THE BRICK INDUSTRY ASSOCIATION TECHNICAL NOTES on Brick Construction
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Technical Notes 3A - Brick Masonry Material Properties
December 1992

Abstract: Brick masonry has a long history of reliable structural performance. Standards for the structural design of masonry which are periodically updated such as the *Building Code Requirements for Masonry Structures* (ACI 530/ASCE 5/TMS 402) and the *Specifications for Masonry Structures* (ACI 530.1/ASCE 6/TMS 602) advance the efficiency of masonry elements with rational design criteria. However, design of masonry structural members begins with a thorough understanding of material properties. This *Technical Notes* is an aid for the design of brick and structural clay tile masonry structural members. Clay and shale units, mortar, grout, steel reinforcement and assemblage material properties are presented to simplify the design process.

Key Words: brick, grout, material properties, mortar, reinforcement, structural clay tile.

INTRODUCTION

The Masonry Standards Joint Committee (MSJC) has developed the *Building Code Requirements for Masonry Structures* (ACI 530/ASCE 5/TMS 402) and the *Specifications for Masonry Structures* (ACI 530.1/ASCE 6/TMS 602). In this *Technical Notes*, these documents will be referred to as the MSJC Code and the MSJC Specifications, respectively. Their contents are reviewed in *Technical Notes* 3. The MSJC Code and Specifications are periodically revised by the MSJC and together provide design and construction requirements for masonry. The MSJC Code and Specifications apply to structural masonry assemblages of clay, concrete or stone units.

This *Technical Notes* is a design aid for the MSJC Code and Specifications. It contains information on clay and shale units, mortar, grout, steel reinforcement and assemblage material properties. These are used in the initial stages of a structural design or analysis to determine applied stresses and allowable stresses. Material properties are explained to aid the designer in selection of materials and to provide a better understanding of the structural properties of the masonry assemblage based on the materials selected.

CONSTITUENT MATERIAL PROPERTIES

Because brick masonry is bonded into an integral mass by mortar and grout, it is considered to be a homogeneous construction. It is the behavior of the combination of materials that determines the performance of the masonry as a structural element. However, the performance of a structural masonry element is dependent upon the properties of the constituent materials and the interaction of the materials as an assemblage. Therefore, it is important to first consider the properties of the constituent materials: clay and shale units, mortar, grout and steel reinforcement. This will be followed by a discussion of the behavior of their combination as an assemblage.

Clay and Shale Masonry Units

There are many variables in the manufacturing of clay and shale masonry units. Primary raw materials include surface clays, fire clays, shales or combinations of these. Units are formed by extrusion, molding or dry-pressing and are fired in a kiln at temperatures between 1800^{o}F and 2100^{o} (980^{o}C and 1150^{o}C). These variables in manufacturing produce units with a wide range of colors, textures, sizes and physical properties. Clay and shale masonry units are most frequently selected as a construction material for their aesthetics and long-term performance. Consequently, material standards for clay and shale masonry units contain requirements to ensure that units meet a level of durability and visual and dimensional consistency. Clay and shale masonry units used in structural elements of building constructions are brick and structural clay tile. Material standards for brick and structural clay tile include: ASTM C 216 (facing brick), ASTM C 62 (building brick), ASTM C 652 (hollow brick), ASTM C 212 (structural clay facing tile) and ASTM C 34 (structural clay load-bearing tile).

While brick and structural clay tile are both visually appealing and durable, they are also well-suited for many structural applications. This is primarily due to their variety of sizes and very high compressive strength. The material properties of brick and structural clay tile which have the most significant effect upon structural performance of the masonry are compressive strength and those properties affecting bond between the unit and mortar, such as rate of water absorption and surface texture.

Unit Compressive Strength. The compressive strength of brick or structural clay tile is an important material property for structural applications. In general, increasing the compressive strength of the unit will increase the masonry assemblage compressive strength and elastic modulus. However, brick and structural clay tile are frequently specified by material standard rather than by a particular minimum unit compressive strength. ASTM material standards for brick and structural clay tile require minimum compressive strengths to ensure durability, which may be as little as one-fifth the actual unit compressive strength. A recent Brick Institute of America survey of United States brick manufacturers resulted in a data base of unit properties [6]. A subsequent survey of structural clay tile manufacturers was conducted. The compressive strengths of brick and structural clay tile evaluated in these surveys are presented in Table 1. As is apparent, all types of brick and structural clay tile typically exhibit compressive strengths considerably greater than the ASTM minimum requirements. Compressive strength of brick and structural clay tile is determined in accordance with ASTM C 67 Method of Sampling and Testing Brick and Structural Clay Tile.

