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SUSTAINABLE MEDIUM-STRENGTH CONCRETE (CS-CONCRETE) FROM COLLIERY SPOIL IN SOUTH WALES UK

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Abstract. This paper reviews one way in which colliery spoil can be utilized in low-strength concrete. Colliery Spoil (CS) (minestone), a by-product of coal mining, is abundant in most parts of the world. It has potential as a construction material but it has not been fully appreciated. This is partly because colliery spoil is not easy to utilize, due a number of drawbacks. The major problems identified in attempts to utilize CS in construction include excessive wear, expansive behaviour, leaching of heavy metals and even radioactivity. Thus, to date, the bulk of the CS utilization is limited to isolated cases of highway embankments, backfilling of mines, quarries and other surface tips, or in extreme cases subjected to marine and other disposal. This paper reports on the scope of technological benefits of utilizing colliery spoil (CS) in low to medium strength concrete. There has been intermittent pursuance of the benefits of utilizing colliery spoil in the United Kingdom. However, there is still no well-accepted and/or positive feedback on any colliery-based technology and/or construction material, apart from that relating its use for bulk fill. This 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 fractions of colliery spoil were mixed in equal proportions and used for concrete where the binder was PC, or novel binders comprising of either Wastepaper Sludge Ash (WSA) or WSA combined in equal proportions with Ground Granulated Blastfurnace Slag (GGBS), themselves industrial wastes or by-product materials. Compressive strength of compacted cube specimens was monitored for a period of up to 56 days of curing. Results indicate that the performance of systems incorporating CS and WSA were of very poor workability, but the resultant strength was within the low to medium category usable for blinding concrete and or for use in bound granular fill or foundations.

Keywords: coal, mining, waste, colliery, stabilization, wastepaper, sludge, ash.

1. Introduction

The abundance of colliery spoil in most parts of the world necessitates a plan for its disposal, reclamation, treatment and exploration into its possible use and re-use. Most researchers report its availability as predominantly as a cohesionless (Ulusay *et al.* 2004; Kinuthia *et al.* 2007) mass comprising of both fine and coarse fractions. Colliery spoil is commonly associated with overburden minerals such as aragonite, dolomite, illite and kaolinite, with some quartz and montmorillonite in a few spoil samples (Kinuthia *et al.* 2007).

Due to increasing need for sustainable infrastructure development and maintenance, the potential for use of marginal materials such as colliery spoil is timely. Sustainable construction practices therefore necessitate a review of the current construction practices, including prevailing techniques and sources of raw materials (Kinuthia *et al.* 2001; Powrie and Dacombe 2006; Poon and Chan 2007). Waste materials and by-products that in the past have received little or no attention such as Colliery Spoil (CS) require further consideration. CS is an industrial by-product of many years of coal mining in most parts of Europe (Kinuthia 2004; Kinuthia and Gailius 2005). Its full potential as a construction material has not been fully realized, as evidenced by abundant piles of the waste material.

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, especially as bulk fill material for earthworks. The problems associated with the utilization of CS include excessive wear, expansive behavior, leaching and radioactivity (Kinuthia and Gailius 2005; Guemandi *et al.* 2008; Chaipanich *et al.* 2005). Leaching by water is generally regarded as an important factor in the utilization of colliery spoil. When clay minerals such as illite and kaolinite are present, the loss of cations such as the monovalent potassium (K^+) and to some extent so-

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dium (Na^+) weaken the silicate layers, causing weakening of the inter-layer bonding and thus exacerbating dispersion (Kinuthia *et al.* 2007; Chia and Zhang 2004; Poon and Chan 2006; Mozaffari *et al.* 2006). Other problems include the oxidation of the pyrites commonly associated with colliery spoil into products with expansive potential such as sulphates, further enhancing excess weathering and breakage. As use of colliery spoil is also in competition with many other sources of waste products, the problems either encountered or associated with its application have reduced the scope of its application (Kon and Poon 2008; Gribniak *et al.* 2008). It is therefore important that a review of the current methodologies of its application is carried out, as well as continued research into more techniques and varied uses of CS.

As colliery spoil predominantly found as all in material comprising of equal fractions of the fine and coarse fractions, this paper tries to enhance the scope of technological benefits of utilizing colliery spoil in construction, by utilizing both fine and coarse fractions of the CS waste. The research was triggered by the proximity of large supplies of CS in the South Wales region of the UK, a significant interest in soil- and cement-based cementitious systems, as well as interest in advances in sustainable construction.

