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Compressive strength of novel alkali activated stabilised earth materials incorporating solid wastes

Abhilash Holur Narayanaswamy B.E., PGP-ACM, PhD
Research Associate, Centre for Sustainable Technologies, Indian Institute of Science, Bengaluru, 560012, India

Peter Walker* BSc (Eng.), PhD, MIEAust, CEng FIStructE, MICE
Professor of Innovative Construction Materials, BRE Centre for Innovative Construction Materials, University of Bath, Bath, BA2 7AY, UK
*Corresponding author. Email: p.walker@bath.ac.uk. Tel: +44 (0)1225 386646

B.V. Venkatarama Reddy, B.E. (Civil), MSc (Eng.), PhD
Chairman, Centre for Sustainable Technologies, Indian Institute of Science, Bengaluru, 560012, India

Andrew Heath BSc (Eng.), MS, PhD, CEng MICE
Professor of Geomaterials, BRE Centre for Innovative Construction Materials, University of Bath, Bath, BA2 7AY, UK

Daniel Maskell MEng, PhD
Lecturer, BRE Centre for Innovative Construction Materials, University of Bath, Bath, BA2 7AY, UK

Abstract:

The research presented in this paper is aimed at developing novel alternative sustainable stabilised earth materials for use in loadbearing affordable housing construction. Prototype stabilised earth materials have been produced in the laboratory incorporating a range of solid wastes, including aggregates derived from construction and demolition waste as well as industrial processes. The earth construction materials were stabilised with either Portland cement, Portland cement and lime, or through alkali-activation. Experimental results for compressive strength are reported, together with findings from a comparative Life Cycle Inventory analysis. Construction and demolition waste shows promise as a potential aggregate for stabilised earth construction. The use of processed ground blast furnace slag together with fly ash is also promising for development of alkali-activated stabilisation.

1. Introduction

Over the past few decades interest in traditional and stabilised earth construction techniques, such as rammed earth and compressed earth blockwork, has increased significantly amongst researchers and practitioners (Minke 2006; Venkatarama Reddy & Kumar 2010; Hall et al 2012; Harries and Sharma 2016). However, despite significant progress in research understanding of materials, and a growing list of published design guidance documents (King 1996; Standards Australia 2002; Walker et al. 2005) and national standards (NZS 1998; Dachverband Lehm e.V. 2009; DIN 18945 2013; IS 1725 2013; ASTM E2392 2016), the uptake of modern earthen materials has largely remained fringe compared to market leading materials such as concrete and conventional masonry (Maskell & Keable 2016). There are exceptions, however, where modern stabilised earthen construction techniques, in particular compressed earth blockwork, have made a significant market impact. One such example is around Bengaluru, Karnataka, South India, where during the last 20 years many thousands of buildings, mostly housing, have been successfully completed using stabilised compressed earth blocks and, to a lesser extent, stabilised rammed earth [Figure 1].

Figure 1. Modern stabilised compressed earth block building, Bengaluru, India

Stabilised earth construction materials largely rely on the addition of cement, together with compaction, to enhance strength and durability. However, concerns about the environmental impact of construction materials manufacture, and in particular cement, evaluated using Life Cycle Analysis (LCA), have led manufacturers and researchers to seek alternative solutions (Maskell et al. 2016). The carbon dioxide emissions associated with cement manufacture remains a wider concern for concrete materials as well as stabilised earth products. In recent years, in parallel with work on alkali-activated (geopolymer) cements and concrete, researchers have also been investigating and developing alkali-activated based solutions for earth construction stabilisation.

Alkali-activated materials are formed through the reaction of aluminosilicates under alkaline conditions, which produce a hardened binder formed of hydrous alkali-aluminosilicates and/or alkali-alkali earth-aluminosilicates (Provis 2018). Common aluminosilicate ‘precursor’ materials used for alkali-activated materials are fly ash and metakaolin, whilst a common alkaline ‘activator’ is sodium hydroxide. Hardening often relies on curing at temperatures around 50-80^{o}C for a few days. The main attraction of alkali-activated materials is their potential to reduce embodied carbon dioxide emissions, compared to cement stabilisation, whilst maintaining the benefits of stabilised earthen materials.

To date there has been relatively little research on alkali-activated materials applied to earth construction materials. In 2007 Freidin (2007) reported on the development of pressed blocks incorporating fly ash, bottom and sodium silicate. Muñoz et al. (2015) successfully produced stabilised materials using clay soils together with alkali-activators. Using a combination of Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_2), and a curing regime of 7 days at 65°C, the authors produced materials with a compressive strengths of 7.6 N/mm^2. Elert et al. (2015) developed alkali-activated solutions for the consolidation of earthen structures. Trials on adobe test blocks showed significant improvement in water resistance and mechanical strength. They used 5M NaOH and 5M Potassium Hydroxide (KOH), cured for 50 days, at room temperature. Meanwhile, Silva et al. (2015) found most success using fly ash as a precursor in the production of alkali-activated self-stacking compressed earth blocks. With up to 15% fly ash and 13.7% alkali activator they produced blocks with compressive strengths up to 12 N/mm^2. Rui et al. (2016) have presented work on alkali-activated stabilisation of silty sand soils in Portugal with using a fly ash precursor with an alkali-activator comprised of 1:2 mix of sodium silicate and sodium hydroxide.

