EFFECT OF MUNICIPAL SOLID WASTE ASH ON THE STRENGTH OF EARTHEN BRICKS AND WALLS

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Abstract
Masonry units are usually joined using cement mortar. A good bond between the bricks is essential and determines how the masonry units transfer and resist stresses due to applied loads. In this study interlocking brickswere used to construct a wall without the use of cement mortar. The aim of this study was to evaluate the effect of different amounts of Municipal Solid Waste Ash (MSWA) on the strength characteristics of the walls subjected to compressive loads. The soil used for making the bricks was stabilized using MSWA applied at the rate of 0%, 2%, 5% and 10% of the weight of soil. The compressive strength of individual soil bricks moulded in a CINVA-Ram machine was obtained during the curing period and samples were tested on days 7, 14 and 28; after the start of the curing period. Walls, 840 mm high and 1100 mm long, were constructed using the bricks after curing them for 28 days. A compressive force was applied on the masonry walls in a direction normal to joints. Addition of 2% MSWA gave the bricks the highest compressive strength on Day 28. The failure pattern of the wall constructed using bricks stabilized with 2% MSWA followed diagonal cracks and bulging of the wall from the sides. At failure the wall had a maximum crack width of 40 mm and a vertical central deflection of 20 mm at failure. The ultimate stress of the stabilized wall was 2.47N/mm^2 occurring at a strain of 11. On the other hand un-stabilized Juja soil masonry wall had a maximum compressive stress of 2.5 N/mm^{2}occurring at a strain of 9.5. The failure of the un-stabilized Juja soilbrickwall was mainly due to vertical cracks forming below the load application point. For the un-stabilized brick wall, the central deflection at failurewas 14 mm, and was less than the deflection of the stabilized wall at failure. This indicated that the stabilized brick wall was more ductile than the un-stabilized brick wall. Compared to the wall constructed using bricks stabilized with 2% MSWA which had diagonal cracks, the un-stabilized walls had nearly vertical cracks. The failure of the stabilized brick wall was consistent with the provisions of the design code BS 5628 Part 1 of the year 2005.

Key words: Compressive strength, failure mode, interlocking bricks, municipal solid waste ash (MSWA), stabilization

1.0 Introduction

Earth as a building material is affordable and has good insulation and fire resistance properties (Arumala and Gondal 2007). Therefore, it is often used in the rural areas of many developing countries, such as Kenya. Clay bricksare formed by extrusion, moulding or dry-pressing and fired in a kiln at a high temperature (Adam, 2001). This is done to ensure that the bricks are strong and that they do not crumble when wet. Brick baking uses much wood fuel, and is likely to cause environmental deterioration due to excessive tree cutting. As an alternative to baked clay bricks, soil can be stabilizedwith small amounts of cement or lime (Akinola, 1997).

Walker (1995) assessed the influence of soil characteristics and cement content on the physical properties of stabilized soil bricks. He concluded that soils for brick production should have plasticity index between 5 and 15. Soils with higher plasticity index, such as heavy clay soils, are not suitable for stabilization with cement. This is because they tend dry and shrink excessively. The resulting bricks would have low compressive strength and would lack the desired durability.

Since masonry walls are subjected to vertical loads, they must have adequate compressive, tensile, flexural and shear strength. The compressive strength of individual bricks contributes to the ultimate compressive strength of a masonry wall (Hendry, 1990; 1998). Ordinarily, building of walls with bricks requires the use of cement mortar in the joints (Drysdale, *et al,* 1994). The failure of masonry under compression depends on the interaction of the brick and mortar in the joints. The biaxial state of tension-compression stress in brick walls causes micro-cracking and deformation of the wall. It is thatdeformation which leads to failure, causing either tension cracks parallel to the direction of loading or shear failure along some lines of weakness (Berto *et al*, 2005). Since mortar is confined laterally at the brick-mortar interface, shear stresses at the brick-mortar interface result in an internal state of stress and this consists of tri-axial compression in mortar and bilateral tension. This state of stress initiates vertical splitting cracks in bricks that can lead to the failure of the wall (McNary and Abrams, 1985).

