Site trials of concrete with a very low carbon footprint

P. Claisse, E. Ganjian & H. Sadeghi-Pouya
Faculty of Engineering and Computing, Coventry University, Priory Street, Coventry CV1 5FB UK

ABSTRACT: This paper reports on six site trials of sustainable concrete mixtures. The first three were concrete barriers for landfill, the fourth was a trench fill and the fifth and six were roads and car parks. The methods and mixtures evolved from moderately conventional designs containing ashes and slags and some cement which were blended at the plant to a super-sulphated pre-blended powder containing waste plasterboard and no cement. The strengths were not as high as a typical structural concrete but were fully adequate for each application. The paper concludes that while the technical viability of each mix was demonstrated, problems with insurance, capital funding, and environmental regulators have prevented their wider application

1 INTRODUCTION

1.1 *The six trials*

This paper reports on six site trials of sustainable concrete mixtures carried out by the Construction Materials Applied Research Group at Coventry University. The objectives of the paper are:

- To illustrate how a wide and evolving range of sustainable concrete mixtures have performed well under site conditions.
- To investigate the design and exploitation of the site trials.
- To discuss how trials of this type may be optimised for their primary purpose which is to persuade industrial enterprises to exploit the results of the underlying research.
- To demonstrate a wide range of applications for concrete with relatively low strength.

The first three trials were intended to demonstrate the viability of concrete barriers as part of a composite waste containment system for landfills. They were constructed in 1999-2000 with a total of 70 m^3 of concrete. Each cell contained two different concrete mixtures.

The fourth trial was a trench trial of a single mix intended for use as mine or trench backfill. It was constructed in 2004 with 7 m^3 of concrete.

The fifth trial was a slab in a car park built in 2006 with 16 m^3 of semi-dry concrete

The sixth trial was an access road which was constructed in 2006 by stabilising 72 m^3 of soil with a sustainable "cement" and then placing 6m^3 of a semi-dry paste (grout) as a road base.

Extensive monitoring of the first three trials was carried out until 2006 when they were demolished. Monitoring of the fourth is planned and is in progress on the fifth and sixth.

1.2 *The "Novel Blended Cement"*

For the first four trials the cementitious components were delivered to the batching plant and mixed on site (in the plant for mixes trials 1 to 3 and in the truck-mixer for trial 4). This was found to be inaccurate and difficult and also unlikely to lead to commercial exploitation. Therefore for trials 5 and 6 a pre-blended powder was made which could be treated exactly like cement at a batching plant.

The components of the "novel blend" are:

- Basic oxygen slag from steel manufacture (80%)
- Waste plasterboard (15%)
- Kiln by-pass dust from cement manufacture.(5%)

These components were chosen partially because the client was interested in finding uses for waste gypsum. Once the gypsum had been included to make a "super-sulphated" mix any cement could have caused problems with expansion. The components were inter-ground to form a grey powder which looks exactly like cement.

2 TRIALS 1-3

2.1 *Introduction*

Three cells were constructed on a licensed landfill operation site at Risley, Cheshire UK with different cementitious composite mineral waste materials [Claisse, 2000, 2003a, 2003b, 2006, Ganjian 2004a, 2004b, 2006a, 2006b]. This landfill site receives both domestic and industrial waste.

2.2 *Layout and construction methods of the cells*

A typical test cell is shown schematically in Figure 1. The barrier is made up of two layers of concrete with a layer of clay between them. These inverted pyramid shape cells measured 8 metres wide and contained waste to a maximum depth of 1.1 metres. The slopes of the cell sides were 30° and the cells contained 5.4 m^3 of waste. The excavation was carried out with a hydraulic excavator which was also used to place the concrete and paste mixes designed for the different cells. The compaction of concrete layers was carried out by two poker vibrators and the compaction of clay layer was carried out using the outside surface of the excavator's bucket

2.3 *Mixture Designs*

The primary containment method for the barriers is "chemical" containment. In this system any leachate entering the barrier is buffered to high pH which causes harmful species to precipitate and become bound in the barrier. The mix designs were therefore developed to give a good buffering capacity. This was measured by monitoring the "through pH" of the eluent from the permeability test cells. The mix designs and their properties are shown in tables 1 and 2. Waste sodium sulphate solution from lead-acid battery recycling was used as mix water in two mixtures.

