METHOD OF AMENDED SOILS FOR COMPRESSED BLOCK AND MORTAR IN EARTHEN CONSTRUCTION

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ABSTRACT

The paper presents the results of a research conducted aiming at developing a method of producing building block and mortar from locally available natural soils and earth minerals. The main focus of the effort is to establish or advance wall making building blocks and jointing/binding mortars from amended soils with cementitious raw lime/non-factory manufactured and pozzolanic minerals. The targeted beneficiaries of the success are the over eighty million disadvantaged Ethiopians residing in the rural and semi-rural areas of the country. They deserve a decent, sustainable, eco-friendly and a popular technology based habitat.

The long journey towards achieving the noble goal was initiated by investigating the suitability of soils and earth minerals, preparation and testing of informative specimens and the production of mortar cubes and proto-type building blocks in their actual size to simulate field application conditions. The specifics of this particular move is thoroughly focusing on the two prime parameters of compressive strength and durability (water resistance) which are the determinant factors for the viable application of earth based wall making in puts.

The attained results of the effort indicated that the designed mix proportioning of the ingredients confirmed that the products are acceptable both in compressive strength and durability terms for the intended purpose. To this effect, the blocks produced using the proposed method, are named as amended compressed earth blocks (ACEBs).

***Keywords**: Amended compressed earth block (ACEB), Earthen construction, Durability Earthen construction, Durability Earth minerals, Mortar*

BACKGROUND

Background to alternative building materials research

The search for alternative building materials especially, those of the low energy, low cost and the minimally dependent on non-renewable natural resource types are the order of the day in the post-Koyoto climate protocol era. The effort is also meant to address the vital issues of: affordability, sustainability and the provision of decency to the human habitat without over taxing the equilibrated environment. In countries where local building inputs are not supported with indigenous research and development (R&D) to compete with those industrially produced ones, their chance of sustained existence is always at stake.

This in turn is a reflection of lack of set standards for local materials improvised through continuous research and development. As a result, recognition of buildings made out of local materials is not taken seriously by financing agencies and insurance corporations. The other factor is the negative attitude which haunts the society due to the pejorative that houses built of local materials, such as; soil mud is a sign of miserable life or primitiveness [1, 2].

As President Nyerere of Tanzania said in his 1977 assessment of the Tanzanian economy; “The widespread addiction to cement and tin roofs is a kind of mental paralysis” [1].This calls for a home grown applied research, focusing on naturally available materials to develop low cost, low energy, affordable green binder and wall making alternative inputs to care for and modernize the fragile habitat.

Background to local building construction materials and housing

According to the Ethiopian situation, geographic locations are designated as Dega (high land), Kola (low land) and Woina-Dega (lying between high and low lands). With the geographic influence come mode of life and style of built environment. The climatic condition also dictates the endowed natural resources for the construction of houses and their type. The other factor that influences the type of housing development is the kind of work to which the particular local people are accustomed to for their livelihood (agrarian, pastoralist, etc.). The vegetation within the eco-system and the geological formation as a source of building material in their locality is an equally governing factor to create a built space.

Keeping all the above intricate situations in mind, the research focuses on utilizing abundantly available earth raw materials and minerals pertinent to any local endowment. That is to say, the solution has to have various alternatives; possibly to suit any geographic location with little environmental tuning up where ever the need arises. According to literatures, nearly any soil can be made into a better building material with the addition of the CORRECT stabilizer [3].

Objectives of the research

The core objectives of the research are:

To assess and study the possibility of finding an alternative binding material to innovate wall making inputs from natural soils and earth minerals which are available locally.

To evaluate the basic requirements of compressive strength and durability (water resistance) of the earth based wall making binding material for the appraisal of its possible application.

Approach to raw materials selection, testing and block production

INTRODUCTION

One of the major obstacles which hinder the affordability of shelter is the high cost of building construction inputs [2, 8, 31, 35]. This is especially true for those people who are living in rural and semi-rural areas of Ethiopia. In this regard, the up-grading of the existing architectural and structural building forms and providing alternative construction materials is the way forward to properly address the problem. If one considers the mentioned segment of the Ethiopian society, everything related to building construction or housing is very much dependent on naturally endowed raw materials with little or no improvisation. Innovating existing building materials in a sustainable manner can reduce the uncontrolled use and abuse of non-renewable natural resources. However, since exercises of this nature are not practiced, there is little or no improvement in the vernacular housing constructions of the indigenous type. If this continues, sooner/or later our housing culture including generation of artisans (skills honed over years), the typology of the structures and the advantages of affordable self-help communal construction (a means of cost reduction practice) shall be swallowed by the newly arriving but yet expensive and technically intensive technologies [2, 8, 9,10, 11].

Selection and testing of ingredient raw materials

To properly manage the aforementioned situations alternative local technologies have to be developed which could enable us to lay foundation for sustainable housing development. In this particular research, the basic technology is focusing on earth materials, lime and natural local pozzolans (Table 1); which are considered to be useful and suitable for the production of building blocks and mortars in earthen construction [12,13, 14].

