RESEARCH ARTICLE

Mechanical Properties of Ancient Clay Bricks of Jethawana Sthupa

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Abstract:
Sthupas which are also called Dagabas are huge brick structures built to honor Lord Buddha. They are in different shapes and different sizes. Jethawana sthupa which was built by King Mahasen in 269 – 296 AD is the largest sthupa in Sri Lanka. It is the third tallest and the largest brick structure in the world. The bricks and the plasters that have been used to construct the sthupa should have excellent mechanical and physical properties, since they survived for more than 1700 years.

For mechanical properties, the compressive strength, modulus of rupture, critical stress intensity factor and the material removing rate of ancient bricks were studied and compared with those properties of modern bricks. The three point bending method was used to determine the modulus of rupture of the bricks. Single edge notch beam was used in three point bending configuration to find out the critical stress intensity factor of the bricks. Density of the material and the porosity of the bricks were also investigated. Material removing rate of the bricks was calculated by studying the material removing by a silicon carbide wheel. Ferrous and ferric ion concentration present in the ancient bricks and modern bricks were found by a titration method. X-Ray Diffraction (XRD) analysis has been carried out for the ancient bricks and the modern bricks of Jethawana sthupa.

Modulus of rupture and critical stress intensity factor of the ancient bricks were nearly two times higher than those of modern clay bricks. However, compressive strength of the ancient bricks did not show a much difference from that of modern bricks. Material removing rate of the ancient bricks was one tenth of the value of modern bricks indicating that the hardness of the ancient bricks was very much higher than that of modern bricks. The density and the porosity of the ancient bricks and modern bricks did not show a marked difference. Enhancements of the mechanical properties of the ancient bricks even with having nearly the same physical properties as in the modern bricks may be due to some other factors such as qualitative and quantitative difference in the chemicals presents in the ancient bricks and thermal treatment.

Key words: Mechanical properties, Compressive strength, Modulus of rupture

Introduction

Sthupa/ Dagaba
Sthupa/Dagaba is a monumental structure built to honor Lord Buddha. They are venerated by the Buddhists and their imposing, yet simple, features give one a feeling of stability, strength, nobility, and grandeur [1].

Those constructions are always related with Buddhist temples. Dagabas contain sacred relic of Lord Buddha or they are constructed to mark the sacred spots where some important events connected with the religion had taken place.

The construction of Buddhist sthupas started while Buddha was alive and they are not tombs but a memorial which symbolizes the supremacy of the Lord Buddha and his dharma or teaching.

Architecture of Sthupa
Sthupas are solid structures mostly made up of burnt clay bricks. The main components of a sthupa[2] are shown in Figure 1.

Dome is the main and the biggest component of a sthupa. It lies on two or three cylindrical terraces called basal rings. It contains the relic in a relic chamber. Dome carries the square chamber at its top. It is a solid structure but there are some square chambers which have hollow structure. One or more cylinders called abode of gods lie on the top of the square chamber. Conical spire is a solid one. At top of the conical spire there is a crystal set on a gift mineral [3].

Some sthupa contain an umbrella on the top or some other small sthupa is surrounded by another structure with a roof that is called *Vatadaage*.

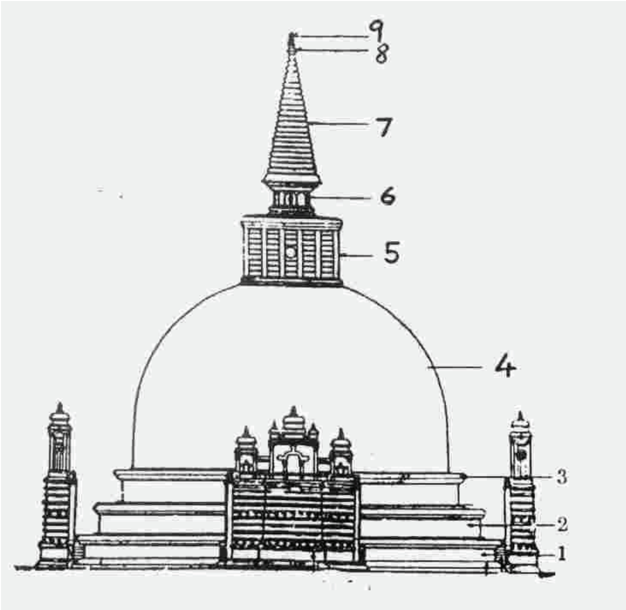


Figure 1: Main components of a sthupa

(1, 2 and 3. Basal rings, 4. Dome, 5. Square Chamber, 6. Abode of God, 7. Conical Spire, 8. Mineral, 9. Crystal.) *Reproduced from Ranaweera* [2]

