

# Effect of slag and siliceous additions on the performance of stabilized coal waste backfill

J.M. Kinuthia<sup>1</sup> and R.M. Nidzam<sup>2</sup>

<sup>1</sup> Civil Engineering Research Unit (CERU), Faculty of Advanced Technology, University of Glamorgan, Pontypridd, Rhondda Cynon Taff, CF37 1DL, Wales, UK.

<sup>2</sup> Department of Building, Faculty of Architecture, Planning and Surveying, University Technology MARA, 40450 Shah Alam, Selangor. Malaysia

KEYWORDS: coal, mining, waste, colliery, stabilization, slag, ash.

## ABSTRACT

Coal mine waste rejected from coal mining process has remained unused due to difficulties in stabilizing it using traditional methods and practices, leading to poor performance. However, the abundance of the waste has enormous potential for application in certain areas, such as for road base or sub-base construction, which requires relatively lower strength and reactivity.

This paper presents experimental results of a study on the mechanical and hydration properties of cementitious materials prepared by stabilizing coal mining waste comprising of a 50-50 blend of fine and coarse-grained mine wastes, compacted into cylinders of 50mm in diameter and 100mm in height. The binder comprised of either quicklime ( $\text{CaO}_2$ ) or Portland cement (PC), blended with varying amounts of Ground Granulated Blastfurnace Slag (GGBS). Parallel mixes were also prepared with classified fine Pulverised Fuel Ash (PFA) or Lower Oxford Clay (LOC) soil as extra siliceous additions to the coal waste. Results have indicated that the coal mine waste generally had almost no improvement when quicklime alone was used. By blending the lime or PC with GGBS, or when extra siliceous matter was added, the strength and hydration was significantly enhanced.

## 1. INTRODUCTION

Colliery Spoils are the low-energy value waste material from the coal mining industry. It can be generally classified into fine and coarse discard which basically consists of a mixture of rock types, including mudstone, siltstone, sandstone and ironstone associated with coal. The main use of colliery spoil is as a bulk fill materials in construction projects such as road embankments. Problems to construction activities occur apparently due to its composition (for example high percentage of carbon and sulphide and sometimes swelling clay minerals) and its physical structure (i.e. rapid breakdown, variability, high compressibility and a tendency to undergo large settlement when saturated). These factors tend to make the spoil unstable and thus unsuitable as a foundation bearing material for construction works. However, the abundance of the waste has enormous potential for application in certain areas, such as for road base or sub-base construction, which require relatively lower strength and reactivity, compared to other applications for example in the manufacture of building components, such as beams, slabs, bricks and blocks.

## 2. EXPERIMENTAL PROCEDURE

### 2.1 Materials

#### 2.1.1 *Colliery spoils (CS)*

The colliery spoil that was used in this research were obtained from Tower Colliery, Aberdare South Wales UK. Two different colliery materials were used, a fine non-plastic fraction ( $CS_f$ ) of low plasticity and a coarser fraction ( $CS_c$ ). These two fractions were blended in equal proportions.

#### 2.1.2 *Siliceous materials*

*Pulverised Fuel Ash (PFA)*: PFA, a by-product from the combustion of pulverised coal, is widely used as a cementitious and pozzolanic ingredient in hydraulic cement concrete. PFA is a "pozzolan" defined as "a siliceous or siliceous and aluminous" material that in itself possesses little or no cementitious value (in most cases, especially for low-calcium PFA) but that will, in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties. These properties contribute to strength gain and may

improve the performance of stabilized materials. The use of PFA may result in more economical construction materials (ACI, 2004<sup>1</sup>).

*Lower Oxford Clay (LOC):* LOC was used as a siliceous material in this investigation. The clay is grey in colour and known to have high sulfate and sulfide contents, the former as gypsum, the latter as pyrites. It was supplied by Hanson Brick Ltd., Stewartby, Bedford, UK. Investigation by Wild et al. (1996<sup>2</sup>) established that LOC consisted predominantly of chlorite, kaolinite, mica, feldspar (sanidine and anorthite), quartzite, and calcite, with minor quantities of gibbsite, goethite (a hydrated iron oxide) and anatase (titanium oxide). Mineralogy and chemical analyses established that LOC has many minor ingredients, such as pyrites and gypsum, which can be contributors to the formation of deleterious minerals such as ettringite and thaumasite during its stabilization with lime.

### 2.1.3 Stabilizers

Lime (L) and Portland cement (PC) were used as control stabilizers, supplied by Buxton Lime Industries, Derbyshire, UK and Rugby Group plc UK, respectively. Ground Granulated Blastfurnace Slag was also used, and was supplied by Civil and Marine Slag Cement Ltd. Llanwern, Newport, UK. The chemical and oxide composition, physical and other properties of the CS, PFA, LOC, Lime, PC and GGBS are presented in Table 1.

## 2.2 Mix compositions and specimen preparation

### 2.2.1 Unconfined compressive strength

In all the stabilized systems in the current research work, compacted cylindrical test specimens (of dimensions 50mm in diameter and 100 mm in height) were used. The total weight of material used was maintained at 470g, comprising of 6wt% stabilizer, 15wt% water content and 10wt% siliceous addition (either PFA or LOC), all expressed as percent of the total target colliery waste material. Table 2 shows the various mix compositions used.

