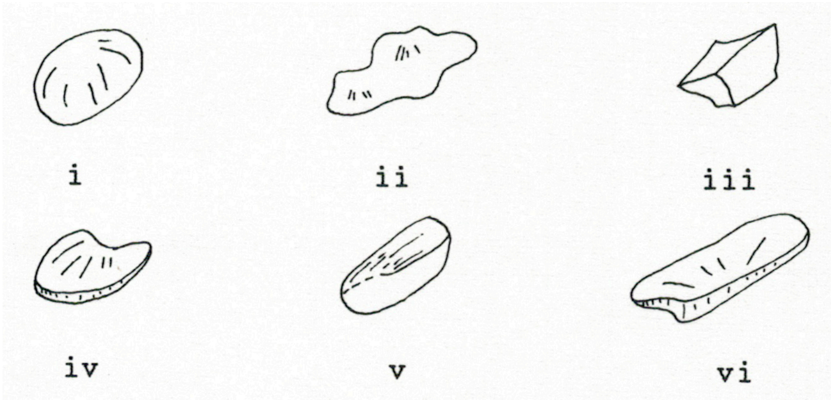


Figure 5.1. Particle shape: i, rounded;
ii, irregular; iii, angular; iv, flaky;
v, elongate; vi, flaky and elongate.
Collis and Fox (1985).

The actual measurements of the shape of individual fragments is illustrated in figure 5.2, based on the arbitrary limits of p and q (Lees, 1964). In this scheme the British Standard limits are 0.55 for elongation and 0.6 for flakiness.

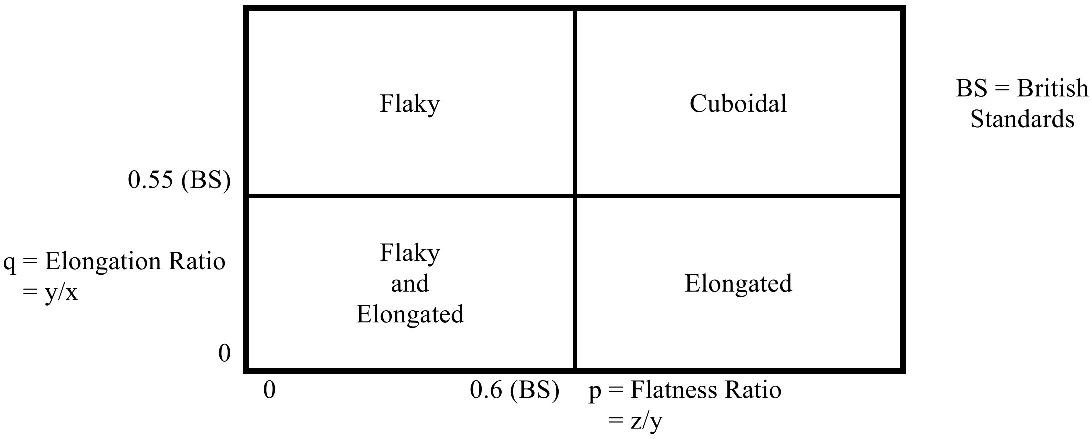


Figure 5.2. Aggregate Shape Measurements.

5.1.3 Aggregate Angularity

Aggregates angularity is a measure of the lack of rounding of individual particles. This lack of roundness of an aggregate affects the workability and stability of bituminous mixes, rounded particles providing better workability and angular particles better stability. As shape characteristics rely heavily on individual particle measurements, several attempts have been devised for more rapid determinations, the most common being a measure of the angularity of an aggregate relative to that of a smooth well-rounded gravel (BS812: Part 1. 1975). This is based on a computation of the percentage of voids in a compact4ed aggregate expressed as;

$$V = 100\left(1 - \frac{M}{CGa}\right)\%$$

where; M is the mean mass (g) of the aggregate in the cylinder, C is the mass (g) of water to fill the cylinder and Ga is the relative density of the aggregate on an oven-dried basis.

Since the angularity number (AN) = V-33, where 33 is the percentage of voids in a very well-rounded river gravel, the expression for V can be substituted to express AN;

$$AN = 67 - \left(\frac{100\ M}{CGa}\right)$$

(Collis and Fox, 1985)

The angularity number is reported to the nearest whole number varying from 0 to 12, the higher the number being typical of freshly crushed rock.

5.1.4 Aggregate Sphericity and Roundness

Sphericity (φ) is the deviation of a particle from a sphere ie, φ is the ratio of the surface area of a sphere with the same volume as the particle the surface area of the particle.

Roundness is a measure of the sharpness of the corners ie, smoothness;

$$P = \Sigma \frac{(r \;/\; R)}{(\;N\;)}$$

where; r is the radius of curvature of a corner of the particle surface, R is the radius of the maximum inscribed circle in the projected plane and N is the number of corners. With wear r approaches R and p approaches 1 (Harr, 1977).

5.1.5 Aggregate Surface Texture

Representative, visual characteristics of coarse aggregate particle surface texture are given under six headings in BS812: Part 102. 1975. They are intended to convey the impression gained from a visual inspection of hand specimens, and no attempt is made to call on petrographic terms. They are helpful to the practising engineer and technician, and the headings are as follows;

- Glassy — Conchoidal fracture.
- Smooth — Water-worn or smooth owing to fracture of laminated or very fine grained rock.
- Granular — Fracture showing more or less uniform grains.
- Rough — Rough fracture of fine or medium-grained rock containing no easily visible crystalline constituents. (This is the typical texture of aggregates produced from Whin Sill dolerite).
- Crystalline — Containing easily visible crystalline constituents.
- Honeycombed — Containing visible pores and/or cavities.

(Pike, 1990).

5.1.6 Relative Density

The relative density of an aggregate is the ratio of its mass to the mass of an equal volume of water. For aggregate coarser than 10mm a thoroughly saturated sample is weighed in water (mass B). It is then surface dried and weighed (weight A). Finally it is oven-dried for 24+ hours at 110°C, cooled and weighed (weight C).

$$\text{Relative Density (oven-dried)} = \frac{C}{A - B}$$

$$\text{Relative Density (saturated and surface dry)} = \frac{A}{A - B}$$

$$\text{Apparent Relative Density} = \frac{C}{C - B}$$

$$\text{Water Absorption (\% dry mass)} = \left(\frac{A - C}{C}\right) \times 100$$

(Collis and Fox, 1985).

5.1.7 Bulk Density (Unit Weight)

The bulk density or unit weight of an aggregate is its mass per unit volume eg, kg/m^3 or g/cm^3. This is described in BS812: Part 2 and is primarily intended for comparing the properties of different aggregates. A cylindrical container of known volume is filled with either oven-dried or saturated and surface-dried aggregate in three tamped layers, and the bulk density is calculated in kg/m^3 by dividing the mass of the aggregate by the volume of the container.

Bulk density measurements throughout the Whin Sill have been made by Dunham and Strasser-King (1982) and give a mean value of 2.983±0.009, although the following table of relative density measurements made by Teall (1884), shows variations from 2.820 to 2.959.

	2.924
Hot Bank near Crag Lough	2.906
Longhoughton near Alnwick	2.945
Greenhead Quarry near Haltwhistle	2.945
Barrasford Quarry, N. Tyne	2.944
Crags near Bourgovicus	2.959
Tinkler’s Syke	2.820
Teward’s Bridge near Forest Church	2.840

Crushed rock aggregates require values of 2.6 or greater to be accepted for roadstone usage, and as can be seen from all of the data for Whin Sill shown here, it is well above this limiting value.

5.1.8 Elongation Index

An aggregate particle is elongated when it has one dimension significantly greater than its other two dimensions. This shape factor is numerically standardised in BS812: Part 1 by defining an elongate particle as one whose greatest dimension is more than 1.8 times the mean dimension. Measurement has been facilitated by the design of the standard gauge, figure 5.3. (Collis and Fox, 1985).

$$\text{Elongation Index } (I_E) - \frac{\text{Mass of particles refused by gauges}}{\text{Total mass of particles tested}} \times 100$$

“The elongation index is rarely prescribed in standards for bituminous mixtures and road dressings, possibly because an elongate particle of aggregate has a tendency, on average, to be flaky, and the flakiness index using slotted sieves can be determined more quickly... However, it is also argued that, because there is no clear dependent relationship between elongation and flakiness for many aggregates and chipping’s for rolled asphalt, it is appropriate to determine elongation index directly in such cases.” (Pike, 1990).

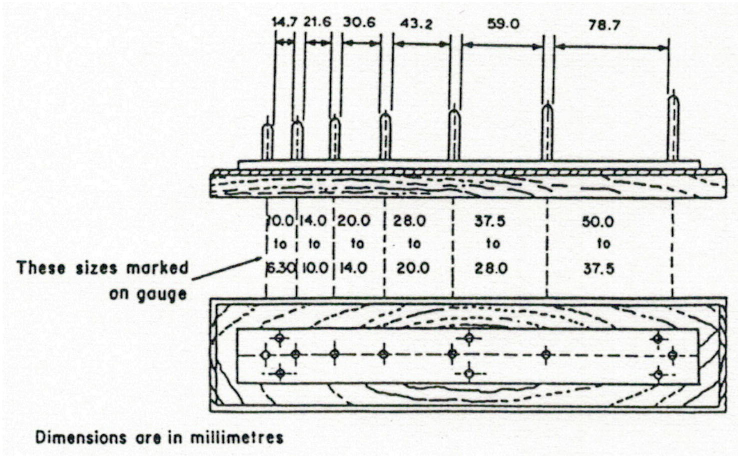


Figure 5.3. British Standard Length Gauge
(BS812. 1975), after Collis and Fox (1985).

The results obtained for Whin Sill aggregate from Barrasford, Swinburne and Divet Hill quarries are shown in table 5.1.

Quarry	Rock Type	Elongation Index (%)			
Barrasford	Fresh dolerite	10	11	11	11
Swinburne	Fresh dolerite	25	36	36	32
Divet Hill	Fresh dolerite	16	16	15	17

Table 5.1. Results for Elongation Index.

5.1.9 Flakiness Index

The flakiness index is restricted to aggregate coarser than 6.5mm and a particle is said to be flaky when it has one dimension significantly less than its other two dimensions. This shape factor is numerically standardised in the flakiness index test of BS812: Section 105.1. 1989, by defining a flaky particle as one whose dimension is less than 0.6 times the arithmetic mean of the aperture size of the two square-holed test sieves, that delimit the size fraction of the particle. For example, in 10mm to 14mm aggregate this would be 11.125mm. Measurement has been facilitated by the design of the standard shape gauge as shown in figure 5.4. (Collis and Fox, 1985).