These structures are for protection of sthupa and both umbrella and *Vatadaage* are exceptional cases. With the passage of time and the sthupas becoming larger in size, some other extra components were added to the structure like; a small separate structure with tables to offer flowers and a plinth for the dome.

All large sthupas and some small sthupas were also provided with a projection called *Vahalkada* or frontispieces. One may contain 2 or 4 frontispieces. All those are ornamental structures for a sthupa [3].

According to the shape of dome sthupas can be categorized into six groups [4]. Most common shapes are the bell shape and then the bubble shape. But the most stable shape is the paddy heap shape since the stresses on the structure are mostly compressive [5]. Pot and lotus shaped domes are rare and there are no existing examples of the 'Nelli fruit' shape.

Jethawana Sthupa

History and the Dimensions of the Sthupa

The Jethawana sthupa was built by king Mahasen (269 – 296 AD) and the construction was completed by his son king Kithsirimewan I (303–331 AD)[3]. The dimensions of the Jethawana sthupa are shown in Figure 2.

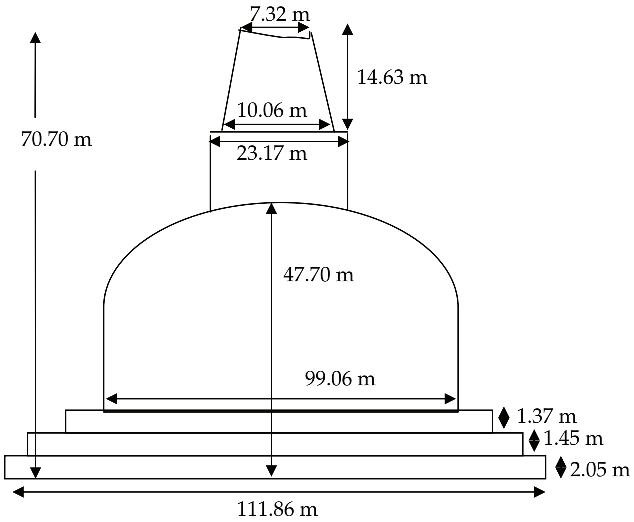


Figure 2. Dimensions of Jethawana sthupa

The total height of the remaining structure is 70.7 m. But earlier the height of the complete structure was 121.9 m [3]. At that time it was the third tallest structure in the world, surpassed only by the two great pyramids in Giza, Egypt [6]. Jethawana sthupa is the largest brick building in the world and its volume is about 233,000m^3. The dome of the sthupa is in paddy heap shape.

Bricks, Plaster and the Mortar in the Sthupa

The main building block of the sthupa is burnt clay brick (Figure 3). The bricks in the sthupa are different in sizes. The ancient bricks used to build the sthupa are much larger than modern clay bricks. Bricks of different sizes have been used for different parts of the sthupa [7], larger ones for the basal rings and dome, and much smaller one for the spiral.

The mortar used in Jethawana sthupa construction is very thin and fine butter clay like slurry (Figure 4). The thickness of the mortar is about 5 mm. With this thin mortar, the bricks essentially sit one on top of the other, the slurry filling the gaps. This gives a strong brick work unlike the modern brick works which uses a thick mortar which can weaken the brick work.

The outer surface of the brick work is water proofed using a thick (thickness - 1.5 cm) plaster (Figure 5).

Stresses Applying on the Sthupa

The building materials of the sthupa should be in good quality and the bricks should have good compressive strength (the main loading on the sthupa is its self-weight).Most parts of the sthupa are under compression [5,8,9,10].

Figure 3. Bricks used to construct the spiral of Jethawana sthupa.

Figure 4. Mortar used in the square chamber of Jethawana sthupa (reddish colour area is the mortar which is used for the conservation).