2. Materials

2.1. Aggregates

The colliery spoil used as the target source of both fine and coarse aggregates for the research was obtained from an active colliery (Tower Colliery) in Aberdare, South Wales, UK. It was obtained as two materials, a fine fraction (CS-F) of low plasticity, and a coarser non-plastic fraction (CS-C). The two fractions were blended in equal proportions to produce a well-graded colliery spoil material, as shown in Fig. 1.

Stone aggregates and sand were used as coarse aggregate and fine aggregate respectively for the control concrete. The coarse aggregates were limestone (10 mm maximum size) from Aberkenfig quarry in South Wales. The sand was dredged from the Bristol Channel, and contains significant amounts of seashells.

2.2. Binders

The control binder was Portland cement (PC) supplied by Lafarge Group plc. UK. It was used to make both the control concrete and also the concrete from the colliery waste (CS-concrete). In order to enhance the sustainability of the low-strength CS-concrete, Wastepaper Sludge Ash (WSA), a waste material from the recycling of waste paper that has shown some cementitious potential (Kinuthia and Gailius 2005; Brower and Ferraris 2005; Banfill and Frias 2007), was also used (in place of PC) to make CS-concrete. The 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. It has also been established (Kinuthia *et al.* 2001; Chaipanich *et al.* 2005; Mozaffari *et al.* 2006) that WSA performs better as binder when used in combination with Ground Granulated Blastfurnace Slag (GGBS), a by-product material from the manufacture of steel. This material was supplied by Civil and Marine Slag Cement Ltd, Llanwern, Newport, UK.

The relative particle size distributions of PC, WSA, GGBS, PC and Sand used in the research were determined for the unblended states, using a bench top Malvern Mastersizer 2000 with Scirocco dry feed unit. The results are shown in Fig. 1. The particle size analyzer is also capable of determining the specific surface of powders, and the values established for PC, WSA, GGBS, PC and Sand used in the current work were 355, 162, 421, 140 and 10.8 m²/kg, respectively. The chemical and oxide compositions, physical and other properties of the CS, WSA, GGBS and PC used were also established, and are shown in Table 1.

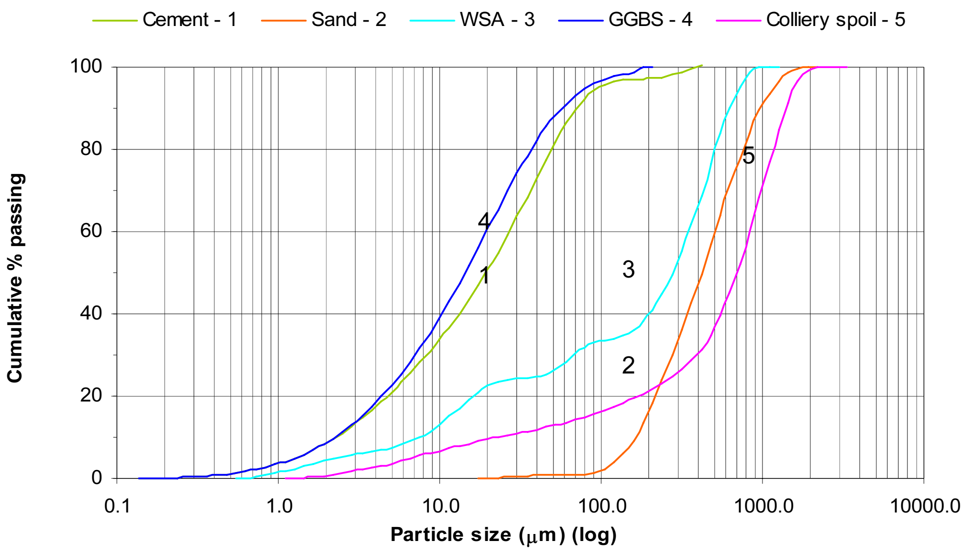

Fig. 1. Particle size distribution of PC, WSA, GGBS, CS and Sand

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

Oxide	Composition %				
	CS-F	CS-C	WSA[3]	GGBS[4]	PC
CaO	0.03	0.30	37.0	42.0	63.0
SiO_2	0.28[1]	0.07[1]	34.0	35.5	20.0
Al_2O_3	23.34	20.00	18.39	12.0	6.0
MgO	0.02	0.01	5.04	8.0	1.0
Fe_2O_3	2.09	1.08	1.77	0.4	3.0
MnO	–	–	–	0.4	<1
S_2	–	–	–	1.2	–
SO_3	0.01	0.07	1.05	0.2	2.0
Insoluble residue	98.4[2]	94.8[2]	38.6	0.3	0.5
Specific gravity	1.8	1.8	2.52	2.90	3.15
Bulk density, kg m^{-3}	–	–	–	1200	1400
Colour	Dark	Dark	Off-white	Off-white	Grey
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.

