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Exposure Condition Survey and Measurement of Defects in Compressed Stabilized Earth Block Structures in Uganda

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Abstract
Inadequate provision of shelter remains a global challenge. The high cost of building materials is responsible for this situation. The compressed and stabilised earth block (CSEB) has been promoted as a low cost material. While its other properties are well understood, the behaviour of the material over time has not been properly researched. The principal objective of this research was to investigate their in-service exposure and measure defects in a humid tropical environment. Such areas are characterised by extremes of weather. The soils are also varied. The paper examines the effects of natural exposure conditions on the deterioration of CSEBs. The methodology involved literature review, visual inspection, exposure condition survey, and measurement of defects. It was confirmed that premature deterioration was widespread in exposed structures, with visible defects. The paper recommends an urgent need for improvement in the production and use of CSEBs through dissemination of location specific appropriate specifications, standards and codes. It further proposes the need for improved protective measures in the humid tropics. Additional improvement can be achieved via better inter-granular bonding, reduction in voids, lowered water absorption, and protective designs and specifications. Hence, future challenges can be prevented and the effects of identified deterioration agents minimised.
Keywords: Building Survey, Compressed Stabilised Earth Blocks, Defects, Exposure Condition, Structures

1. Introduction
The performance of CSEBs can be better understood through a combination of theoretical knowledge, study of precedents and assessment of their in-use behavior over a period of time. The experience accrued by their users can also provide further insights. This paper is meant to present and discuss the methods and findings from a study that measured the defects in CSEB structures with prolonged years of exposure in service, to normal environmental or weathering conditions. The causes of the identified defects were investigated and efforts to prevent future occurrences were also explored. The field investigation was undertaken in Uganda. The country was selected for two main reasons: firstly, it's geographic location within the humid tropics, and secondly due to the large stock of CSEB structures found in the country. CSEB structures in this case include: houses, perimeter walling, amphitheaters, experimental walls, and other farm structures. The exposure conditions were considered to be representative of those typically encountered within the humid tropics. Several potential deterioration agents were identified. These included: water, temperature, radiation, wind, air, chemicals, and biological agents. The focus was on CSEB structures of various ages and stages of completion, but preferably above five years in service. The methodology involved: random inspection of existing structures, in-service testing, scrutiny of maintenance records, and other test records. Interviews to gauge the opinions and experiences of randomly selected respondents was also done. The different types of defects observed were recorded. These included; mass loss, cracks, disintegration, surface pitting and roughening, and volumetric changes. Both surface and bulk properties were affected.

This paper is presented in five sections. After this introductory section, the rest of the paper covers the research objectives, methodology, findings and discussions, and conclusion. References are provided at the end of the paper.

2. Research Objectives
The principal objectives of this research were to: (i) investigate the actual in-service exposure conditions of CSEB structures; (ii) identify and measure common and prominent defects resulting from environmental exposure elements over a prolonged period in a humid tropical location. The scope of the study was limited to CSEB structures exceeding five years of in-service use within Uganda.

3. Methodology
Three main methods were used for the survey, namely: documentation review, visual inspection under in-service conditions, and exposure condition measurement of selected defects. All available project documents including original drawings, bills of quantities, standards and specifications were examined prior to undertaking visits to building project sites in Uganda. The focus of this paper is on visual inspection and in-service measurements.

4. Findings and Discussions from the Field Work

4.1 Inventory of CSEB Structures in Uganda

The purpose of seeking information on the inventory of CSEB structures in the country was to obtain an indication of the overall total number of existing units. The same exercise was also used to get information on current building programs and future plans. It was found that since the introduction of CSEB structures in the country in the late 1980s, over 1000 buildings and other structures such as perimeter walls, experimental sections, amphitheaters, etc., have been constructed. The projected housing backlog in Uganda by the year 2000 was estimated at 3 million dwellings. It has since quadrupled. CSEB structures were targeted for the high density, low income urban areas. Other CSEB structures were built in rural areas in the form of public buildings such as health centers, schools, community centers, etc. These were initially built in the central region districts of Kampala, Luweero, Mpigi and Kiboga. There are plans to construct at least 100 CSEB buildings annually over the next few years. The largest single concentrations of CSEB structures in the country are located at: Namuwongo Urban Upgrading Project (central region), and at Masese and Malukhu Housing Estate Projects, both in the eastern regions. These sites were extensively inspected and in-service tests conducted. From various interactions with users, it was found that the demand for CSEB structures is likely to remain very high in the foreseeable future. The rider is that preventive measures be adopted early enough to minimize deterioration and thus prolong their durability in use.

