

Field Trial of Resin-Based Composite Materials for the Treatment of Surface Collapses Associated with Former Shallow Coal Mining

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II. BACKGROUND

Abstract—Effective treatment of ground instability is essential when managing the impacts associated with historic mining. A field trial was undertaken by the Coal Authority to investigate the geotechnical performance and potential use of composite materials comprising resin and fill or stone to safely treat surface collapses, such as crown-holes, associated with shallow mining. Test pits were loosely filled with various granular fill materials. The fill material was injected with commercially available silicate and polyurethane resin foam products. *In situ* and laboratory testing was undertaken to assess the geotechnical properties of the resultant composite materials. The test pits were subsequently excavated to assess resin permeation. Drilling and resin injection was easiest through clean limestone fill materials. Recycled building waste fill material proved difficult to inject with resin; this material is thus considered unsuitable for use in resin composites. Incomplete resin permeation in several of the test pits created irregular ‘blocks’ of composite. Injected resin foams significantly improve the stiffness and resistance (strength) of the un-compacted fill material. The stiffness of the treated fill material appears to be a function of the stone particle size, its associated compaction characteristics (under loose tipping) and the proportion of resin foam matrix. The type of fill material is more critical than the type of resin to the geotechnical properties of the composite materials. Resin composites can effectively support typical design imposed loads. Compared to other traditional treatment options, such as cement grouting, the use of resin composites is potentially less disruptive, particularly for sites with limited access, and thus likely to achieve significant reinstatement cost savings.

The use of resin composites is considered a suitable option for the future treatment of shallow mining collapses.

Keywords—Composite material, ground improvement, mining legacy, resin.

I. INTRODUCTION

HISTORIC coal mining in the United Kingdom (UK) has resulted in areas of unstable land. The Coal Authority has undertaken a field trial to investigate the potential use of composite materials comprising resin and fill or stone to treat surface collapses, such as crown-holes, associated with shallow coal mining. The trial aimed to assess whether the resin composites can achieve the required strength and settlement characteristics as well as structural adequacy under the minimum required design loading.

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The Coal Authority manages the effects of past coal mining in the UK, including those subsidence damage claims that are not the responsibility of licensed coal mine operators.

The Coal Authority owns and manages over 26,000 km² of underground coal mine workings. In Britain, 8 million properties sit on the coalfield. Of these, 130,000 have a mine entry either on their property or within 20 m of their boundary. There are over 172,000 known mine entries (shafts and adits) across the UK.

The Coal Authority adopts a risk-based approach to the management of ground instability and mine entry hazards. Services provided by the Authority include:

- inspection, assessment and management of mine shafts, adits, shaft caps, tips and other mining structures;
- provision of monitoring and action plans to mitigate impacts and protect the public and the environment;
- emergency planning and response advice and provision; and
- design and installation of short-term and long-term engineered solutions (including capping, grouting, drainage works, ground and slope stabilization).

The Coal Authority responds to over 1000 hazard and subsidence claims each year. Developing more efficient and cost-effective methods of treating ground instability is a key priority for the Coal Authority.

Resin grouts have been used since the 1960s [1]. However, resin materials have been utilized by the Coal Authority on an infrequent basis to date, mainly as a void filler to treat shallow ground collapses. The Coal Authority identified a need to quantitatively corroborate the performance of resin foams to provide greater confidence in specifying the use of these materials when treating surface collapses associated with historic shallow coal mining. The research also aimed to investigate the use of resin foams in conjunction with other materials to enhance the properties of both. Presumptive strength values for granular soils treated with chemical grouts are not reliable, and it is recommended that testing is undertaken for each particular grout type-soil combination [2]. Therefore, when planning the field trial, the focus was on trialling grout types and fill materials readily available to, and thus most likely to be used by, the Coal Authority.

III. METHODOLOGY

A. Fieldwork

The field trial was undertaken at the former Strafford Colliery, near Barnsley in Yorkshire, UK.

Nine test pits (TP01 to TP09) were excavated, with dimensions 1.5 m wide, 1.5 m long and 1.5 m deep.

The near-surface ground conditions at the trial site comprise made ground, predominantly consisting of colliery spoil. The uppermost horizon of the made ground comprised up to 1.2 m of sandy to very gravelly clay. The clasts generally comprised brick, mudstone, coal and burnt shale with some fragments of wood, metal and fabric. Underlying the clay horizon, clayey, sandy gravel was encountered to below the depth of interest (1.5 m, the specified depth of the test pits). The gravel generally comprised fragments of mudstone, burnt shale, sandstone and coal with some brick, glass and tile fragments. No groundwater was observed within any of the pits.