2.3. Admixture

The superplasticizer Daracem SP11 was used with a view to improving on the workability of the mixes that showed reasonable strength development but were too dry. The superplastisizer, supplied by W.R. Grace Ltd. UK, is based on the salt of a polymeric naphthalene sulphonate. Its typical properties are shown in Table 2.

Table 2. Properties of Daracem SP11 (Data provided by W.R. Grace Ltd., UK)

Appearance	Dark brown liquid
Specific gravity	1.19 at 20 °C
Maximum alkali content	0.80%
Maximum chloride content	<0.1%
Freezing point	–5 °C
High range water reducing admixture for concrete	EN 934-2:T3.1/3.2

3. Experimental procedure

3.1. Blending proportions

3.1.1. Preliminary (base-line) mixes

Previous research work on the stabilization of CS using WSA and GGBS (Kinuthia 2004; Kinuthia and Gailius 2005) has established that mixtures of CS with WSA, with or without the presence of GGBS, are very difficult to mix. It was therefore necessary to start by establishing an initial "baseline" workable mix, upon which improvements (for further workability, strength and durability) were to take place. The mix proportions of the baseline control mix were established after several trials as 1 : 0.5 : 2.9 : 2.7 (Cement:Water:Sand:Aggregate), which showed a slump value of 40 mm. For the coarse aggregate, the mix was contained equal proportions of 10 mm and 20 mm aggregate.

Using the baseline control mix, CS was then used to replace both sand and coarse aggregates. Thus the starting baseline CS concrete was made using the mix composition of 1 : 0.5 : 5.6 (Cement:Water:All in CS). This did not work out as it turned to be too dry. The CS concrete needed a completely new approach as the all in CS absorbed twice the amount of water needed in the PC control mix. To obtain a mix with a medium workability slump value of 60, the necessary mix proportions were established to be 1 : 1.4 : 5.6 (Cement:Water:All in CS). It was not clear at this stage what performance was to be expected from a concrete with a w/c ratio 1.4, especially in terms of strength development. Using these mix proportions for a baseline CS-concrete, an attempt was also made at a novel CS-concrete made by replacing the entire PC with a 50–50 WSA-GGBS blend. Thus, the initial novel baseline CS-mix for investigation was of composition 0.5 : 0.5 : 1.4 : 5.6 (WSA:GGBS:Water:CS). This gave a slump value of 30 mm, which was judged as marginally acceptable, based on previous problems with workability, and bearing in mind that there was no PC present in the mix. Table 3 illustrates the water demand for the initial trial mixes. It is clear that for the equal amounts of water in the mix, lower workability would be expected for CS-mixes made with the novel binder (WSA-GGBS), compared to either the traditional concrete (PC, sand and stone) or to a novel concrete made with PC but utilizing CS.

Table 3. Composition of initial ("baseline") mixes

Mix (M)	Type	Water : Binder	Slump
1 – Control	Sand-Stone-PC	1 : 0.5	40
2 – Novel 1	CS-PC	1 : 1.41	60
3 – Novel 2	CS-(WSA-GGBS)	1 : 1.41	30

3.1.2. Advanced (base-line) mixes

Further modifications were carried out on the base-line CS-containing mixes shown in Table 3 to address several factors, in particular to reduce the water demand and therefore increase the chances for enhanced the strength. Three approaches were adopted:

i to incorporate normal sand in CS-concrete of reduced CS content, or

ii to incorporate both normal sand and stone aggregates in CS-concrete of reduced CS content, or

iii either of these options together with a superplasticising admixture.

Tables 4–6 show the mix proportions investigated, expressed as both ratios and percent, with and without the presence of the admixture.

