Available online at www.sciencedirect.com
ScienceDirect
Cement and Concrete Research 37 (2007) 751–758
Cement and Concrete Research

The effect of clay content in sands used for cementitious materials in developing countries

V.A. Fernandes, P. Purnell *, G.T. Still, T.H. Thomas

School of Engineering, University of Warwick, Coventry, CV4 7AL, UK

Received 16 December 2005; accepted 23 October 2006

Abstract

The cost of building materials in Less Economically Developed Countries (LEDCs) is one of the single largest contributing factors to housing costs. They are often transported over relatively large distances at considerable expense. Local sands may contain significant amounts of clay, considered by local artisans to be detrimental to concrete strength; however, in an LEDC context, there is little evidence to support this. In this study, the compressive strength and workability of representative LEDC clay-contaminated concrete was determined. Clay-cement interactions were studied using X-Ray Diffraction (XRD). Different clays appeared to have fundamentally different effects on both workability and strength. No chemical interactions were detected. It was concluded that satisfactory concrete could be made from clay-contaminated sand.

Keywords: Workability; X-Ray diffraction; Compressive strength; Clay

1. Introduction

A significant demand exists for housing in Less Economically Developed Countries (LEDCs), where it has been estimated that more than 100 million people are homeless and about one billion people are inadequately housed [1]. Approximately twenty-one million new housing units are required each year [2].

The main costs of shelter provision are land purchase, building materials, machinery, man-power and loan interest payments [3]. Building materials are often the single largest component of housing cost in LEDCs; accounting for up to 70% of a standard low-cost housing unit [1]. By contrast, it is estimated that in the UK, only about 20% of the cost of a housing unit is for building materials, because the majority of costs are incurred for finishes, such as electricity, lighting and carpets; these are luxuries that the poor cannot afford. For the lack of more local suppliers, some 'quality' building materials in LEDCs are transported over relatively large distances (e.g 50 km) and at considerable expense, despite natural resources being available nearby that might be suitable for building materials production.

Building aggregate consists of two types; coarse (gravel or crushed stone) and fine (natural or manufactured sand). In the provincial areas of LEDCs, there is often an absence of a coarse-aggregate industry, so most cementitious products are made with only fine aggregates. Thus, with cement, sand is the major component needed for producing concrete and mortar for low-cost housing components. In LEDCs, for such reasons as the high cost of transport in relation to labour, cementitious components of low-cost housing use as aggregate either on-site soil or 'sand' from within 1 km of the site. In consequence there is a strong incentive to use sand that would not meet British Standards (BS EN12620:2002) with respect to grading and clay content. However, the effects of clay on concrete performance are poorly understood and specifications restricting their use tend to be vague [4,5]. If clay-containing local sand could be used, housing materials would be more cheaply and readily available.

Several different clays exist in soils and their characteristics are likely to have an effect on the properties of concrete containing them. The main clays found in tropical regions are kaolin and montmorillonite. Clay minerals have the ability to

* Corresponding author.
E-mail address: pp@eng.warwick.ac.uk (P. Purnell).

0008-8846/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconres.2006.10.016

attract water molecules; a surface phenomenon called adsorption. Owing to their large surface areas and chemical structures, both clays have a great affinity for water and can also assimilate it into their microstructure. However they have different structures; the approximate specific surface area for kaolin is 10–20 m^2/g and for montmorillonite, 800 m^2/g [6]. This large specific surface, combined in the case of montmorillonite with the ability to absorb water into its microstructure, is reflected in the increased water content needed for adequate workability in fresh clay-contaminated concrete. The two essential functions of water in a mix are to hydrate the cement and to provide adequate workability. With clay in the mix, the amount of water needed for good workability can be considerably more than that needed for hydration (to a greater extent than in normal concrete). Therefore, once the concrete is cured and a portion of the water is chemically bound by hydration, a greater remainder than is usual evaporates leaving an increased content of voids (capillary porosity) in the hydrated assemblage, reducing the strength of the material [7].

The propensity of the clays to affect the normal storage and transport of water within cementitious matrices suggests that they can also affect the dimensional stability – shrinkage – of the resultant concrete; this is recognized by us and previous investigators [8]. Although not forming part of this report, a series of parallel experiments are ongoing to investigate the magnitude of this shrinkage, which will be reported in a companion paper.

In addition to the cementing reaction, the chemical interaction of cement and clay particles may have an effect on the properties of concrete and may explain why clay-contaminated concretes have different physical properties [9]. Very little analytical research has been undertaken on clay-contaminated sand for use in concrete production, especially in the context of use in low-cost housing. Parsons [10] concluded that clay is much more detrimental to the strength of concrete if present as a surface coating surrounding the sand grains, than if evenly distributed throughout the mass. When the clay forms such a surface coating, it is bound only by weak electrostatic forces, which led many researchers to suggest that clay particles interfere with the bond between the sand particles and cement paste matrix [11–14]. If the bond between either the clay coating and the sand, or the clay and the cement paste, is weaker than the normal cement–sand bond (which is thought likely) then *strength* and durability problems may result [14]. However, although many have concluded that clay surface coatings weaken the sand/cement paste bond, there is little experimental evidence that this reduces concrete strength and durability. Moreover, Parsons [10] suggested that if the clay is distributed *evenly* within the sand, there is no detrimental effect and it might increase the strength of the concrete by filling in the spaces between the larger particles. If both sand *and* clay could be regarded as chemically inert components, the cement would bind evenly-distributed sand and clay grains together during hardening, forming a roughly continuous matrix of a hard, strong material enclosing particles of sand and clay.

