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Compressive strength of extruded unfired clay masonry units

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Interest in traditional unfired clay building materials has grown in the UK in recent years. Although the use of traditional vernacular techniques, such as cob, adobe and rammed earth, have raised the profile of earthen architecture, wider impact on modern construction is likely to come from modern innovations such as extruded unfired masonry units. A large driver behind the move to unfired clay masonry is the significant reduction in embodied energy when compared with fired bricks and concrete blockwork, and the passive environmental control provided by clay. This paper summarises the results of extensive testing on commercial mass-produced extruded unfired clay bricks. The focus of this study was to investigate the properties affecting the compressive strength of these building products. Both theoretical models and test results demonstrate that the clay content plays a large role in defining the compressive strength of these materials. The reduction in strength with increases in moisture content are similar for different material sources and these strength reductions are unlikely to cause problems under normal operating conditions, even at relative humidity levels up to 95%.

1. INTRODUCTION

In 2002 the UK brick manufacturing industry used approximately 5·4 TWh of power,[1] and approximately 85% of the energy from the production of fired bricks goes into firing.[2] With the increasing financial and environmental cost of energy production, low-energy alternatives to conventional construction materials are becoming increasingly popular. One potential low-energy construction material is unfired clay masonry.

Unfired clay masonry has been used in the construction of dwellings for thousands of years but has largely been replaced by high-energy materials, particularly in developed countries. Commercially produced extruded unfired clay units (bricks or blocks) have about 14% of the embodied carbon of fired clay bricks and about 24% of the embodied carbon of lightweight blockwork.[3] Although there are advantages to using modern, high-energy materials, which generally have a higher strength and water resistance than unfired clay, there are many situations where these properties are not required and the cost and energy saving from using unfired clay masonry instead of high-energy materials in appropriate situations is attractive. In addition, unfired clay masonry has been shown to provide passive environmental control in buildings by buffering both humidity and temperature fluctuations,[4,5] which results in reduced heating, cooling and ventilation demands.

This paper presents the results of investigations into the compressive strength of unfired clay masonry. Other aspects that affect the use of unfired clay units are erodibility, abrasion resistance, shrinkage and flexural strength of panels and these topics are discussed elsewhere[5–7] and are beyond the scope of this paper. The unfired clay bricks tested as part of this research are anticipated to be used for internal, non-load-bearing applications only.

The bricks used for testing for the purposes of this study were all commercially produced, extruded bricks. Twelve different types (labelled A–K in this paper) were used but, because of the difficulty in producing consistent quality extruded bricks on a laboratory scale, each brick type was produced in a different brick plant as part of the normal production run. All materials are used commercially for fired bricks, and in most cases, were taken off the production line after drying but before firing. Two of the bricks (A and B2) are, however, produced specifically as unfired bricks. For reasons of commercial confidentially, the manufacturers of the different bricks are not identified.

Basic unfired clay unit properties are summarised in Table 1 below and additional properties are listed throughout the paper. The dimensions given are an average of six different samples as required for in BS EN 772-16.[8] The average variability across all sources was a standard deviation of 0·4 mm for length, 0·4 mm for width and 0·5 mm for height. Even the sources with maximum variability (1·3 mm for length, 1·1 mm for width and 0·9 mm for height) were well within the limits specified for all classes of high-density fired clay masonry units.[9] As there was no firing of the units, any distortion normally occurring during the firing process is eliminated.