Few tensile zones are present in the square chamber and the spiral and at the outer surface of the dome having shapes other than the paddy heap shape. It is reported that in the paddy heap shaped dome of Jethawana, the largest sthupa ever built the maximum compressive stress occurs at the centre at foundation level and its value is 839 kPa [4]. Hoop and radial stress in Jethawana dome are also compressive, having a maximum of 280 kPa at the base center [7].

Figure 5. Outer plaster of the square chamber of Jethawana sthupa.

It is also reported that the square chamber of Jethawana sthupa also has some tensile regions at the top.

Some mechanical properties of Jethawana bricks recorded[2] are shown in Table 1.

Table 1. Some mechanical properties of Jethawana sthupa bricks

Property	value
Compressive strength	8500 kPa
Tensile strength	850 kPa
Young's modulus	4.5 GPa
Poisson's ratio	0.25

Aim of the Study

Most bricks, mortar and plasters in Jethawana sthupa are under compressive stress and had survived for more than 1700 years having being opened to weather changes. This study was undertaken to investigate chemical phases available and the mechanical properties such as; compressive strength, modulus of rupture, critical stress intensity factor, and the material removing rate as well as some other relevant physical properties of the bricks.

Materials and Methods

Brick samples were cut from the original brick by using metal cutting blades (slow speed cutting was used). The average dimensions of a cut sample were; length 5 cm, width 2.5 cm and height 1.5 cm.

Investigation of Modulus of Rupture of the Bricks (MOR)
MOR of a material gives an idea about how much load it can bare without any failure. The MOR of a material can be found out by using either 3 point bending method or 4 point bending method. Three point bending method was used to investigate MOR of the bricks.

Investigation of the Compressive Strength
Compressive strength gives an idea about how far a material can bear compressive stress on it without any failure. Sample was kept on the cross head of the testing machine and then the cross head moved against the load cell. The load was noted down at the time when the sample failed.

Investigation of Critical Stress Intensity Factor (K_{IC})
K_{IC} gives an idea about how much the material would resist to propagate a fracture. To find K_{IC} three point bending method was used. Surfaces of the cut sample were polished by using a sand paper in order to remove deep flaws on the surface of the sample. A notch was put on the sample by using a metal cutting blade (Figure 6). The average depth of the notch was 5 mm.
K_{IC} was calculated using;

$$K_{IC} = \frac{3Pda^{½} [1.93 - 3.07(a/w) + 13.66 (a/w)^2]}{bw^2}$$

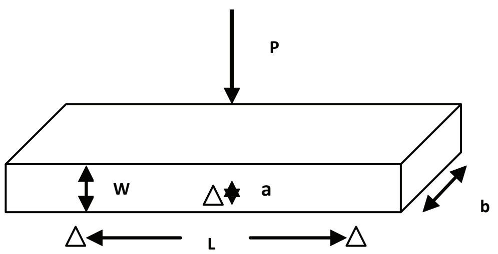


Figure 6. Single edge notch beam specimen for 3 point bending method

Investigation of Material Removing Rate (MRR) of the Brick Samples
MRR of the brick samples was found in order to have an idea about the hardness of them. One sample was taken from each brick. The initial mass of the sample was noted. The sample was then moved against a rotating silicon carbide wheel. The time was noted and the final mass of the sample was measured. MRR was calculated using;

$$MRR = \frac{IMS - FMS}{rpm \ X \ DM \ X \ time}$$

IMS: Initial mass of the sample
FMS: Final mass of the sample
DM: Density of the material

Investigation of the Density of the Bricks and the Plasters
By immersing the brick samples in mercury, the density was measured. The porosity was measured by immersing the samples in distilled water,
Fe^{2+} and Fe^{3+} concentration in the brick samples were measured using a chemical method.