Infill material was discharged directly into eight of the trial pits from a dumper truck in order to replicate the method of filling likely to be adopted in practice. Four different infill materials were selected to be trialled: 10 mm pea gravel, 40 mm single-size clean limestone, 75-150 mm clean limestone and 6F2¹ graded recycled material derived from demolition rubble. The infill materials selected, with the exception of the 6F2 graded recycled material, are already commonly used by the Coal Authority as standard fill materials when treating voided ground. Recycled material was also selected for trial as a potential fill material because it is commonly available on sites, especially where demolition of damaged structures is required prior to ground treatment. Each type of fill material was placed in two test pits.

Commercially available resin foam products were utilized during the trial. Two different resin types were trialled on each of the four fill materials: silicate foam² and polyurethane foam³. Resin injection was undertaken using a hand-held rotary percussive rig, R25 self-drilling hollow bars (lances) and SK90 gear pumps. The resin curing period was a minimum of 24 hours. In addition, the final test pit was filled using phenolic foam⁴.

Super-Heavy Dynamic Probe (DPSH) testing of the infill material was undertaken *in situ* before and after resin treatment. The DPSH testing was undertaken in general accordance with BS EN ISO 22476-2 [4]. The DPSH was driven to the full depth of the test pits (1.5 m) while recording the number of blows for each successive 100 mm penetration (N_{10}).

Plate tests using a 0.6 m diameter plate were undertaken post-treatment. The plate load testing was undertaken *in situ* in accordance with BS 1377: Part 9: 1990 [5]. The adopted plate size provided a stressed depth range of approximately 1 m. Pressure was loaded in five increments, nominally 6, 12, 18,

24 and 30 kN/m². Thereafter, the loading was increased steadily until the maximum available load from the 8 tonne excavator was applied or until the ground failed (i.e. excessive settlement was observed).

At the end of the field trial, the resin-treated test pits were excavated so that the patterns of resin migration through the fill material could be assessed in more detail.

B. Laboratory Analysis

Representative samples of the four fill materials underwent particle size distribution analysis to assess conformity with the material specification.

Samples of the composite materials underwent unconfined compressive strength testing. Samples of the composite materials were created in the laboratory as the material cannot be readily cored without affecting its properties.

Three different methods for creating composite samples for laboratory testing were trialled:

1. The fill material was placed in plastic pipes, then resin was injected. The injection process displaced fill material from the pipe, leaving pure resin with the pipe. This method was consequently aborted.
2. The fill material was placed in steel casing, then resin was injected. The high pressure and constrained environment resulted in the resins not foaming properly, leading to samples not curing in a representative manner. Thus, this method was also aborted.
3. The fill material was placed in plastic pipe capped with metal grills to confine the sample material within the pipe, then resin was injected. This method produced the best samples but there is still some residual uncertainty as to how representative these samples were of resin composites created in the field.

Triplicate samples of composite materials were produced using the third method for combinations of 10 mm pea gravel and clean limestone with both types of resin. Owing to the large aggregate size and the constraints of the testing equipment available, it was not possible to prepare representative samples of composites using 75-150 mm clean limestone that would be suitable for unconfined compressive strength testing. Unconfined compressive strength testing of composites made from 6F2 graded recycled material was not considered worthwhile based on the field test results.

IV. RESULTS

A. Fill Material Conformity

Particle size distribution analysis confirmed adherence with the material descriptors with the exception of the material specified as 40 mm single-size clean limestone, which was found to range in size evenly between 14 and 37 mm.

B. Resin Take

The fill materials that were easiest to drill and inject with resin were the 14-37 mm clean limestone and 75-150 mm clean limestone. Resin foam takes for each combination trialled are presented in Table I.

¹ The specification for 6F2 graded recycled demolition material was as per Table 6/2 of the Manual of Contract Documents for Highway Works [3].

² Willkat silicate foam (foam factor x50)

³ Strata Bond HF polyurethane foam (foam factor x10)

⁴ Mine-Fill phenolic foam (foam factor x55)

TABLE I
FOAM RESIN TAKES

Test Pit	Fill Type	Resin Type	Resin Foam Take (kg)
TP01	10 mm pea gravel	Silicate foam	200
TP02	10 mm pea gravel	Polyurethane foam	165
TP03	14-37 mm clean limestone	Silicate foam	225
TP04	14-37 mm clean limestone	Polyurethane foam	195
TP05	6F2 graded recycled material	Silicate foam	40
TP06	6F2 graded recycled material	Polyurethane foam	35
TP07	75-100 mm clean limestone	Silicate foam	335
TP08	75-100 mm clean limestone	Polyurethane foam	260
TP09	No fill	Phenolic foam	80

The 6F2 graded recycled material fill proved very difficult to inject with either resin. This was evidenced by the small quantities of accepted resin foam (Table I); the resin foam did not surface. As a consequence, no test samples of the 6F2 graded recycled material/resin composites were prepared for laboratory analysis.