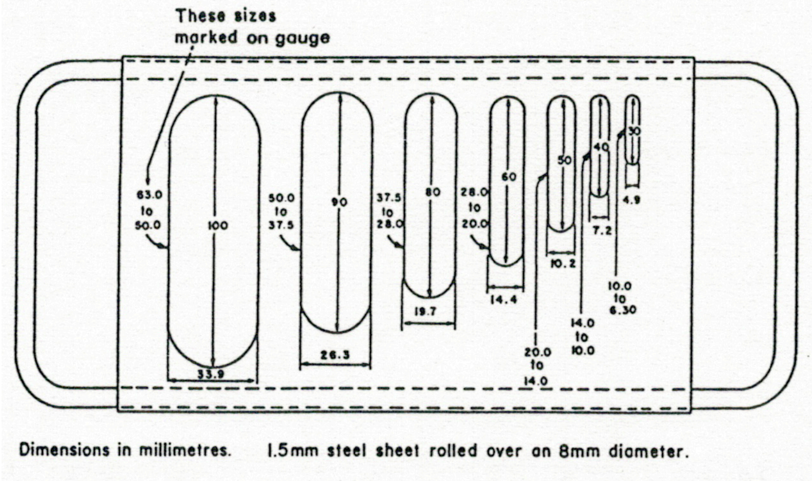


Figure 5.4. British Standard thickness gauges
(BS812. 1975), after Collis and Fox (1985).

$$\text{Flakiness Index } (I_F) = \frac{\text{Mass of particles passing gauges}}{\text{Total mass of particles tested}} \times 100$$

The range of flakiness indices specified for aggregates in the United Kingdom ranges from the limit of 25% for surface dressing aggregates to 45% for crushed rock and gravel aggregates.

The flakiness index results obtained for Whin Sill dolerite are shown in table 5.2, and as can be seen, the results fall well within the indices specified within the United Kingdom.

Quarry	Rock Type	Flakiness Index (%)			
Barrasford	Fresh dolerite	72	70	70	73
Swinburne	Fresh dolerite	69	72	82	72
Divet Hill	Fresh dolerite	48	47	50	48

Table 5.2. Results for Flakiness Index.

"The definition of a flaky or flat particle is not the same in every country. Different sieve sizes and dimension ratios are used, and in some cases the principal dimensions of each particle are checked with a proportional caliper. For these tests, limits for the width : thickness ratio ranging from 1.58 to 3 or even 5 may be set for flaky or flat particles, and the ratio of length : thickness, which is sometimes termed the shape coefficient, may have limits from 2.5 to 5. Clearly there is scope for harmonisation in Europe and the acceptance of a simple, rapid, and reasonably precise test(using flake-sorting sieves) with comprehensible and relevant limits that will facilitate quality control and the exchange of information." (Pike, 1990).

The draft European Standard (prEN 933-6, 1992) is available for public comment and the principal is very similar to that of the British Standard determination of the Flakiness Index. “The test consists of two sieving operations. First, using test sieves, the sample is separated into various granular classes d/D, where D = 1.25d. Each of the granular classes d/D is then sieved using grid sieves which have parallel slots of width D/2. The flakiness index of each granular class d/D is calculated as the mass of particles passing the corresponding sieve, expressed as a percentage by mass of that granular class. The overall flakiness index is calculated as the total mass of particles passing the grid sieve expresses as a percentage of the total dry mass of particles tested.” prEN 933-6 (1992).

The flakiness index for each granular class is calculated as;

$$Mi / Ri \times 100$$

where; mi is the mass of the material in each granular class d/D passing through the corresponding grid, as specified in Table 5.3, and Ri is the mass of each granular class d/D, in g.

Granular class d/D (mm)	Width of slot grid sieve (mm)
63 – 80	40
50 – 63	31.5
40 – 50	25
31.5 – 40	20
25 – 31.5	16
20 – 25	12.5
16 – 20	10
12.5 – 16	8
10 – 12.5	6.3
8 – 10	5
6.3 – 8	4
5 – 6.3	3.15
4 - 5	2.5

Table 5.3. Grid sieves. prEN 933-6 (1992).

5.1.10 Quick Absorption Test

The quick absorption test (I_{QAT})% was adopted by Hamrol (1961) and it is intended to measure the void index, defined as the mass of water contained in a rock sample after a period of immersion as a percentage of its initial desicator-dry-mass. The results obtained from samples of Whin Sill dolerite are shown in table 5.4. The index is correlated with porosity, hence also with such properties as degree of weathering or alteration.

Quarry	Rock Type	Quick Absorption Test (%)					
Barrasford	Fresh dolerite	0.012	0.020	0.016	0.012	0.004	0.012
Swinburne	Fresh dolerite	0.016	0.012	0.024	0.012	0.020	0.012
Divet Hill	Fresh dolerite	0.016	0.012	0.024	0.012	0.020	0.020

Table 5.4. Quick Absorption Test results
on Whin Sill dolerite.

5.1.11 Porosity

The porosity of a rock can be determined as the percentage of pore space within a given volume, and can be expressed as absolute porosity or apparent porosity. The absolute or total porosity, η, is a measure of the total void volume per unit volume of the rock. Total porosity is usually determined as the excess of grain density over dry density, per unit or grain density, which is expressed as;

$$\text{Total porosity, } \eta, = 1 - \left(\frac{\text{Dry density}}{\text{Grain density}}\right) \times 100$$

Effective porosity is experimentally determined as the excess of saturated weight over dry weight per unit of bulk volume, and is expressed as;

$$\text{Effective porosity} = \left(\frac{\text{Saturated weight} - \text{Dry weight}}{\text{Grain density}}\right) \times 100$$

The results obtained for effective porosity on 38mm diameter cores of Whin Sill dolerite are shown in table 5.5.

Quarry	Rock Type	Effective Porosity (%)					
Barrasford	Fresh dolerite	0.028	0.016	0.020	0.016	0.028	0.020
Swinburne	Fresh dolerite	0.020	0.016	0.024	0.016	0.016	0.016
Divet Hill	Fresh dolerite	0.036	0.024	0.028	0.032	0.032	0.028

Table 5.5. Results for Effective porosity of Whin Sill dolerite.

"Porosity is primarily affected by the grain size, grain shape, sorting, fabric, packing, cementation, and to a lesser extent by mineralogical composition. Furthermore, the secondary agents, alteration and weathering can have a marked affect on porosity by changing mineralogical composition, solution and leaching, and micro fracturing. In the case of very low porosity rocks such as Whin Sill dolerite, which in the fresh state is practically impermeable (as can be seen from the results in table 5.5), this secondary porosity due to alteration and weathering is particularly important in the understanding of the behaviour of the rock." (Rowshanaei, 1986).

Water absorption and porosity have a limiting value of 3 percent for roadstone aggregate and the values shown in tables 5.4 and 5.5, indicate that fresh Whin Sill dolerite is well within the acceptable limit.

5.1.12 Weinert Weathering Classification

The National Institute for Road Research South Africa use a simplified method for determining an 'index to weathering' to help in selecting igneous rocks for road work. In this method the state of rock weathering is determined by judging three properties; lustre, hardness and consistency, and state of crystallisation. Values between 1 and 4 are assigned to stages of weathering under each property, the higher the number the more advanced the decomposition. The three values are added together and the degree of weathering called the 'Total Index Value' is determined using table 5.6.

Total Index Value	Classification
12, 11	Residual Soil
10 – 8	Badly Weathered
7 – 5	Weathered
4, 3	Fresh

Total Index Value = Lustre Index Value + Hardness and Consistency Value + Crystallisation Index Value

Table 5.6. Classification of the Weathered State of Aggregate by N.I.R.R. (S. Africa), after Weinert (1964).

5.2 Mechanical Tests for Classification

5.2.1 Aggregate Impact Value

The aggregate impact value (AIV) gives a relative measure of the resistance to crushing of an aggregate in the 12.25mm to 9.5mm size range subjected to repetitions of a suddenly applied force. The standard is described in BS812: Part 3. A measured volume and mass of sieved and surface-dried aggregate is tamped in a single layer of depth 27mm in a 102mm diameter by 50mm deep steel cup. The aggregate is then subjected to 15 blows from a hammer (13.5 – 14 kg) falling through a head of approximately 380mm. The crushed aggregate is removed from the cup and the mass of material passing a 2.36mm test sieve is determined. Then, where A is the mass (g) of the surface-dried aggregate and B is the mass (g) of the crushed aggregate passing through the 2.36mm sieve;

$$AIV = \frac{B}{A} \times 100$$

"Compared with the ACV and 10% Fines tests, the AIV test has the advantages of a smaller, simpler, and more portable machine, a quicker test procedure, and a smaller sample." (Pike, 1990). Plate 5.1, shows the apparatus used for the determination of aggregate impact values and table 5.7, shows the results obtained from tests undertaken on fresh Whin Sill dolerite from Barrasford, Swinburne and Divet Hill quarries.

Quarry	Rock Type	Aggregate Impact Value (%)			
Barrasford	Fresh dolerite	7.6	6.1	6.6	7.6
Swinburne	Fresh dolerite	12.5	12.5	13.0	14.3
Divet Hill	Fresh dolerite	5.5	7.7	8.9	9.2

Table 5.7. Aggregate Impact Value Results.

Plate 5.1. Aggregate Impact Value apparatus.

The acceptance limits for aggregate impact value results is 45 percent for general use as roadstone aggregate and 30 percent for wearing surfaces. As can be seen, all of the results for fresh Whin Sill dolerite fall well below both the limiting values, indicating that this material is suitable for both general use and wearing surfaces.

5.2.2 Aggregate Crushing Value

The aggregate crushing value (ACV) givers a relative measure of the resistance of a 2kg aggregate sample to crushing, when subjected to a continuous load of 400kN which is reached over a period of 10 minutes. The standard test is described in BS812: Part 3. Surface-dried 10mm to 14mm aggregate is tamped in three layers to a depth of 100mm in a 150mm diameter steel cylinder, which is then subjected to the aforementioned load conditions.

Plate 5.2. Aggregate Crushing Value and
10% Fines Value apparatus.

