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Studies on Uniaxial Compressive Strength of Laterite Masonry Prisms

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Abstract: Laterite is a well known conventional building material in Asian countries. In spite of its large popularity in construction, a systematic characterization of this material, as a building block, has not been seriously attempted so far. The strength and elastic properties of laterite masonry are influenced by the individual properties of the laterite blocks and the mortar. In the present study, characterization of the laterite block and the mortar and compressive strength of laterite masonry prisms have been investigated using detailed laboratory experiments and numerical analysis. The experimental results, related to the compressive strength and stress-strain characteristics of laterite and mortar and compressive strength of laterite masonry prisms are presented. Finite element analysis of laterite masonry prism has also been carried out. The studies have shown that the modulus of elasticity of laterite blocks tested is less than that of mortar used in making the laterite masonry. Further, the laterite masonry prisms have been observed to have failed by bond failure and subsequent splitting of laterite blocks. Also, increase in thickness of mortar joint gives rise to a decrease in laterite tensile stresses in mortar joint leading to higher prism strengths, if bond remains intact.

Keywords: *Masonry, Laterite, Cement Mortar, Compressive Strength, Modulus of Elasticity, Finite element modeling.*

List of symbols:

E_{lt} - modulus of elasticity of laterite
E_m - modulus of elasticity of mortar
ν_{lt} - Poisson's ratio of laterite
ν_m - Poisson's ratio of mortar
p_y - applied pressure in vertical direction
σ_1 - first principal stress

Introduction:

Laterite is a prime masonry material for housing construction in western coastal areas of India. Laterite stone blocks are being used as masonry material for housing construction in this area, for ages. Laterite is used in its natural form without any manufacturing process and hence proves a sustainable material. The term laterite was first proposed by Buchanan to describe the reddish ferruginous, vesicular, unstratified and porous material with yellow ochres occurring extensively in Malabar, India [Gidigasu (1974)]. The freshly dug material was soft enough to be cut into brick-like blocks with iron instruments but rapidly hardened on exposure to air and was fairly resistant to the weathering effects. This material was locally used as building blocks and was hence called "laterite" derived from the Latin word "later" meaning brick [Gidigasu M.D (1974)]. Laterite is a surface formation in hot and wet tropical areas which is rich in iron and aluminium. It develops by intensive and long-lasting weathering of the underlying parent rock. Laterite cannot be placed in the triplet family of rocks, namely igneous, sedimentary or metamorphic. It may be considered to be a metasomatic rock [Kasthurba et al. (2007)]. Metasomatism is a metamorphic process by which the chemical composition of a rock or rock portion is altered in a pervasive manner and which involves the introduction and/or removal of chemical components as a result of the interaction of the rock with aqueous fluids (solutions). During metasomatism, the rock remains in a solid state [Zharikov, et al. (2007)]. In India, Laterites are found in the states of Kerala, Karnataka, Goa, Maharashtra, Tamil Nadu, Andhra Pradesh, Orissa, Bihar, Assam and Meghalaya. They are mainly used as building blocks for construction of masonry in buildings [IS 3620-1979]. In spite of widespread use of laterite in buildings, no systematic research study has been undertaken on the engineering properties, particularly the strength and durability aspects [Kasturba A.K (2005-a)] of them.

Literature Review:

Kasthurba et al. (2005-b) carried out a detailed study of laterite building stones from four major quarries in widely scattered locations of Malabar region, Kerala. The compressive strength of laterite blocks were evaluated according to Indian standard specifications. According to this study, the strength values of laterites depend on the specimen size and its geometry. Also, the decrease in the size of cube specimens is accompanied by increase in the compressive strength, as in concrete cubes. In the reported results, compressive strength of most of the specimens tested were below 3.5 MPa, which is the prescribed minimum for use in laterite stone masonry, as per IS 3620-1979. Since the local practitioners vouch for the good quality of these laterites from the local quarries, this study has suggested a relook into the codal provisions. It has also been suggested that the strength evaluation of laterite be carried out on standard size blocks, used for masonry, like in the case of bricks and hollow blocks, instead of cubes. Kasthurba et al. (2006-a) evaluated laterite blocks based on their performance in traditional buildings and also by determining engineering properties of fresh laterite from widely located quarries within Malabar region, Kerala. There is a wide variation in the experimental results of compressive strength (1.3 MPa - 4.3 MPa) of commercially available, machine-cut laterites from Malabar region. From a comparison of wet and dry strengths, it is observed that there is a significant reduction in strength (47-75%) due to saturation. Hence, it is suggested that laterite masonry is to be protected from dampness. Kasthurba et al. (2006-b) studied the weathering forms and properties of laterite building stones used in historic monuments of Western India. This study found that the deterioration of laterite masonry may be caused due to a variety of causes. They have identified dampness as a major factor which induces deterioration and hence protection from dampness would prolong the life of laterite monuments. Kasthurba et al. (2007) investigated laterite stones used for building purpose from Malabar region of Kerala state in India. According to their study, laterite stones show a wide variation in their engineering properties depending on the geographic location of the quarry and within a quarry, with depth. It was noted that specific gravity and compressive strength decrease with depth whereas water absorption increases with depth, which results in a decline in quality of laterite blocks of the deeper layers. Also it was observed that, laterite stones with dark reddish brown to red colour, taken from top portion of the profile, generally possess better strength, higher specific gravity and lower water absorption and hence are good for building purposes. McNary W. Scott and Daniel P Abrams (1985) investigated strength and deformation of clay-unit masonry under a uniaxial concentric compressive force. Biaxial tension-compression tests of bricks and triaxial compression tests of mortar were also done for various brick types and mortar strength. This study considers soft cement-lime mortar and stiff fired-clay bricks. Shear stresses at the brick mortar interface result in an internal state of stress which consists of triaxial compression in the mortar and bilateral tension coupled with axial compression in the brick. This stress state initiates vertical splitting cracks that lead to failure. Again measured properties of brick and mortar were used as input to a numerical model. The prism strengths and deformations calculated using this model were then compared with experimental results to verify the theory. Although failure of prism occurred as a result of lateral tensile splitting of masonry unit, it was the mortar that induced the tensile stresses. These stresses increased disproportionately with compressive forces because of the nonlinear deformational properties of the mortar. Prism strength was also dependent on the strength of the masonry units which are under bi-axial tensile and uniaxial compressive stresses. Felix (1999) studied the compressive strength and modulus of elasticity of masonry prisms by computer simulation and laboratory testing of masonry units, mortars and prisms. Low and high strength masonry units (30 -100 MPa) in combination with low and high strength mortar mixes (2 -15 MPa), in different combinations were tested. But in all the cases, units were much stronger than mortar, which is generally the case in western countries. During the numerical simulations, when Poisson's ratio of the masonry unit was reduced, without changing the other parameters, the tensile stress of the elements in the masonry unit in the horizontal directions, increased. The higher the difference of Poisson's ratios between the masonry unit and the mortar, the faster the prisms fail. Similar is the case with modulus of elasticity: the higher the relative difference, the higher the tensile stress in the masonry unit and lower the prism strength. The computer simulations identified the interface of the mortar and the unit as the most critical area. Again it is found that modulus of elasticity of prisms is mainly controlled by the properties of the masonry unit. Jahangir Bakhteri et al. (2004) numerically verified the results of experimental investigations on the effect of mortar joint thickness on compressive strength characteristics of axially loaded brick-mortar prisms. Micro-modeling with two different material assumptions was attempted. In one, both phases of the materials are replaced with an equivalent homogeneous material with derived elastic properties and the other treats the masonry as a composite material consisting of the brick and the mortar. Composite material model gave more accurate prediction of the stress distribution in the prisms and hence this model is more appropriate than the homogeneous material model. FEM model with mechanical properties taken from the experimental study led to large discrepancies between experimental and FEM results, confirming that the properties of mortar inside the joints are different from the properties of mortar cubes. Even after correcting such material properties, there were differences between the experimental and numerical results. Therefore, to get the actual compressive design strength of brick masonry, the finite element analysis results had to be enhanced by a factor of 1.5. Sarangapani et al. (2005) conducted a series of tests on masonry prisms constructed with very soft bricks (modulus of elasticity ~ 500 MPa) and different mortar grades. It was observed that for the soft brick-stiff mortar masonry, the compressive strength of masonry increases with, increase in the bond strength. It was also observed that unlike in western countries, here, elastic modulus of mortar is an order of magnitude larger than those of the bricks used. For soft brick-stiff mortar, the brick will be in triaxial compression while the mortar will be in biaxial tension and uniaxial compression. In the event of bond failure at the brick-mortar interface, the horizontal compression induced by the shear stresses will vanish and the brick will fail by lateral tension. Thus, one of the failure mechanisms in soft brick-stiff mortar masonry is dependent on the shear-bond strength of the brick-mortar interface. Hemanth B Kaushik et al. (2007-a) observed from experimental results that the modulus of elasticity of masonry varies between 250 and 1100 times the prism strength of masonry. The compressive strength of masonry was found to increase with the compressive strength of bricks and mortar. The trend was more prominent in case of masonry constructed with weaker mortar. Hemanth B Kaushik et al. (2007-b) have studied stress strain characteristics of clay brick masonry under uniaxial compression. Using linear regression analysis, a simple analytical model has been proposed for obtaining the stress-strain curves for the masonry. During compression of masonry prisms constructed with stronger and stiffer bricks, mortar of the bed joints are in triaxial compression and the bricks are in bilateral tension coupled with axial compression. Modulus of elasticity of brick, mortar and masonry are given in terms of their compressive strength. Gumaste et al. (2007) studied the properties of brick masonry using table-moulded and wire-cut bricks of India with various types of mortars. The strength and elastic modulus of brick masonry under compression were evaluated for stiff-brick/soft-mortar and soft–brick/stiff-mortar combinations. Both, prisms and wallettes were studied. In western countries, brick masonry generally consists of bricks, which are strong and stiff compared to the mortar adopted. Such bricks are found to have compressive strengths in the range of 15-150 MPa and elastic moduli anywhere between 3500 and 34000 MPa. On the contrary, bricks of India show relatively lower strengths (3-20 MPa) and elastic moduli (300-15000 MPa). The state of stress developed in brick and mortar components of masonry depends on their relative elastic properties. When bricks are relatively softer than mortar, if the brick-mortar interface bond remains intact until the failure of masonry, the brick will be under triaxial compression and mortar will be under uniaxial compression and bilateral tension. In such a scenario, the failure of masonry is initiated by the tensile splitting of the mortar in the joint. The mortar failure will then extend to the brick causing masonry failure. Three more mechanisms are also possible:

1. if the brick-mortar interface fails in shear due to loss of bond, the lateral compression in the brick will vanish and the brick will fail by tensile splitting.
2. if one of the brick is relatively very weak (due to large coefficient of variation), it can also fail by crushing ahead of the splitting failure of other bricks.
3. in the case of masonry walls, mortar in the vertical joint can cause splitting failure in the brick below, since the stress in the mortar is much higher because of its greater stiffness.