Table 1: Descriptive data of some pozzolans available in Ethiopia [15]

Chemical Compositions	Mass Percentage		
	Pumice	Scoria	Diatomite
SiO_2	56.7	39.7	74.6
Al_2O_3	13.6	12.7	4.2
Fe_2O_3	6.7	16.9	4.3
CaO	16.3	22.5	15.0
MgO	1.1	6.9	0.7
K_2O	3.3	0.3	0.4
Na_2O	2.2	0.9	0.6
P_2O_5	0.0	0.3	0.0
Residue	0.0	0.1	0.0
L.O.I	1.8	1.1	5.6
Free moisture	1.3	1.1	2.4

For a cursory assessment, pertinent raw materials were collected from accessible sites. The selection was based on visual identification, touch, adhesion and sedimentation tests; as deemed necessary. Before going into further details, all rocky and granular materials were sorted out. Soil, raw lime and various pozzolanic mineral lumps were pulverized in the lab to the required possible powder size for the casting of suggestive mortar specimen cubes. Moreover, some physical properties of the raw materials were determined in the laboratory per laid relevant procedures. Atterberg limits, granulometric compositions, specific gravity, and optimum moisture content, maximum dry density and linear shrinkage measurements were noted.

The planned effort was launched with the very basic probing of the bonding possibilities that could exist between standard sand as a primary input, lime and pozzolans in separation and in combination. The move was started by casting mortar cubes of (50X50X50) mm for compressive strength test. In addition, two crossly jointed fired bricks (cross-brick couplet) with the same mortar mix were prepared to check the tensile strength that could be developed; if used as a mortar (Table 2). The compressive strength test results are shown in the scatter diagram of Figure 1.

Table 2: Test results of crossly jointed bricks (tension) and mortar cubes (compression)

Sample No.	**Load Area (mm^2)**	**Strength (MPa)**		**Remark**
		Comp.	**Tension**	
T.1.1	-----	-----	-----	FBL
T.1.2	12,604	-----	0.01	
T.2.1	-----	-----	-----	FBL
T.2.2	10,950	-----	0.10	
C.1.1	2500	0.22	----	
C1.2	2500	0.23	----	
C.2.1	2500	0.24	----	
C.2.2	2500	0.29	----	
C.3.1	2500	0.21	----	
C.3.2	2500	0.21	----	
C.4.1	2500	0.21	----	
C.4.2	2500	0.21	----	

Note:-FBL – Failed Before Loading ; **C** – Compression Specimens; **T** – Tension Specimens

The cross- brick couplet method measures a direct tensile strength of the bond between the mortar and masonry unit [9, 13]. The specimens were cured under the ambient air dried moisture condition for their 28th day strength tests. All the test results of the investigation are shown in Table 2 above.

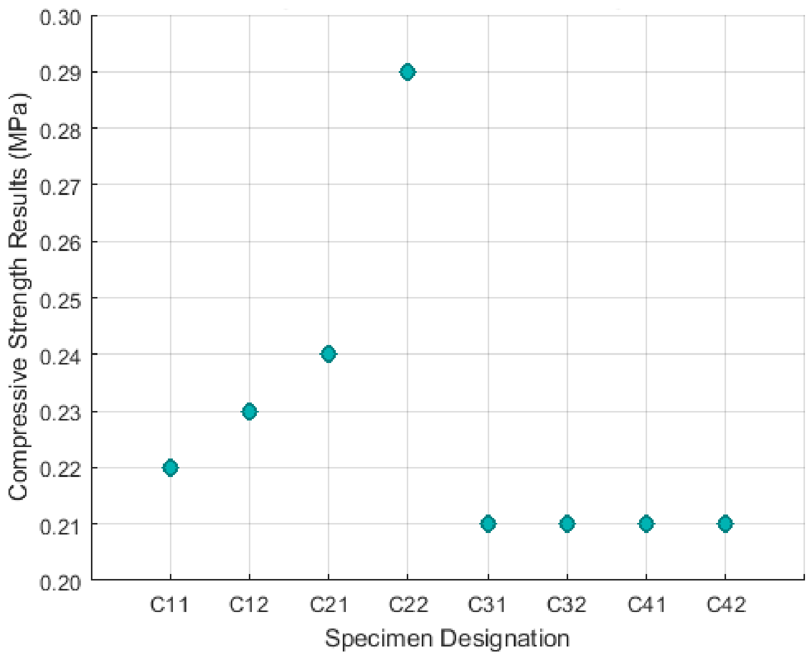

Figure 1: Scatter diagram of compressive strength test results

Preliminary casting and testing of compressed earth blocks

Amending soils for construction purpose is meant to improve the performance of any available natural soil and convert it to the state that it could be used in the making of sound mortar and building block units for the purpose of constructing walls [13, 14, 17, 18].

Following the above suggestive results it was decided to apply the method by considering a given soil type as a major constituent, the lime pounded in the lab and the pozzolans to play the role of amending. The results obtained indicated that amending a given soil with earth minerals (lime and pozzolan) enhances its performance both in strength and durability terms as presented in Tables 3-5.

In general, the indication so far is that all amended compressed earth blocks (ACEBs) and mortars could be used as a wall making input for low cost house construction in lieu of cement stabilized earth blocks[14, 19, 20,21,37]. The examined amending earth minerals were raw lime and pozzolans[3,13, 15,22, 23, 24, 25, 26, 27, 28,29,30, 31,35]. Both of these materials were pounded in the lab to get a powder of granule size of 4.75 mm. maximum. After pounding, all were kept under the lab hangar shed condition till the mixing and casting day. No special care was needed to handle.

