

5 COLLIERY SPOIL HEAP CHARACTERISTICS

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5 COLLIERY SPOIL HEAP CHARACTERISTICS

5.1 Introduction

5.1.1 Deep mining

The deep mining of coal generates large quantities of spoil materials. The volume of such spoil is dependent on site-specific factors of which the most important are:

- the amount of mine development work required;
- the geology of the area;
- the coal:spoil ratio;
- the mining methods employed.

Since the industrial revolution, which initiated the use of coal as the major energy source throughout the industrialised countries, spoil has been deposited in tips, heaps and in tailing ponds, and has been used to fill voids.

Dereliction resulting from deep coal mining has increased in significance as mining technology has become more mechanised. In the past shafts were relatively shallow and manual sorting of non-combustible material and 'small coal' was carried out below ground and the material with no saleable value was back stowed.

Waste was tipped from tramway tubs and railway wagons producing gently graded spoil heaps which consumed large areas of land as they fanned out from the original dumping ground.

Mechanisation of coal mining, involving the use of mining machines to extract the coal, led to more rapid and less labour intensive mining but resulted in an increase in the proportion of waste brought to the surface.

Modern coal cutting resulted in spoil being extracted along with the coal and transported to the surface by conveyor for separation. The increased scale of roadway construction also led to larger quantities of spoil being produced. The ratio of coal to spoil production has often been as low as 1:1, although for many pits the ratio is higher. The introduction of computer controlled coal cutting operations has resulted in the ratios being improved.

The introduction of mechanised tipping by overhead ropeways and buckets and conveyors led to greater volumes of spoil being deposited per unit surface area by allowing spoil heaps to rise above 50m in height. The mechanically produced conical or ridge tips became common features of coalfield landscapes (see Photograph 5.1). The lack of compaction of the spoil in the tipping process left large air-filled voids which in combination with their high coal content made them prone to spontaneous combustion and instability (see Chapter 7).



Photograph 5.1: Colliery spoil heaps at Loos en Gohelle, Nord-Pas de Calais, France (source: EPF)

Modern tips throughout Europe are often created by tipping from rubber tyred dump trucks which result in spoil heaps of a plateau-like structure, frequently no more than 15m in height. Tipping in this manner enables the waste material to be easily compacted by the dump trucks as they run over the spoil heap. This compaction and the shape of the waste heap makes future reclamation somewhat easier and increases tip stability.

At some mines the coal is washed to improve its quality. The washery process can involve the use of chemical flocculants and produces a fine-grained waste that in the past was deposited in lagoons as a slurry but in more modern operations may be mixed with run-of-mine waste after being dewatered in a filter press (see Section 8.3.4).

5.1.2 Open pit mining

In open pit mining extraction of coal follows the removal and storage of overburden. This overburden is generally stored so as to retain the different types of soil material removed from the profile and thereby facilitate restoration once the extraction of coal has been completed. Restoration is generally carried out as part of the mining operation and where this occurs open pit mining does not produce colliery spoil heaps. However early extraction by opencast methods was often not accompanied by restoration and overburden and spoil materials from between coal seams may have been deposited in many small heaps or only roughly levelled. As a result some dereliction has resulted from opencast mining. This takes the form of undulating land comprised of a mixture of spoil and overburden. The characteristics of the materials are similar to those of deep-mined spoils although chemical and physical characteristics will not be as extreme where the proportion of subsoil mixed with spoil is high.

5.2 Impact of spoil heaps

The physical and environmental impact of spoil heaps is dependent on their location, size, age and the nature of the tipped materials.

Significant impacts include:

- visual (see Figure 13.1);
- air pollution from combustion and dust (see Section 7.3);
- water pollution arising from weathering and erosion of spoil (see Section 12.2).

Colliery spoil heaps may also be considered local landmarks and therefore worthy of retention rather than being reshaped. Large scale reclamation of derelict sites can endanger the preservation of industrial monuments, and past reclamation projects intended for amenity provision have, in some cases, incorporated sites of industrial archaeological value (see Sections 4.7 and 17.8.2). Similarly some spoil heaps are of ecological value and may be preserved for this reason.

5.3 Spoil characteristics

5.3.1 Heterogeneity of spoil material

Colliery spoil consists of material from the sedimentary strata adjacent to the coal seams, waste produced from the sinking of shafts and other works, dirt and fragments of coal. If washery waste has been deposited the residues of the chemicals used in the washing process may also be found. Materials from demolished buildings, railway sidings and other wastes will also be mixed with spoil materials (see Photograph 5.2).

Spontaneous combustion of spoil can occur, particularly in loose tipped, highly aerated heaps with a high coal content. Combustion in a tip can lead to the fusion of large blocks of spoil, collapse of the surface of tips,

production of noxious gases and a fused red 'shale' (see Table 5.1 and Section 7.3). The combination of these factors, the mining of more than one seam at one site and hence deposition of spoil with different characteristics, the use of more than one tipping method at a site and importation of spoil from other mines result in considerable heterogeneity of physical and chemical characteristics of most colliery spoil heaps.

5.3.2 Chemical characteristics of spoil

Mineralogically colliery spoil is made up of components of two important and distinct origins:¹⁸⁷

- the detrital minerals; those which were incorporated into the sediments of the coal basin as a result of weathering and erosion of the surrounding area such as quartz, feldspar, illite, kaolinite, montmorillonite and muscovite. These minerals, already weathered, will weather further only slowly;
- the diagenetic minerals; those which were formed during sedimentation and later geological events in the rocks themselves. The two commonest types are carbonates, such as ankerite and siderite and the carbonates of calcium, magnesium, iron and manganese, and sulphides, of which the most frequently occurring and important is iron pyrites.

The diagenetic minerals weather rapidly on exposure. An indication of the relative proportions of the various minerals in colliery spoil is given in Table 5.2. The data in Table 5.2 indicate that colliery spoil is variable and that spoil from different sites can have very different compositions.

Freshly exposed colliery spoil often has a pH of 7 or more and may have a high electrical conductivity level. The high conductivity levels are often associated with high concentrations of sodium, calcium and magnesium and indicate elevated concentrations of dissolved salts. The most common salts of these elements are carbonates, sulphates and chlorides of which the carbonates are the most easily leached.

Table 5.1: The sequence of spontaneous combustion in colliery spoil heaps (after Goodman and Chadwick, 1978¹⁰⁴)

Temperature, °C	Effect
20	Over 90% of the oxygen content absorbed. Where gases escape they contain (v/v dry basis): <div style="margin-left: 40px;"> $< 0.005\%$ O_2; $0-10\%$ CH_4; $2-10\%$ CO_2; $2-10\%$ N_2. </div>
100	As burning increases, trace amounts of CO are released.
200	Depending on the oxidation state and flow rate of the gas stream, varying amounts of CH_4 , CO, CO_2 , C_2H_6 , C_4H_8 , H_2S and SO_2 are released.
300	Carbonisation occurs and coals become fluid.
450	All interstitial water is eliminated.
500	Fumes of $(NH_4)SO_4$ and NH_4Cl are produced; NH_3 , tar, SO_2 , CO, SO_2 , H_2S and N_2 released.
600	Micaceous material begins to break down.
800	Clay content is eliminated and brick produced.



Photograph 5.2: Demolition waste deposited in a colliery spoil heap in South Yorkshire, UK (source: Richards, Moorehead and Laing Ltd)

Table 5.2: Proportion and composition of minerals found in colliery spoil

Mineral	Components	Quantity (%)	
		Bouroz (1964) ³⁸	Bradshaw and Chadwick (1980) ⁴⁰
Quartz	SiO ₂	32.5	} 90
Clay minerals	alumino-silicates	5.6	
Ankerite	Fe, Ca, Mg, Mn; CO ₃	-	} 5
Siderite	Fe; CO ₃	2	
Iron pyrite	FeS ₂	-	
Gypsum	CaSO ₄	-	} 1-2
Jarosite	K, Fe; SO ₄	-	
Feldspar	K, Al; SiO ₂	2	-
Chlorite	Mg, Fe, Al; SiO ₂ , OH	2	-
Calcite	Ca; CO ₃	trace	-
Amorphous material	SiO ₂ , Al(OH) ₃ , Fe(OH) ₃	-	1-2

Conductivity levels often drop as these salts are leached out of the surface layers. A strong link between net percolation of water and salinity levels on colliery spoil has been noted.⁷⁵

Despite the short-term nature of high levels of salinity in colliery spoil because of leaching, the consideration of salinity is important during reclamation because movement of spoil will expose unweathered saline materials.