Venkatarama Reddy B.V et al. (2009) studied the influence of bed-joint thickness and elastic properties of the soil-cement blocks and the mortar on the strength and deformation behavior of soil-cement block masonry prisms. Masonry compressive strength was found to be sensitive to the ratio of modulus of block to that of the mortar (E_b/E_m) and masonry compressive strength decreases as the mortar joint thickness is increased for the case where the ratio of block to mortar modulus is more than 1. Again the lateral tensile stresses developed in the masonry unit are sensitive to the E_b/E_m ratio and the Poisson's ratios of mortar and the masonry units.

Experimental Investigations:

Compressive Strength of Laterite Stone Blocks:

Compressive strength of laterite block was determined as per guidelines of the Indian standard code IS 3620-1979 and IS 1121(Part 1)-1974, which recommends testing of 50mm cubes. But it is difficult to cut laterite into 50 mm cubes. Moreover, the strength of laterite blocks of size as used in masonry construction are required and hence, blocks of such size were tested in this study. Laterite blocks, from three different quarries of Mangalore region of Karnataka state, have been tested. As prescribed in the code, the two faces of the laterite block were capped using cement mortar. Before testing, the blocks are immersed in water for 72 hours and tested in saturated condition. The blocks were subjected to uniform compressive loading in a compression testing machine. Fig.1 shows the laterite block capped with cement mortar and Fig.2 shows the failure pattern after testing the block in compression. The test results are shown in Table 1. As observed by Kasturba et al. (2007), there can be a large variation in compressive strengths of laterites from quarry to quarry. In the present investigation, the average compressive strength of laterite blocks varied from 2.07 MPa to 4.58 MPa. The minimum compressive strength specified for laterites for use in masonry, by IS: 3620-1979 is 3.5 MPa. The compressive strengths of commercially available machine cut laterite from Malabar region are in the range 1.3-4.3 MPa [Kasturba et al. 2006-a]. In case of masonry materials, a decrease in specimen size is normally accompanied with an increase in the compressive strength [Kasturba 2005-a]. Manu et al. (2009) have reported that laterite blocks used in masonry construction in most parts of Ghana, generally have, compressive strengths in the range of 3.1 MPa to 17.2 MPa. Thus it can be stated that, the values of compressive strength of laterite blocks tested herein are comparable to values reported by other investigators.

Modulus of Elasticity of Laterite:

Modulus of elasticity of building blocks is normally not tested. But modulus of elasticity would be required in finite element modeling and hence, an attempt is made in this study, to find the modulus of elasticity of laterite blocks. For testing of modulus of elasticity, blocks of size as used in construction practice, were selected from the 1st quarry, as they have a higher compressive strength. 6 laterite blocks, were immersed in water for 72 hours, taken out and were tested in a compression testing machine in saturated condition. Strains were measured using a demec gauge of gauge length 100mm and of accuracy 0.002m/m [Fig.3]. Graphs were plotted using noted stress strain data. The stress-strain variations for minimum and maximum moduli are as shown in Fig.4. Secant modulus calculated at 30% of ultimate stress, is considered as the modulus of elasticity of the block. It was observed that the elastic modulus of laterite blocks varies from 749 MPa to 1240 MPa.

Compressive Strength of Cement Mortar Cubes:

Generally, 1:6 cement mortar is used for laterite masonry construction, in south-western coastal belt of India. Hence this type of cement mortar was selected for this study. Ordinary Portland cement (43 grade) and river sand was used for the preparation of mortar mixes. Compressive strength of the mortar was determined by testing 70mm cubes, according to IS: 2250-1981. Compressive strength of mortar depends on the water cement ratio and cement content. Code specifies quantity of water as that required for working consistency. Working consistency of the mortar is usually judged by the mason during its application. Water should be enough to maintain the fluidity of the mortar during application, but at the same time it shall not be excessive [IS: 2250-1981]. In this study water cement ratio was maintained at 0.8 and cement to sand ratio at 1:6. Testing of the mortar specimen in a compression testing machine is illustrated in Fig. 5. The results obtained during compression tests of mortar cubes are shown in Table 2. In the present investigation, the average 28 day compressive strength of 1:6 cement mortar with water cement ratio 0.8 was obtained as 7.33 MPa and the average density 2179.78 Kg/m^3. Sarangapani et al. (2005) have reported compressive strength of similar cubes with water cement ratio 0.8 as 7.32 MPa. Hemanth B Kaushik et al. (2007) have reported 28 day compressive strength of 1:6 cement mortars with water cement ratio 0.7 to 0.8 as 3.1 MPa. Gumaste et al. (2007) have reported 28 day compressive strength of 1:6 cement mortar cubes (70 mm) with water cement ratio of 1.1 as 6.6 MPa and 28 day compressive strength of 150 mm x 150 mm x 300 mm prisms as 5.14 MPa. Prajwal Lal Pradhan et al. (2009) have reported ultimate strength of 1:6 cement mortar with 0.7 water-cement ratio as 4.06 MPa. Again it can be seen that large variations can exist between the compressive strength of mortar depending on proportions, water-cement ratio, age, size and shape of the specimens.