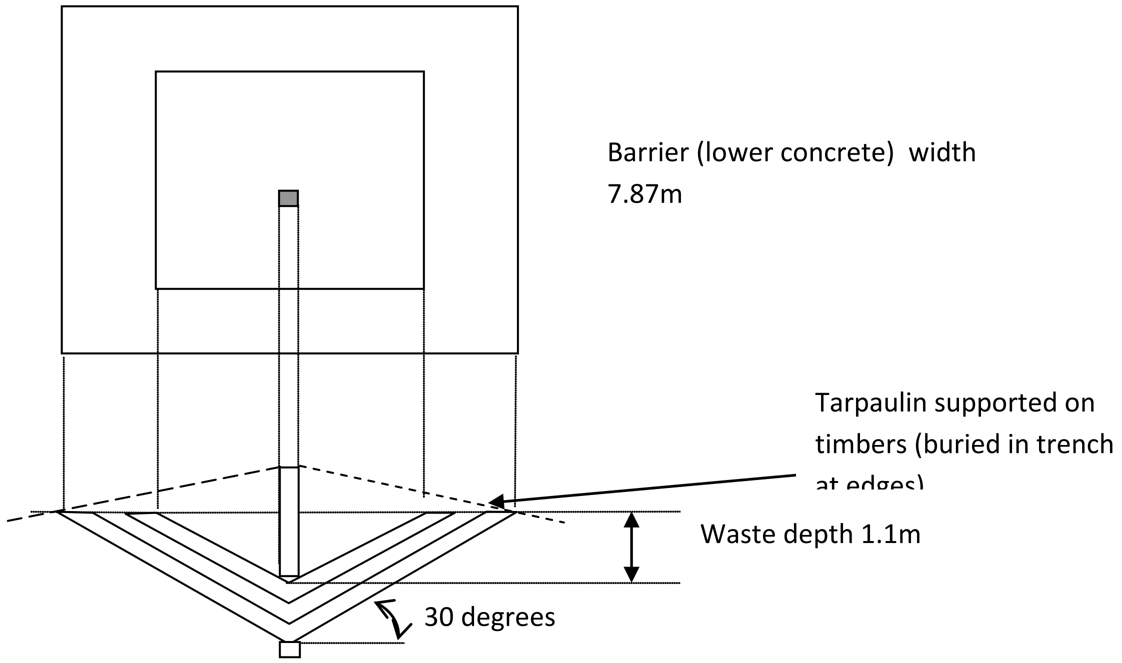

Figure1: Typical trail test cell layout.

Table 1. Composition of mixes used in the three trial cells at Risley.

	Proportions Used kg/m^3	% By mass
Composition of top layer concrete for cell No.1:		
Spent Borax from silver refining	450	18.5
Ferrosilicate sand	895	36.8
20mm Limestone	1085	44.7
Water	210	
Composition of top layer mortar for cell No.2:		
Ferrosilicate slag sand (< 5mm)	1575	65.9
Cement Kiln Dust (CKD)– 60%	490	20.5
Lagoon Ash from coal burning – 40%	325	13.6
Water	200	
Composition of top layer concrete for cell No.3:		
Ferrosilicate slag (< 150mm to dust)	0	
Limestone (<20mm)	715	29.8
Ferrosilicate slag sand (< 5mm)	1105	46
Cement Kiln Dust – 60%	340	14.2
Lagoon Ash from coal burning– 40%	240	10
Water	220	
Composition of lower layer concrete for cell No.1:		
Ground Granulated Blastfurnace Slag (GGBS)	180	7.6
Ordinary Portland Cement (OPC)	20	0.9
Chrome Alumina Slag (40mm)	1515	64.2
Green Sand (ex-casting)	645	27.3
Na_2SO_4 solution from battery recycling	295	
Composition of lower layer concrete for cell No.2:		
Chrome Alumina Slag (< 40mm)	1175	49.6
Chrome Alumina Slag (< 5mm)	720	30.4
Green sand from casting moulds	100	4.2
Cement Kiln Dust – 60%	165	7
Pulverised Fuel Ash – 40%	210	8.8
T1Sodium sulphate Solution (lt)	165	
Composition of lower layer concrete for cell No.3:		
Chrome Alumina Slag (< 40mm)	1175	50.3
Chrome Alumina Slag (< 5mm)	720	30.8
Green sand	110	4.7
Ordinary Portland Cement – 5.2%	25	1.1
Cement Kiln Dust – 69.8%	185	7.9
Lagoon Ash from coal burning– 25%	120	5.2
Water	240	

Table 2. Properties of concrete used in cells 1,2 and 3.