The variation in spoil chemical characteristics that can occur over time and with depth from the surface is illustrated in Table 5.3 and Figure 5.1. Colliery spoil may contain significant concentrations of the trace elements found in coal (see Table 5.4). Surface concentrations of some trace elements may be high because of additional aerial deposition from coal combustion in the vicinity (see Section 10.3).

One of the more important consequences of weathering on colliery spoil is the fall in pH caused by the oxidation of iron pyrites. Shales from iron ore mining in Lorraine are also pyritic (see Section 9.1.2). Pyrite is stable until exposed to air and water, when it is oxidised to produce, amongst other products, sulphuric acid. The reactions involved in pyrite oxidation are summarised in Box 5.1. Above pH 4, iron-oxidising bacteria are relatively inactive and the oxidation of pyrite is slow and regulated by the supply of oxygen, but below pH 4, oxidation is much faster due to the activity of iron-oxidising bacteria,¹⁹⁵ the overall rate being determined by that of Equation 5.5 or 5.7 (Box 5.1). Pyrite oxidation may be by chemical oxidation alone, or by a combination of chemical and bacterial oxidation. The latter is considerably faster than the former: iron-oxidising microorganisms, such as *Thiobacillus ferrooxidans*, can significantly increase the rate of pyrite oxidation by mediating the oxidation of Fe^{2+} (Equation 5.5, Box 5.1). The rate of Fe^{2+} oxidation may be increased by a million-fold and the overall rate of acid generation increased by up to twenty-fold. These bacteria tend to be most active between pH 2 and 4.

Table 5.3: Mean electrical conductivity and associated cation levels in freshly exposed spoil in 1975 and in subsequent years at two sites in the United Kingdom

	Thorne (S Yorkshire)			Abertysswg (Mid-Glamorgan)		
	1975	1978	1982	1975	1978	1980
Conductivity (Ms/cm)	6.7	0.36	0.45	0.56	0.15	0.26
K (mg/kg)	35	15.6	20.0	41	17.3	17.2
Na (mg/kg)	821	19.6	13.4	8.7	13.0	8.5
Mg (mg/kg)	184	12.8	16.0	22.5	3.7	4.7
Ca (mg/kg)	368	31.5	31.9	36.2	5.2	9.0

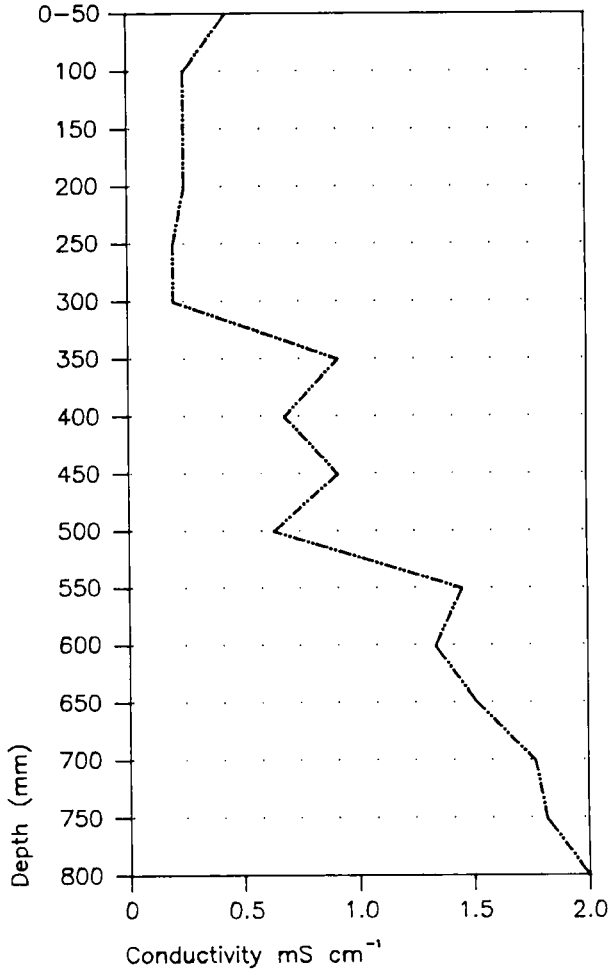


Figure 5.1: Electrical conductivity down the spoil profile six years after spoil exposure at Thorne in South Yorkshire, UK

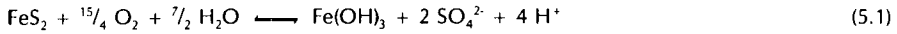
Table 5.4: Some records of the elemental content of coal and coal ash (after Bouska, 1981³⁹)

Element	Coal	Coal Ash	Element	Coal	Coal Ash
Aluminium	0.4-6.8%	6-16%	Molybdenum	3-10	up to 0.6%
Antimony	< 200	0.3%	Nickel	-	0.001-8%
Arsenic	< 1-60*	80-10,000	Niobium	-	10
Barium	90-27,000	0.01-4.7%	Nitrogen	0.2-3%	-
Beryllium	0.8-2.8	< 1-200	Phosphorus	21-240	up to 1594
Bismuth	< 1-10	200	Platinum	-	0.5
Boron	1-300	18-14,000	Potassium	-	up to 3.2%
Bromine	4.1-41.6	-	Radium	< 0.001	< 0.001
Cadmium	-	3-30	Rhenium	0.08-0.3	-
Calcium	very high	1.3%	Rubidium	30-250	-
Caesium		27-11	Scandium	5	24-400
Chlorine	0.43-0.77%	-	Selenium	10-30	-
Chromium	up to 0.1%	0.02-1.3%	Silicon	-	14-19%
Cobalt	92	0-2000	Silver	< 10	< 10
Copper	-	150-4000	Strontium	-	290-2380
Fluorine	0-175	-	Sulphur	0.2-15%	-
Gallium	< 1-500	< 10-4000	Thallium	0.3-2.3	-
Germanium	1-300	< 0.01-7.5%	Tin	20	3-6000
Gold	-	< 1mg/kg	Titanium	up to 2.1%	0.2-14.6%
Indium	-	2mg/kg	Tungsten	up to 0.2%	up to 5%
Iron	up to		Uranium	up to 1%	up to 1%
Lead	up to 3000	up to 3000	Vanadium	< 100-1000	up to 3.5%
Lithium	30-250	27-500	Yttrium	-	< 100-800
Magnesium	-	1.7%	Zinc	10-7800	100-5000
Manganese	-	0.01-2.2%	Zirconium	-	0.5%
Mercury	< 0.1-1.3	-			

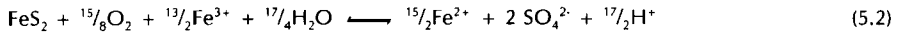
Concentrations are in mg/kg unless otherwise stated.

Box 5.1: Pyrite oxidation^{25, 92, 137, 195, 259}

The overall reaction can be written:

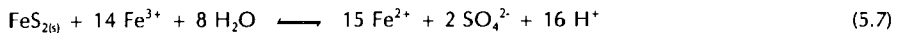
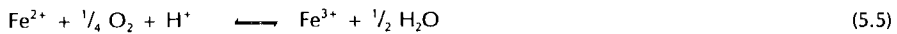
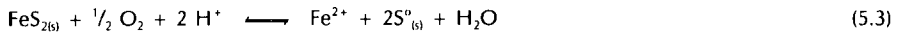


if the pH is greater than 2.3, or



if the pH is less than 2.3.

Intermediate reactions 5.3 to 5.7 have been identified.