To eliminate use of wood fuel during brick making and reduce production of greenhouse gasses, use of interlocking stabilised soil bricks has been suggested (Gordon, 2009). With interlocking bricksit becomes unnecessary to usecement mortar in the joints. The interlocks also increase the structural stability of the wall and reduce the amount of cement needed as mortar.

When well-graded soil is stabilized and adequately cured, this produces strong long-lasting bricks (Ahmed *et al*, 2011) and gives the brick desirable strength characteristics. However, cement and lime which have been used for soil stabilization are expensive and there is need for alternative stabilization agents.

The aim of this study was therefore, to develop an affordable soil stabilization agent. The municipal solid waste ash (MSWA) obtained after incineration of solid waste has pozzolanic characteristics which could be used in the stabilization of clay soils (Berg and Neal, 1998; Lin *et al*, 2003). The predominant chemical constituents of MSWA are lime, silicates and aluminates, all of which are also found in Ordinary Portland Cement. MSWA consists of fine, powdery particles which are predominantly spherical in shape and mostly amorphous in nature. Tay and Cheong (1991) found the compressive strength of concrete mixture containing 10% MSWA, to be higher compared to that of ordinary concrete. Rebeiz, and Mielich (1995) found that municipal solid waste ash could be used as a cement replacement. The objective of this study was to assess the effect of MSWA on the compressive strength of earthen bricks and walls constructed with such bricks.

2.0 Methodology

2.1 Materials Preparation

Sieve analysis for particle size distribution of the soil used in this study was done according to British standards (BS 1377 – 1:1990). The particle size analysis was done not only for Juja soil, but also for Murang'a soil for comparison purposes. The chemical composition of the soil and MSWA was obtained using the X-Ray Diffractogram (XRD) analysis. The mineralogical composition of the soil was established forsoil depths 0 – 20 cm and 20 – 40 cm. The top soil (from a depth of 0 – 20 cm) contained large amounts of organic matter. The bricks analyzed in this study were made using Juja soil from a depth of 20-40 cm.

2.2 Moulding of the Stabilized Interlocking Bricks

The MSWA used in soil stabilization was sieved through a 600 µm sieve. After sieving, soil was mixed with MSWA at the rate of 0%, 2%, 5% and 10% of the weight of soil. Water was then gradually added to the mixture until it had the right consistency ready to mould bricks. Bricks were made using a CINVA-Ram machine. Once the interlocking bricks were extruded, they were placed under a shade and covered to allow for slow drying. The brick size was 230 mm long, 225 mm wide and 130 mm high. Individual brickstrength was determined after curing for 7, 14 and 28 days.

2.3 Determination of the Mechanical Properties of Soilbricks Andwalls

The mechanical properties of thebricks weredetermined in accordance with BS EN 772-1, 2003. Walls were constructed using the guidelines of design code EN 1052-1 of 1999. The wall height was 840 mm and its length was 1100 mm. In one case two walls (two replicates) were constructed using un-stabilized clay bricks and in another case two walls (two replicates) were constructed using bricks stabilized with 2% MSWA. A load was applied on the wall using a load cell (capacity of 50 metric tonne force) and a hydraulic pump (Figure 1). A transducer was used to measure the vertical deflection of the wall anda data logger was used torecordthe ultimate load and the stress-strain relationship of the wall. Crack patternon the failing wall was visually observed.

Figure 1: Typical arrangement of wall model for testing

3.0 Results and Discussion

3.1 Physical and Chemical Characteristics of Juja and Murang'a Soils

Particle size distribution of Juja soil was compared against that of Murang'a soil. Juja soil was uniformly graded while Murang'a soil was gap graded (Figure 2). Murang'a soil had no particles in the range 0.2 – 0.5 µm (Figure 2). According to Smith (1981), gap-graded soils are more compressible. Juja soil had a coefficient of uniformity (C_u) of 5.0 and coefficient of curvature (C_c) of 1.3. Murang'a soil had a coefficient of uniformity (C_u) of 8while the coefficient of curvature was 3.1. The fact that Murang'a soil had a higher C_u than Juja soilsuggests that Murang'a soil had lower plasticity than Juja soil. Plasticity is higher in soils that have high clay content. Murang'a soil was found to have low content of clay particles as compared to Juja soil.