4.2 Characterization of the Natural Exposure Conditions in Uganda

The characterization of the exposure environment in which CSEBs were being used was considered to be a crucial undertaking during the research. The objective was to identify the main naturally occurring agents whose effects were likely to remain deleterious to the CSEB structures over their service lifetime. The approach led to the listing of the different types and ranges of deterioration agents as well as their potential deterioration mechanisms. The highlights of the mode of occurrence of the main deterioration agents (rain, temperature, relative humidity) and the results of the visual inspection of defects were used to produce a provisional severity ranking of deterioration mechanisms. It was found that the type of agent acting on a block and the severity of its actions were closely correlated to the geographic location of the CSEB structure. Moreover, local topography and geographic features were also linked to modification of climate. This includes the micro-climatic level.

The location of the country Uganda has a direct bearing on its overall climatic condition. In terms of macro-climatic and global weather classification, Uganda falls within the Equatorial belt. This humid, tropical belt stretches between 6°N and 6°S. The climatic characteristics of interest to this research are rainfall, wind, humidity and temperature (Spence, 1975; McIllven, 1998). The country is located astride the Equator, lying between latitudes 4°12N and 1°29S, and within longitudes 29°34E and 35°0E. Although the total land area is 241,000 square kilometers, about 20% of it is covered by water bodies (lakes, rivers), and about 30% by forests (UDIH, 2011). Located at the highest altitude in Africa, the elevation above sea level (ASL) varies between 620 meters ASL and 5110 meters ASL. About 85% of the country lies between 900-1500 meters ASL. It was established that these geographic features (water bodies, forest cover, high winds, elevation ASL) did have a considerable influence in modifying the climatic conditions in the country. It was further noted that the use of CSEBs under such unique climatic conditions could present unique challenges. The description of the average climatic conditions in the country would not have been complete without mentioning these geographic features.

4.2.1 Mean Annual Rainfall

The *Mean annual rainfall* in Uganda is an important factor. It was established that the mean annual rainfall was about 1500 mm per annum (UDIH, 2011). The rainfall, which is seasonal, is fairly well distributed throughout the country. Two distinguishable rainfall seasons were recorded; the long rains of March to May, and the short rains of September to November. In analyzing the potential deleterious effects of rainfall on CSEB structures, it was found that the mode of occurrence of the rain within the immediate proximity of the block which was critical. The intensity and duration of the rainfall were established as having direct bearings on the degree and rate of deterioration. The intensity of rainfall in the country, a measure of the quantity of rain falling in a given time, is reported as being greater than 7.5mm/hr. This falls within the classification for heavy rains (>7.5mm/h) as opposed to light rains (<2.5mm/h) or moderate rains (2.5–7.5mm/h) (Blanchard, 1948). The maximum fall of rain in any 24 hours was recorded as 300 mm in Ssesse Islands (UDIH, 2011). The average drop size was found to vary between 0.5mm and 6.0 mm. The duration of rainfall in the country, a measure of the period of time in which it falls, also varied a great deal. Periods of between less than one hour and six hours are reported as being typical (McIllveen, 1998). It is well documented that the higher the intensity of rainfall in the country, the shorter is the duration in which it occurs. It is this intensity-duration relationship that can considerably influence the erosive potential of rain (Evans, 1980). The erosivity of rain can also be determined by the rain drop-size, its distribution, fall velocity and impact kinetic energy (Laws, 1941). As can be expected, an erosive threshold below which no surface erosion will take place ought to exist. A similar approach has been successfully used in soil erosion sciences. It was established that the erosive threshold for loose soil in terms of rainfall intensity was about 25mm/h (Evans, 1980). This is a theoretical cut-off point above which erosion of soil can take place. Since CSEBs are much denser, stronger and more structurally stable than natural soils, the erosive threshold is likely to be several times higher than the 25mm/h suggested for loose and weakly bonded natural soils. Intense rainfall on a CSEB surface is more likely to initially wet the surface and generate surface flow than immediately dislodge material from the block surface. The rainfall characteristics in the country suggest that water-related deterioration of exposed block surfaces is likely to take place repeatedly during the service lifetime of the block.