A study of dry-stack alkali-activated compressed blocks, incorporating soils and construction and demolition waste, was reported by Miranda et al. (2017). The strength development of the alkali-activated blocks under ambient conditions continued for around 150 days, but overall performance confirmed that the blocks were suitable for low rise loadbearing masonry applications. Sore et al. (2018) found that 10-15% alkali-activated binder content (using NaOH and metakaolin) was able to produce blocks having at least 4 N/mm^2 compressive strength. Dahmen et al. (2018) compared the LCA of cement stabilised and alkali-activated stabilised blocks with conventional concrete blocks. The embodied carbon contents of the cement stabilised and alkali-activated blocks were similar, and between 42-46% less than the concrete blocks. However, using their production methods and materials, Dahman et al (2018) found that the alkali-activated blocks had higher impacts on human health, ecosystem toxicity, water usage, and mineral resource usage. These findings are concerning for developing the use of alkali-activated materials in stabilised earth, and are explored below in a further Life Cycle Inventory analysis. Rather than using fly ash or metakaolin, Marsh et al. (2018) developed alkali-activated stabilised earthen materials using clay soil alumino-silicates as the precursors.

Earth construction techniques rely on the access to suitable raw materials, largely comprised of natural sub-soils. Although non-renewable, raw materials for earth construction are generally widely available and in such large quantities as to provide a sustainable source for future construction. Stabilised earth construction is more suited to sandier soils, with lower clay contents, and so it is quite common for natural sub-soils higher in clay content to be blended with finer aggregates, such as building sand, to achieve a more suitable grading. However, access to high natural quality building sand can be problematic in many areas of the world, which has led to the use of alternatives such as crushed stone (‘manufactured sand’) and seeking alternative supply chains, such as construction and demolition wastes. Jayasinghe et al. (2016) reported that a 1:1 mixture of soil and concrete demolition waste, with 10% Portland cement stabilisation, produced rammed earth with sufficient compressive strength for two-storey residential style construction. Arrigoni et al. (2018) found that incorporating recycled concrete aggregates into cement stabilised rammed earth led to a reduction in compressive strength, however, its inclusion was not deleterious to durability.

This paper reports on a collaborative study between India and UK developing alkali-activated compressed earth blocks and rammed earth, and also exploring opportunities for use of aggregates from construction and demolition waste blended with natural soils. The collaborative research was funded through the UK-India Education and Research Initiative (UKIERI), supporting the exchange of staff between the university partners to undertake specific research tasks. Test results for mechanical strength, compressive stress-strain properties, and thermal properties of alkali-activated and cement stabilised materials are reported, together with findings from a preliminary Life Cycle Inventory analysis comparing their environmental impacts. The novelty of this work lies primarily in developing a high value use for industrial wastes and construction and demolition waste in alkali-activated earth products. In addition, this study includes a comprehensive physical and mechanical property characterisation, and comparative life cycle inventory analysis, of the products. The study will further development of stabilised earth construction in both developed and developing countries at a time when the global demands for affordable housing and lowering the environmental impact of the built environment have never been greater.

2. Aims and Objectives

The overall aim of the work presented here has been to develop the use of solid waste materials in compressed earth construction techniques, and explore the potential for using alkali-activated binders (geopolymers) as alternatives to cement for stabilised earth construction materials. The specific objectives to meet this aim are:

- Compare mechanical performance of cement stabilised and alkali-activated stabilised compacted earth materials;
- Assess potential to incorporate solid inorganic wastes (construction and demolition waste; processed granulated blast furnace slag) into stabilised earth materials;

- Compare embodied carbon footprints of cement and alkali-activated stabilised earth materials.

3. Materials and mix proportions

3.1 Soils and aggregates

A residual natural sub-soil, sourced from a site near Bengaluru, Karnataka, India, was selected for this study based on its suitability as a base material for stabilised earth materials. The clay fraction is comprised of kaolin minerals. The grading curve of the soil is presented in Figure 2, with further properties summarised in Table 1 below.

