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Engineering Properties of Historic Brick – Variability Considerations as a Function of Kiln Type

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KEYWORDS: brick, masonry unit, kiln, variability, historic, strength, absorption

ABSTRACT – Brick produced prior to the mid-twentieth century exhibit high levels of variability in appearance, geometry, and mechanical properties. Understanding historic brick variability is important for accurate performance prediction of existing structures, and for the selection of appropriate replacement units. A lack of uniformity amongst historic brick can be caused by the molding and firing methods, as well as the composition of their raw materials. This paper focuses on one aspect of production-induced disparities: kiln type. Tremendous variance can be shown from this alone, between both kiln type and even within a single firing. Although kilns of past eras were constantly improved for energy efficiency, their products continued to be highly inconsistent in appearance and performance. This paper presents the mechanics of heat distribution in kilns and demonstrates its direct impact on the variability of engineering properties due to inconsistent heat application.

1. INTRODUCTION

Performance characteristics of an individual brick are fundamentally important to the design profession, both when attempting to predict the behavior of existing buildings and in the selection of replacement units for such structures. For the modern design professional performance variability in materials is a largely unfamiliar concept, which makes behavioral prediction extremely difficult, even without taking into consideration the additional complications of age- and weather-based deterioration. Masonry variability is a function of brick and mortar properties and the bonding between them. For historic structures, this variability tends to be extremely high compared to expectations for modern materials. Even by considering only the historic brick (ignoring mortar and bonding related issues), extensive differences can be seen in physical appearance (e.g. color, geometry, surface texture) and engineering properties (e.g. compressive strength, hardness, and absorption), which can significantly impact the performance of masonry structures. Variability in historic brick is caused by the methods with which the brick were produced, as well as the raw materials used. Brick performance is a function of the clay type and processing, as well as the molding, drying, and firing of the brick. This paper concentrates on initial brick variability as a function of differences in firing technology. The firing process can profoundly influence the nature and performance of a masonry unit. To highlight performance differences as a function of the firing process, historic brick and brick replicated to match historic material are compared to modern material.

2. ENGINEERING PROPERTIES

In evaluating masonry studies from the early twentieth century and more recent research related to replicated historic brick, kiln selection appears to be a major cause of historic brick's inconsistent engineering properties. Early twentieth century brick testing clearly documents substantial variability in compression, tension, and absorption. Brick data from 4 parts of the United States (Chicago, Detroit, Mississippi, and New England), from as recently as 1929, display a large amount of scatter across a wide variety of engineering properties (Table 1). Compressive strengths ranged from 19,375 kN/m^2 to 71,019 kN/m^2, tensile strengths from 1,531 kN/m^2 to

4,144 kN/m^2, bending strengths from 4,358 kN/m^2 to 10,136 kN/m^2, and shear strengths from 7,585 kN/m^2 to 24,477 kN/m^2 (McBurney, 1929).

In a separate 1929 study, McBurney's testing of over 500 brick representing 27 manufacturers demonstrated that specimen behavior is influenced by method of manufacturing, type of raw materials, lamination characteristics, cracks, nodules, black cores, other inclusions, texture (e.g. granular, glassy), and degree of firing (Table 2) (McBurney, 1929). Given the extensive variability of the product from a single kiln, manufacturers often offered as many as four or five grades of brick (best, first, second, and third class, and clinkers) (Keele, 1908). Clinkers were overfired brick, and salmons were underfired ones, because of their light coloration. These defective brick were often sold for non-structural purposes due to their relatively poor strength characteristics, although their compressive strengths generally exceeded modern ASTM requirements.

The high level of performance variability of historic material stands in strong contrast to modern expectations and experience. Modern standards categorize brick depending upon one of three weathering grades (negligible, moderate, or severe). For each, minimum performance standards are set for strength (Table 3) (ASTM, 1999). According to this standard, 5 randomly selected brick must exhibit a minimum compressive strength of 10,343, 17,238, and 20,685 kN/m^2 for the negligible, moderate, and severe grades, respectively (ASTM 1999). There are similar, slightly less rigorous standards for any individual brick, which include absorption and saturation limits (Table 3). ASTM C62 also limits dimensional variations by specifying the maximum amount of variation from the standard dimensions (e.g. 5 mm in any direction for a 76 mm to 102 mm wide brick) (ASTM, 1999). Extensive testing by Subasic and Borchelt (1996) on modern materials show performance capabilities far in excess of these minimum requirements, with an average compressive strength of 5.4 and an average 24 hour cold absorption of 12,040.

Modern performance prediction of historic material is difficult because of the wide range of performance possibilities and the poor correlation between various performance indicators. Amongst 13 engineering properties tested by Stang and associates (1929), there was an average of 287% difference between the low and high results (based upon 4 to 10 specimens per brick type), with poor correlation, if any, between brick types (Table 1). Work by McBurney (1929) on over 40 categories of brick demonstrated no relationship between compressive strength and modulus of rupture or between other testing procedures (Table 2). Given the potential for nearly an order of magnitude difference in various engineering properties across various historic brick, identification of proper prototype values for historic materials remains a major challenge (Laefer, 2001). Value selection for compressive brick strength is of particular importance as it is a required input variable for determining overall masonry strength (ACI, 2002).

Since unit compressive strength is known to have an inverse relationship with absorption (Table 4) and a direct correlation with firing temperature, an investigation into the application of heat in various firing methods and equipment will help form realistic expectations regarding the anticipated range of performance values.

