RECLAMATION OF ABANDONED UNDERGROUND MINES IN THE UNITED KINGDOM [1]

David Brook [2]

Abstract: Since 1980, the Derelict Land Grant program has supported reclamation of abandoned mines in the United Kingdom. The stabilization of large-scale limestone mines in the West Midlands has stimulated the development of new methods of bulk infilling using waste materials as thick pastes. Colliery spoil rock paste develops strengths of 10 to 20 kPa to support roof falls and prevent crown hole collapse. Pulverized fuel ash rock paste develops strengths over 1 MPa where lateral support to pillars is required. Smaller scale mine workings in the West Midlands and elsewhere have been stabilized using conventional grouting techniques, hydraulic and pneumatic stowing, foamed-concrete infill, bulk excavation with controlled backfill, and structural support using bolts, mesh, and shotcrete.

Introduction

The United Kingdom has a long history of mining dating from prehistoric flint mines such as those at Grimes Graves in Norfolk. The bulk of British mining activity has been during and since the Industrial Revolution. Britain was at various times the principal world producer of copper, tin, lead and coal. Mining continues today on a much reduced scale.

Mining has taken place at some time in every county in England and Wales and, except for the Western Isles, every region in Scotland (fig. 1), although in some areas it has only been of minor extent. However, reliable records exist only from the last part of the 19th century, and much development has taken place over areas that were previously undermined. The methods of mining (fig. 2) and the general absence of any attempt to stabilize the mines when they were abandoned have resulted in a widespread legacy of potential subsidence.

Britain also has a long history of mining subsidence including the collapse of a large area above a limestone mine in Walsall in 1828 and the sudden collapse of the floor of a house in Norwich in 1853. More recently, on October 19, 1990, an earthquake caused by the collapse of the Tennant salt mine at Carrickfergus, Northern Ireland had a Richter magnitude of 2.5; an area of about 200 by 150 m subsided by up to 8 m in a single event (Griffith 1991).

Examples from Department of the Environment (DOE) research projects illustrate the scale of the problems. In the former limestone mining area of the West Midlands (Ove Arup and Partners 1983), 100 subsidence events in 150 yr have been identified, the majority from mines shallower than 30 m. In the South Wales coalfield (Statham and Treharne 1991) the majority of over 400 subsidence events identified between 1960 and 1993 are associated with mine entries (shafts or adits). In the tin and copper mining area of the Kerrier District in Cornwall (Arup Geotechnics 1990), 41 out of 74 subsidence events recorded between 1974 and 1990 were due to shaft collapse.

Conventional grouting methods have long been used to stabilize land prior to development and following subsidence events. In very few cases, however, was mine filling used to remove the risk of subsidence on a wider scale. In the early 1970's parts of limestone mines beneath Dudley in the West Midlands were infilled by flushing in sand through boreholes to prevent subsidence affecting housing and other development. This was only partly successful, and one or two subsidence-damaged houses over parts of the mines that were infilled have been demolished subsequently. More recent investigation has also shown that there are significant voids within the infilled areas, and a risk of subsidence still remains.