Modulus of Elasticity of Cement Mortar:

Mortar cylinders of size 15 cm diameter and 30 cm length were cast with cement (Ordinary Portland cement 43 grade) and sand (river sand) in the ratio 1:6 and with water to cement ratio 0.8. After keeping it immersed in water for 28 days, they were taken out and tested in saturated surface dry condition in a compression testing machine. Modulus of elasticity was determined by applying a gradually increasing axial compressive load to the mortar cylinder and measuring the compression at different load levels. A compressometer with gauge length of 200 mm was fixed to measure the axial compression and hence the strain. With the help of these readings stress strain graphs were plotted [Fig.6], from which modulus of elasticity was obtained. Modulus of elasticity was calculated from the stress strain curves by measuring the slope of secant at 25% of ultimate stress. Sarangapani et al. (2005)

have reported secant modulus at 25% of ultimate stress of 1:6 cement mortar with water cement ratio of 0.8 as 5766 MPa, while Gumaste et al. (2007) have reported such modulus with water cement ratio 1.1 as 8568 MPa, both using 150 mm x 150 mm x 300mm prisms. Hemanth B Kaushik et al. (2007) have reported average secant modulus considering chord joining ordinates at 5% and 33% of ultimate stress, of 1:6 cement mortar with water cement ratio of 0.7 to 0.8 as 545 MPa. Prajwal Lal Pradhan et al. (2009) have reported, modulus of elasticity of similar mortar with water cement ratio 0.7 as 2616 MPa and Poisson's ratio at 0.14. Thus literature reveals a wide variation in modulus of elasticity [545 MPa to 8568 MPa]. In the present investigation average elastic modulus, evaluated as secant modulus at 25% of ultimate stress, of 1:6 cement mortars with water cement ratio 0.8, has been obtained as 2879 MPa. Again for finite element modeling, in this study, modulus of elasticity of mortar has been taken as 3000 MPa.

Compressive Strength of Laterite Masonry Prisms:

Compressive strength of laterite masonry was determined by testing stack-bonded prisms as per guidelines of IS: 1905-1987. Laterite blocks from 3 quarries were tested for compressive strength and the best quality ones, i.e., from the 1st quarry were selected for prism testing. IS: 1905-1987 suggests testing of masonry prisms of minimum height 400 mm with height/thickness (h/t) ratio between 2 and 5 for determining the compressive strength of the masonry. Five-block high, stack-bonded, laterite masonry prisms were cast using laterite blocks of size 360 x 220 x 170 mm in 1:6 cement mortar. Ordinary Portland cement (43 grade) and river sand were used for the preparation of mortar mixes. The prisms were capped with the same mortar in order to get a level surface (Fig. 7). The prisms were cured for a period of 7-days and 28-days and tested in wet condition. Joint thicknesses were maintained at 10mm as recommended in SP 20-1991. A steel plate of 10 mm thickness was kept on top of the prism to distribute the load. An axial compressive load was applied through a hydraulic jack and measured with a proving ring. Table 3 gives the compressive strength of the prisms tested. Fig.8 shows the typical failure patterns of laterite masonry prisms. Failure was observed to be due to bond failure and vertical splitting of the laterite block. During the present investigation, masonry prisms were tested 7 days and 28 days after casting. Significant strength improvement has not been observed from 7 days to 28 days. This could be because laterite is weaker than mortar and the failure of prism occurred by the failure of laterite blocks. Average compressive strength of laterite prisms tested is 1.24 MPa and the ratio of compressive strength of masonry prism to that of laterite block is 0.27. It has been observed that for compressive load acting normal to bed joints, the failure primarily occurred by vertical tensile splitting of the blocks. Even though the block compressive strength is lower than the mortar compressive strength, with the compressive stress at failure being much lower than the compressive strength of the laterite blocks, failure has not been due to crushing of the blocks. Uniaxial compressive testing of laterite masonry prism has shown bond failure along with splitting of blocks, in all the prisms tested herein. Gumaste et al. (2007) have studied the bond strength of brick (modulus ~ 500 MPa) with 1:6 cement mortar and have reported that failure of prism is by bond failure. The failure of masonry is initiated by the tensile splitting of the mortar in the joint, if the brick mortar bond is intact. The mortar failure will then extend to the brick causing masonry failure. On the other hand, if the brick-mortar interface fails in shear due to loss of bond, the lateral compression in the bricks will vanish and the bricks will fail by tensile splitting. Bond between mortar and masonry unit is thus more important, in this case, than compressive strength of mortar. Use of composite cement-lime mortar, because of its better bond strength, gives a stronger masonry than that with plain cement mortar, even though plain cement mortar may have a higher compressive strength [SP 20-1991].