3. KILN TYPES

Dimensional and behavioral variability in brick can be considered a direct outgrowth of the firing process, which is highly dependent upon kiln type. Kilns have traditionally been distinguished by fuel type, efficiency and position of their heat source, heat distribution and heat continuity. In order to demonstrate how the technology has changed along with the resulting products produced, examples of periodic updraft and down-draft and continuous draft kilns and their affiliate products are compared to tunnel kilns.

3.1. UPDRAFT

Updraft kilns date back to the ancient Greeks and have remained relatively unchanged in their basic features to the present (Rhodes, 1968). Updraft kilns incorporate an enclosure in which to house the brick, lower apertures to insert fuel, and a chimney mechanism up above. A primitive but popular variant was the scove kiln, also known as a field kiln. Used extensively in the 18th century, with limited continued usage in the 20th (Conner, 1910 and Ritchie, 1960), this temporary kiln was constructed out of raw brick that were fired as part of the overall process. Thus, some of the brick that were fired were stacked to form the outside structure of the kiln (Fig. 1). Thus, some of the raw clay units were an inherent part of the firing apparatus (Rhodes, 1968). The brick were placed in mounds creating the appearance of a long rectangle with slightly slanted sides and were strategically stacked to allow the flames and heat to access different sections of the mound via “passageways” (Fig. 1) (McKee, 1973). The outer-brick, prior to firing, were covered with a layer of clay and grass to allow venting of the vapors. In a single firing 40,000 – 50,000 brick could be fired.

For scove kilns, initially brush, and then coal, was used as fuel (Rhodes, 1968). The fires were fed and stoked for a week, and then the fire holes were covered with brick and mortar to prevent the heat from escaping. During this period the fires burned out, but the greater portion of the heat remained. While the kiln remained closed the heat was allowed to dissipate for approximately one week.

During the firing, brick were exposed to varying temperatures up to 982°C resulting in very inconsistent strengths (Rhodes, 1968). Brick close to the fires were over-fired and sometimes vitrified, while brick far from the flames were softer and often more porous, causing them to be less desirable because of their lower strengths.

Replication of historic material has also shown highly variable performance. Quarter-scale, extruded clay units were fired in a permanent, updraft kiln located in the University of Illinois' Ceramics Engineering Department (Laefer, 2001). The brick were dried for a minimum of 24 hours at 66° C. The units were fired in a stationary (porcelain) kiln with electrical heating elements on five sides (Fig. 2). The brick were placed in two masses, each 464 mm by 597 mm by 127 mm high, containing approximately 1,400 brick per firing. Approximately 25,000 brick were fired in over a dozen firings. Firing occurred at 496° C (verified by a #09 Orton cone) for at least 12 hours, with an additional day of kiln time for cooling.

The goal was to create high absorption, low strength brick, typical of low firing. Since the power source was electrical (as opposed to gas or coal), the oxidizing (as opposed to reducing) atmosphere facilitated a rough correlation between coloration and brick absorption and strength with the darker color being indicative of less absorptive and stronger brick; as the temperature increased the iron oxide within the clay reacts and exhibits color change (Tables 4 and 5). Using a Munsell Color Chart, the brick were designated into five categories and sorted according to color (Table 6). The classification numbers ranged from one to five, one being lightly fired and five most fired.

The results of two firings demonstrated both the variability within a single firing and between firings that will occur, even under highly controlled procedures using Orton cones and timed firings (Fig. 3) (Laefer, 2001). The variability from a single firing exhibited over a 100%

strength difference between the strongest and the weakest brick. Although higher temperature firing or firings for longer periods of time would result in less variability, as well as a stronger product, the larger mass of brick needs to be considered since such comparative data is not fully available. The data presented here in may be considered qualitatively although not quantitatively indicative. These model brick were also compared to a similar miniature product produced in a modern tunnel kiln, which resulted in a profoundly different product (designated by the number 20) that achieved strengths nearly 5 times greater than any of the lightly fired products (Fig. 4).

Despite wide variability of the final product, the scove kiln was popular and commonly used, because it did not require the construction of a permanent facility (Rhodes, 1968). The relative ease of constructability and mobility allowed the temporary placement of these kilns at the point of use, instead of miles away from the construction site, where transportation would have posed economic and logistical impediments. Scove kilns are known to have been used in the construction of the College of William and Mary, and remains of seven of these temporary kilns have been found in Williamsburg, Virginia (McKee, 1973).

3.2. DOWNDRAFT

A more refined version of a draft kiln with better heat distribution was the downdraft kiln, which was especially well-suited to burn smaller quantities of higher grade fuel (Hoehne, 1910) and accommodate large quantities of brick (50,000 – 60,000). The brick were placed in stacks, with narrow spaces between them, to allow the heat to pass around the stacks (Fig. 5) (MIW, 2000). The downdraft kiln incorporated a multitude of evenly spaced fireplaces and a flue beneath the kiln floor. The flames were initially directed upward, and then the heat was drawn downwards from the top to fire the brick (Fig. 6). The heat was collected by flues, which lead to an externally placed chimney. This method promoted a more consistent heat exposure to all brick than the scove kilns, but it still lacked a high level of uniformity in the heat distribution and, thus, in the final product. Similar to scove kilns, a significant portion of downdraft kiln brick were excessively porous and soft (HCF, 2002).

A popular example of a downdraft kiln dating back to the 17th century was the beehive kiln, which was round and, thus, derived its name from the beehive it resembled (Fig. 7). The kiln was made of mortar and previously fired brick, and the dome was wrapped with steel bands to accommodate heat expansion (Fig. 7). The fuel was introduced through side portals at specific points around the circumference of the kiln (Fig. 6). The fire was partitioned from the raw clay units by low wall enclosures (Fig. 5).