	7 days strength (MPa)	28 days strength (MPa)	Intrinsic permeability to water @ 28 days (m/s)	Intrinsic permeability to leachate @ 28 days (m/s)	Thro' pH water#	Through pH leachate#
Cell 1 top	5	4.5	1.5×10^{-8}	4.0×10^{-8}	10	_
Cell 1 base	11	13	No flow	2×10^{-12}	_	8.5
Cell 2 top	1.1	1.7	4.5×10^{-9}	5×10^{-9}	11.8	12.3
Cell 2 base	4.4	6.9	2.3×10^{-9}	4.5×10^{-9}	10.1	9.9
Cell 3 top	0.9	1.3	1.2×10^{-8}	7.5×10^{-9}	12.2	12.1
Cell 3 base	2.8	6	1.2×10^{-8}	6.2×10^{-9}	8.5	7.6

* Initial pH of leachate: 5.1 - 5.4

\# The 'through pH' is the pH of the outflow from the permeability test

2.4 *Observations from the construction*

During the construction of cell numbers 2 and 3 the mix proportions actually used were different to what was designed in laboratory due to some practical problems encountered in the batching plant and placement of some of materials (inaccurate weightings of different materials and partial hydration of CKD while stored at the plant). The mixes actually made were tested and showed higher permeabilities than the mixes designed initially in the laboratory.

2.5 *Emplacement of waste and leachate*

Due to size and shape constraints of the cells shredded waste was used. It was placed and compacted up to the top level of the test cells. A leachate which provided the most aggressive solution representing the leachates found in the landfill was obtained from the leachate treatment plant for the site and the cells were filled 100 mm below the top giving a 1 m head at the deepest point. The cells were covered with a tarpaulin rain cover to prevent rainwater ingress and contain odour.

2.6 *Instrumentation and sampling*

Two types of sampling lines were used between the layers of the cell liners using 3 mm plastic tubes in both. In one type the end of the 3 mm plastic tubes were glued inside porous stone discs of 60 mm diameter. In the other type the layer was drilled and the 3 mm plastic tubes ends were sealed in place in the set concrete with sponge around the end of the line. The sampling lines were placed as an array in the various liner materials and levels. Liquid samples were obtained by applying a vacuum to the lines.

2.7 *Initial Observations*

Cell 3 needed to be refilled after 12 months. The reason for this was inadequate compaction of the clay layer leading to an increased permeability. The effective indicated permeability was calculated and found to correspond to nearly the same permeability as a Bentonite Enhanced Sand liner and indicates satisfactory performance even when very poor construction practice was evident but it did affect the modelling considerably. The permeability calculated from these site observations was therefore used for the clay layer.

2.8 *Comparison between model and observations*

The capacity factor, and diffusion coefficient values obtained from laboratory diffusion tests on the top and bottom mixes used in the site trial cells together with the initial concentrations of different elements in site leachate and the mixes used in the cell (from pore pressed solutions) were used to model the transport in the barriers. The model simulates pressure driven flow and diffusion using a finite step code written to run as a macro in Microsoft Excel. The modelled concentration is plotted against measured collected sample concentration values in figures 2 to 4 for Ca, Na and K for cell 2. On these graphs error bars are shown between the 10th and 90th percentiles from the probability calculations at ages of two and four years. The observed concentrations which are shown on the graph are based on the average from up to four different samples taken in different parts of the cells. For some of these a considerable spread of results was recorded.