4.2.2 Ambient Temperature

The ambient temperature in Uganda is high. The average daily ambient temperature was found to be 25°C. The highest mean daily temperature recorded in the country was 35°C. This was in the Karamoja region in the north east of the country. The lowest mean temperature recorded was -5°C. This at the peak of the Ruwenzori Mountains in the west of the country. The sunshine hours in the country average between 8 and 10 hours. The mean total evaporation was recorded as 1950mm. As can be expected these temperature conditions provide the basic setting for temperature-related deterioration to occur in CSEB structures. The presence of large, fresh water bodies in the country such as lakes and rivers and the high temperatures ensure that the level of humidity in the country is also high. Typical ranges for relative humidity were found to be between 30 and 90% depending on the cloud cover. The data presented in this section was considered to be adequate enough to provide sufficient information to link the deterioration of CSEB structures to the most common deterioration agents known. The condition survey that follows describes in more detail the most common types of defects found on exposed CSEB wall structures.

4.3 Visual Inspection of Exposed CSEB Structures

Visual inspection is one way of assessing the performance of CSEBs under natural exposure conditions was selected for several reasons. They include the following: firstly, the CSEB specimens being inspected within the exposed structure are at their 'full scale' during the assessment. This makes it possible to closely examine their current condition on a full scale basis. Any defects due to dimensional changes and the effects of the restraining action of adjacent blocks and mortar can be observed directly. The effect of such restraint is very difficult to accurately simulate experimentally. Secondly, the weathering conditions under which the defects were caused are genuine. Because of this, the full effects of the entire range and distribution of deterioration agents acting on the surface of the structure can be directly observed. A cause-effect link between defect and action of agent(s) can be deduced. Thirdly, through visual inspection, more severe cases of deterioration can be distinguished from less severe ones. Using the severity ranking (defects, agents), further in-service tests and measurements can be recommended based on visual observations. The selection of test types can only follow on from the visual inspection report. This is time and cost saving (BS 7543, 1992; Bungay and Millard, 1996). Fourthly, it is possible to use a number of non-destructive measurement techniques and instruments. Some of the instruments used included: depth gauges, electronic calipers, crack gauges, hand-held microscopes, rulers, set-squares, etc. Fifth, the in-use conditions of the structures being inspected are genuine. All user induced influences on the normal wear and tear of the CSEB structure can be assessed. Six, through the use of a sufficient number of samples, it is possible to reach fairly reliable results and therefore generalize. In this way the interpretation of findings from visual inspection can be considerably facilitated. With the above reasons in mind, a systematic inspection was made of several CSEB structures in Uganda.

The number and types of CSEB structures inspected were varied, all chosen at random. All the five regions of the country were visited: central, southern, western, eastern and northern. CSEB structures had been used for building houses, perimeter walling, amphitheaters, experimental sections, etc. In this way a total of one hundred and twenty CSEB structures were inspected, representing a sample size of about 12% of the officially recorded number of CSEB structures in the country. This is above the 10% minimum normally required statistically for reliable inferences to be made. Using a checklist of all possible types of defects, the average time taken to inspect each structure was about three hours. The inspected structures were of different periods of exposure ranging from five years to those with over twelve years of exposure. The structures were also in various stages of completion: completed or abandoned structures. Buildings found abandoned at wall-plate level and below without roofing appeared to be the most severely damaged. This is equitable to normal experimental exposure situations. It is from such structures that further in-service measurements were made. The measurements included determination of recessed volume of block, width of cracks, degree of pitting and roughening, mass loss, and molding. The line Ministry of Works and Housing provided background information on the period of exposure of each structure, types of constituent materials used and the processing method employed to make the blocks (Robb et al, 2010; AEI, 2011). By compiling the list of defects and comparing the findings with the information obtained on each structure, a number of useful conclusions were made.