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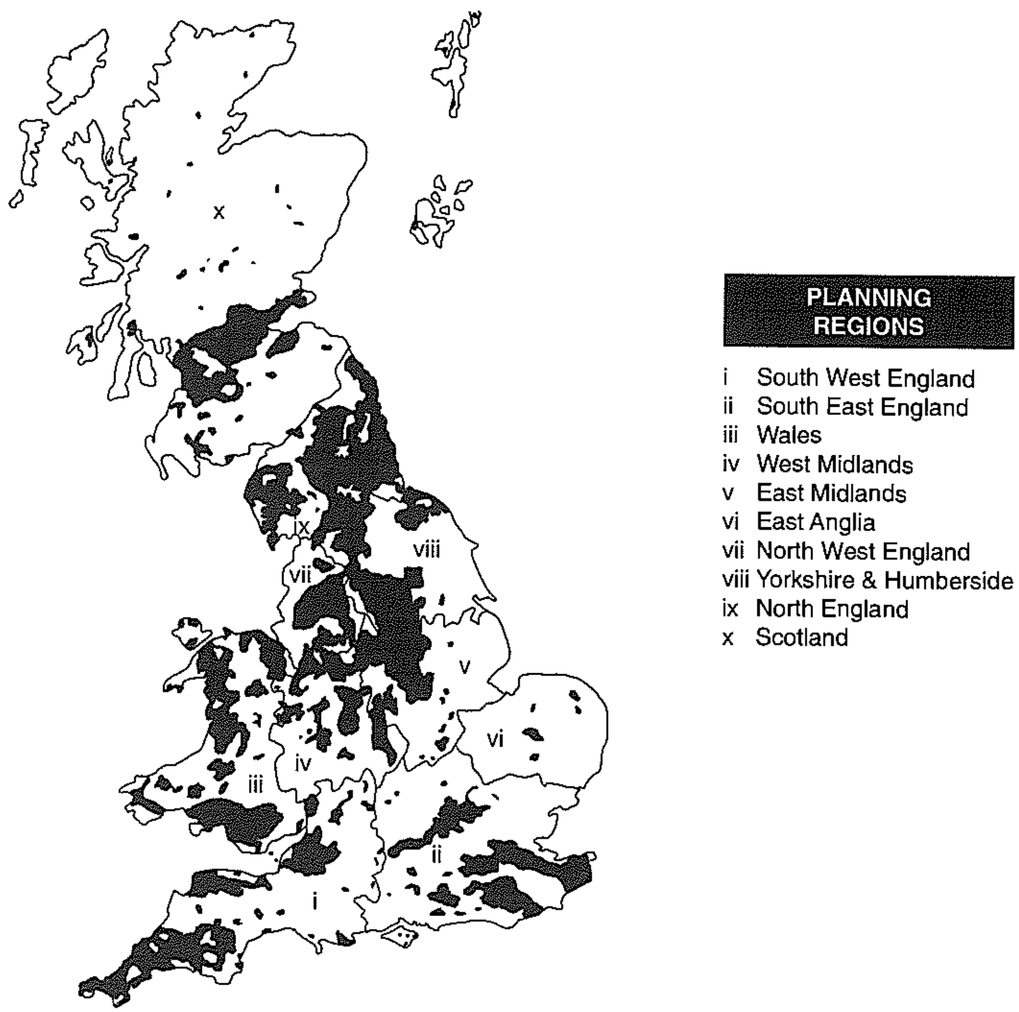

Figure 1. The extent of mining in Great Britain.

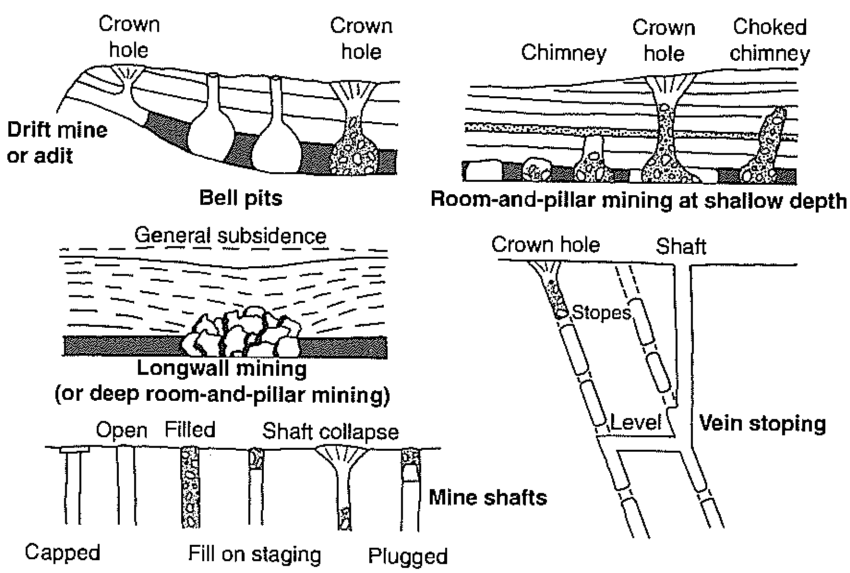

Figure 2. Mining methods and effects on the surface.