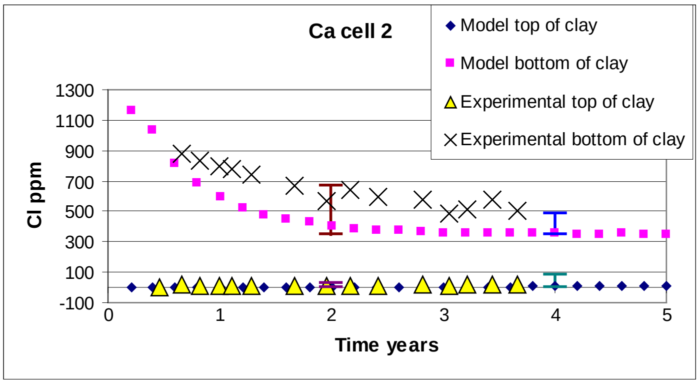

Figure 2. Concentrations of calcium in site trial cell 2

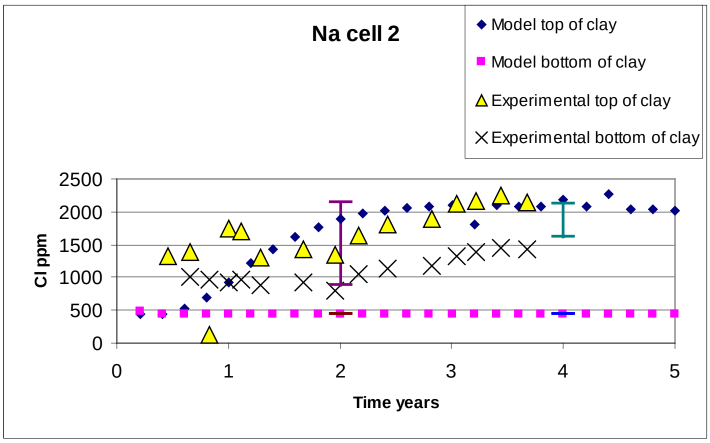

Figure 3 Concentrations of sodium in site trial cell 2

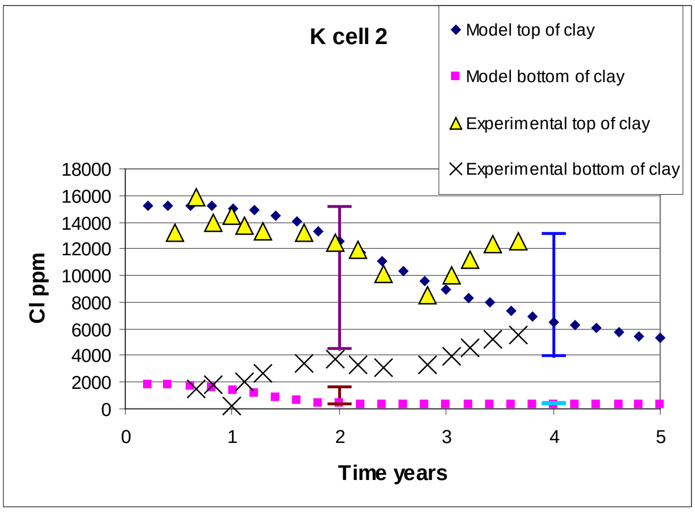

Figure 4 Concentrations of potassium in site trial cell2

TRIAL 4

Introduction

This trial was a trench fill. The total quantities of materials used were:

Red Gypsum: 5.3 Tonne

BOS weathered slag: 8 Tonne

Water: 2400 litres

Calculated yield: 7.4 m^3

This mix was selected to give a strength which was adequate for trench filling but not too high for subsequent excavation if this became necessary.

Mix procedure.

Both the slag and the gypsum were supplied in sling bags containing approximately one tonne each. These were discharged onto a conveyor and loaded directly into a truck-mixer. The trench was approximately 5 meters long by 1 meter wide by 2 meters deep. The mix filled the trench to within 0.5 meters from the top.

2.9 *Observations.*

2.9.1 *From loading mixer:*

- Some difficulties were experienced with the conveyor and the entire loading process took approximately two hours.
- The anticipated problems with handling the red gypsum did not occur.
- The gypsum had not consolidated in the sling bags and flowed freely out of them.

2.9.2 *From Samples taken*

- The flow of the first sample was measured to be 545 mm (very close to 560mm target).
- Some unmixed lumps of red gypsum were observed. These were extracted using a 5mm sieve. The quantity was observed to decrease from the first to the second sample but increased again for the third sample.
- Initial set was 1.5 hours from discharge and final set approximately 7 hours.

2.9.3 *From Discharge*

- The material was observed to flow freely in the trench.
- A small number of agglomerated lumps up to 150mm in size were observed.