Notes:

(s) Solid

- (5.3) Pyrite is oxidised by oxygen. This is a slow reaction, the rate limited by the diffusion of oxygen releasing ferrous ions and elemental sulphur.
- (5.4) Elemental sulphur is oxidised to sulphate ions and acidity, as H^+ .
- (5.5) Under aerobic conditions, ferrous ions are oxidised to ferric ions. This reaction is catalysed by iron-oxidising microorganisms such as *Thiobacillus ferrooxidans*.
- (5.6) Above pH 3.5, ferric ions are not stable in water. Ferric hydroxide is formed which precipitates, and pH is lowered further. Ferric hydroxide is very insoluble, so few Fe^{3+} ions are left in solution.
- (5.7) Any Fe^{3+} ions remaining in solution are free to oxidise pyrite. Further acidity is generated by this reaction. Since ferric ions are stable below pH 3.5 and are not removed by precipitation, this step is significant in the production of very acid spoil or drainage.

Key features of the reactions shown in Box 5.1 are as follows:

- pyrite can be oxidised by two oxidising agents: oxygen and Fe^{3+} . Oxygen gas from outside the deposit is the ultimate oxidising agent;
- oxidation generates acidity;
- the oxidation of Fe^{2+} (Equation 5.5) is the slow step;
- once Fe^{3+} ions have been produced, these rapidly oxidise pyrite further unless removed by precipitation;
- iron-oxidising bacteria, such as *Thiobacillus ferrooxidans*, can significantly increase the rate of pyrite oxidation by catalysing the oxidation of Fe^{2+} (Equation 5.5);
- above pH 4, iron-oxidising bacteria are relatively inactive and the oxidation of pyrite is slow and regulated by the supply of oxygen, but below pH 4, oxidation is much faster due to the activity of iron-oxidising bacteria,¹⁹⁵ the rate being determined by the rate of Equation 5.5 or 5.7 (see Box 5.1).

In an acidic environment, a cycle of acid generation develops in which ferrous ions released from the pyrite are oxidised by *T. ferrooxidans* to ferric ions, which can then oxidise pyrite and generate large quantities of acid. This acid generation can have various effects:

- it may provide a very acidic substrate for plant growth, preventing vegetation from becoming established;
- revegetation of reclaimed spoil heaps may revert as a result of acid generation, killing off any established vegetation;
- acid generation can result in acid mine drainage which in turn can acidify ground and surface waters (see Section 12.2.3) and result in visual pollution by the deposition of metal oxides, most notably iron oxide, on stream beds;
- high sulphate concentrations formed can cause deterioration of concrete (see also Section 10.5.2).

There are several factors that can influence the kinetics of pyrite oxidation by bacteria,²⁰⁷ including:

- pyrite reactivity, which can vary considerably;
- amount of pyrite and its surface area;
- bacterial contact with the pyrite;
- oxygen availability;
- pH;
- temperature;
- the presence of inhibitors.

This oxidation step can continue, if conditions are suitable, until all the pyrite has been oxidised. This can take thousands of years.

The rate of fall in pH of a colliery spoil site is not a simple function of pyrite reactivity. The presence of carbonate minerals such as siderite and ankerite in spoil can neutralise the acidity produced and thereby buffer the pH.^{51, 187} In neutralising the acidity secondary minerals such as gypsum (CaSO_4) and jarosite ($\text{KF}_3(\text{OH})_6(\text{SO}_4)_2$) are produced. A considerable range of pHs, pyrite contents and acid neutralising capacities have been found in colliery spoils (see Figure 5.2).

The pH profile through an extremely pyritic spoil is shown in Figure 5.3. Acidification of spoil also occurs by other means including leaching of bases, secretion of humic acids by plants, nitrogen fixation by legumes and addition of fertilisers. The result is that the pH of all colliery spoils will fall over time except for those where the rocks from which they are derived are calcareous (see Figure 5.4).

The consequence of unneutralised acidity on colliery spoil can be detrimental to plant growth. Cation exchange sites will become dominated by hydrogen ions with the resultant loss of bases previously occupying the sites. At low pH iron, aluminium, manganese, copper and zinc will be solubilised creating toxic conditions. Aluminium and manganese can be very toxic in low concentrations in acid conditions.

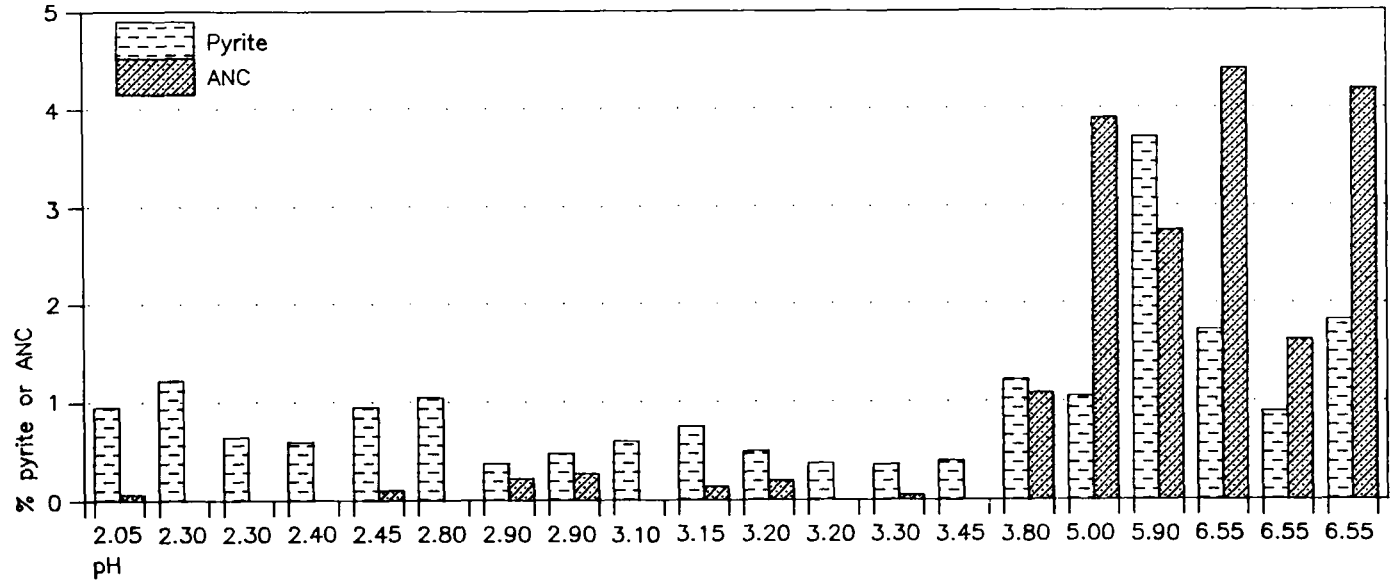


Figure 5.2: Percentage pyrite content and acid neutralising capacity (ANC) ranked against pH for twenty spoils from various parts of England and Wales (after Costigan, Bradshaw and Gemmill, 1981⁵⁸)

Low pHs can also affect the availability of the major nutrients needed for plant growth: nitrogen, phosphate and potassium. Phosphate can be fixed and made unavailable to plants at low pH and potassium may be made unavailable by the formation of jarosite and lost from the clay minerals through the destruction of clay lattices. Even moderately low pHs can cause aluminium and manganese toxicity and inhibition of microbial activity resulting in a build-up of undecomposed organic matter and inhibition of nitrogen mineralisation.