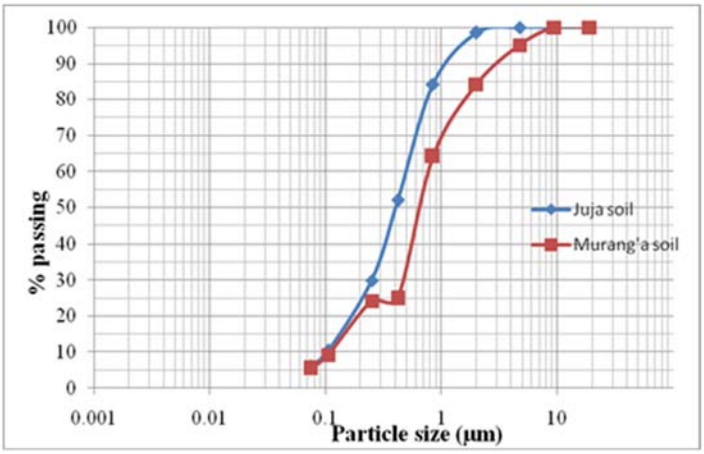

Figure 2: Particle size distribution curves for Juja and Murang'a soils.

The principle constituents ofthe MSWA were calcite (57.6%), quartz (14.1%), microcline (13.2%), aluminium oxide (2%) and iron oxide (1.6%) (Table 1). Alumina and iron oxide can react with calcium hydroxide to form complex compounds (ACI Committee, 2001). The sum total of SiO_2, Al_2O_3, and Fe_2O_3 in MSWA used in this study was less than 70% of the whole sample. Therefore, according to the ASTM C 618 (2003) the ash qualifies for classification as Class F pozzolana. Studies have indicated that addition of a stabilizer containing calcium carbonate helps to bond the clay particles together creating acementitious gel that enhances plasticity to the soil paste (De Silva and Glasser, 1992). The presence of calcium carbonate in MSWA was therefore expected to help in bonding the clay particles of the clay soils. This would increase the compressive strength of the clay bricks moulded from the soil paste.

Table 1: Mineralogical composition of MSWA and soil samples

Mineral	**Mineral composition (%)**		
	Juja (0 – 20 cm)	**Juja (20 – 40 cm)**	**MSWA**
Quartz (SiO_2)	39.7	19.7	14.1
Microcline ($KAlSi_3O_8$)	31.7	17.3	13.2
Montmorillonite	9.4	16.8	-
Geothite ($Fe_3O(OH)$)	19.2	11.3	-
Clinocore	-	26.5	-
Illite	-	8.4	-
Kaolinite	-	-	-
Muscovite	-	-	-
Albite	-	-	-
Calcite ($CaCO_3$)	-	-	57.6
Hematite (Fe_2O_3)	-	-	1.6
Corrundum (Al_2O_3)	-	-	2.0
SiO_2+ Al_2O_3 + Fe_2O_3			17.7

Juja soil at a depth of 20 – 40 cm containedclay minerals: including clinocore, microcline, montimorillonite and illite (Table 1). Clay minerals in soil are likely to react with the pozzolanic constituents in the soil (AASHTO, 1986). Montimorillonite is a clay mineral that can expand several times its original volume when it comes in contact with water. Hilt and Davidson (1960) showed that Montimorilloniteclaysoils retain hydrated lime ($Ca(OH)_2$), far in excess of their cation exchange capacities (CEC), as measured at pH 7. This higher requirement must be satisfied before a long-term pozzolanic reaction can be achieved. As shown in Table 1, the 20 – 40 cm Juja soil layer had about 8.4% Illite and about 16.8% montimorillonite. The presence of these minerals in Juja soil is likely to result in pozzolanic activity and high CEC. According to Grim (1968) as quoted by (WHO, 2005), illite reacts with both inorganic and organic ions providing the additional CEC for the pozzolanic reactions. It should be noted thatkaolinite minerals in clays do not expand when in contact with water and that they reduce absorption of water (Sturz, 1998).