Derelict Land Grant

The National Parks and Access to the Countryside Act 1949 conferred powers on local authorities to acquire land and to carry out works to enable derelict, neglected, or unsightly land to be reclaimed, improved, or brought into use. The Local Government Act 1966 extended Derelict Land Grant (DLG) coverage throughout England and allowed a national program of reclamation to be set up based on schemes carried out by county and district councils; in Scotland and Wales, separate Development Agencies carry out such works among others.

DLG is restricted to land that is so damaged by industrial or other development as to be incapable of beneficial use without treatment. The DLG program has achieved the reclamation of substantial areas of derelict surface mineral workings and of spoil heaps and tips, especially those from disused collieries, as well as areas of land already damaged by mining subsidence.

The Local Government Planning and Land Act 1980, now consolidated in the Derelict Land Act 1982, extended the scope of DLG to include land which, though not derelict, is likely to become so by reason of actual or apprehended subsidence due to the collapse of underground mine workings. Abandoned coal mines were excluded because there was already statutory compensation for subsidence damage; their inclusion would also have increased the potential scale of the problems faced by the DLG program.

The 1980 legislation had essentially been triggered by the situation in the West Midlands, where almost 500 ha of the conurbation, including land near the town centers of Walsall and Dudley and substantial residential and industrial development, were potentially at risk from subsidence due to abandoned limestone mines.

The Development of Rock Paste

In 1981, the DOE, together with the local authorities concerned, funded a research study (Ove Arup and Partners 1983) to assess the extent and degree of risk of surface disturbance attributable to old limestone workings in the West Midlands and to consider what remedial action was required. Subsequently, DLG funds were earmarked to permit work on site investigation, monitoring, and remedial works to preserve surface stability above the mines. This Limestone Program has formed a major element in the national DLG program since 1983, and expenditure is currently about £10 million per year.

The scale of these old limestone mines, with rooms up to 11 m high, extraction ratios of the order of 75% to 80% and individual mine volumes of up to 500,000 m^3, at depths of up to 200 m, meant that conventional grouting techniques would be prohibitively expensive and alternative means of stabilization were needed.

Since there were considerable amounts of waste materials from coal mining in spoil heaps in the West Midlands area, which could be available at a nominal price, it was suggested that these should be examined as a potential bulk filling material. This would have dual environmental benefits in enabling the risk of subsidence to be removed at the mine sites and in reclaiming derelict spoil heaps at the source sites.

Flushing of this material into the mines with water would require large numbers of boreholes and the disposal of large amounts of contaminated water, and might not achieve the desired objectives. It was therefore proposed that the colliery spoil should be injected through boreholes as a thick paste able to flow considerable distances within the mine (fig. 3) and to achieve complete filling to the mine roof even at high points where some roof collapse had already occurred.

While the pumping requirements would dictate the need for a low strength paste, consolidation within the mine would increase the strength sufficiently for its use to be effective. The objective was not that the paste should be load-bearing but that it should fill the mine voids and provide sufficient strength to support material falling from the roof, enabling developing chimneys, which could otherwise propagate as crown holes to the surface, to become effectively self-choking.

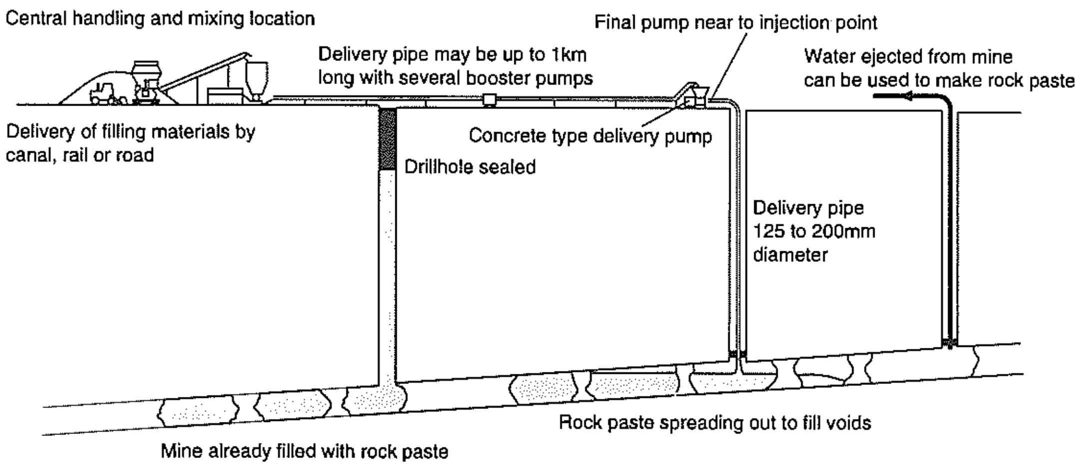

Figure 3. Rock paste infilling as originally proposed.