Dry material comprising of colliery spoil, blended stabilizer and a siliceous additive, enough to produce one compacted cylindrical test specimen, were mixed in a Kenwood Chef mixer for 2 minutes before slowly adding the pre-calculated amount

of water. Hand mixing with palette knives was necessary to achieve a homogeneous mix. A steel mould fitted with a collar, was used to compress the cylinders. After compaction, achieved using a hydraulic jack, the cylinders were extruded using a steel plunger, trimmed, and wrapped in several runs of cling film and cured for 7 and 28 and 90 days, before testing for UCS. Two specimens were used for each mix composition and curing period, and the average strength value determined.

Table 1: Oxide composition of target material and stabilizers

Oxide	Composition %						
	CS <sub>f</sub>	CS <sub>c</sub>	PFA	LOC	PC	Lime	GGBS
CaO	0.03	0.30	8.70	6.15	63.0	95.9	42.0
SiO <sub>2</sub>	0.28	0.07	54.90	46.73	20.0	0.90	35.5
Al <sub>2</sub> O <sub>3</sub>	23.34	20.00	25.80	18.51	6.0	0.15	12.0
MgO	0.02	0.01	1.80	1.13	1.0	0.46	8.0
Fe <sub>2</sub> O <sub>3</sub>	2.09	1.08	6.90	6.21	3.0	0.07	0.4
MnO	-	-	-	0.07	<1	-	0.4
S <sub>2</sub>	-	-	-	-	-	-	1.2
SO <sub>3</sub>	0.01	0.07	0.60	-	2.0	-	0.2
CaCO <sub>3</sub>	-	-	-	-	-	2.2	-
TiO <sub>2</sub>	-	-	-	1.13	-	-	-
K <sub>2</sub> O	-	-	-	4.06	-	-	-
FeO	-	-	-	0.8	-	-	-
P <sub>2</sub> O <sub>5</sub>	-	-	-	0.17	-	-	-
N <sub>2</sub> O	-	-	-	0.52	-	-	-
Insoluble residue	98.4	94.8	-	-	0.5	-	0.3
Specific gravity	1.8	1.8	-	-	3.15	2.3	2.90
Bulk density, kg m <sup>-3</sup>	-	-	-	-	1400	-	1200
Colour	Dark	Dark	Grey	-	Grey	White	Off-White

### 2.2.2 Linear expansion

Immediately after specimen fabrication, approximately 10mm of the bottom of a specimen intended for linear expansion tests (one specimen for each of the mix compositions used) were exposed by cutting and removing the cling film. The partially exposed test specimen was placed on a porous disc placed on a platform in a Perspex container as shown in Figure 1. Separate Perspex containers were used for individual test specimens. The Perspex containers were covered with lids fitted with dial gauges and a layer of water always maintained below the platforms to provide high humidity and ensure that there was no excessive evaporation from the test specimen. This process is termed moist curing was commenced immediately after specimen fabrication. After moist curing for 7 days, the specimens were partially immersed in water to a depth of the exposed 10 mm above their bases. This

process is termed soaking. Linear expansion during moist curing and subsequent soaking was monitored on a daily basis for a combined period of at least 100 days.

Table 2: Mix compositions

Mix Composition	CS (g)	L (g)	PC (g)	Binder (g)	PFA (g)	LOC (g)	Water (g)	Total (g)
CS+L	386	23	-	-	-	-	61	470
CS+PC	386	-	23	-	-	-	61	470
CS+L-GGBS (30:70)	386	-	-	23	-	-	61	470
CS+L-GGBS (50:50)	386	-	-	23	-	-	61	470
CS+PC-GGBS (30:70)	386	-	-	23	-	-	61	470
CS+PC-GGBS (50:50)	386	-	-	23	-	-	61	470
CS+PFA+L	347	23	-	-	39	-	61	470
CS+PFA+PC	347	-	23	-	39	-	61	470
CS+PFA+L-GGBS (30:70)	347	-	-	23	39	-	61	470
CS+PFA+L-GGBS (50:50)	347	-	-	23	39	-	61	470
CS+PFA+PC-GGBS (30:70)	347	-	-	23	39	-	61	470
CS+PFA+PC-GGBS (50:50)	347	-	-	23	39	-	61	470
CS+LOC+L	347	23	-	-	-	39	61	470
CS+LOC+PC	347	-	23	-	-	39	61	470
CS+LOC+L-GGBS (30:70)	347	-	-	23	-	39	61	470
CS+LOC+L-GGBS (50:50)	347	-	-	23	-	39	61	470
CS+LOC+PC-GGBS (30:70)	347	-	-	23	-	39	61	470
CS+LOC+PC-GGBS (50:50)	347	-	-	23	-	39	61	470