2. BASIC MATERIAL PROPERTIES

The basic material properties were determined according to BS 1377-2[10] and are summarised in Table 2. The liquid limit and plasticity index indicate the predominant engineering behaviour is as either a low- or a medium-plasticity clay, as shown in

Unit code	Length: mm	Width: mm	Height: mm	Perforations: number and % of gross area	Notes
A	226·5	106·8	66·2	3 holes, 6%	
B1	218·0	105·0	66·5	10 holes, 21%	Same material and plant but B2 has
B2	222·8	105·6	66·9	10 holes, 21%	added wood fibre
C	225·2	107·6	67·0	3 holes, 19%	
D	222·6	105·2	65·9	3 holes, 17%	
E	218·8	105·1	66·5	3 holes, 15%	
F	215·4	103·4	64·4	3 holes, 16%	
G	227·0	108·2	68·6	0%	Solid unit
H	221·8	105·2	68·1	3 holes, 23%	
I	223·4	107·9	68·7	0%	Solid unit
J	227·0	106·8	69·2	0%	Solid unit
K	228·8	108·6	68·9	0%	Solid unit

Table 1. Basic unfired brick properties (average of six samples)

Figure 1. In the figure the axes do not cover the full extent used for conventional soils testing as none of the materials was high, very high or extremely high plasticity.

The particle size distribution of the samples is summarised in Table 3 and the particle size limits are shown in Figure 2. The sizes of the particles were determined according to BS 1377-2.[10]

As can be expected, the samples are all below fine gravel in size because the extrusion process required fine material. Although the plasticity limits (Figure 1) indicate the materials will behave as clays, in reality most of these brick 'clays' are actually predominantly silt sized. The clay content was between 20 and 40% for all samples, which is considerably higher than that used for other earth construction materials such as rammed earth, for which between 5 and 20% is recommended.[11]

3. COMPRESSIVE TEST PROCEDURES

The European standard for the compressive strength of masonry units is BS EN 772-1:2000.[12] This standard specifies a number of different conditioning procedures (air dry, oven dry, conditioning to 6% moisture content and conditioning by immersion). Immersing unstabilised, unfired bricks is considered inappropriate as provided the materials are handled correctly and a building is detailed correctly, it is improbable that samples will ever achieve this condition in service.

In general three different curing conditions were used which were based on BS EN 772-1:2000.

(*a*) Oven dry – the samples were dried to constant mass at 105℃ and then left to cool to ambient condition (20℃) before testing.
(*b*) Air-dry – samples stored in a controlled environment of 20℃ and 60% relative humidity for a minimum of 14 days before testing.
(*c*) Applied moisture – moisture is added to samples so they are tested at 2% ($\pm$0·5%) above ambient moisture content. For this curing condition the water was added to the bricks with a fine sprayer at a rate slow enough to prevent surface deterioration of the units. The bricks were then sealed in a polythene bag and stored at 20℃ for at least 7 days before testing. This time was sufficient to ensure moisture equilibration throughout the samples.

The bricks were tested in a conventional concrete/brick compression machine at a load rate of 0·05 N/mm^2 until failure. This is the standard rate for masonry units with a peak compressive strength below 10 N/mm^2 in BS EN 772-1:2000, but for consistency this rate was used even for the units which had a strength slightly above 10 N/mm^2.

The strengths presented in this paper are the net strength of the material (i.e. total load across the cross-section of the actual

Unit code	Liquid limit: %	Plastic limit: %	Plasticity index: %	Linear shrinkage: %	Ambient moisture*: %	Net dry density: kg/m^3
A	29	17	12	7·0	1·67	2021
B1	45	18	27	10·8	3·01	1793
B2	48	22	26	9·1	2·89	1597
C	34	19	15	7·2	1·51	1971
D	31	22	9	8·8	1·94	1937
E	34	22	12	9·4	2·03	2038
F	34	22	12	9·5	2·16	1974
G	33	18	15	8·9	2·12	2057
H	44	20	24	10·4	2·54	1972
I	36	17	19	9·0	2·18	2063
J	37	17	20	8·6	1·93	2060
K	37	18	19	8·9	2·06	2058

*Ambient moisture is equilibrium moisture content at 20°C and 60% RH.