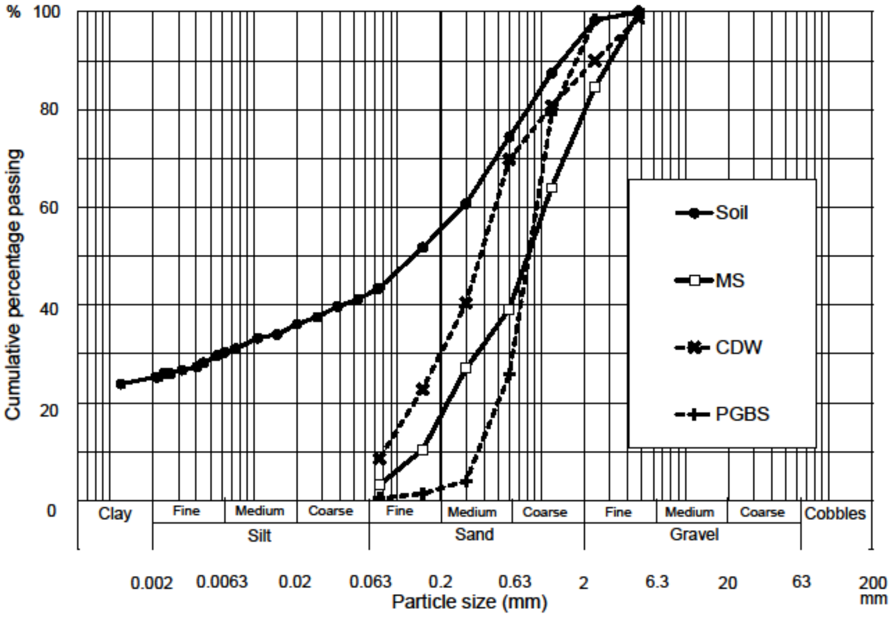

Figure 2. Particle Size Distribution curves for aggregates

Table 1. Soil properties

Property	
PSD summary	
Clay content	41%
Silt content	12%
Sand content	47%
Gravel content	0%
Atterberg limits	
Plastic limit	16%
Liquid limit	36%

In this research various aggregates [Manufactured Sand (MS); Construction and Demolition Waste (CDW); Processed Granulated Blast-furnace Slag (PGBS)] were blended with the natural soil to improve suitability for stabilised earth construction. The MS is produced by crushing granite rock quarried locally to Bengaluru; it has become an established alternative to river sands for use in concretes and mortars. The grading curves for the RS and MS are also presented in Figure 2.

Two solid waste materials were selected for use in this study: CDW, and PGBS. The CDW was sourced from a supplier in Gujarat, India. The graded waste material is a residue from crushing and recycling concrete, and other building demolition waste, including ceramic bricks and mortars, following extraction of larger aggregates for reuse in concrete. The grading curve for the CDW is presented in Figure 2.

The PGBS was sourced from the JSW steel plant, Toranagallu, Bellary, Karnataka, India. PGBS is a granulated aggregate material, and like the more commonly known Ground Granulated Blast Furnace Slag (GGBS), is sourced from cooling molten ash in the process of steel production. PGBS is, however, not as finely ground as GGBS, and its chemical composition also differs from GGBS. The grading curve for the

PGBS is presented in Figure 2, whilst the chemical composition of the PGBS, and CDW, determined by SEM/EDX, are presented in Table 2. In this study PGBS was used primarily as an aggregate substitute, whilst GGBS was used as a precursor for the alkali-activation.

Table 2. Chemical composition of PGBS, GGBS and FA

Parameter	PGBS	GGBS	FA	CDW
Si	34.0%	38.3%	26.8%	18.3%
Al	22.0%	10.5%	20.9%	10.9%
Ca	25.0%	5.1%	1.3%	21.6%
Mg	6.0%	-	-	4.4%
K	1.0%	1.6%	2.1%	0.5%
Fe	1.0%	3.2%	5.1%	-
Na	-	3.1%	-	-
Mn	1.0%	-	-	-
Ti	-	-	1.9%	0.4%
S	-	-	-	0.7%
Loss on Ignition	10%	-	-	-

3.2 Cement, lime, precursors, and alkali activators

The study used a Portland Cement (PC) [Grade 53, IS 269 (2013)]. An hydrated building lime [IS 712 (1984)] was used together with the PC to stabilise the rammed earth and compressed earth blocks.

GGBS from JSW Steel Limited, Karnataka and Fly Ash (FA) from the Raichur Thermal Power plant, Karnataka, India, were used as precursors for the alkali-activation. The chemical compositions of the GGBS and FA are also given in Table 2. Sodium Hydroxide (NaOH) was used as the alkali-activator. The NaOH pellets were dissolved in water, and used in 12M concentrations throughout together with the GGBS and FA. As mentioned earlier, clay minerals can be activated using NaOH or similar alkali activators, and it is therefore likely that the clay minerals in the mix contributed to the total precursor amount.

3.3 Mix proportions

The mix proportions for material characterisation tests are presented. Sufficient MS, CDW and PGBS were added separately to the natural residual soil to reduce the total clay content of each mixture to 15% by dry mass of aggregates, considered suitable for stabilised earth construction. Each of the four cement stabiliser quantities and five alkali-activated stabiliser quantities, in the proportions outlined in Table 3, were combined with the three different soil mixtures represented as CDW, MS and PGBS in Table 4. The total quantity of water added for the cement stabilised and alkali-activated materials was 10% (by mass) in all cases. The specimen density was controlled (to around 1800 kg/m^3), and a compaction moisture content of 10% was sufficient to achieve a mix suitable for preparation of specimens using a static compaction process.