Table 4. Mix proportions (expressed as ratios, for all constituents)

Mix (M) No.	w/b ratio	Mix proportion (ratio)					
		Binder ratio			Aggregate ratio		
		PC	WSA	GGBS	CS	AGG.	SAND
1	0.5	1	0	0	0	4	2
2	0.9	1	0	0	6	0	0
3	0.9	1	0	0	4	0	2
4	0.9	1	0	0	3	3	0
5	0.7	1	0	0	3	1	2
6	0.7	0	0.5	0.5	0	4	2
7	1.3	0	0.5	0.5	6	0	0
8	1.1	0	0.5	0.5	4	0	2
9	0.9	0	0.5	0.5	3	3	0
10	0.9	0	0.5	0.5	3	1	2
11	0.9	0	1	0	0	4	2
12	1.5	0	1	0	6	0	0
13	1.5	0	1	0	4	0	2
14	1.3	0	1	0	3	3	0
15	1.3	0	1	0	3	1	2

Table 5. Mix proportions (expressed as %, separate for binder and for aggregates)

Mix (M) No.	Mix proportion (%)					
	% Binder			% Aggregate		
	PC	WSA	GGBS	CS	AGG.	SAND
1	100	0	0	0	67	33
2	100	0	0	100	0	0
3	100	0	0	67	0	33
4	100	0	0	50	50	0
5	100	0	0	50	17	33
6	0	50	50	0	67	33
7	0	50	50	100	0	0
8	0	50	50	67	0	33
9	0	50	50	50	50	0
10	0	50	50	50	17	33
11	0	100	0	0	67	33
12	0	100	0	100	0	0
13	0	100	0	67	0	33
14	0	100	0	50	50	0
15	0	100	0	50	17	33

Table 6. Mix proportions (expressed as ratios for all constituents) in the presence of admixture

Mix (M) No.	w/b ratio	Mix proportion (ratio)					
		Binder ratio			Aggregate ratio		
		PC	WSA	GGBS	CS	AGG.	SAND
4	0.5	1	0	0	3	3	0
5	0.5	1	0	0	3	1	2
9	1.0	0	0.5	0.5	3	3	0
14	1.3	0	1	0	3	3	0
15	1.3	0	1	0	3	1	2

3.2. Specimen preparation

Cubes of dimension 50 mm × 50 mm × 50 mm were produced. The dry materials were first mixed using a Croker AP 50 pan mixer for one minute before slowly adding the calculated amount of water. During mixing, some mixes were found to be too dry, and therefore it was decided to increase the amount of water untill a visually workable mix was obtained. The mixing process was continued for a total period of 3 minutes.

In order to investigate the effects of the admixture, two aggregate mix compositions were selected, both containing 50% CS and the remainder 50% comprising of either aggregates of partly aggregate and partly sand. This selection was based on the fact that either aggregate or a combination of both aggregate and sand were the most likely method of diluting the CS, rather than using sand alone. The deductions were made based on the 7-day compressive strength test results. The selected mixes are shown in Table 6, and all the three binders (PC, WSA and WSA-GGBS) were used to investigate these effects. The dosage of superplasticizer was expressed in percentage by weight of binder (2%). This percentage was selected as the amount that achieved a reasonably workable mix. The superplasticizer Daracem SP11 was added to the concrete mixtures during the mixing process, at the same time as the water. In the cases where the mix was still too dry, the amount of water was increased until a reasonably workable mix was achieved. All the other mixing and casting processes were kept constant as those adopted without the admixture. The freshly cast specimens were covered with cling film to prevent moisture loss. The samples were de-moulded after 24 hours and placed in a curing tank for 7, 28 and 56 days. The temperature of water in the soaking tanks was maintained at 20 °C ± 1 °C.

3.3. Testing for compressive strength

The compressive strength of both the CS-concrete and the control (PC-aggregate) concrete was monitored for curing periods of up to 56 days. Three cubes were tested for each curing period, and the data presented is the average of three test results.

4. Results and discussion

Fig. 2 shows the unconfined compressive strength results obtained from the preliminary investigation of the starting "baseline" mixes. As seen earlier for these mixes, CS-containing mixes required quite high water contents (see Table 3). The results compare the compressive strength of cubes made using the traditional stabilizer (PC), normal sand and stone aggregates), with the strength of the novel (CS) concrete made with either PC or with the novel stabilizer (WSA-GGBS), without sand or aggregate.