Table 2. Basic material properties

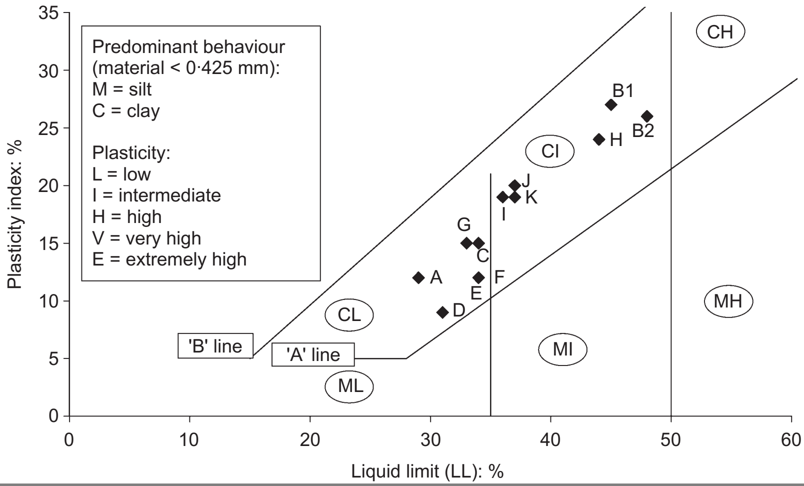

Figure 1. Plasticity of samples

Unit code	Gravel, 2–60 mm: %	Sand, 0·06–2 mm: %	Silt, 0·002–0·06& mm: %	Clay, < 0·002 mm: %
A	9·5	31·7	33·8	25·0
B1	0·0	11·2	50·9	37·9
B2	0·5	13·1	49·0	37·4
C	0·2	34·1	45·5	23·0
D	5·2	35·1	36·2	27·5
E	5·1	42·7	28·2	26·0
F	1·2	23·9	47·3	34·0
G	0·7	26·3	34·9	38·1
H	1·0	23·6	41·2	34·3
I	7·7	34·1	32·0	26·2
J	5·8	35·4	33·8	25·0
K	0·3	36·6	38·0	25·0

Table 3. Particle size distribution

material) and no correction was applied for unit size. According to BS EN 772-1:2000[12] the strengths should be reduced by approximately 85% for a standard size brick (used for this research), but recent unpublished research has indicated this reduction factor could be influenced by the number and size of voids in the unit and may not be appropriate for these materials.

Hansen and Hansen[13] investigated the relationship between relative humidity (RH) and unfired clay brick moisture content and demonstrated that RH levels of over 95% are required to achieve moisture contents over 5% by mass. This should be considered in the light of measurements by Morton *et al.*[4] which showed that the RH in houses constructed with unfired clay masonry remains fairly constant at approximately 60% throughout the year. Although peaks of higher humidity levels are possible in bathrooms, the measurements by Morton

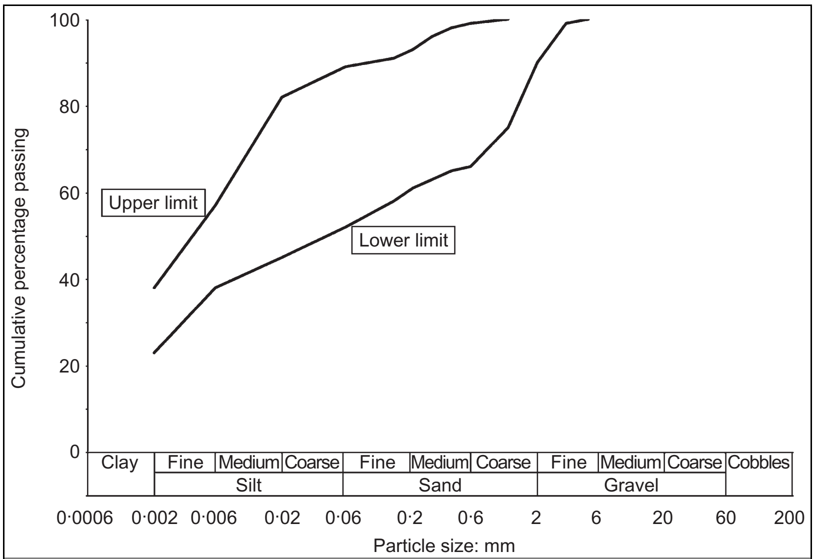

Figure 2. Limits of particle sizes

et al.[4] demonstrated these are very short term (unlikely to significantly affect brick strength) and the long-term RH in the monitored bathroom remained below 65%. Unpublished test data from isotherm tests performed on the bricks used for this research showed that none of them achieve moisture contents of over 6% at RH levels up to 95% and the 6% maximum water content under normal operating conditions is therefore justified. Accidental wetting can be limited by appropriate detailing,[7] including inclusion of a few courses of fired bricks at the base of walls.