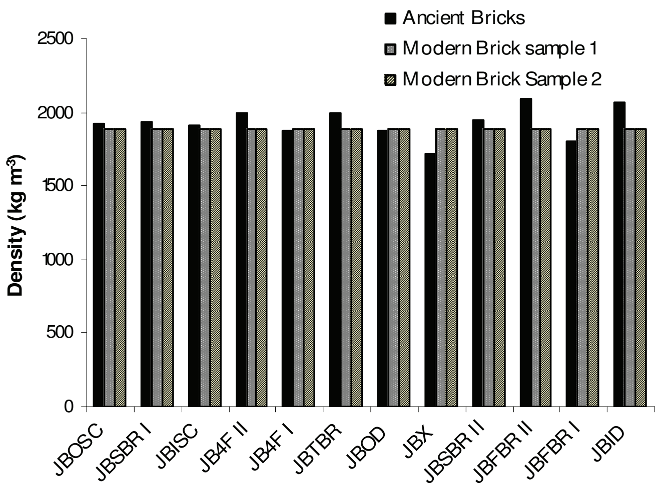
Results and Discussion

There was no significant difference in the value of the densities of the ancient brick and new bricks (Figure 7).

Porosity of the bricks in foundation, second basal ring, outer cover of the dome, outer cover of the square chamber and the third basal ring is lower than that of the modern bricks. Porosity of the bricks in first basal ring, inside the square chamber and the brick from the site area is greater than that of the modern bricks (Figure 8).

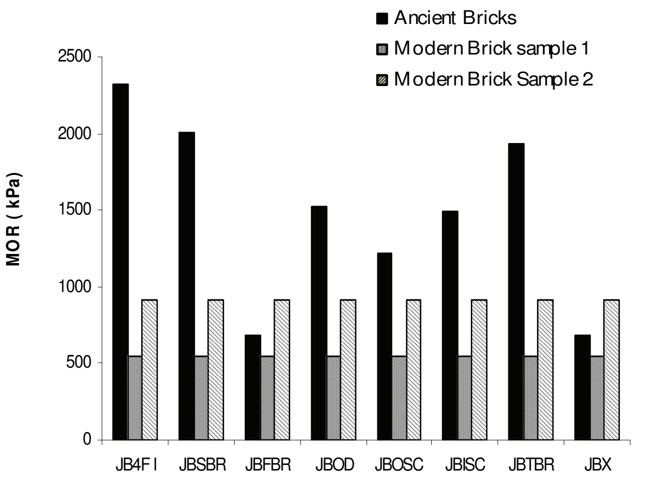
MOR value of ancient bricks was found to be higher than that of new bricks used for reconstruction except those ancient bricks collected from the first basal ring and ancient bricks collected from the site area (exact position of the brick is unknown). Highest MOR values were shown for the bricks which were collected from the foundation from the second basal ring and from the third basal ring (Figure 9). Even after exposing to weather changes, and mechanical forces for more than 1700 years still they show a higher value for MOR than for modern bricks.

Maximum compressive strength was shown for



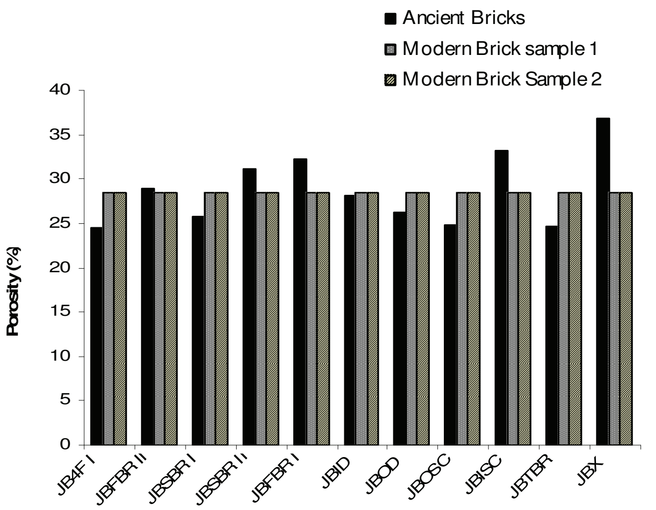
OSC – Outside of Square Chamber, SBR – Second Basal Ring, ISC - Inside of Square Chamber, 4F- 120 cm Below the Ground surface, TBR - Third Basal Ring, OD – Outside of Dome, X –unknown, FBR – First Basal Ring, ID- Inside of Dome

Figure 7. Density of the bricks of Jethawana sthupa (JB).