The material which was required for the casting of three (50x50x50) mm soil only cubes and three (50x50x50) mm soil plus amending mineral mortar cube specimens were prepared (Table 3).

Table 3: Soil only and soil plus mineral mortar cubes

IT. No.	Mortar Cube Description	Dimension (mm)	Unit Weight (KN/m^3)	Compressive Strength (MPa)
1	Soil only	44.0x44.0x44.0	17.1	0.5
2	Soil only	44.0x44.0x44.0	17.3	0.6
3	Soil only	44.0x44.0x44.0	17.3	0.5
1	Soil + Mineral	47.5x43.0x43.0	18.5	0.7
2	Soil + Mineral	44.0x44.0x44.0	17.5	0.7
3	Soil + Mineral	44.0x44.0x44.0	17.3	0.7

Sequentially, for the actual blocks (CEB and ACEB) production a second set mix was prepared out of which one batch was soil only mix for three (50x50x50) mm cubes and three (50x50x50) mm cubes with mineral additive as a second batch(Table 4).

Table 4: CEB and ACEB mix cubes of soil only and soil plus mineral

IT. No.	CEB Mix Description	Dimension (mm)	Compressive Strength (MPa)
1	Soil Only	47.0x46.5x47.0	2.0
2	Soil Only	47.0x46.5x47.0	1.7
3	Soil Only	47.0x46.5x47.0	1.8
1	Soil + Mineral	47.0x46.0x46.5	2.2
2	Soil + Mineral	47.0x47.0x46.0	2.7
3	Soil + Mineral	46.5x47.0x47.0	2.0

Similarly, mixes with soil only and soil plus mineral additives were prepared to cast four (250x155x100) mm of actual size CEB and four ACEB units (Table 5). In both cases, the fourth specimens were tested for compression after going through the drip-test for a suggestive assessment.

Table 5: CEB and ACEB actual size units

It No.	CEB Description	Dimension (mm)			Compression Strength (MPa)
		L	W	D	
1	CEB	224	146	82	2.1
2	CEB	235	149	88	2.1
3	CEB	230	146	83	2.3
4	CEB (post-drip)	235	153	82	1.5
1	ACEB	229	142	86	3.1
2	ACEB	226	146	85	3.3
3	ACEB	225	142	88	3.1
4	ACEB (post-drip)	230	145	90	3.3

As can be easily observed, the comparison between soil only and soil plus mineral results of Table 3, there is an improvement in compressive strength of 27.5% on average between the mortar cubes of soil only and the ones with additive minerals. Likewise, the results from the actual mix for CEB and ACEB units in Table 4 are witnessing a 26.8% increment in compressive strength for the cubes with mineral additives. From the results of Table 5, it is evident that there is a 44.3% increase in compressive strength of the blocks made of soil plus mineral additives. It is worth to note here that, at this preliminary stage the test was meant to evaluate the improvement gained by amending the selected natural soil with some customary mineral additives to probe the suggestive outcome.

At this point, the durability (drip test) of the CEB and ACEB units were checked on one specimen from each product, to assess the impact of erodibility/water erosion (Table 5).The test was the Geelong drip test [12, 13, 22, 23, 32, 33] on the fourth specimen of each group; designated as CEB (post-drip) and ACEB (post-drip) in Table 5. For Geelong test, the specimen is placed on an inclined wedge of 1 V: 2 H. A 100 ml of water is allowed to drop from a height of 400mm on to the sloped face of the specimen. The time taken for the 100ml water to drip completely is set to be between 20 minutes minimum and 60 minutes maximum. At the end of the drip, the pit depth is measured with a cylindrical probe having an end diameter of 3.15mm

The compressive strength increase from soil only block to soil plus mineral block is 115.6%. It is vital to note here that, a close monitoring of the CEB and ACEB specimens a day after the drip test was conducted indicated that:

The physical appearance of the CEB (soil only) was intact without any further weakened moistened exposed surface area.

The ACEB (with additive minerals) wetted surface area was having lots of cracks and curling up of the drip affected moistened face. The block seemed very much weakened in strength. However, in the contrary, the compressive strength test result showed that the physical appearance of the block did not influence the bearing capacity as compared to the soil only block. For clarity, observe the compressive strength of the post-drip numerical test results of Table 5; as a matter of proof. It is further elaborated in the section on block units for field application.

According to Standards Australia, 2002 [41], the dry density (unit weight) for CEB soils is in the range of 17-22kN/m^3, as it is also confirmed by the findings of this research (Table 3). Moreover, per the above standard the unconfined compressive strength of CEB units is in the range of 0.4–0.6 N/mm^2, and or New Zealand, NZS4298, 1998, this value is 0.5N/mm^2 [35]. From this investigation the findings are; the average compressive strength for soil only (CEB) mortar cubes is 0.5 N/mm^2 and for soil + mineral (ACEB) mortar cubes is 0.7 N/mm^2 (Table 3). Regarding the mixtures for soil only (CEB) and soil + mineral (ACEB) units the test results are: 1.8 N/mm^2 and 2.3 N/mm^2; respectively (Table 4). It shows that both the mortar and block making mixtures with soil only and those with additive minerals satisfy the requirements set in the two mentioned standards. In the case of the mixtures prepared to cast prototype building blocks of (235x150x90)mm for the CEB units the results are: soil only 2.2 N/mm^2 and for soil + mineral (ACEB) 3.2 N/mm^2 on average (Table 5); indicating that the obtained results exceed the set limits in both the cited standards.