Fig. 2 shows a significant strength reduction in moving from the traditional concrete to the novel (CS) concrete, irrespective of the type of binder used (PC or WSA-GGBS). It was not possible to achieve a strength of 10 N/mm^2 even with the traditional PC and prolonged curing to 56 days. This reduction in strength must clearly be partly due to the high water content in the CS-concrete, resulting from the high water demand of the CS. It is also thought that it is the fine fraction of the CS (CS-F) that has the higher water demand relative to the coarser fraction (CS-C). The baseline mixes were therefore improved by adding either sand or aggregate, with and without the presence of a plasticizing admixture, and the results observed will now be presented and discussed.

Fig. 3 shows the unconfined compressive strength test results obtained from the improved baseline mixes, for all the mixes made using PC. The maximum curing period of 56 days was maintained so as to compare performance with the original base-line mixes. The strength of the control mix improved slightly, although made at a w/c ratio of 0.5 as with the baseline mix seen earlier. The CS-concrete was made at two higher w/b ratios of 0.7 and 0.9, a reduction from the much higher water content in the baseline mixes with a w/b ratio of 1.41 (Table 3). From Fig. 3, it is evident that there was some improvement in strength from the baseline mixes, since the CS-concrete mix containing both aggregate and sand (CS-Ag-S; M5) was fairly workable at a w/b ratio of 0.7, and achieved and average strength value exceeding 20 N/mm^2 at the early curing period of 7 days. All the other CS-mixes with neither aggregate or sand, or with either sand or aggregate only (CS, CS-Ag & CS-S) could only be mixed at a w/c ratio of 0.9, and all achieved approximately identical strength magnitudes at all curing period, all below 20 N/mm^2 even at 56 days of curing. The CS-PC specimens (M2) showed the lowest performance throughout, confirming the need to improve on the baseline mixes that were made using CS as the only agregate.

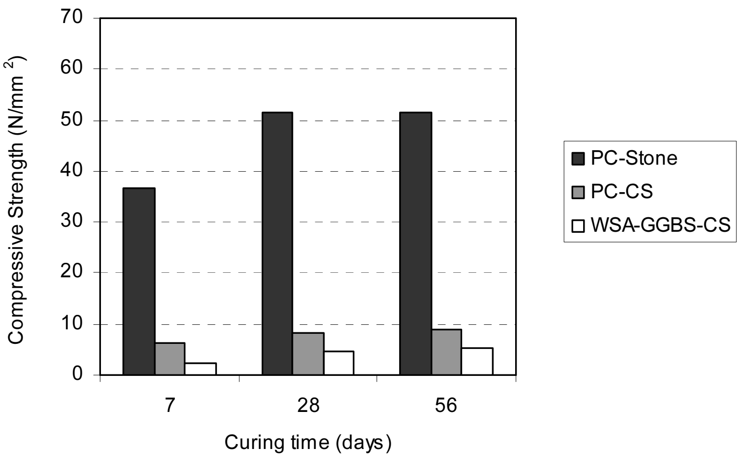

Fig. 2. Comparison of strength of PC-Stone concrete with that of PC-CS and WSA-GGBS-CS

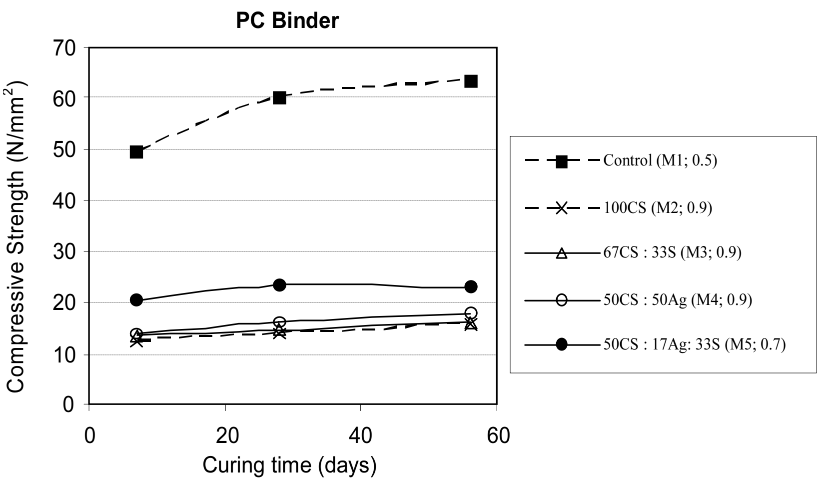

Fig. 3. Compressive strength of CS-concrete made with PC and incorporating sand and/or stone aggregate (control)

Fig. 4 shows the results from Fig. 3 expressed relative to the control (normal concrete). The best performing mix (CS-Sand-Aggregate mix) shows a relative strength of 42% of the control. This illustrates that with further fine-tuning of the mix design, it is possible to achieve at least 50% of the normal-strength concrete while incorporating significant proportions of colliery spoil in the concrete.