Sand is normally regarded as chemically inert and unlikely to affect any chemical changes taking place in resultant concretes. Some work has however been published on clay–cement interactions.

According to Herzog & Mitchell [15] a clay–cement mixture cannot be regarded as a simple mixture of hydrated cement matrix bonding together unaltered clay particles, but should be considered as a system in which both clay and hydrating cement combine through secondary reactions. When the mixture is in its fresh state, cation exchange and flocculation effects occur causing structural stabilization of the clay [16]. During the hardening of the clay–cement mixture, the hydration of cement takes place, forming the usual cement hydration products; calcium silicate hydrates, calcium hydroxide $Ca(OH)_2$, and hydrated aluminates [17]. The calcium hydroxide formed in the primary phase, together with the soluble alkalis released during cement hydration which raise the pH of the pore solution to >13, could initiate attack of the clay particles and also cause a breakdown of amorphous alumina and silica, which then could combine with the calcium ions liberated from the hydrolysis of cement to form a secondary cementitious material [9]. This secondary reaction is known as the pozzolanic reaction [18], and could form products that are initially amorphous but may later become crystalline. X-ray investigations undertaken by Eades and Grim [19] of samples cured at 60 °C indicated a destruction of montmorillonite clay structure and moderate attack on kaolin clay in the presence of calcium hydroxide. This could be because of clay mineral structure breakdown and/or interaction with cement at the particle surfaces. However, any secondary cementitious material so formed remains unidentified.

Herzog and Mitchell [9] proposed a model of the resultant microstructure in which (using their terminology in quote marks) a “matrix” of sand and unreacted clay is surrounded by a “skeleton” of hydrated cement. They proposed that some of the clay reacts with (or is captured on the surface of) the skeleton, thereby strengthening it. The remainder of the clay stays in the clay–sand matrix. They did not, however, publish any micrographs or other evidence supporting this theory.

Thus there are two mechanisms by which clay might strengthen relatively weak concrete mixes: either pore-filling by the fine clay particles; or a chemical reaction between the clay and the hydrating cement and/or its hydration products producing further insoluble hydrates.

This paper presents the findings of experimental work on clay–cement–sand composites, the properties of which have not been well documented in the open literature. Despite clay being considered deleterious in normal concrete production, experimental evidence is offered to assess the use of clay-contaminated concrete blocks as a suitable building material for low-cost housing in LEDCs. An analytical research has been undertaken to try and identify whether the proposed secondary cementitious materials do actually form. While the primary context of this paper is assessing the use of clay-contaminated building materials in LEDCs, concrete aggregates in developed countries are also becoming increasingly scarce, so alternative sources also need to be found and proved; this research may also have applications in that regard.

2. Experimental methodology

2.1. Materials

The clay-free basic sand (sand ‘S’) used in experimentation was selected to be representative of concreting sands used in LEDCs [20]. XRD analysis of the sand used showed it to be a pure quartz sand with no significant impurities.

Two other sands were then synthesized by dry mixing, consisting of this Sand S with the substitution of either 20% of mass by kaolin (kaolin-contaminated sand, referred to as Sand K), or 20% by montmorillonite (montmorillonite-contaminated sand, referred to as Sand M). The composition of sands K and M were chosen to be as close as possible to a wide range of natural sands in LEDCs and were used for testing, as the quantities of samples needed were not practically obtainable directly from LEDCs.

The cement used during testing was Type 1 OPC. At present this cement (or its local analogue) is the most widely available and quality-consistent stabilizer in LEDCs, and is likely to remain so for at least the next ten years [21]. The water used was untreated laboratory tap water.

2.2. Methods of testing

100 mm concrete cubes were made using sand types S, K and M respectively. The data consists of sets of varying sand types, water/cement ratio and sand/cement ratio, with each sample consisting of 6 cubes. For every combination of each of the three sand types and for four sand/cement ratios (3, 5, 7, 10), the water/cement ratio was altered until an optimum compressive strength was achieved after 28 days curing in polyethylene bags. In general, fully compacted concrete has a monotonic strength relationship with w/c ratio; as the w/c decreases, strength increases. However, below a certain w/c ratio, the concrete will have insufficient workability for full compaction to be achieved, and the strength will then begin to decrease with decreasing w/c. Thus there is an optimum w/c ratio with regard to strength and an iterative process was adopted to find it. The workability of each iterative mix was also measured using slump and Vebe tests (but it is important to note that finding an ‘optimum workability’ was not an objective of this study).

The concrete mix was made starting with the selected (dry premixed) sand and clay, then adding the water, then adding the cement. Each mix was mixed in a pan mixer until a homogeneous mix was formed. Preliminary studies showed that seemingly adequate mixing could produce a highly uneven distribution of cement so extra care was taken to ensure homogeneity. The average mixing time was around 5 min.

The cubes were cast in lubricated steel moulds, being compacted using vibration, according to BS 1881: Part 108:1983. The manufactured cubes were placed under damp hessian overnight, and de-moulded the following morning. After the cubes were de-moulded, they were stored in sealed polyethylene bags. This prevented water from within the cube from escaping as surface evaporation was almost non-existent in an environment of approximately 100% humidity. This was considered an appropriate optimal curing environment with regard to local practice. The temperature of the curing process, approximately 19°C, was determined by laboratory conditions.