Through its research program and the DLG program, the DOE has funded the development of this novel method of mine infilling, designated rock paste, since 1982. Small- and large-scale pumping trials and heap spreading experiments were carried out by the Building Research Establishment (Hills 1983, Hills and Ward 1985, Ward and Hills 1985).

Small-Scale Pumping Tests

Exploratory trials included the measurement of spoil properties before and after mixing and pumping, methods of mixing the spoil and water, and the pumping of mixes of different water contents and size gradings round a 26-m-long, 125-mm-diameter pipeline at about 15 m^3/h using a small concrete trailer pump. These trials showed that spoil could be mixed satisfactorily in a pan mixer to produce pumpable mixes with water contents in the range 13% to 38%, shear strengths of 1 to 6 kPa and consolidation of 4% to 20%.

Large-Scale Pumping Tests

In the large scale trials, 1000 mt of colliery spoil was mixed with 30% to 45% water and pumped through pipelines of 125- and 260-mm diameter at rates of up to 80 m^3/h and over distances of up to 220 m using standard construction equipment. Handling, mixing and pump and pipeline performance were examined, and the results provided the basis for the specification of a subsequent field trial at a mine site in the West Midlands.

Spreading Tests

During these trials, small heaps were pumped out onto an approximately level surface, and measurements taken of the central height and horizontal spread of the heap, with penetrometer measurements to indicate the shear strength of the rock paste. At the end of the trials, two larger heaps (up to 100 m^3) were pumped out, one onto an approximately level road surface and one onto a sloping grass field. These experiments showed that the paste flowed over surfaces as a self-weight mass obeying the theory of plasticity, except when its undrained shear strength was exceptionally low (<0.3 kPa). Flow within the mine could be expected to be up to 60 m. Based on small-scale laboratory tests, it was estimated that typical pastes would consolidate <0.5 m with 90% consolidation in 2 to 12 yr.

Examination of the capacity of the paste to prevent roof collapse suggested that when the paste is in contact with the mine roof, even the weaker pastes would provide adequate support. However, as the gap increases to 0.5 m the weaker pastes would not provide support even with a large bulking of the collapsed rock. With a stronger paste or a smaller gap, the simple model used for analysis showed that collapse would terminate within about 2 m of the original roof.

Trial Infill

A fully instrumented trial infilling of part of the Castlefields Mine in Dudley was carried out in 1985. This site was chosen because the workings were at shallow depth (18 to 24 m) and drained, enabling access to inspect the mine, install barriers to contain the rock paste, and install instruments to measure the progress of infilling.

About 6,600 m^2 of 4-m-high workings with an extraction ratio of about 80% were isolated by a reinforced concrete wall flanked by grouted gravel dams (where the roof condition was too dangerous to allow access). Colliery spoil, screened to minus 50 mm, was transported 35 km to the site by road, mixed with water extracted from the flooded part of the mine, and injected into the mine via two boreholes at a mean rate of 53 m^3/h. Over a period of 3 months, 29,100 m^3 of rock paste were placed, and the practicability of the method was successfully demonstrated. Rock paste within the mine behaved broadly as predicted, flowing around mine pillars and rising into chimneys in the mine roof.

Modified Rock Paste

Postinfill monitoring of the Castlefields trial showed excessive consolidation (15%) of the rock paste within the mine, probably due in part to underdrainage due to a layer of sand (overflow from earlier infilling by sand flushing in an adjacent area) on the floor of the mine. The results also indicated that the long-term strength would not be sufficient to prevent surface collapse and that topping up of voids due to consolidation would be required.