As in the AIV the result is calculated by measuring the mass (g) of surface-dried aggregate tested (A) and the mass (g) of the crushed aggregate passing the 2.36mm sieve (B), thus;

$$ACV = \frac{B}{A} \times 100$$

Plate 5.2, shows the apparatus used for the determination of the aggregate crushing values and the results obtained for tests carried out on fresh processed Whin Sill aggregate are shown in table 5.8.

Quarry	Rock Type	Aggregate Crushing Value (%)			
Barrasford	Fresh dolerite	11	11	10	10
Swinburne	Fresh dolerite	15	13	12	12
Divet Hill	Fresh dolerite	8	9	7	8

Table 5.8. Aggregate Crushing Value Results.

Very strong aggregates have an ACV of about 10, with commonly used roadstones ranging from about 15 for basalts and porphyry through 25 for limestone to 28 for blast furnace slag. In general, an aggregate with an ACV of 25 or less will have sufficient strength for all road making purposes, and as can be seen from table 5.8, Whin Sill aggregates have sufficiently low values.

5.2.3 10% Fines Value

This is a variation on the aggregate crushing value and it presents the compressive force required to generate 10% by mass of crushed aggregate passing the 2.36mm test sieve, after loading in the standard ACV apparatus at a rate that achieves the required force in 10 minutes. The test is described in BS812: Part 3 and requires the fines less than 2.36mm to fall within the range of 7.5% to 12.5% of the initial mass. Then where, x is the maximum force (kN), and y is the mean percentage fines of two determinations at x kN;

$$\text{10\% Fines Value} = \frac{14x}{y + 4} \text{ kN}$$

Plate 5.2, shows the apparatus used for the determination of 10% fines values and table 5.9, shows the results obtained for tests undertaken on fresh dolerite from Barrasford, Swinbunre and Divet Hill quarries. The results are reported to the nearest 10kN for forces of 100kN or more, or to 5kN for loads of less than 100kN.

Quarry	Rock Type	10% Fines Value (kN)			
Barrasford	Fresh dolerite	400	440	440	450
Swinburne	Fresh dolerite	340	320	300	320
Divet Hill	Fresh dolerite	470	480	460	450

Table 5.9. 10% Fines Value Results.

The limiting acceptance values for the 10% fines test is a minimum of 50kN for aggregates used as roadstone, and as can be seen from the results shown above, fresh Whin Sill dolerite has sufficiently large values.

5.2.4 Franklin Point-Load Strength

The Franklin point-load strength apparatus is a simple, portable device for obtaining an indirect measure of the compressive strength of rock cores or small irregular lumps that may be obtained in the field. (Brock and Franklin, 1972). A load is applied through round-end conical platens, the ram being driven by a small hand operated pump. (Plate 5.3).

In loading through point contacts the specimens fail in tension at a fraction of the load required in the standard laboratory compression tests. Plate 5.4, shows the failure mode of samples tested for point load strength.

"The values obtained in this test correlate well with the laboratory uniaxial compression test" (Collins and Fox, 1985). Over the last two decades research has been carried out into the nature and distribution of stresses involved in point loading of rock, the effect of size and shape, and to propose an internationally acceptable equation which best defines a point load strength index from the applied load at failure.

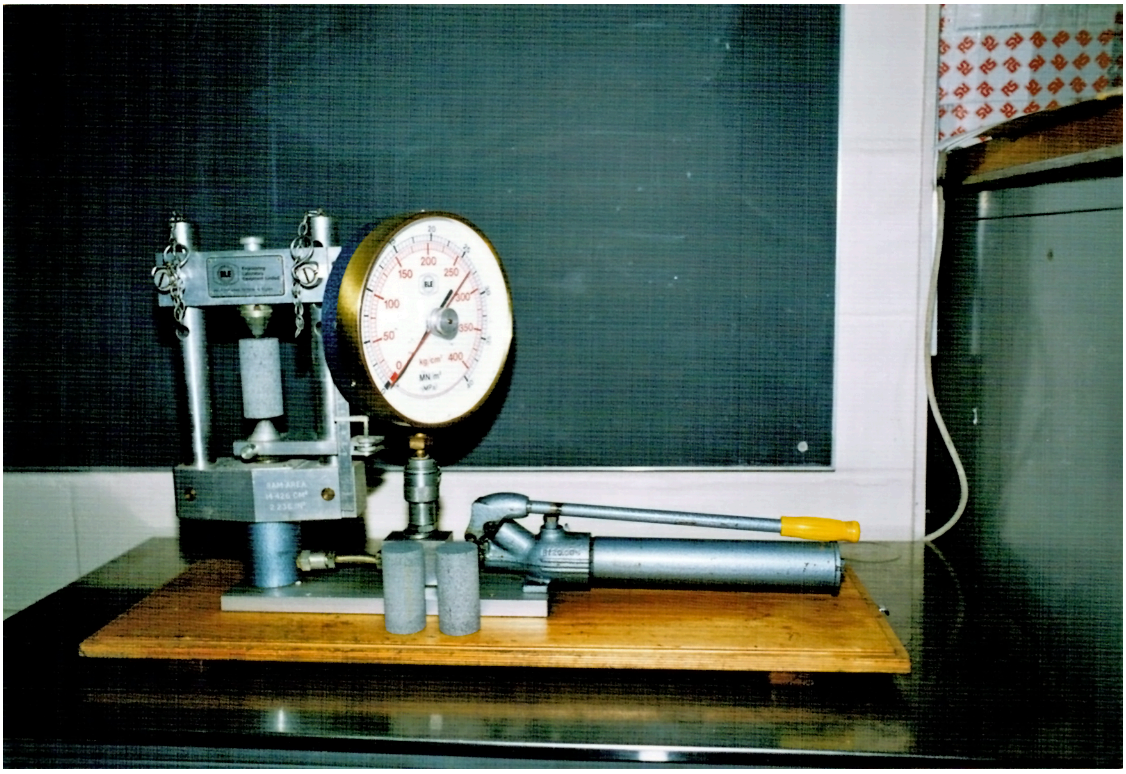


Plate 5.3.   Franklin Point-Load Strength Apparatus.

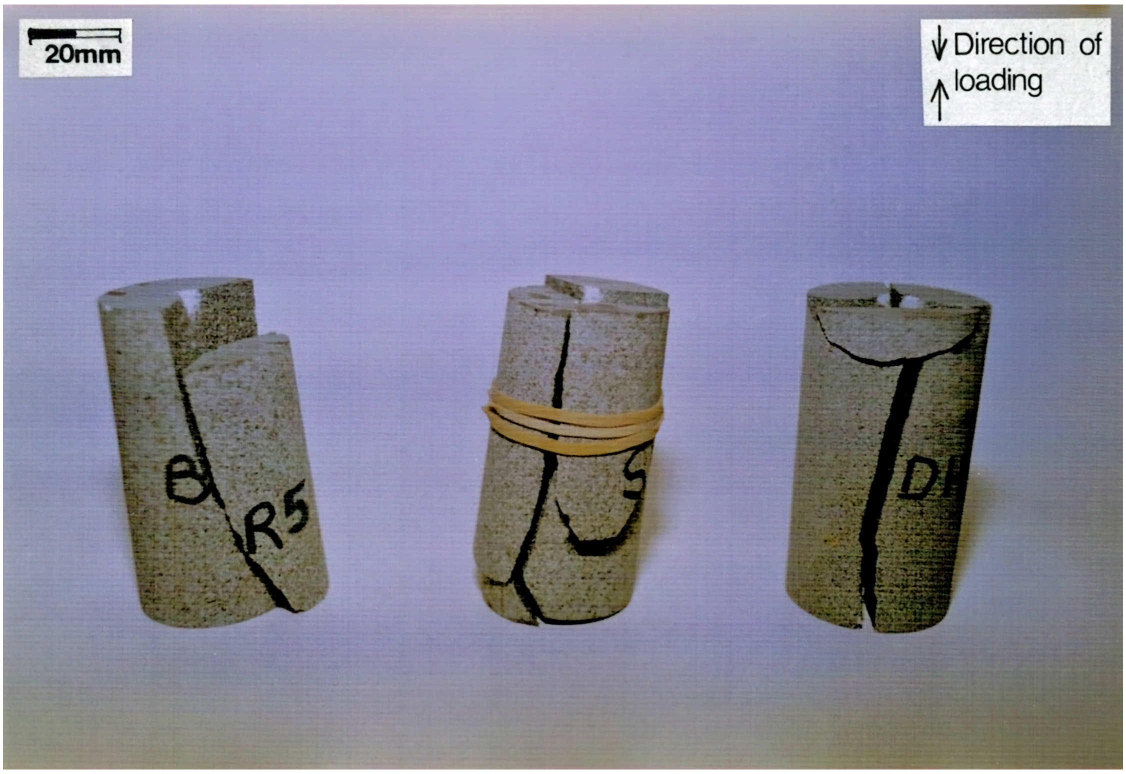


Plate 5.4.   Tensile failure of Whin Sill dolerite cores.