After 28 days, the cubes were tested to failure using a compression test machine at 200 kN/min (BS 1881: Part 108: 1983), with maximum load and type of failure recorded. The total number of cubes tested in this study was 900.

In addition to the testing of the strength of cured blocks, X-Ray Diffraction (XRD) was used to detect any reactions between the clay and cement. A sample of each concrete block was taken and tested at 28 days and 1 year, from blocks manufactured with a sand/cement ratio of 5:1 at their respective optimum w/c ratios, (0.95 for sand S mix, 1.15 for sand K mix and 1.8 for the sand M mix). The samples were monitored using a BRUKER D5005 X-ray diffractometer machine over a period of eight hours, giving a range of 4° 2Θ to 70° 2Θ. The experimental data was examined to identify the peaks and relative intensities corresponding to the compounds of interest (as calibrated via the International Center for Diffraction Data [22]).

3. Results

3.1. Workability

Figs. 1 and 2 show slump and Vebe measurements (as a function of water/cement ratio) for all three sands at two different sand/cement ratios. These selected curves show the general trend but data is also available for the other sand/cement ratios. Since the lines are roughly parallel, we can summarize all the data by tabulating the ‘extra’ water required by a clay-contaminated mix (in terms of w/c) in order to restore its workability to that of the uncontaminated mix S. This data is given in Table 1. Note that the s/c = 20:1 mixes are not included in this table as they have insufficient workability for slump to be measured or Vebe time to be recorded. In addition, for example, label (a) on Fig. 1 shows the ‘extra’ water mix K requires (in terms of w/c) with s/c of 3:1 in order to restore its workability to that of the uncontaminated mix S with s/c 3:1.

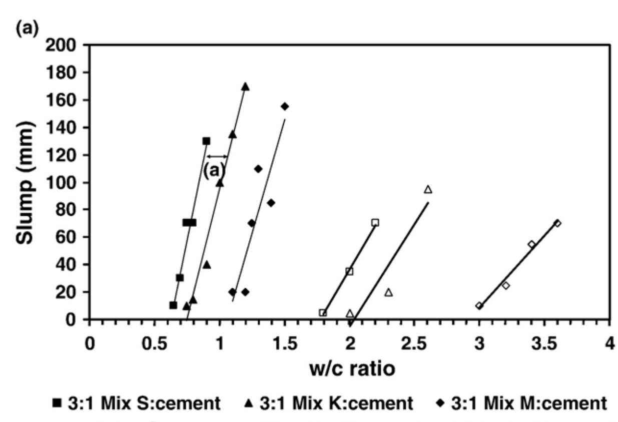

Fig. 1. Effect of sand type on slump for two sand/cement ratios.

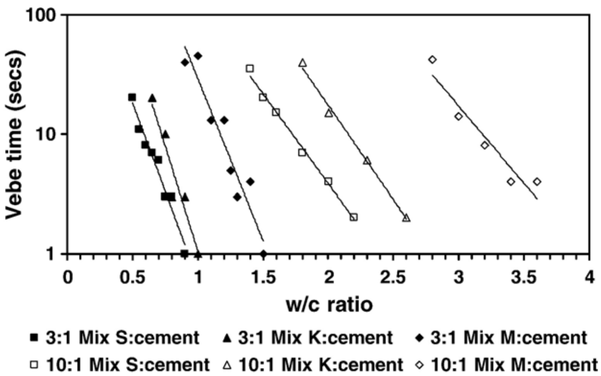

Fig. 2. Effect of sand type on Vebe for two sand/cement ratios.

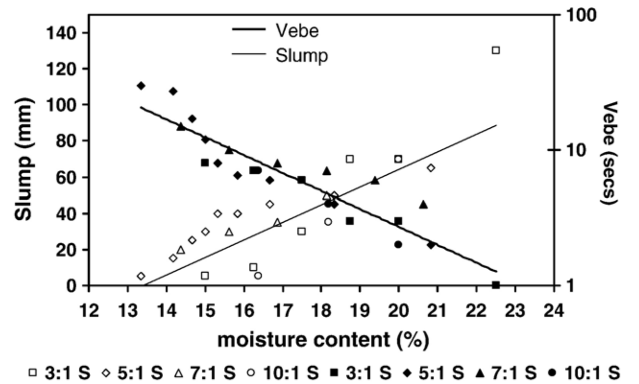

Fig. 3. Graph showing slump and Vebe vs. % moisture content relationship for mix S. Bold line/filled symbols denote Vebe results, light line/open symbols denote slump results. Legend numbers = s/c ratio.

For a given s/c ratio and w/c ratio, both clays significantly reduce the workability, montmorillonite having a greater effect than kaolin and therefore requiring the larger addition of water to restore required workability. As expected, for a given w/c ratio and sand type, increasing the s/c ratio reduces workability.