To reduce consolidation and ensure reliable long-term strength, testing of rock paste mixes with various additives was carried out between 1985 and 1987. The results led to the development of a modified rock paste (Cole and Figg 1987) comprising colliery spoil with about 4% pulverized fuel ash (pfa) and 1.5% to 3.0% lime, depending on the ultimate strength requirements. For straightforward bulk infilling (i.e., with no requirement to provide lateral support to pillars), the design strength after one year ranges from about 10 to 20 kPa compared to the strength of 2 to 4 kPa required for the paste to be pumped and achieve maximum dispersion within the mine.

Mine Infilling Using Modified Rock Paste

The concepts described were first applied to flooded workings at the Littleton Street Mine in Walsall. In 1986-88, 500,000 m^3 of 4- to 8-m-high room-and-pillar workings at 35 to 60 m below surface with a plan area of about 13 ha were filled with modified rock paste via only 13 injection holes at a cost of £6 million. The mixing process is shown diagrammatically in figure 4. Full monitoring of all materials and paste produced was undertaken, and the infilling process was continually monitored from the surface. Postinfill monitoring using piezocone tests (Braithwaite et al. 1988) confirmed that the 20-kPa design strength was achieved. The 600,000 mt of colliery spoil required was won from three derelict spoil heaps, which, on completion of operations, were restored for future amenity use.

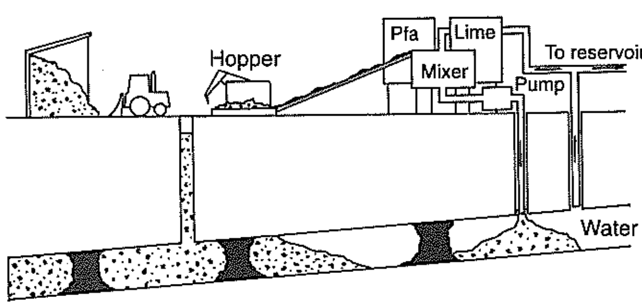

Figure 4. Modified rock paste infilling

Modified rock paste has also been used to infill 77,350 m^3 of the Castlefields Mine, Dudley (including topping up the adjacent trial infill area) in 1987-88 and 110,000 m^3 at the Arboretum and Moss Close Mines in Walsall in 1989-91. Together with the Littleton Street infilling, these works have allowed the removal of the threat of subsidence from about 30 ha of land variously used for residential, industrial, and commercial purposes.

Pfa Rock Paste

Where the quantity of infill required has been too low to justify the cost of plant at source and infilling sites required for colliery spoil rock paste, a pfa rock paste with about 4% cement has been used. This method has been used successfully to infill small mines at Lincoln Hill (20,600 m^3), Ironbridge in 1987; at Bear Pit cavern and part of the East Castle Mine (58,000 m^3), Dudley, in 1988; at Broadway Cavern (94,000 m^3), Dudley, in 1989; and at the Cinder Hill Mines (20,000+ m^3), Wolverhampton, in 1992-93.

Pfa rock paste can also achieve far greater strengths, in excess of 1 MPa, and has been used in situations where pillars are over-stressed and support other than preventing roof falls is required. It has been used successfully at the Castlefields Mine (160,000+ m^3), Dudley, and three large contracts are currently in progress to infill the Wolverhampton Street Mine (360,000 m^3), Walsall, the Cow Pasture Mine (216,000 m^3), Sandwell, and the remainder of the Castlefields Mine (about 250,000 m^3).

With time, it has been found that colliery spoil is less readily available than was previously thought. It is also a very variable material, particularly in comparison with pfa, which is essentially homogeneous, and it is currently proving to be more expensive than pfa, in contrast to the position a few years ago. Pfa rock paste is, therefore, now the preferred material. Each infilling scheme is, however, assessed on its merits, and the choice of infill material requires a full evaluation of the scheme requirements and the availability and cost of materials.

Other Methods of Reclamation

The rock paste infilling of limestone mines in the West Midlands has been the major focus of reclamation of underground mine workings in Britain. However, the problem of potential subsidence is widespread, and a number of other methods have been used in different areas. Many of these have been funded through the DLG program, whilst others have been funded by the landowner or developer.

