Waste-Treated Waste: Stabilization of Colliery Waste from South Wales (UK) using Wastepaper Sludge Ash (WSA)

John M. Kinuthia[1] and **GAILIUS, A**[2].

[1]University of Glamorgan, Building Materials Research Unit (BMRU), School of Technology, Pontypridd, Rhondda Cynon Taff, CF37 1DL, United Kingdom; [2]Faculty of Civil Engineering, Vilnius Gediminas Technical University, Saulètekio al. 11, 10223 Vilnius-40, Lithuania

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ABSTRACT

Sustainable construction requires a critical review of prevailing practices, techniques and sources of raw materials. Focus is turning to industrial wastes and by-products that have previously received little or no attention. One such waste is Colliery Spoil (CS) (minestone), a by-product of coal mining. Albeit its abundance in most parts of the world, its potential as a construction material has not been fully realized, as evidenced by the large piles of the waste, usually unrecognizable due to vegetation overgrowth. The major problems identified in attempts to utilize CS in construction include excessive wear, expansive behavior, leaching and radioactivity, reducing its use to merely backfilling of mines, quarries and other surface tips, or subjected to marine and other disposal options. The different options have environmental consequences of varying impact.

This paper advances the scope of technological benefits of utilizing CS in construction, by utilizing waste-activated slag. The research was triggered by proximity of large supplies of both CS and slag in South Wales, UK, as well as the authors' interest in advances in sustainable construction. Two sulfate/sulfide-bearing colliery wastes were stabilized with a blended stabilizer comprising Wastepaper Sludge Ash (WSA) and Ground Granulated Blastfurnace Slag (GGBS), themselves industrial wastes or by-products. Compressive strength of compacted cylinder specimens was monitored for a period of up to 180 days of curing and linear expansion for up to 50 days of soaking. Results indicate that the performance of systems incorporating WSA was generally superior to that of systems using Portland Cement (PC) or lime, the common traditional stabilizers.

1.0   INTRODUCTION

It is increasingly becoming obvious that the way forward towards sustainable construction is to review the current construction practices, including prevailing

techniques and sources of raw materials. Focus is therefore turning to waste materials and by-products that in the past have received little or no attention. One such waste material is Colliery Spoil (CS), also known as colliery waste or minestone. It is an industrial by-product of many years of coal mining in most parts of Europe.[1-5] Its full potential as a construction material has not been fully realized, as evidenced by abundant piles of the waste material usually unrecognizable due to vegetation overgrowth.

In the past, mining methods produced relatively little waste above ground as coal excavation by hand was highly selective and most waste was separated and left underground. With mechanized systems dirt interspersed with coal seams are also extracted and brought to the surface for further separation to produce a marketable product, resulting in abundant colliery waste.

There have been several attempts to utilize CS in construction. Examples of its application are numerous and varied, ranging from bulk material for earthworks, manufacture of building materials, extraction of minerals such as aluminium, to marine construction in the protection of harbours[6]. In the utilization of CS, the major problems identified include excessive wear, expansive behavior, leaching and radioactivity.[1-6] As use of colliery spoil is also in competition with many other sources of waste products, the problems either encountered or remotely associated with its application have reduced the scope of its application to that of merely backfilling of mines, quarries and other surface tips, or subjected to marine and other disposal options. The different options all have environmental consequences of varying impact. It is therefore important that a constant review of these methodologies is maintained, as well as continued research into more techniques and varied use of CS. In practice, it is a question of striking a balance between environmental and economic benefits.

This paper tries to further advance the scope of technological benefits of utilizing colliery spoil in construction, by utilizing waste-activated slag. The benefits of successful utilization of CS would are additive to those already existing, making its utilization an attractive and viable option. The research was triggered by the proximity of large supplies of CS in the South Wales region of the UK, a significant understanding of soil- and cement-based cementitious systems, as well as interest in advances in sustainable construction.

2.0   MATERIALS USED

2.1   Colliery Spoil (CS)

Two different colliery waste materials were used. CS1 was a well-graded non-plastic material, with a particle size ranging from fine sand to gravel fractions (i.e. 0.06 – 6 mm). It was obtained from an old and disused site near Bridgend in South Wales, UK. This material was used for a basic study on the possible stabilization of CS, where the longest curing period was just below 90 days. The second material was obtained from

an active colliery – Tower Colliery – in Aberdare, South Wales, UK. It was obtained as two materials, a finer fraction (CS2-F) of low plasticity, and a coarser non-plastic fraction (CS2-C). The two fractions were blended in fairly equal proportions to produce a well-graded material (CS2).

2.2 Stabilizers

WSA was supplied by Aylesford Newsprint Ltd. UK, in the form of a dry fine to coarse powder with a small percentage (less than 10%) of sandy particles. For blending with WSA as an alternative to utilizing WSA on its own, Ground Granulated Blastfurnace Slag (GGBS) was used. It was supplied by Civil and Marine Slag Cement Ltd, Llanwern, Newport, UK.

The control stabilizers included lime (applicable to CS2 only), supplied by Buxton Lime Industries, Derbyshire, UK, and Portland cement ((PC) for both CS1 and CS2), supplied by Rugby Group plc. UK. The chemical and oxide composition, physical and other properties of the CS, WSA, GGBS, PC and lime used are shown in Table 1.