Finite Element Analysis of Laterite Masonry Prism:

There are different approaches to numerically simulate the behaviour of masonry structures. They are:

1. macro modeling- masonry is assumed as an equivalent homogenous material. This method is suitable for studying large size structures.
2. smear line element- horizontal and vertical mortar joints are represented by line elements. This method is suitable for studying individual elements of the structure.
3. micro modeling- masonry unit and mortar are defined separately with individual properties. This method provides more accuracy and hence is suitable for the modeling of the masonry prisms.

In the present study, a five blocks-high stack-bonded laterite masonry prism has been modeled using micro modeling approach with ANSYS software. The prism size of 360 mm x 220 mm x 890 mm, made up of, 5 laterite blocks of size 360 mm x 220 mm x 170 mm and 4 mortar joints of 360 mm x 220 mm x 10 mm, has been considered. The blocks and joints were modeled using solid- 45 elements, available in ANSYS software which has eight nodes each, with three degrees of freedom; translations in the nodal x-, y- and z-directions. A linear elastic analysis has been carried out to understand the nature and distribution of stresses in the laterite block and mortar joint.

Modulus of elasticity of laterite and mortar determined experimentally were given as input in the analysis. Poisson's ratios of laterite and mortar were assumed. The block and the joint were modeled by micro-modeling approach, assuming a perfect bond between them. With the data sets employed, analyses results have shown that under uniaxial compressive load, laterite blocks are in triaxial compression and mortar joints are in uniaxial compression and bilateral tension as shown in Fig.9. There being a difference in stiffness between the two materials, i.e., laterite and mortar, for strain compatibility at the interface, with a good bonding between the two materials, the stiff mortar will try to pull the soft laterite inwards. In the event of bond failure at the brick-mortar interface, the horizontal compression induced by the shear stresses will vanish and the brick will fail by lateral tension [Sarangapani 2005]. Literature review shows a large variation in the values of elastic modulus of 1:6 cement mortars, even in the Indian context [545 MPa to 8568 MPa]. According to the present investigation the value obtained is 2879 MPa. These values of modulus of elasticity go as an input into the finite element model. Incorporating such large variation in values of modulus of elasticity of mortar will definitely have an effect on the results of finite element analysis. Hence an extensive parametric study is required to understand the effect of this parameter on the state of stresses in the laterite masonry prism and possible prediction of failure. Studies have shown that [Felix 1999], more than the individual values of modulus of elasticity of the block and the mortar, it is the ratio of modulus of elasticity of the block to that of the mortar which plays a major role.

Parametric Studies:

In order to understand the influence of different factors on the laterite masonry prism strength, simulations were conducted by varying certain parameters. When one parameter was varied, all other parameters were kept unchanged. Table 4 gives the reference and range of values of different parameters considered. It is difficult to do such a study experimentally. Moreover, stress distribution can also be obtained from analytical results.

Poisson's Ratios of Laterite and Mortar:

Poisson's ratios of the masonry unit and the mortar are not normally tested for and reported in the traditional compressive testing, but are important in computer simulation as they influence the lateral expansion of the masonry unit and the mortar under compressive loading [Felix 1999]. The effects of varied Poisson's ratios of laterite block and mortar have been investigated and the results are plotted. In the first analysis, modulus of elasticity of laterite and mortar were taken as 1300 MPa and 3000 MPa respectively and the Poisson's ratios of laterite and mortar as 0.15. The thickness of mortar joints was taken as 10mm. Fig. 10 shows the maximum principal stress (lateral tensile) in mortar joint, for a vertically applied pressure of 2 MPa on the laterite masonry prism, as 381713 N/m^2 (0.382 MPa). In the same manner analyses were conducted, by changing the parameters and stress distributions are extracted. Table 5, shows the maximum compressive and tensile stresses (lateral) in laterite and mortar respectively for different values of Poisson's ratios. Without changing the other parameters, when Poisson's ratio of laterite was changed to 0.2, the maximum principal stress (lateral tensile) in mortar was observed to be 0.608 MPa as shown in Table 5. When only the Poisson's ratio of laterite is increased from 0.15 to 0.2, there is an increase in maximum principal stress (lateral tensile) in mortar by 59%, for a vertical applied pressure of 2 MPa. At the same time, the maximum lateral compressive stress in laterite block has increased by 49%. When the prism is subjected to vertical loading, the masonry units and the mortar will expand laterally at different rates due to their different moduli of elasticity even if their Poisson's ratios are the same [Felix 1999]. If Poisson's ratio of laterite is increased, the difference in the rates of lateral expansion is further increased, causing an increase in the lateral tensile stresses in the mortar. This might reduce the compressive strength of the prism. Similarly, as the Poisson's ratio of mortar is decreased from 0.15 to 0.1 without changing the other parameters, the lateral tensile stresses in mortar have increased. Table 5 shows that the maximum principal stress (lateral tensile) in mortar increased from 0.382 MPa to 0.466 MPa when the Poisson's ratio of mortar is reduced from 0.15 to 0.1, with all other parameters kept unchanged which amounts to an increase of 22% (for a constant vertical applied pressure of 2 MPa). No significant change in the maximum lateral compressive stresses, in laterite blocks, however, has been observed in this case. Increase in Poisson's ratio of laterite or decrease in Poisson's ratio of mortar thus results in an increase in lateral tensile stresses in mortar. Such an increase in lateral stresses has been observed to be more when the Poisson's ratio of laterite was increased.

