# "A TREATISE ON MASONRY CONSTRUCTION" APPLICATION TO THE MODERN PRACTICES FOR HISTORIC BUILDING RESTORATION

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## ABSTRACT

Ira O. Baker in 1889 published a major and significant textbook, entitled '*Treatise on Masonry Construction*, which had been reprinted ten times by 1914. This widely used text covered the theoretical and construction subjects of masonry, reinforced concrete, steel, and timber using a significant number of case studies of now famous structures such as the Eads Bridge in St Louis. Baker correctly identified the dynamic modulus of elasticity long before the advent of modern damage and fracture mechanics. Baker has published a significant set of test results on strength of materials, modulus of elasticity, and tensile capacity of mortars. He provides specific details of the methods of analysis used in the late 19th century for masonry and reinforced concrete which provide a wealth of data for the historic professional assessing a late 19th century to early 20th century structure. This paper will summarize and review the critical data and methods from the treatise that can be used in a modern analysis of historic buildings masonry, and comment on the use of the information in historic preservation of masonry structures, whilst not deviating into a formal consideration of modern analysis methods.

**KEYWORDS**: historic masonry, historic masonry texts

## INTRODUCTION

Ira O. Baker was educated at the University of Illinois in Urbana Champaign as a civil engineer, ending his career as the Head of the Civil Engineering Department. He wrote a number of text books [1, 2] adopted as standard texts at the time in the fields of masonry and road construction. The purpose of this paper is to present some of the data from Baker's masonry textbook to highlight the standards used in the testing, and the available results from test data for materials from the late 19th and early 20th century, and to consider the use of this data in an analysis of a historic structural restoration, whilst not deviating into the modern analysis techniques which are presented elsewhere [3]. The majority of the test results were completed at the Watertown Arsenal in the North Eastern region of the USA, making this paper particularly significant for this region. The test data assembled from Baker's text covers the physical properties of cement, lime, mortar, brick, and masonry elements.

## TEST METHODS, LOCATION AND NOMENCLATURE

The tests used to describe the properties of the bricks, as listed by Baker, are form texture, absorptive power, crushing strength, and transverse strength. The Watertown Arsenal in the northeastern region of the United States provided one of the first testing machines to determine the compression and tensile properties of masonry. Baker also provided data on shear strength.

Baker classified the bricks according to the descriptors listed in Table 1.

**Table 1 – Brick Nomenclature**

| Brick | Bakers' Exact Description | Closest Modern Description |
|---|---|---|
| **Soft-mud brick** | "A brick moulded by placing soft clay in a mould. It may be moulded either by hand or machine." | Soft Pressed Bricks |
| **Stiff-mud brick** | "One moulded by forcing a prism of stiff clay through a die and afterwards cutting it up into bricks" | Extruded Bricks |
| **Stiff-mud brick** | "One moulded by pressing dry or semi-dry clay into a mould." | Pressed Brick |
| **Re-pressed brick** | "Usually a stiff-mud brick which has been subjected to enormous pressure to render the form more regular and to increase its strength and density." | Re-pressed Brick<br>Baker noted "It is doubtful whether re-pressing increases the strength or density. |
| **Slop Brick** | "In moulding brick by hand, the moulds are sometimes dipped in water just before being filled with clay, to prevent the mud sticking to them." | Not commonly made even in Baker's time.<br>Baker noted "It is deficient in colour and has a comparatively smooth surface and rounded edges." |
| **Sanded brick** | "Ordinarily, in making soft-mud brick, sand is sprinkled into the moulds to prevent the clay sticking." | Baker noted "In hand moulding, when sand is used for this purpose, it is certain to become mixed with the clay and occurs in streaks in the finished brick, which is very undesirable … every third brick is bad." |

The following terms were used to classify the bricks, compass brick, feather edge brick, face brick, sewer brick, paving brick and vitrified brick. The compass brick is used as a liner in tunnels, with one edge being shorter than the other edge. The feather edge is a voussoir brick. The face brick is used for building work and is usually re-pressed or pressed brick. The sewer brick is noted as being smooth, regular in form and hard. The paving brick is a hard ordinary brick. The vitrified brick was introduced for street paving in the early 1890's, although by the early 20th century these bricks were used for building and other structures as structural elements. The position in the kiln also affected the strength properties of the bricks. The clinker bricks were over-burnt, which resulted in a brittle weak brick. The hard bricks are used for construction. Salmon bricks are under-burnt and soft. The salmon refers to the colour of the brick and this was used as a marketing ploy to allow the bricks to be sold, even though they were classed as substandard at the time.