3.2 Compressive Strength Characteristics of Interlocking Clay Bricks

The volume of clay bricks was held constant; hence the weight of the bricks depended on the characteristics of the soil paste used to make them. Compared to bricks made from Juja soilstabilized with 2% MSWA, those made from un-stabilized soil had higher shrinkage and addition of 2% MSWA resulted in heavier bricks (Table 2). The average compressive strength of interlocking bricks from Juja soil stabilized with 2% MSWA was 3.696 N/mm^2 with low variations (Table 2). The addition of more the 2% MSWA reduced the compressive strength of the bricks, but increased brick shrinkage (Figure 3).

Table 2: Properties of interlocking bricks used in the study

Treatment	Properties of bricks used in the study		
	28 day compressive strength (N/mm^2)	Averagebrick weight (kg)	Average shrinkage (%)
Juja soil	2.633±0.34	9.51±0.20	2.80±0.2
Juja soil + 2% MSWA	3.696±0.09	10.10±0.11	1.86±0.05

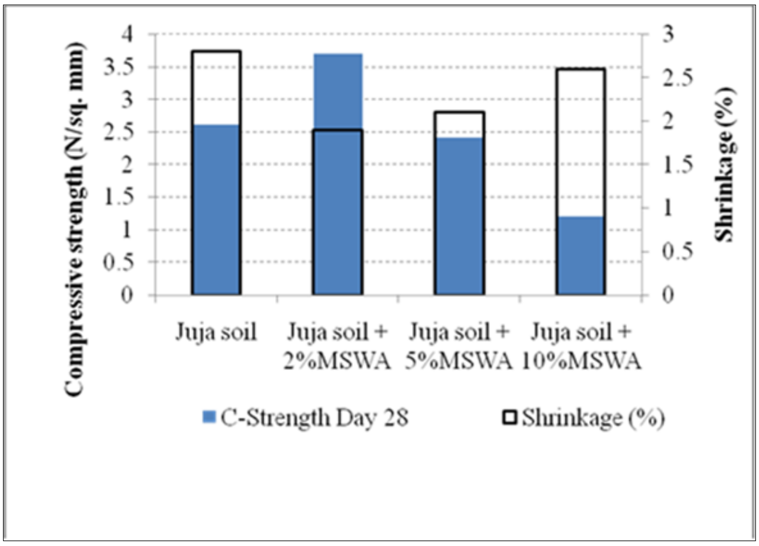

Figure 3: The effect of MSWA on the compressive strength and shrinkage of soil bricks

The compressive strength of clay bricks linearly increased with increasing brick weight (Figure 4). However, shrinkage decreased with increasing brick weight

(Figure 5). Since a dense brick has fewer voids, it is expected that the shrinkage would reduce with increase in brick weight. Soil stabilization causes bonding of soil particles and therefore results in a more densely packed mass of soil. From these results, it appears that brick weight can be used as an indication of the compressive strength of the brick.

According to the Kenyan Design Standard (KS 02-300, 1983), the minimum requirement for compressive strength of internal bricks on the 28th day is 3 N/mm^2. Therefore, the compressive strength for Juja soil bricks stabilized with 2% MSWA was above the minimum requirement.

