

**GROUNDWATER RECOVERY PROBLEMS ASSOCIATED WITH OPENCAST MINE BACKFILLS
IN THE UNITED KINGDOM.**

by

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ABSTRACT

The paper presents the main findings of the research work conducted over the past three years into the environmental effects associated with surface mining. Especial considerations have been given to the re-establishment of the natural groundwater regime, as a consequence of opencast site restoration. A summary of the results of the research is presented and two specific topics, namely, the stability of backfilled masses and the pollution of groundwater are detailed. The project was based on field and laboratory investigations, and details of this work along with some general conclusions are given.

INTRODUCTION.

The research project describes the environmental problems associated with the re-establishment of the hydrological regime following the restoration of a surface coal mining operation. Two principal effects have been established;

- o The collapse settlement of opencast mine backfills as a consequence of physical weathering from groundwater contact, and
- o The pollution of groundwater from contact with physically and chemically weathered rockfill materials.

Detailed investigations into groundwater recovery, backfill settlement and groundwater quality have been conducted on a substantial number of both current and completed opencast mine sites in the United Kingdom, with the co-operation of the National Coal Board, (recently renamed British Coal), Opencast Executive, (Reed 1986).

THE SEQUENCE OF GROUNDWATER RECOVERY

During the life of a surface mine excavating below the level of the natural water table, the necessary site dewatering operations, either passive or active, depress the groundwater level. (Nghah, Reed and Singh, 1983). When mining terminates, pumping operations cease and the groundwater table is allowed to recover to its natural level both in the solid unworked strata and the mine backfill. If a mine has not produced enough waste for the excavated void to be fully restored, then the possibility of the formation of a final void lake exists. The generalised sequence is presented in figure 1. The rate and degree of recovery is related to a number of site specific factors, (Singh, Denby and Reed, 1985).

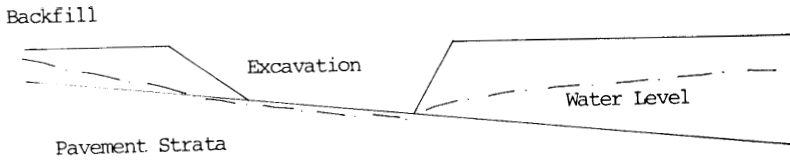
- o Areal extent and depth of mine site.
- o Local hydrological conditions and sources of recharge.
- o Changes in local hydrogeology owing to excavation and backfilling.

The areal extent and depth of the site are important because the larger the volume of the site, the greater the volume of water that will be required to saturate the fill to a given level. The nature of the recharge will affect the quantity of water entering into the fill over a specific period of time. A typical example of recharge would be in cases where old deep mine workings, commonly excavated in British opencast mines connect with the backfill mass. A standard measure to protect both the surface mine and any hydraulic link to a working deep mine is to apply clay seals to the horizon of old workings in the final excavated wall. If these seals are not 100% efficient then water may either enter the fill from the deep mine workings or conversely drain the backfill mass. Climate may have an important role to play depending on the permeability of the near surface layers of fill. Both these points will be discussed in detail later. The hydrogeology of the mining area has become disrupted with intact rock strata transformed into a broken rock fill with a wide size distribution, the permeability of which may be significantly different to the original. Rock mass permeabilities as part of this research have indicated variations in fill permeability from being unable to hold water during a pumping-in test to being more impermeable than the original rock strata.

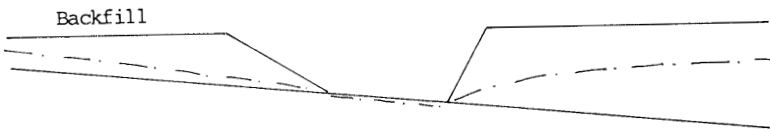
RESEARCH INTO BACKFILL STABILITY

Environmental effects of backfill displacements

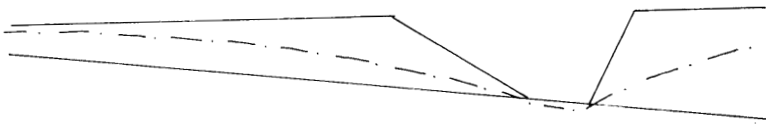
The stability of a rockfill mass has a great importance in deciding its further use, either for agricultural or structural development purposes. In the case of agricultural development, standard restoration procedures include the provision of adequate drainage for both subsurface water and surface water by constructing water courses, drains and adequate surface gradients. Differential settlements of backfill materials can occur to alter these restored surface levels and may also alter the surface flow patterns. A typical result of this would be the creation of ponds over the restored sites. Differential movements themselves may occur for a variety of reasons with factors such as fill depth, fill boulder size, degree of saturation etc. each having a significant effect.



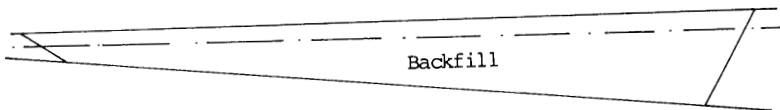
a). Advancing Down-Dip Surface Mine. Groundwater Depressed by Pumping.



b). As Mine Progresses, Water Recovers within the Spoil.



c). Mine Approaches Completion, Groundwater Rising through Spoil



d). On Completion, Groundwater Recovers to Equilibrium Level.

Direction of Advance →

Figure 1. The Sequence of Groundwater Recovery.

Both vertical and lateral differential movements are of importance to the construction of structures on opencast lands. It is generally agreed that whilst uniform movements in one direction may be tolerated by a structure, differential vertical or lateral movements may cause severe structural damage.

The extraction of one tonne of coal may typically entail the removal of 20 m of overburden under British conditions, (Charles et al, 1977). This spoil material is commonly excavated by draglines and cast to one side of the pit to form the advancing loosewall of the mine. Alternatively in the case of face shovel use, the overburden may be loaded onto dump trucks and end tipped to form the loosewall in high lifts. The backfilling operation in this way infills the area from which the coal has just been extracted. As a consequence of the backfilling operation, opencast mining leaves areas where the depth of loose backfill materials can be considerable. This unconsolidated material has the capability to undergo significant settlement, and the degree and timescale of such movements can be of extreme importance in cases where workings are required for surface development. From observations in the 1940's, the Department of Civil Engineering at Newcastle University undertook a programme of research on behalf of the Opencast Executive, investigating the stability of restored sites, (Kilkenny 1968). The research presented settlement results from the Chibburn Site in Northumberland reporting a semi-logarithmic relationship between average settlements and time.