The moisture content at which the bricks will stabilise under conditions of 20℃ and 60% RH is presented in Table 2 which appears to be related to clay content, as illustrated in Figure 3. Although this is not a well-defined trend, it appears to show increasing equilibrium moisture content with increasing clay content. If a linear relation with normal distribution is assumed (not necessarily indicated by the data), the likely limits of equilibrium water content at given clay contents is illustrated on the figure.

As shown, there is a general trend for increasing equilibrium moisture content with increasing clay content. This is most likely because of increased soil suction with finer-grained soils which have smaller pore spaces.[14] The maximum ambient moisture content of approximately 3% would have to increase by 3% to achieve the 6% upper limit used in this paper and this would only occur with forced wetting (rather than from changes in RH) under normal operating conditions.

Provided detailing of a building is appropriate, the most likely source of this wetting would be from the application of render to an unfired clay brick wall. If 15 mm of render were added to a wall with a moisture content of 20% (typical for clay renders), the increase in moisture content would be approximately 3% if 100% of the moisture is absorbed into the bricks (no evaporation). A 2% increase in water content during the short term could be considered more likely if evaporation is taken into account. In order to ensure this is the maximum moisture content achieved, appropriate detailing such as that in Morton[7] should be used. This should limit damage from accidental wetting (e.g. from dripping water pipes).

4. THEORETICAL BASIS

The effect of moisture content on the strength of unfired clay bricks has been previously reported,[13] but this been done on a purely empirical basis and the factors influencing this effect have not been established.

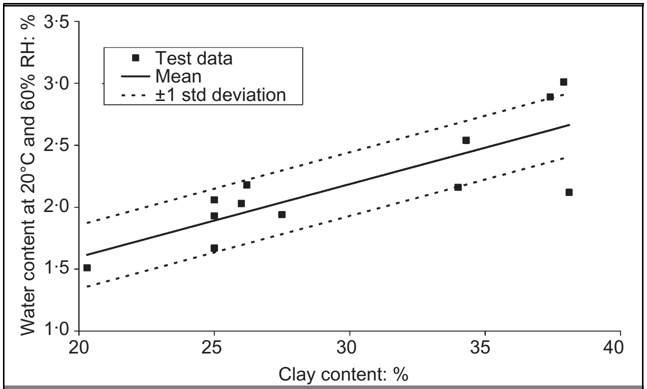

Figure 3 Effect of clay content on moisture content at 20℃ and 60% RH

Heath *et al.*[15] demonstrated that the strength of compacted unsaturated soils can be represented by Equation 1 if the frictional component of strength is linearly related to effective confinement and there is no chemical bond between particles (typical for newly deposited fine-grained soils, such as unfired clay masonry units)

$$f_c = \frac{2\sin\phi}{1 - \sin\phi}\sigma'_3 = K\,\sigma'_3 \tag{1}$$

where f_c is the ultimate (confined) compressive strength in any stress units, ϕ is the effective friction angle for the soil in degrees, K is a unitless constant and σ'_3 is the effective confining stress (sum of applied confinement and confinement from soil suction) in the same stress units as f_c. In a standard masonry unit compression test there is no applied confinement, so if end effects are ignored then only suction contributes to the effective confinement. Geometrical effects including end effects during compression testing are beyond the scope of this paper, but can be addressed through geometrical correction factors.[12]

