Compressive strength characteristics of cement stabilized rammed earth walls

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Abstract

In order to minimize the environmental impacts caused by over exploitation of natural resources for the production of building material, the possibility of using cement stabilized rammed earth for load-bearing walls has been assessed. Since the vertical load carrying capacity primarily depends on the compressive strength, a comprehensive study was conducted for rammed earth walls constructed with three commonly available laterite soil types in Sri Lanka. The results indicate the possibility of using rammed earth for single storey houses which may also be extended to two storey houses. The load deformation characteristics were used to determine the suitable partial safety factors for the structural design.

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1. Introduction

The provision of good quality housing is recognized as an important responsibility for the welfare of people in any country. For this, building materials based on natural resources are often used. Some examples are the use of clay for making bricks and river sand for making cement sand blocks. The commercial exploitation of these resources often leads to various environmental problems. If clay mines are not properly filled up, they can collect water and allow mosquitoes to breed. Extensive sand mining can lower the river beds and allow salt water intrusion inland. Therefore, the development of as many alternative walling materials as possible will be of immense benefit to minimize the impact on the environment.

One such material that has captured the interest of many researchers in the recent past is earth [1–4]. Earth can be used for construction of walls in many ways. However, there are a few undesirable properties such as loss of strength when saturated with water, erosion due to wind or driving rain and poor dimensional stability. These drawbacks can be eliminated significantly by stabilizing the soil with a chemical agent such as cement [4–6]. Cement stabilized soil is generally used as individual blocks compacted either with manual or hydraulically operated machines. Significant research data are available for these applications either as block strength or wall strengths [7,8]. After an extensive research programme carried out at University of Moratuwa there were several housing projects done in various parts of Sri Lanka with stabilized soil bricks using locally available soils. These practical uses indicated the suitability of various types of laterite soil available in Sri Lanka. Another possible application is cement stabilized rammed earth which is gradually introduced in many countries. In order to use this material for wider applications, it is necessary to develop strength characteristics based on
locally available soil types. This will assist in reducing transport costs, embodied energy and life cycle costs when soils of desirable characteristics are obtainable locally [9,10].

This paper highlights findings of a detailed research carried out on structural properties of rammed earth using laterite soil commonly available in areas with tropical climatic conditions.

After a successful testing programme at the University, this technology has been introduced to several housing projects in Sri Lanka and completed successfully.

2. Objectives

The research was carried out with the following objectives:

1. Selection of suitable soil types that can be used for rammed earth construction.
2. Determination of strength characteristics of cement stabilized rammed earth walls.
3. Suggestion of desirable practices for rammed earth wall construction.

3. Methodology

The following methodology was adopted to achieve the above objectives:

1. The various soil types recommended in the literature were reviewed and three different soil types commonly available in areas with tropical climatic conditions were selected.
2. Wall panels were constructed with these soils to determine the important physical and structural properties such as density, failure stress in compression and load deformation behaviour.
3. The above parameters were used to assess the performance of rammed earth walls when used in single storey houses.

4. Soil types for rammed earth walls

The composition of soils in different parts of the world varies considerably due to the origin and the climatic conditions. The literature indicates the uses of laterite soils and clayey soils [7,11] for cement stabilized soil blocks. A comprehensive study carried out in India indicates the strength values in the range of 2.5–10.0 N/mm² for individual blocks and 0.9–3.87 N/mm² for masonry prisms [8]. The dry and wet strength varies with the mortar used for binding. In a detailed study carried out with cement stabilized soil blocks manufactured with a manually operated machine giving a compaction ratio of 1.65 indicated block strengths of about 2–4.5 N/mm² and wall strengths in excess of 0.9 N/mm² with 6% and higher cement contents [7]. The compaction ratio was the ratio between the initial volume of soil to the final volume. For machine moulded blocks, it is the difference between the initial height and the final height.

Rammed earth differs from cement stabilized soil blocks in the method of compaction and construction. Compaction can be given using a steel rammer as shown in Fig. 1. Construction can be carried out with steel slip forms as shown in Fig. 2. In a construction method adopted in Sri Lanka for rapid construction of single storey houses, a special vertically sliding formwork system was used. This system slides between corner and middle columns constructed with interlocking cement stabilized soil blocks as shown in Fig. 2. It is often suggested that formwork is a significant labour intensive activity consuming about 50% of the site time for erecting, aligning, checking, stripping, cleaning, moving and storing of the formwork [4]. This system eliminates most of these activities since once in place, the formwork can slide continuously. The corner and middle columns can be erected rapidly with interlocking cement stabilized soil blocks manufactured with either hydraulically or manually operated machines. The slip formed wall will have the same thickness as the block work. This operation can be further improved with a mechanical rammer instead of a manually operated rammer. However, for countries with lower labour costs, manual rammer could be a better solution. A pneumatic rammer was developed jointly with Mechanical Engineering Department of the University and found successful in application.

