Soil-cement for low-cost housing

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Experience with test houses in Dar es Salaam determined the cement content required for different housing components made of soil-cement. The results also showed that soil-cement was cheaper per year of occupancy than alternative materials.

In Tanzania, as elsewhere, soil has been the basic construction material for houses for centuries. Walls constructed out of soil, if well compacted, have adequate compressive strength under dry conditions. However, they will lose strength under adverse moisture movements. Alternate wetting and drying will erode and deteriorate the walls. All soils can be improved by adding a stabiliser, the most commonly used stabiliser being cement. When the right soil is available, soil-cement is a permanent building material.

Many workers in the field of low-cost housing have raised the possibility of using soil-cement as a building material (refs 2, 5, 6 and 9). In fact several housing schemes have been completed employing this material for walls, foundations or floors in various parts of the world. However, after many years research and development, it still finds only limited use in the construction of low-cost durable shelters.

This point implies that either soil-cement cannot compete economically with rival durable building materials (such as bricks or concrete blocks) or that its introduction is still being hampered by lack of precise knowledge of how to utilise soil-cement effectively, in addition to the normal problems facing the introduction of a new material. The answer to these questions will vary from country to country, but it is the opinion of the authors that soil-cement is an economic alternative in most countries where the per capita income is low.

These conclusions derive from laboratory tests and experience gained in the construction of a three-room test house in Dar es Salaam, of two larger building projects which have used soil-cement and of a few other small projects in Tanzania.

Selection of soil

Soils suitable for making soil-cement products should fulfill the following general requirements:

(a) the soil should be readily friable upon drying;

(b) the soil should be easily compacted;

(c) the compacted stabilised soil should be able to dry without harmful shrinkage.

If the percentage of fines (i.e. silt and clay) is too small, the blocks will not have enough cohesion to be handled immediately after compaction. A too small amount of fines will also increase block breakages at low cement contents. If the proportion of fines (especially clay) present is too high, both soil pulverisation and mixing of soil, cement and water will be difficult, and compacted density will be low. The compressive strength of soil-cement, as for sun-dried soil blocks, depends on the compacted density. A high content of fines also requires large cement percentages to obtain the desired durability. Generally, the combined percentage of silt and clay should not be less than 10 per cent and not more than about 40 per cent.

The soil used for the laboratory tests and for building the test-house proved very suitable for soil-cement blocks, foundations and floors. The engineering properties of the soil, which was a representative sample taken from the field site, are given below (grain sizes are according to AASHO classification).

Gravel (fine)	7 %	Liquid limit	37 %
Sand	67 %	Plastic limit	21 %
Silt	6 %	Plasticity index	16 %
Clay	20 %		

Preparation of soil

The top-soil must first be removed. The pit from where the soil is taken can be as deep as convenient,

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but the soil may get more difficult to remove as depth increases. The soil should be broken up as much as possible when it is dug out.

The soil should then be allowed to dry in the sun, and turned by using a rake. The soil in the present tests was then passed through a 10 mm screen. If the soil is friable, most lumps will break on impact. Those that do not can be discarded, as it is usally easier to "process" more soil than to spend time breaking up lumps.

The soil is now ready, provided it does not get wet. If it does get wet before mixing with cement, it will have to be dried and screened again.

Mixing in cement and water

The amount of cement to be used for making soil-cement will depend on the soil type used and the building component considered, e.g. internal or external walls, foundations, floors etc (refs 3 and 7).

Volume batching is easier in the field than weight batching and experience has shown that volume batching gives satisfactory results when the soil is dry. Soil and cement can be mixed either by using shovels or a drum type mixer.

Water is most conveniently added through a sprinkler (fig. 1). If the soil is very sandy, a drum mixer can be used; otherwise this work has to be done by hand. The mixing must go on while water is added, until the soil-cement mixture has the right water content. There is a simple procedure to follow to determine when the proper amount of water has been added (figs 2, 3 and 4). The authors' experience is that people quickly learn to determine the proper water content by the feel and appearance of the mix.