Modulus of Elasticity of Laterite and Mortar:

Keeping the modulus of elasticity of mortar at a reference value of 3000 MPa, analyses were conducted for values of modulus of elasticity of laterite varied as 300 MPa, 750 MPa and 1300 MPa. In all the cases Poisson's ratio of both the laterite and mortar were taken as 0.15 and thickness of mortar joint as 10 mm. Fig.10 shows the variation of principal stress (σ_1) for modulus of elasticity of laterite, 1300 MPa. Table 6 shows the maximum principal stresses (lateral) for different values of modulus of elasticity. When modulus of elasticity of laterite is reduced from 1300 MPa to 750 MPa, maximum lateral tensile stress in mortar has increased from 0.382 MPa to 0.78 MPa. The increase is more than double. When the modulus of elasticity of laterite is further reduced to 300 MPa, maximum lateral tensile stress in mortar has further increased to 1.71 MPa, with a total increase of stress of 4.5 times. In this case, the tensile stresses developed in mortar are much higher than the tensile strength of mortar. Keeping the modulus of elasticity of laterite at a reference of 1300 MPa, analyses were conducted by varying the modulus of elasticity of mortar from 3000 MPa to 6000 MPa. Table 6 gives the maximum principal stresses (lateral). When modulus of elasticity of mortar is increased from 3000 MPa to 6000 MPa, without changing the other parameters, maximum lateral tensile stresses have increased from 0.382 MPa to 0.906 MPa, the increase being about 2.4 times. For a constant modulus of elasticity of laterite, higher the modulus of elasticity of mortar, higher the tensile stresses in the mortar. The results also show that, for a constant modulus of elasticity of mortar, the lower the modulus of elasticity of laterite, higher are the tensile stresses in mortar. This proves that the ratio of elastic modulus of laterite block to mortar is more significant than the individual values of these elastic moduli. As the ratio of modulus of elasticity of laterite block to modulus of elasticity of mortar (only $E_{lt}<E_m$ considered) reduces, there is an increase in the lateral tensile stresses in the mortar.

Mortar Joint Thickness:

In order to study the effect of thickness of mortar joint, a parametric study is conducted by varying the thickness of mortar joint, keeping the other parameters a constant. In this case moduli of elasticity of laterite and mortar are taken as 1300 MPa and 3000 MPa respectively, and Poisson's ratio of laterite and mortar are taken as 0.15. Table 7 gives the comparison of maximum principal stresses for a joint thickness of 10 mm and 20mm. In the first case the maximum lateral tensile stress in mortar is 0.382 MPa and in the second case it is 0.324 MPa. As the thickness of mortar joint increases from 10 mm to 20 mm the lateral tensile stresses in mortar reduces by 15%. Analytical results show that when the mortar joint thickness is increased, without changing the other parameters, the lateral stresses in the mortar reduce. This leads to an increase in prism compressive strength with increase in joint thickness, provided bond is intact. Thus if the modulus or strength of brick/block is less than that of the mortar, then increase in joint thickness leads to increased masonry prism compressive strength [Shrinivasa Rao et al. 1995, Venkatarama Reddy et al. 2009].

Conclusions:

Detailed experimental investigations have been carried out on the strength characteristics of laterite blocks, cement mortar specimens and stack-bonded laterite masonry prisms under uniaxial vertical pressure. Parametric studies were also conducted by finite element analyses on laterite masonry prisms and results obtained have been discussed. Based on all these studies, the following general conclusions are made:

1. When laterite blocks of sizes used in practice were tested, the compressive strengths obtained were much lower than the strengths of the mortar cubes tested. Hence laterite masonry can be classified under weak unit-strong mortar masonry.
2. Modulus of elasticity of laterite blocks tested was found to be less than that of mortar used in making laterite masonry; hence, laterite masonry can be classified as soft unit-stiff mortar masonry.
3. Laterite masonry prisms were observed to have failed by bond failure and subsequent splitting of laterite blocks.
4. According to analytical results, in laterite masonry prisms subjected to uniaxial vertical pressure, laterite blocks were observed to be in triaxial compression and mortar joints in uniaxial compression and bilateral tension.
5. Values of Poisson's ratios of the materials used is an important aspect in deciding strength-deformation behavior of laterite masonry prisms. As seen from analytical results, increase in Poisson's ratio of laterite blocks or decrease in Poisson's ratio of the mortar, without changing the other parameters, results in increase in lateral stresses in the mortar joint. Lateral stresses in mortar joint are more sensitive to the Poisson's ratio of the laterite blocks than the Poisson's ratio of the mortar.
6. Reducing the modulus of elasticity of laterite blocks or increasing the modulus of elasticity of mortar joints, results in increase in the lateral tensile stresses in mortar joint, in the laterite masonry prism, at a given vertical pressure. As the ratio of modulus of elasticity of laterite block to modulus of elasticity of mortar is reduced (only $E_{lt}/E_m<1$ considered), there is an increase in the lateral tensile stresses in the mortar.
7. Increase in thickness of mortar joint, results in a decrease in lateral tensile stresses in mortar joint, indicating higher prism strength, if bond remains intact.
8. Prism strength will improve with better bond strength, higher ratio of elastic modulus of laterite and mortar (only $E_{lt}/E_m<1$ considered) and lower Poisson's ratio of laterite.