Production of ACEB units for practical application

In section three, tests on earth materials (soils) and minerals (lime and pozzolans) were made to assess their suitability as basic and amending ingredients; respectively. This was followed by mortar and earth block production and testing. The findings highlighted that, there is a possibility of extending the method to the level of practical application.

What follows is, the production of actual amended compressed earth block units starting with a natural soil of 64% sand, 20% silt and 16% clay; directly from site. Amending this soil with lime (mineral 1), pozzolanic material (mineral 2) plus minerals 1 and 2 together six more distinct mixtures were created to have seven series of specimen blocks in total; as depicted in Table 6 with series designations of SD1-SD7.

Table 6: Granulometric analysis of soil plus minerals for practical application

Series Designation	Mix Ingredients	Compositions (%)			Shrinkage (%)	PI (%)	OMC (%)
		Sand	Silt	Clay			
SD-1	Soil Only – S	64	20	16	10	43	35.8
SD-2	Soil + Lime (2%) - S+L	47	17	36	10	28	35.8
SD-3	Soil + Lime (3%) - S+L	44	30	26	13	36	34.0
SD-4	Soil + Pozzolan (3%) -S+P	40	17	33	9	27	34.0
SD-5	Soil + Pozzolan (4%) -S+P	48	28	24	10	32	36.3
SD-6	S+ L (1.0%) + P (3.5%)	52	20	28	9	25	34.4
SD-7	S+ L (2.5%) + P (7.0%)	40	33	27	13	25	32.0

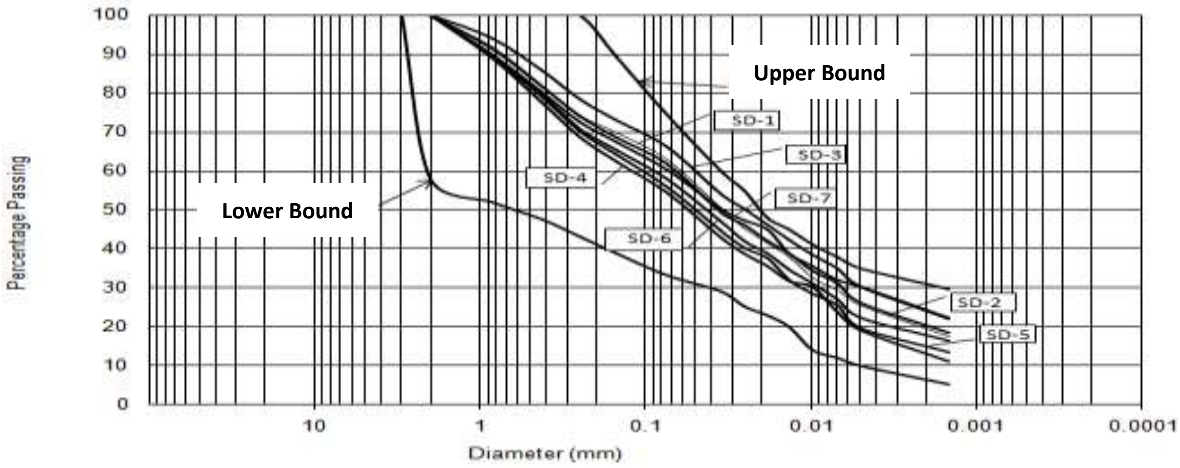

Figure 2: Grain size distribution curve[34]

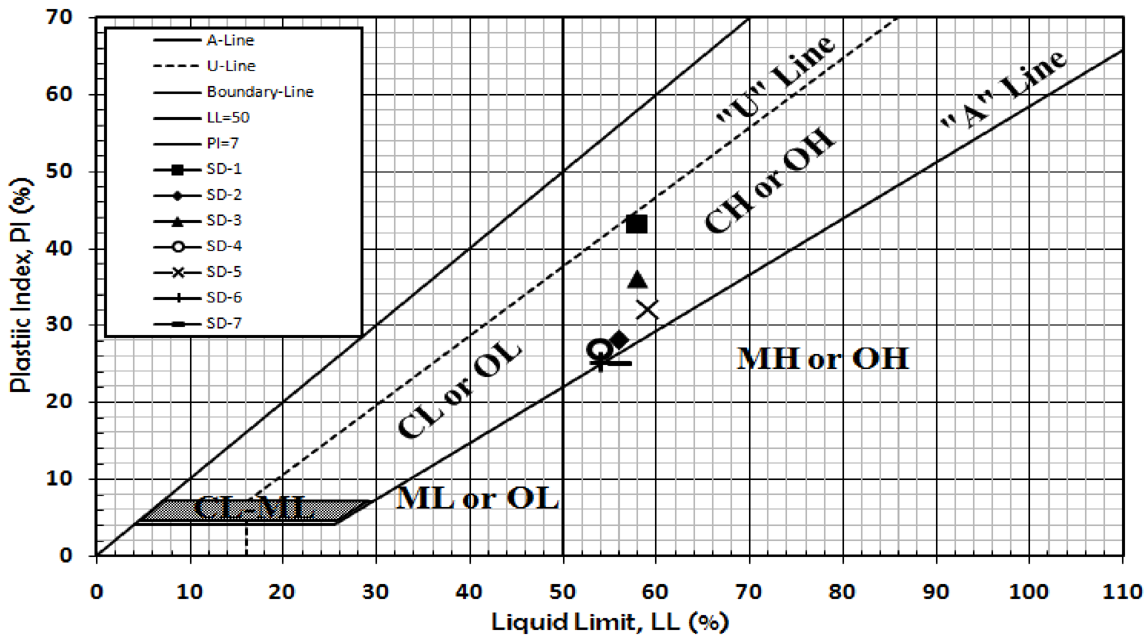

Figure 3: Casagrande plasticity chart showing amending effectiveness [35]

