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The determination of the acceptability of selected fragmenting materials for earthworks compaction

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Executive Summary

The crushing of particles during compaction is often viewed as a problem. However, crushing may confer benefits to the compacted mass; small particles resulting from crushing may fill voids and thus produce higher densities and lower air voids than would otherwise be the case. This will, in turn, tend to produce a more stable compacted mass.

This report considers the potential use of four materials likely to crush during compaction: unburnt colliery spoil, burnt colliery spoil, spent oil shale and weak sandstone.

Unburnt colliery spoil is widely used as general fill but is excluded from use in more critical selected fill applications due to its chemistry and the long-term potential for mechanical breakdown of aggregated particles within the fill.

Burnt colliery spoil and spent oil shale can be used successfully as general fill. However, due to their high quality and short supply they are more suited to use as selected granular fill or sub-base. In particular, cement stabilisation will reduce their frost susceptibility and may be a particularly appropriate outlet for these materials for use as sub-base. However, an increase in control and testing may be required, having an effect on the cost of using such materials.

The clauses in the Specification for Highway Works for granular sub-base refer to ‘well burnt non-plastic shale’ which embraces both burnt colliery spoil and spent oil shale. The clauses for selected granular fill refer specifically to well burnt colliery spoil but could well be phrased in the same manner as those for granular sub-base.

Weak sandstone can be used as both general fill and capping layer material. However, it is important that the compaction process reduces the material to its fully residual state.

All of the fragmenting materials considered must be compacted to low air voids and the resulting earthworks treated as described in the Specification for Highway Works in order to limit the potential for water ingress. In this manner their durability is maximised and stable earthworks produced. Notwithstanding special procedures identified for weak sandstone, it is considered that acceptability can be determined for granular and cohesive materials using conventional British Standard compaction test or MCA procedures.

Maximising the use of natural materials such as weak sandstone yields both economic and environmental benefits, and this blend of benefits must be achieved if waste materials are to be successfully used in road construction. Contractors will only be encouraged to use waste materials if there are economic benefits and it is then important that environmental benefits, such as savings in the use of finite natural aggregate resources, can be demonstrated.

Local supplies of burnt colliery spoil are likely to be more limited than those of unburnt colliery spoil and spent oil shale. Weak sandstone is likely to be used only where it forms part of a cut and fill operation or where available from a suitably located borrow pit.

1 Introduction

Methods are required for determining the acceptability of fragmenting materials (such as colliery shale, spent oil shale and weak sandstones) for earthworking. Although fragmenting materials are used infrequently in earthworks, there is considerable potential for locally available materials such as spent oil shale, unburnt and burnt colliery spoil and weak sandstone to be used.

Although Table 6/1 of the Specification for Highway Works (MCHW 1) defines 43 classes of fill only three relate to General Fill, as follows:

- Class 1: General Granular Fill.
- Class 2: General Cohesive Fill.
- Class 3: General Chalk Fill.

In addition, each material is defined on the basis of a compaction and grading requirement. In addition certain materials are specifically excluded:

a peat, materials from swamps, marshes and bogs;

b logs, stumps and perishable material;

c materials in a frozen condition;

d clay having a liquid limit exceeding 90 or plasticity index exceeding 65;

e material susceptible to spontaneous combustion except unburnt colliery spoil which may be used as general fill provided that it is compacted in accordance with Clause 612;

f non-hazardous materials other than those permitted in Table 6/1 and Appendix 6/1 of the Specification.

These materials are classified as unacceptable material Class U1. Class U2 materials are defined as those having hazardous chemical or physical properties requiring special measures for their excavation, handling, storing, transportation, deposition and disposal.

In addition, while being acceptable for general fill purposes, frost susceptible materials are not permitted within 450mm of the road surface and materials with a high sulphate content may not be placed within 500mm of metallic items, lime, concrete, cement bound or other cementitious materials. Also comprehensive warnings have been given on the damage caused by mixing high sulphate materials with cement and lime (HA74 - DMRB 4.1.6; Perry *et al.*, 1996a; 1996b).

This report is limited to three basic materials:

- Colliery Spoil (including both unburnt and burnt colliery spoil).
- Spent Oil Shale.
- Weak Sandstone.

In general, each of these are Class 1 (granular) materials, although unburnt colliery spoil may occasionally have a grading such that it corresponds to a Class 2 (cohesive) material.

Each of these three materials is susceptible to fragmentation during compaction but this does not preclude their use as general fill. The only fragmenting material which is dealt with explicitly in the Specification is Chalk. This can be categorised as a General Fill Class 3 material and the Saturation Moisture Content (SMC) is used to determine acceptability and the Chalk Crushing Value (CCV) to determine the site excavation method (Parsons, 1967; Ingoldby and Parsons, 1977). Chalk is also permitted in a number of other classes such as Fill to Structures Class 7A and can be used as Class 1 or 2 if it does not meet the requirements of Class 3.

The purpose of this report is to outline the physical and chemical properties of colliery spoil, spent oil shale and weak sandstone and to identify possible means of determining their acceptability for earthworks compaction.

2 Fragmentation

The degree of breakage, or fragmentation, that will occur during the compaction of a granular material depends upon the original particle size distribution, the crushing strength of the grains and the stress level applied (Leslie, 1963; Marsal, 1967; Marsal, 1973; Lee and Farhoomand, 1967).

Essentially, if a brittle particle is subjected to a stress in excess of its ultimate strength it will break. The stress may place the particle in either tension, compression, flexure, shear or, less likely, torsion. In addition, a particle may be worn away by another particle: that is, subjected to attrition.

Fundamentally, size reduction (or breakage) is the separation of a particle into two or more parts and the creation of additional surface area, equal to twice the area over which the separation has taken place. The more times a particle is divided the larger the surface area created, unless surfaces due to cavities or pores are blocked in the process. The change in the surface area of a granular media is therefore a measurement of the change in the size of its particles.

The surface areas of a series of geometrically similar figures are related as the squares of the lengths of any similar sides of those figures. There is an underlying assumption in particle size determinations that the particles are geometrically similar. Therefore, at least for powders, the surface area can be calculated from the particle size distribution (British Standards Institution, 1970). From the foregoing, it can be inferred that the change in particle size distribution is a good indicator of the degree of fragmentation experienced by a granular media as a result of the compaction process.

The surface area of the particles within a granular mass influences the number of particle contacts present, and hence the distribution of contact forces created within the mass due to externally applied loadings. Clearly, the intensities and directions of contact forces will vary widely and in an irregular way. In order to take account of this, a probabilistic distribution theory for interparticular contact forces was proposed (Marsal, 1963; Marsal and Wilson, 1979). Watt (1991) made approximate calculations to estimate the mean point contact forces for a medium sand, a gravel and rockfill from a uniform loading of $98kN/m^2$, as follows:

- Medium sand: 9.8N.
- Gravel: 9.8kN.
- Rockfill: 9.8MN.

This demonstrates that low applied stresses may cause high point contact stresses and breakage in a rockfill. In contrast, an applied stress several orders of magnitude greater would be required to induce similarly high contact stresses in a medium sand.

While some brittle materials will be especially prone to fragmentation during compaction it is important to recognise that all materials will fragment provided that the energy applied during compaction is sufficient. The degree of fragmentation will depend on the original particle size distribution, the crushing strength of the grains and the stress level (or compactive energy) applied.

The effect of particle size distribution on fragmentation can be illustrated by data acquired in connection with research in a related area (Winter and Suhardi, 1993). Heavy 4.5kg rammer compaction tests (British Standards Institution, 1990) were carried out on two soils and the particle size distribution determined before and after compaction at the optimum moisture content. Data were acquired for stone contents in the range 0 to 75% and are illustrated in Figures 1 and 2. It is clear that the maximum change in particle size distribution is in the size range 2mm to 20mm. Figure 3 illustrates the changes in percentages passing a 20mm sieve for Soils 1 to 9 (see Winter and

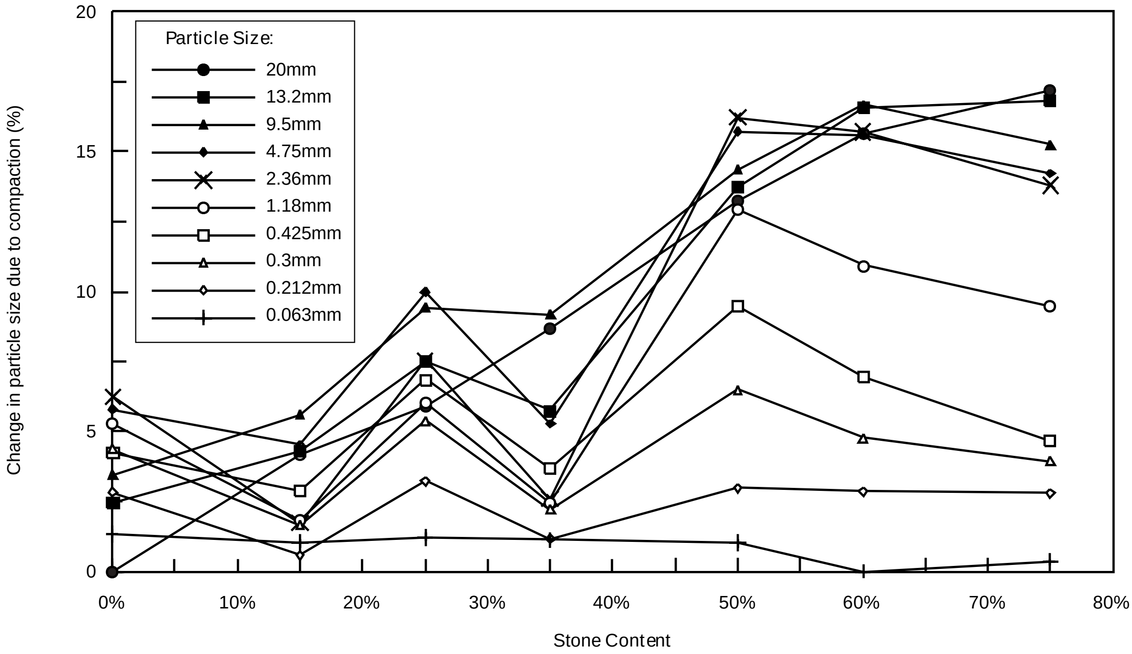

Figure 1 The influence of heavy compaction on percentage passing (Soil 1)