TABLE 1
Brick and Structural Clay Tile Unit Compressive Strengths

Unit Type			Mean Unit Compressive Strength, psi (Mpa)	Standard Deviation of Compressive Strength, psi (MPa)
Solid brick	Forming Method	Extruded	11305 (77.9)	4464 (30.8)
		Molded	5293 (36.5)	1822 (12.6)
	Raw Material[1]	Fire clay	15346 (105.8)	5065 (34.9)
		Shale	11258 (77.6)	3487 (24.0)
		Other[2]	9169 (63.2)	3988 (27.5)
Hollow Brick[3]			6736 (46.4)	2447 (16.9)
Structural clay tile[3]		Vertical coring	10057 (69.3)	5578 (38.5)
		Horizontal coring	5119 (35.3)	2067 (14.3)

[1]Extruded only.

[2]Made from other materials or a combination of materials.

[3]Based on gross area.

Unit Texture and Absorption. Unit texture and absorption are properties which affect the bond strength of the masonry assemblage. In general, mortar bonds better to roughened surfaces, such as wire cut surfaces, than to smooth surfaces, such as die skin surfaces. Cores or frogs provide a means of mechanical interlock. The bond strength of sanded surfaces is dependent upon the amount of sand on the surface, the sand's adherence to the unit and the absorption rate of the unit at the time of laying.

In practically all cases, mortar bonds best to a unit whose suction at the time of laying is less than 30 g/min/30 in^2 (1.55 kg/min/m^2). Generally, molded units will exhibit a higher initial rate of absorption than extruded or dry-pressed units. Unit absorption at the time of laying is an alterable property of brick and structural clay tile. In accordance with the MSJC Specifications, units with initial rate of absorption in excess of 30 g/min/30 in.^{2} (1.55 kg/min/m^2) should be wetted to reduce the rate of water absorption of the unit prior to laying. In addition, suction of very absorptive units may be accommodated by using highly water-retentive mortars.

Mortar

The material properties of mortar which influence the structural performance of masonry are compressive strength, bond strength and elasticity. Because the compressive strength of masonry mortar is less important than bond strength, workability and water retentivity, the latter properties should be given principal consideration in mortar selection. Mortar materials, properties and selection of masonry mortars are discussed in *Technical Notes* 8 Series. Mortar should be selected based on the design requirements and with due consideration of the MSJC Code and Specifications provisions affected by the mortar selected.

Laboratory testing indicates that masonry constructed with portland cement-lime mortar exhibit greater flexural bond strength than masonry constructed with masonry cement mortar or air-entrained portland cement-lime mortar of the same Type. This behavior is reflected in the MSJC Code allowable flexural tensile stresses for unreinforced masonry, which are based on the mortar Type and mortar materials selected. In addition, masonry cement mortars may not be used in Seismic Zones 3 and 4.

Other MSJC Code and Specifications provisions are the same for portland cement-lime mortars, masonry cement mortars and air-entrained portland cement-lime mortars of the same Type. These include the modulus of elasticity of the masonry, allowable compressive stresses for empirical design and the unit strength method of verifying that the specified compressive strength of masonry is supplied. Following is a general description of the structural properties of each Type of mortar permitted by the MSJC Code and Specifications.

Type N Mortar. Type N mortar is specifically recommended for chimneys, parapet walls and exterior walls subject to severe exposure. It is a medium bond and compressive strength mortar suitable for general use in exposed masonry above grade. Type N mortar may not be used in Seismic Zones 3 and 4.

Type S Mortar. Type S mortar is recommended for use in reinforced masonry and unreinforced masonry where maximum flexural strength is required. It has a high compressive strength and has a high tensile bond strength with most brick units.

Type M Mortar. Type M mortar is specifically recommended for masonry below grade and in contact with earth, such as foundation walls, retaining walls, sewers and manholes. It has high compressive strength and better durability in these environments than Type N or S mortars.