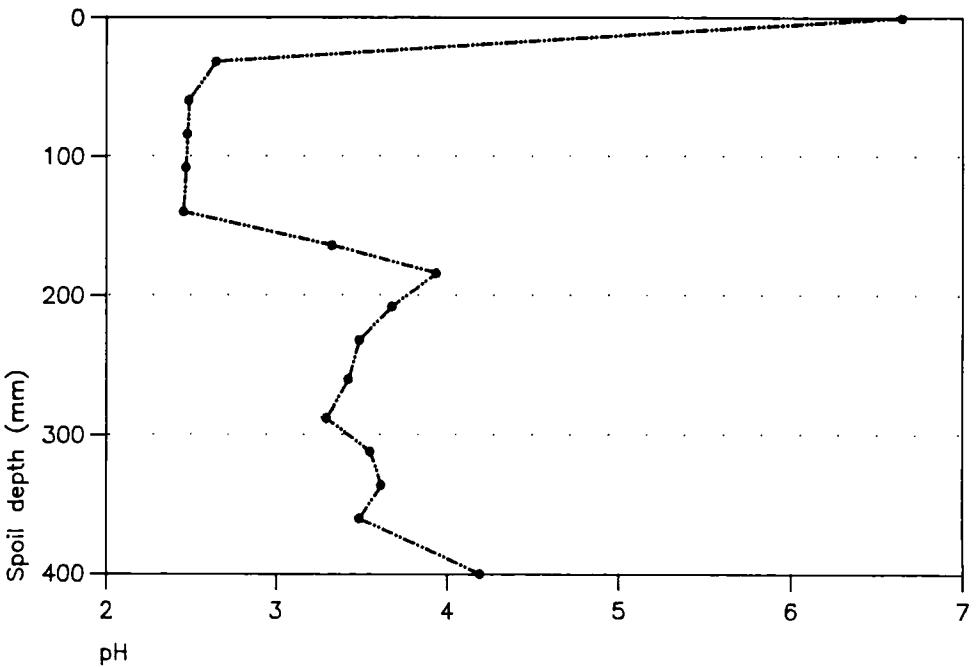


Figure 5.3: pH variation with depth in a highly pyritic spoil. The spoil had been limed at the surface resulting in a high pH and had been cultivated to a depth of about 350mm resulting in greater penetration of air and water and the resultant oxidation of pyrite to produce very low pHs

5.3.3 Physical characteristics of spoil

Freshly exposed colliery spoil can weather rapidly; large boulders may be reduced to silt and clay-sized particles in a short time (Table 5.5). The rate of weathering depends in part on the extent to which sediments were compressed during their formation. Sediments which have been subject to pressure, such as those associated with anthracite deposits, do not weather as readily as some of those associated with bituminous coals.

The proportion of fine-grained particles is important in the water relations of the spoil. A high proportion of fines results in greater moisture holding capacity and better plant establishment. Colliery spoil, because of its particle size distribution and lack of organic matter, is also susceptible to surface waterlogging in the winter and drought in the summer.²⁰⁵

Poor structure in spoils is caused by the paucity of finer grained particles, or where these do occur, to their lack of aggregation which gives a dense, massive structure rather than an open, crumbly structure. Poor aggregation is due mainly to the scarcity of plant roots, microorganisms and organic matter which can bind the fine-grained particles together into crumbs and thus open up the matrix.

Table 5.5: Weathering of spoil materials (after Skarzynska, 1987²¹⁹)

Sample	Fraction %			
	Boulder	Gravel	Sand	Silt and clay
Original	38	58	3	1
After 22 months *	6	61	20	13

* 40kg samples were placed in boxes and compacted to 0.1m and exposed to the atmosphere for 22 months.

The lack of aggregation combined with pressure and compaction results in the spoil particles packing closer together. This close packing reduces the pore space between particles, and the lack of macropores gives the spoil a low infiltration rate, since it prevents excess rainfall draining quickly through the spoil under the influence of gravity. The resulting surface waterlogging can lead to puddling which blocks the smaller pores and aggravates the drainage problems further. Poor drainage can lead to the presence of standing water in depressions on flat areas of spoil during wet periods, and erosion effects brought about by the surface run-off of water on slopes (see Photograph 5.3). Lack of infiltration leads to low spoil moisture availability and drying. Following drying of the surface during summer periods, water stress to plants is increased, and the lack of organic matter, which acts as a moisture conserving material, adds further to the problem. Water stress is intensified by high spoil surface temperatures.



Photograph 5.3: Erosion of washery waste in a poorly designed reclamation scheme (source: Richards, Moorehead and Laing Ltd)

Surface physical properties are worsened by the practice of compacting spoils to reduce voids and to reduce the likelihood of spontaneous combustion, subsidence and landslip.

Table 5.6 shows the influence of compaction of colliery spoil by different types of machinery and Table 5.7 the effect of compaction on infiltration rates.

Reorientation of fine-grained particles during and after rainfall may produce a low porosity and low permeability layer at the colliery spoil surface. Anaerobic conditions may develop under the surface pan and the low porosity of the pan will mean that it is easily saturated by rain, so infiltration will be low and runoff high. Upon drying the surface can form a hard crust up to many millimetres thick. The extent of panning will be dependent on the size distribution of the spoil and the degree of weathering. A smooth surface, whether caused by vehicle trafficking or surface panning, is a great impediment to plant establishment because of difficulty in root penetration and risk of desiccation.

5.3.4 Calorific value

The calorific value of spoil is variable and dependent on:

- the coal content of the spoil;
- the carbon content of the sediments adjacent to the coal seam and forming the bulk of the spoil materials;
- the amount of other combustible materials such as wood, oily materials and general rubbish.

The coal content of older tips is usually higher than modern tips because early methods of coal processing were less efficient than modern ones (see Section 8.1).

The calorific value of the spoil together with other factors such as degree of compaction and pyrite content will determine the likelihood that the

Table 5.6: The influence of modern earth moving machinery on spoil compaction as indicated by penetrometer readings. The higher the reading the greater the compaction (from Ayerst, 1978¹⁵)

Traffic	Penetrometer reading (kg/cm ²)
None - newly tipped	19.9
Levelled by bulldozer	51.0
Levelled, plus bulldozer track (one pass)	98.4
Levelled, plus bulldozer track (four passes)	189.2
Lorry track (laden)	219.1

Table 5.7: Influence of compaction on infiltration rates

	Bulk density (g/cm ³)	Infiltration rates (cm/min), after compaction at: (kg/cm ²)		
		0	0.5	5.0
Unvegetated	1.48	0.31	0.26	0.05
Vegetated	1.50	0.67	0.25	0.05

spoil will combust. This is discussed in detail in Section 7.2. The calorific values of some colliery wastes is presented in Table 7.1.

5.3.5 Surface temperature

Most colliery spoils are black in colour and therefore absorb significant quantities of heat and light generated by solar radiation. Burnt colliery waste is red in colour and as a result reflects some of the incoming solar radiation.

The major site influences on surface temperature are slope, aspect and the nature of the spoil material. The importance of other factors varies with the season. In the northern hemisphere, south-facing slopes are the first to warm in the spring but can produce conditions that become limiting to plant growth in the summer months. The nature of the spoil influences the amount of heat energy absorbed and its later dissipation by conduction and re-radiation. The more mineral matter, or conversely less organic matter and water content, the greater the thermal conductivity. Thus, the spoil conditions most likely to produce temperatures damaging to vegetation are very black spoils on sites with little organic matter and a low moisture regime. Temperatures of $>50^{\circ}\text{C}$ have been found on British spoil heaps in the summer months. In Nord-Pas de Calais surface temperatures of spoil heaps were found to vary dependent on whether there was a vegetation cover, and were much affected by combustion within a tip (see Table 5.8). On well-vegetated grey spoils temperatures are lower than on unvegetated black spoils but temperature between the surface and 100mm below can still differ by as much as 5°C (see Figure 5.5).

Table 5.8: Spoil temperatures ($^{\circ}\text{C}$) at different depths in spoil heaps in Nord-Pas de Calais (after Petit, 1980¹⁹¹).