Even from within one downdraft kiln and across one firing, brick strength and density properties vary based on brick position within the kiln. Compressive strength and density tests were conducted in 1907 on brick sampled from various positions (top, one-third height from the top, one-third height from the bottom, and the bottom) within a single kiln firing (Table 7). Both mud brick and dry pressed data from 1907 exhibit a trend of increasing brick strength and density with proximity to the heat source, despite the brick being formed by two different molding processes. The results clearly confirm the location of the heat source as the top of the kiln, as well as the potential for a large range of final products. Many of the beehive kilns were closed in the U.S. in the 1960's, because of an inability to economically convert them from coal consumption.

3.3. CONTINUOUS DRAFT

Initially used in the first century A.D., chamber kilns are typified by multiple firing sectors within a single kiln. From the beginning, they were extremely fuel efficient, because the excess heat from one chamber was transferred to another chamber through the use of flues, thereby minimizing heat wastage. These kilns were widely used until the mid-nineteenth century, at which time the continuous chamber kiln was developed (Rhodes, 1968). The continuous chamber kiln invented by Hoffman and Hieut in 1858 was a refinement of the previous design and consisted of a series of single chamber kilns adjoined to each other. Each chamber is fired sequentially throughout the multipart kiln, and the process of firing, cooling, and brick loading occur progressively through the series of chambers. Unused heat from one chamber is transferred to the next for preheating (Fig. 8). To prevent interruptions in this cycle of preheating, firing, and cooling, the kilns were placed in a circular manner, which results in reducing fuel consumption by two-thirds (Roberts, 1962). Stang and associates' 1929 study demonstrated a wide range of brick performance. Based upon their manufacturing date, the brick were probably products of a continuous chamber kiln (Table 1), as Hoehne (1910) estimated that by 1910 90-95% of all brick kilns in Europe were continuous chamber kilns and that the trend was beginning in the U.S. The original circular chamber design (Fig. 8) was first modified by Hoffman in 1870 in order to decrease product variability caused by the non-uniform geometry of the original design. Hoffman's modification of the circular design was to use two long tunnels connected by curved end sections (Roberts, 1962). Visually, this design is clearly a predecessor for the tunnel kiln.

3.4. TUNNEL KILN

The tunnel kiln is similar to the chamber kiln in its continuous application of heat, but differs because it is substantially more heat efficient and because the brick, instead of the heat, move through the kiln. In a tunnel kiln the heat source remains stationary while the brick travel, facilitating mass production and resulting in minimized maintenance costs because of the reduced stress on the kiln (Fig. 9). Previous kilns underwent cycles of heating and cooling, which induced cyclical strains in the kiln structure. In contrast, the only portion of the tunnel kiln that is heated remains so continuously (Norton 1952), therefore the heat-based cyclic straining does not occur.

Although the first tunnel kiln was built in 1751 in France, popularization did not occur until the late 1800's in England, with Bock's innovation in sand seals (Fig. 10). Previously, poor seals between the actual cars and the firing chambers failed to insulate the cars' mechanisms from the extreme heat of the fire (Rhodes 1968). The top of Bock's new seal mechanism was made of a refractory material sufficiently thick to protect the metal. Along each side of the kiln walls was a trough filled with sand. A steel blade attached to the cart dipped into the sand trough, creating a highly efficient gas-tight seal, which is a trademark of modern tunnel kilns (Norton 1952). The earliest tunnel kilns operated in a similar manner to modern kilns in that the brick passed though three stages: preheating, firing, and cooling. The brick were placed on cars that ran on a track through a tunnel adjacent to the heat source. Throughout their preheating cycle, the brick were subjected to increasing temperatures until the firing cycle, where a maximum temperature of 1066^{o} C was reached and maintained (Rhodes, 1968).

As part of the normal 36 hour trip from entering the kiln to exiting it, the brick next passed through the cooling stage. The cooler air entered the end of the tunnel via a blower and was collected at the end of the firing zone. Similar to the draft kilns, the dissipating heat from the firing cycle was blown to the beginning of the tunnel for the pre-heating portion (Fig. 11) (Norton 1952). Slow cooling was introduced to reduce cracking and pitting, which could ultimately induce strength loss (MIW, 2000).

The difference between the modern and early tunnel kiln is the use of blowers for both preheating and cooling. Ducts and blowers promote a more uniform distribution of the heat in the drying, preheating, firing, and cooling cycles (Rhodes, 1968). Another reason for improved consistency in later tunnel kilns was the fuel source. Early versions of these tunnel kilns, including Bock's, continued to rely on combustion fuels, such as coal, which had to be continuously fed. When oil and gas burners were introduced (c. 1900 and c. 1920 respectively) (Rhodes, 1968), the tunnel kilns became more economical and produced a more uniform product because they were less reliant on human tending of the fuel.

Since the brick in a tunnel kiln are more uniformly exposed to the same heat treatment throughout the tunnel kiln, there is a much higher level of uniformity in the final product. Furthermore, the actual temperature could then be sustained at a higher temperature (nearly 1093^{o}C versus the typical 538^{o}C found in direct draft kilns) and automatically controlled by computers that continuously monitor and adjust the temperature at various stages of the process and change the speed at which the brick pass through the kiln (MIW, 2000).

To better understand the impact of kilns on the engineering properties of brick, modern shale units were compared to pre-civil war brick (Table 8). The latter were salvaged from the demolished Jakes Home in Urbana, Illinois in 2000. The modern units were fired in a tunnel kiln and obtained randomly from a local supplier. The firing equipment for the pre-civil war brick is unknown (Fig. 12) but is thought to have been fairly primitive because of low compressive strengths and orange color, both of which are indicators of low firing temperatures. Nine of each brick type were compression tested: three flat, three on edge, and three on end. Consistently within each testing orientation, denser brick correlated with lower absorption and higher strength (Fig. 13). Although 150 years of weather exposure may have also negatively influenced strength characteristics, quantification is impossible without control units. The topic of weather-based deterioration is largely outside of the scope of this paper and has been extensively studied elsewhere.