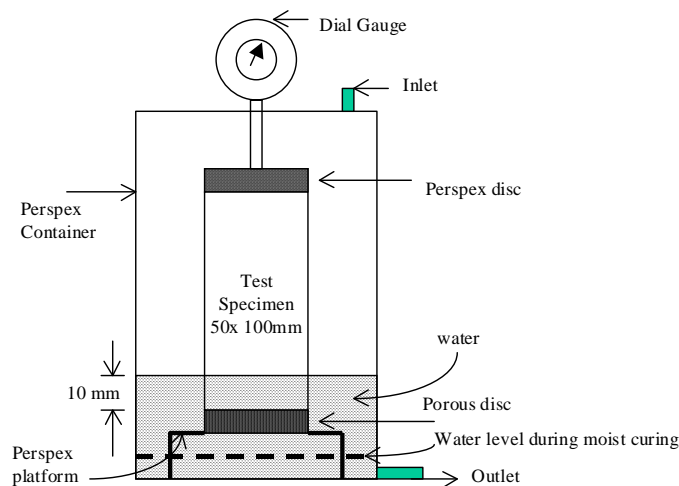


Figure 1: Schematic diagram of the test set-up for measuring linear expansion during moist curing and subsequent soaking.

### 3. RESULTS

#### 3.1 Unconfined compressive strength

Figure 2 shows the unconfined compressive strength of cylindrical specimen of colliery spoil stabilized with the traditional stabilizers of lime and PC, and with the blended stabilizers of Lime–GGBS and PC–GGBS at two blending ratios of 30:70 and 50:50 for each traditional stabiliser. Colliery spoil when stabilized with lime on its own did not show any strength development throughout the 90 days of moist curing, and the strength instead decreased with prolonged curing. There was some increase in strength up to 28 days of moist curing when PC was used as stabilizer on its own, but the strength dropped at 90 days of curing.

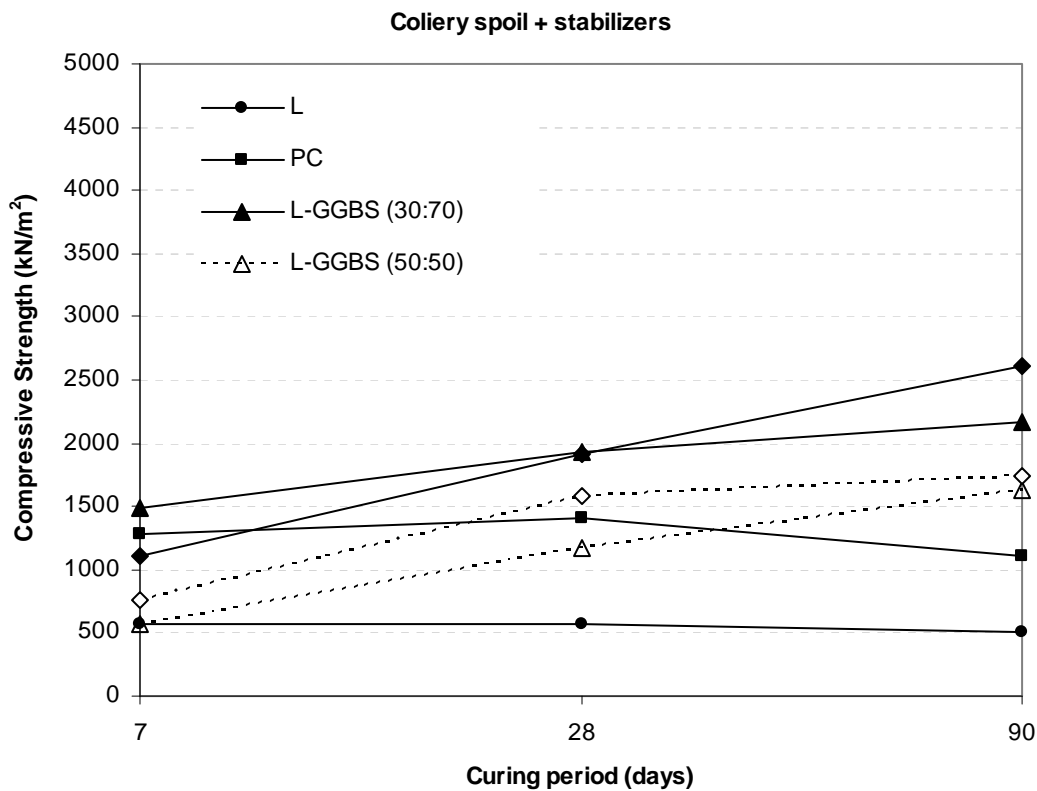


Figure 2: Compressive strength of stabilized CS

When Lime–GGBS blends (at 30:70 and 50:50 blending ratios) were used as stabilizers, there was an improvement in strength development throughout the 90 days of curing, with the 50:50 blend recording slightly lower strength compared with 30:70 blend. Colliery spoil stabilised with blended PC–GGBS at the same blending ratios (30:70 and 50:50) resulted in a steady strength development throughout the 90 days of curing, again with the 30:70 blending ratio showing the higher strength values compared with the 50:50 blend. The results appear to suggest better prolonged strength development as the proportion of GGBS increased in both Lime–GGBS and PC–GGBS blended stabilisers, with the latter showing better strength development relative to the equivalent Lime–GGBS system.