A detailed study carried out at University of Bath indicates that the compressive strength of about 1.0–3.0 N/mm² can be obtained with unstabilized rammed earth [12]. Soils recommended were reasonably well graded between gravel and clay sized particles. However, there are strong indications that laterite soil can perform much better than clayey soils when stabilized with cement. Therefore, in this study it was decided to concentrate on various
types of laterite soils available in Sri Lanka which is also usually found in the areas with tropical climatic conditions.

5. Laterite soils for rammed earth

Laterite soils are formed due to the weathering process of igneous or metamorphic rock over millions of years. These soils are rich in aluminum and ferrous oxides that give either yellowish or reddish colours. These soils are available in most parts of Sri Lanka except in some coastal areas and low lying areas.

In a detailed study carried out in Sri Lanka for cement stabilized laterite soil blocks, it was found that the fines content consisting of clay and silt particles smaller than 0.06 mm should be less than 30% for obtaining better results. A drastic drop in strength was observed when the fines content increased above 40%. Therefore, a maximum fines content of 30% is generally recommended for load-bearing construction [7].

For machine moulded cement stabilized soil blocks, the block is immediately removed from the mould (green block) and hence very low fines content is also not desirable. Therefore, fines content between 20% and 30% is generally considered as the optimum. However, rammed earth is manufactured with slip formed moulds and hence there is no handling required at the green stage. Thus, even soils with very low fines content can be used for rammed earth. Laterite soils are generally formed due to long term weathering of igneous rocks and hence available as laterite hills. When the weathering is less, it is available as hard laterite hills or laterite soil with hard lumps. These two types are not used with cement stabilized soil blocks due to difficulties in obtaining a good finish.

For rammed earth walls, compaction is obtained in a special way which is closer to dynamic compaction than static or pseudo static compaction generally achieved in block making machines. For rammed earth walls, steel moulds made with 0.6, 1.2, 1.8 m of length are used to form walls of length 0.6, 1.2, 1.8, 2.4, 3.0 and 3.6 m. The soil, prepared with some moisture and cement, is placed in layers of about 150 mm and compacted with a manually operated rammer. Once the soil is compacted well, the formwork is slipped upwards for the next lift of the wall using the long screws available with the moulds shown in Fig. 2.

Due to this special compaction and slip forming, rammed earth offers an ideal opportunity to use laterite soil with hard lumps or laterite soils with very low percentage of clay and silt. However, the soils shall not contain particles larger than 38 mm in diameter [5]. The compaction method with rammers can break up hard laterite lumps to smaller pieces and give a good finish. Since the green strength is important to a lesser extent for slip forming, even soils with lower clay and silt (fines) contents can provide a stable wall with a good finish. The soils with hard lumps would act more like a mass concrete where mortar and aggregate forms the structure since the soil is sieved through a 38 mm mesh before mixing with cement.

Sieve analysis was performed on three types of soils used for the experimental study. The results are given in Table 1. Although the sieve analysis gave detailed breakdown for percentages, clay and silt (fines < 0.06 mm) percentage was reported together. This is due to the difficulties in separating them at site conditions using a simple jar test. In this test, a soil sample is placed in a bottle to about 1/3 the volume and the rest is filled up with water. It is shaken well after adding some salt and then left for about 24 h to settle. The composition of soil sample can be seen as layers. It is an ideal test for identifying the approximate composition of a soil [11]. Table 1 gives the fines content obtained from the jar test as well.

It can be seen from Table 1 that the soil identified as Sandy has a very low fines content and a high sand content. The soil identified as Hard Laterite had 14.4% fines and high percentage of particles larger than 19 mm and gravel. During dynamic compaction, the composition can change to a certain extent since some of the large particles will break into smaller particles and hence gives a reasonably smooth surface for the wall. A similar finding was reported by Bahar et al. [1], who suggested that rammed earth technology is suitable for soils with high percentage of large grain size particles.

6. The construction aspects

It was shown that rammed earth will allow a wide variety of soils with different composition to be used since the green strength is not very important and also due to compaction of dynamic nature. Nevertheless, there are certain quality controlling measures that should be adopted for these walls.

One parameter that can influence the compaction very much is the moisture content used. If too little moisture is available, the wall may not have sufficient green strength to be stable as the slip formwork is raised upwards. If too
much water is used, it may hamper the compaction process since the soil may become too sticky. It can also affect the density to a certain extent.

According to Bahar et al. [1], the optimum water content is about 9.5–11.0%. With these moisture contents, a dry density of about 20 kN/m³ was obtained. It is also reported that mechanical stabilization by dynamic compaction appear to give better results as compared with static or vibro-static compaction. Achieving a value as high as possible for dry density is considered important since density is related to strength and durability.