The Bulkage of Backfill Materials.

Broken rock strata when used as a backfilling material can exhibit considerable volume changes as compared with the original intact material. Silts and plastic clays will soften and expand considerably when excavated wet, whilst soft organic materials such as peat can compress on dumping. On a normal surface mine site, despite the fact that 4-10% of the excavated strata is removed as coal, the overall bulkage of the backfill will usually result in the final landscape being at least the level of the original, if not even higher. Examples of recorded backfill bulkages for completed sites were recorded by Ferguson (1984), the range can be seen to be -3 to +12.2% with the lower figures being attributable to peaty sites.

Effect of Mining Method.

In general the plant which operates on surface mine sites is large, cumbersome and heavy, giving complimentary compaction to the backfill mass. Strip mining operations using draglines, or tipping by truck and shovel operations result in a limited amount of layering with effective compaction at bench level. At the other end of the scale, spoil handled by motorised box scrapers is given the most efficient system of compaction and consolidation excepting cases where some deliberate form of compacting machinery is used, (e.g. sheeps-foot roller).

Typical opencast mine backfills are left reasonably compacted on the completion of operations, even those deposited by draglines, and it is the initial bulkage of the fill material which affects the total degree of settlement which the mass will undergo in time. The initial bulkage is in turn related to initial particle size. The larger the particle sizes within the fill than the greater the degree of size breakdown that can occur and consequently the greater the degree of settlement which will arise. An investigation conducted by Knipe, (1981). In general both

scrapers and dump trucks were used to lay the fill, but in some area spoil was left loose dumped resulting in a relatively unconsolidated fill mass. The curves illustrate well the differing degrees of settlement which can occur on a single site as a result of different backfilling techniques.

The Physical Weathering of Coal Measure Rocks.

The stresses exerted by the action of water may have a great effect on the backfill particles owing to the ability of water to weaken rock strength. The strength of a rock is proportional to its surface energy, and thus when the surface of the rock is wetted then the surface energy is reduced and consequently its compressive strength.

The physical weathering of rocks by water can be divided into four groups;

- a). Scouring Action of Particles.
- b). Swelling.
- c). Air Breakage.
- d). Freeze Thaw.

These being described by Huggins, (1975). Overall the breakdown of backfill materials by both chemical and physical weathering will result in the consolidation of the fill mass as the larger particles within the fill are broken down.

Consolidation Settlements of Backfill Materials.

In deep fills self-weight is often the principal source of settlement, (Charles 1978), this primarily occurring on the immediate placement of the fill. (Along with compactive effects from mining machinery). Collapse settlements may then occur in the presence of groundwater. Following these effects significant movements can still occur under conditions of constant effective stress and moisture content - this being termed creep settlement. Creep settlements have been observed to follow the logarithmic decay such as was indicated by Kilkenny (1968) in his work on opencast fill settlements.

The Effect of Groundwater Recovery.

A recovering water table will have the effect of accelerating the processes of physical and chemical weathering as it rises through the fill, (Charles et al, 1977, 1984). Results from a unique experiment on the Horsley opencast mine site in Northumberland have shown a significant influence on settlement induced by groundwater. The experiment investigated five predominant features on the site which could influence the degree and nature of backfill settlements, namely;

- i). Oldest Fill.
- ii). Deepest Fill.
- iii). Fill in the vicinity of lagoons.
- iv). Fill previously overlain by a spoil heap.
- v). Most recent fill.

The most important results from the Horsley experiment were as follows.

- a). Settlement characteristics are heavily influenced by such features

as lagoons, which presaturate the fill resulting in ultimately less settlement and by spoil heaps, which act as fill surcharges. On the removal of an overburden heap on the Horsley site small heaving movements were observed.

b). A significant proportion of the measured settlement was found to be due to compression in the upper 10 m of fill which had not actually been saturated by the water table.

Further Observations.

Several cases of destructive damage to structures constructed on opencast mine sites have been recorded. Leigh and Rainbow, (1979) report on a factory built in 1971 on fill which was 18 m deep and restored in 1953. Substantial damage to the factory occurred in 1977. Pumping in the area from underground mining had ceased by 1972, initiating groundwater recovery. Following damage, a site investigation revealed that the lower portions of the fill had been saturated resulting in a compression of 4.5% of the fill depth.

Guest, (1975) reports damage inflicted on a block of terrace houses constructed in 1973 on fill of 10 m thickness and 13 years old. Structural damage was reported in 1973. Investigations showed that drain trenches had filled with water indicating that saturation had been a major influence on the degree of differential settlement.

Knipe (1981) presented results of backfill settlements on five opencast mine sites in the West Midlands. The project studied backfill settlements on sites on similar fill characteristics and thus evaluated the effect of mining method. The work however did not evaluate the effect of groundwater on fill settlements.

Recent studies of backfill settlements have been conducted by Smyth-Osbourne, (1984) who examined the settlement of a factory and damage induced by siting the structure partially on opencast backfill material, ie over a highwall. Additionally, Buist, (1984) studied deformations in a motorway carriageway which had been constructed on a restored surface. Both researchers reported that changes in groundwater levels may have had effects on backfill settlements.

Research Programme.

Research into backfill settlements has resulted in ten sites of different mining characteristics being evaluated for groundwater recovery and associated backfill displacements. The objectives of the research were as follows;

- a). Observe and characterise backfill movements in the presence of a recovering water table.
- b). Observe the effects of different types of fill, thicknesses etc.
- c). Evaluate the effect of mining method on the degree of backfill settlement.
- d). Observe and record degrees and rates of groundwater recharge.
- e). Evaluate the effect of time on backfill settlement.
- f). Evaluate backfill permeabilities and relate these to backfill settlements.

A summary of the sites investigated, instrumentation and observations are presented in table 1.

Table 1. Summary of Site Investigations. – Backfill Settlement Research.