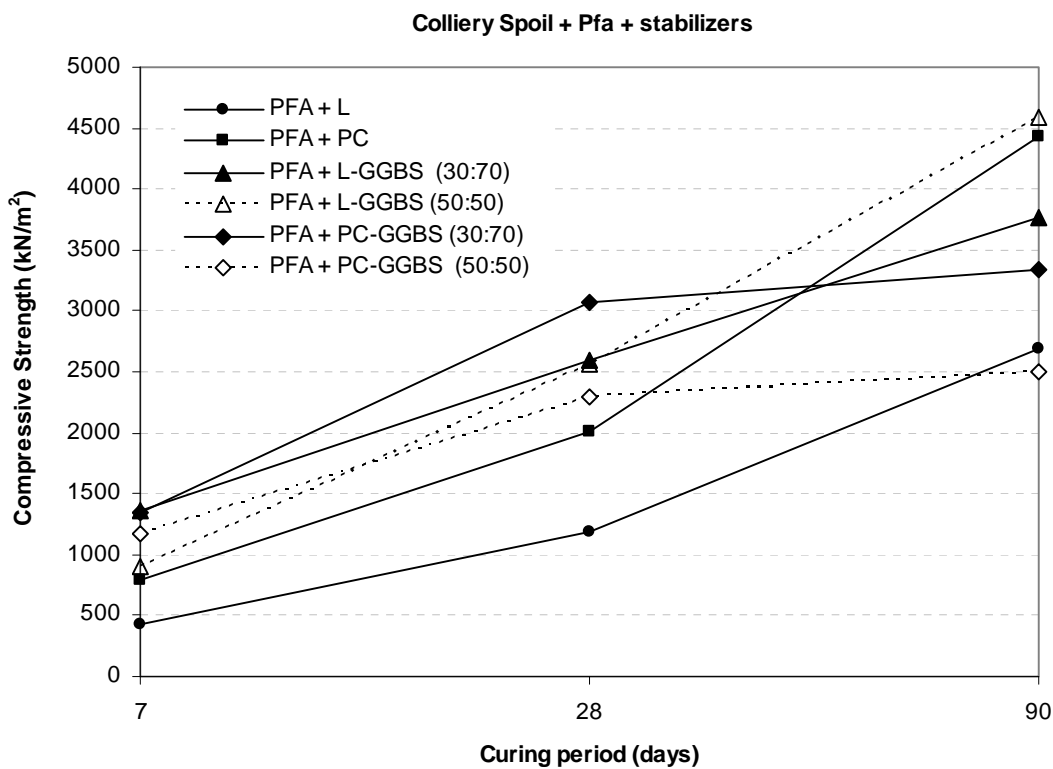


Figure 3: Compressive strength values of stabilized CS with addition PFA as siliceous additive.

Figure 3 illustrate the strength development of colliery spoil when PFA was used as a siliceous additive material in the system. Overall, there was significant strength improvement with all stabilizers used throughout the 90 days of curing. All strength

values were higher than the equivalent systems that did not incorporate siliceous additive material. Strength improved also when the colliery spoil was stabilized with lime or PC on their own without GGBS, particularly at 90 days of curing where the strength values were recorded at 2690 kN/m<sup>2</sup> and 4424 kN/m<sup>2</sup> respectively.

Blending lime with GGBS (at 30:70 and 50:50 ratios), marked relatively the same strength at 28 days of curing, but the 50:50 blending ratio achieved a higher strength value at 90 days of curing (4586 kN/m<sup>2</sup>) compared with the 30:70 blending ratio (3772 kN/m<sup>2</sup>). Interestingly there was little strength improvement from 28 to 90 days curing period when both PC–GGBS binders (30:70 and 50:50) were used to stabilize the colliery spoil with 10wt% PFA additive as siliceous material. The 30:70 PC–GGBS blend gave higher the strength values, at all curing periods, compared with the 50:50 blend.

Figure 4 illustrates the strength development of colliery spoil when Lower Oxford Clay (LOC) was used as the siliceous additive material instead of PFA. The overall strength performance of the stabilized colliery spoil in this system was generally below the system incorporating PFA as the siliceous additive. There is however significant strength improvements with prolonged curing period throughout 90 days with all the stabilized systems incorporating LOC, relative to the system using the CS on its own (Figure 2). The highest compressive strength value of 3192 kN/m<sup>2</sup> was achieved with lime-GGBS at the blending ratio of 30:70. The lime-GGBS blend at 50:50 ratio and the PC–GGBS blends at both 30:70 and 50:50 ratios all showed comparable strength values at 7, 28 and 90 curing periods.