The type and range of defects observed from the surveyed CSEB structures inspected were varied. Also evaluated in addition to the type of defects, were the orientation of the façade, section, height or elevation in which they occurred, likely causes, age of structure and frequency with which the defects were observed. Six key points were noted. Firstly, surface erosion, resulting in mass loss, or volume reduction and surface cracking resulting in bond breakage, segregation and disintegration were the two most common defects observed in CSEB structures left exposed to the elements. In the tally of number of structures inspected and frequency with which a particular defect was observed, surface erosion including roughening and pitting, occurred in 75% of all the cases. Surface and bulk cracking occurred in 21% of all cases. Other defects all counted together only occurred in 4% of the structures observed. Secondly, surface erosion occurred more severely on the lower sections of a wall, rather than on the middle and upper sections. The combined effect of direct abrasive action of rainwater, surface run-off and splash from the ground is thought be account for this difference. Thirdly, surface cracking and crazing occurred more on the east-west facing facades than on the north-south facing facades. With the country located astride the Equator, the effect of the direction and period of sustained solar radiation from the east (sunrise) and west (sunset) ought to be taken into account when explaining the difference. Fourthly, cracking of the bulk mostly occurred within the framework of the wall rather than in the corners. The unusually thick and non-uniform mortars used (10mm to 20mm) is believed to be responsible for some of the cracking in the bulk. Mortars are designed to be weaker than the block to allow for flexibility due to dimensional changes. Where the mortar is unnecessarily thick, the restraint on movement can result in enhanced cracking (Neville, 1995; Jackson and Dhir, 1996; Kerali, 2001). Five, the corners of walls were the worst affected. A likely explanation is that at wall corners, rain is able to strike the block from all directions. Moreover, wind velocities are highest at corners. The level of erosion is therefore likely to be higher in such parts of the wall than in others. Finally, defects due to causes other than environmental factors can also occur in CSEBs. These include defects due to overall foundation settlement, biological agents and impact from users. Also, observed were defects related to improper material design, workmanship and processing methods. The results of the visual inspection of exposed CSEB structures confirm that premature deterioration of CSEBs can occur in humid tropical environments.

4.4 In-Service Measurement of Defects

The two most common defect types, namely surface erosion and cracking, were identified for further direct measurement. The measurements included: volume reduction, depth of pitting, and width of cracks. CSEB structures left abandoned at wall-plate level without roofing were also surveyed. Some of the originally abandoned structures were being rebuilt. The sites had been hoarded off. But access was granted. These structures were taken as being representative of the worst case of severe deterioration from long-term exposure. The walls could be equated to similar walls built on normal experimental exposure test sites (BRE, 1980). Lack of protection from environmental elements due to the absence of roof cover and external render meant that the full extent of deterioration from weathering agents could be said to have reached its maximum during the eight and twelve years of exposure respectively. Moreover, the weathering conditions, normal and severe, under which the defects were caused, were all genuine.

4.5 Volume Reduction Estimates of Surface Erosion

Surface erosion leads to irrecoverable mass loss. This in turn results in the reduction of the volume of a block. By measuring the overall depth, width and length of surface material lost due to erosion, the volume of the recessed block surface was determined. By deducting the recessed volume of the block from the original volume, determined from original block dimensions, a volume reduction percentage for each block was obtained. The procedure adopted to obtain the recessed volume for blocks was the same. For each structure, thirty six blocks per building were measured. This total number was arrived at as follows. For each abandoned building, the nine most severely affected blocks per façade (north, east, south, and west) were identified for measurement. The nine blocks on each façade comprised three blocks each from the upper, middle and lower courses of the wall. In this way, not only would any differences in defect severity per façade be obtained, but also differences per section of the wall in which the block was embedded. Where the degree of recession was high, the determination of the recessed volume was easy to measure and calculate. Where loss of mass was spread out on the block, the block surface was divided into four sectors. In each sector, the dimensions of recession were measured, and the total recessed volume obtained by adding up. All measurements were done using an electronic caliper complete with a depth gauge (Mitutoyo brand). This light, hand-held caliper displayed the depth, width and length of eroded surface zones directly on its mini-screen.

From the results, it was confirmed that mass loss resulting in volume reduction does occur when CSEBs are left exposed and unprotected in a humid, tropical environment. The reduction in volume is however not the same for all facades and levels in a wall. The results show that surface erosion varies according to the: (i) elevation of the block within the wall (upper, middle and lower sections) (ii) orientation of the façade (north-south and east-west) (iii) age of the building (period of exposure under similar conditions). The explanation for the above variations are likely to be several as discussed in the following sections.