For a sample at low to medium saturation levels (below approximately 60% saturation), the effective confinement provided by suction can be described by a 'limiting suction curve',[15] which is a modified form of the van Genuchten equation.[16] This limiting suction curve has been shown to be density independent at low to medium saturation levels.[15]

$$\sigma'_3\ (\text{from suction at medium to low saturation}) = cw^B \tag{2}$$

where w is the gravimetric water content as a percentage, c is a constant in the same stress units as σ'_3 and B is a unitless constant. The term c in Equation 2 is largely dependent on particle size and increases for finer-grained soils as the pore size decreases. In other words, as the clay content in a soil increases, the parameter c should also increase.[15]

If only the low to medium levels of saturation are considered and no external confinement is applied during testing, Equations 1 and 2 can then be combined to give the following

$$f_c = Kcw^B = Aw^B \tag{3}$$

where $A = Kc$ is a constant with the same stress units as f_c and the other terms are as previously described. Term A should increase with increasing clay content and increasing frictional angle for the material. At 6% moisture content (the maximum assumed for this paper) the saturation is below 45% for all samples. This decreases to below 10% saturation at 1% moisture content and justifies the simplification used to combine Equations 1 and 2 to obtain the simple exponential form of Equation 3.

The inherent variability in suction measurements at low saturation levels prevents their effective use for predicting performance. In the absence of accurate suction measurements, empirical fitting of test data to Equation 3 meets both the theoretical and practical requirements for predicting the effect of moisture on the compressive strength of unfired clay bricks at moisture contents below 6%.

As the moisture content increases, Equation 3 will no longer be valid as the suction and therefore effective strength of the material will deviate from the simple exponential model until the suction approaches zero at full saturation and in this case the full form of the van Genuchten[16] equation must be used.

5. TEST RESULTS

The effect of moisture content on the strengths of units A–E and F–K are illustrated in Figures 4 and 5, respectively. As shown, all units show a similar trend of increasing strength related to decreasing moisture content. The solid lines indicate a curve with the exponential form of Equation 3.

As shown in Figures 4 and 5, there is some variation in moisture content (and therefore strength) for samples subjected to the same environmental conditions, and it is therefore difficult to produce a table with average strength or standard deviation in strength, and a table with the coefficients from Equation 3 and the coefficient of correlation is more useful for describing the material behaviour (see Table 4).

The excellent agreement between the curves for samples B1 and B2 in Figure 4 should be noted. B2 has added wood fibre, which resulted in a decrease in density of approximately 12%, but the effect of moisture content on compressive strength was almost identical. As shown in Table 2, the ambient moisture content decreased slightly with the addition of wood fibre but the effect on strength is negligible.

6. ANALYSIS OF RESULTS

The exponents and coefficient of correlation from fitting Equation 3 to the test data using the least squares method, and the strength predicted at ambient moisture content are summarised in Table 4. The ambient moisture contents are presented in Table 2.

The coefficient of correlation indicates good agreement between the theoretical model of Equation 3 and experimental data within the range of moisture contents tested. The coefficient of correlation varied from 0·94 to 0·99 for the different material sources which illustrates that the theoretical model accurately represents behaviour. The high coefficient of correlation also indicates that there is limited variability in the samples, and the majority of the variability is from inconsistent moisture contents under given environmental conditions rather than from inaccurate model predictions.

Although the data are not presented for all samples in this paper, additional test results indicated the correlation is not as good