It is anticipated that the results reported here in would prove helpful in the actual practice for the reliable design of laterite masonry.

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Table 1: *Compressive Strength of Laterite Blocks*

S. No.	Size (LxBxH) (All in mm)	Failure load kN	Compressive strength (MPa)
Quarry 1			
1	360x230x170	400	4.83
2	370x220x160	330	4.05
3	360x220x170	350	4.42
4	360x220x160	400	5.05
Average			**4.58**
Quarry 2			
1	360x230x160	200	2.4
2	370x230x160	240	2.8
3	375x215x170	210	2.6
4	370x220x160	220	2.7
Average			**2.63**
Quarry 3			
1	360x220x180	180	2.27
2	355x215x200	150	1.97
3	360x230x190	150	1.81
4	375x230x190	180	2.09
5	365x225x210	180	2.19
6	365x200x205	150	2.06
Average			**2.07**

Table 2: *Compressive Strength of Cement Mortar Cubes*

Sample No.	Mass (gm)	Density Kg/m3	Load (kN)	Compressive Strength Mpa
1	756	2204.08	40	8
2	752	2192.42	40	8
3	710	2069.97	40	8
4	756	2204.08	40	8
5	761	2218.65	30	6
6	751	2189.5	30	6

Table 3: *Compressive Strength of Laterite Masonry Prisms*

No.	Age (days)	h/t	Size (LxBxH) All dimensions in mm	Load (kN)	Compressive Strength (MPa)
1	7	3.955	360 x 220 x 870	92.31	1.17
2		3.82	360 x 220 x 840	100	1.26
3		3.48	370 x 230 x 800	53.85	0.63*
4	28	3.82	360 x 220 x 840	92.31	1.17
5		3.77	360 x 220 x 830	107.69	1.36
6		3.82	360 x 220 x 840	100	1.26

**Failure of the Prism Occurred at an Early Stage*

Table 4: *Reference Values and Range of Parameters*

No.	Parameter	Reference Value	Range
1	E_{lt}	1300 MPa	300, 750, 1300
2	E_m	3000 MPa	3000, 6000
3	ν_{lt}	0.15	0.15, 0.2
4	ν_m	0.15	0.1, 0.15
5	t_m	10 mm	10, 20

Table 5: *Laterite Masonry Prisms under Uniaxial Compression- Effect of Poisson's Ratio of Laterite and Mortar on Principal Stresses (MPa)*

E_{lt}= 1300 MPa E_m = 3000 MPa p_y= 2 MPa					
ν_{lt} = 0.15 ν_m = 0.15		ν_{lt} = 0.2 ν_m = 0.15		ν_{lt} = 0.15 ν_m = 0.1	
Maximum lateral compressive stress	Maximum lateral tensile stress	Maximum lateral compressive stress	Maximum lateral tensile stress	Maximum lateral compressive stress	Maximum lateral tensile stress
0.441	0.382	0.658	0.608	0.441	0.466

Table 6: *Laterite Masonry Prisms under Uniaxial Compression- Effect of Moduli of Elasticity of Laterite and Mortar on Principal Stresses (MPa)*

ν_{lt} = 0.15 ν_m = 0.15 p_y= 2 MPa							
E_{lt} = 1300 MPa E_m = 3000 MPa		E_{lt} = 750 MPa E_m = 3000 MPa		E_{lt} = 300 MPa E_m = 3000 MPa		E_{lt} = 1300 MPa E_m = 6000 MPa	
Maximum lateral compressive stress	Max. lateral tensile stress	Maximum lateral compressive stress	Max. lateral tensile stress	Maximum lateral compressive stress	Max. lateral tensile stress	Maximum lateral compressive stress	Max. lateral tensile stress
0.441	0.382	0.439	0.780	0.433	1.71	0.438	0.906

Table 7: *Laterite Masonry Prisms under Uniaxial Compression- Effect of Mortar Thickness on Principal Stresses (MPa)*

E_{lt} = 1300 MPa E_m = 3000 MPa ν_{lt} = 0.15 ν_m = 0.15 p_y= 2 MPa			
t = 10 mm		t = 20 mm	
Maximum lateral compressive stress	Maximum lateral tensile stress	Maximum lateral compressive stress	Maximum lateral tensile stress
0.441	0.382	0.439	0.324