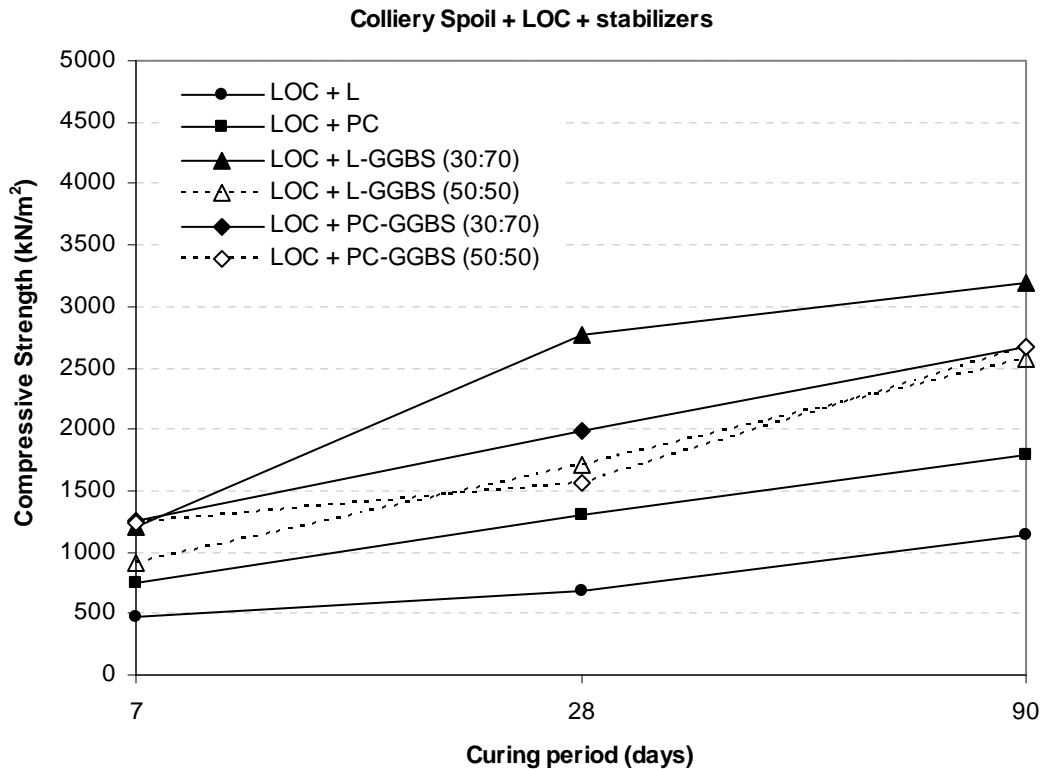


Figure 4: Compressive strength values of stabilized CS with addition LOC as siliceous additive.

### 3.2 Linear expansion

Figures 5 – 7 (a) and (b) illustrate the linear expansion of Lime–GGBS and PC–GGBS-stabilized colliery spoil systems. The effects of the extra siliceous materials on the linear expansion are illustrated in Figure 6 (PFA as additive) and Figure 7 (LOC as additive). In each of these Figures, a bar chart of the linear expansion magnitude at 100 days is also presented. Over the 100 days observation period, all the systems continued to expand, although the bulk of the expansion occurred immediately after soaking. In all the systems, about 90% of the ultimate expansion occurred within the first 30 days of soaking.

Figures 5 (a) and (b)) show linear expansion of colliery spoil stabilised on its own without an additive. Very little expansion (below 0.5%) was observed in all specimens at 100 days soaking except for the specimen stabilized with lime only.

Figure 6 illustrates the effects of PFA as the siliceous additive material on the linear expansion of the stabilized colliery spoil. Over 100 days soaking, the same trend was observed as for the colliery spoil stabilised without a siliceous additive, where linear expansions for all the test specimens were below 0.5% except for the specimen stabilized with Lime–GGBS at the blending ratio of 30:70 which recorded an expansion of 0.7%.

The effect of LOC as an additive on linear expansion of stabilized colliery spoil is illustrated in Figure 7. Specimens stabilized with lime-GGBS (50:50) and PC-GGBS at both blending ratios (30:70 and 50:50) recorded linear expansion magnitudes below 0.5%. However, for the specimens stabilized with Lime–GGBS (30:70) and when traditional stabilizers of lime and PC were used in the system, the linear expansion magnitudes were beyond 0.5%. Lime-stabilized CS and PC-stabilized CS marked the highest linear expansion magnitude of about 2.5% and 1.2% respectively, at 100 days of soaking. In this system, the overall expansions for all stabilized specimens are marginally higher than in the system containing no siliceous materials, or the one containing PFA. When lime was used as the only stabilizer in the presence of LOC, the expansion was very significant. This is likely to be due to LOC having minor ingredients, such as pyrites and gypsum, which can be contributory to the formation of highly expansive and/or deleterious materials such as ettringite and/or thaumasite.