Figure 1

Adding water through a sprinkler

Figure 2

Too little water. A handful of soil-cement mortar is squeezed by closing the hand. It will barely stick together and no water will appear on the surface

Compaction

Although density can be varied in the laboratory, the authors' experience with compaction of blocks using a slightly modified form of the Cinva-Ram (blocks 29 × 14 × 9 cm instead of 29 × 14 × 12 cm) was that after several days' experience with the machine, the operators produced blocks the densities of which varied only within narrow limits. Of 53 blocks tested for density, the average (dry) density was 1.76 gm/cc with a standard deviation of 0.04 gm/cc.

For foundations, the soil-cement was poured directly into the trench without the use of shuttering, and compacted in 5 cm thick layers with bush poles. The average dry density achieved by this method was measured as 1.77 gm/cc, similar to that of the blocks.

Floors can be made with the same type of mix as blocks and foundations. The floor slab should also be compacted in layers of 5 cm. No delays are caused by compacting in many layers because the construction men can walk on the soil-cement immediately after compaction. A floor is made by first tamping the slab to the required thickness, then placing a thin screed on top of this a few weeks later.

Blocks made in simple wood or steel moulds are compacted in the same way as foundations. The density obtained is also the same.

Figure 3

Too much water. A handful of soil-cement mortar is squeezed. Free water will appear on the surface, and mortar will squeeze out between the fingers

Figure 4

Correct amount of water. Soil-cement squeezed in the hand will make a firm lump with a shiny surface caused by the water which just appears on the surface when the hand is opened

The curing process

The blocks, after moulding, should be placed on the ground in the shade, as close together as possible, and immediately covered with wet bags. After one to two days the blocks should be stacked, covered with damp bags and watered daily for at least one week (preferably two if possible). After this period the blocks can be moved out into the sun, and they should then be allowed to air-dry for two to three weeks before use.

Foundations and floors, after compaction, should be covered with grass, bags etc. and watered. It has been found that foundations are still damp several days after they have been watered.

Mix design and water content

The mix design problem consists in selecting suitable proportions of soil, cement and water. Water content is considered in this context. The most suitable water content from the viewpoint of both compaction and curing appears to be at optimum water content—as determined by the standard AASHO (dynamic) compaction test—for foundations, floors and the Cinva-Ram blocks. For the soil used in the experiments this figure was 14 per cent. As mentioned previously, it can be easily judged after a few days experience by the feel of the mix, and measurements of water can then be dispensed with. In the field-tests the standard deviation from the average water content of 14 per cent was only 0.5 per cent as determined from 13 samples. In any case, a series of laboratory tests (ref 4) showed that both strength and density results are fairly insensitive to variations in moulding water content in the range of 11-15 per cent.

Mix design and cement content

Selection of the cement content is the most important cost consideration in using soil cement both for block-walls, foundations, and floors. The first consideration is the cement content needed to resist stresses arising from handling and stacking during early curing. Some breakages can be tolerated, as some half-blocks are needed during construction. Any excess over this number, however, is waste and merely increases the unit cost of the usable blocks. For single-storey buildings, load stresses will be small, and any blocks that have survived handling and stacking are structurally strong enough.

However, building blocks need durability as well as strength, i.e. they must be able to resist progressive deterioration throughout the useful life of the structure. In Tanzania, this deterioration is caused by the eroding action of heavy rains and by the repeated wetting and drying. Handling and loading stresses will be generally similar for all blocks, regardless of their position in the building, but the durability requirements will be far greater for exterior than interior walls and, for exterior walls, greater for low courses of blocks than for those under the eaves. For a one-storey house the durability will determine the minimum cement content. The authors' experience indicates the minimum cement content for handling is about 5 per cent by weight of dry soil. Durability tests indicate that 7 per cent by weight of dry soil might be the minimum cement content for external walls (see below).