As w/c ratio (for a given workability) rises with s/c ratio, we might expect moisture content, λ (defined as the ratio by mass of water to solids), to correlate more simply with the workability measures than w/c ratio does. Fig. 3 plots slump and Vebe time against λ for a single sand type, S (note that Vebe time is on a logarithmic scale). The data for all four s/c ratios (3, 5, 7 and 10; data for s/c = 20 is not included for the reasons outlined above) appear to follow a single linear relationship. This implies that workability for these mixes depends only on λ and not on s/c ratio. This also appears to apply for sands K and M, and all the relevant data is plotted on Fig. 4. The fit lines are approximately parallel, thus we can deduce a constant a that represents the additional moisture content needed to keep workability constant when switching from standard sand S to clay-contaminated sands K and M. For example, $a_{\mathrm{m,\ Vebe}}$ and $a_{\mathrm{k,\ Slump}}$ (as shown by the arrows on Fig. 4) represent the additional moisture content required to restore: the workability of a montmorillonite-contaminated mix (as measured using the Vebe test); and that required to restore workability of a kaolin-contaminated mix (as measured using the slump test) respectively. All values of a are given in Table 2. Note the similarities between values derived for both slump and Vebe tests, implying that either method may be used without affecting the results.

Table 1
Addition to w/c required to restore uncontaminated workability to clay-contaminated mixes

	s/c 3:1	s/c 5:1	s/c 7:1	s/c 10:1
Slump test				
Mix K	+0.14[a]	+0.37	+0.46	+0.26
Mix M	+0.45	+0.79	+1.12	+1.05
Vebe test				
Mix K	+0.18	+0.24	−0.11	+0.36
Mix M	+0.62	+1.43	+0.68	+1.53
Average of both tests				
Mix K	+0.16	+0.31	+0.18	+0.31
Mix M	+0.54	+1.11	+0.90	+1.29

[a] Marked (a) on Fig. 1.

3.2. Compressive strength

Strength results are summarized in Figs. 5–7. It can be seen that in general, for each s/c ratio, the strength does indeed goes through an optimum. For very lean samples, i.e. with s/c = 20:1, this optimum is poorly defined (and indeed absent in sand M), as effects related to the cohesiveness of the clay tend to dominate over those related to hydration of the cement.

At low s/c ratios, the clay lowers the achievable optimum strength, the effect of montmorillonite being significantly greater than that of kaolin (Fig. 6). At higher s/c, the effect is indistinct and for sand K, may even be reversed; the clay may be marginally beneficial *vis a vis* strength. There is a good linear correlation between the s/c ratio and w/c ratio at optimum strength (Fig. 7). Note that the sand S and K lines virtually coincide, while that for sand M is rather different.

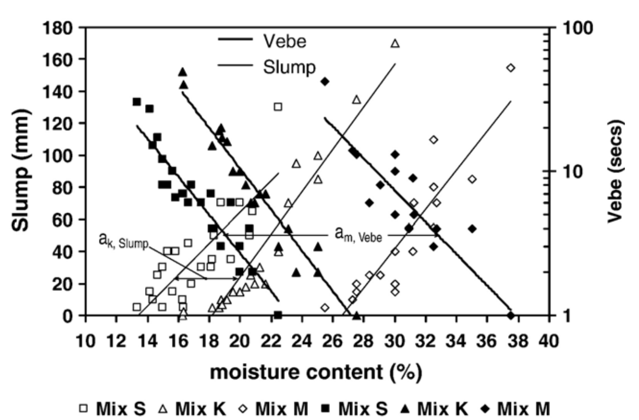

Fig. 4. Graph showing combined Slump and Vebe vs. % moisture content relationships for all mixes at s/c of 3:1–10:1. Bold line/filled symbols denote Vebe results, light line/open symbols denote slump results.

Table 2
Additional moisture contents ***a*** (%) needed to keep workability (slump or Vebe) constant when switching from mix S to mix K or M

$a_{k,\ slump}$	3.5±0.8
$a_{m,\ slump}$	12.2±0.6
$a_{k,\ Vebe}$	4.4±0.2
$a_{m,\ Vebe}$	13.0±0.9

3.3. XRD analysis

XRD analysis was undertaken on a variety of samples at 1, 7 and 28 days, 9 months and one year. The results showed that there is no change in peaks for the different sand types after cement hydration, apart from the formation of Gypsum in the sand K after 1 year. No unusual chemical reactions have taken place. Figs. 8 and 9 show examples of the results obtained for the three mixes at 28 days and at 1 year.