Besides, the grain size distribution curve of Figure 2 clearly shows how the amending effort changes the curve position with a slight variation of percentage dosing. The curves of the ingredient materials of this research fall in between the upper and the lower bounds of suitable soils for the production of good cement stabilized blocks [7, 13, 14, 28, 32, 34, 36, 37].

In addition, the plasticity chart of Figure 3 clearly indicates the improvement made by changing the highly plastic soil to low plasticity, i.e., from 43 to 25 PI; and the soil class from CH or OH (inorganic or organic clays) to MH or OH (inorganic silts or organic clays); which in turn reduces the characteristics of the given natural soil shrinkage potential from the high to the low range. The increase in compressive strength is also an indication of an enhanced performance brought about by the proposed amending method of natural soils with lime and pozzolans as shown in Figure 4.

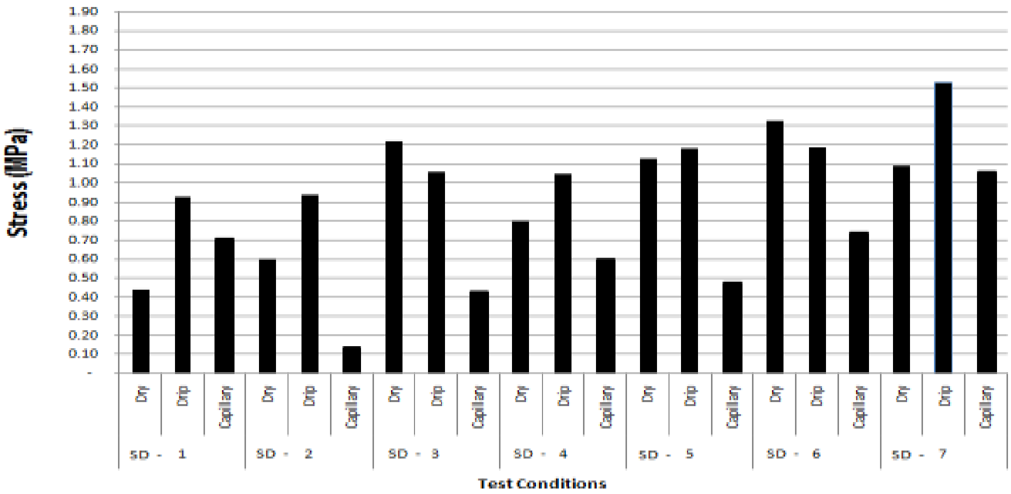

Figure 4: Compressive strength test results of CEB and ACEB units vs. various testing conditions

With respect to earthen wall input evaluation in the already concluded two stages, the making of mortar cubes and block units was by using hand compaction into their respective steel moulds. However, at this stage a block pressing machine of Elson Block-Master model is made use of. The pressing machine is of a single mould type of (300x230x175) mm internal dimension, mechanical and having a compacting pressure of 5 MN/m^2. The semi-skilled man power required was four in number. The raw materials required were; soil, lime and pozzolanic minerals. All materials were sorted out very carefully and pulverized as deemed necessary. The temperature and humidity were just the laboratory indoor conditions. The measurements were all in individual weight recording followed by thoroughly dry mixing per the designed proportion using ordinary shovels on the smooth concrete laboratory floor. A systematic and progressive water sprinkling (referenced to each mix batch OMC) was pursued until a smooth homogeneous mix was obtained.

The mix batch types were seven in total. They were identified as; series SD1, SD2, SD3, SD4, SD5, SD6 andSD7 as shown in Table 6.The rationale behind creating six more batches starting with the naturally obtained soil designated as series SD1 is to verify how amending a given soil by the proposed method improves its physical characteristics. Mixing was ended and workability checked by the field method of expeditious test, where a handful of the material was rolled into a glossy ball mass and was dropped on to the floor from a one meter height. The formation of a pyramidal shape with few scattered fragments was observed per the suggestion of [5, 39], which is an indication of a mix at the proximity of its optimum moisture content (mix batch OMC) and of good workability. The casting of blocks was made by measuring with a scoop noting equal takings and lightly tempering into the steel mould.