4.5.1 The Elevation of a Block

The position of a block in a wall, i.e. within the upper, middle or lower section of a wall, can influence the rate of deterioration for several reasons. To begin with, the author was advised by the users and technical staff that most of the surface erosion appeared during the rainy seasons. Very little surface erosion if any occurred during the dry seasons. The main mechanism for surface erosion was therefore rainwater related. In each wall sector, although the amount and intensity of rain striking the wall might be about the same, the overall effect varies. The results show that the reduction in volume is greater at the lower courses of a wall than at the higher ones. For the lower courses, volume reduction percentage for the most severely deteriorated blocks varied between 31% and 39%. Similar values for the upper sections were between 28% and 32%. The amount of surface run-off created by raindrop splash from the upper section of a wall, and from the ground appear to contribute to the higher erosion at the lower wall sections. At the upper wall sector, whereas raindrops may strike the block surface, the surface might not begin to erode immediately. The raindrop striking the surface expends some of its energy in striking the wall and some in creating a splash. It is the splash which then wets the block surface and may also progressively soften it. Erosion is likely to take place after a period of wetting and softening of the surface fabric (Walker, 2004). Meantime, the accumulation of rain splash transformed into surface run-off will flow downwards along the vertical profile of a wall. In the process, the middle and lower sections of the wall, in addition to being struck directly by rain drops from the same storm, will have to contend with the surface flow from the upper sections. The surface flow can increase in momentum and volume, washing away any loose soil particles from the blocks along its path. It is unfortunate that for the lower course blocks, surface erosion can be further increased by back-splash from raindrops striking the apron or ground immediately below it. The combination of direct raindrop impact, spray surface run-off and ground back splash appear to account for the increased severity of surface erosion in the lower courses of a wall than in the higher ones. As can be expected, the effect of raindrop erosion can be considerably increased in storms accompanied by strong winds (>20 m/s). Despite these theories, the mechanism of rain erosion on CSEB structures is not yet well understood. A considerable scope for reappraisal and review still remains. Another key observation made was that the lower corners of walls appeared to be more severely eroded than similar blocks at the same level. The fact that it is only at the corners that rain from all directions can strike the block is thought to account for this variation. More research is needed into this and other phenomena associated with raindrop erosion of block surfaces.

4.5.2 The Orientation of a Wall Façade

Wall orientations were examined in north-south and east-west directions and were found to affect the extent of volume reduction. The highest average volume reduction percentage for east-west facing walls were between 32% and 39% respectively. Corresponding volumes for roofed buildings can be expected to be lower. Whereas several explanations to account for the differences may exist, the most plausible one is likely to be connected to the direction of sunrise (east) and sunset (west). While all facades may experience similar amounts and intensity of rain abrasion, the east-west facades may dry up much faster on the reappearance of the sun soon after the rains stop. The duration of most storms in the humid tropics as mentioned earlier in the paper is short, between 2-6 hours at a time. After such short periods of wetting, the reappearance of the sun can ensure that the wet block surfaces absorb considerable amounts of solar radiation. Absorption of solar radiation causes temperatures of the block surfaces to rise. This warming up effect can cause the block surface to dry up more quickly on the east-west facades than on the north-south facades. This can happen within a matter of only a few hours, causing moisture to evaporate from the wall surface, thus changing the moisture profile in the block. The absorbed radiation can raise the temperature of the block by an amount depending on the specific heat of the block (on average between 0.65 and 1.00 kJ/kg), and on the thermal conductivity of the block (on average between 0.23 and 1.04 W/m°C) (Houben et al, 1994). As both values are positive for CSEBs, thermal expansion and contraction of a block surface can therefore occur with changes in temperature. This is likely to lead to both temporary and permanent alterations in the physical and chemical properties of the block. Surfaces of blocks experiencing such cyclic changes in temperature can ultimately crack. Cracking can then expose the block surface to easy entry of moisture. Moisture within a block is likely to initiate otherwise dormant chemical activity between the constituent materials which make up the material. This phenomenon is also likely to occur in the reverse order of heating and cooling. Before the rainy seasons, sunlight can heat the block surfaces very fast (more on the east-west facades than on the north-south facades). Raindrops striking the already hot block surfaces can apply a severe quenching shock to it. The bonds between the soil particles and OPC hydrates can thus experience their first disruptive action (Baker et al, 1991). This can lead to weakening of the surface fabric thus exposing it to further abrasive attacks from raindrops. Surfaces which are weak can be easier to erode than those which are more intact. The combined cyclic action of wetting-and-drying can progressively lead not only to mass loss, but also to loss of strength, loss of hardness, rigidity and stiffness, as well as loss of appearance (pitting, roughening, cracking, etc.) (ASTM, 1975; Kerali, 2001; Guetala et al, 2006; Deboucha et al, 2010).