There is a simple test that can be used to check the approximate moisture content called “drop test”. A ball is made in the palm using a small sample of soil and then it is dropped on to a floor from about 1.0 m height. If it breaks into 4–5 pieces, the moisture content is satisfactory. If it crumbles away, the soil is too dry or if it stays as one pat, it is too wet [10].

Another parameter that can be critical to the strength and durability is the cement content. Since cement is a relatively costly material, the determination of minimum percentages required for strength and durability is of importance. It can also improve the elastic modulus as reported by Bahar et al. [1]. Cement stabilization increases the slope of the curve and hence the elastic modulus of the material increased from 1.89 GPa for unstabilized soil to 2.51 GPa for 10% cement stabilized soil [1].

Durability improves considerably with the addition of stabilizers. For walls constructed with 5% cement soil blocks, no deterioration has been observed in a comprehensive durability study of stabilized earth [13,14].

Shrinkage of cement stabilized soil increases rapidly during first four days and at latter ages the increase is very slow. Hence, curing for the first four days is very important in reducing drying shrinkage and cracking. Sand particles reduce the shrinkage as it opposes the shrinkage movement [1]. In the construction method adopted, it can be seen that the maximum length of a wall between block work columns is limited to 3.6 m and hence shrinkage problems were not experienced with the model houses constructed.

7. Strength characteristics in compression

One of the most important strength parameters needed for any load-bearing walling material is compressive strength. Compressive strength can be determined by using wall panels. BS 5628: Part 1:1992 [15] allows the use of any suitable wall panel size when new masonry materials require the determination of wall strengths. From each parameter, two panels should be tested. There were two identical panels tested to determine the average compressive strength of rammed earth walls. Characteristic strength of wall panels was determined by Eq. (1) using the average or mean strength [15]. For cement stabilized rammed earth walls, wall panel dimensions were determined so that slenderness effects will not be predominant. The wall thickness is 160 mm. The length was about 1000 mm. The height was selected as about 650 mm. This gives a slenderness ratio about 4.0. The panels were constructed with three soil types mentioned in Section 4. The panel was tested as shown in Fig. 3. The dial gauges were fixed at top and bottom levels of the panel to determine the deformation characteristics. The load versus deformation curves can be plotted to determine the elastic modulus of rammed earth. Chart 1 shows the load–deformation curves for three different soil types. Chart 2 explains the strength increase with cement percentage.

It should be noted that rammed earth indicated a behaviour somewhat different to brickwork panels. Brickwork generally fails at much lower loads than brick compressive strengths due to interaction between the bricks and mortar [16]. The absence of mortar joints make the failure of rammed earth is more of a crushing failure than a tensile failure. Therefore, rammed earth is less likely to give an adequate warning in the form of vertical cracks. Hence, it is recommended to use an adequate factor of safety against failure.

Once the ultimate load is known, the failure stress can be determined. In this experimental programme both panels gave approximately similar ultimate loads. The average failure stress of two panels can be used to determine the
The factor 1.2 is introduced to relate the characteristic value to the mean value. Both $F_m$ and $W_u$ are taken as 1.0 since there are no mortar joints. The average strength given in Table 2 is the average of the two values obtained for the identical panels. BS 5628: Part 1: 1992 uses this 1.2 factor instead of using statistical distribution owing to difficulties of testing large number of panels and also due to the high overall factor of safety used for masonry design.

According to the results obtained for the three different soil types, sandy soil gave better results for the characteristic strength. This confirms the findings made in University of Bath, United Kingdom [12].

Another important parameter for rammed earth is wet strength. According to Heathcote [3], the ratio of wet to dry strength is an indicator of durability of earth wall components. The ratio of wet to dry strength of 0.33–0.50 may be regarded as suitable depending on the severity of the rainfall. In order to determine the wet strength, panels were completely immersed in water for 24 h prior to testing. The wet strengths are indicated in Table 3 for two soil types.

Table 4 shows the panels made with even Hard Laterite and Clay soils give a ratio more than 0.33. Therefore, the strength of rammed earth walls under adverse conditions will be adequate.