C. Resin Migration

Incomplete resin penetration was observed in several of the excavated test pits. In several pits, the injected resin foam has migrated along preferential lines of weakness within the freely tipped and un-compacted fill material to form irregular shaped 'blocks' of composite (Fig. 1).

Resin foam permeation was very poor through the 6F2 graded recycled material, consistent with what was expected given the low resin take results.

Resin foam permeation was poor through the 10 mm pea gravel fill. The polyurethane foam permeation was slightly better than the silicate foam permeation. In both cases, the resin did not permeate the entire test pit. It is suggested that closer injection points and/or increased resin foam reaction times may improve resin permeation through pea gravel.

The resin foam migration was more extensive through the 14-37 mm limestone fill but minor untreated areas remained.

Resin foam permeation was good through the 75-150 mm limestone fill, forming well-defined monolithic cubes.



Fig. 1 Photograph of excavated TP02 showing polyurethane resin foam migration through 10 mm pea gravel fill

D. Material Properties

1. Field Measurements

The injected resin foams significantly improved the stiffness and resistance (strength) of the fill materials.

a. DPSH Testing

DPSH testing provides an indication of material stiffness and strength. The results of the DPSH testing are presented in Table II.

TABLE II
DPSH TEST RESULTS

Parameter	Fill Type			
	10 mm pea gravel	14-37 mm clean limestone	6F2 graded recycled material	75-150 mm clean limestone
<i>Before resin foam injection</i>				
Maximum blows per 100 mm (N_{10})	1	2	3	12
Maximum total blows to 1.5 m depth	3	9	14 ^a	98
<i>After resin foam injection</i>				
<i>Silicate foam</i>				
Maximum blows per 100 mm (N_{10})	1	9	1	14
Maximum total blows to 1.5 m depth	2	62	7	141
<i>Polyurethane foam</i>				
Maximum blows per 100 mm (N_{10})	1	5	1	29
Maximum total blows to 1.5 m depth	5	49	4	195

^a Total blow count adjusted for probable anomalous material in base of pit.

The resin composites based on 14-37 mm clean limestone fill showed the greatest improvement in DPSH test results after resin treatment. However, the incomplete resin permeation must be taken into account in relation to the post-treatment DPSH results. In particular, the DPSH results for the composites made using 10 mm pea gravel are considered likely to be underestimates owing to the observed geometry of the resin permeation post-excavation compared with the DPSH test locations. Particle size and roundness influence how the fill compacts during placement, consequently influencing resin migration and thus material stiffness.

b. Plate Load Testing

The results of the plate load testing are presented in Table III. The plate load testing provides an indication of a material's ability to resist immediate elastic deformation (deflection) under load.

The maximum applied bearing pressures achieved by the materials exceeded typical design loads adopted by the Coal Authority; a variable action (imposed load) of 10 kN/m² is assumed for the treatment of shallow mine workings in most domestic situations.

Upward displacement of near-surface clasts was observed on site during resin injection. This phenomenon is interpreted to have potentially affected the accuracy of the plate loading test results. The separation of the near-surface clasts has the

potential to allow increased compression and deformation of the treated fill material located directly below the bearing plate. This is a potential concern when considering structural or building loading or for future unrestricted access over the treated ground.

The type of resin foam does not appear to be a significant factor in determining the elastic stiffness of the materials.

TABLE III
PLATE LOAD TEST RESULTS

Parameter	Fill Type				
	10 mm pea gravel	14-37 mm clean limestone	6F2 graded recycled material	75-150 mm clean limestone	No fill
<i>Silicate foam</i>					
Maximum applied pressure (kN/m ²)	199.3	200.2	99.6	169.6	-
Maximum deformation (mm)	10.6	8.9	21.4	9.7	-
Modulus of sub-grade reaction (MN/m ³)	56.6	31.7	17.3	11.7	-
<i>Polyurethane foam</i>					
Maximum applied pressure (kN/m ²)	148.8	96.2	99.4	100.0	-
Maximum deformation (mm)	5.8	11.8	17.5	13.1	-
Modulus of sub-grade reaction (MN/m ³)	45.2	31.9	15.2	12.3	-
<i>Phenolic foam</i>					
Maximum applied pressure (kN/m ²)	-	-	-	-	100.5
Maximum deformation (mm)	-	-	-	-	11.4
Modulus of sub-grade reaction (MN/m ³)	-	-	-	-	13.0

The results for the phenolic foam alone with no fill are similar to those observed for the 75-150 mm fill composites. This is considered to be consistent with the hypothesis that the stiffness of the treated fill material is a function of the particle size and pore size.