**FORM**

Baker noted on form:

> *'A good brick should have plane faces, parallel sides, and sharp edges and angles. In regularity of form re-pressed brick ranks first, dry-clay brick next, then stiff-mud brick, and soft-mud brick last. Regularity of form depends largely upon the quality of the clay and the method of burning. A good brick should not have depressions or kiln marks on its edges caused by the pressure of the brick above it in the kiln.'*

**TEXTURE**

Baker noted on texture:

> *'A good brick should have a fine, compact, uniform texture; and should contain no fissures, air bubbles, pebbles, or lumps of lime. It should give a clear ringing sound when struck a sharp blow with a hammer or another brick. A brick which gives a clear ringing sound is strong and durable enough for any ordinary work.'*

**ABSORBTION**

Baker from U.S War Department test results from 1894 to 1896 [4] noted on absorptive power:

> *Soft under-burned brick, such as are frequently used in filling in the interior of walls, will absorb from 30 to 35 per cent of their weight of water; some good dry-clay or pressed brick have an absorption of 15 to 20 per cent, while others run from 5 to 10 per cent; and some vitrified brick absorb only 1 to 2 per cent.* [1]

Baker was not convinced that absorption had any impact on the frost resistance or breakdown due to freeze-thaw actions.

**COMPRESSION TESTS**

Compression tests were conducted with the bricks set in plaster of Paris, with tests undertaken on the endwise, edgewise and flat-wise with the last test method being the commonly used method at the Arsenal. Experiments were completed at the Arsenal to determine the relative strength of hard-burned face bricks for the flat-wise, edgewise and endwise with a sample size of four bricks. The means results for these tests are shown in Figure 1.