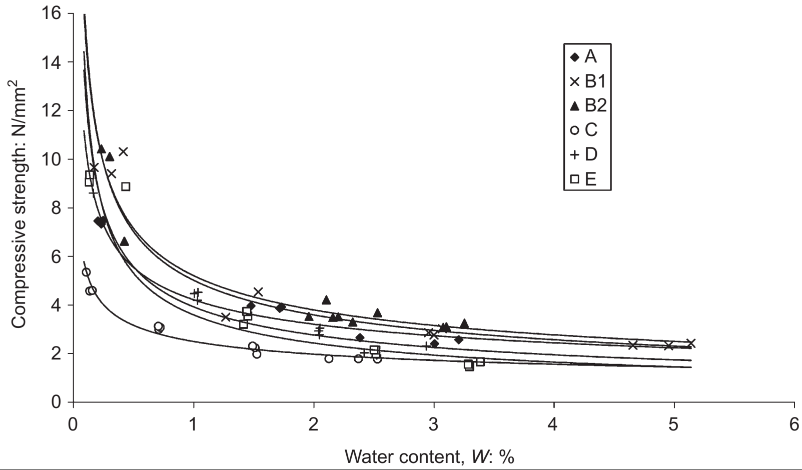

Figure 4. Effect of moisture content on net compressive strength of units A–E

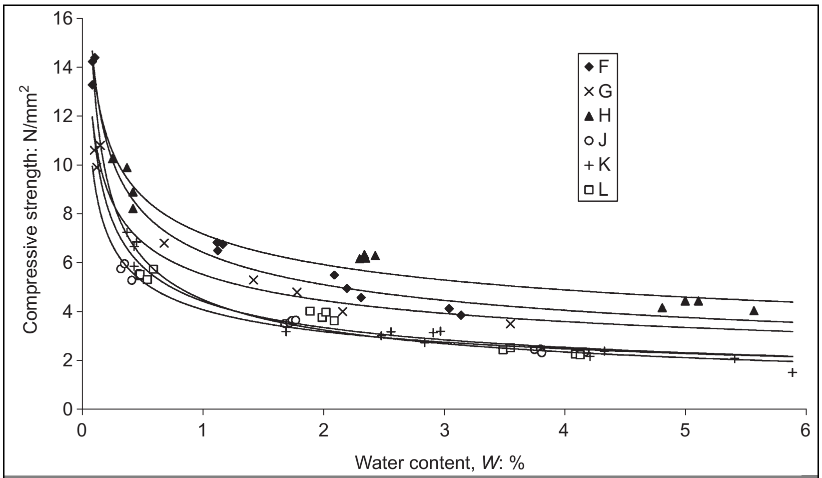

Figure 5. Effect of moisture content on net compressive strength of units F–K

Unit code	Coefficient *A*: N/mm^2	Coefficient *B*: unitless	Coefficient of correlation	Strength at ambient moisture: N/mm^2	Strength reduction for 2% moisture increase: %
A	4·27	−0·37	0·99	3·5	25
B1	5·18	−0·44	0·94	3·2	20
B2	5·22	−0·47	0·98	3·2	22
C	2·53	−0·32	0·99	2·2	24
D	3·96	−0·44	0·98	3·0	27
E	3·90	−0·45	0·94	2·8	27
F	6·53	−0·32	0·99	5·1	19
G	5·63	−0·29	0·98	4·5	18
H	7·18	−0·26	0·97	5·6	14
I	4·09	−0·34	0·99	3·1	20
J	4·50	−0·45	0·98	3·3	27
K	4·41	−0·36	0·96	3·4	22

Table 4. Coefficients, coefficient of correlation and strength at ambient moisture content from Equation 1

with the model tending to overpredict strengths at higher moisture contents where suction is likely to be lower than that predicted by an exponential model, as discussed earlier. These more complete data are presented for one brick in Figure 6 below illustrating this trend.

Coefficient *A* represents the compressive strength at a moisture content of 1%. This coefficient appears to be largely related to clay content where it increases with increasing clay content as shown in Figure 7.