Table 3. Binders for Small Cylinder Tests (proportions by mass)

Cement stabilised	Geopolymer stabilised
7% Cement	12M NaOH
10% Cement	
7% Cement+ 2% Lime	12M NaOH + 5% GGBS
10% Cement+ 2% Lime	12M NaOH +15% GGBS
-	12M NaOH + 5% Fly ash
	12M NaOH +15% Fly ash

4. Research Methodologies

4.1 Research programme

A series of mechanical strength tests have been completed on small cylinders of cement and alkali-activated stabilised compacted earth. These tests were undertaken to establish the most appropriate binder and soil mix proportions for a subsequent investigation on full-size compressed earth blocks, rammed earth cylinders and masonry prisms. A comparative Life Cycle Inventory Analysis was completed to compare the environmental impacts of the cement and alkali-activated materials. All materials were sourced, and all specimens were manufactured, in India.

4.2 Specimen manufacture

A series of 72 cement stabilised and 90 alkali-activated 38 mm diameter and 76 mm high cylinders were produced using the mix proportions outlined above. After mixing the materials the cylinders were compacted inside a steel cylindrical mould using manually controlled threaded piston, as shown in Figure 3. Using the piston, the compaction process was volumetric, producing cylinders 76 mm high with a consistent target density of 1800 kg/m^3. Each fresh mix of materials was carefully batched in sufficient quantity by mass for each specimen to achieve the target dry density of 1800 kg/m^3. The chosen target density, and 10% moisture content at compaction, was based largely on past experience with the soil materials (Reddy and Latha 2014; Reddy and Kumar 2011).

Figure 3. Small cylinder compaction machine

Following compaction the cylinders were extruded from the mould using the threaded piston. The cement stabilised cylinders were moist cured under damp burlap (jute canvas) for 28 days. In contrast, after compaction, the alkali-activated cylinders were heat cured at 80^{o}C for a 72 hour period in a hot air oven.

4.3 Compression tests

The small 38 mm diameter cylinders were tested, in uniaxial compression. The cylinder samples were tested both oven-dry and saturated states at 28 days after manufacture. For saturation cylinders were immersed in water for 48 hours. In testing the compressive loading was applied to each cylinder at a constant displacement rate of 1.25 mm/minute.

5. Experimental results

Results for dry density, water absorption, dry compressive strength and wet compressive strength for the small cylinders are given in Table 4. The results for each series are represented by mean and Coefficient of Variation (C.V.) of three repeat tests.

Table 4. Small cylinder test results

Solid waste	Dry Density (kg/m^3)		Average water absorption	Dry compr. strength (N/mm^2)		Wet compr. strength (N/mm^2)	
	Mean	C.V.		Mean	C.V.	Mean	C.V.
7% cement							
CDW	1800	0.0%	15.0%	4.95	6.1%	2.04	8.8%
MS	1820	0.0%	14.5%	4.43	5.4%	1.92	3.1%
PGBS	1800	0.0%	15.7%	4.94	3.6%	2.33	6.0%
10% cement							
CDW	1820	0.0%	13.1%	7.11	2.5%	3.05	1.0%
MS	1820	0.0%	13.1%	7.06	3.5%	2.95	6.8%
PGBS	1810	0.0%	15.1%	6.64	4.5%	3.92	3.3%
7% cement and 2% lime							
CDW	1810	0.0%	15.0%	5.30	6.8%	2.31	6.0%
MS	1830	0.0%	13.3%	5.50	6.2%	2.59	6.6%
PGBS	1810	0.0%	14.9%	5.87	8.0%	3.35	8.4%
10% cement and 2% lime							
CDW	1800	0.0%	15.0%	7.01	6.0%	3.34	5.7%
MS	1820	0.0%	14.0%	6.81	3.4%	3.56	4.5%
PGBS	1810	0.0%	14.9%	8.44	4.2%	4.99	4.0%
NaOH (12M)							
CDW	1780	0.0%	14.5%	3.40	4.4%	1.60	10.0%
MS	1790	0.0%	13.6%	3.59	2.8%	1.51	13.2%
PGBS	1770	0.0%	14.5%	2.78	20.5%	1.36	35.3%
NaOH (12M) + 5% GGBS							
CDW	1800	0.0%	12.8%	4.03	7.4%	2.87	9.8%
MS	1790	0.0%	13.8%	5.00	12.8%	2.26	16.4%
PGBS	1790	0.0%	13.2%	3.92	3.8%	2.36	15.7%
NaOH (12M) + 15% GGBS							
CDW	1780	0.0%	13.9%	4.89	12.0%	2.90	8.6%
MS	1800	0.0%	14.0%	5.22	10.3%	2.26	16.4%
PGBS	1780	0.0%	13.7%	3.91	6.1%	2.47	2.0%
NaOH (12M) + 5% FA							
CDW	1770	0.0%	14.7%	4.63	13.0%	2.23	8.1%
MS	1780	0.0%	14.1%	4.81	7.9%	2.49	2.0%
PGBS	1770	0.0%	15.0%	4.46	15.7%	2.32	10.8%
NaOH (12M) + 15% FA							
CDW	1780	0.0%	14.3%	7.61	0.5%	4.07	2.5%
MS	1770	0.0%	14.8%	7.00	3.7%	3.75	0.8%
PGBS	1770	0.0%	14.5%	6.72	3.6%	4.16	8.4%

The target density for each series was 1800 kg/m^3. On average the cement stabilised cylinders exceeded the target density by 0.7% only, whereas the alkali-activated cylinders were under target, on average, by just over 1%. The consistency in performance for each series and across the entire sample confirmed that the chosen method of fabrication has been successful.