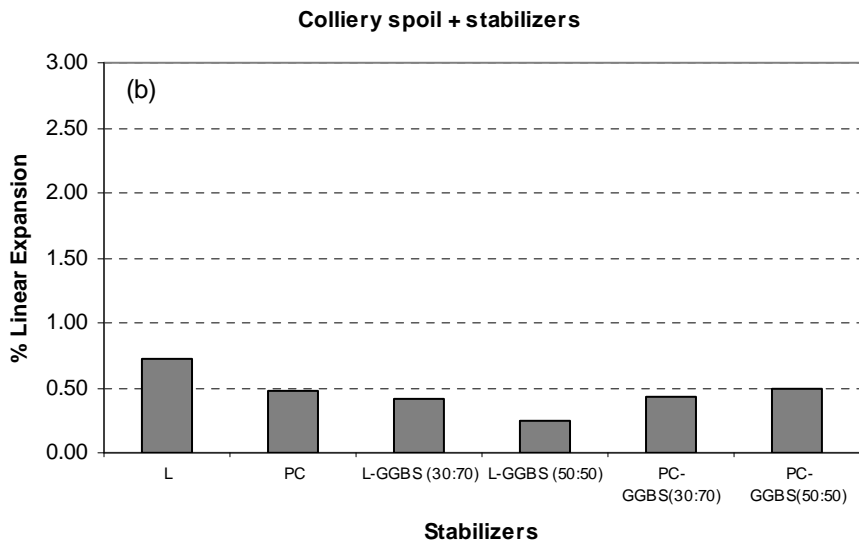
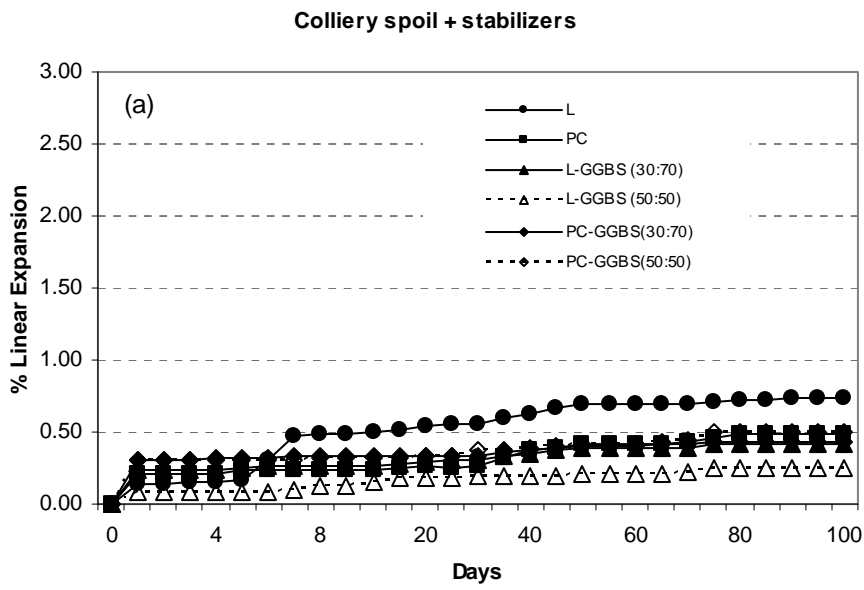


Figure 5: (a) Linear Expansion of stabilized colliery spoil and (b) Expansion magnitudes after 100 days of soaking.

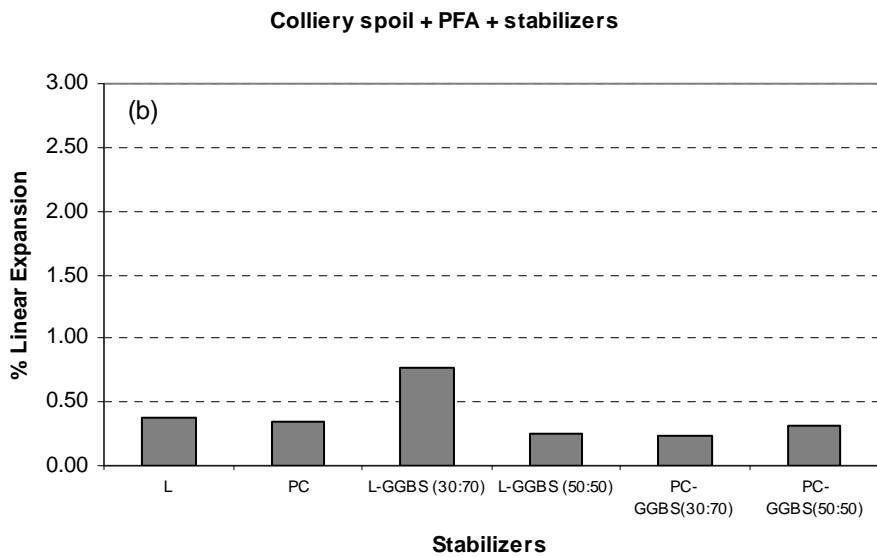
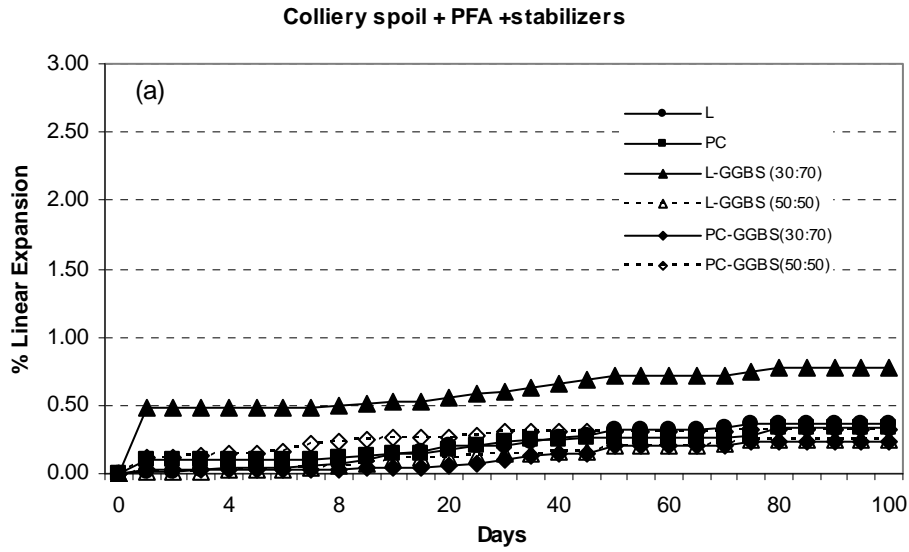