- The material was self-compacting and air could be seen escaping (venting to surface) indicating that vibration was not necessary.
- The trench into which the mix was poured had partly filled up with rain water since it was pumped out earlier in the morning. The first $0.5m^3$ discharge into the trench initially appeared to mix with the water in the trench, but very rapidly “clear” water separated out on top of the mix. The mix did not appear to be adversely affected by being poured into standing water. It is suggested that this degree of cohesion is superior to the performance of foamed concrete where some grout loss might be observed in these circumstances.
- The surface of the pour remained reasonably flat along the trench even though it was only poured from one end. It was difficult to see the exact slope due to the free water on the surface but the final slope was minimal.

2.10 *Testing*

The 28 days result of the average of 3 cubes (50 mm) which were taken from top, middle and bottom of the truck mixer load was 1.8 MP

3 TRIAL 5

3.1 *Introduction*

A 6 m by 17 m area of car park was used for a sub-base trial. The area was stripped of the existing hardcore to expose the sub grade, which was hard clay. This design was adopted to be similar to the existing layers of constructed car park area to provide comparable data between conventional sub-bases and the RCC layer. The mixture design used the “novel blend” and is shown in table 3.

Table 3. Mix proportions of concrete mix used in Lowdham Grange site trial

Mix Code	Mix proportions (kg/m3)				
	Blended novel binder	Water	Recycled Agg.	W/B	Slump
PG15/BPD5/BOS80 (RA-RCC)	400	100	1900	0.25	0

Table 4. Compressive strength of laboratory and site RCC layer

Mix Code	Laboratory tests				Insitue tests			
	Strength at days (MPa)			Density kg/m3	Strength at days (MPa)			Density kg/m3
	3	7	28		14	28	90	
RCC (Lab.)	0.96	2.02	10.80	2390	-	-	-	-
RCC (Site-Truck 1)	0.70	1.20	5.47	2350	-	-	-	-
RCC (Site-Truck 2)	0.68	1.29	4.70	2232	-	-	-	-
RCC (Site-Truck 3)	0.99	1.42	7.10	2293	-	-	-	-
Core (Location 1)	-	-	-	-	Soft	8.7	13.41	2257
Core (Location 2)	-	-	-	-	Soft	10.11	15.43	2226

3.2 *Placing Concrete and Compaction*

To give a thickness of 100mm after compaction a layer of 160 mm of concrete was placed and levelled manually. As the concrete was delivered in three truck loads; placing and compaction of RCC layer was carried out in three segments of the allocated area. As a result, a slightly different moisture content and compaction level was expected for sections. The workability of the mixes on site was, however, observed to be very consistent. The hot weather on the day was compensated for with accurate batching of water content. The placed concrete layer was then compacted using a 3-Tonne vibrating roller.

3.3 *Testing*

The test results are shown in table 4

4 TRIAL 6

4.1 *Introduction*

A 22 m length of the site access road (4 m wide) was constructed using stabilised soil and a paste (grout) sub-base both of which used the “novel blend” in place of cement.

Table 5 shows the proportions of materials used for soil stabilisation and semi-dry paste. The volume of stabilised soil needed for the site trial was estimated at about 72 m^3 in a loose condition including wastage. For the semi-dry paste, the volume of material needed was estimated to be about 6 m^3 . Half of the area was constructed using a conventional base course with same thickness as the semi-dry compacted paste. Finally, the surface of the whole road was paved using 50 mm bituminous of wearing surface.

4.2 *Construction method – stabilised soil*

The blended powder was spread over the area using a volumetric method. In order to achieve the required amount of binder per cubic metre of the compacted soil, 150 mm of the blended powder was spread over the trail area The mixture of soil and powder was blended using a rotavating blending machine. The powerful and heavy blade of the machine provided a homogeneous blend of soil and binder along the road.

As the natural moisture of the soil used was not enough to provide the optimum compaction of stabilised soil, extra water was added to the mixture using a mobile sprinkler. Then the mixture was blended again using rotavating blender and levelled using the JCB. The control of the water content visually was quite challenging at that stage because of the hot weather and quick evaporation. However, despite of this, the moisture content and compaction of the stabilised soil was satisfactory.