On average the water absorption of the alkali-activated cylinders was 14.1%, compared to just under 14.5% for the cement stabilised cylinders. The difference in performance is not particularly significant and is typical of values for stabilised earthen materials, and indeed many fired clay masonry units too. For the cement stabilised cylinders the lowest water absorption trends towards the MS cylinders, whilst the high water absorptions, on average, were associated with PGBS series. In the alkali-activated series the water absorption values on average were similar for all aggregate types.

The average dry unconfined compressive strengths ranged between 2.78 and 8.44 N/mm^2, whilst the corresponding average wet strengths ranged between 1.36 and 4.99 N/mm^2. These values are typical for stabilised earthen materials. On average cement stabilised cylinders were stronger than the alkali-activated stabilised cylinders. The average ratio of dry/wet compressive strengths was 2.0 (Figure 4), again fairly typical for stabilised earth materials and indicative that longer term material durability is likely to be satisfactory. It is, however, noteworthy that a number of the alkali-activated series exhibited greater variance (expressed as a C.V.) in strength performance compared to the cement stabilised materials.

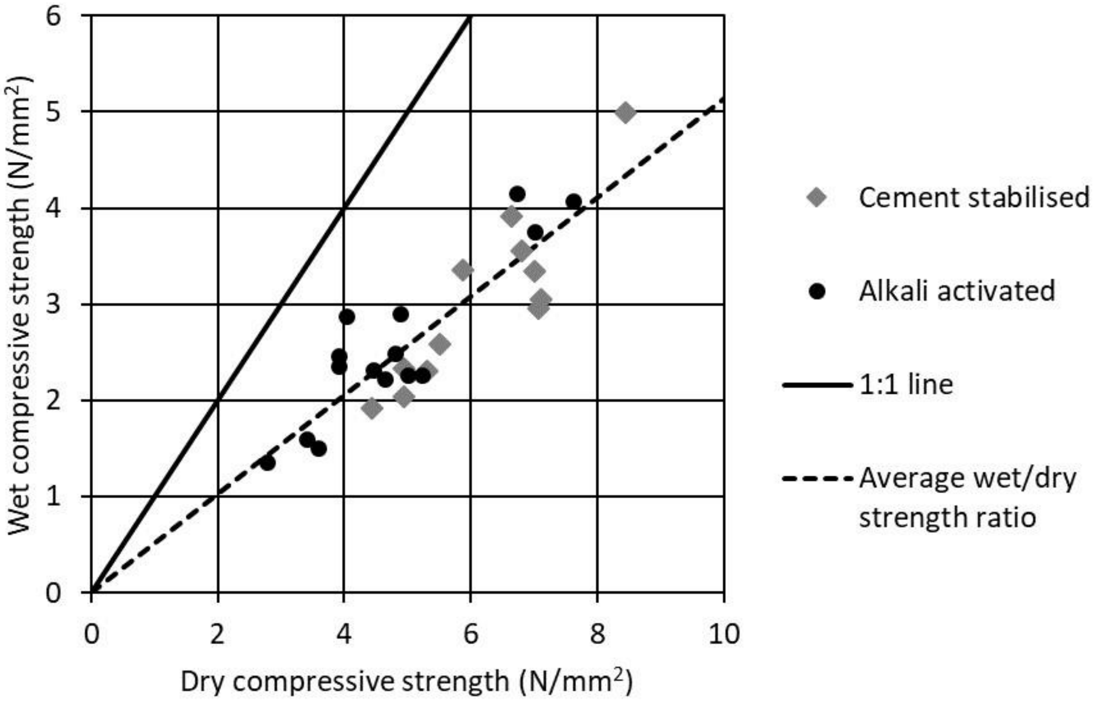

Figure 4. Relation between wet and dry compressive strengths

The dry compressive strengths of cement and lime stabilised specimens were not especially influenced by aggregate type, except for the series with 10% cement and 2% lime and PGBS aggregate, in which the highest dry strength was recorded. The pozzolanic activity of the PGBS combined with the additional lime is attributed to the marked strength gain in this series. The dry compressive strengths increased with cement use, from 7% to 10% by mass. Although generally dry strength also increased with a further 2% lime addition with the cement, in series 10% cement and 2% lime (with both the CDW and MS aggregates) there was no significant improvement with the lime addition. In contrast the wet compressive strengths consistently improved with greater cement and with greater lime contents. Overall 3% addition of cement is more effective at increasing both dry and wet strength than a 2% addition of lime. Whilst there was no significant influence of aggregate type when comparing dry strength, the PGBS specimens showed highest strength when tested wet.