Figure 6: (a) Linear Expansion of stabilized colliery spoil with added siliceous material (PFA) and (b) Expansion magnitudes after 100 days of soaking.

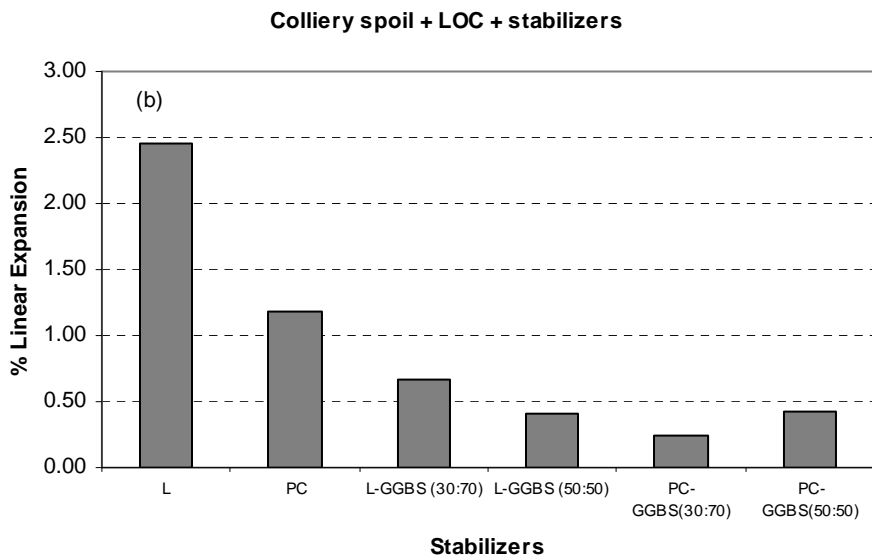
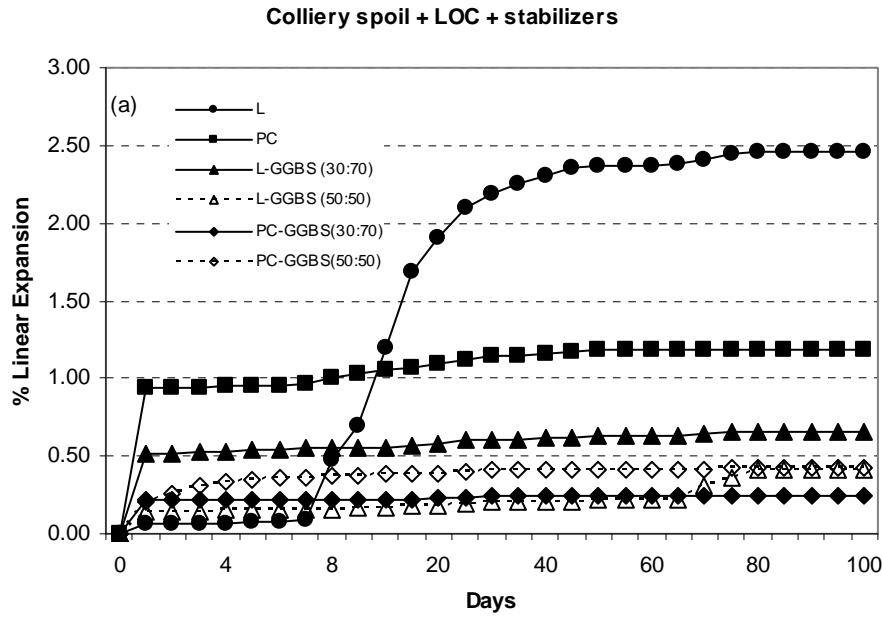


Figure 7: (a) Linear Expansion of stabilized colliery spoil with added siliceous material (LOC) and (b) Expansion magnitudes after 100 days of soaking.