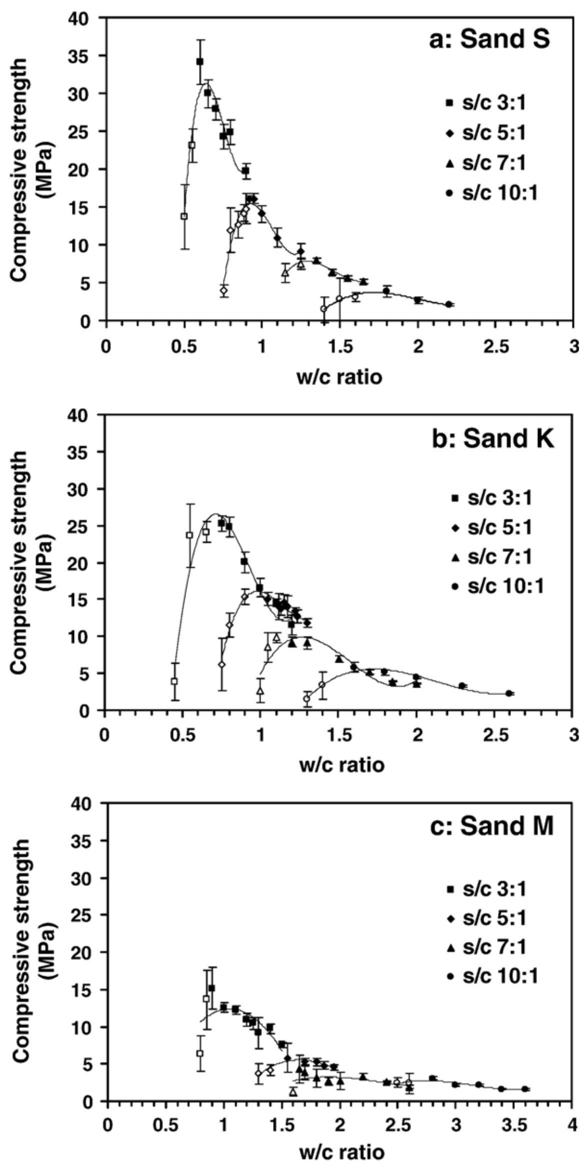

Fig. 5. Compressive strength vs. w/c ratio. Legends refer to sand/cement ratios. Where applicable, open symbols denote incomplete compaction; closed symbols, complete compaction. Error bars are±1 standard deviation (6 replicates). Lines are cubic fits to group data, not intended as analytical.

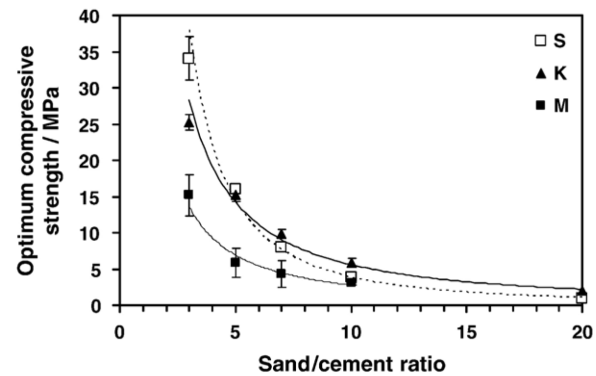

Fig. 6. Optimum compressive strength vs. sand/cement ratio. Error bars=±1 standard deviation. Lines are power law fits to the data.

4. Discussion

Addition of clays in concreting aggregates significantly reduces their workability. As both types of clays examined have large specific surface areas and great ability to absorb water, an increased amount of water was needed to ensure adequate workability of the mix. Montmorillonite has a higher specific surface area (800 m^2/g), along with a chemical structure more suited to absorbing water than silica or kaolin, so montmorillonite-contaminated mixes require a higher w/c ratio for a given workability than do kaolin-contaminated or uncontaminated-sand mixes. Increasing s/c ratio has a similar effect (of reducing workability) as it increases the surface of aggregate to be water-coated relative to the amount of cement.

If the falling branches of the curves in Fig. 5 (i.e. those mixes with sub-optimal strength owing to insufficient workability and compaction) are excluded, the data for all the s/c ratios can be considered together.

There are a number of relationships that can be used to model the strength of concrete (Table 3). Such models either implicitly (in the case of Abram's law [23]) or explicitly (the others in Table 3) relate strength to porosity.

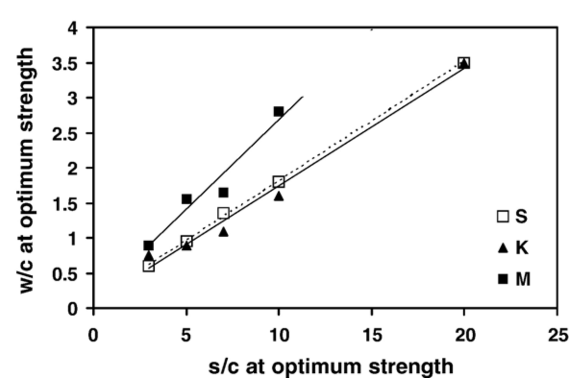

Fig. 7. w/c at optimum strength vs. s/c at optimum strength.

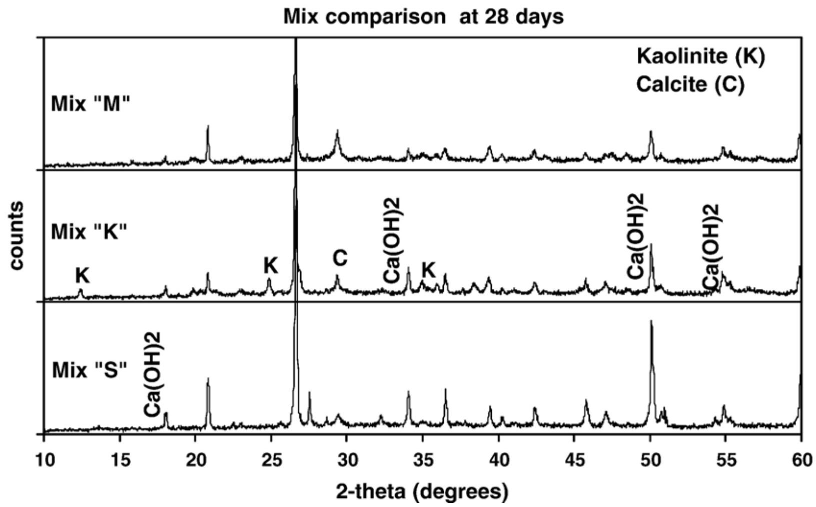

Fig. 8. XRD showing the comparisons between different the sand mixes at 28 days.