Site Description	Instrumentation Details.	Observations.
<p>Site A. Truck-Shovel Operation. Shallow mudstone fill, average depth =17 m, maximum depth = 33 m. Wet site with recharge from old deep mine workings.</p>	<p>5 Magnetic extensometers/Piezometers to monitor settlement and groundwater recovery in the fill. 4 piezometers monitoring recharge in the solid. Instruments in two profiles, one down-dip, one along strike.</p>	<p>Water recovery rapid, 24 m in 144 days. Collapse settlement found to occur directly related to groundwater position. Mudstone swelling following saturation resulted in heave movements. Differential settlements resulted in ponded areas. Settlement over compacted haul road much reduced. Settlement = 1.1% of fill depth.</p>
<p>Site B. Dragline operation, working sandstone-mudstone overburden. Average depth of fill in instrumentation area = 70 m. Final void infilled by dump trucks.</p>	<p>4 Piezometers monitoring recharge in the solid. 2 multi-point piezometers, (5 tips in each), monitoring water behaviour in fill. 2 tension wire extensometers monitor settlement and shear in fill, also used for permeability testing of horizons within the fill.</p>	<p>Slow groundwater recovery, 5 m/year. Substantial vertical and lateral movements in fill over 2 years old. Average permeability akin to intact coal measure strata. Perched water tables present in fill. Permeabilities much greater with depth surface permeabilities very low.</p>
<p>Site C. Truck-Shovel operation working synclinal basins. Sandstone-mudstone fill, 40 – 70 m deep.</p>	<p>4 magnetic extensometers/piezometers monitoring deformations along the line of a road constructed on variable thickness backfill. Instrument depths of 30, 40, 60 and 70 metres. Top 15.5 metres of fill compacted.</p>	<p>Fill saturated to 5 metres below base of compacted at start of monitoring. Compacted zone appears unseceptible to collapse settlement. Small movements measured normally occurring in the base of the fill. Fill depth governing proportion of settlement. No severe differential vertical movement.</p>
<p>Site D. Dragline site, 15 –30 metres depth of fill. Sandstone- mudstone.</p>	<p>23 Surface levelling stations and 3 magnetic extensometers/piezometers monitoring the line of a sewerage pipe constructed over the fill.</p>	<p>Instrumentation commenced 7.5 years after restoration. Negligible movements in the fill. Fluctuating water table had no effect on settlement patterns.</p>

Table 1. (Cont.) Summary of Site Investigations. - Backfill Settlement Research.

Site Description	Instrumentation Details	Observations
Site E. Dragline Site, sandstone-mudstone fill.	3 traverses totalling 30 surface levelling stations over fill area. Correlated to local piezometers for groundwater levels.	Water recovery related collapse settlements were observed. Slow time period for recovery, 7 years. Secondary recovery induced secondary collapse settlements. Settlement not completely related to fill thickness.
Site F. Dragline Site, sandstone-mudstone fill. Depths in area of instrumentation up to 35 metres.	8 surface levelling stations installed over highwall area. Correlated to local piezometers for groundwater levels.	Groundwater recovery related settlement observed followed by long term creep displacements. Settlement independent of fill depth and affected by presence of highwall. 8.5 years after initial recovery, settlement still occurring. Groundwater levels still recovering slowly.
Site G. Shallow truck-shovel site. Sandstone-mudstone fill. No water.	9 surface levelling stations monitoring vertical and lateral fill movements.	Small vertical movement observed in dry fill. Larger lateral movements recorded and found to be differential in both magnitude and direction. Highwall had significant effect on movements.
Site H. Permanent spoil heap mound.	1 tension wire extensometer monitoring settlement and shear. 1 piezometer monitoring groundwater.	Small displacements in dry spoil. Water levels slightly fluctuated at base of heap.
Site I. Dragline Site, sandstone-mudstone fill. Concrete line culvert and lake constructed on restored fill surface.	None	2 years after culvert constructed on fill 14 years old a sudden structural collapse occurred amounting to 3.4% of the fill depth.
Site J. Truck-shovel site on side of hillside. Shallow depth 11 m, sandstone-mudstone fill.	None	Bowl-like depressions of up to 0.5 m occurred in fill of 24 years age over an unknown period. No water issues. Settlement amounts to 4.5% of fill depth.

Summary of Backfill Settlement and Groundwater Recovery Results.

This paper aims to highlight the principal findings from the work presented in detail in these previous publications. The sites involved in each paper is also indicated by the reference.

Groundwater recovery has been seen to occur over various time intervals; an extremely short time in a case of a shallow site measurable in days, or over a period of years in a much deeper larger site. Recovery has been seen to be still occurring within one fill over eight years after the sequence of recovery was initiated.

Instantaneous collapse settlement has been observed in fills and directly related to the groundwater table. Following these large movements the fill can continue to settle at a slow even rate of millimetres per year magnitude or even in the cases of mudstone fills exhibit heaving movements. On one site a recovered water table lowered in the fill over a summer period to recover once again in the winter months. Secondary collapse settlements were observed.

On one site the compaction of a haul road by continuous running of plant resulted in negligible vertical movements compared with uncompacted ground. On a strip mine, permeability testing showed the fill to be much more permeable with depth. The near surface layers which had been restored by scraper operations were very impermeable. The results reflected a particle distribution through the vertical section of the fill with the largest boulders at the base and the smallest rocks near surface.

The monitoring of the displacements occurring within a fill destined for road construction indicated how fills can be stable following groundwater recovery. The depth of fill under the road varied from 30 to 70 metres. No severe differential settlements were recorded despite the significant depth variation.

On two sites the importance of lateral in addition to vertical fill movements were emphasised. On one dry site the lateral movement of a point on the surface of the fill exceeded its vertical settlement.

On one site the construction of a concrete-lined culvert carrying water from a restored lake caused a sudden structural collapse in the fill which had been stable in position for 14 years. The collapse settlement amounted to 3.4% of the fill depth. The cause is presumed due to a leakage of water out of the culvert.

The creation of three large bowl-like depressions over the surface of a surface mine which had been restored 24 years previously resulted in maximum surface displacements of 4.5% of the total fill depth. This is one of the largest vertical displacements in such fills recorded.

WATER POLLUTION ASSOCIATED WITH COAL MEASURES EXCAVATION.

Opencast mine backfill materials can occasionally contain weathered minerals which are able to react with groundwater to produce a polluted discharge. A notable example is the oxidation of pyritic material to form acidic and iron rich, (ferruginous) drainages. On some sites a problem has been created by the inclusion of highly pyritic colliery spoil material within the fill.

The resultant waters in cases of pollution problems are low in organic matter and high in dissolved metal salts. pH values from the presence of sulphuric acid may be as low as 2. The environmental and economic effects of these drainages are currently of great concern, and over recent years the legal constraints applied to such discharges have become increasingly

severe. Successful prosecutions have been made against the National Coal Board for the pollution of watercourses draining restored mine sites.

GROUNDWATER POLLUTION ASSOCIATED WITH MINING OPERATIONS.

General Water Pollution.