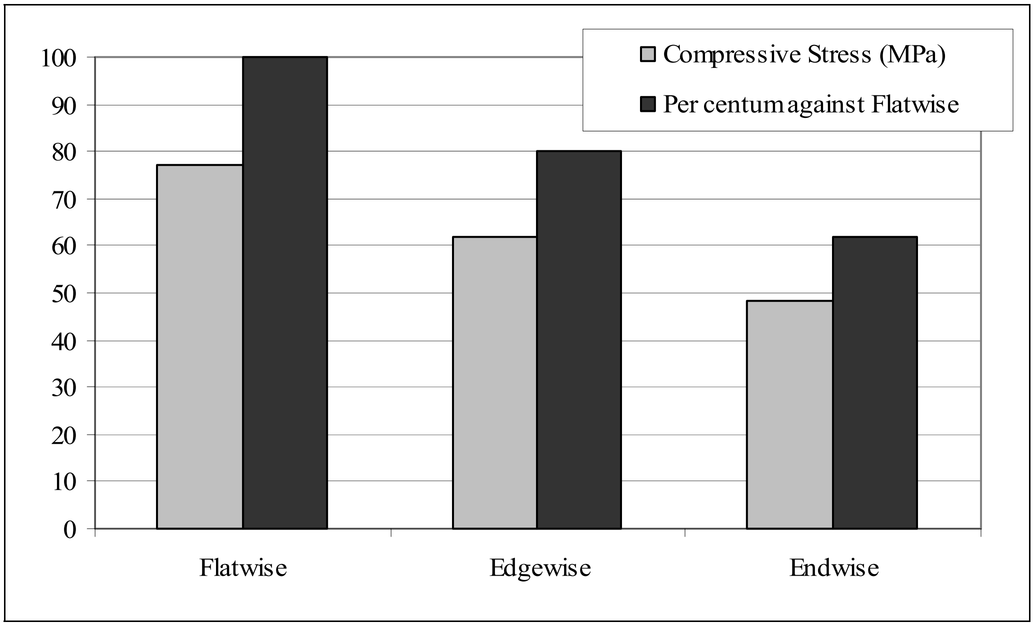


**Figure 1 – A comparison of test method results for the compressive strength of a common brick**

## TRANSVERSE STRENGTH

The Watertown arsenal experimentally tested the transverse strength of bricks from 1883 to 1905. The arsenal tested bricks from six manufactures using sixteen different grades of bricks in the test series. The mean result of these tests was the observation that the transverse strength was 13.5% of the compressive strength when the test was conducted on a half brick tested in the flat-wise mode. The arsenal tested bricks from eleven manufacturers to determine the transverse strength as having a mean value of 7 MPa with a minimum value of 2 MPa and a maximum value of 18 MPa. The tests on thirty seven samples assuming a normal probability distribution suggests a standard deviation of 4 to 6 MPa which is a co-efficient of variation of 33 to 50 per cent.

## SHEARING STRENGTH

Baker noted on shearing strength:

> *'The shearing strength of nine specimens of brick from five factories tested on the U.S. testing machine in 1894 gave a shearing strength equal to 10.1 per cent of the crushing strength flat wise; and sixteen samples from six factories, tested in 1895, gave 14.7 per cent. In the first lot the range was from 7 to 17 per cent; and in the second from 8 to 30 per cent. Apparently a higher compressive strength is accompanied by a proportionally lower shearing strength; but the tendency is not very marked.'*

## LIME, CEMENT AND MASONRY

Two types of lime were tested by Baker; these were High Calcium Lime and Magnesium Lime. The tensile strength of the Lime Mortar samples was determined using Lime Mortar briquettes. The results for the tests are presented in Table 2.

**Table 2 – Lime Mortar Briquettes – Tensile Strength**

| Ref No. | Age when tested | Tensile Strength (MPa) | |
|---|---|---|---|
| | | High Calcium Lime | Magnesium Lime |
| **1** | **Four Weeks** | 0.21 | …. |
| **2** | **Eight Weeks** | 0.25 | 0.20 |
| **3** | **Three Months** | 0.27 | 0.25 |
| **4** | **Four Months** | 0.27 | 0.35 |
| **5** | **Six Months** | 0.35 | 0.57 |
| **6** | **One Year** | 0.31 | 0.64 |

The high calcium lime was given the colloquial name of quick lime and the magnesium lime was slow lime as it has a slower heat evolution. The magnesium limes are also called dolomitic and have at least 10 % magnesium oxide. Limes with less than 10 % magnesium oxide are classified as high calcium limes. The mould used to form the briquettes is shown in Figure 2. This mould was developed by the American Society of Civil Engineers [5]. A similar test mould is used for modern tests of cement mortar. The tests were completed with a 3:1 sand to lime mix.

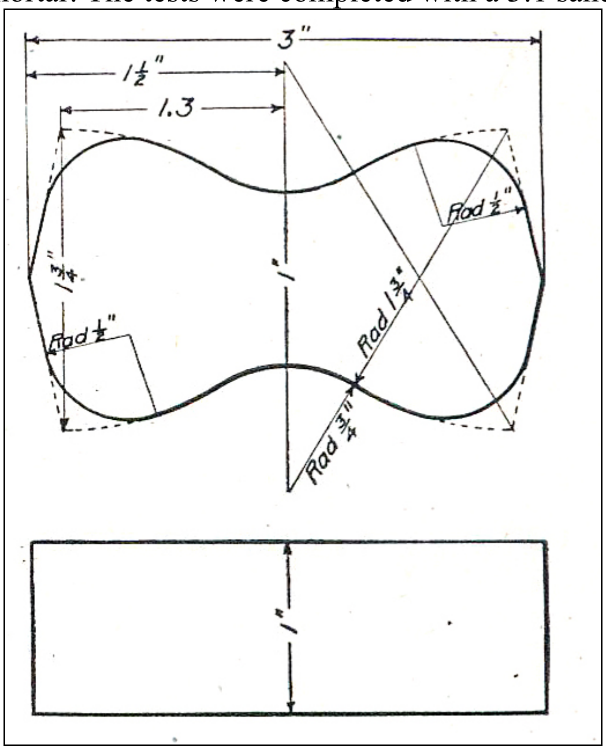


**Figure 2 – Briquette Mould – 1904**

The American Society of Engineers [1, 5] adopted minimum requirements for the tensile strength of cements when tested either neat or as a 1:3 cement sand mix. The test method is the same as for the lime mortars. The minimum requirements are presented in Table 3.