Table 1 – Oxide composition and some physical properties of the materials used.

Oxide	Composition %						
	CS1	CS2-F	CS2-C	WSA[3]	GGBS[4]	PC	Lime
CaO	0.20	0.03	0.30	37.0	42.0	63.0	95.9
SiO_2	0.43[1]	0.28[1]	0.07[1]	34.0	35.5	20.0	0.90
Al_2O_3	20.91	23.34	20.00	18.39	12.0	6.0	0.15
MgO	0.86	0.02	0.01	5.04	8.0	1.0	0.46
Fe_2O_3	3.54	2.09	1.08	1.77	0.4	3.0	0.07
MnO	0.03	-	-	-	0.4	< 1	-
S_2	0.01	-	-	-	1.2	-	-
SO_3	0.15	0.01	0.07	1.05	0.2	2.0	-
Insoluble residue	98.9[2]	98.4[2]	94.8[2]	38.6	0.3	0.5	-
Specific Gravity	-	1.8	1.8	2.52	2.90	3.15	2.3
Bulk Density, kg m^{-3}	-	-	-	-	1200	1400	-
Colour	Dark	Dark	Dark	Off-white	Off-white	Grey	White
Glass content	-	-	-	-	≈ 90	-	-
Specific Surface, m^2/kg	-	-	-	350	510	-	-

Note:
[1] - Soluble silica;
[2] - Comprises, among other minor components, of the insoluble silica, and the insoluble part of the %Al_2O_3.
[3] - From Southern Water Services Ltd. for Aylesford Newsprint Ltd.UK;
[4] - From Civil and Marine Slag Cement Ltd. UK.

Three stabilizer levels were adopted for each stabilizer used. For PC and lime, 2, 4 and 6% were used. These are about the typical stabilizer values used in practice. For WSA and WSA-GGBS, the three dosages were 10, 15, and 20%. These are the dosage values that were observed (in a previous preliminary work on clay soils) to achieve CBR values close or greater than 15%. This is the CBR value stipulated for a lime-stabilized capping layer in road construction in the UK.[7] The blending ratio for the WSA and GGBS was 50:50, the ratio earlier found to achieve optimal strength values in an earlier research on concrete.[8]

3.0   EXPERIMENTAL PROCEDURE

3.1   Preliminary testing
It was necessary to carry out material characterization tests, including sieve analyses and consistency tests, before the materials could be used in the investigation. The two fractions of CS2 were blended in equal proportions to produce a well-graded material. The Atterberg consistency limits tests were therefore carried out on both CS1 and CS2, with a view to establishing not only their properties, but also the applicability of lime as a stabilizer. Lime is generally applicable for stabilization of materials with at least 10% plastic fines. A full oxide analysis of the colliery material was also carried out, and the results are shown in Table 1.

3.2   Specimen preparation

It was necessary to establish a common dry density and moisture content for specimen preparation. Therefore, several BS Proctor compaction tests were carried out in accordance to BS 1377[9], in order to establish mean values of the density and moisture content to be adopted for the preparation of test specimens.


In all the stabilised systems, both the maximum dry density (MDD) and optimum moisture content (OMC) varied within a narrow range. The MDD ranged from 1.520 – 1.560 Mg/m^3 while the OMC ranged from 9 to 11%. Mean values of 1.54 Mg/m^3 and 10% were adopted for MDD and OMC respectively. Using these mean values, CS was mixed with 80%OMC and stored in polythene bags to mellow for 3 days at 20 ± 1°C and 100% relative humidity. During specimen preparation, twice the balance 20% of the water required to achieve OMC was applied (i.e. 40%OMC), so as to bring the mixed stabilised material to wet of OMC (1.2OMC). Compaction was achieved using a steel mould and a hydraulic jack, to compact the material into cylinders of dimensions 50 mm in diameter and 100 mm in height. The specimens were then wrapped in several runs of cling film and moist cured for 7, 28 and 84 days for CS1, and 7, 28, 90 and 180 days for CS2. Curing was carried out in a temperature controlled room at 20 ± 1°C, before testing for Unconfined Compressive Strength (UCS). Three specimens were used for each curing period and for each mix composition, and the average strength value determined.

For a specimen used to monitor linear expansion, an approximately 10mm portion of the bottom of a specimen was exposed immediately after fabrication by cutting and removing the cling film. The specimen was then placed on a porous disc and then placed on a Perspex platform which was in turn placed in a Perspex container. The lid to the container was fitted with a dial gauge. A layer of water was always maintained below the Perspex platform to provide a high humidity thus minimizing evaporation from the sample. One specimen was used to monitor the linear expansion of each mix composition. After moist curing for 7 days, the samples were partially immersed in water to a depth of 10 mm by increasing the water level in the Perspex container using a siphon. The containers were kept in a temperature controlled chamber, maintaining temperatures at 20 ± 1°C and humidity to 65 ± 5% relative humidity. This ensured curing conditions of about 20°C and 100% relative humidity. Linear expansion during moist curing and subsequent soaking was monitored daily for about 55 days for CS1 and 30 days for CS2 (on-going).