4. CONCLUSIONS

Variation in the appearance and engineering properties of historic brick is a direct reflection of quantity and distribution of heat within a kiln. The high-level of variability in historical materials may be unanticipated by modern designers schooled in the production techniques of twentieth century tunnel kilns. Although nineteenth century brick could and did regularly achieve modern brick strengths, as well as minimum strength standards, a much wider performance range should be expected for historic units. As such, the results of selective, limited brick testing should be used with great care when choosing engineering properties for analytical input, computer modeling, or material replacement specification.

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Table 1. Comparative Brick Testing (data from Stang et al., 1929)

	Brick Type	Chicago	Detroit	Mississippi	New England	High/Low difference (%)
Absorption (%)	5 hr boil	16.5	22.3	21.7	9.2	242
	48 hr soak	11.7	20.7	16.7	6.9	300
Bending (KN/m^2)	Flat dry	8,446	4,620	5,654	10,687	231
	Flat wet	10,136	4,358	5,171	9,653	233
	Edge	9,239	4,689	5,240	11,308	241
Compression (KN/m^2)	Whole brick dry	23,857	22,443	24,994	64,951	289
	Half brick dry	22,616	24,408	23,512	59,297	262
	Half brick wet	25,305	17,375	24,270	48,196	277
Compression edge (KN/m^2)	Whole brick dry	19,375	23,305	22,064	71,019	367
	Half brick dry	23,098	22,547	24,994	79,086	350
	Half Brick wet	24,960	21,823	24,960	75,983	348
Tension (KN/m^2)		2,875	1,531	2,186	4,144	271
Shear (KN/m^2)		7,585*	8,033*	10,963*	24,477^	323
					Average	287

Chicago: end cut, stiff mud, containing lime nodules Detroit: soft mud, with one face frog

New England: soft-mud, sand struck, one face frog, very hard burned Mississippi: dry press

*Average of 10 tests on half brick ^Average of 4 tests on 1” thick cut slabs

Table 2. Excerpts of Brick Properties Tested at Various Orientations (McBurney, 1929)

Forming Method	Brick Type	Modulus of Rupture (KN/m^2)	Comp. Strength Flat Half Brick (KN/m^2)	Comp. Strength Edge Half Brick (KN/m^2)	Mod. of Rupture/Flat Comp. Strength (%)	Mod. of Rupture/Edge Comp. Strength (%)	Comp. Strength Flat/Comp. Strength Edge (%)	No. of Samples
D.P.	well made, no laminations	7,764	39,715	37,323	0.195	0.218	1.060	3
D.P.	commons, no laminations	5,516	24,270	25,029	0.227	0.220	0.970	98
D.P.	underfired salmons, weak	972	12,825	7,874	0.07	0.123	1.620	5
D.P.	experimental shale	13,928	130,867	80,672	0.106	0.173	1.620	4
S.D.P.	clinker, warped, cracked	5,875	53,160	49,782	0.111	0.118	1.070	3
S.D.P.	less cracked	6,116	50,334	50,334	0.121	0.121	1.000	3
S.D.P.	salmon	2,020	16,755	17,031	0.120	0.119	0.985	3
S.M.	some warpage	3,551	18,754	21	0.189	0.170	0.900	5
S.M.	select common, occasional nodules	4,620	22,891	23,167	0.201	0.200	0.990	50
S.M.	select common, many lime nodules	3,372	21,443	21,850	0.157	0.155	0.982	50
S.M.	heart and core	10,687	59,366	79,982	0.180	0.134	0.742	100
S.M.	salmons, grains visible	2,406	13,218	15,445	0.182	0.160	0.856	6
S.M.E.C.	lamination and black cores	9,101	23,236	26,063	0.392	0.349	0.891	94
S.M.E.C.	very salmon	4,723	18,685	14,066	0.251	0.336	1.330	7
S.M.E.C.	lamination and black cores	8,929	20,961	21,995	0.426	0.406	0.953	5
S.M.E.C.	clinker, warped, cracked	6,530	47,644	49,644	0.160	0.131	0.960	5
S.M.E.C.	good, slight lamination	8,619	45,162	46,748	0.191	0.184	0.965	5
S.M.E.C.	salmon	2,882	16	14,480	0.178	0.199	1.120	4
S.M.E.C.	well made shale	10,846	73,845	62,772	0.154	0.173	1.122	50
S.M.S.C.	salmon	5,351	42,011	37,095	0.127	0.144	1.130	11
S.M.S.C.	well made shale	14,686	97,220	74,121	0.151	0.198	1.320	6
S.M.S.C.	well made shale, hard fired	19,540	77,638	71,294	0.151	0.175	1.090	5
S.M.S.C.	well made shale, medium fired	8,508	95,013	71,984	0.090	0.117	1.330	5
S.M.S.C.	common shale, med. fired	10,184	55,746	51,126	0.183	0.200	1.090	2
S.M.S.C.	Hard shale commons	19,927	155,827	130,660	0.128	0.153	1.190	25
S.M.S.C.	shale internal cracks top	12,852	41,025	38,336	0.314	0.335	1.070	5
S.M.S.C.	highly die laminated	4,971	41,301	26,311	0.120	0.189	1.570	3
S.M.S.C.	salmon, laminated	2,117	24,450	13,997	0.087	0.151	1.750	3
S.M.S.C.	face shale, hard fired	22,271	146,174	97,909	0.152	0.227	1.490	3
S.M.S.C.	fillers, salmon	6,805	43,094	40,612	0.158	0.168	1.060	4