At the end of each fill the top of the mould was leveled smooth; the upper lead of the press lowered to cover the content; locked and pressed by a pre-assigned and trained person. The pressing into the mould was a one go uninterrupted process which was held in its final at full compression position until the block is carefully removed from the mould by a slow extrusion. The wet block was left on a bench for a day (24hrs.) and the bottom plate (pallet) removed for the next casting the following day. Curing was without watering but only keeping under the lab hangar shed. Monitoring and observing of any physical unusual appearance or damage was rigorously attended to note any detrimental manifestations. Nothing serious was observed in almost all the cases. It is to be noted that, since the casting was done during the long rainy season (July) curing was slow due to a fairly low ambient temperature and the age of the blocks at testing was extended to ninety (90) days. However, in all the previous two stages a standard curing period of twenty eight days was exercised followed by the required tests. Ninety days testing ages were also used by [27]. At the end of ninety days, for each series three types of tests were conducted; compressive strength, drip and capillary absorption (described by water absorption coefficient A_t) [22, 36, 38, 39, 40]. Here it is vital to note that, each set was composed of three specimen block units designated as 1, 2 and 3. In all the series No.1 is for dry compression test, No. 2 is for drip test and No. 3 is for capillary absorption test. All the blocks which underwent the drip and capillary tests were also subjected to the compression test at the end (Figure 4) For all the cases, the results (average of 3 specimens) are as recorded in Table 7.

Table 7: Summary of CEB and ACEB units test results for practical application (average of 3 specimens each)

CEB/ACEB		Test Type	Age (days)	Dry Weight (N)	Wet Weight (N)	Comp. Strength (MPa)	Water Effect			Remark
Series	Sample No.						Penetration (mm)	Wt. Gain (N)	% Gain	
SD-1	1.1	Dry	90	92.7		0.5	---			CEB
	1.2	Drip	90	105.8		0.9	15			CEB
	1.3	Capillary	90	114.1	126.0	0.6	---	11.9	10.40	CEB
SD-2	2.1	Dry	90	91.0		0.6	---			ACEB
	2.2	Drip	90	103.6		0.9	15			ACEB
	2.3	Capillary	90	102.7	105.4	0.2	---	26.5	2.60	ACEB
SD-3	3.1	Dry	90	107.3		1.2	---			ACEB
	3.2	Drip	90	100.0		1.1	13			ACEB
	3.3	Capillary	90	101.8	104.2	0.5	---	24.6	2.40	ACEB
SD-4	4.1	Dry	90	108.0		0.9	---			ACEB
	4.2	Drip	90	100.8		1.1	12			ACEB
	4.3	Capillary	90	103.8	106.0	0.6	---	21.5	2.10	ACEB
SD-5	5.1	Dry	90	120.2		1.1	---			ACEB
	5.2	Drip	90	125.4		1.2	12			ACEB
	5.3	Capillary	90	132.3	132.8	0.5	---	5.5	0.40	ACEB
SD-6	6.1	Dry	90	114.3		1.3	---			ACEB
	6.2	Drip	90	112.4		1.2	10			ACEB
	6.3	Capillary	90	113.1	113.8	0.8	---	6.7	0.60	ACEB
SD-7	7.1	Dry	90	132.4		1.1	---			ACEB
	7.2	Drip	90	117.0		1.5	10			ACEB
	7.3	Capillary	90	116.7	117.5	1.1	---	7.7	0.70	ACEB

Note: - L- Block length W-Block width D - Block depth/thickness

Results, analysis and discussion

From all the three sequential stages (sections 3.2, 3.3 and 4), it was learnt that there are result improvements in the performance of the test specimens through amending; be it as a mortar or as an actual amended compressed earth block (ACEB); the analysis and discussion of which are as follows.

On selection and testing of ingredient materials

The introductory effort of the research was a suggestive assessment for an alternative cementitious material which can play the role of the conventional cement for the intended type of work. In this regard, the materials in focus were; lime, pozzolanic minerals and standard sand plus ordinary tap water.

Two types of lime were taken; one was a processed and packed factory lime from the market and the other was a natural raw limestone broken down and pounded in the lab. The raw lime alternative was considered to assess the possibility of using hand ground/powdered limestone where factory lime is not available or affordable by the target population. The pozzolanic minerals were also collected from quarry sites and pounded in the lab; for there is no ready-made powder of these in our current market. The pounding of both the lime and the pozzolanic materials produced a fine powder passing sieve No.40 (425µm).

After preparing all the input ingredients, two groups of trial specimens were designated. Each group contained two sets; marked as (Lime + Pozzolan one + Standard Sand) and (Lime + Pozzolan two + Standard Sand). Mortars of each group were prepared with identical mix design and proportions; but with a mixing water variation from 21 to 27% of the gross solid mass. In actual fact, the mortar mix prepared from a factory lime consumed more water on an average of 4% in excess of the raw and lab pounded one. This may be attributed to the extra fineness of the factory lime as opposed to the one pounded in the lab.

Compressive strength tests were also carried out on four sets of cube specimens (50x50x50) mm and the following results were obtained: 0.23 MPa for factory lime with pozzolan one and 0.27 MPa for factory lime with pozzolan two; 0.21 MPa for pounded lime with both pozzolans one and two; separately. All the indicated results are averages of two test specimens from each set as a suggestive evaluation (Table 2 and Figure 1).

At the same time, as presented in section 3.2, to assess the bonding strength of mortar the tensile tests conducted on two crossly jointed (couplet) fired bricks according to [3, 22, 37], indicated that the mortars prepared with both the lime ingredients separately with pozzolan one failed before any load was applied. However, those prepared using both lime types separately with pozzolan two were able to withstand applied tensile loads achieving tensile stresses of 0.01MPa and 0.10MPa; respectively. This shows that pozzolan two has a better bonding property with standard sand in the presence of lime, if used as a jointing mortar in ACEB wall construction (Table 2).