4.0   RESULTS AND DISCUSSION

4.1   Preliminary testis

Particle size distribution: The particle size distribution curves for CS1 and for the unblended fractions of CS2 are shown in Figure 1. The two fractions of CS2 were blended in equal proportions to produce a well-graded material (CS2), with a higher proportion of fines than CS1.
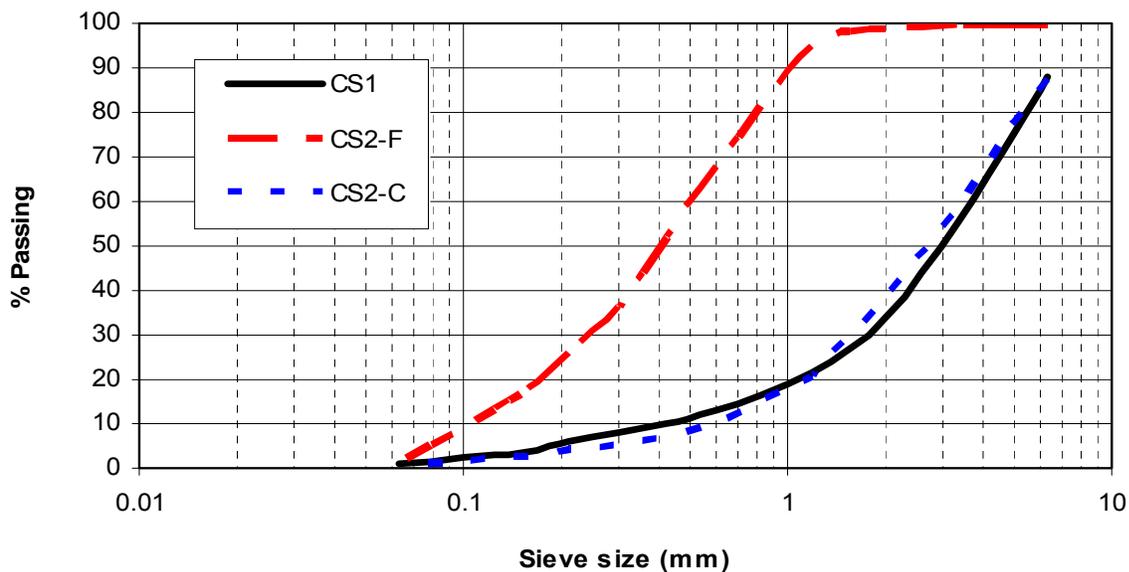
Fig. 1 – Particle size distribution of the Colliery Spoil materials CS1 and CS2.

Consistency: Table 2 shows the Atterberg limits of the two colliery spoil materials. The consistency limits of CS1 show it to be non-plastic, with a low liquid limit value of 36%. CS2 was significantly plastic, with a plasticity index of 13%. Thus, both materials more or less conform to plasticity levels of other CS materials from other parts of Europe – generally low plasticity ($Ip<10\%$[2]). The limits for two typical colliery spoil materials from Europe are summarized in Table 3. However, not all CS is non-plastic as reported in ($LL=38\%$; $Ip=23$[5]). As lime-stabilization requires a minimum of about 10% plastic fines, the use of lime-stabilization as a control was found inappropriate for CS1, but was however used for CS2. Portland cement was therefore used as control for both CS1 and CS2.

Table 2 - Engineering Properties of CS1 and CS2

	CS1	CS2-F	CS2-C
Consistency Limits			
Liquid limit (%)	36	41	41
Plastic Limit (%)	-[1]	28	28
Plasticity Index	0	13	13
Proctor Compaction Properties			
Maximum Dry Density (MDD)(Mg/m^3) (Standard BS Compaction)	1.5	1.6	1.8
Optimum Moisture Content (%)	9	14	9

Notes
[1] – i.e. Non-plastic

Table 3 - Engineering properties of two typical colliery wastes from Europe

	Przezchlebie (Poland)[7]	Gale Common (UK)[7]
Consistency Limits		
Liquid limit (%)	28 – 35	30 – 38
Plastic Limit (%)	20 – 49	16 – 22
Plasticity Index	10 – 15	14 – 16
Proctor Compaction Properties		
Maximum Dry Density (MDD)(Mg/m^3) (Standard BS Compaction)	1.7 – 1.9	1.5 – 1.6
Optimum Moisture Content (%)	9 – 11	8 – 9