Depth (mm)	Spoil heap 85, Hénin Beaumont		Spoil heap 119, Ostricourt (Burning)
	Bare spoil	Vegetated	
20	46	28	-
50	32	26	36
100	29	23	49
150	-	-	53

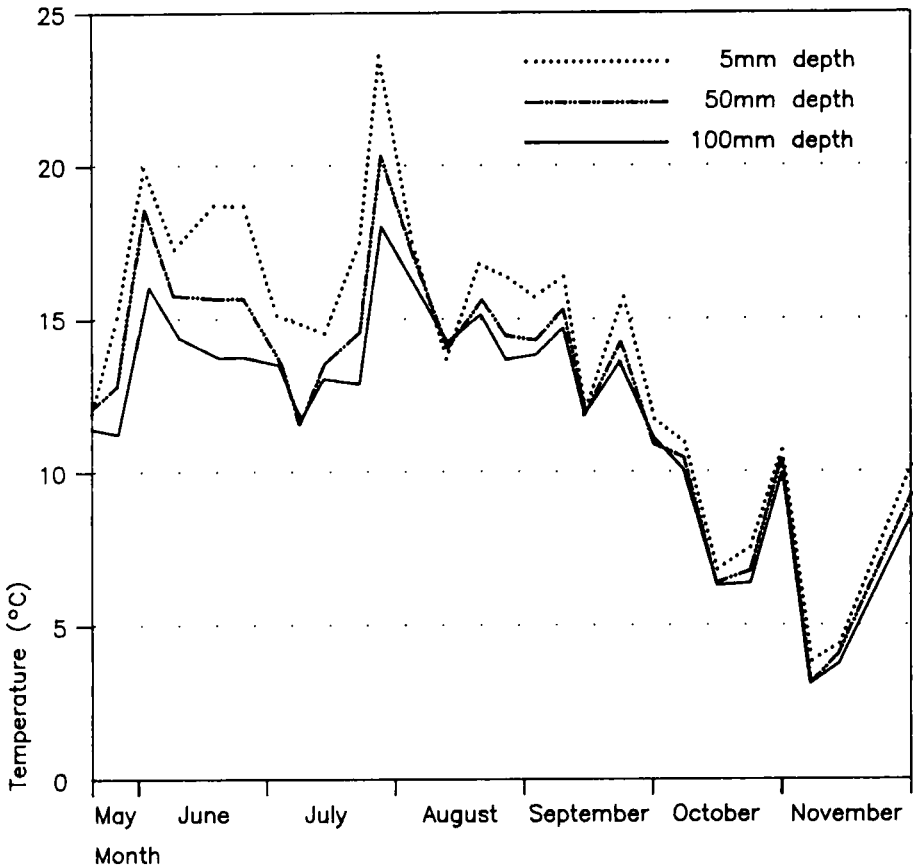


Figure 5.5: Temperature differences in vegetated grey colliery spoil, at different depths during the growing season at a South Yorkshire spoil heap, in the UK.

5.4 Colliery spoil as a substrate for plant growth

5.4.1 Introduction

Compared with other types of derelict land colliery spoil has characteristics which make it one of the least favourable for plant growth (Figure 5.6). The chemical and physical characteristics of colliery spoil have been described in previous sections and their influence on plant growth is summarised in Box 5.2.

Of the characteristics in Box 5.2 the most important are acidity (low pH) and nitrogen status.

5.4.2 Acidity

The greatest levels of acidity found in colliery spoil are caused by pyritic oxidation (see Box 5.1). Usually where pyritic oxidation is ongoing and the natural neutralising capacity of the spoil has been consumed, the pH is so low (<3.5) that no plants will establish or survive and the spoil is devoid of other life except some microorganisms which can withstand the low pH (see Photograph 5.4). At such low pH values very high soluble concentrations of elements such as aluminium and zinc may be found which make the spoil extremely phytotoxic. In some cases pHs of approximately 3.5 may be found in old well-vegetated spoil heaps. Here the toxic elements associated with this acidity will have been leached out of the surface layers over the years and any pyrite present will have been oxidised. It is likely that organic matter will have built up in surface layers. Under these conditions plants tolerant of low pH can establish and survive.

5.4.3 Nitrogen

A major factor limiting plant growth on despoiled land is lack of nitrogen. For vegetation to establish and grow the plants need a source of nitrogen *e.g.* ammonium or nitrate, to form amino acids, protein and other compounds associated with cell growth.

Waste material	Constraint												
	Stability	Combustion	Slope angle	Flooding stress	Toxicity	Compaction	Temperature	Wind erosion	Nutrients	Stoniness	Uneven surface	Erosion	Soil fauna and microbes
Colliery spoil	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Smelter slag	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Slate and shale	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Metal wastes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Quarry pits	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Brick pits	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Peatland	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
China clay	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ironstone	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Chemical waste	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
PFA	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sand and gravel	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Domestic refuse	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure 5.6: Constraints on vegetation development on different wastes (after Kent, 1982¹³⁵)

In fertile soils nitrogen is supplied from the breakdown of organic matter in the soil and supplemented by nitrogen in rainfall. The organic matter in the soil is replenished by the decomposition of plant and animal remains by microbes. This is the basis of nitrogen cycling and a typical nitrogen cycle is shown in Figure 5.7. In nitrogen deficient systems,

Box 5.2: Physical and chemical characteristics of colliery spoil and their impact on plant growth

Characteristics	Implications for plant growth.
pH	<p>< 4 very few species survive</p> <p>4.0-5.5 many grasses and clovers grow successfully</p> <p>> 8 limited species survival.</p>
Electrical conductivity	High conductivity (> 2.5mS/cm) indicates high levels of dissolved salts which will affect seedling establishment and plant growth. High conductivity is usually associated with high and low pHs. High conductivity is often only a problem with freshly exposed spoils.
Nitrogen status	Plant-available nitrogen is very low and restricts colonisation on many spoils.
Phosphate status	Plant-available phosphate is very low. Added phosphate, e.g. in rainfall, rapidly becomes unavailable to plants through sorption by clay minerals. Low phosphate concentrations restrict root growth and nitrogen fixing plants such as legumes.
Potassium status	Potassium supply is adequate for natural colonisation and is replenished from the breakdown of clays. Potassium may be limiting in productive swards.
Trace elements	Colliery spoil has an adequate supply of trace elements for plant growth. Some elements may reach toxic proportions, e.g. aluminium, manganese, zinc and copper, particularly at low pH.
Organic matter	Readily decomposable organic matter is virtually non-existent on freshly exposed colliery spoil even though traditional methods of soil analysis for organic nitrogen, organic carbon and organic matter will indicate that there are substantial quantities of these determinants. This is because these methods are recording 'fossil' organic compounds which do not readily decompose. Low organic matter content results in poor nutrient cycling, poor moisture retention and poor soil structure.
Physical	Compaction, surface panning, poor moisture retention, poor soil structure, high surface temperatures all impede plant establishment and productivity.



Photograph 5.4: Vegetation, which has developed on a thin layer of limed spoil, peeling away from the more acid underlying spoil (source: Richards, Moorehead and Laing Ltd)

cycling is at a low level because inputs of nitrogen are low and is also often impeded because nitrogen is bound up in compounds of high carbon to nitrogen ratio or immobilised in microbial biomass (see Box 5.3). In such situations the carbon to nitrogen ratio in organic matter means that microbial decomposition is limited by nitrogen supply and any available nitrogen arising through mineralisation is quickly taken up and immobilised by microbes. This interruption of cycling is often assisted by factors other than microbial action, such as low pH. Mineralisation and nitrification are the most common areas of interruption of the nitrogen cycle on reclaimed land (see Figure 5.7). Figure 5.8 illustrates how microbial substrate availability in terms of ammonium and fluctuations in pH (as affected by lime additions) influence nitrification, a microbially controlled process. The message is clear: for nitrogen to be supplied to vegetation there has to be a steady supply of ammonium to be nitrified and the pH has to be high enough for that nitrification to take place.