For foundations, handling stresses do not arise, and for a small house supported on good soil the loading stresses will usually be less than stresses occuring in the walls. Durability of foundations will be less critical than for external walls, because the eroding action of direct heavy rain is not present and water seepage velocities are small. Further, changes in water content are not as rapid as for exterior walls, and foundations, being buried, are not subject to ordinary wear and tear. A foundation may for long periods of time be partly or wholly submerged in water. This means that the strength contribution from the clay's apparent cohesion can not be counted on. For a foundation it is thus the soaked strength (specimen soaked in water at least 24 hours) which determines the minimum cement content.

The main wearing action on a floor is caused by people walking on it. Present experience indicates that a well compacted soil-cement floor has an adequate wearing strength for light traffic if the cement content is above 7 per cent.

Experimental results

The laboratory experiments were performed in the soils laboratory, Dar es Salaam Technical College. All specimens for both strength and durability tests were dynamically compacted to the densities specified, using soil pulverised to pass 2 mm or 10 mm sieve. The strength tests were performed on 10 × 10 × 10 cm cubes, cured for one week, then soaked for 24 hours. The durability test cylinders were made and treated in accordance with ASTM Standard 1559-65 for the wet-dry brushing test. Ambient temperatures ranged from 20-28 °C throughout the test period.

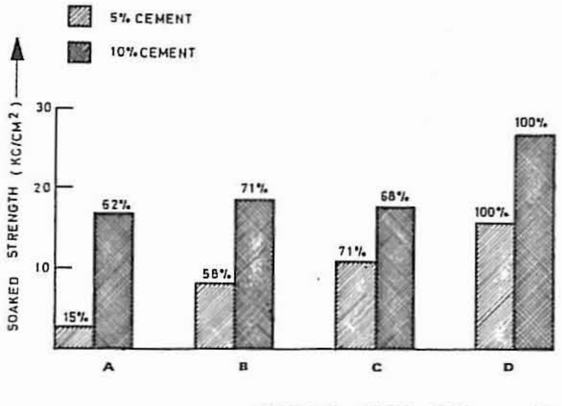

Figure 5

Strength in relation to curing conditions. The horizontal axis measures increasing curing care, the vertical axis soaked strength in kg/cm². *Histogram A = dried in sun and mud, B = dried in shade and protected from wind, C = protected from sun and wind and covered with damp sacks, D = moist cured at 100 % relative humidity*

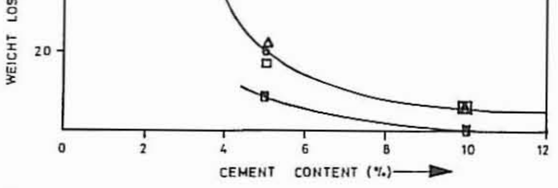

Figure 6

Percentage weight loss in wet-dry test (vertical axis) in relation to cement content (horizontal axis). Dry density is 1.88 ± 0.04 gm/cc. The blank square represents moulding 11 % m/c, 10 mm maximum lump size; the triangle 13 % m/c and 10 mm; the circle 15 % and 10 mm; and the shaded square 15 % and 2 mm maximum lump size

Fig 5 shows the strength variations with curing conditions, at two levels of cement content. The moulding moisture content was 15 per cent, and all dry densities were 1.89 ± 0.01 gm/cc. Maximum lump size was 10 mm. The results indicate that for bad curing conditions, very serious strength reductions can occur for low cement contents. On the other hand, for 10 per cent cement, about two-thirds of the potential strength was still available under inferior curing conditions.