The various types of water pollution may be divided into four categories, namely:

- a). Chemical; Organic and Inorganic.
- b). Physical; Colour, Turbidity, Temperature, Suspended Solids, Foam, Radioactivity.
- c). Physiological; Taste and odour.
- d). Biological; Bacteria, Viruses, Animals and Plants.

Of these it is the chemical forms of pollution which give rise directly to physical and physiological effects that are of greatest importance.

Chemical Pollution.

a). Organic.

Organic pollutants, (carbon compounds), have three main harmful properties:

- i). They interfere with natural water self-purification.
- ii). They prevent re-aeration of water forming a thin surface film.
- iii). Toxicity.

Examples of organic pollutants include fats, soaps, waxes, rubber, coal, oil, phenol, dyes, detergents and cyanides.

b). Inorganic.

Inorganic pollutants can be subdivided into three groups;

i). Acids and Alkalis; These corrode both metals and concrete. They destroy bacteria, fish and other life forms.

ii). Dissolved Toxic Compounds; Free chlorine, ammonia and soluble sulphides are classed amongst many others as dissolved toxic compounds. Heavy metal salts are particularly toxic.

iii). Soluble Salts; the chlorides, sulphates, nitrates, bicarbonates and phosphates of sodium, calcium, potassium, magnesium, iron and manganese all induce salinity into the water.

Physical Pollution.

Physical pollution can manifest itself in one or a combination of the following ways; colour changes, turbidity, temperature, suspended solids, foam or contamination by radioactivity.

Physiological Pollution.

Physiological pollution manifests itself in the form of tastes and odours. Dissolved sulphur compounds invariably give rise to the presence of hydrogen sulphide within a water course producing the familiar acrid 'rotten eggs' odour.

Biological Pollution.

A form of pollution which is not associated with the mining industry but is included for completeness. Bacteria and viruses can be transmitted through water. The problem is of particular importance in the disposal of sewerage plant effluents.

LEGISLATION.

The legislation regarding the pollution of natural waters by mining effluents has become increasingly stringent over the past few years, with the National Coal Board being prosecuted and fined on a number of occasions.

Since 1951, all the groundwater pumped off a surface mine has been required to comply with various River Pollution Acts passed in that year. The most recent legislation has been the Control of Pollution Act 1974, (H.M.S.O. 1974), designed to bring the law into line with E.E.C. directives on water pollution relevant to fish and drinking water abstraction.

Pumping off surface mine sites requires a discharge consent obtained from either the River Board or Local Authority. The 1974 Act makes no exemptions to the period of abandonment of a mine and thus makes the operator liable for post-mining pollution.

ACIDIC AND FERRUGINOUS DISCHARGES.

Iron and Sulphur minerals are widespread within coal bearing strata. Pyrite, and Siderite, are typical sources. A severe water pollution problem in the opencast mines of Scotland has arisen from the presence of ironstone bands associated with the excavated strata, (Norton 1983).

The Effects on Environment of Acid and Ferruginous Discharges.

The most obvious effect of an acid discharge is the deposition in a watercourse of ferric hydroxide. The rate of hydroxide deposition is enhanced by the presence of neutral ferrous oxidising bacteria in the natural waters which oxidise ferrous salts and trap the precipitated ferric hydroxide to form a slime blanket in the bed of the affected stream around the discharge point. This blanket engulfs the plankton and micro-organisms which form the basis of the natural food chain. Fish are particularly affected by levels of acidity with natural breeding cycles being affected at pH values lower than 5, (Norton 1983).

MECHANISMS OF ACID AND FERRUGINOUS WATER PRODUCTION.

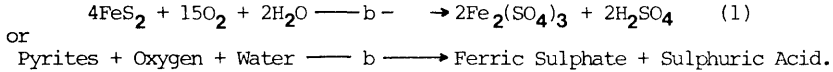
General Mechanism.

The formation of acid mine water occurs when sulphide minerals within the excavated strata are exposed to the atmosphere. Oxidation of these minerals has been shown to be bacterially catalysed, (Atkins and Pooley 1982). In general the pyritic material in the presence of oxygen oxidises to form a series of soluble hydrous iron sulphates. These commonly appear as yellow or white crusts on weathered rocks. When natural waters flow over these salts, hydrolysis occurs to form acidic drainages of high

sulphate and ferrous iron concentrations. The ferrous iron may be subsequently oxidised to the ferric state complexing with ferrous and ferric oxyhydroxides which impart deep red and yellow colours characteristic of acidic drainages.

Bacterial Catalysis.

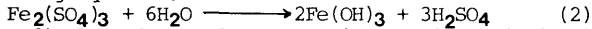
The oxidation of iron pyrites has been shown to be catalysed by micro-organisms termed iron bacterium, (Atkins and Singh 1982, Rawat and Singh 1982). The generally accepted formulae are as follows;



where $-b-$ denotes bacterial catalysis.

The reaction once initiated is self-catalysing. It is considered that if the pH of affected waters falls to below 4.5 then all acid soluble iron compounds will become available for reaction, (Henderson and Norton 1983). Contrary to this, if pH values rise to above 5 then the reaction is severely inhibited.

The red, ochreous deposit of iron hydroxide previously mentioned as a classic effect of such drainages forms as a result of the dilution of ferric sulphate in a natural water course. The mechanism can be described by the following equation;



Thus the final products of the reaction consists of ferric hydroxide precipitate and sulphuric acid.

Factors affecting the rate of Bacterial Catalysis.

The factors which affect the rate of bacterial leaching can be summarised as follows, (Atkins and Singh 1982, Granger 1984).

- a). pH.
- b). Oxygen and Carbon Dioxide Concentrations.
- c). Temperature.
- d). Bacterial Concentrations.
- e). Nutrients.
- f). Particle Sizes.
- g). Mineralogical Factors.
- h). Metal Tolerances.
- i). Secondary Mineral Formation.
- j). Pressure and Light.

These factors have been investigated by many authors in addition to those above and a detailed analysis is not presented here.

RESEARCH INTO GROUNDWATER POLLUTION.

Owing to recent stringent legislation, research into groundwater pollution from opencast mine sites was held by the National Coal Board, Opencast Executive with great reserve. After a degree of persuasion however samples of water were obtained from sites in all areas of the

Executive. These regions conveniently subdivided geographically into six, Scotland, North-East, North-West, Central East, Central West and South Wales. Initially a questionnaire was circulated around each area to obtain some basic background information- details of current water samples, water treatment methods etc. The next stage of the research was to sample waters which were inflowing into mines through old workings, highwalls and backfills and to supplement these results by obtaining samples from piezometers installed in backfill. All water analyses were performed in Mining Engineering Department at Nottingham University and a full analysis consisted of the following determinations;

pH

Na, Ca, K, Mg, Fe (ferrous and ferric), Mn, Al

SO₄, Cl, NO₃

The equipment utilised in these tests consisted of a Pye Unicam PU8600 UV/Vis Spectrophotometer, (Fe, Al, Mn, NO₃), a Jenway PFP7 Flame Photometer, (Na, Ca, K) and other standard chemical laboratory equipment. Iron oxidation states were stabilised in the field by acidifying a second water sample with HCl.