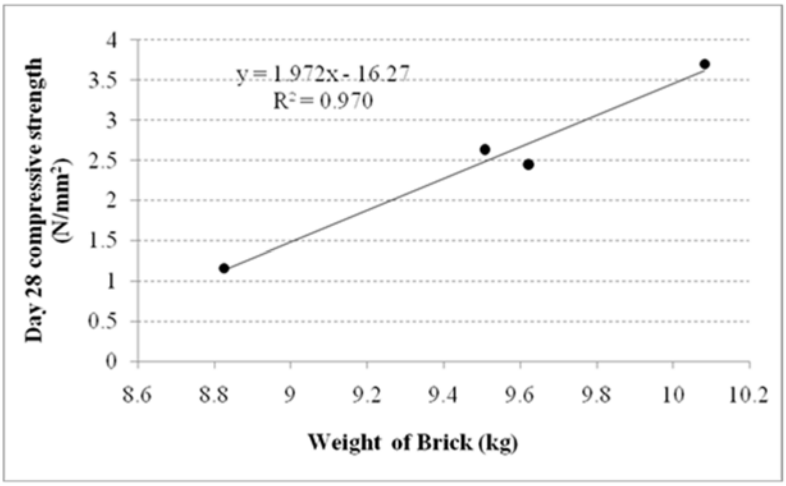

Figure 4: Variation of brick compressive strength with brick weight

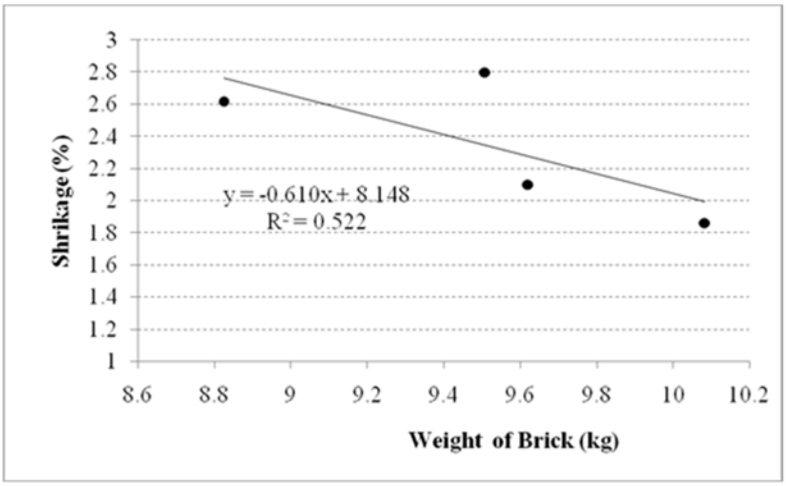

Figure 5: Variation of brick shrinkage with weight of the brick

This study established that during the curing period the bricks gained strength (Figures 6 and 7). This phenomenon was clearest in the case of addition of 2%

MSWA. When more than 2% MSWA was added, this caused the curing effect not to be obvious, and the compressive strength did not seem to change significantly after day 7. This further confirms earlier observation that there exists an optimum amount of pozzolanic material beyond which gain in compressive strength, during the curing period, ceases. Stabilization of Juja soil with 2% MSWA reduced shrinkage by 32% and increased compressive strength by 42%.