D.P. -- dry press
S.D.P. -- semidry press
S.M. -- soft mud
S.M.E.C -- stiff mud, end cut
S.M.S.C. -- stiff-mud side cut

Table 3. Physical Requirements (from ASTM, 1999)

	Minimum Compressive Strength (KN/m^2)		Maximum Water Absorption by 5-h boiling (%)		Maximum Saturation Coefficient	
	Average of 5 Brick	Individual	IRA	IRA Individual	Average of 5 Brick	Individual
Grade SW	20,685	17,238	17	20	0.78	0.8
Grade MW	17,238	15,169	22	25	0.88	0.9
Grade NW	10,343	8,619	no limit	no limit	no limit	no limit

SW: Severe Weathering MW: Moderate Weathering NW: Negligible Weathering

Table 4. Compressive Strength as an Inverse of Absorption Capacity

(Fried and Law, 1995)

Clay Brick Type	Compressive Strength (KN/m^2)*	Water Absorption (%)
Low absorption, solid	79,299	5.7
Medium absorption, solid	45,004	12
High absorption, frog	31,800	21.8

*Tested in non-standard manner of a full single brick capped with mortar on top and bottom

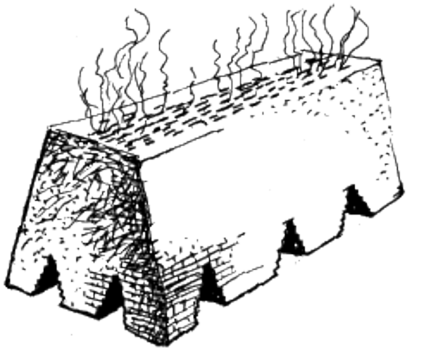


Fig. 1. Scove Kiln (Rhodes, 1968)

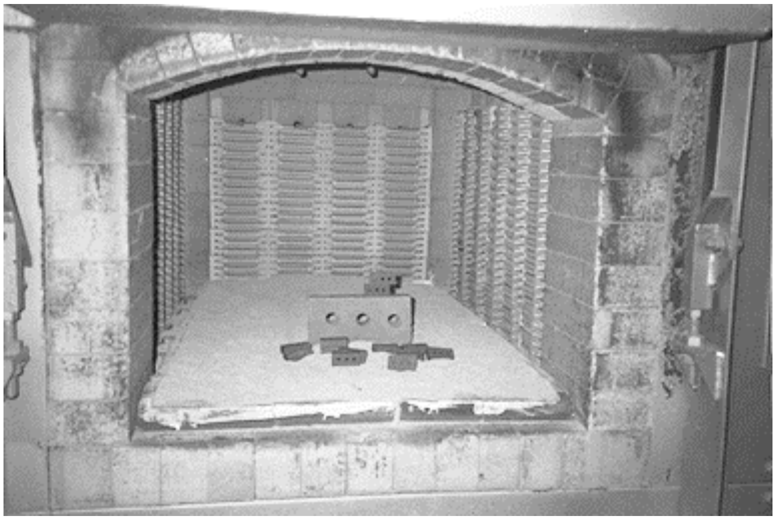


Fig. 2. Electric, Updraft Kiln with Miniature Brick

Table 5. Brick Absorption by Coloration (Laefer, 2001)

Brick Designation	Absorption (%)	Average Strength (KN/m^2)
1	16.4	3,103
2-3	16.2	3,916-5,978
4-5	15.8	7,350

Table 6. Munsell Color Chart Description of Brick to Depict Fire Designation

(Laefer, 2001)

Laboratory Designation	0	1	2	3	4	5
Munsell Hue Page	5 yellow grey	7.5 yellow red	5 yellow red	5 yellow red	2.5 yellow red	2.5 yellow red
Munsell Classification	8/2	7/4	6/8	6/8	6/8	5/10