The dry compressive strengths for the specimens using alkali-activation were higher than the corresponding wet strengths. The further addition of both GGBS and FA generally increased material dry compressive strength, with the FA overall producing higher strengths than the GGBS specimens. The MS aggregate specimens consistently showed highest dry strength when using alkali-activation. For wet compressive strength the CDW produced highest strengths when using GGBS, but with the FA the best performing aggregate was the PGBS. In contrast to the dry strengths the wet strengths of specimens using 5% and 15% GGBS did not improve with the 10% further addition of GGBS. However, for the FA specimens there was a consistent and linear increase in wet compressive strength with the increasing FA addition from 5% to 15%. The FA specimens consistently out-performed the GGBS specimens. In summary, the CDW and PGBS proved most effective for use as alternative aggregates in both cement and alkali-activated stabilised earth construction materials. FA proved most effective as a precursor in the alkali-activated stabilised materials.

The statistical significance of the results was assessed using Multivariant Analysis of Variance (MANOVA), considering the variables of Primary stabiliser, Secondary Stabiliser and Supplementary aggregate, with the dependent variables of Dry strength, Wet Strength and Density. The results indicate that each factor and their interactions are statistically significant (based on $p<0.05$), with the exception of the interaction of all three variables. This result confirms the importance of correct mix design when considering the primary stabiliser, secondary stabiliser and aggregate and their combined effects.

6. Life Cycle Inventory Analysis

6.1 Methodology

Life Cycle Analysis (LCA) for construction materials produced in a laboratory is difficult as theoretical rather than actual processes need to be analysed. A comprehensive LCA should be undertaken using data which are specific to the location (Martínez-Rocamora, et al, 2016), but as there are a lack of comprehensive LCA data for the Bengaluru region, the western Europe EcoInvent database was used for the water, aggregates, NaOH, cement and lime. Because some of the categories in this database are location specific (e.g. freshwater ecotoxicity), it was decided to focus on the global warming potential through the 100 year embodied CO_2 equivalent (CO_2-eq) as an indicator of environmental impact. CO_2-eq is commonly used to compare the environmental impact of construction materials and has global implications.

In any LCA analysis assumptions are necessary, and in this case these were based on the principle that a comparison between the different materials was required, and that the location of the construction was in Bengaluru, India. Similar to other researchers (e.g. Heath et al, 2014), the system boundary was taken as the factory gate for the materials, and therefore this approach is that of a Life Cycle Inventory (LCI) that can be used within a larger LCA. This applies the assumption that the materials would be used in the same manner, and that the mixing and compaction would be identical whether alkali-activation or cement stabilisation was used. The only exception to this was for the alkali-activated materials, which also required heating to 80°C as part of the curing process.

In the case where heating was required, the CO_2-eq was calculated by assuming the materials required heating from an ambient temperature of 30°C and the CO_2-eq was 0.167g CO_2-eq/°C per kg material. This impact was calculated by taking the typical firing temperature and CO_2-eq emissions from manufacture of fired clay bricks in the informal sector in India (Manoharan, et al, 2011; Maheshwari, and Jain, 2017), and assuming a linear relation between temperature change and CO_2-eq emissions. This is most likely a slightly conservative assumption as the time required for heating fired bricks is longer than for alkali-activated bricks, and the infrastructure for the different methods is substantially different.

Regardless of the aggregate type, values for mined natural sand were used as there was insufficient data to make any assumption. The benefits of reusing waste materials are not always apparent when only considering global warming potential (GWP) as it does not consider the broader benefits of reducing materials to landfill or reducing mining of natural aggregates. The values for FA and GGBS were taken from Habert et al. (2011) assuming an economic allocation of impacts to these industrial by-products.

6.2 Results and discussion

As shown in Figure 5, the different mixes have different GWP but it cannot be concluded that either cement stabilised or alkali-activated is the preferred approach as some types of cement stabilisation can have a lower GWP than some types of alkali-activation, but the reverse is also true. The slight overall difference between the GWP of cement stabilised and alkali-activation of earth materials was also noted by Dahmen et al (2018); this similarity is why the effect of the stabilisation on engineering properties needs to be considered along with the GWP of the mixes. In all cases the stabiliser (which is taken to include heat curing) has the largest contribution to GWP, varying between 95.5% and 97.8% of the total for the raw materials. This is similar to the trends noted for other stabilised earth masonry units (Maskell et al, 2018) and for alkali-activated concrete (Habert et al, 2011).