The theoretical model did predict that increases in clay content would increase parameter *A*, and this is confirmed by the experimental model. As *A* is affected by both the particle size and the frictional characteristics of the material, it is difficult to predict this parameter accurately, but clay content appears to provide the best correlation. The mean relationship and ± 1 standard deviation were determined assuming the relationship is linear and the error is normally distributed. Although there are insufficient data to confirm whether or not this is the case, the figure does give an indication of strength at 1% moisture

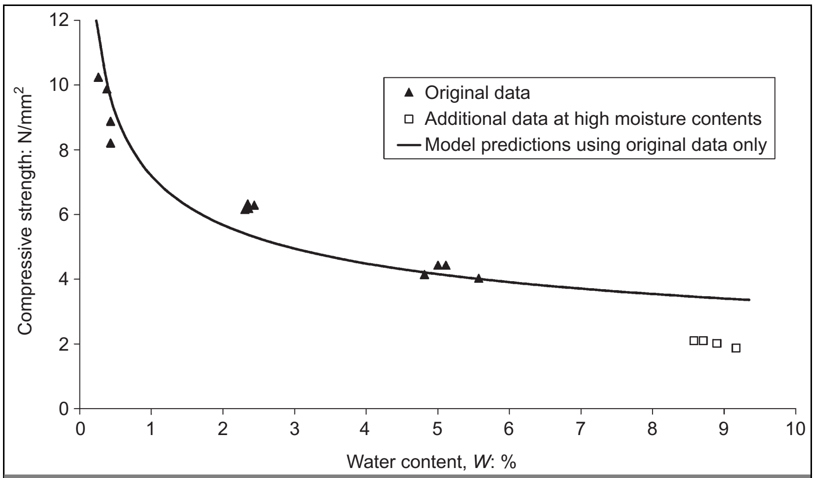

Figure 6. Deviation of model at high moisture contents

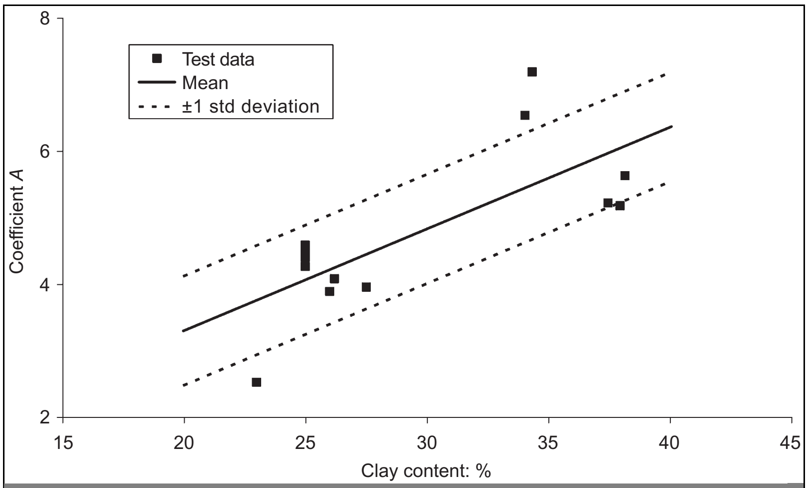

Figure 7. Relationship between clay content and coefficient *A*

content at a given clay content, and does indicate that increases in clay content are likely to result in increases in strength at 1% moisture content. However, as illustrated in Figure 3, the equilibrium moisture content generally increases with increasing clay content and as a result there is no well-defined relationship between strength at equilibrium moisture content and clay content or any other material or brick parameter (e.g. density).

The coefficient B describes the reduction in strength with increases in moisture content. As shown in Table 4, there is a very narrow range in this parameter, indicating that the reduction in strength with changes in moisture content is very similar for all the different extruded unfired bricks tested. If the strengths of all bricks are normalised by their strength at 1% water content, the similarity between the relationships is clearly evident in Figure 8. There appears to be no correlation between parameter B and material properties.

As shown, there is little difference between the behaviour of the samples and there is an average reduction in strength of 51% when the water content increases from 1 to 6% (standard deviation of 6% decrease in strength). As the equilibrium moisture content at 20℃ and 60% RH varies between approximately 1·5 and 3%, what is possibly more important is the reduction in strength with an increase in water content.

As shown in Table 4, this reduction varies between 14 and 27% for an increase in water content of 2% above ambient water content and does not appear to be closely related to material properties.