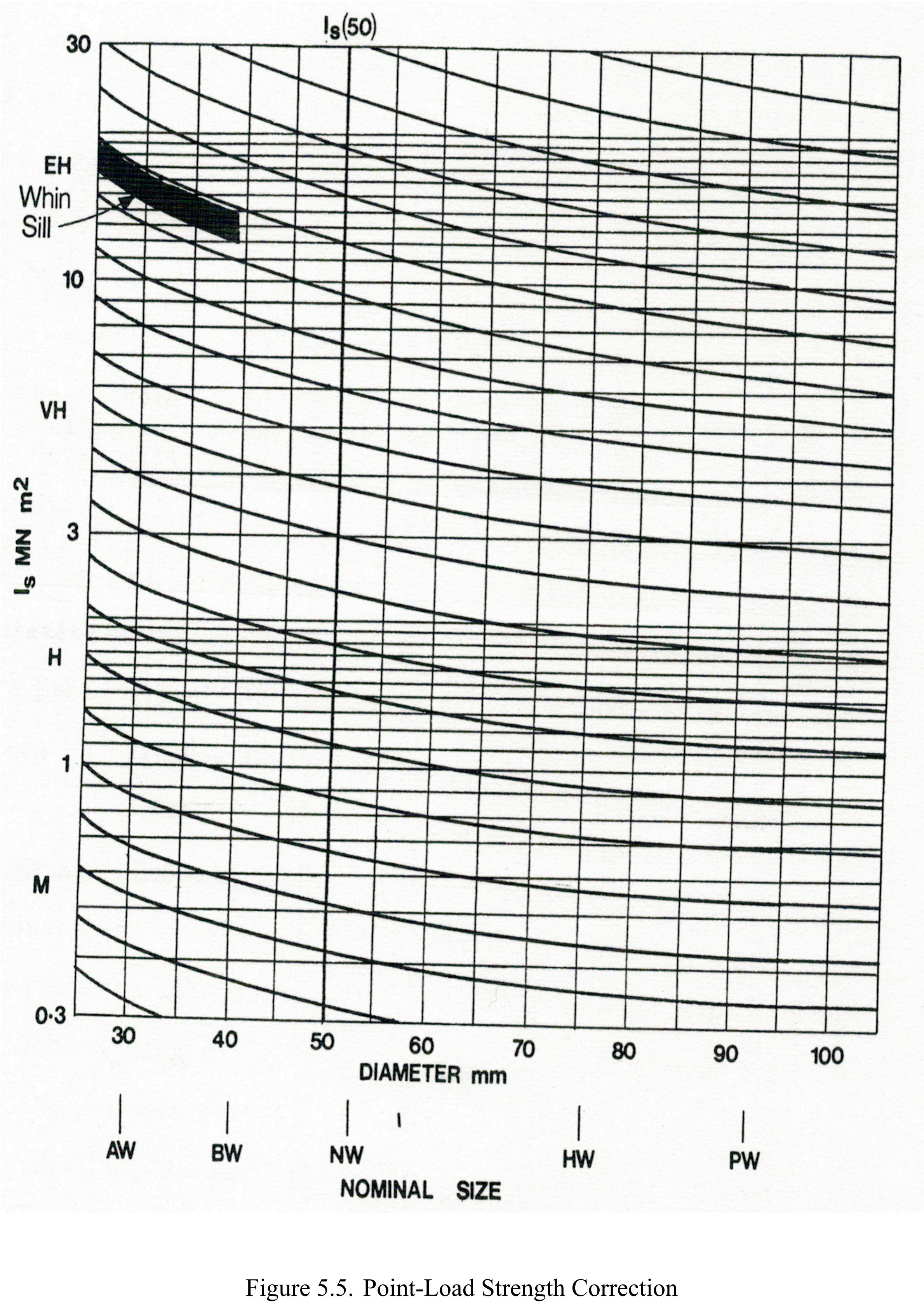


Figure 5.5. Point-Load Strength Correction Chart. (Brock and Franklin, 1972).

Brock and Franklin (1972) proposed the following simplified formula;

$$I_S = P/d^2$$

where; I_S is the strength index, P is the load and d is the distance between loading points. They suggest the use of standard 50mm diameter cores to overcome the considerable variations in strength values observed for different sizes and shapes. The results obtained for test undertaken on 38mm diameter Whin Sill dolerite cores are shown in table 5.10.

Quarry	Rock Type	Point Load Strength (mN/m^2)		
Barrasford	Fresh dolerite	17.0	16.5	18.7
Swinburne	Fresh dolerite	19.0	19.0	17.8
Divet Hill	Fresh dolerite	19.0	17.5	17.0

Table 5.10. Results of Franklin Point-Load Strength Tests.

The use of correction chart, figure 5.5, allows us to determine the relative hardness of the fresh Whin Sill samples and, as one would expect, all of the samples are classed extremely hard and would therefore be suitable for roadstone aggregate.

5.2.5 Schmidt Rebound Number

Hardness is a concept of material behaviour rather than a fundamental property and is dependant upon type and quantity of the various mineral constituents and the bond strength that exists between the mineral grains.

The Schmidt hammer determines the rebound hardness of the material being tested and also gives a qualitative impression of the toughness, elasticity and state of freshness of a rock from the impact sound. The device was originally developed for use with concrete, but has been adapted for rock. Fresh igneous rocks give values of around 50 and greater, and where weathering is present the rock is less elastic and more porous and therefore lower values are recorded.

"The hardness value obtained can be affected by experimental techniques as much as or even more than it is influenced by the behaviour of the material. Factors which are known to produce testing errors are orientation of the hammer, presence of cracks or localised discontinuity in the rock, effect of test surface (smoothness and flatness of rock surface), vibration and movement of the specimen during the test." (Rowshanaei, 1986). The biggest advantage of this test is its portability and easy/speed of operation in the field, and when combined with other tests such as point-load strength, it is a vital tool.

The rebound numbers obtained for a number of Whin Sill dolerite samples are shown in table 5.11, along with there respective quarries and quality of rock.

Quarry	Rock Type	Schmidt Rebound Number					
Barrasford	Fresh dolerite	43	53	49	56	45	52
Swinburne	Fresh dolerite	35	52	51	38	48	38
Divet Hill	Fresh dolerite	39	47	50	54	48	54
Knowesgate	Woodhead	32	28	45	36	28	38
Ewesley	Woodhead	31	50	34	25	38	20
Wards Hill	Fresh dolerite	44	34	40	49	35	49

Table 5.11. Schmidt Hammer results on fresh
dolerite and woodhead from various quarries.

As can be seen from the results in table 5.11, the inferior woodhead material has, on average, a much lower rebound number, this being representative of the strength of the material.

5.2.6 Unconfined Compressive Strength

The unconfined compressive strength test is one of the simplest measures of strength, the oldest, and most widely used rock test in engineering practice. Although its application in design is becoming limited due to the simple stress condition of testing, it affords some indication of rock behaviour under more complex stress systems, and indeed it allows comparisons between rocks and is commonly used for characterisation and classification of intact rock material. Plate 5.5, shows the equipment used for conducting unconfined compressive strength tests.

This method of test is intended to measure the uniaxial compressive strength of a rock sample in the form of specimens of regular geometry. The maximum stress at failure is taken as the unconfined compressive strength (δ_c) of the rock from the following equation;

$$\delta_c = P / A$$

where; P is the maximum applied load at failure and A is the initial cross-sectional area transverse to the direction of force. Results obtained on 38mm diameter cores of fresh Whin Sill dolerite are shown in table 5.12.

Quarry	Rock Type	UCS (mN/m2)			δ_c (MPa)		
Barrasford	Fresh dolerite	295	324	314	84.1	91.9	89.1
Swinburne	Fresh dolerite	340	285	346	97.0	81.3	99.2
Divet Hill	Fresh dolerite	323	369	370	92.1	105.8	105.5

Table 5.12. Results of Unconfined Compressive Strength Tests.

The mode of failure of strong to extremely strong dolerite can be classified into three groups:

- Brittle fracturing – Crumbling of the specimen by internal fracturing, followed by violent shattering and the formation of wedge shaped segments.
- Plastic failure – Failure tends to be along a single diagonal plane of shear inclined to the axis of the specimen.
- Mechanical sliding – Formation of multiple cracks in the direction of the applied load, leading to conical end fragments together with longitudinal slivers of rock.

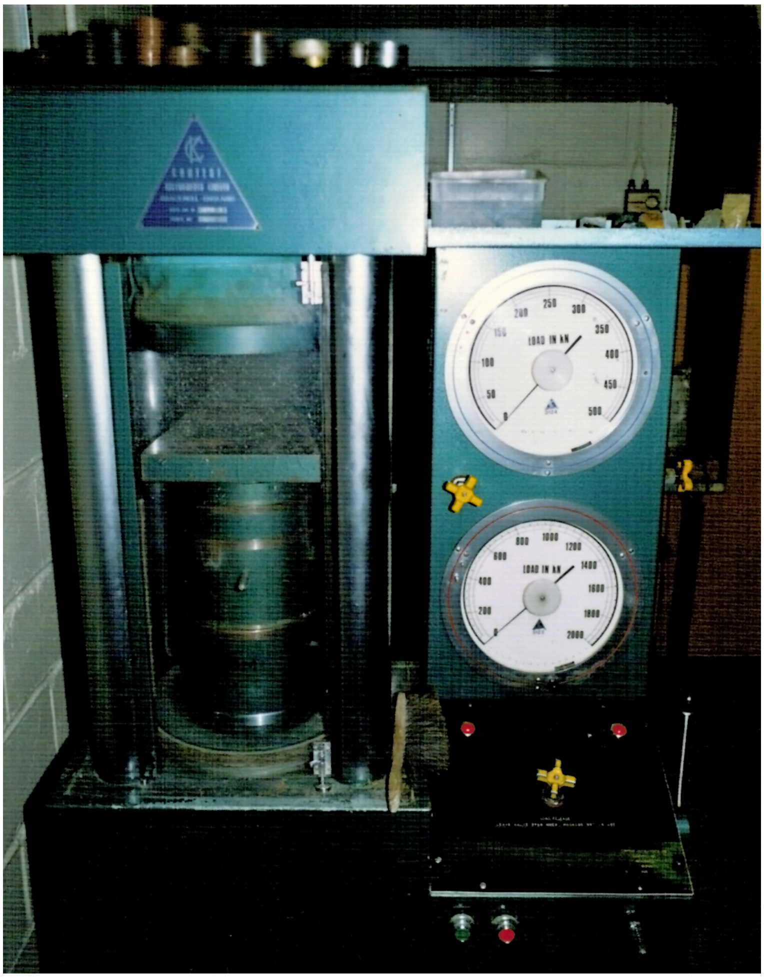


Plate 5.5. Equipment used to conduct Unconfined Compressive Strength Tests on Whin Sill dolerite.

Plate 5.6, shows sheared samples of Whin Sill dolerite obtained from the Unconfined Compressive Strength tests.

Plate 5.6. Sheared specimens of 38mm diameter Whin Sill dolerite.

Besides the inherent properties of the rock and the environmental conditions, the unconfined compressive strength is also influenced to some extent by the test conditions which include; contact problems between specimen and platens, eccentric loading, rigidity of the loading system, rate of loading and specimen geometry.

5.2.7 Ultrasonic Velocities

Portable equipment can be used to make rapid, accurate laboratory measurements of the velocity of ultrasonic pulses through materials. Using 'PUNDIT' apparatus (C.N.S. Instruments Ltd.) (Plate 5.7.) an empirical relationship appears to hold up for porosity's up to approximately 50%.