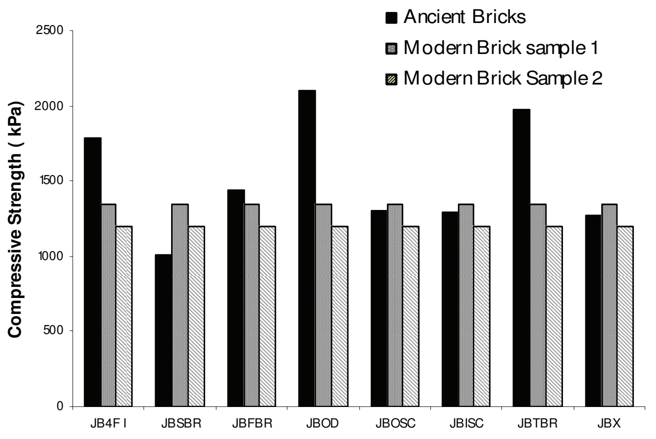
4F- 120 cm Below the Ground surface, SBR II – Second Basal Ring, FBR I – First Basal Ring, OD – Outside of Dome OSC – Outside of Square Chamber, ISC - Inside of Square Chamber, TBR - Third Basal Ring, X –Jethawana Bricks unknown

Figure 9. Modulus of rupture of the bricks in Jethawana sthupa (JB) in kPa showing high MOR value for ancient bricks.



4F- 120 cm Below the Ground surface, FBR I – First Basal Ring, SBR II – Second Basal Ring, ID- Inside of Dome, OD – Outside of Dome, OSC – Outside of Square Chamber, ISC - Inside of Square Chamber, TBR - Third Basal Ring, , X –Jethawana Bricks unknown

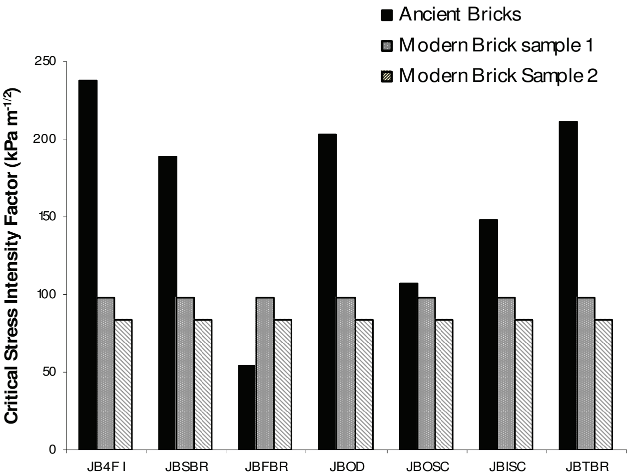
Figure 8. Porosity of the bricks of Jethawana sthupa (JB).



4F- 120 cm Below the Ground surface, SBR II – Second Basal Ring, FBR I – First Basal Ring, OD – Outside of Dome OSC – Outside of Square Chamber, ISC - Inside of Square Chamber, TBR - Third Basal Ring, X –Jethawana Bricks unknown

Figure 10. Compressive strength of the bricks of Jethawana sthupa (JB).

the bricks from the foundation, from the outer cover of the dome and from the third basal ring (Figure 10). Compressive strength of ancient bricks from other places did not show much difference from the values of the modern bricks. This may due to the weathering of the bricks and exposure to high compressive forces for long time. Almost all the ancient bricks showed very high value for critical stress intensity factor than for modern bricks. Most bricks from the places like foundation, outer cover of the dome and the third basal ring showed K_{IC} value twice that of new bricks (Figure 11) (Only the brick from first basal ring shows a lower value than new bricks). Optical microscopy revealed many sand particles in ancient bricks of different sizes and of different shapes. This may be the reason for showing high values of K_{IC} in ancient bricks than in the modern bricks because those sand particles may reduce the propagation of crack inside the brick. Material removing rate for the ancient bricks is very low than that of the modern bricks (Figure 12) and it is nearly one tenth of that of the modern bricks. This is not valid for the ancient bricks which were collected from the site area (the exact place where it was in the sthupa is unknown). Ancient bricks are much more resistance to wear than the modern bricks.



4F- 120 cm Below the Ground surface, SBR II – Second Basal Ring, FBR I – First Basal Ring, OD – Outside of Dome OSC – Outside of Square Chamber, ISC - Inside of Square Chamber, TBR - Third Basal Ring

Figure 11. Critical stress intensity factor of the bricks of sthupa, showing high K_{IC} value for the ancient bricks.