Table 5. Mix proportions of stabilised soil and semi-dry compacted paste (grout) mixes used

Mix Code	Soil %	Binder %	Moisture content %
Stabilised soil (soil50/Binder50)	50	50	14
Semi-dry paste (PG15/BPD5/BOS80-.13)	-	100	13

4.3 *Construction method – base course*

A layer of 100 mm semi-dry compacted paste was designed to be laid on top of the stabilised soil. As the water content of the paste was limited to 13%, a volumetric mixer was used to mix the blended binder with water. The mixer contained a vessel to accommodate the binder and a 1600 litre tank of water. The binder passed to a screw by means of a belt conveyer where the water was added and mixed in the extending arm. The only challenge was measuring the amount of water because the mixer was not equipped by any means to measure the water added to the mixture. Therefore, the required amount water was adjusted based on visual inspection and past experience.

4.4 *Test Results*

The test results are shown in tables 6 and 7.

5 DISCUSSION

5.1 *Strengths.*

The strengths of the mixtures from all of the trials (except the soil stabilisation) are summarised in table 8. It may be seen that the material for trials 5 and 6 are the highest despite having no ordinary cement in it. This was helped by the very low water contents in the mixtures but it still demonstrates that viable mixtures can be made without cement. The "novel blend" was not designed for use as a partial replacement of cement and is not recommended for use with any cement.

5.2 *Interpreting the trials*

Transport processes in landfills are associated with a high degree of uncertainty. The processes which were modelled in trials 1-3 used real landfill leachate which was undergoing biological reactions throughout the experiment and took place in a site environment with all of the associated uncertainty. The combination of these factors with the uncertainty associated with the stated assumptions in the model has given rise to some unexpected events. Nevertheless this is a useful exercise to indicate likely trends in a real environment. Long term results which will involve transport processes far closer to the steady state are actually likely to be more accurate.

In all of the trials the batching was less accurate than it was in the laboratory work but in every case the mix proved tolerant enough to perform adequately. The conditions of a site trial are likely to be worse than full-scale production because of problems with plant. For example in trial 4 the mixing in the truckmixer was visibly incomplete but the mix still performed well. In each case it was concluded that the mix would perform adequately in full scale use. The road in trial 6 has been used by heavy vehicles and plant for a considerable time and is performing very well with no signs of distress.

5.3 *Future use of the research.*

The experimental programme for trials 1-3 cost over 0.5 million pounds and the barriers were scheduled to be tested in a full-scale waste containment cell (approximately one hectare) but the site operator's insurers would not carry the risk, despite further containment being designed to go below the experimental liner.

A major mine backfill project has been planned with the mix from trial 4. This would involve placing 100,000 m^3 per year for the foreseeable future (the void to be filled is 10 million m^3). The material would be poured down bore-holes into a partially flooded mine. This project has received full regulatory approval but awaits funding. This project would require a significant capital investment and the company has recently been taken over so there may be a long delay.

A further site trial was planned with the "novel blend" used in trials 5 and 6. This would have involved filling a dis-used pedestrian subway in Coventry city centre. Despite being fully contained by the existing structure this pour did not receive approval from the Environment Agency and will not now go ahead. The environmental concerns were all addressed but the relevant committee twice delayed the decision to subsequent monthly meetings and did not give approval in time. The matter was complicated because the committee mistakenly associated the trial with complications at the local cement works including tyre burning trials and a release of kiln dust which spread across a large part of the town.

Nevertheless the pressure is growing to reduce the environmental impact from cement production and site trials represent the only route to take solutions from the laboratory into practice.

Table 6. Compressive strength of stabilised sub-grade together with in-situ density and moisture

Table 7. Compressive strength of laboratory and site semi-dry paste layer

Mix Code	Laboratory tests	Insitue tests

Mix Code	Laboratory tests: Strength at days (MPa) 3	7	28	Moisture %	Dry Density kg/m3	Insitue tests: Moisture %	Dry Density kg/m3
Unstabilised Soil-B (Lab.)	0.08	0.21	0.13	13.40	1835.1	-	-
Soil-B 50/Binder 50 (Lab.)	0.94	1.43	5.98	13.90	2030.15	-	-
Soil 50/Binder 50 (Site-Mid)	0.78	1.11	5.80	8.02	2033.06	8.90	1755
Soil 50/Binder 50 (Site-End)	0.96	1.15	5.10	7.90	2027.55	8.90	1793