**Table 3 - Tensile Strength Cement – ASCE Minimum Requirements 1904**

| Age when tested | Average Tensile Strength (MPa) | |
|---|---|---|
| | **Portland** | **Natural** |
| **Clear Cement** | | |
| **1 day – 24 hours in moist air** | 1.0 - 1.4 | 0.35 – 0.7 |
| **7 days – 1 day in moist air and 6 days in water** | 3.1 – 3.8 | 0.7 – 1.4 |
| **28 days – 1 day in moist air and 27 days in water** | 3.8 – 4.5 | 1.4 – 2.1 |
| **1 Part Cement, 3 Parts Standard Sand** | | |
| **7 days – 1 day in moist air and 6 days in water** | 1.0 – 1.4 | 0.17 – 0.5 |
| **28 days – 1 day in moist air and 27 days in water** | 1.4 – 2.1 | 0.5 – 1.0 |

Baker provided the results of about 10,000 tests on cement mortar samples completed in 1904 and 1905. One set comprised 16 types of cement, with 783 samples involving 7000 test. The remaining tests were completed on 12 types of cement. The results are summarized in Table 4.

**Table 4 – Tensile Tests – Cements (MPa)**

| Age When Tested | Portland | | | Natural | | |
|---|---|---|---|---|---|---|
| | **Min** | **Max** | **Mean** | **Min** | **Max** | **Mean** |
| **Clear Cement** | | | | | | |
| **1 day** | 1.4 | 4.5 | 2.6 | 0.86 | 1.25 | 1.01 |
| **7 days** | 3.4 | 5.6 | 4.7 | | | 1.40 |
| **28 days** | 4.1 | 5.9 | 5.2 | | | 1.95 |
| **1 Cement to 3 Standard Sand** | | | | | | |
| **7 day** | 0.85 | 2.0 | 1.6 | … | … | … |
| **28 days** | 1.1 | 2.5 | 2.2 | … | … | … |
| **1 Cement to 1 Standard Sand** | | | | | | |
| **7 day** | … | … | … | 0.66 | 1.07 | 0.70 |
| **28 days** | … | … | … | 1.16 | 1.42 | 1.25 |
| **1 Cement to 2 Standard Sand** | | | | | | |
| **7 day** | … | … | … | 1.14 | 1.35 | 1.23 |
| **28 days** | … | … | … | 1.83 | 2.13 | 1.99 |

The results in Table 4 show that the manufacturers of the cements and the natural cements were able to meet the requirements of the ASCE Committee. The difficulty in the use of the results is the inability to directly calculate the characteristic strength. The standard sand used at the time of Baker is equivalent to the modern ASTM C 788-02 20-30 sand [6]. As Baker noted:

> *'the natural sand from Ottawa, Ill., screened to pass a sieve having 20 meshes per linear inch and retained on a sieve having 30 meshes per linear inch. The wires of the sieves are to have diameters of 0.0165 and 0.0112 inches respectively, i.e., half the width of the opening in each case. Sand having passed the No. 20 sieve shall be considered standard when not more than one per cent passes a No. 30 sieve after one minute of continuous sifting of a 500-gram sample'*

Twenty two masonry piers ranging in height from 300 mm to 3metres were tested at the Watertown arsenal. The piers were constructed by a common mason who was observed to take '*little care'*, using untested cement purchased commercially. The piers were 300 mm on edge at the base. The bricks used in the test had a compressive strength from 90 to 103 MPa when tested flat-wise between steel. The likely endwise test result is in the order of 50 to 60 MPa for these bricks. The test results for the masonry piers are presented in Table 5.