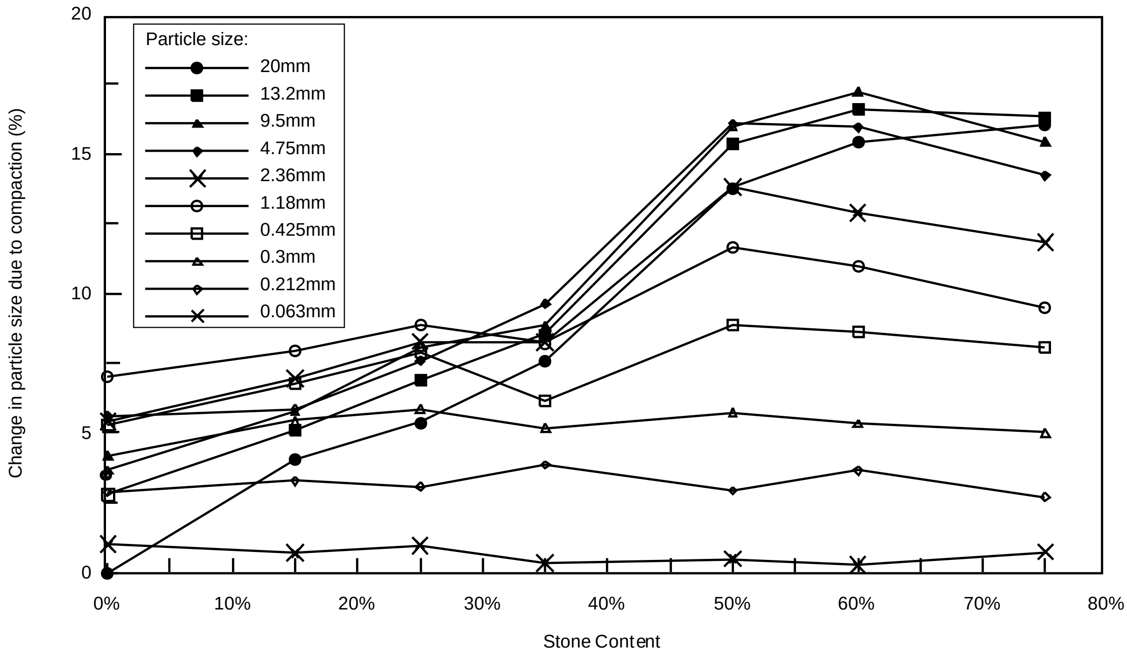

Figure 2 The influence of heavy compaction on percentage passing (Soil 2)

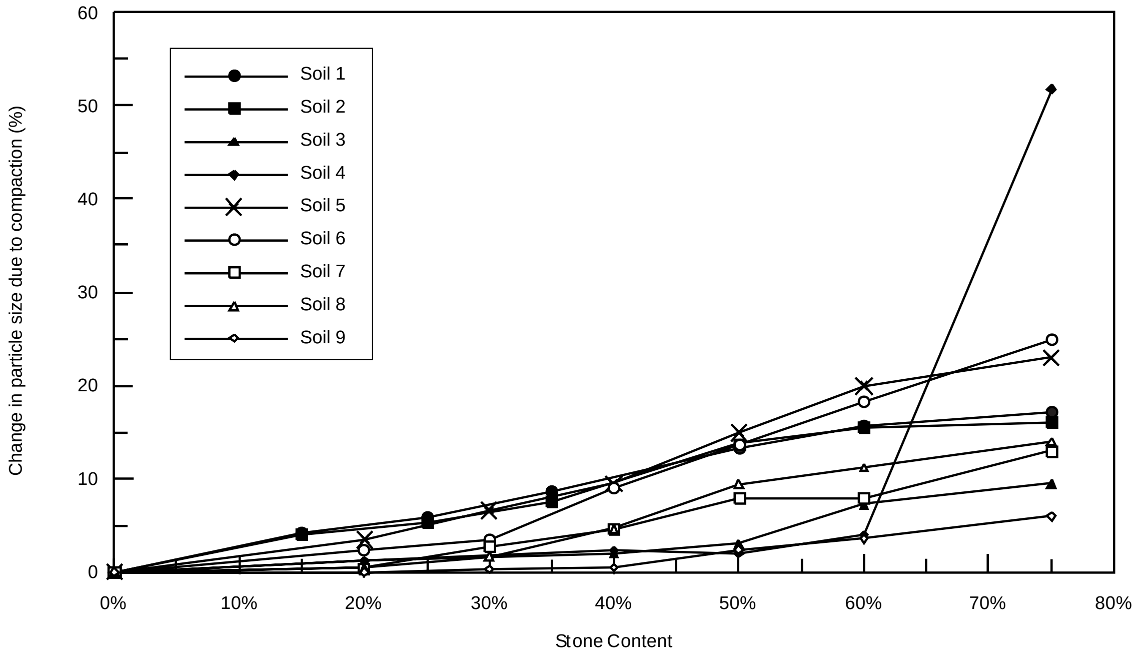

Figure 3 The influence of compaction on percentage passing a 20mm sieve for Soils 1 to 9

Suhardi, 1993). The data for Soils 1 and 2 are from heavy rammer compaction tests and those for Soils 3 to 9 from standard 2.5kg rammer compaction tests, all conducted to British Standards Institution (1990). With the exception of Soil 4[1] the maximum change in percentage passing 20mm is less than 25%, in each case at a stone content of 75%. It is clear that as the stone content increases and the compacted sample becomes coarser then the degree of crushing increases. This reinforces the conclusion drawn by Watt (1991): that for a given loading higher contact stresses are experienced by coarse particles compared to fine particles. It follows that particle size has a greater effect on crushing than energy input. Particle size distributions before and after compaction at stone contents of 0% and 75% are given for Soil 1 (heavy compaction) and Soil 8 (standard compaction) in Figures 4 and 5.

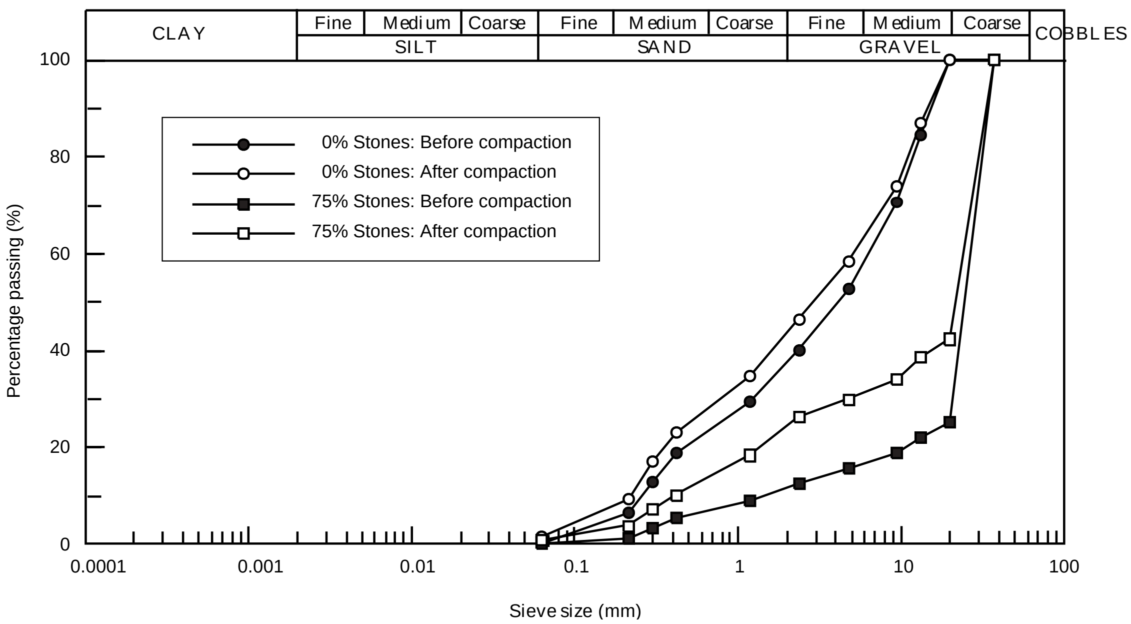

Figure 4 Particle size distributions for Soil 1 with 0% and 75% stones before and after heavy compaction

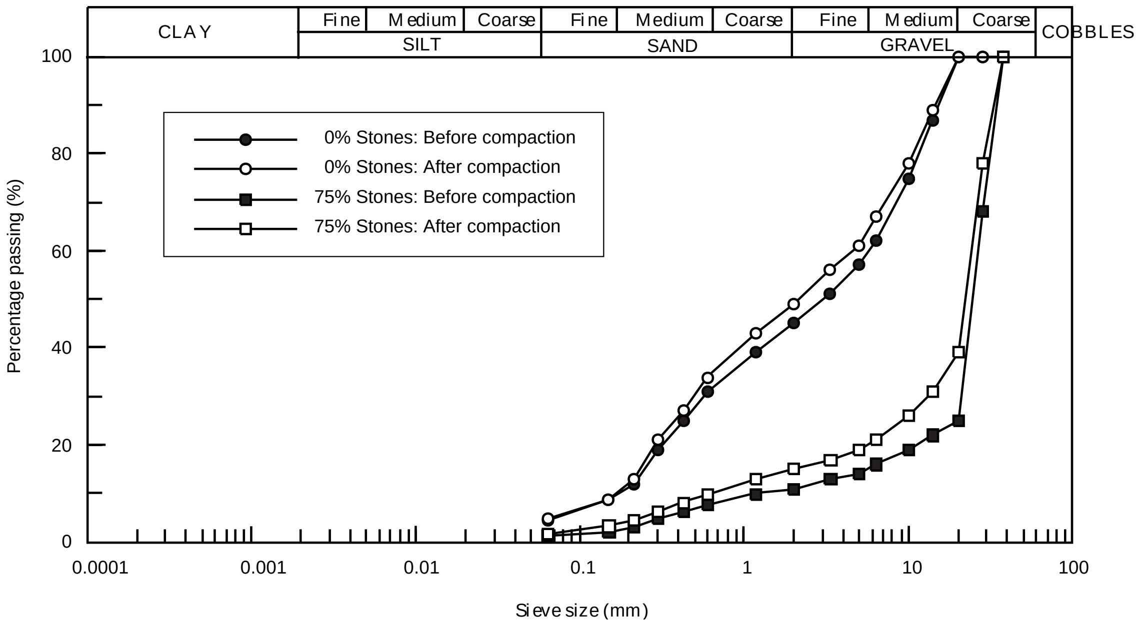

Figure 5 Particle size distributions for Soil 8 with 0% and 75% stones before and after standard compaction

3 Fragmenting materials

3.1 Colliery spoil

Colliery spoil is available in the coal mining areas of Great Britain in large quantities. In Scotland this includes the areas to the north and south of the Forth-Clyde river valleys, parts of Fife and a large part of Ayrshire. In Great Britain as a whole the estimated annual production of colliery spoil was 45 million tonnes during 1988/89 (Whitbread *et al.,* 1991). An estimated 3,000 to 3,600 million tonnes is also available in stock piles arising from past production, some of which has been used in land restoration and is therefore not available for use (Sherwood, 1974; 1994a; 1994b).