For compliance with the MSJC Specifications, mortars should conform to the requirements of ASTM C 270 Specification for Mortar for Unit Masonry. Field sampling of mortar for quality control should follow the procedures given in ASTM C 780 Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry. Test procedures for masonry mortars are covered in *Technical Notes* 39 Series.

Grout

Grout is used in brick masonry to fill cells of hollow units or spaces between wythes of solid unit masonry. Grout increases the compressive, shear and flexural strength of the masonry element and bonds steel reinforcement and masonry together. For compliance with the MSJC Specifications, grout which is used in brick or structural clay tile masonry should conform to the requirements of ASTM C 476 Specification for Grout for Masonry. Grout proportions of portland cement or blended cement, hydrated lime or lime putty, and coarse or fine aggregate are given in Table 2.

TABLE 2
ASTM C 476 Grout Proportions by Volume

Grout Type	Portland Cement or Blended Cement	Hydrated Lime or Lime Putty	Fine Aggregate[1]	Coarse Aggregate[1]
Fine	1	0 to 1/10	2 1/4 to 3 times the sum of the volumes of the cementitious materials	NONE
Coarse	1	0 to 1/10	2 1/4 to 3 times the sum of the volumes of the cementitious materials	1 to 2 times the sum of the volumes of the cementitious materials

[1]Aggregate measured by volume in a damp, loose condition.

The amount of mixing water and its migration from the grout to the brick or structural clay tile will determine the compressive strength of the grout and the amount of grout shrinkage. Tests indicate that the total amount of water absorbed from grout by hollow clay units appears to be more dependent on the initial water content of the grout than the absorption properties of the unit [3]. Grouts with high initial water content exhibit more shrinkage than grouts with low initial water contents. Consequently, use of a non-shrink grout admixture is recommended to minimize the number of flaws and shrinkage cracks in the grout while still producing a grout slump of 8 to 11 in. (200 to 280 mm), unless otherwise specified.

The MSJC Specifications require grout compressive strength to be at least equal to the specified compressive strength of masonry, f'_m, but not less than 2,000 psi (13.8 MPa) as determined by ASTM C 1019 Method of Sampling and Testing Grout. Test procedures for grout are explained in more detail in *Technical Notes* 39 Series. In general, the compressive strength of ASTM C 476 grout by proportions will be greater than 2,000 psi (13.8 MPa). Prediction of the compressive strength of grout which is proportioned in accordance with ASTM C 476 is difficult because of the many possible combinations of materials, types of materials and construction conditions. However, ASTM C 476 grout proportions produce a rich mix which is recommended to complement the high compressive strength of brick and structural clay tile.

Steel Reinforcement

Steel reinforcement for masonry construction consists of bars and wires. Reinforcing bars are used in masonry elements such as walls, columns, pilasters and beams. Wires are used in masonry bed joints to reinforce individual masonry wythes or to tie multiple wythes together. Bars and wires have approximately the same modulus of elasticity, which is stated in the MSJC Code as 29,000 ksi (200,000 MPa). In general, wires tend to achieve greater ultimate strength and behave in a more brittle manner than reinforcing bars. Common bar and wire sizes and their material properties are given in Table 3. As stated in the MSJC Specifications, steel reinforcement for masonry structural members should comply with one of the material standards given in Table 4.

TABLE 3
Steel Reinforcement Material Properties[1]

Type	ASTM Specification	Grade or Type	Minimum Yield Strength, ksi (Mpa)	Minimum Tensile Strength, ksi (Mpa)
Bars	A 615	40	40 (276)	70 (483)
	A 615	60	60 (414)	90 (620)
	A 616	50	50 (345)	80 (552)
	A 616	60	60 (414)	90 (620)
	A 617	40	40 (276)	70 (483)
	A 617	60	60 (414)	90 (620)
	A 706	60	60 (414)	80 (552)
Wires	A 82	Smooth	70 (483)	80 (552)
	A 496	Deformed	75 (517)	85 (586)

[1]From reference [5].

TABLE 4
ASTM Material Standards for Steel Reinforcement

Steel Reinforcement Type	ASTM Specification
Deformed bars	A 615, A 616, A 617 or A 706
Joint reinforcement	A 82
Deformed wire	A 496
Wire fabric	A 185 or A 497
Anchors, ties and accessories	A 36, A 366, A 185 or A 82
Stainless steel	A 167 - Type 304

ASSEMBLAGE MATERIAL PROPERTIES

The properties of the constituent materials discussed previously combine to produce the brick or structural clay tile masonry assemblage properties. Following is a discussion of the material properties of the masonry assemblage.