REGIONAL OBSERVATIONS OF MINE WATER POLLUTION.

Scottish Region

Opencast mine waters in the Scottish region are typified by exceptionally low pH and high dissolved iron contents forming a very real environmental hazard. Problems arise from ironstone bands interbedded with the excavated strata. These are weathered either on the surface of the exposed slope or in the backfill as broken rock. The problem of acid waters is widespread in the region and successful prosecutions have been made against the National Coal Board for the pollution of water courses. Whilst the fines paid as a result of these prosecutions have been relatively small, (£100-200), the public image of surface mining in the region has been severely tarnished. In particular in attitudes to consents for proposed opencast mine sites.

To illustrate the type of problems which have been encountered in the region, surface springs which have emerged from underneath tip material have been recorded as having pH values of 2.8 and dissolved iron contents of 8,000 - 30,000 ppm, (Norton 1983).

Referring to Site C from the settlement research, which is located in this area some specific pollution problems can be detailed.

Groundwater Qualities on Site C.

The strata encountered on Site C was very argillaceous having a high degree of pyritic material. Some of the worst discharges emerged from the base of overburden dumps with analyses of pH 2.8 and 12-30,000 mg/l iron. A water sample taken a backfilled synclinal basin, showed a pH value of 3.5 and a dissolved total iron content of 5,000 mg/l. Boreholes elsewhere installed in the backfill of the site showed waters at shallow depth of pH 3.9 with iron contents of up to 7500 mg/l. During the installation of the

instruments in the road deformation monitoring scheme, it was noticed that the fill was very susceptible to spontaneous combustion. In the section of the fill just above the level of the water table, rock temperatures were very high initiating the formation of steam within the borehole. A number of other boreholes over the site were inspected and found to be on fire.

The natural water table in the area, previous to mining operations was close to surface and there is a strong possibility that streams will emerge from the backfilled area. An analysis of the backfill mass has indicated a potential iron source of 6,600 tonnes per million tonnes of backfill, producing a possible 12,600 tonnes of ferric hydroxide. Given that the sole discharge point on the site is one small burn, the environmental effects of such chemical loads are expected to be considerable.

This site was an extension to a site which had excavated similar strata to a depth of 250 metres. The site at present has only been partially backfilled and the final void area remains empty. The coal to overburden ratio was relatively low and as a consequence there is not sufficient material to restore the site. Possibilities exist to fill the void with domestic refuse. At the base of this void is an 40 metre deep acid lake of pH of around 2. Pumping is currently keeping water levels to a constant horizon, however some time in the pumping must cease and recovery take place. The original groundwater levels around the area were as on the Extension), at or near surface, there is concern that if the pre-mining equilibrium levels are matched then spring of extremely toxic material may emanate from surface. The presence of the void will lower the natural water levels for the present and thus postpone the problems. In the meantime a solution to what may be the most potentially serious pollution problem ever encountered in the United Kingdom must be found.

Pollution of Groundwater from Restored Opencast Sites.

The restoration of an ironstone tip into the void of a surface mine resulted in a local stream exhibiting pH values of 4.5 and dissolved iron contents of 650 mg/l when the groundwater recovered to emanate out of the fill at surface. Analyses of the pit heap material indicated that the potential iron source was 3,125 tonnes. The emanation of the groundwater occurred practically next to the stream and thus a minimum of dilution occurred prior to mixing with the clean water. The subsequent pollution led to the prosecution of the National Coal Board under the regulations of the Control of Pollution Act 1974, (Norton 1983). An attempt to remedy the situation by lime injection into the fill subsequently failed, resulting in the construction of a small water treatment plant.

Other Areas.

Scotland has been isolated as having by far the worst acidic and iron drainage problem. The other regions have raised the following observations.

North-East.

Many sites in the North-East are excavating old deep mine workings. In the Northern area of Northumberland especially, these workings tend to drain the opencast fills as they are directly linked to a deep mine colliery pump. This obviously is temporarily reducing recovery rates and

levels in a number of restored opencast sites in the area despite a standard restoration policy of applying clay seals to excavated underground workings. The pumping is expected to terminate in 10 years time and further recovery will be initiated over the entire area. This may be of importance if streams re-establish out of backfill, (although the fill is not unduly pyritic) or from the induced collapse settlement of unsaturated fills. Typical water analyses from three backfilled sites are presented in table 2.

North-West

No water treatment facilities save lagoons are currently being utilised in the North-West region. Samples of water obtained from sites however do indicate that the region suffers slightly from waters of poorer quality. This is a trend which has been observed over a few years, when in 1981 the compliance with water discharge consent conditions, (governing the quality of the discharged water), for the North-west was 59% compared with 66% for Scotland and a nationwide average of 75%. Samples taken on several sites showed low pH values and high iron contents with other dissolved metal salts showing high concentrations as well. Whilst the region has no where near the problems of Scotland some environmental problems may occur if voids are considered for the disposal of colliery spoil materials.

Central East/West Regions.

All sites in these regions discharge water of satisfactory nature. One site had water inflows arising from three seams, one of which was high in iron contamination. The iron deposits on the walls of the mine indicated that acid water was present although it was much diluted in the general pit environment. This particular site will be used to reclaim colliery spoil and thus there is a possibility that water from this seam may encourage pH values to drop in the restored fill and thus catalyse the acid forming reaction.

South Wales Area.

The geotechnical settings of opencast mine sites in the South Wales region are such that many sites form parts of hillsides or may be adjacent to restored colliery spoil heaps. No water pollution has been so far recorded from opencast sites although recently a water treatment plant with lime neutralisation facilities has been constructed on one site. It has proved in the past almost impossible to trace water flow through sites owing to the extremely complicated hydrology and hydrogeology of the area.

CONTROL METHODS FOR THE PREVENTION OF POLLUTION FROM BACKFILLED SURFACE MINE SITES.

Basis for Design.

