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INFLUENCE OF INSUFFICIENT WATER CONTENT ON POROSITY, WATER PERMEABILITY AND CALCIUM CARBONATE EFFLORESCENCE FORMATION OF MASONRY MORTARS

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Abstract

The fresh and hardened properties of masonry mortars are strongly dependent on the quantity of water used during mixing. This is particularly evident at the extreme conditions where too much water can result in segregation and too little can lead to insufficient mortar hydration and excessive porosity. While mortar compressive strength requirements are often specified and are known to be related to water content, less obvious hardened mortar characteristics such as permeability, capillary suction, and efflorescence potential are strongly dependent on the water content at the time of placement. An excessively low water content often yields highly permeable mortar.

Calcium carbonate efflorescence is a commonly occurring crystalline deposit on the surface of highly permeable masonry structures. Its presence on masonry is almost always indicative of excessive or uncontrolled water penetration. The properties of the masonry materials, particularly excessively porous and permeable mortar, can exacerbate the severity and pervasiveness of calcium carbonate staining.

The Masonry Standards Joint Committee (MSJC) Code does not have mandatory language dictating maximum or minimum water contents for proportion specifications. Masons are expected to mix mortars to a consistency necessary to lay the masonry units in accordance with the contract documents while using the maximum amount of water possible. Larger masonry units such as random ashlar stone are often placed with mortar mixed to a stiff consistency to support the stone weight, accommodate large joint widths, and maintain

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production while the mortar is plastic. Unfortunately, these excessively dry mortar mixtures can result in poor performance with respect to leakage and efflorescence.

Two of the standard test methods available to relate the water content in fresh mortar to the plastic qualities of the mortar at mixing are American Society for Testing and Materials (ASTM) Standards C1437 and C780, Annex A3. Preliminary testing performed on laboratory-mixed Type N portland cement-lime mixtures indicated that data from either of these methods could be effectively utilized to develop a lower bound for the water content necessary to achieve suitable hardened properties of the mortar and reduce the potential for calcium carbonate efflorescence. Additional testing is necessary in this area to determine the effects of different quantities of cement and lime, the effect of masonry cements, and the effect of different gradations of sand.

Introduction

Masonry mortar is a relatively simple combination of materials (cement, aggregate, and water), but the relationship between the proper ratios of the constituents can have a dramatic effect on the performance of the materials. Often, designers focus on the ratio of cementitious materials and aggregate or the ratio of water to cementitious materials because of the impact that these relationships have on the strength of the mortar; higher cement-to-aggregate ratios and lower water-to-cement ratios generally provide higher mortar strengths. Section 2.1, “Mortar Materials,” of the MSJC specification, ACI 530.1-05/ASCE 6-05/TMS 602-05, “Specification for Masonry Structures,” requires mortar to conform to the requirements of ASTM C270 “Standard Specification for Mortar for Unit Masonry.” While ASTM C270 has specific provisions for the proportions of the cement, lime, and aggregate of mixtures, there are no specific provisions for the quantity of water. In fact, information provided in Note 4 of the document states:

> *“…Mortar for use in the field must be mixed with the maximum amount of water, consistent with workability, in order to provide sufficient water to satisfy the initial rate of absorption (suction) of the masonry units…”*

The basis for this requirement centers around the behavior of brick masonry and mortar where the water content of the mortar is generally governed by the physical properties of the mortar required to construct the walls and provide a properly tooled joint. If too much water is added to the mixture, the mortar will not have sufficient stiffness to support the brick units. If there is not enough water, the bond strength between the mortar and the unit is negatively affected and the masons will have difficulty placing the units and tooling the mortar to provide an attractive finished joint. The mason can add as much water as desired to lay the brick, but the high absorption rates of some clay brick and concrete masonry units will tend to draw moisture from the fresh mortar. Once the initial absorption of the water is complete, it is anticipated that the mortar in place would have properties consistent with that of laboratory tested mortar materials and provide compressive strengths suitable for the masonry design.