4.5.3 The Period of Exposure

Exposure periods corresponding to the age of a CSEB structure were also found to affect the amount of deterioration in the block. The amount of deterioration varied according to the period of exposure, between five and twelve years. The amount of deterioration in five year old structures was markedly less than that in twelve year old ones for each façade and at all wall levels. The highest average volume reduction percentage in the former was 22%, while the corresponding amount for the latter within was 31%. Other factors being constant, the highest estimated annual volume reduction rate was between 2.58% and 2.79% per annum. The difference in the two rates was only 0.21%. This result shows a certain degree of convergence. It can be interpreted to mean that, on the basis of the measurements taken, the highest average rate of volume reduction percent in CSEB structures exposed under similar circumstances can be expected to be less than about 3% per annum. The rate of volume reduction is likely to be influenced by the degree of resistance to surface abrasion that the block can offer. A block surface that is smooth, impermeable, non-reactive and of high inter-granular strength, is likely to offer more resistance to surface erosion than one which is not. The abrasion resistance of block surfaces can be increased in a number of ways. These include the use of surface render, surface coating and surface layering with mixes of higher inter-granular strength. These protective procedures can transform the block surface into a layer of significantly greater wearing resistance. As mentioned earlier in the paper, protection of block surface should remain the main strategy in enhancing its durability. If the block surface is eroded, exposure of its core to similar deleterious action can prove to be more severe since the bulk is its least compacted zone (Houben & Guilaud, 1994). Ways of improving the durability of blocks need to be rigorously investigated experimentally.

4.6 Crack Dimension Measurements

Cracking on CSEB surfaces, sometimes extending deep into the bulk, were commonly observed defects. Classification of the main crack patterns and direct measurement of the most extensive crack widths were done in order to link them to likely deterioration mechanisms and to assess the severity of the phenomena. It is the width of a crack, rather than its length or depth that is commonly measured in like building materials (Neville, 1995; Kerali, 2001). Moreover, maximum permissible crack dimensions are normally specified strictly according to limits based on crack widths. The procedure adopted involved visual identification of three of the most badly affected blocks on each wall façade then measuring their crack widths. The average of the greatest crack widths from each of the three blocks were then determined. To make the measurements, two hand-held crack width measuring instruments were used, namely: an optical crack microscope and a crack comparator scale (Baker et al, 1991; Sjostrom et al, 1996). Both instruments were originally developed for measuring similar cracks in concrete structures. Use of the two instruments side by side did not present any difficulties. The crack microscope used was of the 'ULTRA LOMARA' Mess-Mikroskop make. The instrument powered by a battery, was held against each block surface right over the crack to be measured. The surface was then illuminated by the small internal bulb within the instrument and the magnitude of the crack width measured directly by comparing it against the internal graduated scale that was clearly visible through the eyepiece.

To complement the measurement, the simple hand-held but unmagnified comparator scale was also used for estimating the same crack width. This is sometimes referred to as the crack calculator. The type used was the Colebrand/Abbot Brown crack calculator. The procedure involved is slightly different. To estimate the crack width using this instrument, the comparator was placed directly against the targeted crack on the block. By sliding it upwards or downwards until a comparable thickness was determined, the crack width could then be estimated accordingly. The range of crack widths on the comparator ranged from 0.100 mm to 2.0 mm. Crack widths wider than this maximum value had to be estimated using an electronic caliper whose double tips were inserted between the cracks and extended in opposite directions till firm contact was made. The use of these instruments was found to be necessary because, allowing for human eye variations, the minimum crack width that can be seen by the naked human eye is about 0.13 mm (Neville, 1995). The procedure was laborious and time consuming. It was found that the phenomenon of cracking occurs on all the wall facades of an exposed CSEB structure. The highest mean maximum size crack width measured was 2.9 mm on the east façade of the building. The corresponding lowest mean crack width was 0.65 mm on the north façade. These results compare unfavorably with the maximum permissible crack width limits normally specified for concrete structures (Neville, 1995). The permissible crack width for exterior wall concrete used in normal, and under severe conditions of exposure are given as 0.25 mm and 0.15 mm respectively. The values obtained from the measurements of exposed CSEB walling units (0.65 mm to 2.9 mm) are much higher than the permissible limits for concrete. The comparison will however need to take into account the presence of clay in CSEBs as opposed to concrete where its presence is not allowed. The presence of clay, especially the amount and type, is likely to severely affect the magnitude of cracking in CSEBs (Spence, 1975).