The composition of unburnt colliery spoil varies according to its origin (i.e., depending on whether it is sourced from single or multiple coal seams or from roadways through non-coal bearing rock and depending on whether it was processed by a coal washery). The properties of unburnt colliery spoil can therefore vary considerably between and within tips. The most common rock types found in unburnt colliery spoil are mudstones, siltstones, shales, seat earths, sandstone and, in some areas, limestones (West and O'Reilly, 1986).

There is also an additional variation arising from combustion in the tip. When combustion occurs the physical properties and chemical composition are changed such that burnt spoil (burnt shale, burnt minestone or blaes) varies considerably from the unburnt spoil (unburnt shale or unburnt minestone).

The availability of burnt spoil is declining as, following the Aberfan disaster of 1966, great care has to be taken in the construction of spoil tips; spoil materials are compacted to high densities and, consequently, low air voids to increase tip stability. This, combined with improvements in coal segregation, means that the possibility of spontaneous combustion is negligible. Burnt spoil is therefore only available from old tips and is also in higher demand than the unburnt material, because it is suitable for use in road sub-base (Figure 6) and capping layer construction (Sherwood, 1994a).

The typical chemical compositions of burnt and unburnt colliery spoil are given in Table 1. The most common materials occurring in colliery spoil are quartz, mica and clay minerals and lesser quantities of pyrites and carbonates of calcium, magnesium and iron.

Physical and chemical properties of colliery spoils are given in Table 2. In addition, Rainbow (1989) reports pH values for unburnt colliery spoils in the range 4 to 9 and particle densities between 2.0Mg/m^3 and 2.7Mg/m^3.

The water soluble sulphate content of unburnt colliery spoil is generally too low to be a serious problem (Sherwood, 1994b). However, the water soluble sulphate content of burnt colliery spoil may reach high concentrations due to the oxidation of the pyrites during combustion (Sherwood and Ryley, 1970). Sulphates may thus cause problems by migrating from the spoil and reacting with lime, concrete, cement bound and other cementitious materials (Sherwood, 1994b). MCHW 1 (Clause 601.13) sets an upper limit of 1.9gSO_3/L for water soluble sulphate content for fills placed within 500mm of such elements of the permanent works. A limit of 0.25gSO_3/L is set for fills placed within 500mm of metallic items forming part of the permanent works (Clause 601.14).

Sulphides, in the form of iron pyrites, are common in unburnt colliery spoil but less likely to be present in burnt spoil as they are oxidised during combustion. As oxidation reactions produce sulphates it follows that attack on lime, concrete, cement bound or other cementitious materials may occur. However, even in the absence of concrete other expansive reactions can occur where other calcium sources are available. The calculated volume expansion from iron pyrites reaction products, such as jarosite, ferric sulphate and gypsum, is in the range 115% to 170% (Sherwood, 1994b). There is a mandatory requirement for an upper limit on total sulphate content to be set for Classes 6E, 7E, 7F and

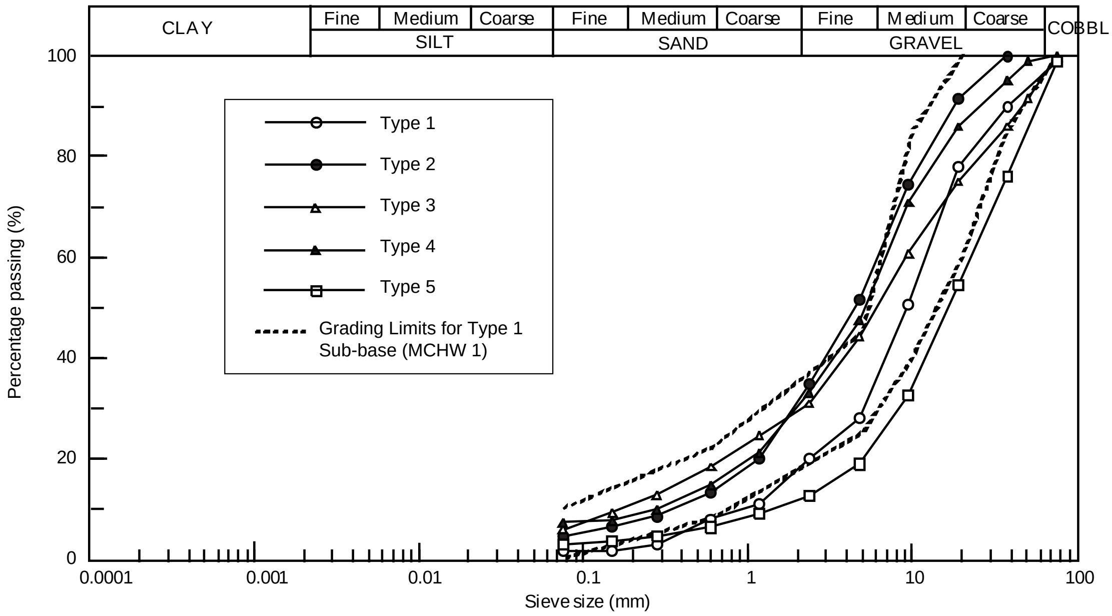

Figure 6 Particle size distributions of samples of burnt colliery spoil (after Fraser and Lake, 1967)

Table 1 Typical chemical compositions of burnt and unburnt colliery spoils

Chemical component	*Composition (%)*		
	Burnt colliery spoil (Sherwood and Ryley, 1970)	*Unburnt colliery spoil (Rainbow, 1989; Sherwood, 1975)*	*Spent oil shale (Burns, 1978)*
SiO_2	45-60	37-55	48.5
Al_2O_3	21-31	17-23	25.2
FE_2O_3	4-13	4-11	12.1
CaO	0.5-6	0.4-4.9	5.3
MgO	1-3	0.9-3.2	2.2
Na_2O	0.2-0.6	0.2-0.8	NR
K_2O	2-3.5	1.6-3.6	NR
SO_3	0.1-5	0.5-2.5	3.2
Loss on ignition	2%-6%	10%-40%	3%

NR = Not recorded.

Table 2 Physical and chemical properties of some colliery spoils (after Sherwood, 1994a; 1994b)

Property	*Burnt spoils*						*Unburnt spoils*				
	A	*B*	*C*	*D*	*E*	*F*	*S*	*T*	*U*	*V*	*W*
Particle size (mm)											
>40	2	0	6	0	3	0	7	5	6	12	15
20-40	22	14	14	20	18	15	33	25	7	18	15
10-20	26	22	23	23	22	25	26	35	10	15	32
5-10	22	21	22	20	19	17	17	16	15	15	18
2-5	11	12	13	12	12	11	6	6	17	10	8
<2	17	31	22	25	32	32	11	13	45	30	12
Particle density (Mg/m^2)	2.65	2.69	2.71	2.72	2.76	2.90	2.60	2.51	NA	NA	NA
pH of shale-water solution	6.5	6.8	5.4	4.2	4.5	8.5	NA	NA	NA	NA	NA
Soluble sulphate (gSO_3/L)	0.6	1.4	1.6	7.0	6.9	1.5	NA	NA	NA	NA	NA

NA = Data not available.

7G. For Classes 6E and 7G this is set at 1% in Table 6/1 of the MCHW 1 while for Classes 7E and 7F advice is given on setting an appropriate limit in HA74 (Paragraph 7.11, DMRB 4.1.6). In general, this limit is expected to be between 0.25% and 1.0% total sulphate content.

Fraser and Lake (1967) demonstrated the effects of compaction on the particle size of burnt colliery shale. For a well-graded material between 19.05mm and 63mm they found that the effects of standard 2.5kg rammer compaction included a 20% decrease in the percentage passing a 10mm sieve (Figure 7). Figures 1 to 3 show that, in general, increases of up to 25% in the percentage passing a 20mm sieve can be experienced for tills with high stone contents, for both standard and heavy rammer compactive efforts even though the latter has a compactive effort some 4.5 times that of the standard test (Head, 1984; Winter, 1989). The data in Figure 7 indicate that, at the higher energy level, the decrease in the percentage of a burnt colliery spoil passing a 10mm sieve may be of the order of 40%. Data are not available on the crushing of unburnt colliery spoil during compaction. However, since the burning of colliery shale generally increases both brittleness and strength it can be inferred that the degree of crushing during compaction of an unburnt material may be less than that of a burnt material.

Sherwood (1994b) notes that, when considering compaction requirements on the basis of those given in the Specification (MCHW 1), most unburnt spoils are classified as well graded granular and dry cohesive soils. However, while being acceptable for use as fill, some may have atypically high fines or moisture contents and could more appropriately be considered as conventional cohesive soils. Certainly, visual inspection of the spoil tip should be carried out to ensure that the type of material delivered to the site does not vary too frequently, otherwise control of compaction may be difficult.

Results from standard 2.5kg rammer compaction tests on burnt colliery shale give values between 1.65Mg/m^3 and 1.76Mg/m^3 for maximum dry density and 15% to 19% for optimum moisture content (Fraser and Lake, 1967; Sherwood, 1975).

Rainbow (1987a) reports results for unburnt colliery spoil which give a range between 1.63Mg/m^3 and 2.16Mg/m^3 for maximum dry density and between 8.1% and 16.5% for optimum moisture content. However, it should be noted that Rainbow's results relate to the vibrating hammer test (British Standards Institution, 1990) in which the energy input is approximately 19 times greater than in the standard 2.5kg rammer test (Head, 1984; Winter, 1989). The choice of test method depends on the compactive effort that can be expected to be achieved in the field. For example, the standard rammer test is recommended for Classes 6D, 6H, 6I and 6J while the vibrating hammer method is recommended for Classes 6N and 6P (HA44 - DMRB 4.1.1).

Most unburnt colliery spoils are not frost susceptible when tested (British Standards Institution, 1989). In contrast, burnt spoils are usually highly frost susceptible. Consequently, such fills should not be placed in an untreated state within 450mm of the road surface, the depth to which it is considered likely that frost will penetrate in Great Britain. The addition of up to 5% cement may reduce the voids content of the material sufficiently to mitigate frost induced heave (Sherwood, 1975). However, it should be noted that such a treatment will only be suitable for relatively low sulphate materials (HA74 - DMRB 4.1.6) when ordinary portland cements are used. However, the use of sulphate resisting portland cements may prove effective with higher sulphate materials.