In theory the rock material is assumed to be elastic, isotropic and homogeneous. With these assumptions the velocity of a pulse of longitudinal ultrasonic vibrations (V_P) can be derived from the following;

$$VP = \frac{E\,(1 - \upsilon)}{P\,(1+ \upsilon)\,(1 - 2\upsilon)}$$

where; *E* is the dynamic modulus of elasticity, υ is Poisson's ration and P is density.

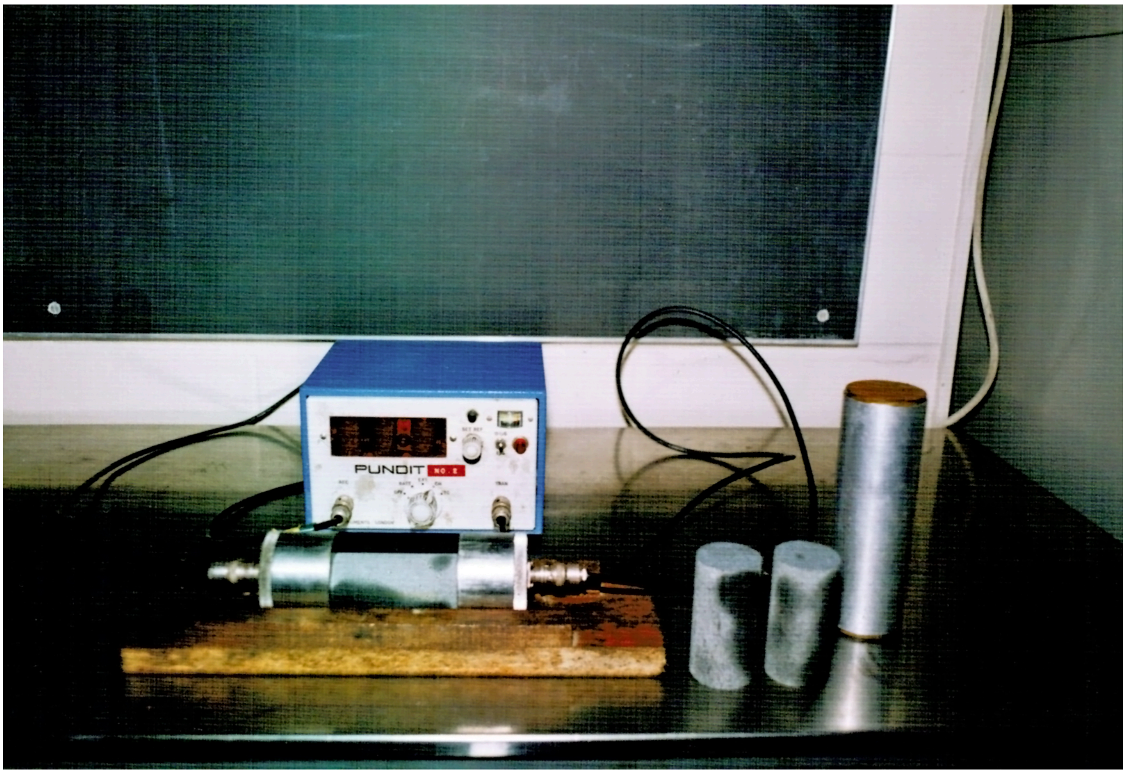


Plate 5.7. "Pundit" apparatus used for
the determination of ultrasonic velocities.

The pulse velocity determination requires measurement of the path length and the transit time of a pulse through the specimen, and is expressed as a ratio of the former to the latter in km/s. Table 5.13, shows the values obtained for samples of both saturated and dry Whin Sill dolerite. The value of sonic velocity in rocks is governed by composition, texture, density, porosity, anisotropy, water content, confining pressure and temperature.

The IAEG has recommended the sonic velocity as an indirect characteristic for quantitative classification of rock and soil material and regards the test as "A good index characteristic of the mechanical properties of hard and soft rocks." (IAEG, 1979).

Quarry	Ultrasonic Velocity (dry) km/s	Ultrasonic Velocity (sat.) km/s
Barrasford (Fresh dolerite)	4.02 3.98 4.05 4.04 3.97 4.05	4.29 4.30 4.35 4.39 4.16 4.35
Swinburne (Fresh dolerite)	3.92 3.93 4.04 4.04 4.01 4.06	4.19 4.16 4.36 4.35 4.30 4.38
Divet Hill (Fresh dolerite)	3.71 4.07 4.11 4.09 4.02 4.04	3.99 4.31 4.50 4.36 4.30 4.36

Table 5.3. Ultrasonic Velocities for Saturated and dry fresh Whin Sill Dolerite 38mm diameter cores.

5.3 Durability Tests for Classification

Specifications commonly require that aggregates "...be hard, durable and clean, and of approved quality." A durable aggregate may be described generally as one capable of resisting wear or decay for a long period of time. Aggregates should remain unimpaired by the diverse effects of seasonal and diurnal variations in such things as temperature, evapotranspiration, moisture content, ultra-violet radiation, ice and snow.

5.3.1 Los Angeles Abrasion Value

The Los Angeles Abrasion Value (LAAV) test is described in ASTM C131 *Standard Test Method for Resistance to Abrasion of Small-size Coarse Aggregate by use of the Los Angeles Machine* for coarse aggregates smaller than 37.5mm, and in ASTM C535 *Resistance to Abrasion of Large-size Coarse Aggregate by use of the Los Angeles Machine* for coarse aggregates smaller than 19mm. The method specified in test C131 is the one normally used for roadstone.

The test is not included in BS812, but it is a well established and internationally recognised test procedure which assesses the resistance of an aggregate to attrition by impact and abrasion forces.

A 500g sample charged with 6 to 12 steel balls is rotated in a closed, hollow steel cylinder with internal dimensions of 711mm diameter by 508mm length, fitted with a 150,, wide covered opening and an 89mm wide by 508mm long removable steel shelf (Figure 5.6.). The aggregate is washed, oven-dried and sieved. The test portion is prepared and rotated in the steel cylinder for 500 or 1000 revolutions at 33rpm for material less and greater than 19mm respectively.

On removal from the machine, the mass of aggregate retained on a 1.68mm test sieve is determined, then where, M1 is the mass (g) of the test portion, and, M2 is the mass (g) of the aggregate retained on the 1.68mm sieve;

$$LAAV = \frac{M1 - M2}{M1} \times 100$$

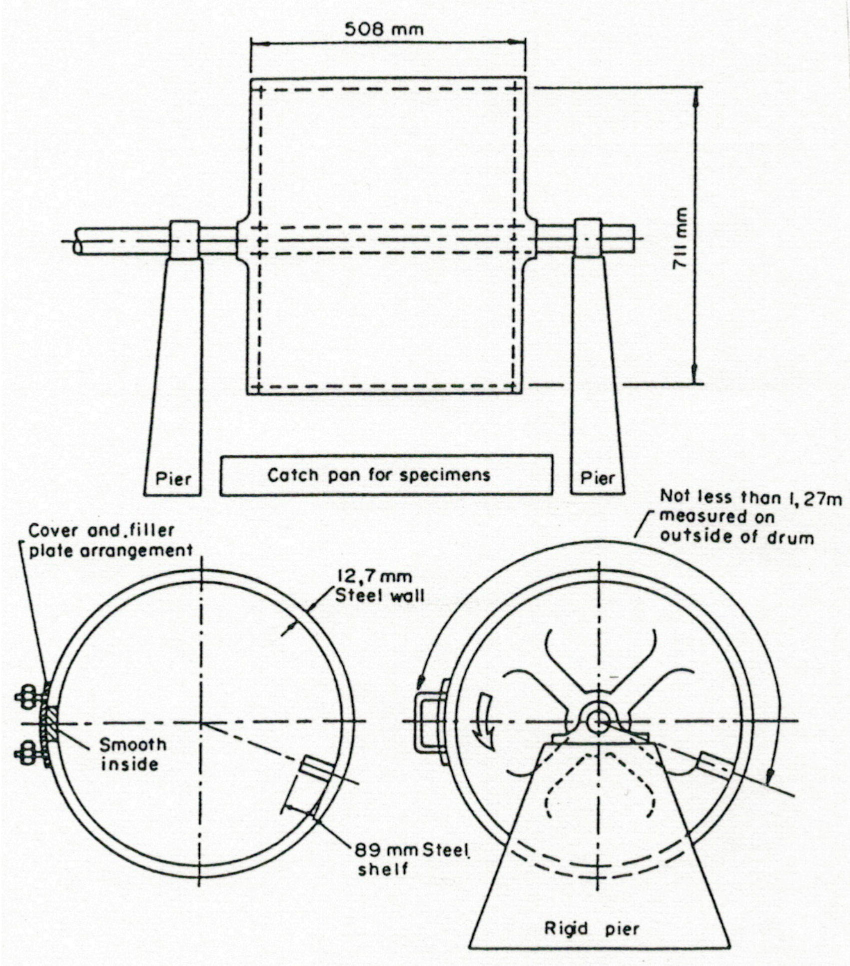


Figure 5.6. Los Angeles abrasion machine. (Collis and Fox, 1993).

The test method is simple, although noisy. The speed of rotation must be uniform, and the shelf, which is subjected to severe wear and impact, must be carefully maintained.

“In 1979, it was proposed that the LAAV test should be standardised internationally, and it is likely to be included as one of the preferred tests in the forthcoming European Standards for aggregates.” (Pike, 1990).