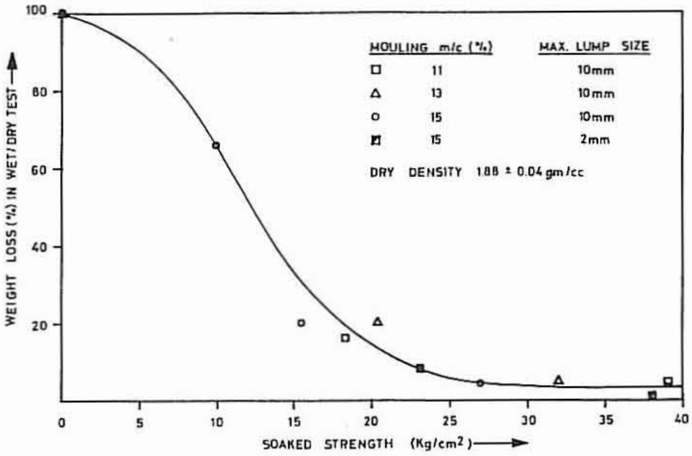

Figure 7

Percentage weight loss in wet dry-test (vertical axis) in relation to soaked strength (horizontal axis) in kg/cm^2. *Dry density and moulding percentages and maximum lump sizes are as for figure 6*

The results of the durability test series are presented in figure 6 as the percentage weight loss in the wet-dry test plotted against cement content (ref 1). In accordance with ASTM standard, the curing conditions were 100 per cent relative humidity. It is evident that weight losses were proportionately higher at lower cement contents and that, although moulding water contents do not affect the durability significantly, the degree of pulverisation does. The decrease in durability associated with increase of maximum lump size from 2 mm to 10 mm suggests that soils difficult to pulverise to less than about 20 mm would result in low-durability soil-cement.

Since previous workers, when discussing durability requirements in the fields, have often specified minimum soaked strengths, the soaked strength results for 10 × 10 × 10 cm cubes have been plotted in figure 7 against the weight losses of the corresponding durability test cylinders. The points all lie on a smooth curve, suggesting that at least for this soil type, soaked strength tests can be correlated with the weight loss in the more time-consuming durability test.

Discussion

The problem still remains, however, of correlating laboratory durability (or soaked strength) with field durability over a given climatic region. The experimental soil-cement test house mentioned above will in time, provide an answer, as a high degree of quality control and three levels of cement content (5 per cent, 7 per cent and 10 per cent by weight of dry soil) were used for the external walls. So far, the test house has only experienced one full rainy season (without visible damage) and no definite conclusions can be drawn. Nevertheless the laboratory experimental results above suggest that below about 5 per cent cement deterioration of external walls would be too severe, and that at 10 per cent cement and above the durability would only be marginally improved. Thus 10 per cent cement seems a maximum figure for external walls, and for foundations about 8 per cent.

Advantages of soil-cement

Soil-cement is a building material which combines many of the advantages of both concrete and sun-dried earth blocks, especially for durable construction and maximum use of locally available materials. Since the soil is used as aggregate, no money is needed for buying sand and gravel, or transporting them. Reduction of transport costs is very important in Tanzania where transport is often a major item in final building costs (ref 8). For example, when concrete blocks are used in Dar es Salaam, transport costs represent about 40 per cent of wall costs, but for soil-cement walls the corresponding figure is under 5 per cent.

In the following comparisons, the unit costs of walls, foundations and floors (for one-storey buildings) made from soil-cement and rival building materials are expressed in US dollars and pertain to Dar es Salaam in mid—1974.

Walls made from blocks

As mentioned earlier the minimum cement content is determined from two criteria, handling strength and durability. Both of these, because of cohesion, result in a cement content lower than that which practically can be used for concrete and sand-cement blocks. Experience with local cement, sand and soil indicate that the minimum cement content (handling strength) for a sand-cement mix is 1: 12 (by volume) but for soil-cement can be as low as 1: 25 (by volume)

Table 1 gives prices for a few simple wall structures. All of them are untreated and are about 15 cm in thickness (except for the brick wall which is 11 cm thick).

Table 1 *Costs per m^2 of wall (in US dollars)*

Building material	Material costs (per m^2)	Labour costs (per m^2)	Total costs (per m^2)
Soil-cement (mix 1:16)	0.75	1,45	2.20
Plastered mud and pole *	1.10	1.10	2.20
Sand-cement blocks ** (mix 1:11)	1.80	1.10	2,90
Factory - made concrete blocks *** (mix 1:3:6)	2.95	0.65	3.60
Factory-made burnt clay bricks	2.95	1.10	3.95

* The traditional structure. Poles are today scarce around Dar es Salaam, and have therefore to be bought.