The possibility of spontaneous combustion is frequently cited as a reason for the exclusion of unburnt colliery spoil as a general fill material. A survey by Fraser (1974) found that 3.9 million cubic metres of unburnt colliery spoil had been placed on 12 contracts without evidence of

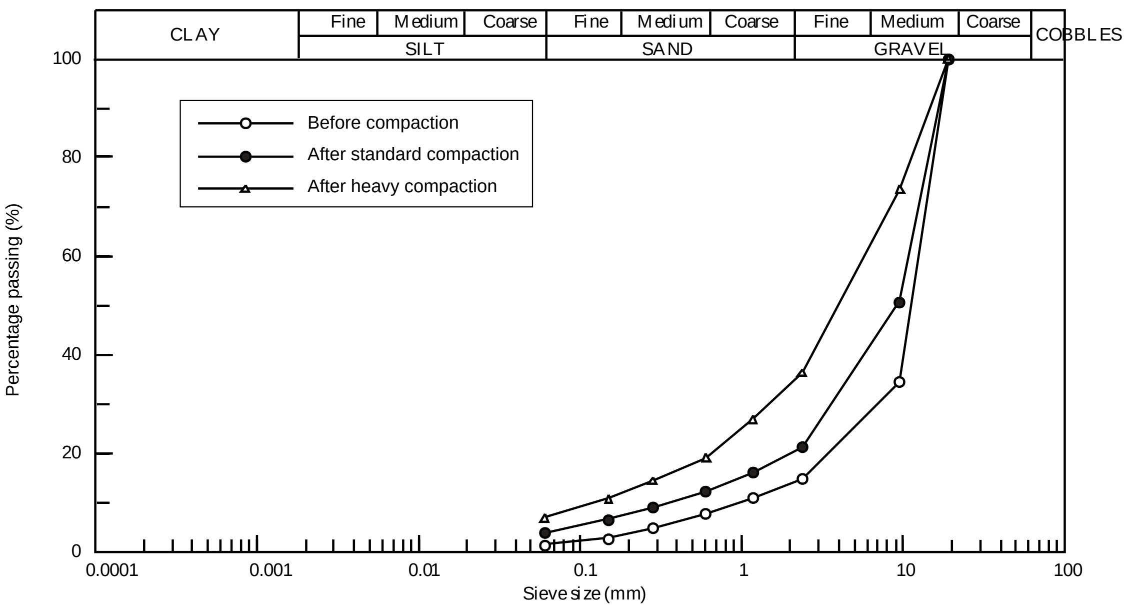

Figure 7 Typical effect of compaction on the grading of burnt colliery spoil (after Fraser and Lake, 1967)

spontaneous combustion. Indeed, both Rainbow (1987b) and Sherwood (1994b) note that although unburnt coal is present in unburnt colliery spoil, spontaneous combustion is highly unlikely. In order for spontaneous combustion to occur air needs to be present in the compacted material in sufficient quantity to allow oxidation of the pyrite. However, the Specification (MCHW 1) requires fill materials to be compacted to low air voids. Experience over nearly 25 years has shown that this is sufficient to mitigate the possibility of spontaneous combustion (Sherwood, 1994b). This fact is recognised in the Specification which does permit unburnt colliery spoil to be used as general fill.

3.2 Spent oil shale

The oil shale industry in the West Lothian area was founded on the invention, by James Young, of a process for obtaining oil from bituminous coal by low temperature distillation, refining the oil by further distillation and chemical treatment (British Patent No. 13292). The industry began in 1851 and reached its peak in 1913 when 3,300,000 tonnes of oil shale was extracted, producing an estimated 73 million gallons of crude oil and naptha. The industry declined rapidly after the First World War and in 1938 less than half the quantity of oil shale was mined compared to the peak. Despite a brief recovery, brought about by the needs of the Second World War, the last Scottish oil shale was mined at Bathgate in May 1962. Kerr (1994) provides an excellent reference on this subject.

The oil shale exists in a layer approximately 900m thick and forms part of the Carboniferous sandstone series lying below the coal and limestone beds which were worked in the Lothians and Lanarkshire but above the volcanics which form, for example, Arthur's Seat in Edinburgh. Although the shale measures are widespread throughout Scotland it was mainly in West Lothian, parts of Midlothian and Lanarkshire and a very small part of Fife that accessible shales were found with recoverable amounts of oil.

The unprocessed shale consisted of tough, fine-grained, thinly laminated material and was generally brown or black in colour. The shales had a rubber-like consistency and miners identified them by their ability to be paired with a knife and to leave a brown streak when rubbed.

The processed (or spent) oil shale, together with materials considered unsuitable for processing, was deposited in spoil heaps, or bings, on land adjacent to the mines and refineries. The locations of the bings are illustrated in Figure 8 and the Five Sisters bing, near West Calder, is pictured in Figure 9. It was estimated that between 100 and 150 million tonnes of such material was stored in 30 bings in 1962 (Burns, 1978). More recent estimates indicate that around 100 million tonnes of spent oil shale occupy an area of 395 hectares of land around Livingston and Bathgate, about 20km to the west of Edinburgh (Whitbread *et al*, 1991; Sherwood, 1994b).

Studies of the spent oil shale (Lake *et al.*, 1966; Burns, 1978) indicate that these materials can vary in colour from pink, red and yellow to dark blue.

The typical chemical composition of spent oil shale is given in Table 1. The range of total sulphate contents for spent oil shale has been reported as between 2.2%(SO_3) and 2.8%(SO_3), with one value of 0.7% (Burns, 1978)[2], and is similar to the range for burnt colliery spoil (Sherwood, 1994b). Consequently, sulphates may cause problems by migrating from the shale and reacting with lime, concrete, cement bound or other cementitious materials (MCHW 1). Because the shale was heated to extract the oil, spontaneous combustion is clearly not a problem. Neither is the presence of sulphides as these will have been driven off or converted to sulphates during the extraction process (Sherwood, 1994b).

Considerable variations are commonly found in the physical properties of spent oil shales, particularly the grading. However, Burns (1978) noted that the particle size distributions for such materials were generally within the grading limits for Type 2 (Figure 10) granular sub-base materials (Specification for Road and Bridge Works, 1976) and were very close to the requirements for Type 1 granular sub-base materials.

The results of standard 2.5kg rammer compaction tests were reported by Burns (1978). These indicated maximum dry densities in the range 1.30Mg/m^3 to 1.44Mg/m^3 and optimum moisture contents in the range 22% to 34%. The relatively high optimum moisture contents and correspondingly low maximum dry densities were probably due to the porous nature of the material. This is indicated by the high values of water absorption (10% to 21%) and the low particle densities for the size range 2.4mm to 37.5mm (2.06Mg/m^3 to 2.42Mg/m^3). Particle densities for particles smaller than 2.4mm were between 2.58Mg/m^3 and 2.76Mg/m^3.

It was observed that these materials were subject to crushing as a result of the compaction process (Figure 11). Burns (1978) noted that in the Specification for Road and Bridge Works (1976) sub-base materials, with the exception of well burnt non-plastic shales, were required to have a minimum 10% Fines Value of 50kN. This exception specifically acknowledged that crushing can occur with this material with no apparent structural disbenefit to the completed sub-base. Under the current Specification (MCHW 1) well burnt non-plastic shales are specifically included in the allowable materials but the exception to the minimum 10% Fines Value of 50kN has been removed. Sherwood (1995a; 1995b) notes that although many burnt colliery spoils (and, by implication, spent oil shales) would be suitable for such a use it is unlikely that many would achieve a 10% Fines Value of 50kN. Further, it is quite possible that a more stable material may result as voids are filled with the smaller particles created by crushing. In addition, the 10% Fines Value has been described as too severe a test to describe a well-graded aggregates ability to withstand compaction stresses (Dawson, 1989).

Most spent oil shales are frost susceptible and therefore should not be placed within 450mm of the road surface. However, the addition of cement reduces the frost susceptibility. Burns (1978) observed that the addition of 5% cement reduced the voids content and, thus, the frost induced heave to acceptable levels for the materials tested. However, he did note that larger proportions of cement may be required for materials from other spent oil shale sources

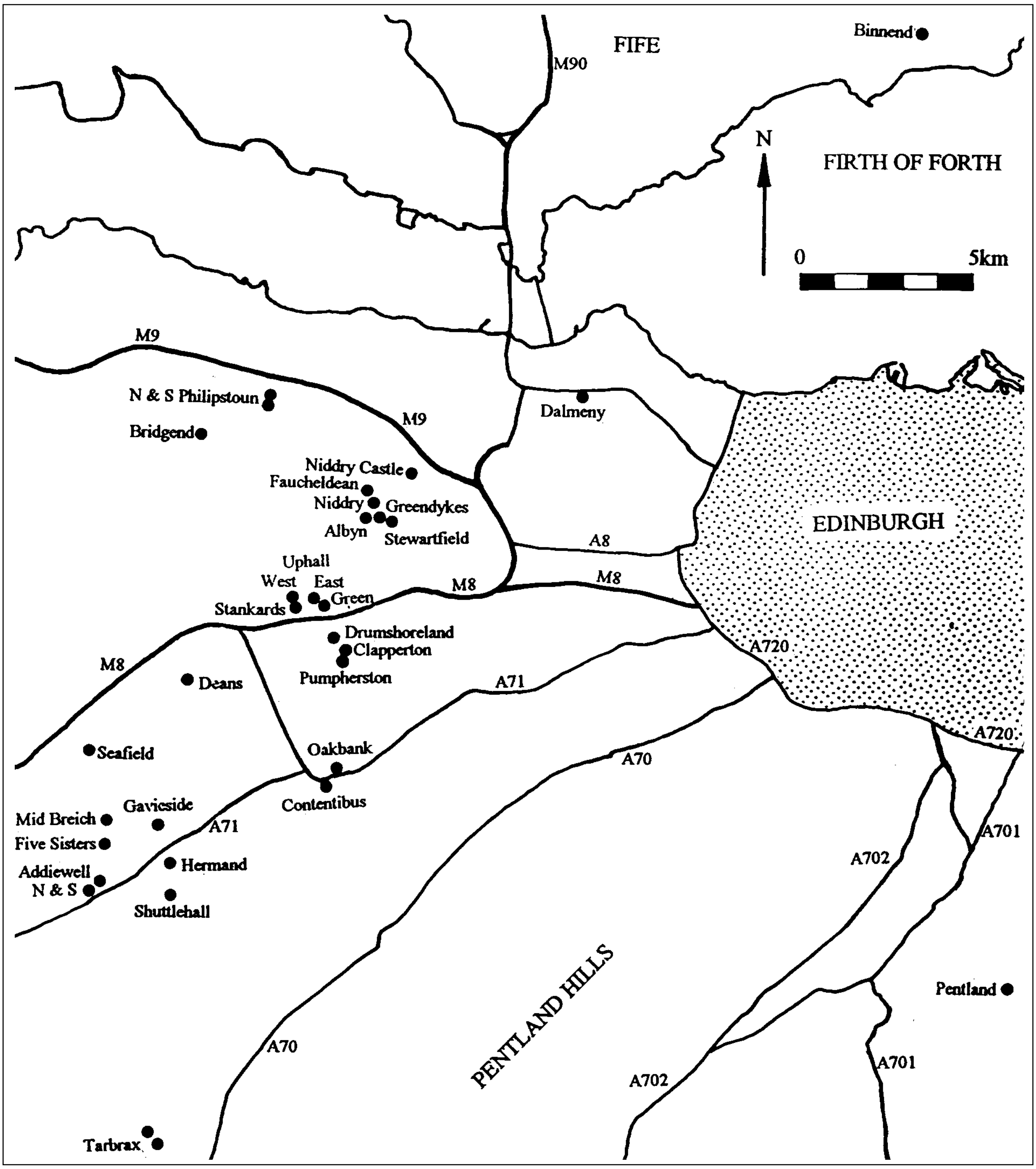

Figure 8 Location map of spent oil shale bings (after Kerr, 1994)