7. CONCLUSIONS

This paper has demonstrated that an exponential function can be used to represent the relationship between unconfined compressive strength and water content for extruded unfired clay masonry units. This function has been shown to be theoretically correct at low to medium saturation levels and accurately represents test data at moisture contents below 6%. At higher moisture contents the exponential model will over-predict the strength, but moisture contents over 6% should not occur during construction or operation of a building provided detailing and use are appropriate.

The strength at 1% moisture content is largely governed by the clay content of the material with increasing clay content producing increased strength. This is partially counteracted by increased clay content also resulting in increased moisture content at given environmental conditions.

The percentage decrease in compressive strength with increase in moisture content is similar for most bricks, with an average decrease of approximately 50% as the moisture content increases from 1 to 6%. A more practical consideration is the decrease in strength of below 30% as the water content in a brick increases by 2% above its equilibrium moisture content at 20° and 60% RH. This increase of 2% is the maximum likely to occur during construction or operation and is related to rendering a wall. This decrease of less than 30% gives an indication of an appropriate reduction factor to apply to test strengths at ambient moisture contents.

The addition of wood fibre to one of the brick types resulted in a 12% reduction in dry density, but had almost no effect on strength or the strength–moisture relationship for the material. This indicates the addition of wood fibre may have benefits for handling or insulation purposes, but does not affect compressive strength.

The test data indicate that conventional brick clays are suitable for manufacture of unfired units, but those that have a higher clay content generally give higher strengths. This is in contrast to observations with mass earth construction such as rammed earth where higher clay contents are not recommended, although these recommendations are largely related to shrinkage concerns. As unfired clay masonry is constructed at low moisture contents, the higher clay content is unlikely to provide the same shrinkage problems observed in mass earth construction which is constructed at much higher moisture contents.

This paper has described the compressive behaviour of commercially produced extruded unfired clay masonry units. Other aspects that affect the use of unfired clay units are

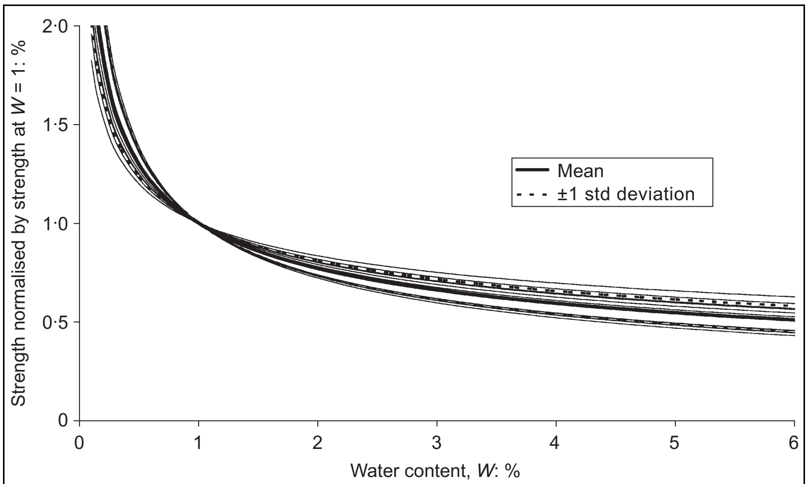

Fig. 8. Changes in strength with moisture content, normalised by strength at 1% moisture content

erodibility and abrasion resistance if they are not rendered, and shrinkage and flexural strength of panels. These aspects are beyond the scope of this paper and although some preliminary work has been performed, further research into these areas is required. In the absence of long-term performance data under extreme conditions, it is intended that these units be used in non-load-bearing indoor applications. Appropriate detailing[7] should limit damage from accidental wetting and should always be used.

While unfired clay masonry is not appropriate in all masonry applications, the high strengths and water resistance provided by high-energy products such as fired clay masonry or concrete blockwork are not required in all indoor applications (e.g. for partition walls or framed structures). Although this effect has yet to be fully quantified, the use of unfired clay masonry could reduce energy usage in buildings by providing passive humidity and temperature control.[4,5]

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