Compressive Strength

Perhaps the single most important material property in the structural design of masonry is the compressive strength of the masonry assemblage. The specified compressive strength of the masonry assemblage, f'_m, is used to determine the allowable axial and flexural compressive stresses, shear stresses and anchor bolt loads given in the MSJC Code.

The compressive strength of the masonry assemblage can be evaluated by the properties of each constituent material, termed in the MSJC Specifications the "Unit Strength Method," or by testing the properties of the entire masonry assemblage, termed the "Prism Testing Method." These methods are not to be used to establish design values; rather, they are used by the contractor to verify that the masonry achieves the specified compressive strength, f'_m.

Unit Strength Method. A benefit of verifying compliance of the compressive strength of masonry by unit, mortar and grout properties is the elimination of prism testing. Each of the materials in the masonry assemblage must conform to ASTM material standards mentioned in previous sections of this *Technical Notes*. For compliance with these material standards, the compressive strength of the unit and the proportions or properties of the mortar and grout must be evaluated. Not surprisingly, there have been attempts by numerous researchers to accurately correlate the assemblage compressive strength with unit, mortar and grout compressive strengths. Testing an assemblage of three materials produces a large scatter of compressive strengths covering all possible combinations of materials. Therefore, estimates of the masonry assemblage compressive strength based on unit, mortar and grout properties are necessarily conservative. The correlations provided in the MSJC Specifications, shown in Table 5, between unit compressive strength, mortar type and the masonry assemblage compressive strength represent a lower-bound to experimental data. In addition, the MSJC Specifications unit strength method does not directly address variable grout strength, multi-wythe construction or the influence of joint reinforcement on the compressive strength of the masonry assemblage. Consequently, compliance with the specified compressive strength of masonry by prism testing will always produce a more accurate and optimum use of brick or structural clay tile masonry's compressive strength than the unit strength method.

The conservative nature of Table 5 should not be overlooked by the designer. A comparison of the predicted assemblage compressive strength by the unit strength method in the MSJC Specifications and a data base of actual brick masonry prism test results [1] reveals this conservatism. The average compressive strength of prisms of solid brick units was found to be about 1.7 times the masonry compressive strength predicted by Table 5. The average compressive strength of prisms of hollow units ungrouted and grouted was found to be 1.9 and 1.4 times the compressive strengths predicted by Table 5, respectively.

TABLE 5
Unit Strength Method of f'_m Compliance in the MSJC Specifications[1]

Net Area Unit Compressive Strength, Psi (MPa)		Net Area Assemblage Compressive Strength, psi (MPa)
Type M or S Mortar	Type N Mortar	
2400 (16.6)	3000 (20.7)	1000 (6.9)
4400 (30.3)	5500 (37.9)	1500 (10.3)
6400 (44.1)	8000 (55.2)	2000 (13.8)
8400 (57.9)	10500 (72.4)	2500 (17.2)
10400 (71.7)	13000 (89.7)	3000 (20.7)
12400 (85.5)	-----	3500 (24.1)
14400 (99.3)	-----	4000 (27.6)

[1]Linear Interpolation is permitted.

Prism Test Method. Prism testing of brick or structural clay tile masonry provides a number of advantages over constituent material testing alone. The primary benefit of prism testing is a more accurate estimation of the compressive strength of the masonry assemblage. Another benefit of prism testing is that it provides a method of measuring the quality of workmanship throughout the course of a project. Low prism strengths may indicate mortar mixing error or poor quality grout.

The MSJC Specifications permit testing of masonry prisms to show conformance with the specified compressive strength of masonry, f'_m. In addition, the material components must meet the appropriate standards of quality. Masonry prisms are tested in accordance with ASTM E 447 Test Methods for Compressive Strength of Masonry Prisms, Method B as modified by the MSJC Specifications. At least three prisms are required by the MSJC Specifications for each combination of materials. The average of the three tests must exceed f'_m. Further explanation of prism testing procedures is provided in *Technical Notes* 39B.