Grouting of Coal Mine Voids

As part of a study of mining subsidence (Statham and Treharne 1991), 39 grouting contracts carried out throughout the South Wales coalfield were examined. Site areas ranged from 250 to 70,000 m^2 with grout takes from nil to 29,000 mt (i.e., 0 to 20,700 m^3). Typical grout mixes were 9:1 or 10:1 pfa-cement with 5:4:1 pfa-sand-cement at the site perimeter and additional pea gravel when significant voids were encountered. Borehole spacing was largely on a 6-m primary grid with infill at 3-m centres but the primary grid ranged from 3 to 10 m and the infill grid from 1.5 to 5 m. Borehole depths were generally in the range of 10 to 30 m but some grouting was undertaken at depths as shallow as 5 m and some as deep as 60 m. Borehole diameter was generally 50 mm though occasionally 100-mm boreholes were used through superficial deposits.

There was little or no grout take in 11 of these contracts, raising serious doubts about the justification for grouting. In those contracts with significant grout takes, residual voidage was calculated to vary from <10% to almost 60%. Grout takes ranged from <1 to >100 mt per borehole, suggesting that collapsed (or back-stowed) stalls accepted very little grout, while roadways, which tend to remain open for many years after mining, were capable of accepting large quantities. This confirms the analysis of subsidence events referred to earlier.

Hydraulic Sand Infilling

At Corbridge, Northumberland, galleries in a fireclay mine, typically 1.5 to 2.0 m wide but up to 3 to 4 m, underlay a site proposed for housing with about 0.5 m of intact limestone cover supporting about 6 m of quarry waste fill (Witherington 1988). Conventional grouting, excavation, and bulk replacement and supporting the houses on deep pile foundations were considered and rejected, and hydraulic sand infill was used to stabilize the land prior to development.

Grouted gravel barriers were used to seal the site and to provide additional support in areas with large roof spans, and the mine was divided into four zones by ungrouted gravel barriers. A uniformly graded fine sand byproduct resulting from coarse aggregate production at a local quarry was hydraulically flushed into the mine via 200-mm-diameter boreholes. Progress was checked by visual inspection, probing, and downhole video inspections, and piezometers were installed to check the drainage of the sand. On completion of sand filling, closely spaced check holes were grouted to infill any residual voids. The total cost was £20/m^3 compared with the estimate of £30/m^3 for conventional grouting techniques.

Pneumatic Stowing of Sand Mines

At Reigate, Surrey, lightly cemented sands of the Lower Greensand (Cretaceous) were mined by room and pillar methods in the 18th and 19th centuries. Two-metre-high rooms with a cover ranging from 2 to 8 m occur beneath roads, houses, and commercial properties in the town centre. In the light of the subsidence history in the town and following a stability survey, parts of the mine were infilled in 1987-88.

To preserve the stability of the surrounding sand, it was necessary to maintain the natural moisture levels of 10% to 12% and a free-draining granular material was specified to be placed by pneumatic stowing. Early trials with waste sand were unsatisfactory owing to clogging of placement hoses. Waste gravel (minus 20 mm) from a nearby fullers' earth quarry was used with success but could not be supplied at a sufficient rate. Finally crushed concrete from demolition work in London was successfully used. The investigation, infilling, and other treatment works (retaining structures, strengthening of pillars) were jointly funded by Reigate and Banstead District Council and the DOE using DLG at a cost of £500,000. Subsequently a wine bar located within the mines beneath a busy main road was acquired and filled.

At Pontefract, West Yorkshire, a previously unknown mine in Lower Permian Sands at 10 m below surface was investigated following subsidence damage to houses. It was found to extend beneath much of the housing estate. In 1991 a trial infill was carried out using pneumatic stowing of 10-mm clean limestone chippings down previously drilled 100-mm-diameter investigation boreholes. The delivery pipe could be rotated to ensure even filling, and up to 95% fill was achieved. 230 mt of material was stowed in 1week at a cost of £10,000 using DLG funding.

The entire mine was subsequently filled by this method, using approximately 5,000 mt of limestone chippings, together with grouting of collapsed areas, at a cost of about £200,000 using DLG funding.