In this study, porosity was not measured; there is still considerable debate over the most appropriate methods to use to measure porosity in cementitious materials since mercury intrusion porosimetry has fallen out of favour (e.g. [24–26]). However, porosity in cement paste is closely related to w/c. According to the widely accepted Powers model [27], the relationship can be approximated to:

$$p=\left((v_\mathrm{w}w_0/c+v_c)-mv_\mathrm{g}(1+w_\mathrm{n}/c)-(1-m)v_\mathrm{c}\right)/(v_\mathrm{w}w_0/c+v_\mathrm{c}) \quad (1)$$

where:

v_w = specific volume of water = 1 L/kg
w_0/c = w/c (free water/cement ratio
v_c = specific volume of unhydrated cement = 0.315 L/kg
m = degree of hydration
v_g = specific volume of gel including pores = 0.567 L/kg
w_n/c = constant = 0.23; w_n is the weight of the combined water, c is the weight of the cement with which it combines

Using an appropriate value for degree of hydration at 28 days (80%) and treating the clay as aggregate, this simplifies to:

$$p=(w/c-0.325)/(w/c+0.315) \quad (2)$$

(We are aware of the limitations of this relationship but consider that it is of sufficient accuracy for the purposes of comparing different models).

This was substituted for porosity in the relations in Table 3 and fitted to the strength–w/c data. (Note: since the strength of the concrete is overwhelmingly dominated by the strength of the paste, we need not consider the porosity of the aggregate). The results are given in Table 4.

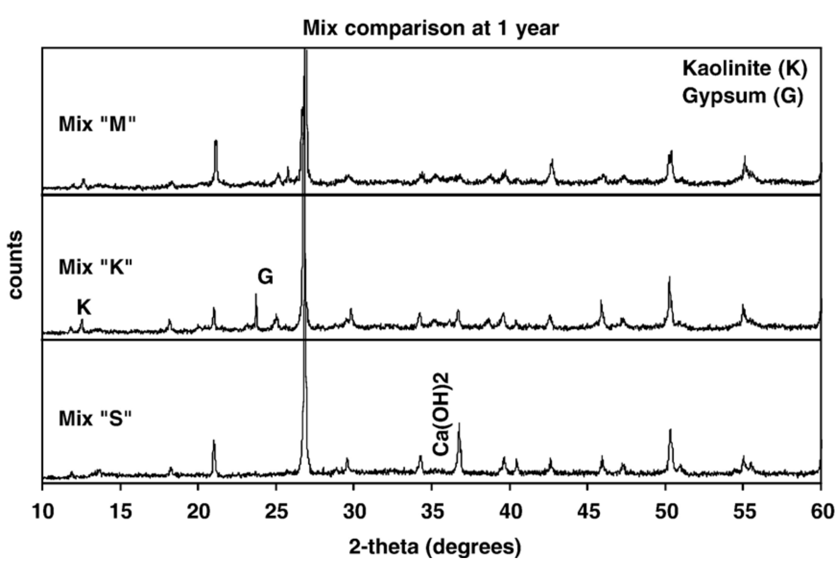

Fig. 9. XRD showing the comparisons between different the sand mixes at 1 year.

Table 3
Relationships for modelling concrete strength σ_c

Author	Law	Reference	Notes
Abrams	$\sigma_c = K_1 K_2^{-w/c}$	Neville (1995) [23]	K_1, K_2 = empirical constants
Ryshkewitch	$\sigma_c = \sigma_0 \exp(-np)$	Aldera (1969) [32]	σ_0 = strength at zero porosity; n = empirical constant; p = porosity
Balshin	$\sigma_c = \sigma_0 (1-p)^n$	Salmoni (1937) [31]	As above
Square	$\sigma_c = \sigma_0 (1-np)^2$	–	As above

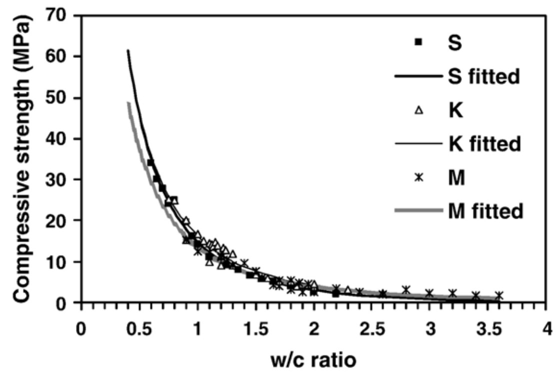

Fig. 10. Fits of Square model to compressive strength data.