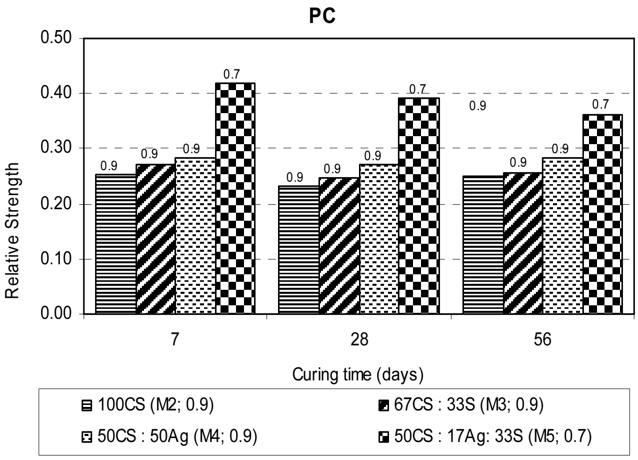

Fig. 4. Compressive strength of CS-concrete made with PC binder, relative to the control (Normal concrete comprising of PC, sand and stone aggregate)

Fig. 5 shows the unconfined compressive strength results obtained from the improved baseline mixes, for all the mixes made using novel binder WSA, up to a maximum curing period of 56 days. The best performing mix (M11; w/b = 0.9) was made using sand and stone without any CS. This mix achieved between 12–16 N/mm^2, lower than the best PC-CS concrete (20–22 N/mm^2). The relative strength of this "best" mix is only about 25% of the control (Fig. 6), and an attempt was therefore made to improve the binding power of the novel WSA binder by blending it with GGBS.

Fig. 7 shows the unconfined compressive strength results obtained from the improved baseline mixes, for all the mixes made using novel binder (WSA-GGBS blends), up to a maximum curing period of 56 days. The best

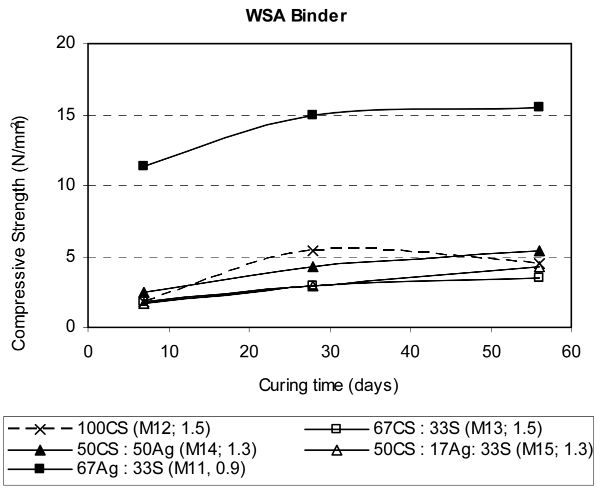

Fig. 5. Compressive strength of CS-concrete made with WSA binder, incorporating sand and/or stone aggregate

performing mix (M6; w/b = 0.7) was made using sand and stone without any CS. This mix achieved between 15–20 N/mm^2, marginally lower than the best PC-CS concrete. Thus, although the binding power of the novel WSA-GGBS binder may appear disappointing, with further fine-tuning of the mix design it is possible to achieve reasonable concrete strength values when the PC binder in normal concrete is replaced with an appropriate WSA-GGBS blend. A combination of both CS and the novel binder resulted in significant strength reduction, and unless a way of reducing the water demand further was possible, it would be difficult to find applications for this type of concrete. The presence of aggregates (Mix 9; w/b = 0.9) or both sand and aggregate (Mix 10; w/b=0.9) was the best way of diluting the colliery spoil, rather than using sand on its own (Mix 8; w/b = 1.1). The latter resulted in the lowest strength. This is perhaps because of the lower reduction in water demand when sand alone is used to dilute the CS rather than using either aggregates or a combination of aggregates and sand. The data in Fig. 7 are also displayed in Fig. 8 relative to the control concrete. The highest strength obtained is seen to be about 30% of the control (compared with 42% when PC binder was used, and with 25% when WSA alone was used).