Foamed Concrete Infilling of Chalk Mines

In the City of Norwich, the collapse of a road beneath a double decker bus and other incidents led to the investigation and treatment of ancient chalk mines at shallow depth. Foamed concrete, a stable preformed foam mixed with sand, cement, and water, was used in preference to grout because it was fluid when pumped but also thixotropic, thus minimizing seepage losses into fissures in the chalk. At a cost of about £90,000, 762 m^3 of foamed concrete was injected. The work was funded jointly by the City Council and the DOE using DLG, with a small contribution from a commercial property owner whose building is above the mine.

Bulk Excavation of Shallow Coal Mines

In many parts of the coalfields, ancient workings are sufficiently near the surface that the most economical method of stabilization is to excavate down to the floor of the workings with controlled backfill to allow development to proceed. The value of the coal extracted is often sufficient to meet the costs of excavation and backfill. At Coatbridge, near Glasgow, this method has saved £4 million over conventional ground treatment techniques in the reclamation of 12 ha of derelict land. The £2.5 million Scottish Development Agency contract is being subsidised by coal sales of about £500,000.

Stabilisation of Voids for Other Uses

A viable alternative to infilling in some cases has been the stabilization of underground voids to allow the underground space to be used. A number of show mines where coal, lead, copper, tin, and limestone were formerly mined have been so treated. In the West Midlands, the Singing Cavern, Castle Hill, Dudley, was stabilized using rock bolts and mesh, and new canals were constructed from the 18th century Dudley Canal to enable a popular tourist attraction to be added to the Black Country Museum. Across the road at Dudley Zoo, a similar walk-in attraction is being created.

Proposals for Treatment of Bath Stone Mines

At Combe Down, in the City of Bath, about 400,000 m^3 of room and pillar workings extend to some 16 ha beneath residential areas at 4 to 8 m below the surface. Following a survey and hazard assessment, a proposal to infill these workings with pfa faced objections from the local community because of the disruption it would cause, the perceived threat to ground water from using pfa, the damage to ecologically valuable open space above the mine if used as a plant site, the destruction of the industrial archaeological heritage, and the threat to a significant colony of Greater Horseshoe Bats, which use the mine for roosting and hibernation; bats are a protected species under the Wildlife and Countryside Act 1981.

Consequently, a feasibility study and environmental assessment were commissioned by Bath City Council (50% funded by DLG). Subject to the environmental assessment, it recommends that 220,000 m^3 (11 ha in plan area) need to be infilled; structural support using fiber-reinforced shotcrete sprayed in place by machine, supplemented in some areas by grouting roof cavities and dowelling, would be feasible over about 3 ha; and, subject to monitoring and any necessary remedial action, a low-risk area of about 2 ha beneath the open space area would require only localized work. This strategy would reduce the impact of the works, particularly with respect to the disruption to the local community and the preservation of the industrial archaeological heritage. Leaving parts of the mine open would also allow the bats to continue to use the mine and would be cheaper than a total infill solution. The estimated cost is £20 million if pfa is used and £29 million for a non-pfa infill, compared with £21 million and £38 million for a total infill operation.

Summary and Conclusions

Britain's long history of mining has led to a widespread legacy of potential subsidence. Legislation enacted in 1980 has enabled the reclamation of underground mines to progress from the individual development site or subsidence event basis to the treatment of mines on a wider scale to remove the threat of subsidence through the Derelict Land Grant program.

The major effort has focused on old limestone mines in the West Midlands, where the scale and potential threat are large, and it has involved the development of new methods of infilling using rock paste based on colliery spoil or pfa as opposed to conventional grouting techniques. These methods have enabled waste materials to be injected into mines through widely spaced boreholes to remove the threat of subsidence beneath existing development and areas for redevelopment. Where the scale of workings is smaller, both in the West Midlands and elsewhere, a number of other techniques have been used successfully.

The DLG program has been administered to date by the Department of the Environment. In 1994, however, administration will pass to the newly formed Urban Regeneration Agency, now known as English Partnerships. This agency will aim to promote development by regenerating land and buildings, to create employment through local enterprise and inward investment, and to improve the environment. It will honour the DLG commitments it inherits and ensure that these projects are completed properly, and it is expected to maintain a commitment to the reclamation of underground mine workings.

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