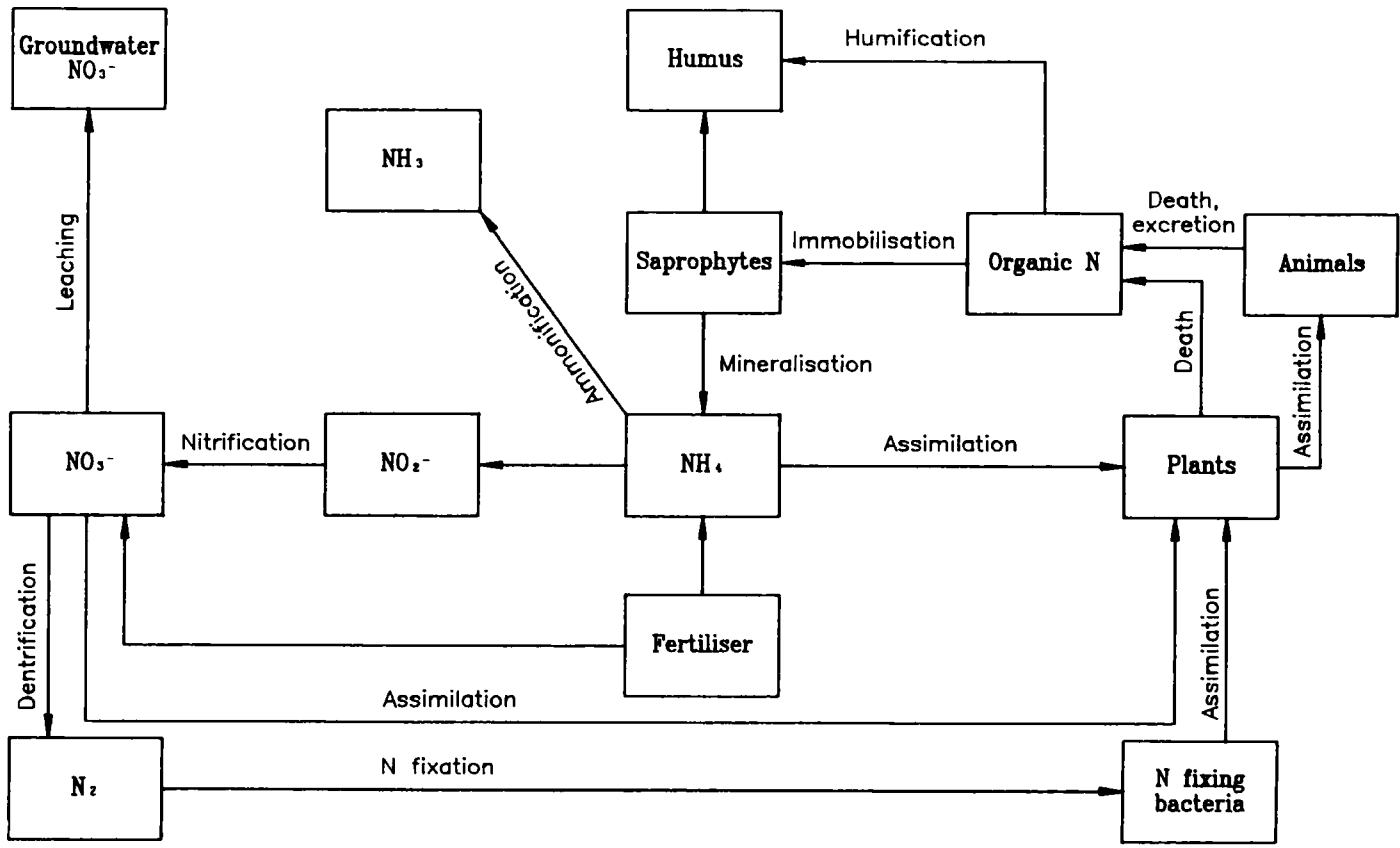


Figure 5.7: A nitrogen cycle applicable to colliery spoil. Decomposition, mineralisation and nitrification are processes likely to be impeded on colliery spoil.

Box 5.3: Nitrogen cycling

In order for nitrogen to be cycled it has to be in compounds where the carbon to nitrogen ratio is low enough for microbes to be able to break them down. The critical carbon to nitrogen ratio is between 25-30:1 and above this level *i.e.* where there is a greater proportion of carbon, microbial breakdown of organic matter may not occur.

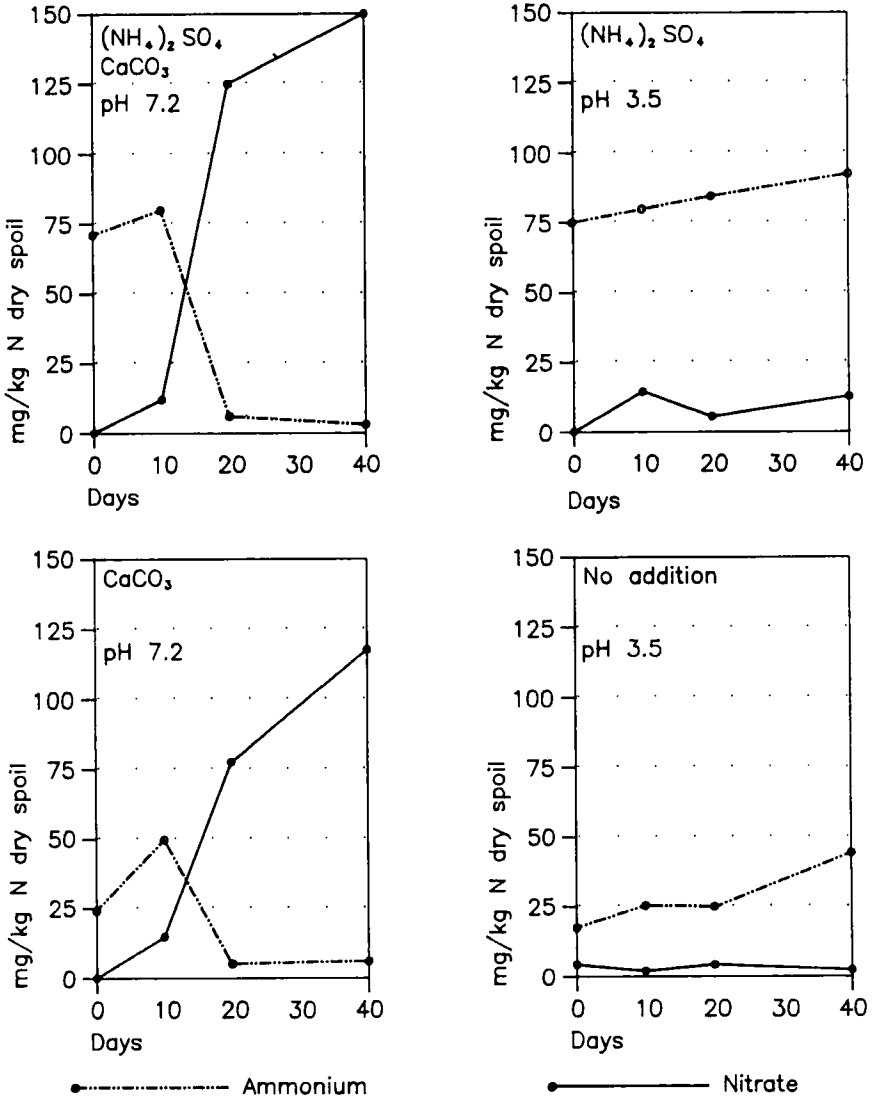
Many grass, herb and tree roots and the woody and dead parts of plants have a carbon to nitrogen ration higher than 30:1 and in order to break these materials down microbes need a supply of nitrogen from elsewhere. In fertile soils this nitrogen is available so materials of a high carbon to nitrogen ratio are broken down and the nitrogen becomes available to be taken up by plants again. In infertile soils there is no freely available nitrogen and nitrogen can become bound up in compounds of high carbon to nitrogen ratio or microbial biomass.

Other mechanisms may cause resistance to microbial breakdown of organic matter *e.g.* (after Stevenson 1982²³¹):

1. Stabilisation of proteinaceous constituents (*e.g.* amino acids, peptides, proteins) through their reaction with other organic soil constituents (*e.g.* lignins, tannins, quinones, reducing sugars).
2. The formation of biologically resistant complexes by the chemical reaction of NH_3 or NO_2 with lignins or humic substances.
3. Protection of organic N compounds from decomposition by their adsorption on to clay minerals.
4. Stabilisation of organic N compounds by the formation of complexes with polyvalent cations.
5. The siting of organic N in pores or voids physically inaccessible to microorganisms.

The significance of these mechanisms will be greater in infertile soils.

COLLIERY SPOIL HEAP CHARACTERISTICS



Colliery spoil incubated at 25°C and 10% moisture for 40 days with additions of ammonium sulphate, calcium carbonate or without additions. The conversion of ammonium to nitrate is microbially controlled and inhibited by low pH. Additions of calcium carbonate raise the pH and facilitate conversion of ammonium to nitrate which is then available to plants.