2. Laboratory Testing

The results of the unconfined compressive strength testing are presented in Table IV. This testing provides an indication of the capacity of a material to withstand loading.

The unconfined compressive strength values recorded are higher for the resin-fill composites than manufacturer values for the resins alone. The composites are broadly comparable in terms of strength to extremely weak to weak rock.

Visual observations suggested that the samples of the resin-fill composites created in the laboratory may not have been representative. Some of the samples had a vitreous texture, suggesting that limited foaming had occurred. Restrictions on foam expansion may have resulted in a more concentrated and stronger form of resin than might be created in the field. Thus, the compressive strength test results may potentially overestimate the properties of resin composites.

TABLE IV
UNCONFINED COMPRESSIVE STRENGTH TEST RESULTS FOR RESIN FOAM – FILL COMPOSITES

Fill type	Resin type					
	Silicate foam			Polyurethane foam		
<i>10 mm pea gravel</i>						
Test results	1.51	2.07	2.83	4.75	5.11	12.50
Average	2.14			7.55 ^a		
<i>14-37 mm clean limestone</i>						
Test results	3.89	3.55	4.22	0.67	0.85	0.97
Average	3.89		0.83			

a If the average is recalculated by weighting according to the lower values in the range, this would give a revised value of 4.99 N/mm²

V. INTERPRETATION

The stiffness of the resin-fill composite materials is interpreted to be a function of the stone particle size and its associated compaction characteristics (under loose tipping) and the proportion of resin foam matrix. The type of fill material is considered to be more critical than the type of resin to the geotechnical properties of the resultant composite materials.

Fill types with larger clast sizes allowed better permeation of the resin foams within the stone matrix. This is interpreted to be due to the larger pore and pore throat sizes associated with larger clast sizes. The better resin permeation means the proportion of the material that is resin foam matrix is also increased. Therefore, the resin foam has greater significance on the geotechnical properties of the composite material. This results in reduced stiffness (strength) and immediate elastic deformation (deflection). In contrast, the smaller pore and pore throat sizes of the finer-grained materials constrained resin migration. However, this could be mitigated by adopting closer resin injection points and/or increased resin foam reaction times.

The resin composites created using 14-37 mm clean limestone fill appeared to give the best structural performance in terms of stiffness (elastic resistance) and unrestrained compressive strength. This also appears to be the most cost-effective option.

Significant improvement was also provided by the resin composites produced from the 75-150 mm stone fill. Although the stiffness results were not as good as for the resin composites made with 14-37 mm stone fill, the 75-150 mm stone fill resin composites are still considered adequate to support typical design imposed loads. The increased resin take would make this option more expensive. However, this would possibly be offset by benefits associated with ease and efficiency of drilling and injecting. Resin also migrates readily through this material, necessitating fewer injection points.

Based on the trial results, 6F2 graded recycled demolition wastes are considered unsuitable for use in resin composites. This is attributed to the presence of fine-grained materials (<6 mm), which limited the effective migration of the resin foams through the fill material. However, other recycled materials, particularly if single-size graded, may be potentially suitable.

Composite materials formed by treating stone or fill with resins have potential applications beyond the treatment of surface collapses associated with historic shallow mining. For example, such materials may be suitable for use in dam construction [6].

Compared to other traditional treatment options, such as cement-based grouting, the use of resin composites is potentially less disruptive to both sites and stakeholders. For shallow collapses, hand-held equipment is capable of treatment down to about 10 m. This has a number of benefits: shorter duration of site works; less noise and disturbance associated with large plant and equipment; fewer requirements for enabling works; and less need for reinstatement. Therefore, where access is limited, the use of resin composites is likely to achieve significant reinstatement cost savings.

The excess composite materials at the end of the trial had to be disposed of off-site at a licensed waste management facility. The composite materials were classified as hazardous waste, leading to more expensive disposal costs than would be expected for excess composite materials created from cementitious grouts. Waste management should be considered during the planning of any future project where large quantities of resin-based composite materials require disposal.

Provided effective resin permeation occurs, resin composites can effectively support most typical design imposed loads. Where not supporting buildings or other structures, the associated short-term deformations are considered unlikely to prove significant in terms of serviceability. However, long-term creep deflection under sustained loading requires further assessment, for example by monitoring a full-scale treatment trial.

VI. CONCLUSION

Resin-stone fill composites are suitable for the treatment of shallow mining collapses for most typical design imposed loads. Further research is required to confirm long-term performance under sustained loading.

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