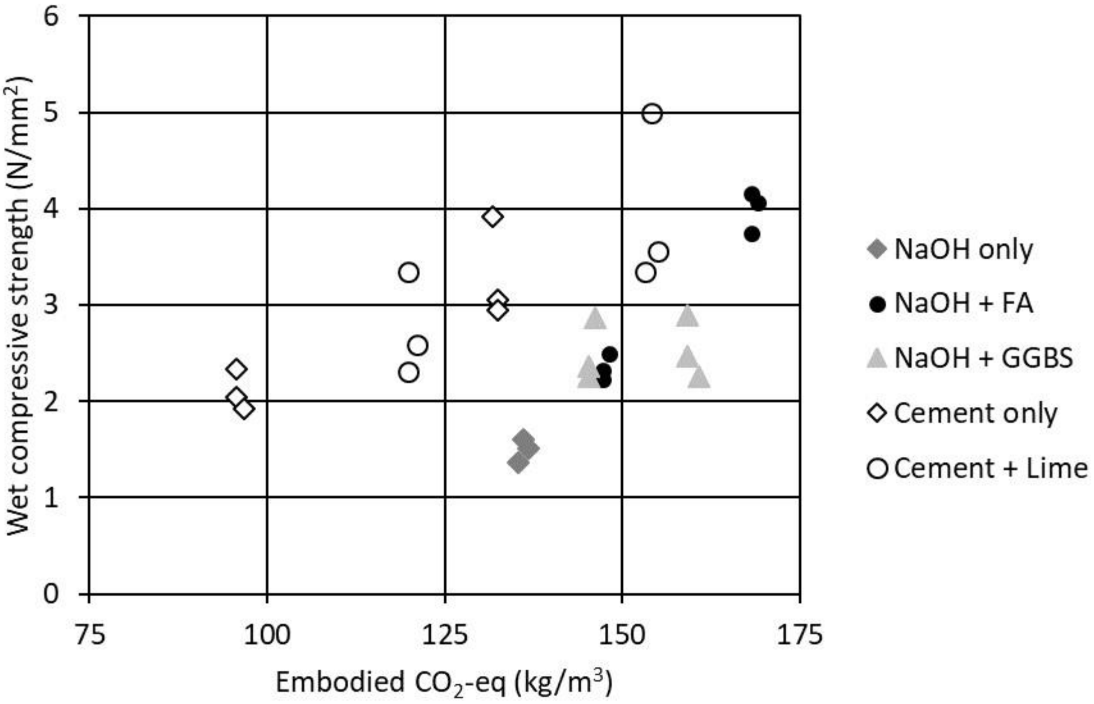

Figure 5. Global warming potential of different mixes

Assessing the relative benefit achieved from stabilization here is more important than comparing the absolute values of GWP, as it provides a more holistic view of a stabiliser's effectiveness. As a primary reason for stabilising is improving strength and durability, the impact of stabilisation on the GWP and on wet strength was assessed, as shown in Figure 6. For both stabilisation approaches (alkali-activated and cement based stabilisation), there is a strong relationship between embodied CO_2-eq and wet compressive strength. This generally shows that, as expected, the addition of more stabiliser results in improved wet strength. It is possible that increasing stabiliser content will increase strength, but it will eventually reach a point where additional stabiliser will cease to improve strength (Venkatarama Reddy and Kumar, 2011; Marsh et al, 2018).

For a wet compressive strength of below 3 N/mm^2, the data in Figure 6 indicates cement stabilisation can produce earth materials with a lower embodied CO_2-eq than the equivalent strength alkali-activated samples, but as the strength and embodied CO_2-eq increases, this difference reduces. As mentioned earlier, the higher strength cement or cement and lime stabilised samples were influenced by aggregate type, where the PGBS aggregate resulted in higher strengths. As shown in Figure 6 and Table 4 stabilisation with high cement and lime contents and the PGBS aggregate produces higher strengths than with the other aggregates, despite the GWP remaining more or less constant between samples.