From the ongoing analysis and discussion of the suggestive test results it can be fairly deduced that:

The compressive strength on the mortar cubes indicated that, the factory lime performed better with pozzolan two; but on the other hand in the case of the pounded raw lime it performed equally well with both the pozzolan ingredients.

In order to check the bonding property of the mortar to be used in the construction of ACEB wall (as a jointing mortar), it was found that the mortar prepared from the selected soil for the construction and both lime types but separately with pozzolan one failed before applying any tensile load. However, the mortar prepared using the selected soil for the construction and both lime types but separately with pozzolan two withstood applied tensile loads registering tensile stresses of 0.01MPa and 0.10MPa; respectively. The finding shows that pozzolan two can develop a better bonding with standard sand in the presence of lime; if used as a jointing mortar in ACEB wall construction.

On preliminary mortar and block units

This stage of the investigation was to identify cementing ingredients and the actual soil type to be used in the making of mortar and building block units, the results of which led to the following findings.

In reference to the soil only mortars and CEBs test results: soils plus mineral mortars are gaining compressive strength from mortar to actual block mix cube samples and further to the point of the real building block units as shown in Tables 3, 4 and 5; respectively.

Since earth block structures are prone to water erosion and capillary action failures, the necessity of durability test is quite imperative. To that effect, the Geelong drip penetration and moisture permeation test [13, 33, 36] was conducted on block units of soil only and soil plus mineral additive specimens designated as 4 (post-drip) in Table 5.These same block units were later on subjected to compressive strength test after one hour of the drip effect observation; for which the results are included in the cited table.

On block units for field application

This section was meant to transform the so far attained results from the suggestive tests to the level of field/practical application. The soil taken was having the following compositions; 64%sand, 20% silt and 16% clay, simulating 64% sand, 18% silt and 18% clay; as referenced in [22]. It is considered that, the two soils are nearly identical if not for the difficulty of separating silt and clay in an exact manner. A definitive method for delineating between clay and silt particles, based on grain size, remains an area of debate in the geo-technical field [39].This basic soil was amended with lime (mineral 1) and pozzolan one (mineral 2) in two different percentage proportions each; as detailed in Table 6. Seven series of blocks were prepared and tested after ninety days. The block types were: soil only (9 specimens), soil plus lime (18 specimens with 2% and 3 % lime), soil plus pozzolan one (18 specimens with 3% and 4%pozzolan one)and soil plus lime plus pozzolan one (18 specimens with 1% lime plus 3.5% pozzolan one and 2.5% lime plus 7% pozzolan one). The basis of considering the above percentage dosing is [1], which took 5, 8 and 12% for the durability of lime stabilized earth blocks.

From each type, the first set of blocks (3 samples) was tested in compression under air dried lab condition, the second set of blocks (3 samples) post-drip and the third set of blocks (3 samples) post-capillary absorption tests [14, 30]. From the results given in Table 7, it can be easily observed that in compressive strength terms, all the blocks tested post-drip scored the highest value in the order of 85.7%, that of the dryly tested blocks covering the remaining 14.3% and the blocks tested after capillary is the least performer as shown also in Figure 3.Hence, it can be deduced that:

The dry, post-drip and post-capillary absorption compressive strength test results with few anomalies are increasing gradually with somehow sustained values for series five (SD5), six (SD6) and seven (SD7). Referring to Figure 4 and taking the compressive strengths of SD6 and SD7 in reference to SD1 (soil only blocks) the increments are: 207% (dry), 28% (post-drip), 6% (post-capillary) and 154% (dry), 63% (post-drip), 53% (post-capillary); respectively. This shows that, the method of amending the specific soil with the given additives has effectively improved, the strength and durability characteristics of the earth based building blocks. In almost all the cases, the blocks tested post-drip have got the highest compressive strength values, while those tested post-capillary absorption have registered the least. The obvious reason for the least compressive strength of the blocks tested post-capillary absorption is the uneven contact surface area with the bottom platen which was not capped for the test. In the case of the blocks tested post-drip, the compressive strength is consistently getting higher and higher. This may be attributed to apparent cohesion [42]. However, since apparent cohesion is an attribute but perhaps not genuine further investigation is required to arrive at a convincing conclusion and repudiate the observed contradiction with the one that is stated in section 5.2.Therefore, the mobilized capillary forces might have given an extra compressive strength to the ACEBs tested post-drip [32, 39, 42].

The drip test (simulates wind driven rain) signifies two scenarios. Scenario one is depth of penetration which varied from 15 mm for series one and two blocks to 10 mm for series six and seven. The second scenario is the moisture permeation over the drip affected area; except for the first series of blocks no such effect was observed. It was only a drip water runoff (in a one or two lines), over the exposed face. At this point it seems quite important to note that the drip duration does not have a significant influence on the drip penetration depth as can be easily observed from Figure 5.