The results also show that cracking is more pronounced on the east-west facades than on the north-south facades. The reasons for the differences were discussed earlier. It should be mentioned here that whereas the kind of cracks measured on a block may simply be symptoms of many causes, the common feature is that they all result from the restraint made on strains. Since stress and strain are supposed to occur together, any restraint of movement can introduce a stress corresponding to the restrained strain. If these stresses and the restrained strain are allowed to develop to the extent that they exceed the strength or strain capacity of the block, then cracking can occur. The diagnosis of the exact cause of cracks in a block might therefore not always be that straightforward. Indeed, cracks can be a result of several causes such as: plastic shrinkage, drying shrinkage (clay and OPC hydrates), chemical action resulting in expanded product formation within the block fabric, settlement of the foundation, improper curing and thermal movement. In summary, whereas a particular cause within or outside the block might be responsible for initiating a crack, its subsequent development and propagation may be due to other causes. The types of cracks observed on CSEB structures were: star shaped, linear, and interconnected. They could therefore have been a result of more than just one cause. Further research is recommended to link particular crack patterns in CSEBs to specific deterioration mechanisms. Limits such as have been specified for concrete should also be set for CSEBs. Such limits should however take into account the presence of clay in CSEBs. The limits can be specified as maximum permissible crack widths for use of CSEBs under normal and severe exposure conditions.

5. Conclusion

CSEBs are likely to remain in great demand in developing countries such as Uganda where the housing backlog is still very high. There is increased use of CSEBs for walling in high density, low income urban and rural areas appears to represent the best way forward in redressing the imbalance of housing backlogs. In humid tropical areas, rainfall and temperature variations can adversely affect the performance of a block exposed to these environmental condition fluctuations. These variations catalyze dormant chemical reactions between the constituent materials forming the block. More research is needed to understand the mechanisms involved, and to explain how individual rainfall parameters such as drop size, drop size distribution, fall velocity and impact kinetic energy, etc., affect the rate of surface deterioration in these types of blocks.

Visual inspection of a sample population of officially documented CSEB structures as well as experimental walls revealed that in the absence or presence of protective render, premature deterioration can take place. The most common defects observed included: surface erosion, surface roughening, surface pitting, detachment of render, surface cracking, surface crazing, bulk cracking, chipped edges and comers, and loose material residuals. Since weathering conditions were genuine and since the blocks were inspected at full scale, a direct link can be said to exist between the symptoms observed and the exposure conditions. Moreover, as a fairly sufficient number of CSEB structures were inspected (more than 12% of the total number). This conclusion is likely to be fairly reliable (cause and effect link). The amount of loose material lost from the original mass of a block was estimated by directly measuring the recessed volume of the material. The loss in volume from unroofed and unrendered blocks over a period of 12 years was about 42%. Losses were higher on the east-west facades than on the north-south facades. Lower courses of walls also experienced more losses than the middle and upper courses of the same wall (about 8-15% more). The increased amount of rainwater and splash experienced by the lower courses, and the increased amount of solar radiation absorbed by east- west facades appear to be responsible for the differences. Surface protection measures are strongly recommended for blocks that are to be used under similar conditions. It was further also found that crack patterns and dimensions followed the above trends. The widest cracks recorded (2.9 mm) were found on the east-west facades of CSEB walls. These cracks are much wider than the normal permissible crack widths in concrete structures. Cracking is undesirable as it makes the block vulnerable to ingress of moisture. The crack patterns observed indicate that drying shrinkage, expanded product formation, thermal expansion and contraction and improper curing can all lead to disruption in bonding. More research is still required to explain the mechanism involved in each of these phenomena. To improve the service life of CSEBs, various surface protection measures were regarded as the most economical way of achieving the goal. Other approaches considered included: improved inter-granular strength, revised specifications, improved dissemination of standards and codes, better architectural design (roof overhang) and better processing methods.

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