The Balshin and Square models fit the data best. They are also far less sensitive than other models to perturbations in the numerical values used in Eq. (2) above. Of the two, the Square model is preferred. A fit of the Square model to the three data sets is given in Fig. 10. It can be seen that at w/c < 0.8, the S and K fitted lines converge, while at w/c > 1.6, the K and M fitted lines converge. Analysis of variance suggests that over the range of w/c used in this study, the S and K data can be represented by a single relationship while the M data is different. This correlates with Figs. 6 and 7, where the K and S data are almost coincident, while the M data follows a different trend. Looking at the Square and Balshin model data in Table 4, we can also see that the 'baseline' strength (i.e. the predicted strength at zero porosity) of the S and K mortars is similar, ~80 MPa, while that for the M mortar is lower, ~60 MPa. This suggests that in K mortars, the clay is acting as 'inert' aggregate and any effect of the kaolin on the strength of a concrete/mortar mix is simply due to increased water demand and/or insufficient compaction; whereas in a M mortar the effect of montmorillonite is more fundamental, actually causing a weaker hydrated matrix to be formed during curing. Thus the effect of clay contamination of aggregate on the properties of a concrete are strongly dependent on the type of clay involved.

The XRD analysis (Figs. 8 and 9) shows results undertaken on samples at 28 days and 1 year. The normal crystalline products of cement hydration, i.e. portlandite, could be seen in all mixes. There is no evidence of any pozzolanic reaction, i.e. no depletion of either portlandite or clay mineral peaks, nor formation of new crystalline compounds, between 28 days and 1 year of curing. This contradicts previous work [28,9].

Table 4
Fit parameters and analysis of fit quality for different models

Model and sand	K_1	K_2	σ_0	n	r^2	Residual error	Fit ratio
Abrams: S	109	7.13	na	na	0.992	0.913	0.913
Abrams: K	80.5	4.88	na	na	0.934	1.57	0.871
Abrams: M	47.6	3.57	na	na	0.936	1.01	0.745
Ryshkewitch: S	na	na	151	4.69	0.966	1.94	0.760
Ryshkewitch: K	na	na	202	5.02	0.914	1.82	0.790
Ryshkewitch: M	na	na	247	5.67	0.914	1.15	0.781
Balshin: S	na	na	85.2	2.46	0.988	1.13	0.902
Balshin: K	na	na	83.5	2.29	0.935	1.56	0.876
Balshin: M	na	na	64.5	2.17	0.938	0.962	0.811
Square: S	na	na	78.9	1.11	0.991	0.989	0.943
Square: K	na	na	77.8	1.06	0.936	1.54	0.886
Square: M	na	na	60.7	1.03	0.938	0.960	0.805

r^2 = Pearson's correlation coefficient between measured and predicted values. Residual error = average magnitude of difference between model prediction and measured value at a given point. Fit ratio = r.m.s. of ratio between predicted and measured value (1 = perfect fit).

These results suggest that the effect of clay contamination on strength is more likely caused by physical mechanisms, such as increased water demand for a given workability owing to increased specific surface area, than chemical reactions. However, there is still a possibility that non-crystalline products have formed, which would not have shown on the XRD traces. The question of how the montmorillonite affects the hydrated assemblage in a different manner to kaolin remains unresolved.

According to Montgomery and Orton [29,30] a compressive strength of 3–7 MPa is common to building materials in LEDCs and is referred to in building standards for masonry including walls, columns and lintels. Therefore, satisfactory concretes *can* be made from clay-contaminated aggregate, permitting these building materials to be used and removing the necessity to transport sand over long distances.

5. Conclusion

- The presence of clay in the aggregate has a significant effect on the workability of concrete. For each sand type (i.e. pure sand, and sand contaminated with either kaolin or montmorillonite), there appears to be a linear relationship between moisture content and slump or log(Vebe), that is independent of s/c ratio. For either measurement method (i.e. slump or Vebe), the relationships appear to be parallel; thus the extra moisture content required to give a contaminated mix the same workability as an uncontaminated mix is approximately constant for a given clay.
- Concretes contaminated with kaolin appear to follow the same strength–w/c relationship as normal concrete, with lower strengths simply attributed to increased water demand and/or increased compaction difficulty. Those contaminated with montmorillonite follow a different relationship, implying that it has an effect on the fundamental strength of the hydrated phases.

- At high w/c ratios, i.e. ≥1.7, montmorillonite-contaminated mixes perform as well as the other materials with respect to strength.
- XRD investigations show no indication of any unusual secondary cementitious material forming in the presence of clay.
- Over the range of w/c and strengths common to building materials in LEDCs, satisfactory concrete components not requiring coarse aggregate, such as mortar and blocks, can be made from clay-contaminated sand but the effect of the clay type is significant. Structural concrete made with such materials would need to be investigated with regard to durability, particularly dimensional stability, which is the subject of current research by this group to be reported later.
- It is not necessary to transport 'quality' sand from long distances because local sands can usually perform as an adequate building material. Concrete blocks of sufficient integrity for low-cost housing may be made from lean mixes of cement with such sands by artisanal builders.

Acknowledgements

This paper is dedicated to the memory of PhD student Vicky Fernandes, who sadly passed away during the review stages of this article based on her work. A poster pre-cursor version of this work also won the Best Student Poster at the 25th Cement and Concrete Science Conference, Royal Holloway College, UK in September 2005.