** Blocks made by small local contractors. The house-builder buys the cement and sand and the contractor charges about 5.5 cents for making one 46 cm × 23 cm × 15 cm block.

*** The material price includes labour in factory.

Table 1 indicates that both for self-help and contractor-built houses soil-cement is the cheapest material per year of occupancy, since the traditional materials are not nearly as durable as the others, which are assumed to have the same useful life span.

Foundations

The cement content for a foundation of a small house supported on good soil (found in most areas of Tanzania) is generally smaller for soil-cement than for concrete. Table 2 gives the costs of soil-cement and concrete strip footings. The footing dimensions are 45 cm wide × 15 cm deep.

Table 2 *Costs per metre of foundation (in US dollars)*

Building material	Material costs (per m length)	Labour costs (per m length)	Total costs (per m length)
Soil-cement (mix 1:14)	0.35	1.00	1.35
Concrete (mix 1:3:6)	1.20	0.65	1.85

Because of the cohesion of the soil it is possible to walk on a soil-cement footing just after it has been made, and, when a strip footing is used, the block laying may start at once, if necessary. If formwork is needed it may usually be removed just after moulding.

Floors

Table 3 compares costs of a thin (5 cm) soil-cement, sand-cement and concrete floor slab. Even though soil-cement is appreciably cheaper than the other two floor materials, its resistance to wear is lower and the use of soil-cement alone is not presently recommended for floors with high traffic loads.

Table 3 *Costs per m^2 of floor slab (in US dollars)*

Building material	Material costs (per m^2)	Labour costs (per m^2)	Total costs (per m^2)
Soil-cement (mix 1:11)	0.25	0.90	1.15
Sand-cement (mix 1:9)	0.85	0.70	1.55
Concrete (mix 1:3:6)	0.95	0.70	1.65

A further advantage of soil-cement compared to sand-cement or concrete is that it is possible to walk on a soil-cement floor just after it has been made.

The prices given in the tables above show that, when durability is taken into account, soil-cement is economically competitive with other common building materials for walls and foundations, and in some circumstances, floors. The economic advantages of soil-cement will be even greater in areas where aggregates are scarce and cement expensive. In addition to its generally lower cost per year of occupancy, some non-economic benefits have been discussed.

The relatively high proportion of labour in the total costs of soil-cement construction may be considered an advantage in labour surplus countries, but there is a potential disadvantage. Making soil-cement requires a better working discipline than making concrete. The processes involved are not difficult, but they have to be done correctly. High strength and durability require a good compaction.

Conclusions

The conclusions from the present work most relevant to construction in soil-cement are:

1. Soils suitable for the manufacture of stabilised blocks should have enough fine material to ensure cohesion in the freshly moulded blocks. However the fines content in any stabilised soil construction should not be too high, or pulverisation of the soil and compaction of the stabilised mix will prove difficult.
2. Selection of the appropriate water content does not present a problem in the field. With a little practice it can be easily judged by the feel of the mix.
3. Several factors are important in determining the minimum cement content to use. For internal

walls, handling and stacking stresses determine the minimum cement content (5 per cent); for external walls, durability requirement considerations suggest that the cement content should be at least 7 per cent, and for foundations, adequate strength under prolonged immersion requires a cement content of about 8 per cent.

4. Inadequate curing has adverse effects on the soaked strength of soil-cement at low cement contents. However, at the 10 per cent cement level, even very poor curing conditions still give soaked strengths about two-thirds of the value for moist cured specimens.
5. Durability was found to be little affected by water content over the small range considered (4 per cent), but increasing lump size caused marked decreases in durability. The durability of soil-cement (as measured in the ASTM wet-dry test) was found to be strongly correlated with soaked strength.
6. Soil-cement was found to have a lower initial unit cost than other common building materials, except for traditional materials. When durability was taken into account, soil-cement proved cheaper per year of occupancy then all other materials considered, if used as a wall or foundation material. The economic competitiveness of soil-cement is largely the result of its utilisation of localy available materials, giving low transport costs.

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