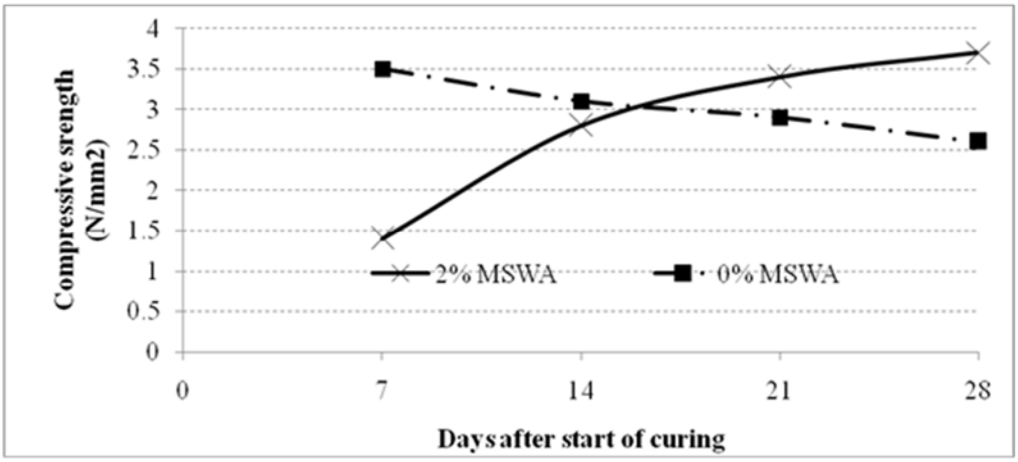

Figure 6: Variation of the compressive strength of clay bricks during the curing period.

After 7 days of curing, un-stabilized Juja soil bricks were strongest, with a compressive strength of 3.5 N/mm^2. However, the strength of un-stabilized bricks reduced with age to a final compressive strength of 2.5 N/mm^2 (Figure 6). According to Okunade (2008) early compressive strength of clay soils is associated with the bonding of clay minerals. However, this strength is not sustained over a long period of time due to weakening of the bonds. Therefore the early strength of un-stabilized Juja soil bricks can be associated with hardening of the soil encouraged by fusion of the clay minerals. Addition of an optimum amount of municipal solid waste ash, in this case 2% MSWA, resulted in a sustained increase in compressive strength during the curing period (Figure 7).

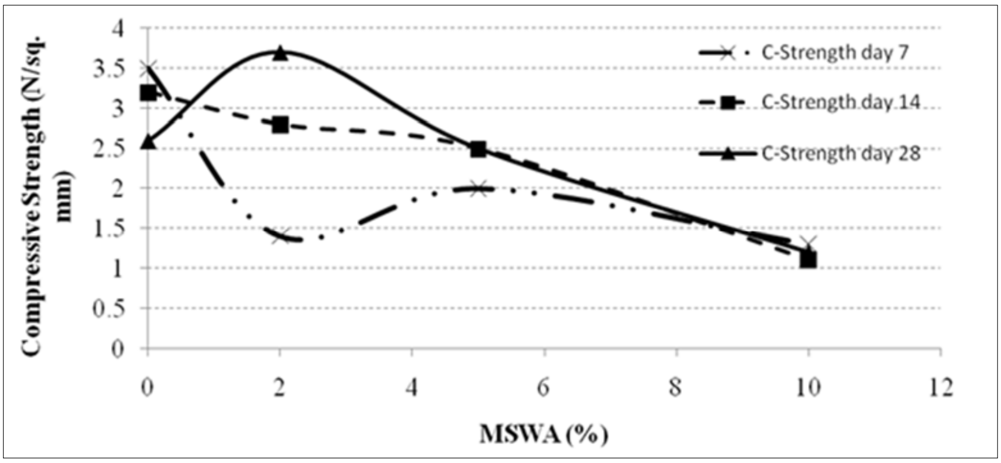

Figure 7: Variation of the compressive strength of clay bricks with the content of stabilizer

Compressive strength of masonry walls constructed using interlocking bricks

As explained in the methodology, walls were constructed based onthe design standard EN 1052-1 of 1999. The wall height was 840 mm and its length was 1100 mm. In one case two walls (two replicates) were constructed using un-stabilized clay bricks and in another case two walls were constructed using bricks stabilized with 2% MSWA. The stress-strain relationship of each wall was also determined. For the wall constructed using bricks stabilized with 2% MSWA the maximum compressive stress on the wall was 2.47 N/mm2, occurring at a strain of 11. On the other hand un-stabilized Juja soil masonry wall had a maximum compressive stress of 2.5 N/mm2occurring at a strain of 9.5 (Figure 8).