#### 4. DISCUSSION AND CONCLUSIONS

The use of PFA and LOC as additive components to the colliery spoil was first considered based on the inability of lime to stabilise the mine waste. It had been established at an early stage during preliminary work that the waste was non-plastic, and it was therefore not very surprising when lime was found unable to influence strength development. It was then found necessary to try materials with known pozzolanic properties as additives, in small quantities relative to the mine waste. A pozzolan is defined as a alumino- and/or siliceous materials which chemically react with lime to form compounds possessing cementitious properties. In this experimental work, the influence of the two different siliceous materials on compressive strength at 7, 28 and 90 days of curing and on the linear expansion upon soaking over 100 days of soaking were studied. The dosage of the additives was maintained at 10wt% of the colliery spoil.

The combined hydration products in the stabilized system stabilised with Lime/PC-GGBS+Additive was found to enhance the compressive strength, thought to be due to increased pozzolanicity of the system, relative to the system stabilised without the pozzolanic additive. It is generally recognised that the principal cementitious product of pozzolanic reaction is calcium-alumino-silicate-hydrate (C-A-S-H) gel (Bell and Coulthard, 1990<sup>3</sup>; Brandle, 1981<sup>4</sup>; Diamond and Kinter, 1964<sup>5</sup>), although the quantity of this and the other large variety of hydration products expected in such a system was not the focus of this part of the investigation. The main focus was on the engineering performance, as established using unconfined compressive strength and linear expansion upon soaking.

The systems stabilised with PFA as the additive not only achieved highest strength values, but also showed least linear expansion. For the Lime-GGBS blended binders, the blend with more lime relative to the GGBS (50:50 blending ratio) showed significantly better strength development beyond 28 days of curing, relative to the blend with less lime (30:70), although the two blending ratio showed comparable strength development up to 28 days. The sustained strength development by the blend with higher lime content further reinforces the fact that the lime-stabilised colliery system requires significant amounts of lime in order to achieve usable

strength values. The lime-PFA pozzolanic reaction helps in sustaining strength development at reasonable lime dosages. Both blending ratios achieved comparable 100-day linear expansion upon soaking. The systems stabilised with PC–GGBS blended binder showed no strength development beyond 28 days. They however showed comparable linear expansion magnitudes with the Lime–GGBS systems.

The systems stabilised with LOC as the additive did not achieve as high strength values compared with their PFA equivalents. However, the strength values were noticeably higher than those achieved without any additive at all. For systems stabilised with lime without GGBS, the strength enhancement is counter-weighted by large linear expansion. For the Lime-GGBS blended binders, the blend with more lime relative to the GGBS (50:50 blending ratio) did not perform in a superior manner was the case for PFA as the additive. In contrast, the blend with more GGBS (30:70) showed significantly better strength development at all curing periods. The sustained strength development by the blend with low lime and higher GGBS has been observed using sulfate-bearing clay soils by Higgins et al. (2002<sup>6</sup>). Similar trends were observed with PC–GGBS blended binders, but the strength magnitudes were lower relative to the Lime–GGBS systems.

In conclusion, it has been found helpful to blend colliery spoil with either PFA or LOC. Where clay soils are freely available, this is a very attractive way round the problem of low strength development, that currently hinders significant utilisation of mine waste. However, caution should apply where swelling can be significant especially for sulfate-bearing clay soils. Used on their own without GGBS, PC performed better than lime. However, used as blended stabilisers with GGBS, lime performed far better than PC blended with GGBS. The blending ratio should maintain a balance between good strength development, relative costs of lime and GGBS, and the swelling that is likely to occur, although the Lime-GGBS system has shown very good volume stability.

## REFERENCES

- [1] American Concrete Institute (ACI) 232.2R-03. Use of Fly Ash in Concrete, 2004, ISBN 0-87031-137-9
- [2] Wild, S., Kinuthia, J. M., Robinson, R. B. and Humphreys, I. Effects of ground granulated blastfurnace slag (ggbs) on the strength and swelling properties of lime stabilised kaolinite in the presence of sulphates. *Clay Minerals*, 1996, 31, 423 - 433.
- [3] Bell, F.G. and Coulthard, J.M. Stabilisation of clay soils with lime. *Municipal Engineer*, 1990, 7, June, pp125-140.
- [4] Brandle, H. Alteration of soil parameters by stabilization with Lime. *Proc. 10<sup>th</sup> Int. Conf. Soil Mechanics and Foundation Engineering.*, Stockholm, 1981, Vol. 3, pp 587-594.
- [5] Diamond, S. and Kinter, E.B. Mechanism of Soil-Lime Stabilisation, *Highway Research Record*, 1964, No. 92, pp 83-102.
- [6] HIGGINS, D. D., THOMAS, B., KINUTHIA, J. Pyrite oxidation, expansion of stabilised clay and the effect of ggbs. *Proceedings of the 4<sup>th</sup> European Symposium, Bitmat4, on Performance of Bituminous and Hydraulic Materials in Pavements*, (Edited by Zoorob, S.E./ Collop, A.C. /Brown, S.F.), Nottingham, UK, 2002, ISBN: 90 5809 375 1.