The basis for the design of control measures against polluting discharges is the inhibition of the pyrite oxidation mechanism. This can be directly, ie bacteriacides or indirectly by controlling oxygen and water access to the polluting strata. Measures can either be preventative or in cases where a pollution problem exists, remedial.

Table 2
Average Chemical Compositions of Water sampled from boreholes on Site B.
(North-East Area).
all mg/l except pH
P2 P3 P4 Piezometer in Fill
on a local site.

	MPP1	P2	P3	P4	Piezometer in Fill on a local site.
pH.....	8.6	8.6	8.0	7.7	7.8
Total Hardness as CaCO ₃ .	182	108	468	372	510
Total Alkalinity.... as CaCO ₃ .	78	408	507	264	326
Alkalinity to phenolphthalein as CaCO ₃	0	60	36	0	0
Sodium.....	27	48	204	180	18
Potassium.....	5	89	105	82	43
Calcium.....	117	166	69	345	46
Iron Total.....	5	43	22	13	9
Aluminium.....	5	1	0	0	0
Chloride.....	2860	660	360	390	80
Sulphate.....	216	680	823	110	540
Oxidised Nitrogen...	0	2	1	1	0.5

Preventative Measures.

Preventative methods for avoiding the formation of polluting discharges include the following;

- a). Water Diversion.
- b). Compaction of Fill.
- c). Surcharge of Less permeable fill on restored surface.
- d). Selective Overburden Placement.
- e). Limestone Placement.
- f). Biological Inhibition.

a). Water Diversion.

This method entails the deflection of surface water away from a mining excavation/backfilled mine site, by the use of surface drainage ditches around the periphery of the mine. The water is then discharged away from the mine site with normally no treatment required.

b). Fill Compaction.

The compaction of backfill into thin layers during the filling process produces a waste with a much lower degree of permeability. This restricts not only the quantity of water that may pass through the fill in a given time, but also the quantities of oxygen and carbon dioxide that the fill holds to perpetuate the acid forming reaction. The method is however marred by the fact that as water flow rates are reduced, so are contact times between weathered rock strata and water.

c). Fill Surcharges.

The final restored surface is recontoured to induce springs at selected places on the mine site using a surcharge of a less permeable fill material. The flow rate and volume through the backfill can be controlled by inducing springs to emerge outside of the restored mine area.

d). Selective Overburden Placement.

Any material within an overburden of particular polluting ability may be segregated within the backfill and sealed off from water by clay caps. It is obviously desirable to have the clay available at the mine rather than having the expense of importing, (Miller 1981). The clay cap is intended to divert the water from the material and should be constructed from a smectite type clay which will expand and contract on the processes of drying and wetting, to create a formation which tends to be impermeable when wet. If the clay source is dry then it must be irrigated in order to achieve an optimum water content of 14.6% by weight. The clay should cover the material in an umbrella shade fashion, figure 2, and must be thick enough to withstand any rupture especially in the case of dragline spoiling. The noxious overburden must be buried deep enough to prevent any future contact with the surface environment and should also be positioned above the level of the anticipated restored water table.

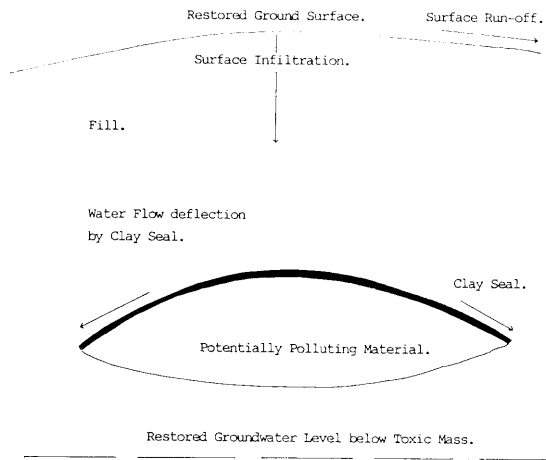


Figure 2 Selective Overburden Placement (Miller 1981)

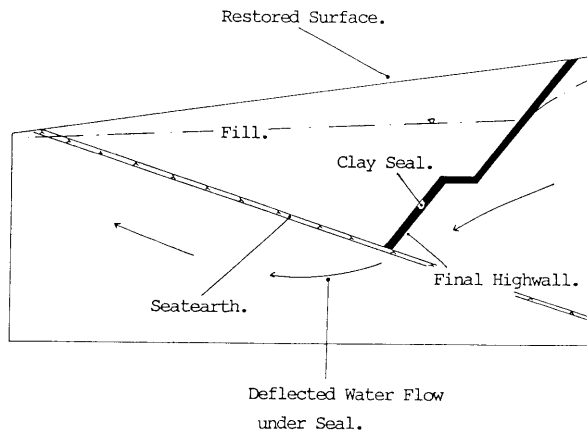


Fig. 3 Sealing of the Final Highwall using Clay Seals. (Norton 1983).

e). Clay Seals.

On opencast mine workings in the United Kingdom it is a stipulation that old deep mine workings must be sealed by clay seals. This operation has two effects, principally water cannot drain into the deep mine workings and come into contact with current extraction and secondly water cannot enter from the deep mine workings into the surface mine. This water may have acid and ferruginous characteristics. Clay seals can also be used in a restoration programme to prevent water entering into a surface mine backfill, especially in cases of mines with impermeable fireclay floors.

Figure 3 illustrates how the toxic mass can be isolated from the passage of water by the application of clay seals to the surface and western edges of the mass. This would induce a spring in the position shown which could have been channelled into the water course. In this way the the relatively cleaner water flowing through the fill would have avoided contact with the noxious ironstone material. It may be wise to seal the ironstone waste on all sides thus preventing water from any source entering the fill. It is most important that the surface is made free draining and a clay seal placed on top of the fill. This ensures that the enclosed fill will not saturate with water gained over time by surface infiltration and thus produce a marshy area of land with polluting water covering the surface.

f). Limestone Placement.

The alkaline nature of limestone not only inhibits the acid producing reaction but can neutralise, partially at least any acid which naturally occurs in the mine waters. The most effective limestones have been found to be those which approach pure calcium carbonate in composition. Stones with a relatively low calcium content but contain calcite and have a high surface area are equally effective. Magnesites are the least effective followed closely by dolomitic limestones, (Geidel and Caruccio 1980, Calhoun 1970). The application of limestone into a backfill can occur in two ways as illustrated in figure 4.

- a). Interbedding of limestones with alternate layers of fill.
- b). Placement of bulk limestone at surface.