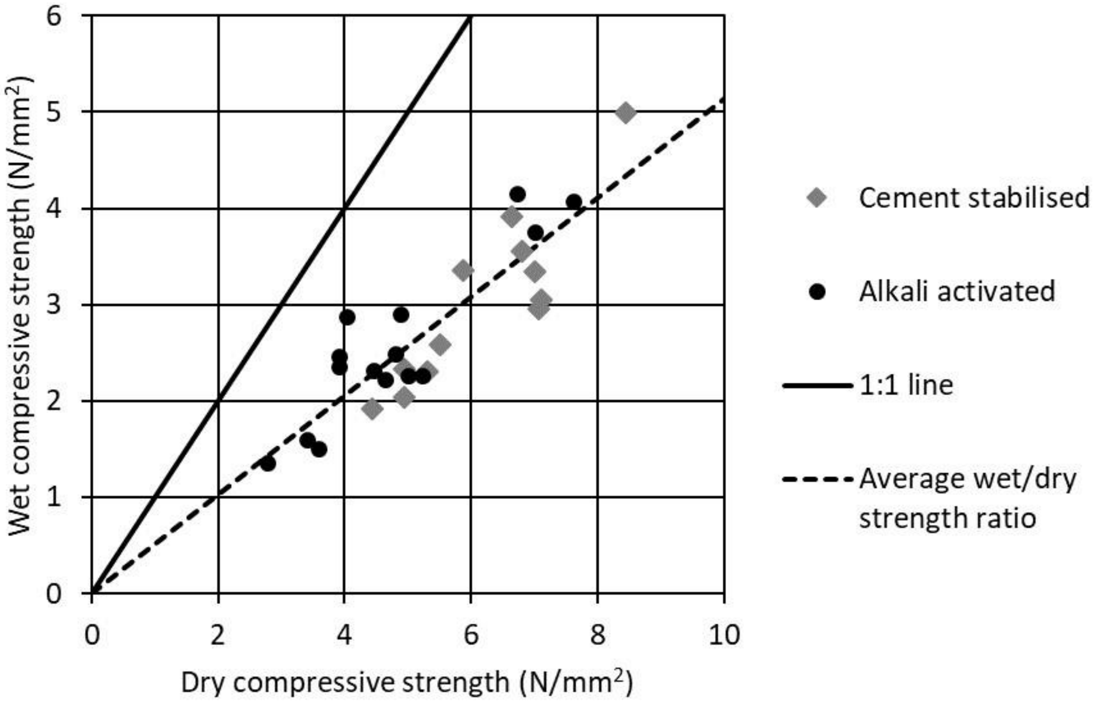

Figure 6. Relation between GWP and wet compressive strength

The data in Table 4 and Figure 6 does directly account for the strong relationship between dry density and wet compressive strength (Venkatarama Reddy and Kumar, 2011) which may affect outcomes, and this is discussed further below.

7. Discussion

The solid wastes, in particular CDW and PGBS, proved effective for use as alternative aggregates in cement and alkali-activated stabilised earth construction materials. Both solid waste aggregates, when blended with a natural residual sub-soil, compared favourably with the performance of specimens using a crushed granite sand (MS). Although for comparison with past work CDW cannot clearly be considered a standard consistent material, the results reported here are broadly supported by the work of Jayasinghe et al (2016).

As noted by Maskell et al (2016) the optimum stabiliser should not be based solely on maximum compressive strength. The optimum stabilisation method should consider other factors such as the environmental impact, cost and constructability whilst maintaining a minimum threshold strength requirement. This results in no uniquely optimal mix, but leads towards a multi-objective optimisation and a Pareto efficiency approach to optimal selection (Maskell et al., 2018).

All stabilisation approaches were effective in ensuring the materials were able to remain intact when placed in water and all were able to provide wet compressive strengths above 1 N/mm^2. There appears to be a consistent relationship where the wet strength is approximately 51% of the dry strength ($r^2 = 0.78$). This factor is not significantly affected by stabilisation approach (0.54 for alkali-activated or 0.50 for cement based) and is consistent across the strength range, as shown in Figure 4.

The addition of lime was generally much less effective at increasing compressive resistance than cement; lime addition was most effective when pozzolanic materials were most available, for example in the specimens containing PGBS. Fly Ash (FA) consistently proved more effective than GGBS in the alkali-activated stabilised materials.

The strength development mechanisms in the two cases are different. In PC stabilised materials, cement hydration products are responsible for the strength gain, whereas in the case of alkali activation, the strength development is mainly due to geopolymer formation. In the ranges of materials used experimentally cement, or cement and lime, stabilisation appeared more effective than alkali-activation as means of improving wet and dry compressive strengths, even when the effect of global warming potential is taken into account (Figure 6). However, as shown in Table 4, the average dry density of the alkali-activated samples (1780 kg/m^3) was generally lower than for the cement or cement and lime stabilised samples (1815 kg/m^3), and the effect of density variations on strength (Venkatarama Reddy and Kumar, 2011) should therefore be considered before making overall judgements as to the best stabilisation approach. In practice, depending on production methods, density would often be expected to vary more than was measured experimentally. The increase in density of the cement or cement and lime stabilised samples can be explained by an increase in dry mass of samples after compaction, brought about by a combination of hydration and carbonation converting liquid water or atmospheric CO_2 into a solid form (Venkatarama Reddy 2012; Venkatarama Reddy and Latha, 2014).

In this current study the samples were compacted to a controlled density to ease comparison, while in a field situation materials are more likely to be compacted with a controlled compaction effort. Following the work reported here, the authors have undertaken further research producing full-sized compressed earth blocks and rammed earth materials using compaction processes directly replicating industry practice. In this work materials were stabilised with 7% cement and 2% Lime, and NaOH [12M] with 15% Fly ash. The CDW, MS and PGBS were used in these prototype trials and are to be reported elsewhere.

8. Conclusions

The following conclusions may be derived from the work presented in this paper:

- The solid waste materials (CDW and PGBS) proved effective for use as alternative aggregates in cement and alkali-activated stabilised earth construction materials.
- The stabilisation approaches used were effective in producing wet compressive strengths above basic threshold levels required for low rise load bearing wall construction.
- Lime was generally less effective than cement as a stabiliser for improving compressive strength. Lime addition was most effective when higher levels of pozzolanic materials were available.
- Fly Ash proved more effective as a precursor than Ground Granulated Blast Furnace Slag in the alkali-activated stabilised materials.
- Of the materials tested in this study, cement based stabilisation provided the better compressive strength performance with lowest global warming potential. However, further research, in which field conditions are more accurately represented, is currently underway to assess which stabilisation approach is preferable for manufacturing earth based construction materials incorporating solid wastes.

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Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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