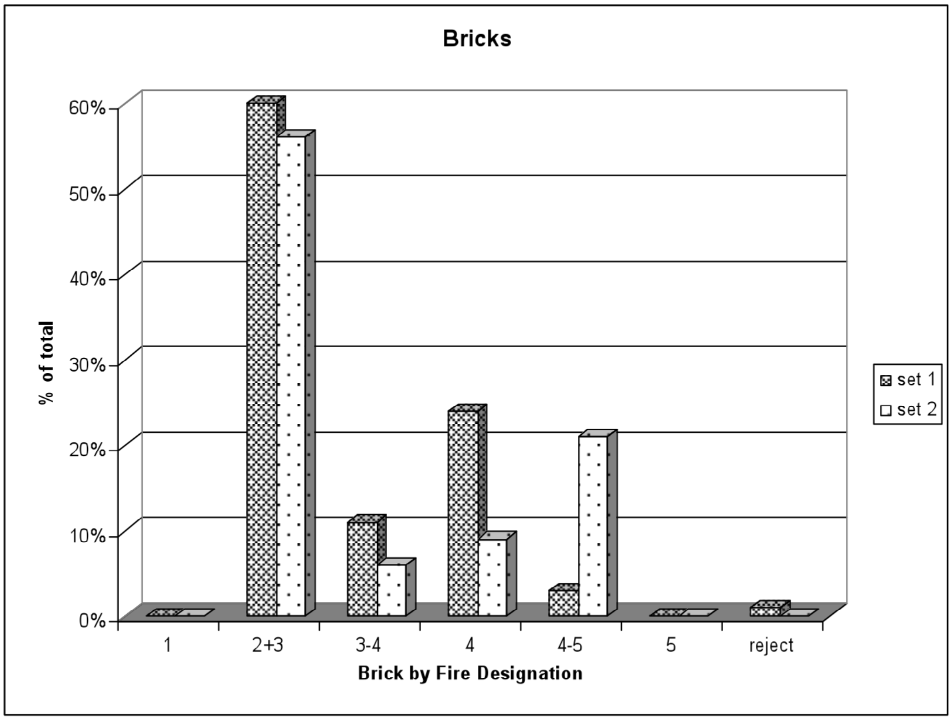
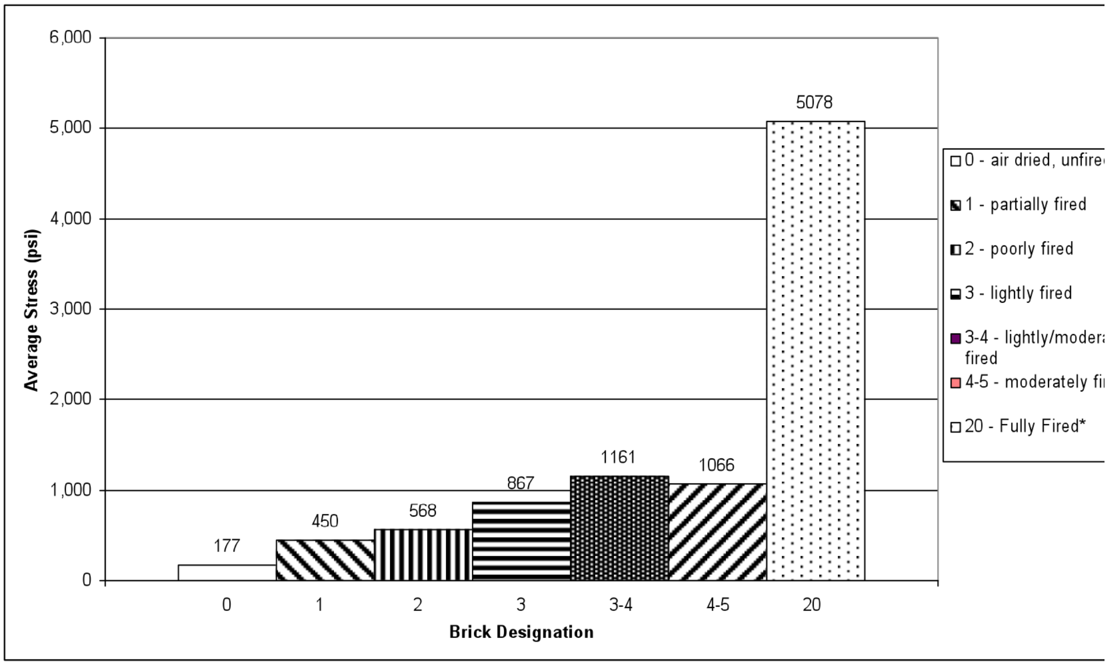


Fig. 3. Results of Two Firings as Sorted by Color Designation (Laefer, 2001)



*Fired in a modern tunnel kiln.

Fig. 4. Average Ultimate Compressive Strength of Various Brick Types

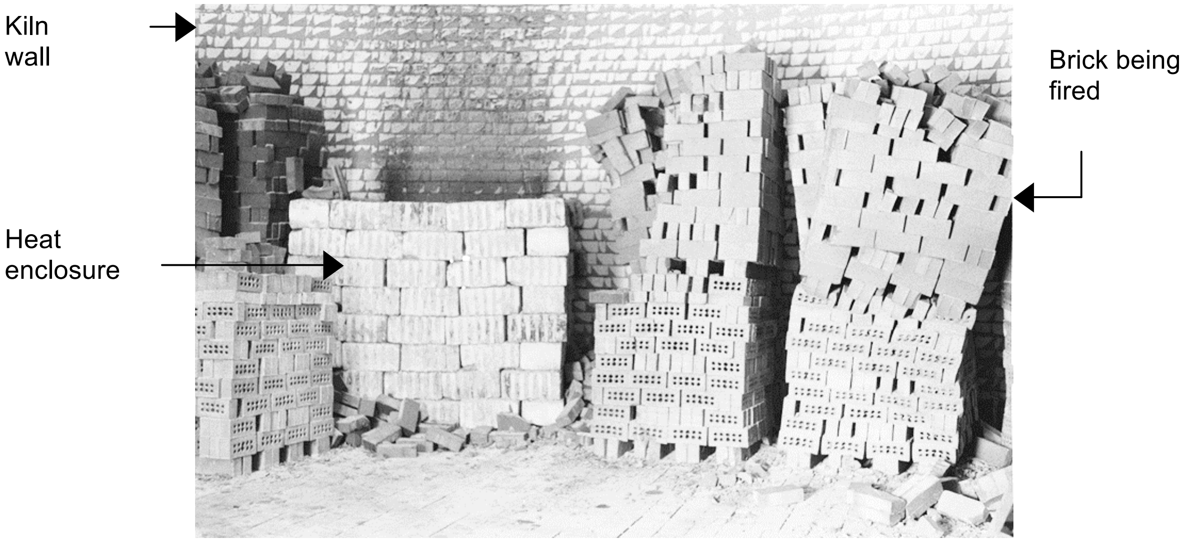


Fig. 5. Brick Stacks inside a Downdraft, Beehive Kiln; Heat Enclosure Visible

(Laefer, 2001)