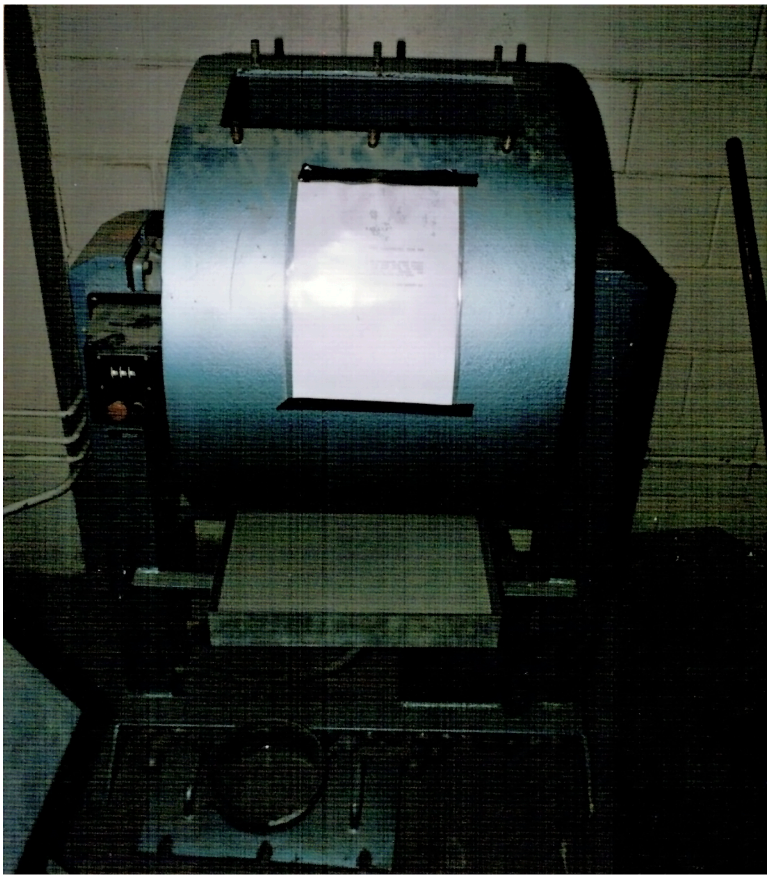


Plate 5.8. Los Angeles Abrasion Value test machine.

5.3.2 Polished Stone Value

The Polished Stone Value is used to predict the wearing quality of an aggregate used in the surface dressing of a road. An accelerated polishing apparatus simulates the motion of laden tyres on a sample of aggregate set in a polyester resin. A 200mm diameter by 38mm broad solid rubber tyred wheel bears on the aggregate with a force of 725N. Abrasion dust and water are fed to the surface of the aggregate during the test procedure. Figure 5.7, shows the typical apparatus used for conducting polished stone values.

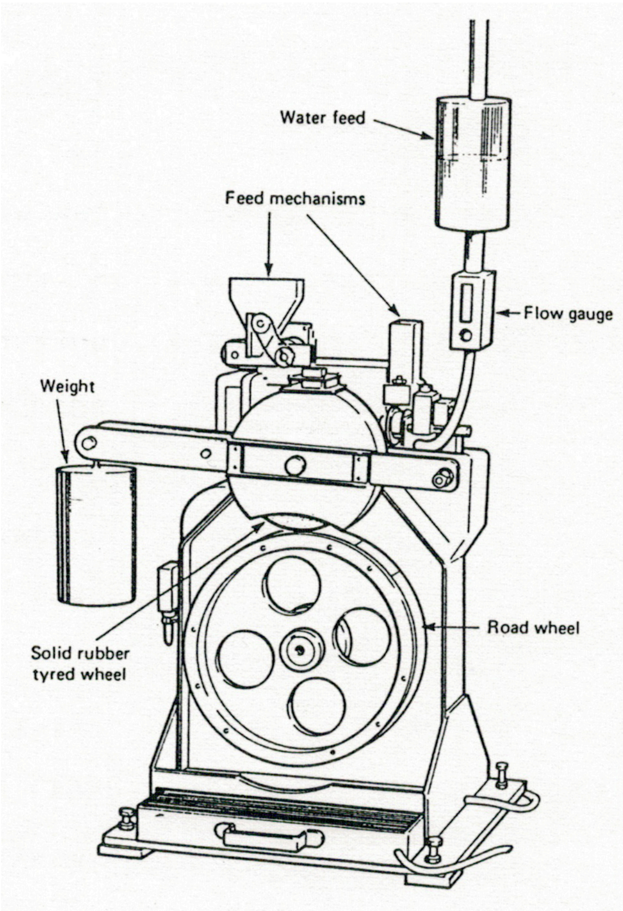


Figure 5.7. Accelerated polishing machine for conducting polished stone values. (Collis and Fox, 1993).

The polish of the specimen is measured using a pendulum arc friction tester, the deflection of the pointer on a calibrated scale yielding the coefficient of friction, which is expressed as a percentage, this being the polished stone value. Values over 65 indicate a highly polish-resistant rock especially suitable for road wearing coarses, but the number of sources of material of this quality ion the United Kingdom is limited, due to the fact that hard and tough rocks do not necessarily yield the best results, as such rocks, because of their dense texture and hardness, can take on a good polish.

5.4 Chemical Tests for Classification

Chemical tests are used to determine the ability of an aggregate to resist excessive volume changes as a result of changes in the physical environment, eg, freeze-thaw, thermal changes above freezing and wetting and drying. Weathering of material can occur in service over a period of months or years in some freshly exposed surfaces.

5.4.1 Sulphate Tests

The sulphate weathering simulation test has been around for a number of years. It has been standardised both in ASTM C88 (1989) *Soundness of Aggregates by use of Sodium Sulphate or Magnesium Sulphate* and BS812 (1989) *Methods for Sampling and Testing of Mineral Aggregates and Fillers*.

In the test a sample of 10mm to 14mm aggregate is subjected to five cycles comprising immersion in a saturated solution of sodium sulphate or magnesium sulphate followed by oven drying at 110°C. This subjects the aggregate to repeated crystallisation of sulphate within the pore spaces. The degree of degradation is measured by the amount of material finer than 10mm produced.

The results of sulphate tests are known to give differing results depending on the nature of the crystallisation medium and the number of cycled involved. The shape, size, porosity and permeability of the aggregate particles also has a marked effect on the result. Sulphate tests are normally only applied to aggregates used in the surface of motorways, trunk roads and airfield runways.

5.4.2 Frost Susceptibility

Frost-heave can occur during prolonged periods of freezing when the temperature of the pavement at depth falls below 0°C.

The test for frost susceptibility is standardised in BS812 (1989). In the test, cylindrical specimens of compacted aggregate are placed in a self refrigeration unit. The unit is designed so that the upper surface of the specimen is subjected to -17°C whilst the lower surface is allowed access to water at 4°C. This temperature gradient leads to frost-heave, and the maximum increase in height recorded is defined as the frost-heave of the aggregate. A material is classified as non-susceptible if the heave after 96 hours is less then 9.0mm and as susceptible if greater than 15mm.

5.4.3 Freeze-thaw Tests

Freeze-thaw tests can be undertaken by immersion of the aggregate or by air freezing of saturated aggregate. In both instances the aggregate is frozen at a temperature of -15 to -20°C for up to 10 hours followed by thawing in water at 20°C for 1 to 5 hours, these cycles being repeated 10 or 20 times for immersion freezing or air freezing respectively. The percentage loss in mass is determined by sieving on the next smaller sieve size.

6 DISCUSSION AND CONCLUSIONS

6.1 Discussion

In quarry development and extension, or in evaluation of the relative merits of materials from different sources the geotechnical engineer is required to predict the likely performance of the aggregate in the differing uses to which it may be put. At the present time there is inadequate understanding of the “in service” behaviour of aggregates.

Some general guidance has been provided on the subject of quantitative assessments, but it is usually very difficult to define an aggregate material completely by quantitative tests and specification limits. Thus, although elements of experience and judgement are inevitably involved when evaluation and approving materials, the aim should always be to minimise these subjective elements.

No matter how accurate a relationship is achieved between laboratory tests and service behaviour there will never be a true performance evaluation of aggregates, as numerous influencing factors will vary.

Once a body of material suitable for development as an aggregate source has been determined, the problem is to decide the boundary between acceptable and non0-acceptable material, and how best to use what is acceptable.

As several demands on aggregate call for different characteristics a wide range of tests have been devised to describe, classify and assess the potential value of a particular material. These tests have the principal functions of predicting the “in service” performance and enabling materials from different sources to be compared. Most assess some physical or mechanical attribute of the material, while some investigate particular durability or chemical characteristics. The majority are performed on the finished aggregate product but some are performed on the rock material itself.

In the quarries studied, the fresh Whin Sill dolerite is affected by typical spheroidal weathering and the production of corestones occurs to a limited degree. The altered woodhead material itself can be found in a distinctive weathered state although its distribution is patchy and unpredictable. This leads to the possibilities that the woodhead material was formed either during initial crystallisation of the Whin magma, or by recrystallisation after the magma had cooled. Due to the nature and occurrence of the woodhead material the obvious formation is by hydrothermal alteration from residual magma solutions. Both the shale's and limestone's which occur above and below the sill are altered by the same mineralisation processes, and have the same alteration products and similar mineralogy in areas where the woodhead is found. It has been suggested that alteration is possibly associated with mineralisation of limestone's found in the Pennine ore field to the south, but this is speculative as there is little mineralisation found in and around the sill itself. It can be said therefore that the production of woodhead material is by hydrothermal alteration, rather than weathering.

In the case of the Whin Sill, suitability for use as a roadstone aggregate is usually determined by the quality of the aggregate available. The main bulk of the Whin Sill, once minimal weathering zones have been delimited and avoided, is in a fresh state and therefore of very high quality. The majority of test undertaken on fresh and altered Whin Sill rock material and processed aggregate shows that there is a significant variation in the quality and suitability of these two materials, with woodhead being inferior to the fresh dolerite.

The main factors causing a reduction in strength of the dolerite in an increase in porosity, grain size and the proportion of soft minerals due to alteration and/or weathering. The presence of voids inside the framework of the rock has a markedly adverse effect on mechanical and physical properties. Voids can be detected by the values of density, porosity and ultrasonic velocities, these properties providing useful information on the behaviour of the rock material.

In general the presence of voids increase porosity and sonic wage velocity whilst decrease bulk density, strength and deformability. A fresh igneous rock containing a high free silica content is more resistant than a basic igneous rock which may have a high ferromagnesian content.

The particle shape of crushed rock aggregates is affected to some extent by the nature of the rock and also by the type of crusher used, and is largely determined by the reduction ratio in the final states of crushing. As the workability and durability of an aggregate product is dependant upon particle shape to some degree, the quality and in service performance of an aggregate is a function of process control and the selection of the correct type of crushing plant for the particular rock type.

Primary sampling allows us to explore the geological variability of the Sill, but the small percentage of woodhead material occurring within the sill yields characteristics which are not representative of the whole rock suite.

6.2 Conclusions

Crushed rock aggregates react in a rational and predictable manner to the standard tests designed for assessing them. Values obtained are a function of the petrological characteristics, geographic location and quarrying methods involved.

The majority of roadstones that are utilised in the United Kingdom and other developed countries are sufficiently strong and durable to undergo little or no weathering during the life of the pavement material of which they form part.