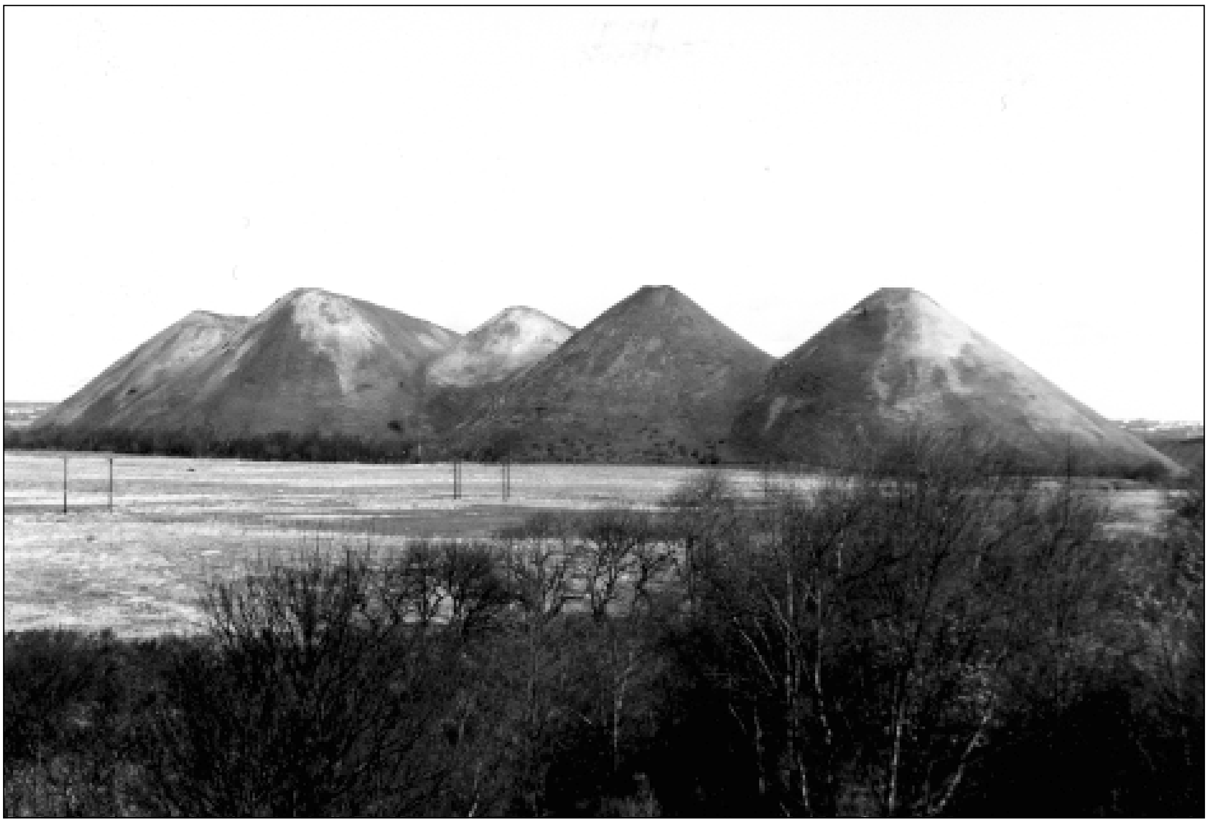

Figure 9 Five Sisters spent oil shale bing, near West Calder, West Lothian

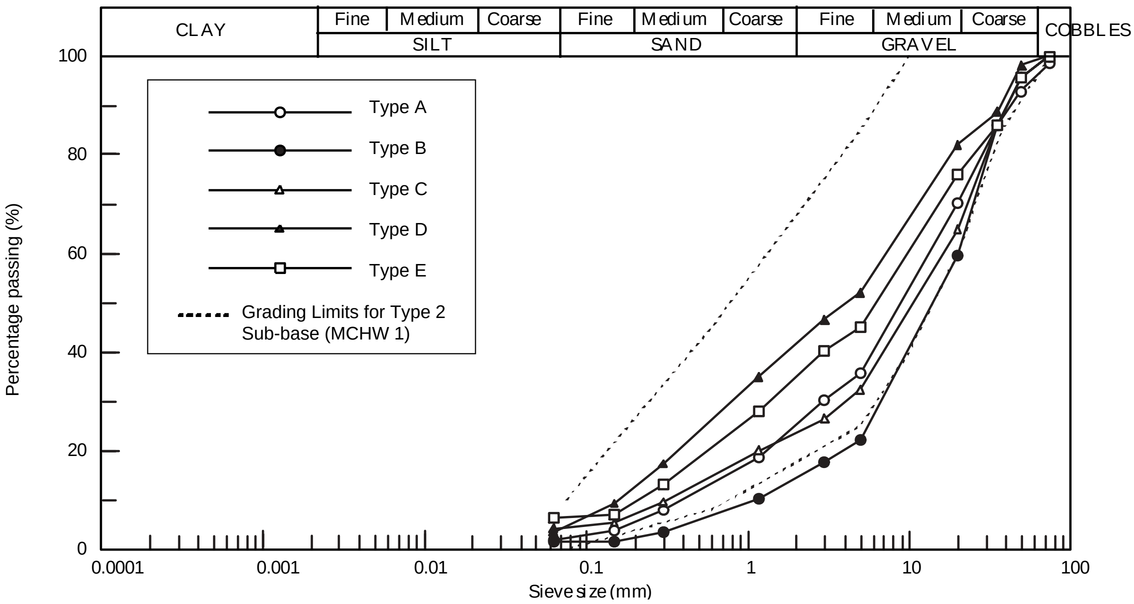

Figure 10 Particle size distributions of samples of spent oil shale (after Burns, 1978)

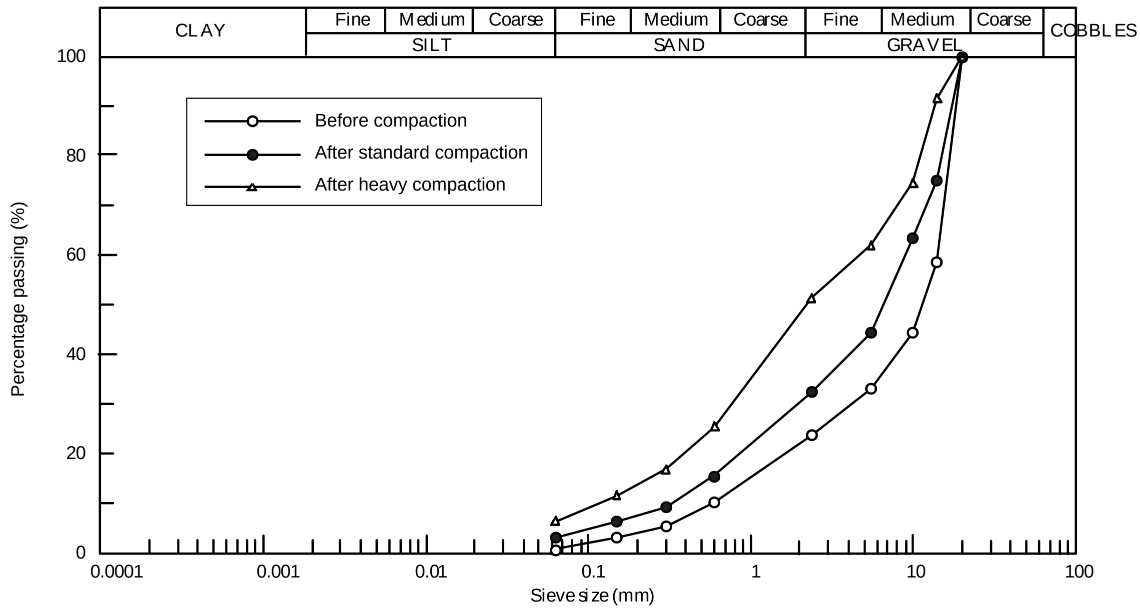

Figure 11 Typical effect of compaction on the grading of spent oil shale (after Burns, 1978)

to reduce heave to acceptable levels. It should be noted that such a treatment will be suitable only for relatively low sulphate materials (HA74 - DMRB 4.1.6) when ordinary portland cements are used. However, the use of sulphate resisting portland cements may prove effective with higher sulphate materials.

3.3 Weak sandstone

Old Red Sandstone sediments are found in many areas of Scotland, as illustrated in Figure 12, and denote the terrestrial (i.e., fluvial, aeolian and lacustrine) sediments which are roughly equivalent in age to the Devonian marine deposits in south-west England and continental Europe (Mykura, 1991; Harris, 1991).

Weak sandstone is found close to the surface in Angus, in the area around Brechin. From the available information (Mykura, 1991; Anon, 1897) it appears that this material is part of the Edzell Sandstone. The material varies from unweathered sandstone to completely weathered sandstone (sand). Problems with determining the acceptability of such materials were highlighted in 1991 after the ground investigation for the upgrading of the A94 Brechin Bypass to dual carriageway. In particular, concerns were raised as to the effect of crushing during compaction.

The ground investigation report for the Brechin Bypass (Anon, 1989) includes only basic data. The sandstone encountered during the ground investigation varied from completely to slightly weathered, generally in a medium dense to dense state in-situ.

The optimum moisture content was found to be in the range 8.8% to 14.8% and the maximum dry density in the range 1.80Mg/m^3 to 2.08Mg/m^3. However, these data should be treated with some caution as the same sample was used for successive moisture contents in the determination of the compaction curve. This procedure allows progressive crushing to take place and may mean that different gradings prevail at each moisture content.

The CBR of the weak sandstone was found to be between 8% and 16%, with one apparently anomalous determination of 1.5%.

The unconfined compressive strength of the moderately to slightly weathered sandstone was found to be in the range 31MPa to 53MPa, and the intact bulk density in the range 2.36Mg/m^3 to 2.45Mg/m^3.

The frost susceptibility of the weak sandstone is unknown. However, in its residual state it is generally a well-graded material and is therefore unlikely to be frost susceptible, provided that crushing during compaction does not increase the fines content to much more than 10% (HA44 - DMRB 4.1.1).