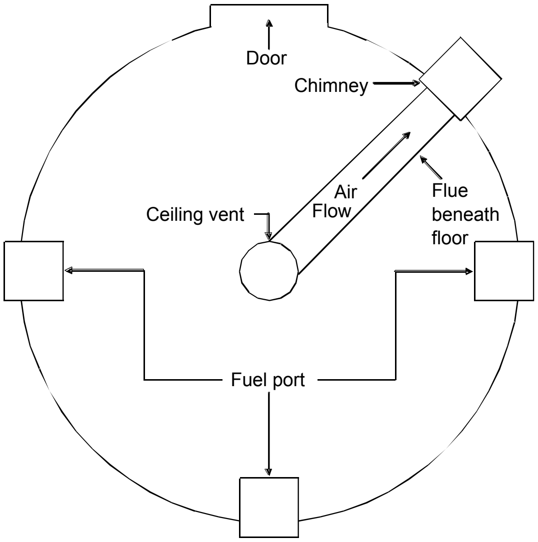


Fig. 6. Plan View of Downdraft, Beehive Kiln

Fig. 7. Exterior of Beehive Kiln (Laefer, 2001)

Table 7. Down Draft Kiln Brick Properties as a Function of Kiln Position

(data from Anon, 1907)

	Mud Brick				Dry Pressed			
Kiln Position	Comp. Strength (kN/m^2)	Density (kN/m^3)	IRA by Weight (%)	Compressibility (%)	Comp. Strength (kN/m^3)	Density (kN/m^3)	IRA by Weight (%)	Compressibility (%)
Top	132,177	22.7	3.0	9,000	71,019	20.2	9	3,333
1/3	108,045	21.4	5.0	7,500	60,262	20.0	11	2,905
2/3	71,846	20.5	8.0	4,600	40,956	19.5	12	2,100
Bottom	74,949	19.7	10.5	4,400	23,995	18.8	15	1,120
High/Low Difference (%)	184	115	350	205	296	107	167	298

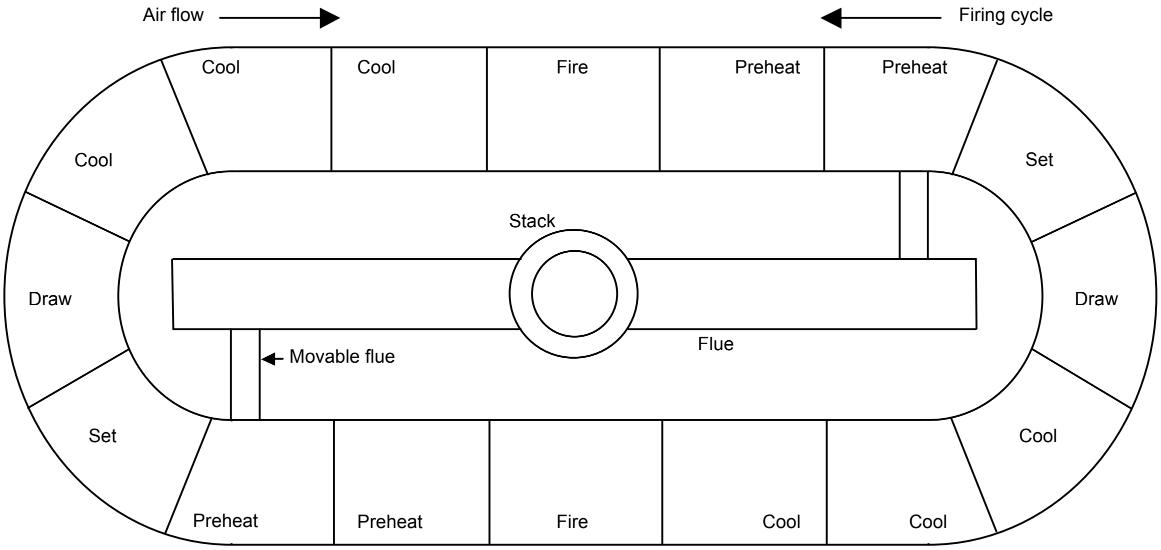


Fig. 8. Circular Placement of Separate Kilns in a Chamber Kiln System

(adapted from Rhodes, 1968)

Fig. 9. Modern Tunnel Kiln (GGB 2003)

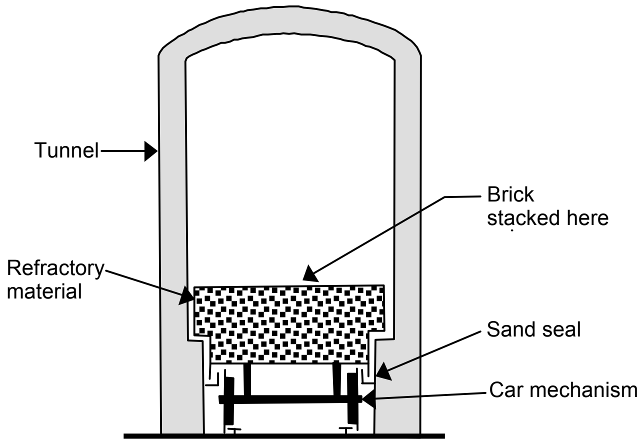


Fig. 10. Cross-section of Tunnel Kiln (adapted from Rhodes, 1968)