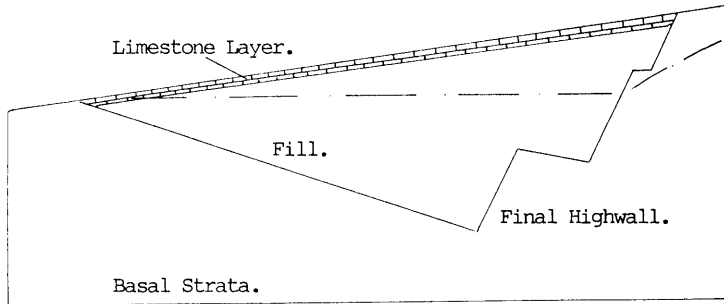
The prediction of limestone quantity is of considerable importance. This prediction may be made following an analysis of strata or backfill cores using simulated weathering tests.

g). Biological Inhibition.

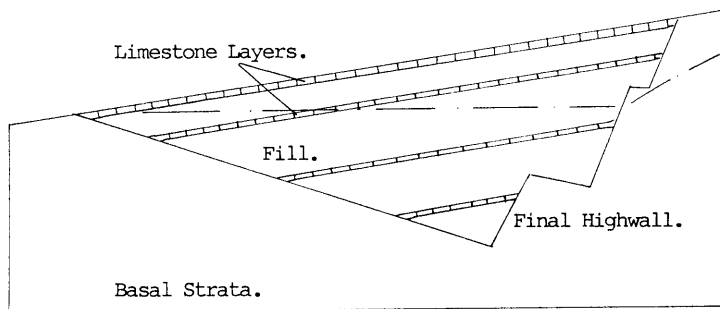
The method of Biological inhibition relies on disrupting the catalysis of the acid reaction by iron bacterium. This can be performed by one of two methods;

- a). Inhibition by other bacteria.
- b). Inhibition by anionic detergents.

Electron microscopy has revealed strains of bacteria called Caulobacter in the neutral waters of certain coal mines (Shearer et al 1968). These waters were found to inhibit acid production in streams passing through pollution producing wastes. The bacteria are in fact harmless to life and have often been isolated from lakes, streams and other such watercourses. Laboratory tests have shown that the field neutralisation costs could be reduced by 5 to 10 times in successfully installed in practice.



a). Limestone applied as a Surface Layer.



b). Interbedded Limestone/Fill Arrangement.

Fig. 4 Prevention of Groundwater Pollution utilising Limestone Placement.

Many biological inhibitors are unselective and could possibly cause dangerous side effects if introduced into natural waters. One class however, anion detergents are inexpensive and environmentally safe at low concentrations, (Kleinman 1980, et al 1981).

Laboratory simulations of coal refuse piles have shown that concentrations of Sodium Lauryl Sulphate of 10 - 20 ppm reduces acid production by up to 40%. At concentrations in excess of 25 ppm conditions become bacteriacidal, resulting in a 90% reduction in acid production. Anionic detergents have the further advantage of only being bacteriacial at low pH values.

The addition of such detergents to elastomer materials has enabled a control release mechanism to be devised. The detergent is slowly released from an elastomer pellet to be washed away by the natural waters. The rate of release has been shown to decrease slowly until about 60% of the detergent has been discharge. The rate then assumes an exponential decrease. The application of this technique to a backfilled surface mine site requires careful consideration - the pellets can only have a certain lifetime and may require a form of replenishment. The technique could undoubtedly reduce effluent concentrations and be used to meet local discharge requirements.

Remedial Techniques.

Remedial techniques are devised with an aim to controlling a pollution problem which has already manifested itself. Techniques include limestone neutralisation, biological treatments and treatment by Reverse Osmosis or Ion Exchange methods. All these methods require the construction of a plant and are thus undesirable.

CONCLUSIONS.

Settlement Research.

This study has involved investigations into backfill stability and groundwater recovery on 10 sites in 3 geographical regions of opencast coal mining in the United Kingdom. Investigations have shown that rates of recovery are extremely variable and may even be delayed owing to external influences, (other pumping operations). The review work has shown that a number of workers have reported investigations of a similar nature, and it is the authors' opinion that these should ultimately be supplemented by further observations into a statistical model. An attempt thereby being made to predict likely post-restoration movements. The measurement of shear displacements as well as vertical settlement have been of value in indicating that lateral movements may actually exceed vertical displacements in magnitude - of importance in post-mining structural development. The study has also shown the timescales which may be involved in time-dependent backfill settlements. Fills have been reported to still be moving up to 24 years after placement, and may substantially move even after groundwater recovery has completed. Of great importance has been to show that some sites do not exhibit substantial movement at all and are in fact quite stable under the normal conditions of no surface structural load.

Water recovery rates an magnitudes can be predicted qualitatively from a knowledge of the following criteria;

- i). Pre-mining piezometric surface.
 - ii). Depth and areal extent of site.
 - iii). Position of old deep mine workings and whether they are discharging or draining water, or lined with clay seals.
 - iv). Knowledge of external influences, e.g. adjacent opencast mines, underground mines etc.
 - v). Degree of fill compaction - related to backfill placement method. Less permeable fills will reduce the rate but not necessarily the total degree of groundwater recovery.
- b). Magnitudes and rates of backfill settlements have been observed to be influenced by the following;
- i). The recovery of the natural groundwater table. The level of the water table has been observed to be associated with collapse settlement.
 - ii). Backfill depth, (although often nullified in cases where significant recovery has occurred or where some form of compaction or restraint, (e.g. highwall), has been involved).
 - iii). Composition of backfill and mining method. Mudstone fills have been observed to undergo collapse settlement followed by small non-differential settlements. Sandstone, dragline fills tend to contain larger boulders at the base of the fill than truck-shovel fills, and consequently may undergo greater magnitudes of settlement.
 - iv). Site features. Monitoring of settlement of a compacted haul road, (site A), showed that the fill in this area was unaffected by the presence of the rising water table. In addition, settlements were substantially lower in this area than on any other part of the site.
 - v). Time. The timespan of backfill settlement has been observed to be very variable. Settlements have been recorded in a fill 11 metres deep, 24 years old, for which no adequate explanation can be proffered. The data presented in this thesis are insufficient to construe any firm conclusions as to the time effect of total backfill movement.

Factors to be considered in the prediction of backfill settlement.

In assessing the suitability of a site for structural development the above general conclusions in addition to the observations presented in this paper and other works must be borne in mind.