4.2   Unconfined compressive strength

4.2.1   WSA vs traditional stabilizers

Figure 2 shows a comparison of unconfined compressive strength of cylindrical specimens of CS1 stabilized with both the traditional stabilizer – PC – and with the novel stabilizer – WSA – for curing periods of up to 84 days. The WSA dosage levels used were 10, 15, and 20%. It is evident that the WSA-stabilized specimens at 15% and 20% WSA dosages showed strength magnitudes very close to those observed for the material stabilized with the traditional stabilizer at 4% and 6% dosage levels respectively. At these dosages, after curing for 84 days, the strength values of the 15%-WSA-stabilized CS specimens equaled those with 4% PC, while those with 20% WSA superseded those with 6% PC. For a (currently) waste material to achieve such a performance so as compare favorably with as much as 6% PC is a major breakthrough. It is undoubtedly an indication of significant potential, even at the relatively high stabilizer application levels of 15% and 20%, of the innovative WSA-CS waste-waste combination. The benefits are not only economic but also environmental. Longer-term investigations on other parameters besides strength and strength development will determine the magnitude of the technological benefits. The current paper, however, only reports on the establishment of possible potential in WSA-stabilized CS, with or without other additives such as GGBS.
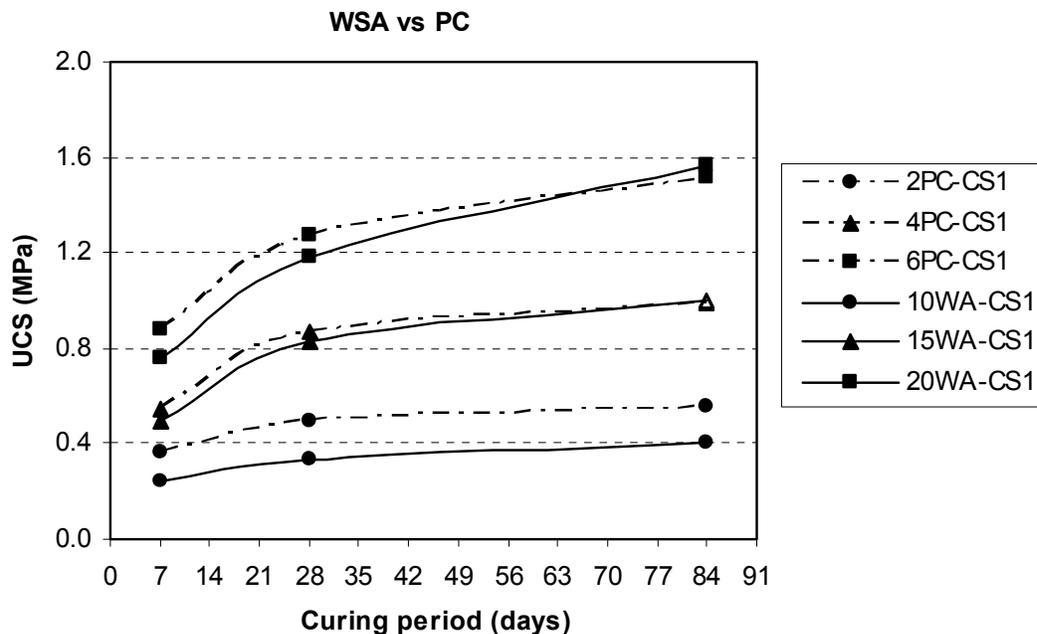

Fig. 2 – Comparison of strength of WSA-stabilised CS1 with that of PC-stabilised CS1.

No attempt was made to stabilize CS1 with lime as the former was found to be non-plastic. However, Figure 3 shows the strength of CS2 stabilized with both (traditional stabilizers) lime and Portland cement. The performance of CS2 with lime is dismal even at 6% stabilizer dosage level. This is likely to be as a result of inadequate plasticity, available (soluble) silica, and/or alumina content to promote significant pozzolanic activity. The strength values obtained with CS2 stabilized with PC and cured for less than 100 days compare very well with those for CS1 stabilized with the same stabilizer, especially at 4% and 6%. The reason for marginally higher strength at the low stabilizer level of 2% PC with CS2 compared with CS1 is likely to be due to the better particle size distribution of CS2. Overall, as far as stabilization of colliery spoil with the traditional stabilizers is concerned, PC appears to have a higher potential relative to lime.
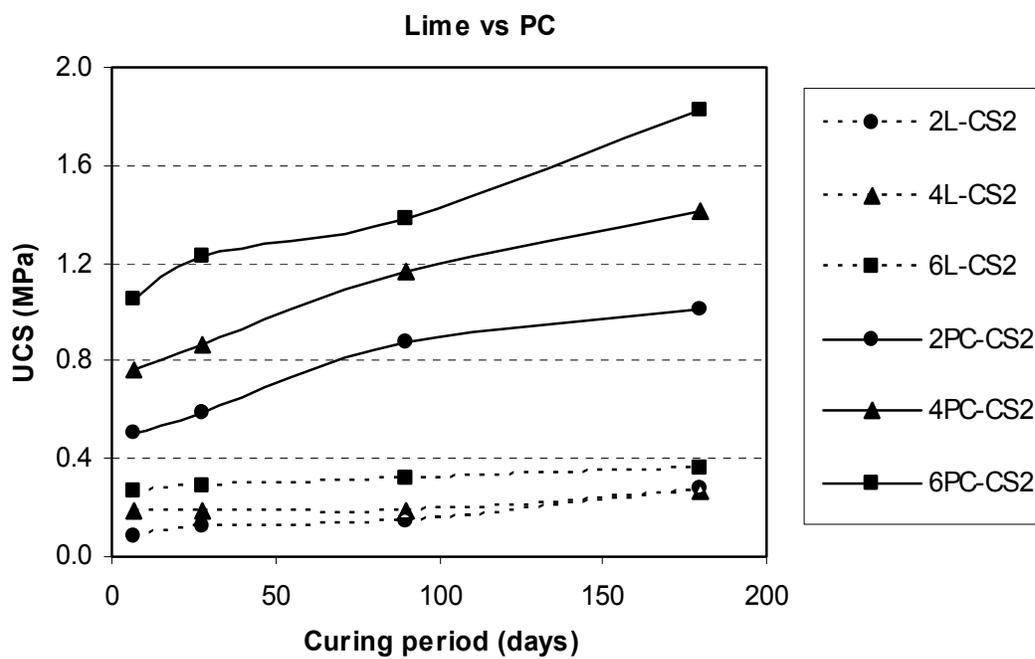

Fig. 3 – Comparison of strength of CS2 stabilised with Lime or with PC.