Shear Strength

The shear strength of a masonry assemblage may be separated into four parts: 1) the shear strength of the unit, mortar and grout assemblage, 2) the effect of the shear span-to-depth ratio, M/Vd, 3) the enhancement of shear strength due to compressive stress, and 4) the contribution of shear reinforcement in the masonry assemblage. All four phenomenon are represented in the allowable shear stresses provided in the MSJC Code. However, only the first and fourth items are controlled by material properties. Items two and three vary with member size and applied loads.

The shear strength of the masonry assemblage is directly related to the properties of the unit, mortar and grout. Shear failure of a unit-mortar assemblage is by splitting of units, step-cracking in mortar joints, or a combination of the two. Unit splitting strength is increased by increasing the compressive strength of the unit. In general, unit splitting is not a common shear failure mode of brick or structural clay tile masonry. Unit splitting occurs in masonry assemblages of weak units and strong mortar and may also occur in shear walls which are heavily axially loaded. Cracking in mortar joints is the more common shear failure mode for brick and structural clay tile masonry assemblages. Mortar joint failure occurs by sliding along bed joints and separation of head joints. Mortar joint shear failure is affected by bond strength and the frictional characteristics between the mortar and the unit. In general, a unit-mortar combination which provides greater bond strength will also provide greater shear strength. Grouting the masonry assemblage will also increase shear strength by providing a shear key between courses. The shear strength of a masonry assemblage may be evaluated in accordance with ASTM E 519 Test Method for Diagonal Tension (Shear) in Masonry Assemblages. The contribution of unit, mortar and grout to the allowable shear stresses stated in the MSJC Code are based on ASTM E 519 tests of masonry assemblages.

Steel reinforcement may be added to the masonry assemblage to increase shear strength. Shear reinforcement should be provided parallel to the direction of applied shear force. The MSJC Code also requires a minimum amount of reinforcement perpendicular to the shear reinforcement of one-third the area of shear reinforcement. When shear reinforcement is provided in accordance with the MSJC Code, allowable shear stresses given in the MSJC Code for reinforced masonry are increased three times for flexural members and one and one-half times for shear walls.

Flexural Tensile Strength

Reinforced brick and structural clay tile masonry is considered cracked under service loads and the flexural tensile strength of the masonry is neglected in design. However, cracking of an unreinforced brick or structural clay tile masonry member constitutes failure and must be avoided. Thus, flexural tensile strength is an important design consideration for unreinforced masonry. Flexural tensile strength is the bond strength of masonry in flexure. It is a function of the type of unit, type of mortar, mortar materials, percentage of grouting of hollow units and the direction of loading. Workmanship is also very important for flexural tensile strength, as unfilled mortar joints or dislodged units have no mortar-to-unit bond strength.

Allowable flexural tensile stresses stipulated in the MSJC Code for unreinforced masonry are given in Table 6. The allowable flexural tensile stresses for portland cement-lime mortars are based on full-size wall tests in accordance with ASTM E 72 Method of Conducting Strength Tests of Panels for Building Construction. Values for masonry cement and air-entrained portland cement-lime mortars are based on reductions obtained with comparative testing. Flexural tensile strength may be evaluated by testing small-scale prisms in accordance with ASTM E 518 Test Method for Flexural Bond Strength of Masonry or ASTM C 1072 Test Method for Measurement of Masonry Flexural Bond Strength, but these results may not directly correlate to the allowable flexural tensile stresses in the MSJC Code.

TABLE 6

MSJC Code Allowable Flexural Tensile Stress for Unreinforced Masonry, psi (MPa)

		Mortar Type			
		Portland cement-lime		Masonry cement and air-entrained portland cement-lime	
Direction of Stress	Masonry Type	M or S	N	M or S	N
Normal to bed joints	Solid units	40 (0.28)	30 (0.21)	24 (0.17)	15 (0.10)
	Hollow units ungrouted	25 (0.17)	19 (0.13)	15 (0.10)	9 (0.06)
	Hollow units fully grouted[1]	68 (0.47)	58 (0.40)	41 (0.28)	26 (0.18)
Parallel to bed joints	Solid units	80 (0.55)	60 (0.41)	48 (0.33)	30 (0.21)
	Hollow units ungrouted and partially grouted	50 (0.34)	38 (0.26)	30 (0.21)	19 (0.13)
	Hollow units fully grouted	80 (0.55)	60 (0.41)	48 (0.33)	30 (0.21)

[1]For partially grouted masonry allowable stresses shall be determined on the basis of linear interpolation between hollow units which are fully grouted or ungrouted and hollow units based on amount of grouting.