The pH of the sandstone varied between 6.1 and 8.0 and the total sulphate content varied between 0.06gSO_3/L to 0.91gSO_3/L. Consequently, sulphates are unlikely to cause problems by migrating from the soil and reacting with lime, concrete, cement bound or other cementitious materials (MCHW 1).

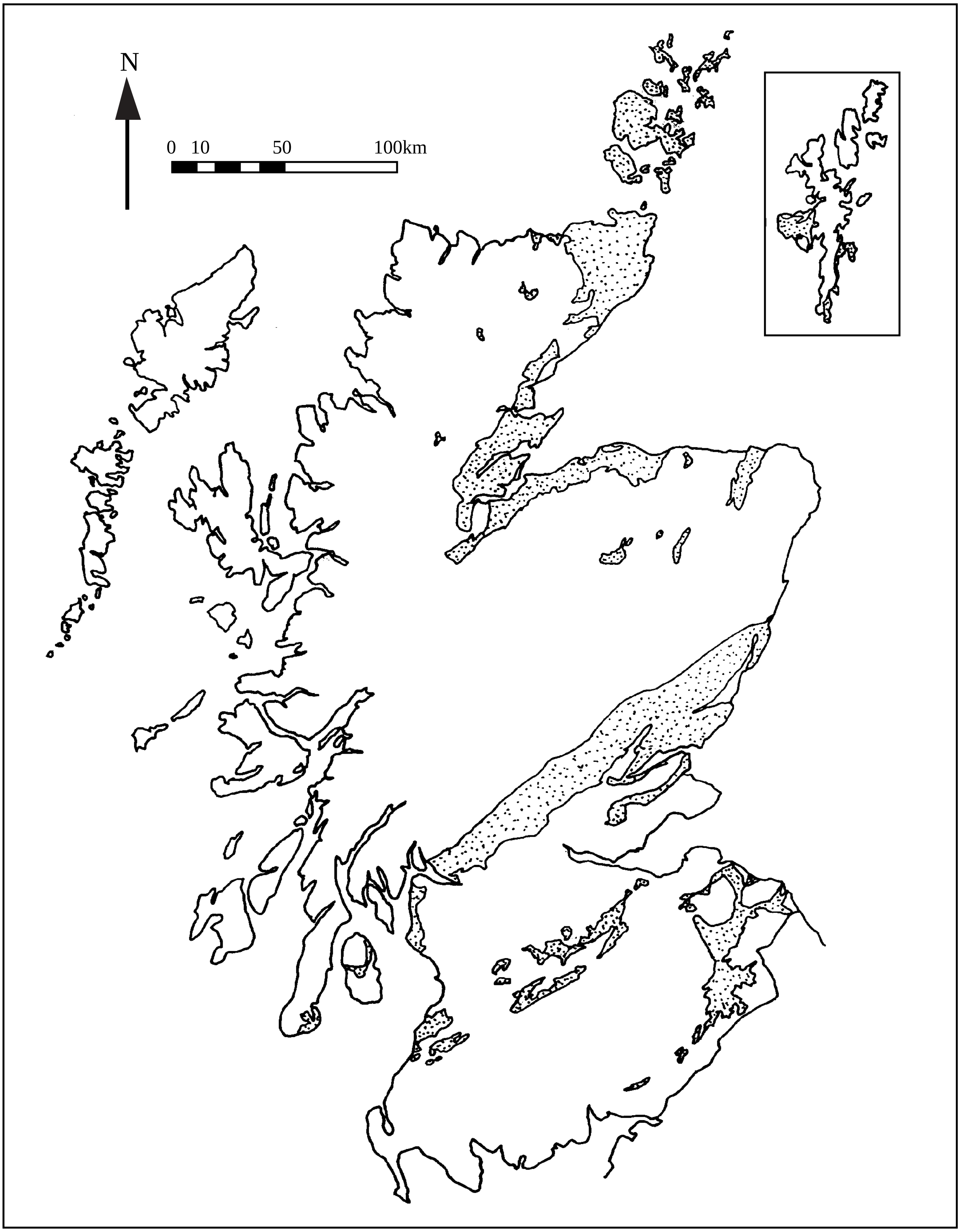

Figure 12 Simplified geological map showing the distribution of Old Red Sandstone in Scotland. (Based on Geological Map of the British Islands 1:1 584000 [25 miles to one inch]. Reproduced by permission of the Director of the British Geological Survey, © NERC. All rights reserved.)

4 Potential use

4.1 Unburnt colliery spoil

There is no technical reason to exclude unburnt colliery spoil from use as general fill. Accordingly, it is included in the current Specification (MCHW 1: Clause 601.15), provided that it meets the appropriate grading requirements and is compacted according to the methods described in Clause 612.

Crushing, while a possibility during compaction of unburnt colliery spoil, should not be seen as a factor weighing against its use. Indeed, it could be argued that crushing may be beneficial to the completed earthworks. Small particles resulting from crushing may fill voids and thus produce higher densities and lower air voids than would otherwise be the case. This will, in turn, tend to produce a more stable compacted mass.

A survey of the use of unburnt colliery spoil as fill on 12 contracts indicated that the materials used formed sound embankments and provided excellent fill material with advantages over most soils particularly during inclement weather (Fraser, 1974). The survey also found that restrictions on the height of embankments had proved unnecessary and recommended that the use of an inert cladding layer, in addition to topsoil, be discontinued, due to problems caused by its inclusion.

Sherwood (1994b) noted that at the peak of the English motorway building programme in the 1970s around eight million tonnes per year were being used as bulk fill. The main problem is the variability within a deposit. Spoil tips may contain unburnt spoil, partially burnt spoil, burnt spoil and mine tailings: all occurring close together. In order to ensure that compaction control is not a problem, visual inspection at the tip is required to ensure that the material delivered to site does not vary too frequently and that mine tailings are excluded.

Most unburnt colliery spoils would be classified as well graded granular (Class 1A) or dry cohesive (Class 2B) materials, by the requirements of the Specification (MCHW 1). However, while being acceptable for use as fill, some may have atypically high fines or moisture contents and could be more appropriately described as conventional cohesive materials (Classes 2A or 2D). HA44 (DMRB 4.1.1) recognises that some unburnt colliery shales can make very good “all weather” general fills although others can be prone to softening and swelling if exposed to water and weathering when stockpiled. It is thus important to ensure that compaction is sufficient to minimise the air voids of the earthworks and that the requirements of MCHW 1 (Clause 602.15) are followed to ensure that water ingress does not cause a long-term durability problem.

The assessment of acceptability for earthworks compaction should be by conventional means:

- granular materials, by control of the moisture content within set limits of the optimum moisture content;
- cohesive materials, by control of the Moisture Condition Value (MCV) within set limits.

A guide to which soils can and cannot be tested using the MCV is given by Oliphant and Winter (1997) and detailed procedures for MCV testing are given by Matheson and Winter (1997). It is important that all design tests should be carried out on the material in the crushed, post-compaction state, not on the excavated material.

Normally the presence of sulphates within the unburnt colliery spoil will not be a problem. However, the presence of sulphides and the probability of their oxidation to sulphates with sulphuric acid formation indicates that caution with such materials is advisable. If the fill is to be placed within 500mm of metallic items, lime, concrete, cement bound or other cementitious materials then the limits given in the Specification (MCHW 1: Clauses 601.13 and 601.14) apply.

Most unburnt spoils are not frost susceptible. However, if the fill is to be placed within 450mm of the finished road surface then the frost susceptibility should be checked.

West and O’Reilly (1986) conducted an evaluation of the potential use of unburnt colliery spoil as fill for reinforced earth structures. They concluded that, given the serious consequences of the failure of such a structure and the potential variability of unburnt colliery spoil, amongst other factors, this material should not be used as a fill for reinforced earth structures.

Unburnt colliery spoil is excluded from use as selected fill, including granular capping (Classes 6F1 and 6F2). This is to avoid reactions between SO_4 contained within the spoil and overlying limestone sub-bases. The product of such reactions is gypsum which generates heave within the pavement foundation and structure (HA44 - DMRB 4.1.1). In addition, the long-term stability of aggregated particles contained within the spoil may be questioned for critical applications (Sherwood, 1994b). It is only for selected granular fills, which require a high quality aggregate, that this factor is likely to cause a problem. While in most cases unburnt colliery spoil is excluded by name, for Class 7A it is excluded only in that it is likely to include argillaceous rock.

Unburnt colliery spoil is excluded from use as a stabilised material for capping (Class 6E), but allowed for cement bound sub-base category 1 (Clause 1036). Sherwood (1994b) notes that this is likely to be due to the way in which the specification is written. The requirements for cement bound sub-base specify the material and the stabilised end-product required but do not define the material to be used. Clause 614, which deals with cement stabilised capping materials, defines the materials to be used but does not give details of the stabilised material required. In terms of compaction, if the specification for cement stabilised capping layers were written as a performance specification, rather than the present method specification, it is possible that unburnt colliery spoil would be more efficiently used. However, so much more control and testing would be required, especially for detecting chemically aggressive agents, that the effect on the cost of using such materials could make their use uneconomical. The oxidation of sulphides to sulphates and the presence of existing sulphates is likely to be a problem in the vicinity of metallic items, lime, concrete, cement bound or other cementitious materials.

Although failures have occurred with cement stabilised unburnt colliery spoil, there is much evidence to show that it can be used successfully (Kettle and Williams, 1978; Tanfield, 1978). The testing regime specified for cement bound sub-base (Clause 1036) includes a durability requirement which should detect any problems that are likely to occur with cement stabilised materials (Thomas *et al.*, 1987; Carr and Withers, 1987; Sherwood, 1994b). Essentially, the compressive strength may not be reduced to less than 80% by soaking in water for seven days. Signs of swelling or cracking, indicate significant quantities of sulphate reaction products in the soaked specimens. This testing has been adapted for lime stabilised capping (HA74 - DMRB 4.1.6). However, such an increase in control and testing will inevitably have an economic effect on the potential for use of such materials. Therefore, in general earthworks, where control of materials is based on fewer tests than on pavement layers and foundations, the use of end-product specifications of this type may lead to either more testing or more failures. A review of cement stabilisation is given by Sherwood (1993).

Because it contains clay minerals which can react with lime it is probable that unburnt colliery spoil could be stabilised with lime. However, as little work has been carried out in this area and sulphates and sulphides are a problem, the current exclusion of lime stabilised unburnt colliery spoil is well justified (HA74 - DMRB 4.1.6).

4.2 Burnt colliery spoil and spent oil shale

Colliery spoil tips may contain unburnt spoil, partially burnt spoil, burnt spoil and mine tailings all occurring close together. The combustion of colliery spoil produces a granular material that can be used in place of natural aggregates. Although burnt colliery spoil could be used as general fill the optimum use is as a selected granular fill or as an unbound granular sub-base.