Figure 4 shows the strength of CS2 stabilized with lime and with WSA. Again WSA shows a high potential relative to a well-established traditional stabilizer. In general, it appears that the performance of WSA is somewhat between that of lime and that of PC.

4.2.1 WSA-GGBS vs traditional stabilizers

Figure 5 shows the strength of CS1 stabilized with a 50:50 blend of WSA: GGBS. It is clear that the WSA-GGBS blended stabilizer has significantly lower early (7-28 day) strength development compared to either PC or with WSA used on its own (see Fig. 2), especially at the lower stabilizer dosages of 10% and 15%.
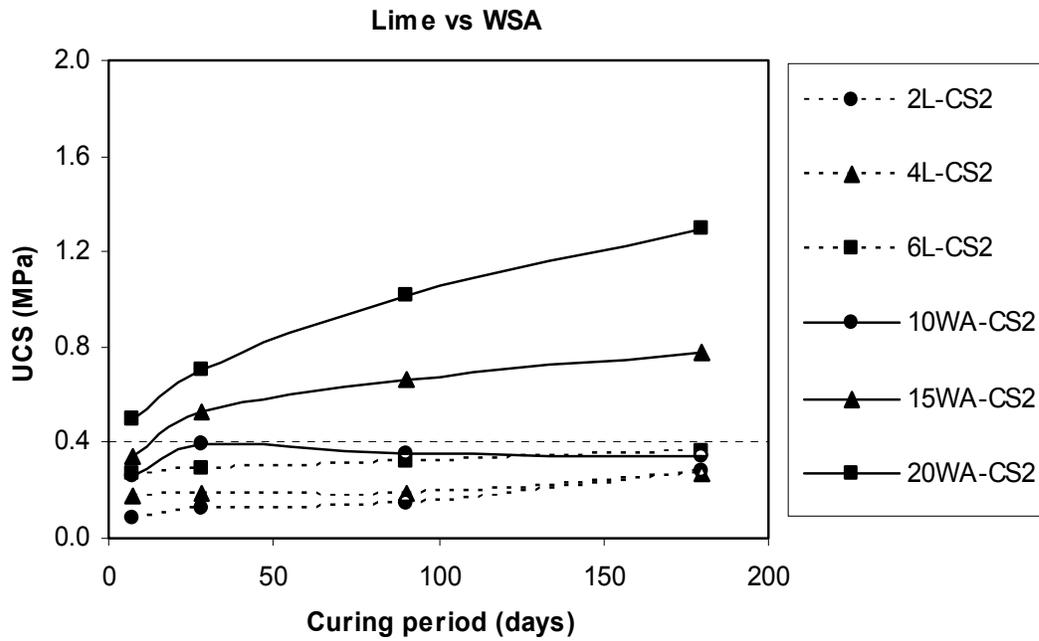
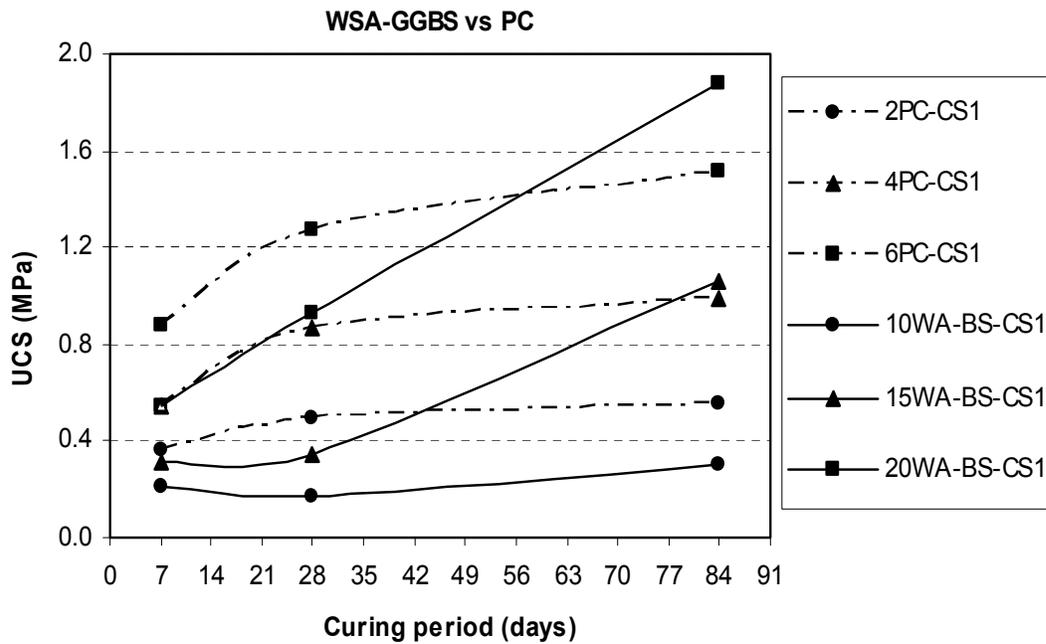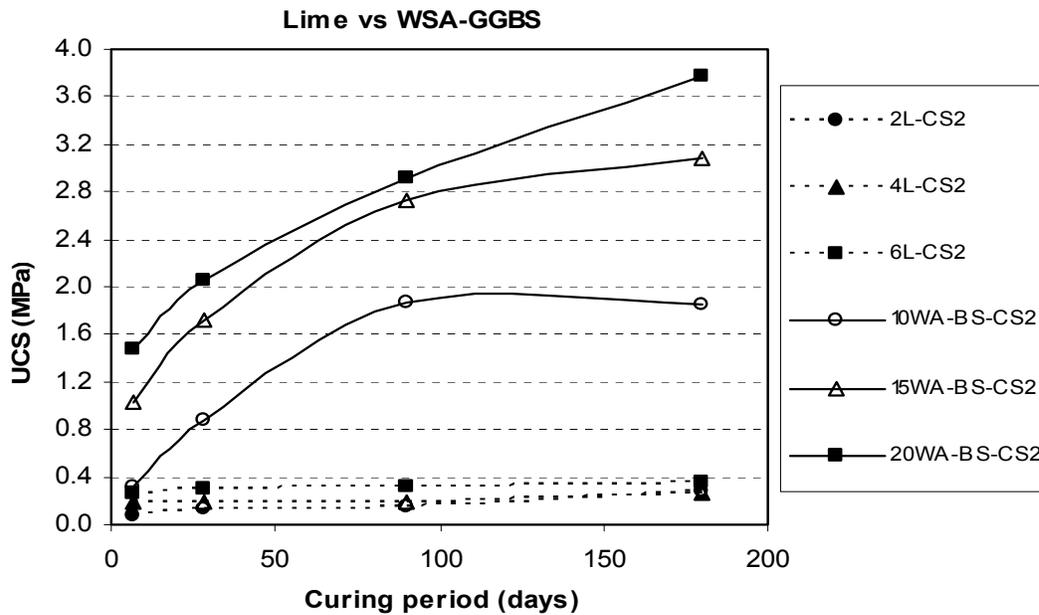**Fig. 4** – Comparison of strength of CS2 stabilised with Lime or with WSA.