References

[1] S. Erguden, Low-cost Housing: Policies and Constraints in Developing Countries International Conference on Spatial Information for Sustainable Development, Housing Policy Section, Nairobi, Kenya, UNCH, 2001, 11 pp.
[2] UNHCS, Global Report on Human Settlements, United Nations Centre for Human Settlements, Oxford University Press, 2004, 310 pp.
[3] A. Ashworth, Cost Studies of Buildings, 2nd Edition, Longman Scientific and Technical, 1994, 330 pp.
[4] A.I.G. Yool, T.P. Lees, A. Fried, Improvements to the Methylene blue test for harmful clay in aggregates for concrete and mortar, Cem. Concr. Res. 28 (10) (1998) 1417–1428.
[5] K. Gullered, S. Cramer, Effect of Aggregate Coatings and Films on Concrete Performance, Wisconsin Highway Research Program #0092–00–07, 2002, p. 1.
[6] T.N.W. Akroyd, Concrete: Properties and Manufacture, 1st Edition, Pergamon Press, Oxford; New York, 1962, 336 pp.
[7] A.M. Neville, J.J. Brooks, Concrete Technology, 1st Edition, Longman Group Ltd, 1987, 438 pp.
[8] D.E. Montgomery, Physical characteristics of soils that encourage SSB breakdown during moisture attack, University of Warwick working paper SSPR03, (Nov 1998), 29 pp.
[9] A. Herzog, J.K. Mitchell, X-ray evidence for cement–clay interaction, Nature 4845 (195) (1962) 989–990.
[10] D.A. Parsons, Strength of Concrete, Res. Natn Bur Standard, vol. 10, 1933, p. 257.
[11] A.T. Goldbeck, The nature and effects of surface coatings on coarse aggregates, proceedings, Highw. Res. Board 12 (1) (1932) 305–319.
[12] L. Dolar-Mantuani, Handbook of Concrete Aggregates: A Petrographic and Technological Evaluation, Noyes Publications, Park ridge, NJ, 1983, 345 pp.
[13] J.W. Schmitt, The effects of mica, aggregate coatings, and water-soluble impurities on concrete, Concr. Int., Des. Constr. 12 (12) (1990) 54–58.
[14] S.W. Forster, S.W. Soundness, deleterious substances and coatings, in: P. Kiegler, J. Lamond (Eds.), Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM 169C, American Society for Testing and Materials, Philadelphia, 1994, pp. 415–426.
[15] J.K. Herzog, A. Mitchell, Reactions accompanying stabilization of clay with cement, Committee on Soil-Portland Cement Stabilization, 1963, p. 144.
[16] S. Bhattacharja, et al., Stabilization of Clay Soils by Portland Cement or Lime—A Critical Review, Portland Cement Association, PCA R&D Serial No. 2066, 2003, p. 3.
[17] M.S. Morsy, El-Enein Abo, G.B. Hanna, Microstructure and hydration characteristics of artificial pozzolana-cement pastes containing burnt kaolinite clay, Cem. Concr. Res. 27 (9) (1997) 1307–1312.
[18] S. Bhattacharja, J.I. Bhatty, H.A. Todres, Stabilization of Clay Soils by Portland Cement or Lime — A critical Review of Literature, Portland Cement Association, PCA R&D, Serial no. 2066, 2003.
[19] J.L. Eades, R.E. Grim, Reaction of hydrated lime with pure clay minerals in soil stabilization, HRB Bull. 262 (1960) 51–63.
[20] D.E. Montgomery, Dynamically-compacted cement stabilized soil blocks for low-cost walling, 2002, PhD Thesis, 280 pp.
[21] D. Gooding, T. Thomas, The potential of cement-stabilized building blocks as an urban building material in Developing Countries, ODA Report, University of Warwick, UK, 1995, 22 pp.
[22] PDF 2, The powder diffraction file, International Centre for Diffraction Data, 2005–2006.
[23] A.M. Neville, Properties of Concrete, 4th Edition, Longman Group Ltd, 1995, 844 pp.
[24] H.S. Wong, N.R. Buenfeld, Patch microstructure in cement-based materials: fact or artefact? Cem. Concr. Res. 36 (5) (2006) 990–997.
[25] S. Diamond, A Discussion of Paper "Patch Microstructure in Cement-Based Materials: Fact or Artefact?", in: H.S. Wong, N.R. Buenfeld (Eds.), Cem. Concr. Res., vol. 36 (5), 2006, pp. 998–1001.
[26] H.S. Wong, N.R. Buenfeld, Reply to the discussion by Sidney Diamond of the paper "Patch microstructure in cement-based materials: fact or artefact?", Cem. Concr. Res. 36 (5) (2006) 1002–1003.
[27] J.M. Illston, J.M. Dinwoodie, A.A. Smith, Concrete, Timber and Metals, Van Nostrand Reinhold Co. Ltd, 1979, 663 pp.
[28] T.W. Lambe, A.S. Michaels, Z.C. Moh, Highw. Res. Board Bull. 241 (1960) (as cited in [9]).
[29] D.E. Montgomery, Minimising the cement requirement of stabilized soil block walling, Stabilized Soil Research Progress Report SSRPR8, Development Technology Unit, School of Engineering, University of Warwick, 2001, p. 14.
[30] A. Orton, Structural Design of Masonry, 2nd Edition, Longman, London, 1992, 159 pp.
[31] R. Salmoni, Verfahren zur Verurzung der Abb indezeit von Tonerdezementen, Deutches Patent 648851, 1937.
[32] A. Aldera, Fluidized Molding Material for Manufacturing Cores and Molds and a Method Therefore, U.S. Patent 3,600.203, 1969.