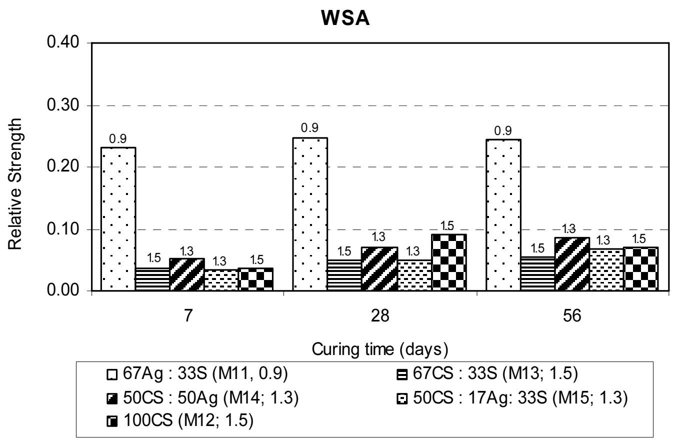

Fig. 6. Compressive strength of CS-concrete made with WSA binder, relative to the control (Normal concrete comprising of PC, sand and stone aggregate)

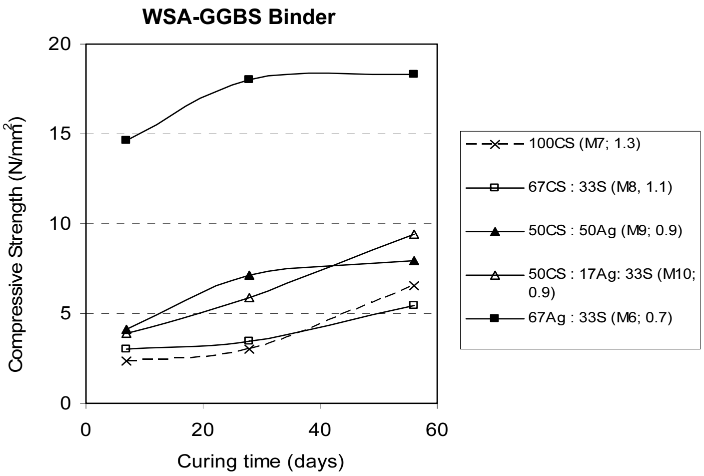

Fig. 7. Compressive strength of CS-concrete made with WSA-GGBS binder, incorporating sand and/or stone aggregate

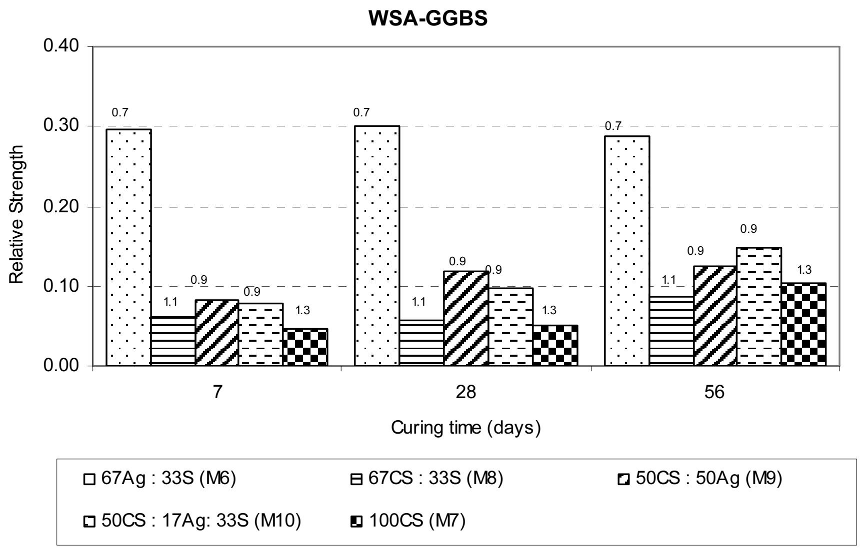

Fig. 8. Compressive strength of CS-concrete made with WSA-GGBS binder, relative to the control (Normal concrete comprising of PC, sand and stone aggregate)