**Table 5 – Compressive Strength of Brick Piers Age at test 18 to 24 months**

| Ref No | Kind of Mortar | Number of Tests | Compressive Stress (MPa) | Strength of the Masonry in terms of that of | |
|---|---|---|---|---|---|
| | | | | Brick Flatwise | Cubes of Mortar |
| 1 | 1 lime paste, 3 sand | 21 | 10.7 | 0.10 | 12.5 |
| 2 | 1 Rosendale natural cement, 2 sand | 36 | 12.6 | 0.13 | 11.3 |
| 3 | 1 Portland cement, 2 sand | 8 | 17.5 | 0.16 | 4.7 |
| 4 | Neat Portland cement | 1 | 15.9 | 0.15 | 0.7 |
| 5 | 1 Rosendale natural cement, 2 lime mortar | 1 | 11.4 | 0.12 | 9.0 |
| 6 | 1 Portland cement, 2 lime mortar | 1 | 9.7 | 0.10 | 7.3 |

A brick display was organized at the Louisiana Purchase Exposition in St Louis in 1904. These bricks were then tested after the Expo at the Watertown arsenal. The test method was flatwise in a neat Portland Cement mortar. Each brick was tested 5 times. The results are shown in Table 6. Although it is not explicitly stated in the text, it is suggested that results 4 to 8 are for bricks from Massachusetts brick kilns. Brick piers were constructed from the eight brick types listed in Table 6. The results for the brick pier tests for the Table 6 bricks are shown in Table 7. The reference numbers are identical between the tables. Baker noted that one month results were sometimes higher than the six month result and that there was a considerable variation in the test results for brick and masonry.

**Table 6 – Louisiana Purchase Exposition – Brick Compressive Stress Results**

| Ref Num. | Kind of Brick | Compressive Stress (MPa) | | |
|---|---|---|---|---|
| | | Min | Max | Mean |
| | **Face Brick:** | | | |
| 1 | Stiff-mud | 61.6 | 105 | 88 |
| 2 | Dry-pressed | 61.6 | 124 | 77 |
| 3 | Re-pressed soft mud | 39.8 | 52.1 | 47 |
| | **Common Brick** | | | |
| 4 | Hard-burned, soft mud, Cambridge | 63.1 | 102 | 78 |
| 5 | Hard-burned, soft mud, Brookfield | 29.9 | 31.6 | 31 |
| 6 | Hard-burned, soft mud, Mechanicsville | 35.2 | 46.4 | 40 |
| 7 | Medium burned, soft mud, Cambridge | 31.8 | 59.2 | 45 |
| 8 | Medium burned, soft mud, Brookfield | 28.9 | 47.2 | 36 |

**Table 7 – Compressive Stress of Brick Piers (MPa) Age at test 6 months uno.**

| Ref Num | Mortar Type | | | Per cent of the mean crushing stress of the bricks (Table 6) | | |
|---|---|---|---|---|---|---|
| | Neat Portland | 1 Portland 3 Sand | 1 Lime Paste 3 Sand | Neat Portland | 1 Portland 3 Sand | 1 Lime Paste 3 Sand |
| **Face Brick** | | | | | | |
| **1** | 27.7 | 16.6* | 9.8 | 31 | 19 | 11 |
| **2** | 19.8* | 16.6 | 10.5 | 26 | 21 | 13 |
| **3** | 13.2 | 11.5 | 8.7 | 28 | 25 | 19 |
| **Common Brick** | | | | | | |
| **4** | 32.4* | 12.4* | 6.8 | 42 | 16 | 9 |
| **5** | 13.6 | 12.4 | 5.0 | 44 | 40 | 16 |
| **6** | 9.7 | 9.7 | 4.9 | 24 | 24 | 12 |
| **7** | 10.4* | 10.5 | 4.9 | 23 | 23 | 11 |
| **8** | 7.3 | 8.4 | 3.2 | 20 | 23 | 9 |
| **Mean (9)** | 14.2 | 11.5 | 7.3 | … | … | … |

*** Strength at One Month.**

The results presented in Table 7 for the compressive stress of brick piers that caused failure of the piers have been plotted in Figure 3. This figure clearly shows the relationship identified by Baker from the data in the table. The results presented in Table 7 for the per cent of the compressive stress at failure of the piers have been plotted in Figure 4.