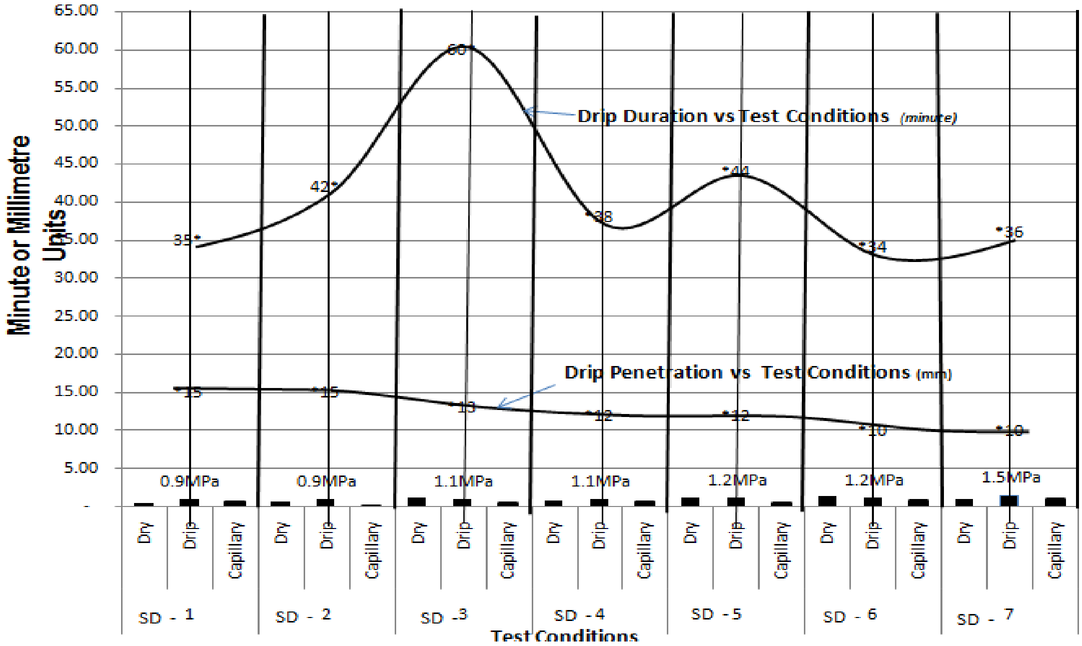

Figure 5: Drip effect on CEB and ACEB units vs. various testing condition

In the capillary (flood simulation) monitoring case, percentage of the absorbed water through the exposed surface area was; 10.4% for series one, 2.6% for series two, 2.4% for series three, 2.1% for series four, 0.4% for series five, 0.6% for series six and 0.7% for series seven (Table 7). Though there are minor anomalies in the progressive improvement of water absorption of the amended compressed earth blocks as in ACEBs of series six (SD6) and seven (SD7), the anticipated positive result is achieved.

To validate the drip and capillary absorption results stated and discussed above which are responsible in reducing the bearing capacity of earthen structures and affect their life expectancy, only the two water erosion effects are dealt with in the current study. Moreover, in conjunction with the above, since rain exposed walls are enduring under wetting and drying cycles such challenges need be dealt with in future researches to ensure sustainability.

In general, referring to international normative of compressed earth blocks, the African Regional Standard Organization (ARSO) [13], has set three mechanical constraint categories for damages inflicted by excessive water absorption. Under the column water absorption percentage, it gives limiting numerical values of ≤ 15% for category one, ≤ 10% for category two and ≤ 5 for category three. Among these, category three is the most stringent; even then, out of the seven series, the six amended compressed earth block (ACEB) types (SD2-SD7) satisfied the requirements of category three by a large margin. The remaining, series one (soil only with 10.4%) block falls under the mechanical constraint of category one; but very close to the border of category two; i.e., 10% < 10.4% <15%. In general, the indication is that amending the given type of soil with the suggested method has proven that the resistance of the blocks to water erosion with respect to capillary absorption action is effectively reduced by an immense proportion. Hence, the produced wall making blocks are resilient to damages inflicted by excessive water absorption; which is a show case for the success of the proposed method of amending natural soils with lime and pozzolans.

CONCLUSIONS

The step by step diagnosis of natural soils, lime and pozzolans aiming at producing building mortar and wall making blocks has proven that both the products are viable for the intended purpose. Starting with the natural soil only ingredient and amending the same with varying doses of raw lime and pozzolan powder in separation and in combination has proven that it is possible to moderate the characteristics of natural soils through an appropriate modification (enhancing the suitability) for earth based construction.

The binding capacity of the mortar was assessed using the crossly jointed brick test (couplet test) method which produced a good result. The Amended Compressed Earth Blocks (ACEBs) were investigated for their compressive strength, durability, such as: erodibility/penetration, capillary absorption and found to fulfill the requirements set in international earth normative of the African Regional Organization for Standardization (ARSO), New Mexico and New Zealand[13, 32, 33].

The conception and developing a home grown method of amending natural soils for the production of compressed blocks and mortar in earthen construction has given a green light for its possible consideration as an alternative local building material.

If the developed technique could withstand the test of time as it did in the laboratory it shall truly be low cost, low energy, affordable, sustainable and eco-friendly popular technology; which can be standardized into the main stream of the local building construction materials. Moreover, the social challenges of accessing affordable and decent shelter shall be mitigated through a continuous culture of material research and development.

RECOMMENDATIONS

Further researches are needed to investigate the increase in compressive strength of theACEBs tested following the drip effect monitoring and relate it to the wetting and drying response of external earthen walls.

Since such researches are influenced by a multitude of factors there is a need of refining the investigation continuously at various locations and localities of the country at large.

A central monitoring and feedback system has to be devised and put in place to develop data base from every point of its experimentation and application.

Standards and relevant guidelines have to be developed for the product and its wider application

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