Fig. 9 shows the effects of the superplasticizer admixture (Daracem SP11) on the 7-day strength of the CS-concrete containing 50% CS as the aggregate, the remainder of the aggregates being either wholly stone aggregate or a combination of stone aggregate and sand. The effects of all the three binders (PC, WSA and WSA-GGBS) are shown and it is clearly evident that the admixture only worked in the cases where PC was the binder. One possible reason for the lack of effective reduction in water demand when either WSA or WSA-GGBS was used was the fact that there were short delays during the addition of the admixture, during which time the concrete mix continued to hydrate. With the ultra sensitive and fast setting WSA binder, this must have reduced the effectiveness of the admixture, and more water was needed in the presence of the admixture than without it. The effects of the admixture with PC were fairly reasonable, increasing the relative strength of the best performing CS-concrete from previously about 42% to 45%. At prolonged curing to 56 days, research has shown this enhancement increases to about 50% of the control.

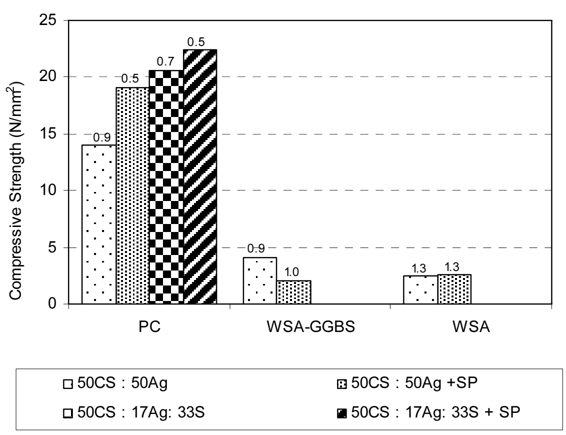

Fig. 9. Compressive strength of CS-concrete made with PC or with WSA-GGBS binder at different water binder ratios, with and without Daracem SP11 superplasticizer, relative to normal concrete comprising of PC, sand and stone aggregate (control)

5. Conclusions

From the work carried out on strength properties of CS-concrete using PC, WSA and WSA-GGBS blends, it may be concluded that:

1. It is possible to utilize PC, WSA or WSA-GBBS blends as binder for the production of CS-concrete. Of these 3 binders, PC is the most powerful followed by WSA-GGBS blends.

2. The use of the significant stockpiles of colliery spoil available worldwide can result in attractive environmental, economic, as well as technological benefits. These benefits increase significantly when the colliery spoil concrete is made incorporating other waste or by-product materials, such as WSA and GGBS.

3. Despite the high water demand, it is possible to utilize the finer fraction of colliery spoil. As this is the fraction that is likely to provide a dense particle packing necessary for a dense concrete, its possible consumption in significant quantities would ensure a wholesome utilization of the colliery waste material, rather than concentrating on the more attractive coarser fraction.

4. It is possible to use admixtures to enhance the workability of CS-concrete made using PC as binder. However, the rapid and flush hydration of WSA makes the use of admixtures in CS-concrete utilizing WSA or WSA-GGBS as binder extremely difficult. The benefits of the admixture are lost, especially if there are even slight delays that allow the WSA to hydrate, further increasing the water demand.

5. Further work is needed in order to include other materials and practices in the utilization of colliery spoil. This, combined with use of further fine-tuning of the mix compositions investigated would improve the compressive strength, especially upon the establishment of ways of achieving enhanced workability at relatively lower w/b ratios than those adopted in the current investigations.

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VIDUTINIO STIPRUMO EKOLOGIŠKAS BETONAS IŠ PIETŲ VELSO (JUNGTINĖ KARALYSTĖ) ANGLIES KASYKLŲ ATLIEKŲ

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S a n t r a u k a

Anglies kasyklų atliekos yra potenciali ekologiška žaliava statybos dirbiniams gaminti, tačiau iki šiol neištirtos jos savybės ir naudojimo galimybės. Staripsnyje pateikti tyrimų rezultatai rodo, kaip, taikant specialias technologijas, savybes modifikuojančius priedus, kompozicines rišamąsias medžiagas, galima anglies kasyklų atliekas naudoti vidutinio stiprumo tvariam betonui gaminti.

Reikšminiai žodžiai: betonas, anglies kasyklų atliekos, stabilizatoriai, plastikliai, popieriaus atliekų šlamo pelenai.

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