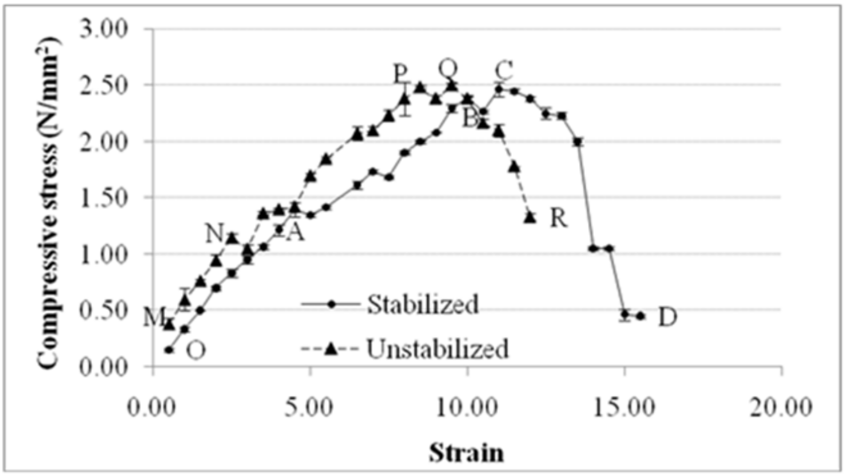

Figure 8: Stress-strain behaviour of 2% MSWA stabilized and un-stabilized soil walls

It was observed that the maximum compressive stress of the walls was lower than that ofthe individual bricks. Hemant et al, (2007) examined the relationship between the compressive strength of a masonry prism and the brick units and concluded that wall prisms have low compressive strength than brick units due to non linearity and composite behaviour of masonry prisms. The current situation is similar to that of Hemant. Our study also suggests that the composite nature of the masonry wall reducesthe ultimate load carrying capacity of the wall.

The stress-strain curve for un-stabilized and stabilized Juja soil wall had three stages (Figure 8). The ascending part of the curve for 2% MSWA stabilized Juja soil masonry wall was found to behave linearly (section OA) up to about half of the ultimate stress. The first crack was observed at point A, where there was a slight fall of stress value. The cracks begun to increase in length, width and number, as the stress increased beyond point A. The wall reached its ultimate stress at point C. Although the wall did not completely collapse, it experienced excessive cracking and bulging at the wall sides and could not support more stress. Point D indicates the total collapse of the wall.

The unstabilized Juja soil masonry wall had its first crack point (point N) occurring at a stress value of 1.15 N/mm2 and a strain of 2.5. This crack occurred at a lower stress than that of the first crack of the stabilized Juja soil wall (1.43 N/mm2). In this study, there was a delayed development of cracks in stabilized Juja soil wall as compared to the un-stabilized wall. This showsthat, the presence of MSWA as a stabilizer increases the ductility of the wall. After attaining the ultimate stress, the stabilized Juja soil wall could not collapse easily as compared to the un-stabilized wall. This was indicated by a short-sharp fall (QR) of the curve for the un-stabilized Juja soil wall. Studies by McNary and Abrams (1985) indicated that the ductility of a wall was negatively affected by the use of strong mortar. Their study showed that wall ductility depends on the strength characteristics of individual bricks. This has been confirmed by the current study.

Failure Mode of Interlocking Soil Brick Wall

The failure mode of the walls was investigated in terms of cracks formation and the vertical deflection. For the 2% MSWA stabilized Juja soil wall, the cracks started directly below the top steel plate (Figure 9a). The cracks propagated diagonally with minor vertical splitting cracks also occurring. Since there was no mortar, the cracks were caused by secondary tensile stresses resulting from the restrained deformation of the frogs in the bed joints of the brick-work. This kind of failure is similar to the normal mode of failure reported by Berto *et al* (2005) for masonry constructed using weaker mortar. The maximum crack width at failure was 40 mm wide while the vertical deflection of the wall was 20 mm (Table 3).