Fig. 5 – Comparison of strength of CS1 stabilized with WSA-GGBS or with PC.

At prolonged moist curing of the WSA-GGBS system, and with 15% and 20% dosage levels, the strength values observed for the WSA-GGBS stabilizer were much higher than those observed with PC or with WSA used on its own. The slow hydration of GGBS is well-established,[10-12] and is likely to be the cause for the poor early strength development. In both WSA and WSA-GGBS systems, the 10% stabilizer dosage performs worse than 2% PC.

Figure 6 shows the strength of CS2 stabilized with the 50:50 blend of WSA:GGBS. The performance of the blended stabilizer on CS2 was phenomenal, compared with the results observed with CS1 stabilized by the same blended stabilizer (compare Fig. 5 with Fig. 6, noting the doubled y-axis scale in Fig. 6). This is likely to be due to a combination of factors. Firstly, the higher degree of fines in CS2 is likely to result in a higher degree of pozzolanic activity relative to that with CS1, resulting from the lime in the WSA component of the binder. Secondly, cementing action of the WSA-GGBS binder is likely to be more effective with the better particle size-distribution of CS2.

Fig. 6 – Comparison of strength of CS2 stabilized with WSA-GGBS or with PC.
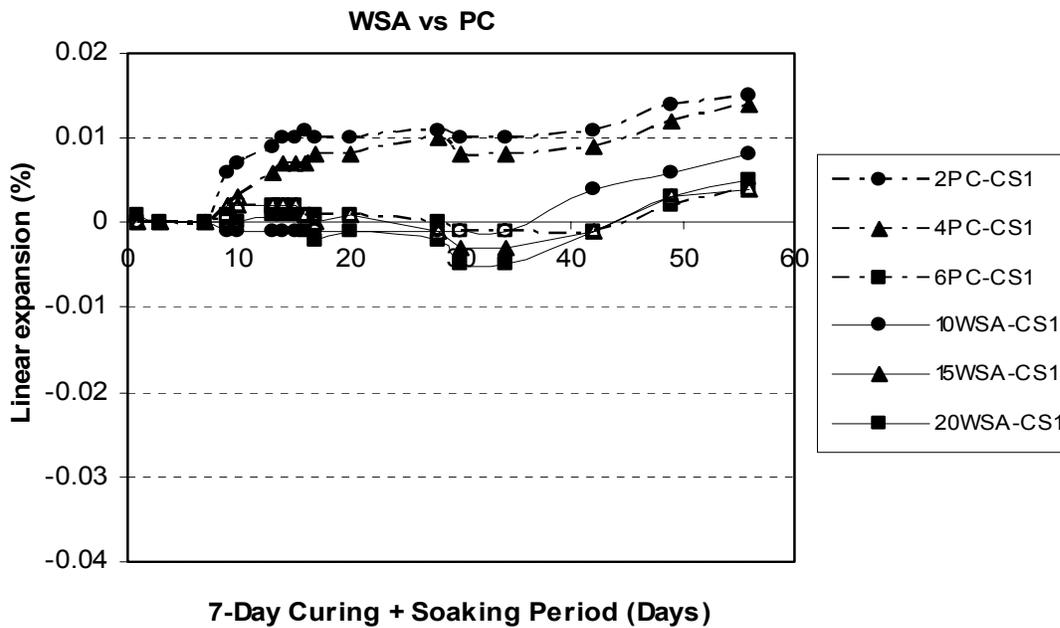
4.3   Linear expansion