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Elastic Modulus

The elastic modulus of the masonry assemblage, in combination with the moment of inertia of the section, determines the stiffness of a brick or structural clay tile masonry structural element. Elastic modulus is the ratio of applied load (stress) to corresponding deformation (strain). The elastic modulus is roughly proportional to the compressive strength of the masonry assemblage. Testing of brick masonry prisms indicates that the elastic modulus of brick masonry falls between 700 and 1200 times the masonry prism compressive strength [4]. If the Unit Strength Method is used to show compliance with the specified compressive strength of masonry, f'_m, an accurate estimation of the actual compressive strength of the masonry assemblage may not be known. Consequently, the elastic modulus of the masonry assemblage is determined by the mortar type and the unit compressive strength. See Table 7. The data in Table 1 can be used to estimate the modulus of elasticity of the masonry assemblage for the type of unit selected.

The elastic modulus of grout is computed as 500 times the compressive strength of the grout in accordance with the MSJC Code. In general, the elastic modulus of grout and the elastic moduli of brick or structural clay tile and mortar masonry assemblages are comparable and are often considered equal for design calculations. However, the MSJC Code recommends that the method of transformation of areas based on relative elastic moduli be used for computation of stresses in grouted masonry elements.

TABLE 7

Elastic Moduli of Clay and Shale Masonry Assemblages[1]

Net Area Compressive Strength of Units, psi (MPa)	Assemblage Elastic Modulus, psi (kPa) x 10^6		
	Type M mortar	Type S mortar	Type N mortar
12000 (82.7) and >	3.0(20.7)	3.0(20.7)	2.8(19.3)
10000 (68.9)	3.0(20.7)	2.9(20.0)	2.4(16.5)
8000 (55.2)	2.8(19.3)	2.4 (16.5)	2.0(13.8)
6000 (41.4)	2.2(15.2)	1.9(13.1)	1.6(11.0)
4000 (27.6)	1.6(11.0)	1.4 (9.7)	1.2 (8.3)
2000 (13.8)	1.0 (6.9)	0.9 (6.2)	0.8 (5.5)

[1]MSJC Code Table 5.5.1.2.

[1] MSJC Code Table 5.5.1.2.

Dimensional Stability

Dimensional stability is also an important property of the masonry assemblage. Expansion and contraction of the brick or structural clay tile masonry may exert restraining stresses on the masonry and surrounding elements. Material properties which affect dimensional stability of clay and shale unit masonry are moisture expansion, creep and thermal movements. Effects of these phenomenon may be evaluated by the coefficients provided in the MSJC Code, which are listed in Table 8. The coefficients in Table 8 represent average quantities for moisture expansion and thermal movements and an upper-bound value for creep. Moisture expansion and thermal expansion and contraction are independent and may be added directly. The magnitude of creep of clay or shale unit masonry will depend upon the amount of load applied to the masonry element.

TABLE 8
MSJC Code Dimensional Stability Coefficients for Clay and Shale Unit Masonry

Material Property	Coefficient
Irreversible Moisture Expansion	3×10^{-4} in./in. (3×10^{-4} mm/mm)
Creep	0.7×10^{-7} in./in./psi (1×10^{-5} mm/mm/MPa)
Thermal Expansion and Contraction	4×10^{-6} in./in./°F (1×10^{-5} mm/mm/°C)[1]

[1]Conversion based on equivalent deformation at 100 ^{o}F (38 ^{o}C).

SUMMARY

This *Technical Notes* contains information about the material properties of brick and structural clay tile masonry. This information may be used in conjunction with the MSJC Code and Specifications to design and analyze structural masonry elements. Typical material properties of clay and shale masonry units, mortar, grout, reinforcing steel and combinations of these are presented.

The information and suggestions contained in this *Technical Notes* are based on the available data and the experience of the engineering staff of the Brick Institute of America. The information contained herein must be used in conjunction with good technical judgment and a basic understanding of the properties of brick masonry. Final decisions on the use of the information contained in this *Technical Notes* are not within the purview of the Brick Institute of America and must rest with the project architect, engineer and owner.

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