	Strength at days (MPa) 3	7	28	Moisture %	Density kg/m3	Strength at days (MPa) 14	28	90	Density kg/m3
Semid dry paste (Lab.)	5.10	12.80	30.55	13	2540	-	-	-	-
Semi dry paste (Site-Begin)	3.20	6.64	19.90	8.55	2487	-	-	-	-
Semi dry paste (Site-End)	2.95	6.20	22.40	7.76	2492	-	-	-	-
Core (Mid)	-	-	-	-	-	10.75	30.1	46.41	2381
Core (End)	-	-	-	-	-	8.64	26.1	38.98	2011

Table 8. Summary of strengths

Trial	Pour	Cementitious component	Strength
1	Cell 1 top	Spent borax 100%	4.5
2	Cell 2 top	CKD 60%, Lagoon ash 40%	1.7
3	Cell 3 top	CKD 60%, Lagoon ash 40%	1.3
1	Cell 1 base	GGBS 90%,OPC 10%, Sodium sulphate	13
2	Cell 2 base	CKD 60%, PFA 40%, Sodium sulphate	6.9
3	Cell 3 base	OPC 5%, CKD, 70%, Lagoon ash 25%	6
4	Trench fill	BOS 60%, Red Gypsum 40%	1.8
5	Sub-base	BOS 80%, PB 15%, BPD 5%	10.8
6	Base course	BOS 80%, PB 15%, BPD 5%	30.55

6 CONCLUSIONS.

Viable mixtures which contain little or no Portland cement can be made for a wide variety of applications.

Site trials represent the best route to develop these mixtures for commercial use.

Pre-blended mixtures are the best way to use powder which contains several mineral wastes.

While it is relatively easy to demonstrate the viability of cementitious mixtures which are sustainable there are many difficulties which may prevent their industrial use. These include:

- Insurance problems
- Lack of capital investment
- Environmental concerns which may or may not have any scientific basis.

ACKNOWLEDGEMENTS

The authors acknowledge the considerable support provided to enable us to carry out the work reported in this paper. Supporting organisations have included ENTRUST, MIRO, Lafarge PLC, Huntsman Tioxide, WRAP, EPSRC and NERC and

our major partners have been Imperial College and Birmingham University.

REFERENCES

Claisse P A, Ganjian E, Tyrer M and Atkinson A, 2000. Concrete without calcium or silica. *Proc. British Cement Association Concrete Communication Conference at University of Birmingham June.* pp.117-122, ISBN 0 7210 1570 0

Claisse, P A Atkinson A, Ganjian E and Tyrer M, 2003a. Recycled Materials in Concrete Barriers. *ACI publication SP212-59. Proc. 6th Canmet/ACI conference on the Durability of Concrete, Thessaloniki, Greece, June* pp.951-971.

Claisse, P A Atkinson A, Ganjian E and Tyrer M, 2003b. Performance criteria for concrete as a barrier for leachate in waste containment. *Proc. International conference on the performance of construction materials, Cairo, Feb. 18-20* . ISBN 977-237-192 pp.1135-1144

Claisse P, Ganjian E, Atkinson A and Tyrer M, 2006. Measuring And Predicting Transport in Composite Cementitious Barriers. *ACI Materials Journal* Vol 103; Numb 2 Pp. 113-120

Ganjian E, Claisse P, Tyrer M and Atkinson A, 2004a. Preliminary investigations into the use of secondary waste minerals as a novel cementitious landfill liner, *Construction & Building Materials Journal*, VOL 18; NUMBER 9; pp. 689-699 ISSN 0950-0618

Ganjian E, Claisse P, Tyrer M and Atkinson A, 2004b. Selection of cementitious mixes as a barrier for landfill leachate containment. *ASCE Journal of Materials in Civil Engineering*, Vol 16 No 5 October . pp. 477-486 ISSN 0899-1561

Ganjian E, Claisse P, Tyrer M and Atkinson A, 2006a. Factors affecting measurement of hydraulic conductivity in low strength cementitious materials. *Cement And Concrete Research* Vol 36; Number 12 Pp. 2109-2114

Ganjian E, Claisse P and Tyrer M, 2006b. Use of Unclassified Ashes as Controlled Low Strength Materials for a Novel Cementitious Landfill Liner. *Ash Tech 2006*. 15-17 May UK Quality Ash Association.