Figure 7 shows a comparison of the linear expansion of cylindrical specimens of WSA-stabilized CS1 with that of PC-stabilized CS1. In the PC system, there was a rapid expansion occurring immediately upon soaking on the 7th day and lasting for about one week, followed by a period of relatively less expansion. In contrast, in the WSA-CS1

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system there was no significant expansion during the early soaking period, until after about 30 days of soaking. The WSA-CS1 cylinders actually recorded a small shrinkage for a period of about 25 days.

In both WSA and PC systems, there is a noticeable significant increase in liner expansion after 30 days. However, at all the stabilizer dosage levels used (WSA: 10, 15, and 20%; PC: 2, 4 and 6%), the linear expansion after 50 days of soaking was still very low at less than 0.02%. Within this low expansion and soaking period, the WSA-CS1 system indicated better volume stability compared to the PC-CS1 system.

Figure 8 shows a comparison of the linear expansion of WSA-GGBS-stabilized CS1 with that of PC-stabilized CS1. In comparison with the WSA-system, the cylinders stabilized with 15 and 20% of the WSA-GGBS blend recorded significant shrinkage for the first 40 days of curing and subsequent soaking. The specimens stabilized with 15 and 20% WSA-GGBS blend are also the same specimens that had recorded significantly higher later (84-day) strength relative to both PC- and WSA-stabilized CS1 (see Figs. 2 and 5). Therefore, there appears to be a correlation between low expansion and even shrinkage and better strength development with time. As with both WSA-CS1 and PC-CS1 systems, the WSA-GGBS-CS1 system also started to expand upon prolonged soaking, albeit after a slightly longer period of soaking. The expansion is however still below 0.02%, which is a very small expansion indeed to warrant any mitigating measures.
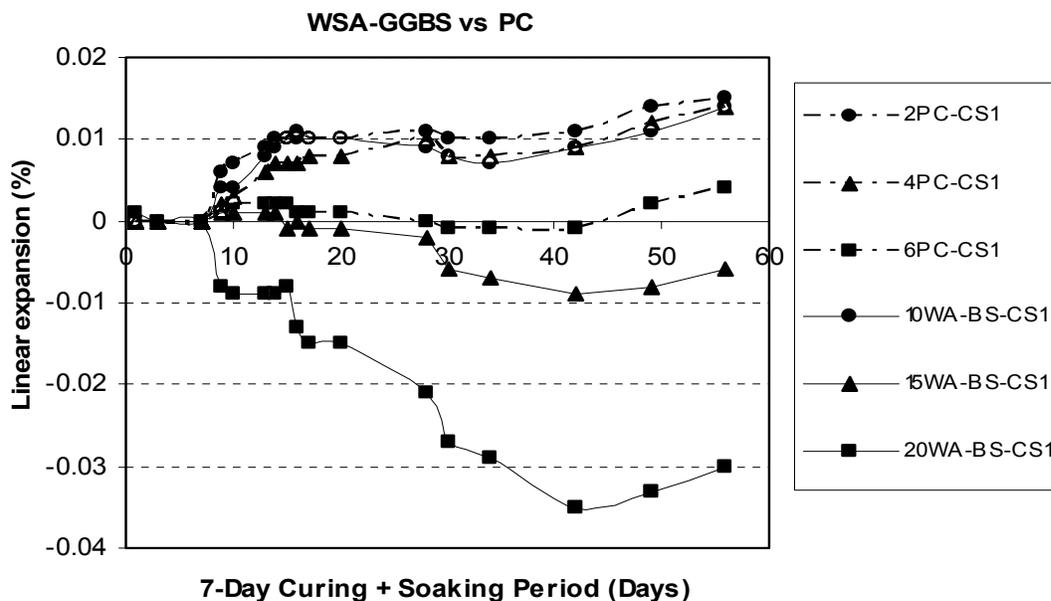

Fig. 7 – Comparison of linear expansion of WSA-stabilised CS1 with that of PC-stabilised CS1 upon soaking for up to 50 days.

GGBS-induced improvement of strength development and volume stability has been observed and reported by the authors on lime-GGBS-stabilized clay soils.[10, 11, and 12] As

the CS1 used in the current investigation is non-plastic and hence lime-stabilization was not applicable, it is logical to expect that the mechanisms operating in WSA-CS1 and WSA-GGBS-CS1 hydration systems are, at least in part, different from those in the lime-GGBS system. It is for this reason that it is worth noting that the GGBS-induced improvements in strength and volume stability have also been observed in PC-GGBS systems is well-established. This is the system more comparable with the current research.