In many ways spent oil shale is similar to burnt colliery spoil. Tips may contain both spent oil shale and material excavated from non-oil bearing areas. The heating of oil shale produces a stable granular material that can be used in place of natural aggregates. The optimum use of spent oil shale is as a selected granular fill or as an unbound granular sub-base although it could be used as general fill.

Nevertheless, Burns (1978) estimated that some 20 to 25 million tonnes of spent oil shale had been used in Central Scotland as general fill since the early 1960s, principally on the M8, M9 and M90 motorways. It has also been used in other bulk fill applications such as the Edinburgh Airport runway, where some 200,000 tonnes were placed. More recently some 15,000m^3 were placed as general fill as part of the construction works for an underpass at the M8/M9 Newbridge interchange. Spent oil shale has also been used as general fill on other recent road construction projects in Central Scotland. Stabilising spent oil shale with cement on a pre-mixed basis has proved commercially viable and Burns estimated that some 0.5 to 1.0 million tonnes had been so used, including as sub-base on the M9 motorway.

Visual inspection of both burnt colliery spoil and spent oil shale at the tip is required to ensure that the material delivered to site does not vary too frequently and, in the case of colliery spoil, that mine tailings are excluded.

Both burnt colliery spoil (Figure 7) and spent oil shale (Figure 11) are susceptible to crushing during compaction. However, crushing may yield higher densities and lower air voids than would otherwise be the case, thus tending to produce a more stable compacted mass. Indeed, this points to one barrier to the use of burnt colliery spoil and spent oil shale as selected granular fill. Previous specifications have relaxed the 10% Fines Value required for well burnt non-plastic shale sub-bases (Specification for Road and Bridge Works, 1976; Burns, 1978) but the current Specification (MCHW 1) retains a requirement for a minimum 10% Fines Value of 50kN. Such a requirement is unlikely to be met by many burnt colliery spoils or spent oil shales and Dawson (1989) described the 10% Fines Value as too severe a test of the ability of a well-graded aggregates to withstand compaction stresses.

Figures 6 and 10 show that both burnt colliery spoil and spent oil shale can be obtained to satisfy the grading requirements of granular sub-base materials and can therefore satisfy the more relaxed criteria for selected granular materials. Well burnt colliery spoil is mentioned by name in the Specification (MCHW 1) for many selected granular fill applications. However, Clauses 803 and 804 of the Specification (MCHW 1), which refer to granular sub-base, allow ‘well burnt non-plastic shale’ which embraces both burnt colliery spoil and spent oil shale. The clauses for selected granular fill could usefully be phrased in the same manner rather than specifically requiring burnt colliery spoil (Sherwood, 1994b), effectively excluding spent oil shale. Similarly, where burnt colliery spoil is excluded then it would be prudent to also exclude spent oil shale by the use of the phrase ‘well burnt non-plastic shale’.

The Specification (MCHW 1) allows burnt colliery spoil and spent oil shale to be used as granular capping, provided that the grading and other specification requirements are met. However, as for selected granular fills, the 10% Fines Value requirement (30kN in this case) is unlikely to be met.

While burnt colliery spoil and spent oil shale may be stabilised to form a capping layer there would generally be little reason for doing so as it would be suitable for use in an unbound form (Sherwood, 1994b). The only exception to this would be if the capping layer were within 450mm of the completed road surface as many burnt colliery spoils and spent oil shales are highly frost susceptible and thus cannot be in such a location. The addition of 5% or more cement has been shown to reduce the frost susceptibility to acceptable levels (Fraser and Lake, 1967; Sherwood, 1975; Burns, 1978). Frost susceptibility is related to voids content and the use of cement reduces the voids content while having the added benefit of increasing the inter-particle strength. For this reason, many sub-bases constructed from burnt colliery spoils and spent oil shales have been stabilised with cement. However, such a treatment is not suitable for relatively high sulphate materials (HA74 - DMRB 4.1.6) when ordinary portland cements are used. To ensure that the material is not susceptible to heave as a result of the reactions between sulphates and the cement (see Section 4.1) it would be prudent to use the durability test given in the Specification

(MCHW 1, Clause 1036) for CBM1. However, as the frequency of testing may have to be increased, such a process may become uneconomical. The use of sulphate resisting portland cements may prove effective with higher sulphate materials.

The assessment of acceptability for earthworks compaction should be by conventional means (i.e., by control of the moisture content within set limits of the optimum moisture content). It is important that all design tests should be carried out on the material in the crushed, post-compaction state, not on the excavated material. However, given that burnt colliery spoil and spent oil shale are generally acceptable for use as selected fill it may be uneconomic to use these materials as general fill.

If burnt colliery spoil or spent oil shale are to be placed within 500mm of metallic items, lime, concrete, cement bound or other cementitious materials then the limit in the Specification (MCHW 1, Clauses 601.13 and 601.14) apply. It seems unlikely that they could be used in close proximity to such materials given the high sulphate content of most burnt colliery spoils and spent oil shales. Doubts also remain as to the potential reactions between both burnt colliery spoil and spent oil shale, and polymeric reinforcing materials.

Notwithstanding the above comments on the exclusion of mine tailings, frost susceptibility and the interaction with cementitious products, the durability of burnt colliery spoils and spent oil shales is unlikely to pose a problem. However, it is nonetheless important to ensure that compaction is sufficient to minimise the air voids of the earthworks and that the requirements of MCHW 1 (Clause 602.15) are followed to ensure that water ingress does not cause a long-term durability problem.

4.3 Weak sandstone

The weak sandstone found in Angus crushes during compaction. This is not a problem and may well increase the density and reduce the air voids of the compacted fill, at least in the upper part of each compacted layer of fill. However, being relatively lightly cemented, further degradation after compaction is highly likely. Accordingly, it is necessary to ensure that sufficient energy is applied to the material during compaction to return it to its fully residual state.

This can be achieved in one of two ways. First, a compaction trial can be conducted to determine the amount of energy and compacted layer thickness required to achieve the fully residual state. Second, a laboratory testing programme can be conducted to ascertain the level of compaction, relative to the standard 2.5kg rammer test (British Standards Institution, 1990), required to achieve the fully residual state. Treating the level of compaction in the British Standard test as equivalent to (say) Method 3[3] compaction in the Specification (MCHW 1) the required compactive effort can be increased to achieve the fully residual state, if necessary. In either case, both visual inspection and measurements of the particle size distribution will be required, after site compaction, to confirm that the fully residual state has been achieved. Sand replacement density tests will also be required to ensure that low air voids are achieved. Adjustments to the level of compactive effort applied can be made at this stage and a method specification devised to achieve the required fully residual state at an early stage of the contract. This will need to be supported by regular visual inspection of the compacted material during the earthworking operations.

The use of compaction adequate to reduce such materials to their constitutive particles combined with the correct treatment of the earthworks with regard to water ingress (MCHW 1: Clause 602.15) should ensure that the long-term durability of such materials does not pose a problem.

Such materials tend to be highly moisture sensitive and thus require careful control of moisture content. The Carrstone is a brown ferruginous lightly cemented sandstone (Anon, 1978) and work in East Anglia has indicated that moisture contents at between optimum -2% and optimum +1% will provide a material suitable for compaction.

In addition, where sandstone is found with a variable degree of weathering it may be necessary to formulate different categories. That is, highly weathered materials may crush to the residual state with Method 3 compaction, while moderately and lightly weathered materials may require additional energy to be applied. This also raises the need for careful site control to ensure that materials with a consistent degree of weathering are placed and that the appropriate level of compaction is applied.

It is important that all design tests should be carried out on the material in the crushed, post-compaction state, not on the excavated material.

The Carrstone has been proven as both general fill and as capping layer on at least three contracts in East Anglia. Although an end-product specification (95% of maximum dry density from BS standard 2.5kg rammer test) was originally proposed on one contract this proved unworkable as the density testing interfered with the contractor's earthworks programme. Subsequently Method 5 (MCHW 1) compaction was adopted. (The lower level of compaction has been shown to be appropriate to Carrstone as some degree of re-cementation after compaction has been observed, making the residual state less crucial.) The grading of the excavated material was restricted to 100% passing 500mm and between 0% and 10% passing 63µm. In addition, a soaked California Bearing Ratio (CBR) value at field dry density of minimum 15% was required for materials to be used as capping. All other requirements, including the minimum 10% Fines Value for capping materials, were waived.

Although this section deals explicitly with weak sandstone a similar approach could be taken with other weathered materials prone to breakdown during compaction. It remains important that an appropriate level of compactive effort is applied. Such materials might include weathered granites, dolerites and basalts. In particular, the approach of breaking down schists to their constituent silt-sized particles has been adopted during earthworks compaction in the Loch Lomond area. Other materials which are formed from the cementation of already aggregated particles may require a slightly different approach as they may first breakdown to the residual state before the aggregated particles themselves suffer further breakdown. In this case it is important to assess the potential for breakdown of the aggregated particles both during and after compaction and ascertain whether it is either possible or desirable to specify compactive effort to break such particles.

5 Discussion

Four materials have been discussed in this report. Of these, three can be defined as industrial by-products. These are as follows:

- unburnt colliery spoil;
- burnt colliery spoil;
- spent oil shale.

The fourth, weak sandstone, is a naturally occurring material. Maximising its use in construction works can only be of benefit in both economic and environmental terms, provided that sound engineering principles are applied. Appropriate techniques for the determination of the acceptability of all four materials for earthworks compaction are summarised in Table 3.

The potential use of the waste materials has important differences from that of the naturally occurring material.

The transport of waste materials to site incurs a cost for haulage. If a waste material is not available within an economic haulage distance of the site then it may be rejected on economic grounds. It is generally accepted that the maximum economic haulage distance for the import of waste materials will depend on a number of factors, including the following:

- the location and nature of the site;
- the location and nature of the waste material source;
- the method of transport;
- the relative costs of the waste material and its alternative.

However, if the waste material is located within economic haulage of the site then its use should be considered and the factors to be taken into account are summarised in Figure 13.

The advantages of using waste materials are:

- removal of waste tips;
- avoidance of borrow pits and consequent savings in the finite sources of natural aggregates;
- avoidance of liability for landfill tax.

It should, however, be noted that it is seldom possible to remove all of a tip due to the mix of materials contained therein. Indeed, planning permission is generally required to remove material from an old tip due to the possibility of aggravating the existing dereliction of an area. In some cases, landscaping a tip to sympathetically blend into the local area may be a more environmentally beneficial solution than seeking engineering uses for the materials contained therein (Sherwood, 1994b).

The disadvantages of using waste materials are:

- increased haulage costs;
- disturbance caused by haulage;
- greater variability of waste materials.

Increased haulage costs are almost certain to be a factor in the substitution of waste materials for site-won bulk fill. For selected materials, haulage costs may increase if waste materials are used. This will however depend upon the relative locations of the waste materials and borrow-pits or quarries from which the selected fills would otherwise be sourced.