It was observed that Fe^{2+} was not present in a detectable concentration level whereas Fe^{3+} concentrations were 0.003 mol dm^{-3} for ancient bricks and 0.002 mol dm^{-3} for modern bricks.

XRD patterns of the ancient bricks and the modern bricks revealed the two samples to have similar components. Both brick samples contain SiO_2 and $(FeMn)PO_4$. The amount of $NaAlSi_3O_8$ and SiO_2 present in the modern bricks are nearly the same. The peak corresponding to $NaAlSi_3O_8$ was not prominent in the XRD pattern of the ancient brick sample whereas peak corresponding to $KAlSi_3O_8$ was prominent. TiO_2 and mullite were present only in ancient bricks whereas $Ca_4Fe_9O_{17}$ is present in modern bricks.

Conclusion

As far as the mechanical properties of the ncient bricks are concerned MOR and K_{IC} are nearly two times higher than those of the new bricks. The material removing rate of the ancient bricks is one

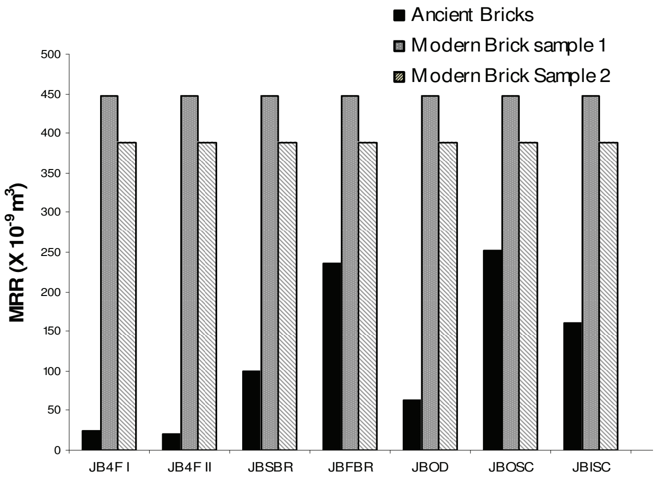


Figure12. Material removing rate of the bricks of Jethawana sthupa showing low MRR for the ancient bricks.

tenth of that of the new bricks. It implies that the resistance to wear is ten times greater than that of new bricks. Therefore, it can be speculated that the hardness of the ancient bricks was very much higher than that of the modern bricks. Although it was observed that the compressive strength of most of the ancient bricks. It implies that the resistance to wear is ten times greater than that of new bricks. Therefore, it can be speculated that the hardness of the ancient bricks was very much higher than that of the modern bricks. Although it was observed that the compressive strength of most of the ancient bricks were slightly higher than that of new bricks, the difference was not significant.

Mechanical properties of the ancient bricks are better than that of the modern bricks. However, there was no significant difference in the density and porosity values of ancient and modern bricks.

According to the XRD analysis of the ancient and modern brick samples SiO_2 (quartz), (FeMn) PO_4, and Fe_2O_3 are present in both bricks where as $NaAlSi_3O_8$ is present only in the modern bricks. Instead of $NaAlSi_3O_8$, $KAlSi_3O_8$ is present in the ancient bricks.$Ca_4Fe_9O_{17}$ is present in the modern bricks, while, TiO_2 and mullite are present in the ancient bricks. The peak height of $NaAlSi_3O_8$is nearly equal to the peak height of SiO_2 present in the modern bricks. But SiO_2percentage of the ancient brick is very much higher when compared with the SiO_2 present in the modern bricks. It is concluded that the better mechanical properties should have a direct affect from the quarts (SiO2) percentage of the bricks.

Enhancement of the mechanical properties of the ancient bricks and ancient plaster may be due to the difference in chemical composition of the materials. Sand particles present in the old bricks in different sizes results in composite material giving a high modulus of rupture and high critical stress intensity factor values for the ancient bricks.

It is of prime importance to perform a quantitative and qualitative chemical analysis to elucidate the toughening mechanisms in ancient bricks and to investigate how the ancient techniques can be used in modern brick production.

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