Quality variations between woodhead and fresh dolerite, rock material and processed aggregate, collected from a number of quarries in Northumberland, can be shown using the standard range of physical and mechanical tests. On the basis of all of the information which has been obtained and correlated from previous work and from current testing, it can be said that the altered dolerite (Woodhead) has inferior qualities than fresh dolerite.

From these results we can say that fresh Whin Sill dolerite is suitable for roadstone aggregate wearing coarse, whereas the woodhead material would only be suitable for road foundation material.

Fluctuations can be seen in all of the results obtained, and this variability is inherent in all types of measurement, arising from the raw materials, nature of the plant and the processing, handling practices and methods of sampling and testing. Of these, sampling and testing are commonly a major source of variability.

6.3 Recommendations for Future Studies

Although the location of the altered woodhead material is patchy and unpredictable, a thorough study into the occurrence of the material, including detailed mapping of the woodhead material within the whole Whin Sill suite may provide more useful information into its formation and possible origin.

There is very little literature reviewing the geochemistry, petrology and mineralogy of the altered woodhead material in comparison to that of fresh Whin Sill dolerite and in this field may provide useful information on the engineering characteristics of this material.

Once publication of the completed European and International Standards takes place, an investigation into the suitability of Whin Sill aggregates can be undertaken in comparison to the current practice in laboratory testing.

A thorough study into the variability, quality and a comparison of Whin Sill aggregates throughout North-East of England from Middleton-in-Teesdale in the south and as far as the Farne Islands in the North may give a greater representation of Whin Sill aggregates as a whole. This may be further explained by comparing the test results of Whin Sill aggregates with aggregates produced from other basic igneous rock intrusions.

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LIST OF SYMBOLS AND ABBREVIATIONS

c.	Approximately
°	Degrees
kN	Kilo-Newton’s
MN	Mega-Newton’s
MPa	Mega-Pascal’s
µm	Micrometres
Mm	Millimetres
cm	Centimetres
m	Metres
km	Kilometres
s	Seconds
g	Grams
kg	Kilograms
V	Void Ratio
Ga	Relative Density
AN	Angularity Number
φ	Sphericity
r, R	Radius
I_E	Elongation Index
I_F	Flakiness Index
I_{QAT}	Quick Absorption Test
η	Total Porosity
I_S	Strength Index
δ_c	Unconfined Compressive Strength

Vp	Longitudinal Ultrasonic Vibration's
E	Modulus of Elasticity
υ	Poisson's Ratio
An	Anorthite
BS	British Standard
CADAM	Classification And Description of Aggregate Material
ASTM	American Standard for Testing and Materials
ISRM	International Society for Rock Mechanics
CEN	Comittee for European Standardisation
ISO	International Standards Organisation
ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
IAEG	International Association of Engineering Geologists
LAAV	Los Angeles Abrasion Value
PSV	Polished Stone Value
PPL	Plain Polarised Light
XPL	Cross Polarised Light

APPENDIX 1

Rock Core Data

Barrasford Quarry

Sample Number	Mass (dry) (g)	Mass (sat) (g)	Porosity (%)	Q.A.T. (%)	δ_c (Mpa)
BR1	248.14	248.21	0.028	0012	84.1
BR2	249.29	249.33	0.016	0.020	91.9
BR3	248.76	248.81	0.020	0.016	89.1
BR4	249.86	2249.90	0.016	0.012	-
BR5	249.48	249.55	0.028	0.004	-
BR6	249.65	249.70	0.020	0.012	-

Swinburne Quarry

Sample Number	Mass (dry) (g)	Mass (sat) (g)	Porosity (%)	Q.A.T. (%)	δ_c (Mpa)
SW1	248.28	248.33	0.020	0.016	97.0
SW2	249.43	249.47	0.016	0.012	81.3
SW3	248.54	248.58	0.024	0.024	99.2
Sw4	249.49	249.55	0.016	0.012	-
Sw5	249.47	249.51	0.016	0.020	-
SW6	249.45	249.49	0.016	0.012	-

Divet Hill Quarry

Sample Number	Mass (dry) (g)	Mass (sat) (g)	Porosity (%)	Q.A.T. (%)	δ_c (Mpa)
DH1	247.05	246.14	0.034	0.016	92.1
DH2	247.15	247.21	0.024	0.012	105.8
DH3	246.75	246.82	0.028	0.024	105.5
DH4	246.55	246.63	0.032	0.012	-
DH5	247.38	247.46	0.032	0.020	-
DH6	246.91	246.98	0.028	0.020	-

Porosity is referred to in section 5.1.11.
Q.A.T. (Quick Absorption Test) is referred to in section 5.1.10.
δ_c is representative of the unconfined compressive strength and is discussed in section 5.2.6.

Rock Core Data

Barrasford Quarry

Sample Number	P.L.S. (mN/m^2)	U.C.S. (mN/m^2)	U.S.V. (dry) km/s	U.S.V. (sat.) km/s	S.R.N
BR1	-	295	4.02	4.29	43
BR2	-	324	3.98	4.30	53
BR3	-	314	4.05	4.34	49
BR4	17.0	-	4.04	4.39	56
BR5	16.5	-	3.98	4.15	45
BR6	18.7	-	4.05	4.35	52

Swinburne Quarry

Sample Number	P.L.S. (mN/m^2)	U.C.S. (mN/m^2)	U.S.V. (dry) km/s	U.S.V. (sat.) km/s	S.R.N
SW1	-	340	3.92	4.19	35
SW2	-	285	3.93	4.16	52
SW3	-	346	4.04	4.36	51
Sw4	19.0	-	4.04	4.335	38
Sw5	19.0	-	4.01	4.30	48
SW6	17.8	-	4.06	4.38	38

Divet Hill Quarry

Sample Number	P.L.S. (mN/m^2)	U.C.S. (mN/m^2)	U.S.V. (dry) km/s	U.S.V. (sat.) km/s	S.R.N
DH1	-	323	3.91	3.99	39
DH2	-	369	4.07	4.31	47
DH3	-	370	4.11	4.50	50
DH4	19.0	-	4.09	4.36	54
DH5	17.5	-	4.02	4.30	48
DH6	17.0	-	4.04	4.36	54

U.C.S. (Unconfined Compressive Strength) is shows here as the maximum load at failure of the specimen, and allows us to calculate δ_c as discussed in section 5.2.6.

Unconfined compressive strength tests and P.L.S. (Point Load Strength) tests are each undertaken on half of the cores as the tests lead to destruction of the specimen. The point load strength test is discussed in section 5.2.4.

U.S.V. (Ultrasonic Velocities) are determined for all the cores in both dry and saturated conditions. Section 5.2.7.

S.R.N. (Schmidt Rebound Number). This test was undertaken on the respective block specimens of dolerite before coring was undertaken.

APPENDIX 2

Quarry	Rock Description	Aggregate Crushing Value (%)	Aggregate Impact Value (%)	Flakiness Index (%)	Elongation Index (%)	Quick Absorption Test (%)	Weinert Number	Point Load Strength (MN/m^2)
Barrasford	Fresh Dolerite	16	10	38	22	0.00	3	2.40
Barrasford	Fresh Dolerite	27	30	18	17	1.00	6	2.26
Barrasford	Fresh Dolerite	38	40	26	21	2.00	8	4.40
Mean for Fresh Dolerite		27	27	27	20	1.00	6	3.02
Ewesley &	Woodhead	32	31	19	11	1.40	6	2.26
Knowesgate	Woodhead	55+	9*	30	73+	0.30	3	--
Ewesley &	Woodhead	32	34	18	21	2.00	6	3.30
Knowesgate	Woodhead	26	31	25	14	3.60	7	3.10
" "	Woodhead	41	39	22	16	2.00	9	3.20
Mean for Woodhead		37	29	23	27	1.90	6	2.97

Notes: * This value appears to be unusually low for this test. + These values appear to be rather too high, the value of 73 for the Elongation Index is more likely to be 27. – indicates that there was no data available for this test.

Standard Tests on Aggregates 1986.

Quarry	Rock Description	Dry Density (Mg/m^3)	Saturated density (Mg/m^3)	Porosity (%)	Ultrasonic Velocity (Dry) (Km/s)	Ultrasonic Velocity (Sat) (Km/s)	Unconfined Compressive Strength (MN/m^2)
Barrasford	Fresh Dolerite	2.910	--	4.240	--	--	244
Barrasford	Fresh Dolerite	2.880	--	3.060	--	--	133
Barrasford	Fresh Dolerite	2.810	--	4.050	--	--	135
Barrasford	Fresh Dolerite	2.910	--	2.990	--	--	--
Barrasford	Fresh Dolerite	2.910	--	5.500	--	--	330
Barrasford	Fresh Dolerite	2.890	--	5.600	--	--	324
Barrasford	Fresh Dolerite	2.890	--	5.600	--	--	325
Barrasford	Fresh Dolerite	2.950	--	5.600	--	--	275
Barrasford	Fresh Dolerite	2.940	--	5.600	--	--	201
Barrasford	Fresh Dolerite	2.940	--	5.600	--	--	282
Barrasford	Fresh Dolerite	2.900	--	5.600	0.400	--	279
Barrasford	Fresh Dolerite	2.890	--	5.600	0.400	--	299
Barrasford	Fresh Dolerite	2.870	--	5.600	0.400	--	281
Mean for Fresh Dolerite		2.900	--	4.960	0.400	--	259
Ewesley &	Woodhead	2.680	--	2.900	--	--	53
Knowesgate	Woodhead	2.730	--	2.100	--	--	52
Ewesley &	Woodhead	2.750	--	3.200	--	--	73
Knowesgate	Woodhead	2.920	2.930	5.400	0.800	5.500	--
Ewesley &	Woodhead	2.390	2.400	5.300	0.800	5.400	--
Knowesgate	Woodhead	2.820	2.830	5.400	0.900	5.400	--
Ewesley &	Woodhead	2.780	2.830	2.750	0.021	--	--
Knowesgate	Woodhead	2.760	2.830	3.470	0.026	--	--
" "	Woodhead	2.740	2.800	3.190	0.024	--	--
Mean for Woodhead		2.730	2.770	3.740	0.429	5.470	59

Notes: – indicates that there was no data available for this test.

Standard tests on rock cores 1986.