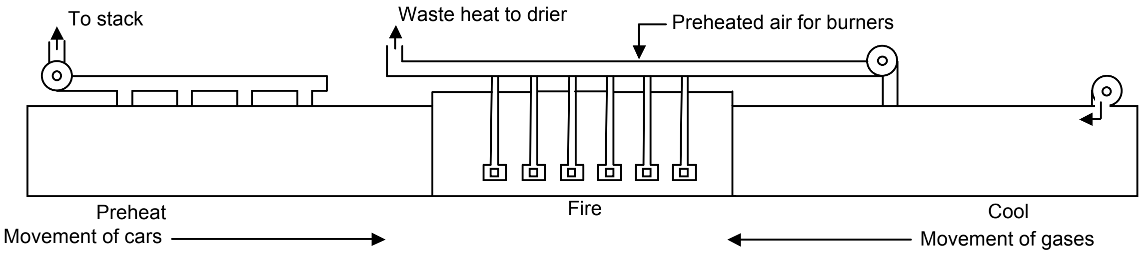


Fig. 11. Modern Tunnel Kiln (adapted from Rhodes, 1968)

Table. 8. Performance Characteristics of Modern Brick versus Pre-Civil War BrickREMOVE

		Old	New
End Loading	Maximum Compressive Stress (KN/m^2)	6,268	60,545
		3,096	34,344
		4,371	29,393
	Avg Stress (KN/m^2)	4,578	41,432
Edge Loading	Maximum Compressive Stress (KN/m^2)	2,930	27,745
		1,338	35,075
		2,420	42,556
	Avg Stress (KN/m^2)	2,227	35,123
Flat Loading	Maximum Compressive Stress (KN/m^2)	11,459	107,362
		11,508	112,540
		37,709	111,272
	Avg Stress (KN/m^2)	20,223	110,389
	Edge/End	0.486	0.848
	Edge/Flat	0.110	0.318
	End/Flat	0.226	0.375

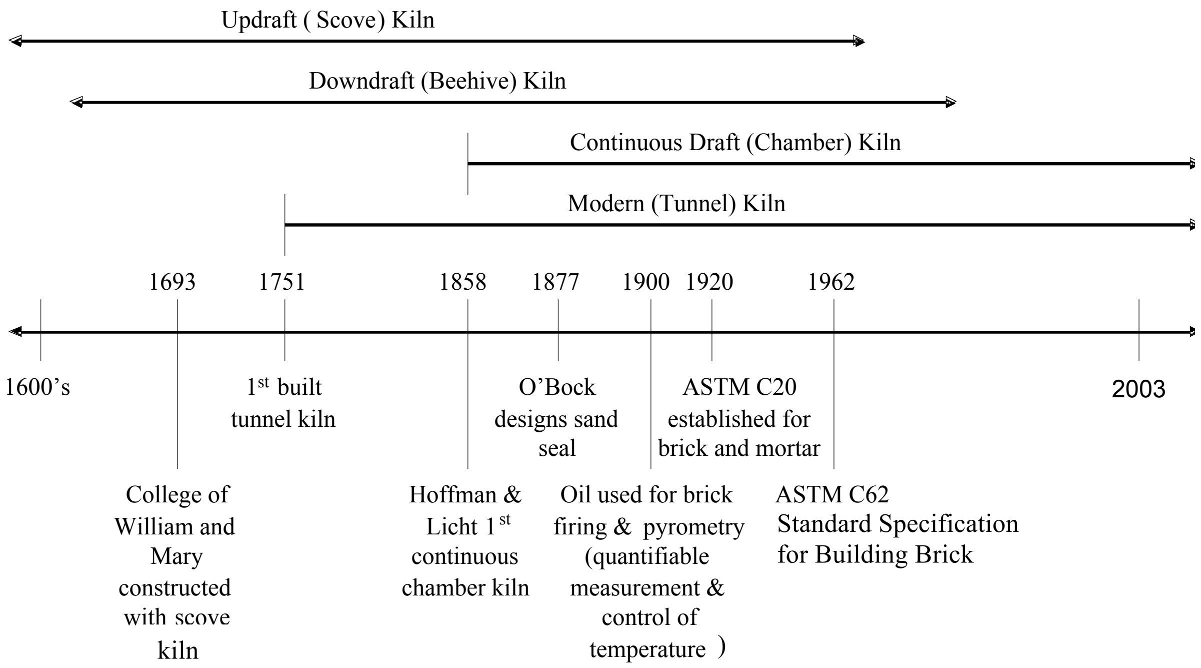


Fig. 12. Timeline of Kiln Development

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Fig. 13. Performance of Modern Brick Compared to Pre-Civil War Brick

Table Captions

Table 1. Comparative Brick Testing (data from Stang et al., 1929)

Table 2. Excerpts of Brick Properties Tested at Various Orientations (McBurney, 1929)

Table 3. Physical Requirements (from ASTM, 1999)

Table 4. Compressive Strength as an Inverse of Absorption Capacity

Table 5. Brick Absorption by Coloration (Laefer, 2001)

Table 6. Munsell Color Chart Description of Brick to Depict Fire Designation (Laefer, 2001)

Table 7. Down Draft Kiln Brick Properties as a Function of Kiln Position

(data from Anon, 1907)

Table. 8. Performance Characteristics of Modern Brick versus Pre-Civil War Brick

Figure Captions

Fig. 1. Scove Kiln (Rhodes, 1968)

Fig. 2. Electric, Updraft Kiln with Miniature Brick

Fig. 3. Results of Two Firings as Sorted by Color Designation (Laefer, 2001)

Fig. 4. Average Ultimate Compressive Strength of Various Brick Types

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Engineering Properties of Historic Brick –

Variability Considerations as a Function of Kiln Type

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Paper Outline (for benefit of reviewer)

1. Introduction

2. Engineering Properties

3. Kiln Types

    3.1 Updraft

    3.2 Downdraft

    3.3 Continuous Draft

    3.4 Tunnel Kiln

4. Conclusions

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