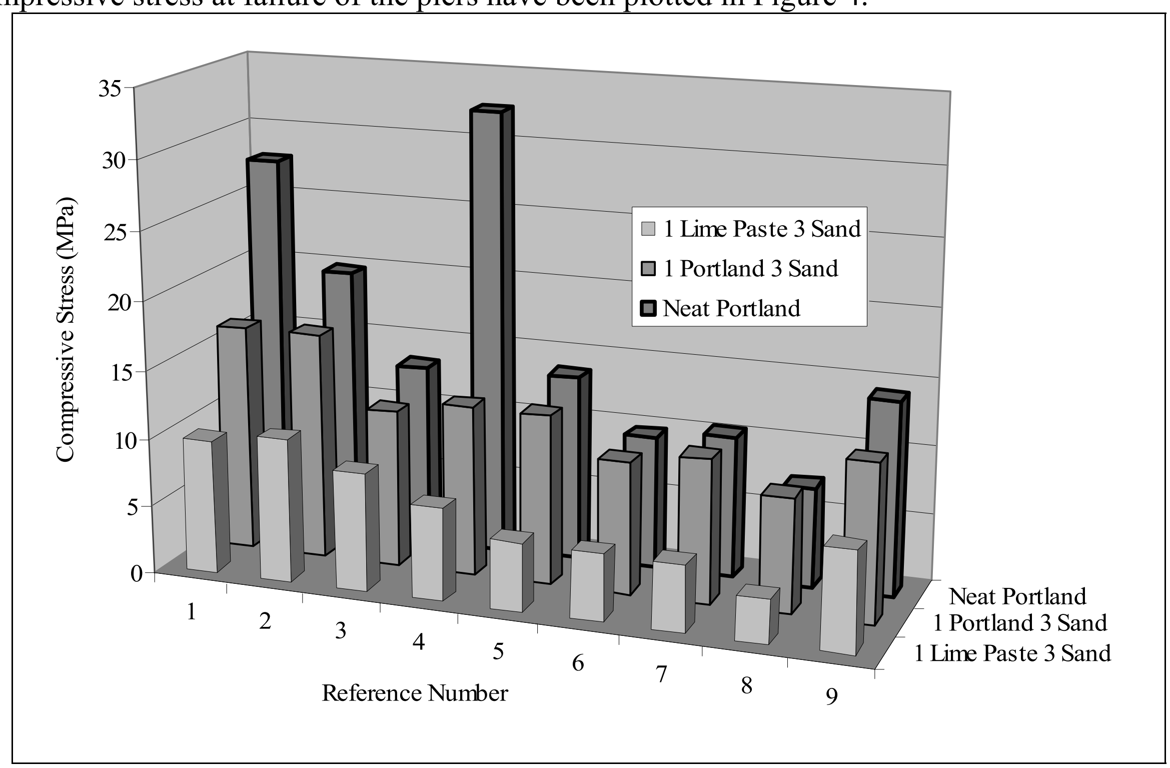


**Figure 3 – Compressive Stress (MPa) for the Louisiana Purchase Brick Piers**

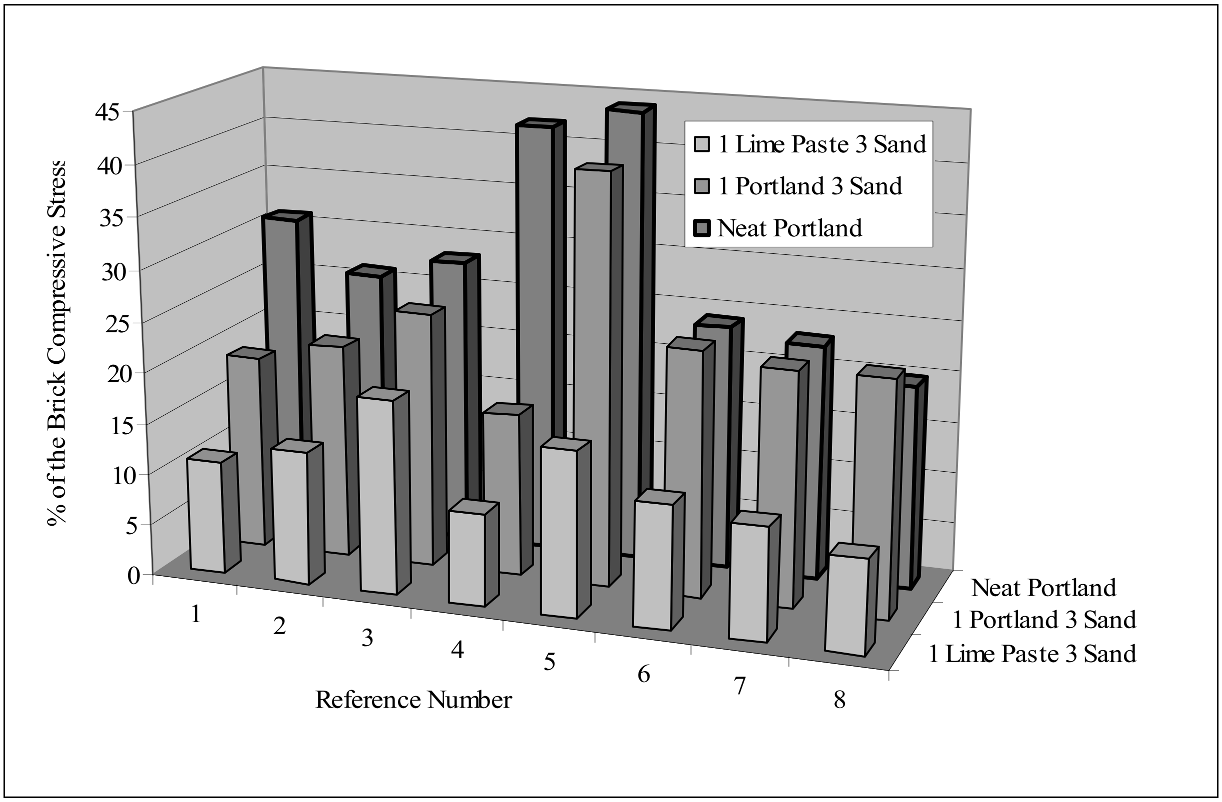


**Figure 4 – Percent of the Brick Compressive Stress for the Louisiana Purchase Brick Piers**

The results from Table 6 and 7 shows the compressive stress at failure of the masonry piers is related to the compressive stress of the mortar at failure, and that the compressive stress capacity of the pier is related to the compressive stress capacity of the brick. This result is shown on Figures 3 and 4. The result matches the later conclusions reached by Page [7] about masonry testing from the 1960s and 1970s. Baker noted that

> *'The only exceptions to these conclusions are abnormal cases where an unusually strong mortar is used with a very weak brick, or where a very weak mortar is used with a very strong brick.'*

**HISTORIC PRESERVATION**

Historic preservation often requires the conservation of buildings dating from the mid to late 19$^{th}$ and early 20$^{th}$ century. Baker provides a detailed set of compressive test results for a range of masonry constructed from soft bricks to hard structural bricks, as well as the test results for lime and cement mortars, and the transverse and compressive stress results for the bricks used to construct the masonry pier samples. The results show that a reasonable estimate can be made of the strength of masonry, particularly in the North Eastern region of the USA, if the compressive stress at failure of the brick can be determined and the petrography of the mortar can be ascertained. The techniques used to repair buildings from this period or earlier depend firstly on determination of the structural capacity and then selection of a suitable conservation method [8-13], with the practices developed in Europe since the late 1940s providing a sound basis for restoration of masonry structures in intraplate regional areas, as New England. The analysis techniques used for a review of an older structure must allow for the changes in material properties with age and the variation in the action effect with time [3].

## CONCLUSIONS

Ira O. Baker textbook on Masonry Construction presented a significant body of information on test results for lime mortars, cement mortars, bricks and masonry piers up to 1914. The bulk of the test results were obtained at the Watertown arsenal that was operated by the U.S War Department from 1816 to about 1995. The results for the brick compressive stress tests and the masonry pier compressive stress experiments show a distinct relationship between the brick strength, the mortar strength, and the masonry pier strength for masonry from the North Eastern region. The test results cover all types of brick from soft mud pressed bricks to hard fired bricks. The test results for the masonry in the late 19th to early 20th century show that modern repair techniques can be used with this type of masonry provided that an assessment is made of the brick strength and the mortar type, and a typical modern code of practice, such as ISO 13822 <u>Bases for design of structures -- Assessment of existing structures</u>, is used for the analysis.

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