Figure 5.8: Nitrogen transformations on reclaimed colliery spoil (after Williams, 1975²⁶¹).

5.5 Natural vegetation on colliery spoil heaps

The natural vegetation of colliery spoil heaps has been much studied. Some studies have related the vegetation found to classical succession patterns *i.e.* vegetation development and species composition goes through a recognised sequence of stages to reach a 'climax' vegetation type. Other studies have found no correlation between vegetation type and time since tipping but a correlation with spoil factors such as pH (see Figure 5.9). Both findings are probably correct:

- where pH is low there will be no succession until the pH is ameliorated, and colonisation will be by those plants that can tolerate low pH only;
- where pH is not limiting colonisation will follow a successional pattern with species composition dominated by local species.

Although successional theory would indicate that trees are not primary colonisers, at some sites colonisation by pioneer trees such as birch occurs within a few years of tipping ceasing (see Photograph 5.5). The rate of colonisation will depend on the extent to which spoil characteristics inhibit plant establishment and growth. In addition to pH, both nitrogen accumulation and salinity level have been shown to influence the rate of ingress of new species.¹⁸³ Examples of successional sequences which have been suggested are shown in Figures 5.10 and 5.11. Some workers have also classified species found on spoil heaps on the basis of life-form (see Table 5.9). Comparison of data on life-form of vegetation on colliery spoil with that from Mediterranean and temperate Europe (non-spoil heap) allows the following conclusions to be drawn:

- the high proportion of phanerophytes (trees and shrubs) indicates their success at colonisation of spoil compared to herbaceous species;
- the low level of geophytes (bulbs and corms) indicates that ecosystem development is at an early stage.

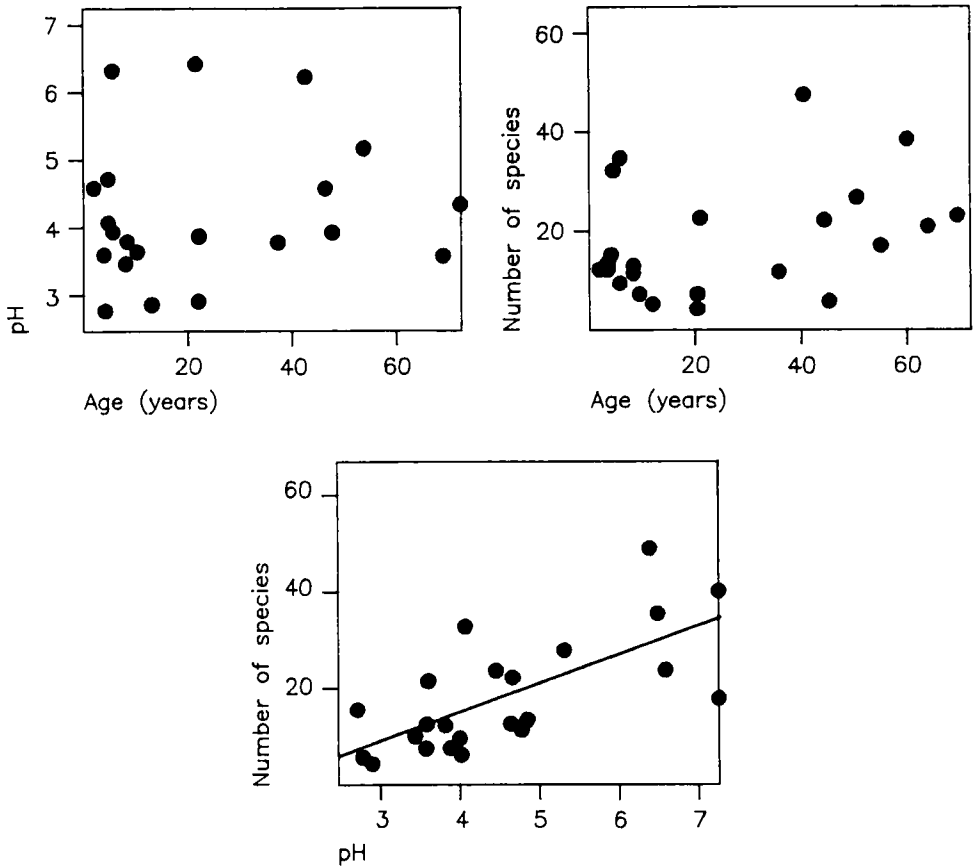


Figure 5.9: The number of species on a spoil heap may correlate more with pH than age of tip although there may be no correlation between age of tip and pH (after Bradshaw and Chadwick, 1980⁴⁰)



Photograph 5.5:
Birch trees colonising acid spoil with little ground cover in the Ruhr, Germany (source: Richards, Moorehead and Laing Ltd)

Table 5.9: Classification of colliery spoil heap species on the basis of life-form in France and the United Kingdom (data derived from Petit, 1980¹⁹¹ and Hall, 1957¹¹⁰).

	Nord-Pas de Calais	UK	Denmark†	Italy†
Phanerophytes	17	18	8	12
Chamaeophytes	3	3	3	6
Theophytes	32	19	20	42
Hemicryptophytes	45	58	56	29
Geophytes	3	3	12	11

† Distribution established by Raunkiaer for temperate Europe and Mediterranean Europe (non-spoil heap)

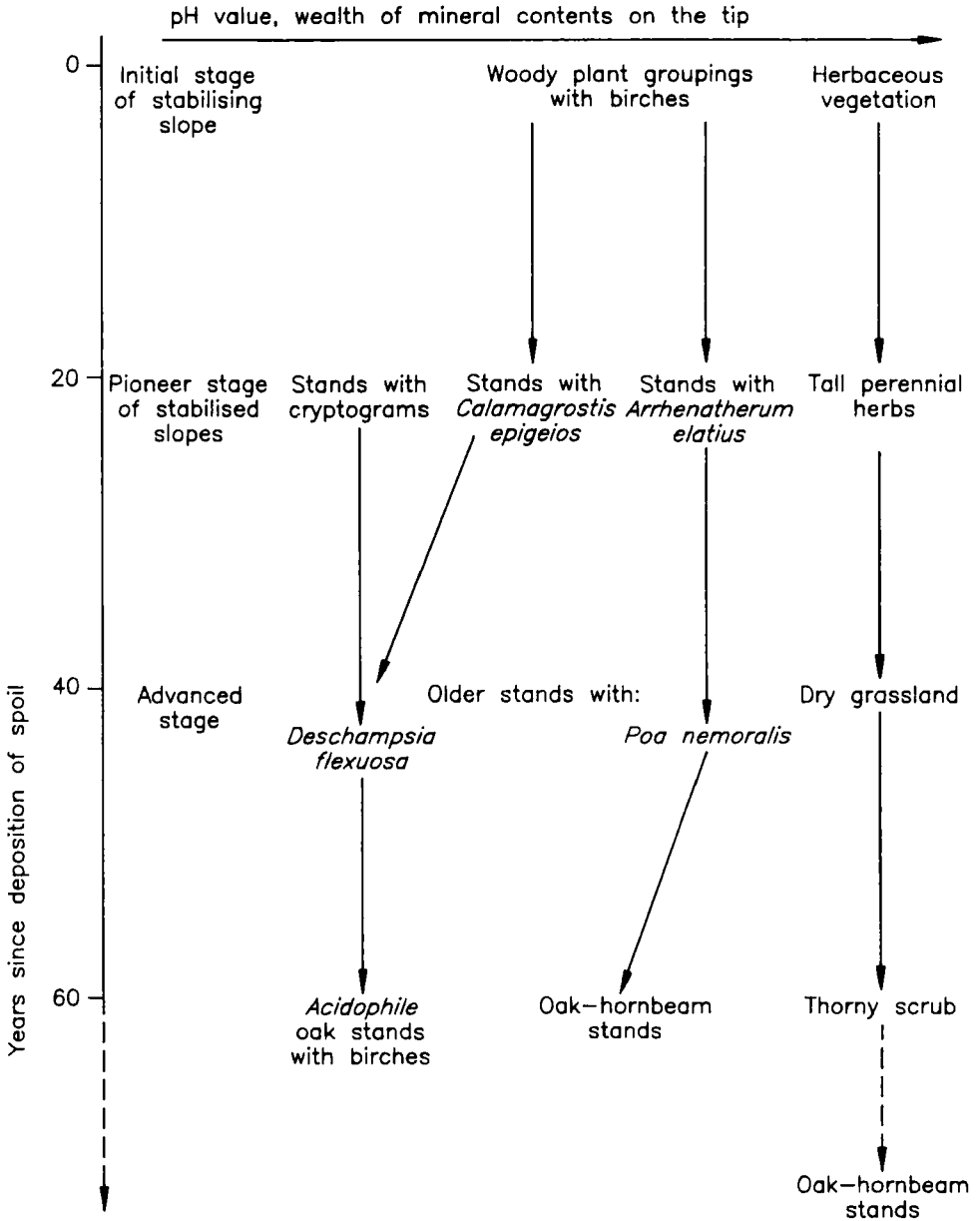


Figure 5.10: Suggested successional sequences on the spoil heaps of Nord-Pas de Calais (after Petit, 1982¹⁹²)