Another useful parameter for structural design purposes is unit weight. The weight of a wall panel varies from 190 kg to 220 kg. The unit weight of rammed earth is in the range of 1800–2000 kg/m³. This is the unit weight obtained in many other studies [5]. In single storey construction, the load is primarily from the self weight of the walls and the portion of the roof supported. This stress is usually in the range of 0.1 N/mm². This means that characteristic wall strength required is about 0.5 N/mm² when a factor of safety of 1.4 ($c_f$) is used for dead loads and 3.5 ($c_m$) is used for material strength variations and workmanship factors as recommended in BS 5628: Part 1: 1992 [15]. BS 5628: Part 1:1992 also allows the use of $c_m = 2.5$ which will give a lower factor of safety. However, the use of 3.5 is advisable due to less warning given prior to failure. This gives an overall factor of safety of 5. This is the value recommended in the New Zealand Standards [17]. The lowest characteristic strength obtained from testing was about

<table>
<thead>
<tr>
<th>Chart 1. Load deformation characteristics of three types of laterite soil wall panels.</th>
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<th>Chart 2. Variation of characteristic strength with cement percentage.</th>
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<th>Table 2</th>
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</thead>
</table>

Average strength of wall panels

<table>
<thead>
<tr>
<th>Soil</th>
<th>Cement (%)</th>
<th>Average strength (N/mm²)</th>
<th>$f_k$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy</td>
<td>6</td>
<td>2.47</td>
<td>2.06</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.525</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3.71</td>
<td>3.09</td>
</tr>
<tr>
<td>Hard laterite</td>
<td>6</td>
<td>2.03</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.97</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.82</td>
<td>2.35</td>
</tr>
<tr>
<td>Clayey</td>
<td>6</td>
<td>1.82</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.06</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.30</td>
<td>1.92</td>
</tr>
</tbody>
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<tr>
<th>Table 3</th>
</tr>
</thead>
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Wet strength results

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Cement (%)</th>
<th>Ultimate load (tonnes)</th>
<th>Dimensions (mm × mm × mm)</th>
<th>Weight (kg)</th>
<th>Loaded area (mm²)</th>
<th>Strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard laterite</td>
<td>6</td>
<td>22.5</td>
<td>1080 × 160 × 630</td>
<td>218</td>
<td>172,800</td>
<td>1.30</td>
</tr>
<tr>
<td>Clayey</td>
<td>6</td>
<td>14</td>
<td>1030 × 160 × 640</td>
<td>216</td>
<td>164,800</td>
<td>0.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4</th>
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</table>

Ratio of wet/dry strength of rammed earth panels

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Cement (%)</th>
<th>Dry strength</th>
<th>Wet strength</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard laterite</td>
<td>6</td>
<td>2.03</td>
<td>1.30</td>
<td>0.64</td>
</tr>
<tr>
<td>Clayey</td>
<td>6</td>
<td>1.82</td>
<td>0.85</td>
<td>0.46</td>
</tr>
</tbody>
</table>
1.5 N/mm² and hence cement stabilized rammed earth can be used with a lot of confidence for single storey houses since the overall factor of safety can be about 15 instead of the value of 5 that is usually used. It was shown with detailed studies in two storey load-bearing houses for small and carefully planned layouts, the maximum design strengths required can be maintained within 0.8 and 1.0 N/mm² when the ground floor wall widths are about 250 mm [18]. The characteristic strength values obtained indicates that cement stabilized rammed earth could be a potential material for two storey house construction when appropriate wall thicknesses are selected.

8. Load deformation curves

Chart 1 indicates a typical load deformation curve obtained for rammed earth panels. It does not indicate much ductility which can be attributed to compressive crushing nature of the failure. Thus, the use of a higher factor of safety is advisable. The strength obtained with laterite soils indicated that it is possible to maintain a high overall factor of safety since the characteristic strengths obtained are high.

This curve can be used to determine the modulus of elasticity. The values were in the range of 500 N/mm². The same value is recommended in the Australian Earth Building Hand Book [6]. The value recommended in New Zealand Standard [17] was 300 × $f_c$ and hence in a similar range.

9. Conclusions

The continuous use of natural resource based building materials has led to many environmental problems. Therefore, it is essential to develop alternative building materials that can give a comparable performance with respect to appearance, structural properties and durability. This detailed study on the compressive strength of cement stabilized rammed earth walls with laterite soils has indicated the following:

1. It is possible to use laterite soils with sandy, hard laterite or clayey compositions for the construction of rammed earth walls.
2. It is advisable to maintain the fines content below 20% to obtain high strengths.
3. The cement content can be either 6% or more. Higher cement contents can provide higher compressive strengths and hence could increase the overall factor of safety.
4. Since the failure of rammed earth walls is of compressive crushing nature, it is advisable to have an overall factor of safety of 5 or more.
5. The elastic modulus of rammed earth will be in the range of 0.5 kN/mm². This can be used to determine the shortening of rammed earth walls in load-bearing construction when adjacent walls are loaded differently.

With all these research findings, now it will be possible to use cement stabilized rammed earth as a walling material with confidence for single storey houses using laterite soil generally available in tropical climatic conditions. It can be a potential material for load-bearing walls of carefully planned two storey houses.

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