It is the opinion of the authors that the following measures must be taken for any surface development on backfill material.

a). A comprehensive instrumentation scheme consisting of at least piezometers and surface levelling stations. Both lateral and vertical displacements must be measured. The scheme should commence at least one year prior to construction to enable a full picture of the fill movements to clarify.

b). A thorough investigation into the position of the water table and

the determination of any external influences e.g. deep mine pumping which may result in a delayed recovery phenomenon.

c). An investigation into the location of deep mine workings from which subsidence movements may be mistaken for fill displacements.

d). Proposed structures should not be constructed over solid ground/fill interfaces, e.g. highwalls, nor over fill areas where substantial fill depth changes occur, i.e. benches or seam limits. If possible structures should lie over backfill of a uniform thickness. This suggestion may be modified for service lines which can contain flexible joints.

Pollution Research.

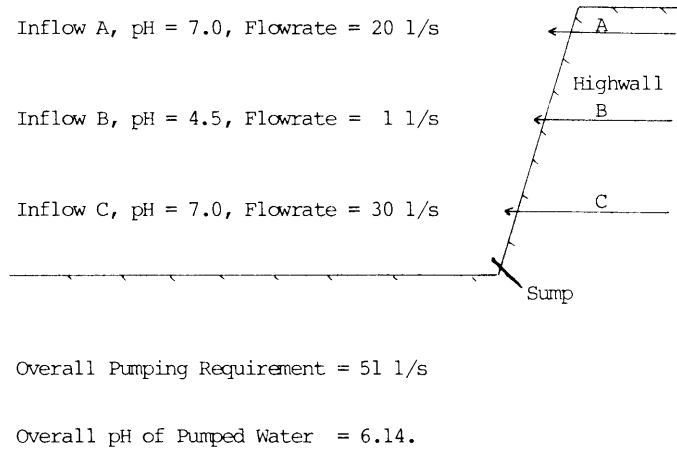
The application of clay seals to noxious overburden within the backfill of a mine is considered the most effective and reliable method of water pollution control. Other techniques such as limestone placement/ injection have been found to be too speculative and unsatisfactory. The key to pollution prevention lies in either reducing water flow or oxygen supply to the backfill mass. Clay seals will prevent both, however fill compaction may be considered as this will lower oxygen supply and reduce water flowrates, thus inhibiting the acid forming reaction. A case for the investigation of bacteriacides may exist, if these could inhibit the reaction until a rich vegetative cover could be established. Once this is done then the vegetation would again deprive the spoil of oxygen. This use of bacteriacides, providing the initial dosage and application to the fill was successful would not require bacteriacide replenishment.

Studies throughout the United Kingdom have shown that the Scottish region has a severe problem with the acidity of waters associated with pyrite oxidation. The technique of advance dewatering has been used successfully to enable mining in dry conditions with the advantages of increased slope stability, lower blasting costs etc, with the minimisation of groundwater pollution during mining. Great care must be taken on all sites however to evaluate likely stream re-establishments and the possible qualities of the discharge.

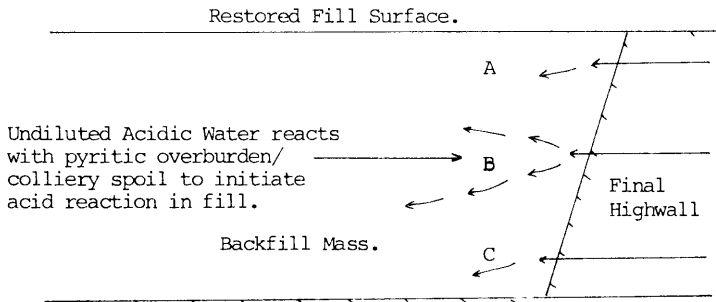
The quality of waters being pumped to settlement ponds elsewhere in the U.K. appears to be quite acceptable. What has been noticed is that as the mines tend to use passive (sump) pumping techniques, the water pumped from the base of the mine may be a mixture of waters from two or three sources, (old workings, run-off etc). The net quality of these waters may well be acceptable but in cases where one small discharge from an old workings horizon is acidic then figure 5 illustrates the problems which may occur as sites throughout England and Wales are selected for the disposal of more pyritic colliery spoil.

The following ideas are suggestions for possible future implementation. They are aimed at predicting a possible pollution problem and at evaluating possible preventative or remedial techniques.

a). The conduction of a pre-mining geochemical survey to assess existing water qualities. In addition to sampling streams, rivers and lakes in the area of the mine, samples of water from exploration drilling boreholes could also be taken. On sites where a pollution problem has occurred or envisaged, than regular water sampling could occur over the life of the mine. This monitoring programme can serve as an "early warning" system against local water pollution. The results may also be able to be used in cases where a surface mine has been blamed for causing



a). Dilution of Acid Drainage in Natural Mine Environment.



b). Dilution effects removed on Restoration.

Figure 5 Possible Scenario for Acid Mine Water Production following Restoration in a Mine previously immune to Water Pollution

water pollution which has in fact originated from another source.

b). For sites which are to be used to reclaim colliery spoil or more pyritic overburden a full geochemical analysis of the inflowing waters must be conducted. To supplement these analyses, some form of leaching tests should be carried out on representative spoil samples in order to determine a potential polluting load. Sites containing acid inflows are considered unsuitable for reclaiming colliery spoil, as a pollution problem may manifest itself which by careful planning may have been avoided completely.

c). On surface mines which are known to have a pollution problem, an estimation should be made of the positions and chemical nature of any spring which may emanate out of the backfill on recovery. On sites where such springs are predicted to occur, the design of clay barriers should be considered in order to force springs to emerge at surface before contact with the contaminating material.

d). On mines operating with advance dewatering methods, samples of spoil should be taken for analysis for polluting materials. Thus it will be known if any serious pollution problem may occur after the water table has recovered.

e). Care should be taken when thin coal seams or ironstone bands are reclaimed into the spoil. Such measures should be examined for their pollution potential, and if need be, selectively reclaimed and isolated from water with clay seals.

f). Some work has been performed in the Scottish Region with the aim of predicting pollution potentials from exploration drilling strata cores. This technique if fully developed could prove an excellent method for determining the overall quality of the water which the mine will have to pump, as well as the final quality of the water in a backfill. These strata cores could also be used for a weathering analysis, monitoring rock degradation with time under laboratory conditions.

g). An investigation into the use of bacteriacides in both the reduction of pollution during operations and in the backfill may enable the design of a cheap and effective method of water pollution control to be devised. This work could be supplemented by an investigation into changes in groundwater geochemistry with time in a restored backfill site. Particularly with respect to the establishment of the vegetative cover.

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