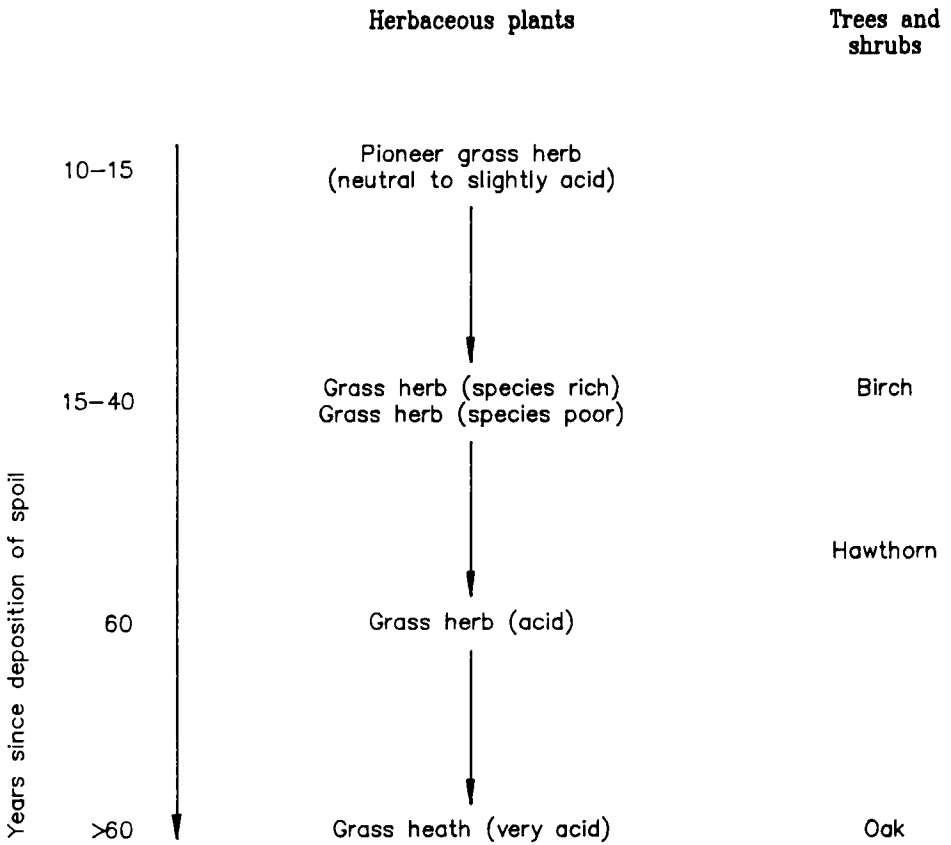


Figure 5.11: Successional sequence of vegetation postulated by Hall (1957)¹¹⁰ using data from a number of spoil heaps in the UK

Mycorrhizal fungi which enable plants to increase their uptake of nutrients have been found to thrive on colliery spoil and undoubtedly assist early colonisers such as birch (see Box 5.4 and Photograph 5.5). On some acid spoils birch trees supported by mycorrhizal fungi but with no herbaceous layer may be found (see Photograph 5.6).

Because colliery spoil heaps take on the vegetation characteristics of the surrounding land a very large number of plant species have been found growing on them. Colliery spoil heaps are not well known for supporting rare species and are more important as tracts of semi-natural vegetation and refugia of species becoming uncommon in the locality because of industrialisation, urbanisation or agricultural use. Such spoil heaps may also be important foraging areas for birds, insects and small mammals and their predators. In some former coal mining areas naturally vegetated heaps have become more important because other heaps have been reclaimed to vegetation which is not ecologically rich.

5.6 Use of colliery spoil

Colliery spoil is non-toxic and has the potential for use as fill material. Burnt colliery spoil is favoured over unburnt spoil because it is unlikely to combust and its engineering properties are preferable. The use of colliery spoil has been reviewed for the UK,²²² Spain,⁴⁷ and for Germany.¹⁴⁷ The general conclusion is that some colliery spoils will meet specifications for engineering use and that the use of other materials, such as sandy material from washery waste, need further research.

Testing should be carried out on spoil materials to assess their suitability prior to incorporation into engineering works (see Box 5.5). The use of colliery wastes in the construction industry has not been widespread because of the ready availability of other aggregates. However, the trend toward encouraging the use of secondary aggregates, because of environmental objections to primary aggregate production, may lead to an increase in the use of colliery spoil for secondary aggregates.

Box 5.4: Mycorrhizal fungi

Mycorrhizal fungi are one of the most extensively occurring groups of beneficial soil microorganisms. Few plants lack them. Mycorrhizal fungi form an intimate mutualistic association with plant roots (mycorrhizae) that extends the absorptive area of the roots (sometimes thousands of times) and contributes greatly to mineral nutrition, water absorption, and root system stabilisation of the host plant. There are many types of mycorrhizae. The two principal groups are the endomycorrhiza and the ectomycorrhiza. In the ectomycorrhizae the fungus penetrates root cell walls and then radiates hyphae (thin filaments) into the soil. In the ectomycorrhiza the hyphae form a sheath around the roots. Both trees and herbaceous plants can be infected and in both types the absorptive area of the roots is increased by the fungal hyphae. Many of the more successful colonisers on colliery spoil have been found to be infected by mycorrhizal fungi.



Photograph 5.6: Fruiting bodies of mycorrhizal fungi in association with colonising birch trees (source: Richards, Moorehead and Laing Ltd)

Box 5.5: Testing of colliery spoil for construction purposes

In order to determine the suitability of colliery spoil for construction purposes testing should include:

Laboratory testing*Geotechnical*

particle size distribution
density
relative density
moisture content
particle strength
shear strength

Chemical

pH
sulphate
pyrite content
coal content

Colliery spoil may have been contaminated by-products of coal carbonisation, demolition materials such as asbestos or other non-coal related wastes. Analysis may need to be carried out for these substances also (see Chapters 2, 9 and 10).

In-situ testing

penetration tests
density
moisture content
load tests to measure settlement characteristics

Increasing emphasis on sustainable development may also encourage such use of colliery spoil. Colliery spoil has been used extensively in engineered fill for road embankments and also for housing and industrial developments. Local use as fill material is likely to continue provided any potential combustibility can be dealt with (see Section 7.7). The

extent of settlement of freshly placed material will be dependent on the depth of the material, method of placement and degree of compaction. Material which has been in place for many years may already have undergone some settlement and be less likely to be subject to further settlement. Colliery spoil has also been used successfully as cover material in reclamation schemes for other wastes (see Section 14.4.4).

Prior to construction on colliery spoil it may be necessary to cover the spoil with a layer of inert material as a precaution against combustion (see Section 7.7).

Pyritic spoil can heave due to formation of gypsum (calcium sulphate), when sulphuric acid formed during pyrite oxidation reacts with lime containing materials. Such heave has been most often documented in relation to the use of pyritic shales as fill or where construction has taken place on pyritic shales *in situ*.^{113, 197, 176}