The enhancement of strength and volume stability in the current research may be associated with activated GGBS hydration, further boosted by some hydration of the WSA itself. From the chemical and oxide analyses of the inputs (see Tables 1 and 2), the most obvious source of activator for GGBS is the free lime in the WSA. By carefully balancing the proportions of WSA and GGBS, and by analyzing and considering the target material for stabilization, a powerful and new stabilizer and stabilized material is on offer. This is the subject of further research, on the WSA-GGBS-waste/soil stabilization system.

Fig. 8 – Comparison of linear expansion of WSA-GGBS-stabilised CS1 with that of PC-stabilised CS1 upon soaking for up to 50 days.

Figure 9 shows the results of on-going linear expansion measurements on cylindrical specimens of lime-stabilized CS2. Compared with CS1 stabilized with either PC, WSA or WSA-GGBS blends, CS2 shows much higher expansion magnitudes. This is likely to be due to the higher clay–sized particles in CS2 and/or any lime-sulfate-induced expansion, resulting from sulfate in CS2 (either originally present in CS2, or resulting from the oxidation of sulfide). Work to establish whether this expansion can be reduced using WSA-GGBS blends as was the case for CS1 is on-going. Since CS2 had shown better

strength development compared with CS1, It is however worth noting that compared with stabilized soil systems which may exhibit expansion magnitudes of the order of 15-20%,[11,12] expansion of stabilized CS is apparently not likely to be a matter for major concern. This is however the subject of currently on-going research by the authors.

CS2-Lime
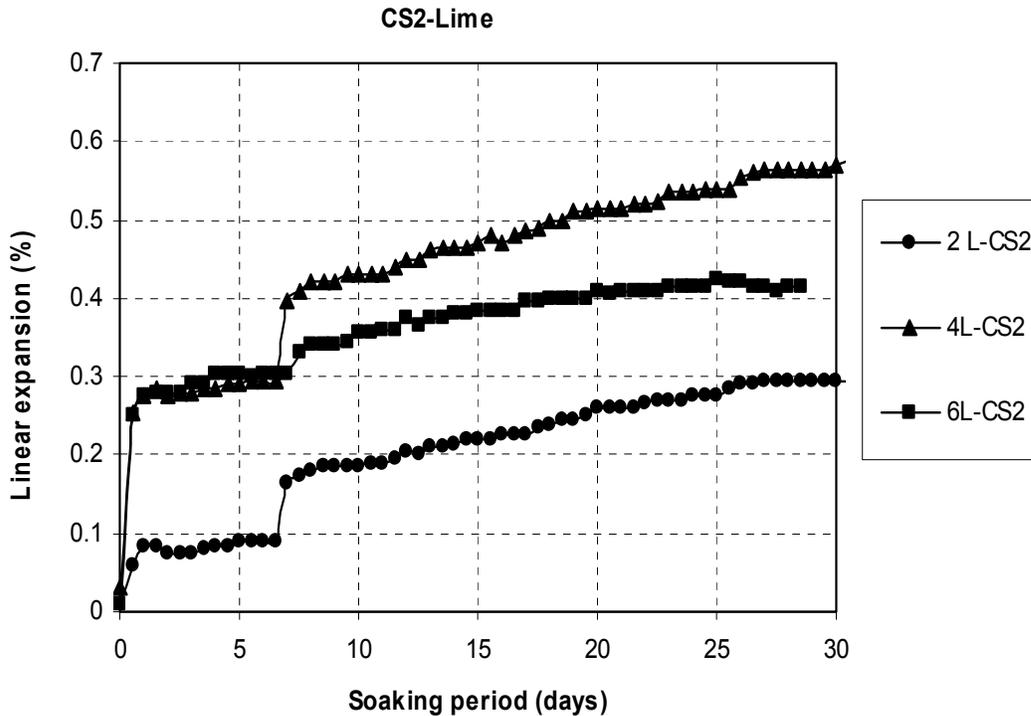
Fig. 9 – Linear expansion of WSA-Lime stabilised CS2 upon soaking for up to 30 days.

5.0 CONCLUSIONS

From the work carried out on strength and linear expansion properties of stabilized CS, it may be concluded that:

1. It is possible to utilize WSA for the stabilization of colliery spoil and similar waste in construction. This is likely to result in attractive environmental, economic, as well as technological, advantages.
2. Within the dosage levels investigated, the strength and expansion properties of WSA-stabilized CS are comparable with those of the PC-CS system. The favorable comparison of WSA with PC gives an indication of the magnitude of benefits likely to accrue from the utilization of WSA-CS material in construction.
3. Upon curing, the strength and expansion properties of WSA-GGBS-stabilized CS are superior to CS systems stabilized with either WSA, PC, or lime, although there is a small risk of a small reduction in the early strength due to the slow hydration of GGBS. However, by blending WSA with a carefully controlled amount of GGBS such

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that early strength is not severely compromised, the performance of WSA is greatly enhanced.

4. Use of the finer fraction of colliery spoil is possible, as this is the fraction likely to provide the necessary plasticity necessary for pozzolanic reactions and also for improvement in particle packing. Utilization of the fine fraction also ensure a wholesome utilization of the colliery waste material.

5. Lime is unlikely to be an effective stabilizer for CS. It does not only fail to generate significant stabilization (even with some medium plasticity CS) but it also results in increased expansion potential.

6.0   ACKNOWLEDGEMENTS

7.0   REFERENCES

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