Figure 1: *Laterite Block Capped with Cement Mortar for Compression Test*

Figure 2: *Failure Pattern in Laterite under Compression*

Figure 3: *Demec Buttons Glued in Laterite Blocks to Measure Strains*

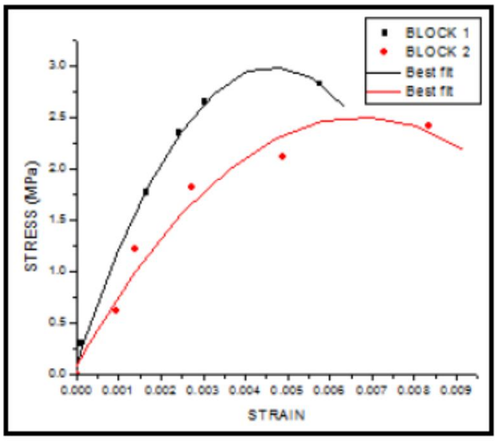

Figure 4: *Stress-Strain Graphs for Laterite Blocks*

***Figure 5:** Compression Testing of Cement Mortar Cubes*

***Figure 7:** Laterite Masonry Prisms Cast for Testing*

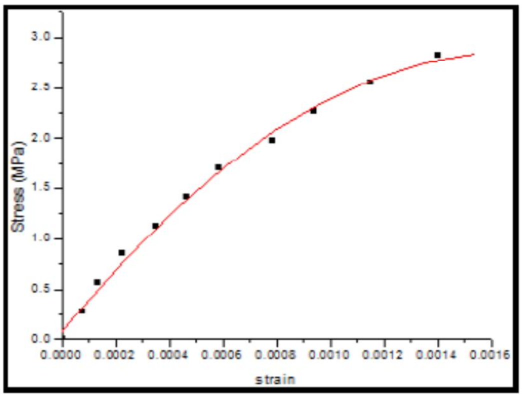

***Figure 6:** Stress-Strain Curve of Cement Mortar*

***Figure 8:** Failure of Stack-Bonded Laterite Masonry Prisms*

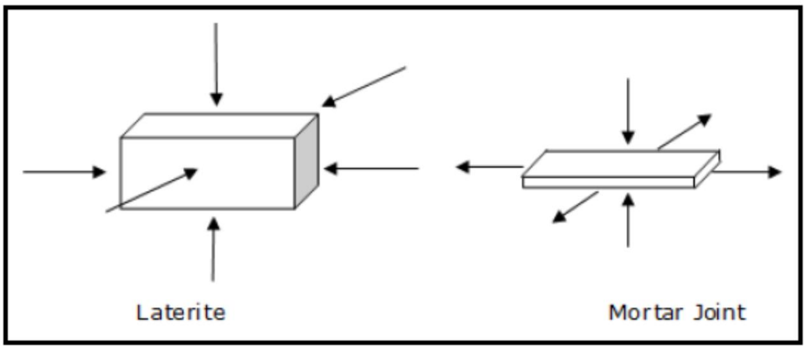

***Figure 9:** State of Stresses in Laterite Block and Mortar Joint in a Laterite Masonry Prism under Uniaxial Compression*

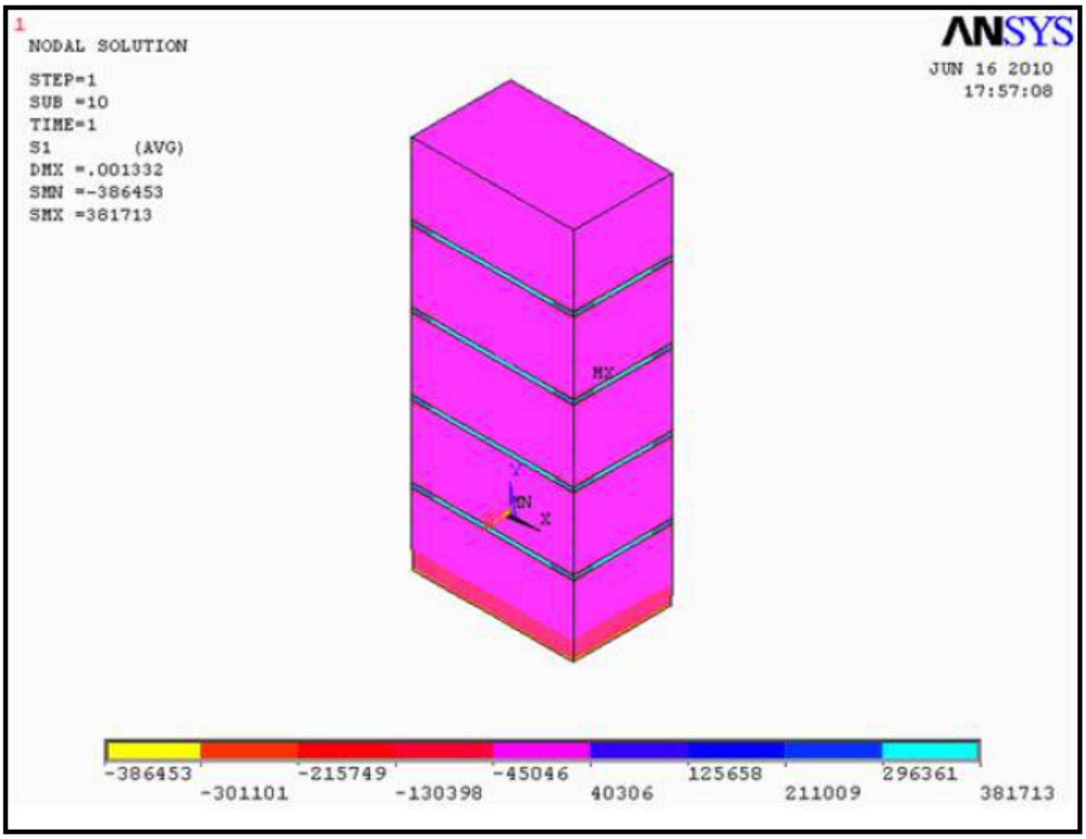

Figure 10: *Variation of Principal Stress* σ_1 *(N/m²)*