Figure 9: (a) Failure of 2% MSWA stabilized brick wall *(b) Failure of un-stabilized brick wall*

Table 3: Properties of the experimental model walls

Masonry wall type	Maximum vertical deflection (mm) at failure	Maximum crack width (mm) at failure	Crack propagation
2% MSWA + Juja soil	20	40	Diagonal
Unstabilized Juja soil	14	50	Vertical

The failure of un-stabilized Juja soil masonry wall was initiated by vertical cracks directly below the load application point (Figure 9b). The cracks propagated vertically below the wall face. When the ultimate stress was reached, the wall bulged from the edges and created disjoints in the interlocking bricks. This could have beendue to high stiffness of the un-stabilized bricks that tend to reduce the lateral strains in the wall leading to a state of tri-axial compressionin the wall. Vertical splitting of the wall can be attributed to the phenomenon of shear failure which can be found in compression of brittle materials (Vonk, 1992). This failure mode indicated that the un-stabilized Juja soil bricks are brittle and when utilised in masonry, their crack development is faster than for Juja soil bricks stabilized the MSWA.

The effect of MSWA on the compressive strength behaviour of masonry wall and the bricks was considered with its contribution of the pozzolanic reaction. The pozzolanic reaction allows a gradual development of strength by cementing the clay particles together. The reaction occurs when calcium oxide (CaO), reacts with silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) to produce a stable calcium silicate and calcium aluminium hydrate. Since there was gain of compressive strength of the stabilized individual bricks from Day 7 to Day 28, it shows that MSWA introduced a pozzolanic reaction. The adding of MSWA as a stabilizer contributed to chemical activity and micro-filler effect in the soil. The MSWA could have enabled formation of solid skeleton from calcium silicate hydrate and formed a cementitious matrix in reacting with active clay minerals. This matrix allowed strain ductility in the masonry wall thus delaying the development and propagation of shear cracks. This enabled the stabilized Juja soil brickwall to behave more ductile as compared to the un-stabilized.

The elimination of mortar in interlocking bricks made the failure not to depend on the weak bonds but on the characteristic of individual bricks. However, in both masonry wall the ultimate failure load was low than for the individual stabilized bricks. Since the bed joints, because of their continuous nature, divide the wall into layers of equal thickness, this gave the masonry the appearance of a laminated composite material (Asteris and Syrmakezis, 2005). Therefore during transfer of the load, the bearing capacity of the wall was reduced as compared to that of an individual brick.

4.0 Conclusion

The effect of MSWA on the compressive strength and failure characteristic of a masonry wall has been discussed. From this study the following conclusions were made:

(i) The sum total of SiO_2, Al_2O_3, and Fe_2O_3 in MSWA is less than 70% of the whole sample. Therefore, according to the ASTM C 618 (2003) the ash qualifies for classification as Class F pozzolana.

(ii) The optimum amount of MSWA replacement in clay soil was 2% of the whole weight of soil, beyond which gain in compressive strength, during the curing period, ceased.

(iii) Stabilization of Juja soil with 2% MSWA reduced shrinkage of bricks by 32% and increased the compressive strength by 42%.

(iv) Addition of an optimum amount of municipal solid waste ash (2% MSWA) resulted in a sustained increase in compressive strength during the curing period. Without the addition of a stabilizing agent, no gain in strength was observed during curing.

(v) While a wall constructed using stabilized bricks could sustain a maximum strain of 15, a wall constructed using un-stabilized bricks could sustain a maximum strain of 12.

(vi) Un-stabilized Juja soil bricks were brittle and when utilised in masonry, their crack development was faster than for Juja soil bricks which were stabilized using MSWA.

(vii) The ultimate compressive strength of 2% MSWA stabilized brick wall was almost equal to that of un-stabilized masonry, however, the compressive strength of individual brick units is higher than for the walls. The stabilized soil brick wall carried almost half its ultimate stress even after development of the first crack.

(viii) While the un-stabilized walls had nearly vertical cracks, the failure of 2% MSWA stabilized soil brick wall was ductile and its cracks propagated diagonally at an angle of45° from the point of load application. This type of failure was consistent with the provision of the design code BS 5628 Part 1 of the year 2005. Therefore, this design code can also be used in the design of MSWA stabilized brick walls.

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