If haulage costs are increased by the use of waste fills then the disturbance caused by haulage will also increase and environmental disbenefits will accrue if public roads are used. These disbenefits will include congestion, noise, pollution, dust and deposition of the material along the haulage route. Such disbenefits are, with the exception of congestion, difficult to price and are frequently ignored by engineers.

The problems of the greater variability of waste materials and their solutions have already been dealt with in Section 4.

Clearly a blend between economic and environmental benefits must be achieved if waste materials are to be successfully used in road construction. Without an economic benefit contractors will not be encouraged to use waste materials. If some economic benefit exists then it is important that environmental benefits can be demonstrated by their use. Such benefits might include savings in the use of finite natural aggregate resources. Designers should identify sources of waste materials and allow contractors to select on an economic basis, within the prevailing environmental legislation (HA44 - DMRB 4.1.1).

Local supplies of burnt colliery spoil are likely to be more limited than those of unburnt colliery spoil and spent oil shale. Weak sandstone is likely to be used only where it forms part of a cut and fill operation or where available from a suitably located borrow pit.

Table 3 Determination of the acceptability of selected fragmenting materials for earthworks compaction.

Fragmenting material	*Cohesive*	*Granular*
Unburnt colliery spoil	Control of MCV within set limits (see MCHW 1, Table 6/1 and Matheson and Winter, 1997)	Control of moisture content within set limits relative to optimum (see MCHW 1, Table 6/1)
Burnt colliery spoil	N/A	Control of moisture content within set limits relative to optimum (see MCHW 1, Table 6/1)
Spent oil shale	N/A	Control of moisture content within set limits relative to optimum (see MCHW 1, Table 6/1)
Weak sandstone	N/A	Control of moisture content within set limits relative to optimum (see MCHW 1, Table 6/1)

N/A = Not Applicable.

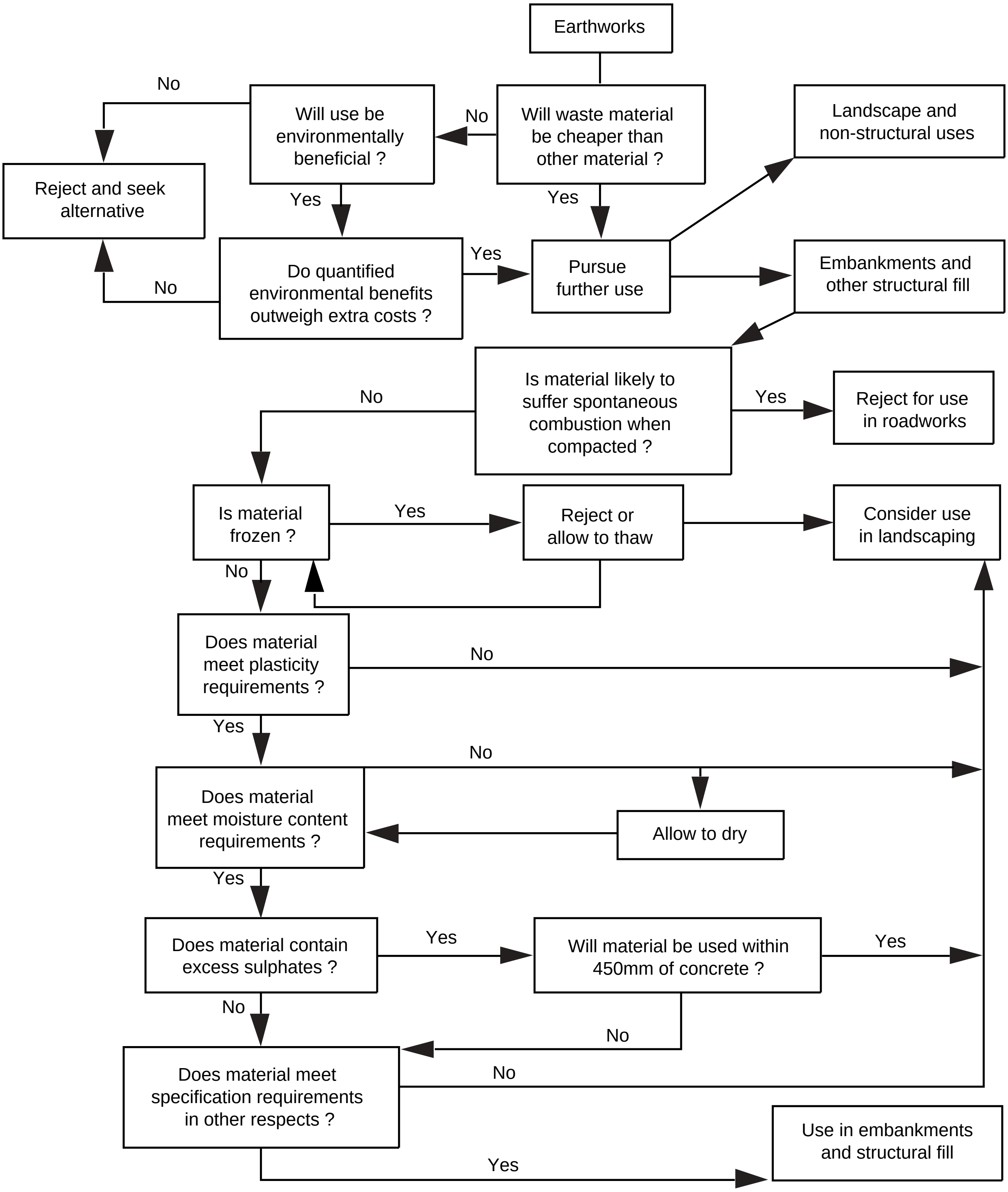

Figure 13 Determining the potential use of waste materials in earthworks construction (after British Standards Institution, 1985; Sherwood. 1994b).

6 Summary

The crushing of particles during compaction is often viewed as a problem. However, crushing may confer benefits to the compacted mass. Small particles resulting from crushing may fill voids and thus produce higher densities and lower air voids than would otherwise be the case. This will, in turn, tend to produce a more stable compacted mass.

The minimum 10% Fines Value requirement of 50kN for granular sub-base materials is severe. In previous specifications this requirement was waived for burnt non-plastic shales, such as burnt colliery spoil and spent oil shale. Although limited crushing during compaction will tend to produce a more stable compacted mass many such materials will be deemed unsuitable on the basis of the 10% fines value. The minimum 10% Fines Value of 30kN required for some classes of capping layer also seems severe.

Unburnt colliery spoil is widely used as general fill but is excluded from use in more critical selected fill applications due to its chemistry and the long-term potential for mechanical breakdown of aggregated particles within the fill. Its durability and chemistry also limit its use as cement bound sub-base category 1 (CBM1). In terms of compaction, if the specification for cement stabilised capping layers were written as a performance specification, rather than the present method specification, it is possible that unburnt colliery spoil would be more efficiently used. However, so much more control and testing would be required, especially for detecting chemically aggressive agents, that the use of such materials may become uneconomical. The oxidation of sulphides to sulphates and the presence of existing sulphates is likely to be a considerable problem in the vicinity of lime, concrete, cement bound or other cementitious materials. Unburnt colliery spoil is not generally frost susceptible.

Burnt colliery spoil and spent oil shale can be used successfully as general fill. However, due to their high quality as aggregates and the short supply of burnt colliery spoil they are more suited to use as selected granular fill. In particular, given their frost susceptibility, stabilisation as sub-base seems a particularly appropriate outlet for these materials. However, as for unburnt colliery spoil it would be prudent to use the chemical durability test given in the Specification (MCHW 1, Clause 1036) for CBM1 to ensure that the material is not susceptible to heave as a result of the reactions between sulphates and the cement.

Burnt colliery spoil and spent oil shale can be obtained to satisfy the grading requirements of granular sub-base materials and can therefore satisfy the more relaxed criteria for selected granular materials. The relevant clauses of the Specification for granular sub-base refers to ‘well burnt non-plastic shale’ which embraces both burnt colliery spoil and spent oil shale. The clauses for selected granular fill refer specifically to well burnt colliery spoil whether including or excluding such materials from use. In either case spent oil shale is not covered, effectively disallowing its use where it could be used and allowing its use where it should not be used.

Burnt colliery spoil and spent oil shale generally have high sulphate contents. Consequently, these materials are unlikely to be suitable for use close to concrete structures or metallic items. Unburnt colliery spoil has low sulphates but high sulphides. Concerns regarding the possible oxidation of sulphides to sulphates mean that they too are unlikely to be suitable for placement in close proximity to concrete structures. The sulphate content of the weak sandstone at Brechin is sufficiently low that it can be placed close to concrete structures.

Weak sandstone can be used as both general fill and capping layer material. However, it is important that the compaction process reduces the material to its fully residual state. All of the materials considered must be compacted to low air voids and the resulting earthworks treated as described in the Specification in order to limit the potential for water ingress, thus maximising their durability and producing stable earthworks. Such materials are unlikely to be frost susceptible unless crushing during compaction generates fines in excess of 10%.

Notwithstanding the requirement to reduce the weak sandstone to its fully residual state, it is considered that acceptability can be determined using conventional BS compaction test and MCA procedures, for granular and cohesive materials respectively.

Maximising the use of site-won materials such as weak sandstone in construction works can be only of benefit in both economic and environmental terms, provided that sound engineering principles are applied. However, a blend between economic and environmental benefits must be achieved if waste materials are to be successfully used in road construction. Without an economic benefit contractors will not be encouraged to use waste materials. Designers should identify sources of waste materials and allow contractors to select on an economic basis, within the prevailing environmental legislation. If some economic benefit exists then it is important that environmental benefits can be demonstrated by their use. Such benefits might include savings in the use of finite natural aggregate resources.

Local supplies of burnt colliery spoil are likely to be more limited than those of unburnt colliery spoil and spent oil shale. Weak sandstone is likely to be used only where it forms part of a cut and fill operation or where available from a suitably located borrow pit.

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Notes

[1] Soil 4 experiences a sharp rise in change in percentage passing 20mm from 4% at 60% stone content to 52% change at 75% stone content and is considered anomalous.

[2] There appears to be an ambiguity in the standard (Anon, 1975) used to determine the values of sulphate content. After some study and debate it appears most likely that the values quoted by Burns (1978) should be reported in units of $g(SO_3)/L$

[3] Method 3 requires a high level of compaction (e.g., 10 passes of a vibratory roller of 2300kg to 2900kg per metre width to compact a 250mm layer) and is generally used for uniformly graded granular materials, whether as general fill or selected granular materials, drainage layer materials and silty cohesive materials.

Abstract

This report considers the use of materials susceptible to crushing during compaction. Such materials include unburnt and burnt colliery spoil, spent oil shale and weak sandstone. It gives recommendations for their use as general fill and, where appropriate, as more specialised selected fills. The potential for the use of such materials is balanced against both economic and environmental factors.

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