APPENDIX 3

Quarry	Rock Description	Aggregate Crushing Value (%)	Aggregate Impact Value (%)	Flakiness Index (%)	Elongation Index (%)	Quick Absorption Test (%)	Weinert Number	Point Load Strength (MN/m^2)
Barrasford	Fresh Dolerite	7	18	36	24	1.10	4	5.40
Barrasford	Fresh Dolerite	16	9	55	20	1.00	4	9.45
Mean for Fresh Dolerite		12	14	46	22	1.05	4	7.43
Ewesley &	Woodhead	--	--	29	82*	1.26	5	2.00
Knowesgate	Woodhead	38	29	77*	77*	1.30	8	4.75
Mean for Woodhead		38	29	68*	80*	1.28	7	3.38

Notes: * These values appear unusually high for the Flakiness
and Elongation Index Tests and are more likely 18, 23, 23
respectively giving means of 26 for Flakiness and 21 for Elongation.
-- Indicates that there was no data available for this test.

Standard Tests on Aggregates 1990.

Quarry	Rock Description	Dry Density (Mg/m^3)	Saturated density (Mg/m^3)	Porosity (%)	Ultrasonic Velocity (Dry) (Km/s)	Ultrasonic Velocity (Sat) (Km/s)	Unconfined Compressive Strength (MN/m^2)
Barrasford	Fresh Dolerite	2.905	--	--	5.593	--	47+
Barrasford	Fresh Dolerite	2.919	--	--	5.690	--	125+
Barrasford	Fresh Dolerite	2.915	2.917	<1	5.662	--	167+
Barrasford	Fresh Dolerite	2.777	2.779	<1	5.520	5.330	--
Barrasford	Fresh Dolerite	2.910	2.913	<1	5.590	5.470	--
Barrasford	Fresh Dolerite	2.901	2.911	<1	5.650	5.450	335
Mean for Fresh Dolerite		2.888	2.880	<1	5.596	5.417	169+
Ewesley &	Woodhead	2.862	2.872	1.808	3.920	3.790	--
Knowesgate	Woodhead	2.717	2.749	3.270	2.170	2.220	48
Ewesley &	Woodhead	2.845	--	--	4.040	--	--
Knowesgate	Woodhead	2.828	--	--	3.490	--	123
Ewesley &	Woodhead	2.7309	--	--	3.470	--	4
Knowesgate	Woodhead	2.730	2.310	2.380	3.940	4.090	51
" "	Woodhead	2.580	2.630	3.770	4.210	4.280	8
Mean for Woodhead		2.756	2.640	2.630	3.050	3.595	47

Notes: + These values for the Unconfined Compressive Strength of fresh
dolerite seem rather low and are possibly due to slight micro fracturing
or weathering of the cores leading to a lower strength.
-- Indicates that there was no data available for this test.

Standard tests on rock cores 1990.

APPENDIX 4

Quarry	Rock Description	Aggregate Crushing Value (%)	Aggregate Impact Value (%)	Flakiness Index (%)	Elongation Index (%)	Quick Absorption Test (%)	Weinert Number	Point Load Strength (MN/m^2)
Barrasford	Fresh Dolerite	10	3	20	15	0.10	4	0.07
Barrasford	Fresh Dolerite	38	17	16	22	0.70	6	13.28
Barrasford	Fresh Dolerite	17	8	26	12	0.00	8	4.25
Barrasford	Fresh Dolerite	37	14	24	27	0.20	7	--
Mean for Fresh Dolerite		26	11	22	19	0.85	6	6.08
Ewesley & Knowesgate	Woodhead	27	27	23	9	0.50	8	10.60
	Woodhead	16	8	24	28	--	--	7.10
Mean for Woodhead		22	18	24	19	0.50	8	8.85

Notes: – indicates that there was no data available for this test.

Standard Tests on Aggregates 1991.

Quarry	Rock Description	Dry Density (Mg/m^3)	Saturated density (Mg/m^3)	Porosity (%)	Ultrasonic Velocity (Dry) (Km/s)	Ultrasonic Velocity (Sat) (Km/s)	Unconfined Compressive Strength (MN/m^2)
Barrasford	Fresh Dolerite	2.870	2.890	--	5.900	4.900	327
Barrasford	Fresh Dolerite	2.550	2.550	0.930	5.560	6.420	298
Barrasford	Fresh Dolerite	2.920	2.940	--	5.400	4.650	--
Mean for Fresh Dolerite		2.780	2.790	0.930	5.620	5.320	313
Ewesley & Knowesgate	Woodhead	2.920	2.920	0.220	6.470	6.060	209*
	Woodhead	2.910	2.910	0.710	5.240	5.220	341*
Mean for Woodhead		2.920	2.920	0.470	5.860	5.640	275*

Notes: * The values for Unconfined Compressive Strength appear unusually high for woodhead material, and are closer to the results for fresh dolerite. – indicates that there was no data available for this test.

Standard tests on rock cores 1991.

APPENDIX 5

Quarry	Rock Description	Aggregate Crushing Value (%)	Aggregate Impact Value (%)	Flakiness Index (%)	Elongation Index (%)	Quick Absorption Test (%)	Weinert Number	Point Load Strength (MN/m^2)
Barrasford	Fresh Dolerite	11	3	12	11	0.30	5	--
Barrasford	Fresh Dolerite	10	3	16	16	0.82	4	--
Barrasford	Fresh Dolerite	10	3	28	13	1.10	6	2.50
Barrasford	Fresh Dolerite	10	3	16	3	0.90	4	11.00
Barrasford	Fresh Dolerite	25	4	18	36	1.00	5	3.85
Mean for Fresh Dolerite		13	3	18	22	0.82	5	5.78
Ewesley & Knowesgate	Woodhead	26	15	22	31	0.39	5	5.00
Mean for Woodhead		26	15	22	31	0.39	5	5.00

Notes: – indicates that there was no data available for this test.

Standard Tests on Aggregates 1992.

Quarry	Rock Description	Dry Density (Mg/m^3)	Saturated density (Mg/m^3)	Porosity (%)	Ultrasonic Velocity (Dry) (Km/s)	Ultrasonic Velocity (Sat) (Km/s)	Unconfined Compressive Strength (MN/m^2)
Barrasford	Fresh Dolerite	--	--	--	--	4.540	269
Barrasford	Fresh Dolerite	2.630	2.630	0.170	4.690	4.690	250
Barrasford	Fresh Dolerite	2.920	3.040	0.120	12.700*	--	384
Barrasford	Fresh Dolerite	3.830+	3.830+	0.030	4.850	--	407
Barrasford	Fresh Dolerite	2.930	2.930	0.380	5.810	5.810	298
Barrasford	Fresh Dolerite	2.640	2.650	--	--	--	263
Mean for Fresh Dolerite		2.990	3.020	0.180	7.010*	5.010	312
Ewesley & Knowesgate	Woodhead	2.810	2.820	0.510	2.000	2.400	75
Mean for Woodhead		2.810	2.820	0.510	2.000	2.400	75

Notes: + These values appear rather high for the density of dolerite.
* The value indicated for Ultrasonic Wave Velocity is extremely high and may be due to miscalculation or defective equipment.
– indicates that there was no data available for this test.

Standard tests on rock cores 1992.

APPENDIX 6

Quarry	Rock Description	Aggregate Crushing Value (%)	Aggregate Impact Value (%)	Flakiness Index (%)	Elongation Index (%)	Quick Absorption Test (%)	Weinert Number	Point Load Strength (MN/m^2)
Barrasford	Fresh Dolerite	12	1	25	18	3.00	4	--
Barrasford	Fresh Dolerite	17	8	37	37	-	6	--
Barrasford	Fresh Dolerite	21	11	17	40	3.00	7	6.40
Barrasford	Fresh Dolerite	25	4	18	36	1.00	5	3.85
Mean for Fresh Dolerite		19	6	24	33	2.00	6	5.13
Ewesley & Knowesgate	Woodhead	22	10	19	13	2.00	9	--
Mean for Woodhead		22	10	19	13	2.00	9	--

Notes: – indicates that there was no data available for this test.

Standard Tests on Aggregates 1993.

Quarry	Rock Description	Dry Density (Mg/m^3)	Saturated density (Mg/m^3)	Porosity (%)	Ultrasonic Velocity (Dry) (Km/s)	Ultrasonic Velocity (Sat) (Km/s)	Unconfined Compressive Strength (MN/m^2)
Barrasford	Fresh Dolerite	2.930	2.930	0.000	5.800	5.600	161
Barrasford	Fresh Dolerite	2.930	2.930	0.000	5.700	5.700	178
Barrasford	Fresh Dolerite	2.780	2.780	0.000	5.300	5.300	281
Barrasford	Fresh Dolerite	2.930	2.930	0.000	5.800	5.500	--
Barrasford	Fresh Dolerite	2.920	2.930	0.060	2.900	3.300	113
Barrasford	Fresh Dolerite	2.920	2.920	0.060	2.800	3.200	205
Barrasford	Fresh Dolerite	2.670	2.680	0.030	3.000	3.300	285
Barrasford	Fresh Dolerite	2.760	2.760	0.000	5.100	5.300	286
Barrasford	Fresh Dolerite	2.640	2.640	0.003	5.100	5.100	229
Barrasford	Fresh Dolerite	2.890	2.890	0.002	5.500	5.700	--
Barrasford	Fresh Dolerite	3.830*	3.830*	0.030	4.900	--	407
Barrasford	Fresh Dolerite	3.840*	3.840*	0.040	4.900	--	354
Barrasford	Fresh Dolerite	3.870*	3.870*	0.030	4.800	--	323
Barrasford	Fresh Dolerite	2.780	2.820	5.090	2.000	2.400	75+
Barrasford	Fresh Dolerite	2.810	2.840	4.270	2.200	2.700	72+
Barrasford	Fresh Dolerite	2.910	2.910	1.990	5.300	5.700	73+
Mean for Fresh Dolerite		3.030	3.030	0.727	4.400	4.500	217
Ewesley &	Woodhead	2.960	2.960	1.200	5.800	5.800	159
Knowesgate	Woodhead	2.910	2.910	--	5.300	5.100	--
" "	Woodhead	2.920	2.890	--	5.800	5.900	--
Mean for Woodhead		2.930	2.920	1.200	5.600	5.600	159

Notes: * The values shown here for density are extremely high.
+ These values for unconfined compressive strength seem extremely low for fresh dolerite, and are more likely the results obtained for woodhead.
– indicates that there was no data available for this test.

Standard tests on rock cores 1993.

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I know I'm probably leaving somebody out, if so, my apologies go out to you accordingly.

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