The implication of this note, although not specifically stated, is that unless there is adequate water available in the fresh mortar, the properties of the mortar will somehow suffer. This is precisely what happens. Inadequate water in the mixture can result in incomplete cement hydration and ultimately result in a reduction of the compressive strength, mortar bond strength, and other hardened properties of the mortar.

If the absorption of the masonry unit is low, one might assume that using additional water in the mortar mixture would be detrimental by increasing the water/cement ratio resulting in lower mortar strengths. As such, reducing the water content of the mixture would then be beneficial in such cases. However, there are no specific provisions providing limits or lower bounds of water content, and essentially the mason is left to judge the water content based on workability. The acceptability of the mixture is then verified by pre-construction testing or testing of field-batched materials. The absence of specific lower bound criteria for water content of mortars has led to confusion and misuse of exceptionally dry, stiff mortars in masonry assemblies, particularly those with larger, heavier units.

Stone Masonry And Water Content

An example of the misuse of excessively stiff mortars is often observed in random stone masonry. Many of the stone units used in ashlar or rubble masonry walls have extremely low absorption rates and do not require excessive water in the mortar; however, in practice the workability of the mortar is perceived to directly impact the production of the mason during construction. Because the coursing pattern of random ashlar stone is irregular, achieving the proper alignment of horizontal joints requires the stone units to be sized so that the shoulders of adjacent stones are straight and level across common joints. Often, this will require additional cutting of the stone or shimming of the unit, which are both time-consuming and labor-intensive activities. In order to expedite production, some masons have resorted to using an excessively dry, stiff mortar setting bed to “prop up” the stone within the wall and allow the shoulders of the units to align in the next mortar joint. This same “dry-pack” mixture is often used to fill collar joints between the stone and the backup to provide lateral stability to the wall during construction. In some cases, the dry-pack mortar is raked back in the joints and a more plastic mortar is pointed into the joints to conceal the dry-pack and provide a properly tooled profile. In others, the dry-pack mortar is wetted and tooled at the surface of the joint. Neither practice provides an acceptable level of water penetration resistance.

This relatively simple adjustment of the mortar mixture has disastrous consequences on the long-term performance of the masonry assembly. The dry-pack mortars eventually strengthen enough to form a solid mortar joint that is adequate to support the weight of the veneer; however, in this extremely dry mortar state, there are substantial quantities of entrapped air and insufficient water to achieve proper hydration of all the cementitious materials, which results in a reduction of the strength of the mortar. The more detrimental and less obvious characteristics of the hardened dry-pack mortar are a substantial increase in permeability, capillary suction, and efflorescence potential. The dry-pack material, normally placed in the wall with a consistency resembling that of damp sand (Figure 1), has an extensive network of interconnected entrapped air voids. The aggregate particles in the dry-pack are coated with a mixture of hydrated and unhydrated cement particles as well as the chemical byproducts of the hydration process such as calcium hydroxide and other soluble salts.

Figure 1. Dry-pack Mortar in Stone Masonry Cavity

Water Penetration And Efflorescence

Normally, a properly constructed stone masonry cladding would offer excellent performance against water penetration. However, with the mortar becoming significantly more absorptive and permeable, the entire masonry assembly becomes much more susceptible to water penetration. Water is pulled into the veneer through capillary action of the network of interconnected pores and entrapped air voids. The water is then stored in the wall system, particularly if there is a collar joint comprised of the same dry-pack material. The presence of excessive and repeated water in the wall system results in dissolution of the soluble calcium salts in the mortar. The calcium-laden water migrates through the mortar behind the veneer until it is discharged from the wall at flashings and other vertical disruptions. In the presence of atmospheric carbon dioxide, the calcium salts are carbonated, forming extensive crystalline deposits of calcium carbonate efflorescence on the masonry surfaces (Figures 2 through 4). This process of calcium carbonate efflorescence formation is expressed by the chemical reaction shown in Equation 1.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad \textbf{[1]}$$

The resulting efflorescence deposits are unsightly and difficult to remove from masonry walls. The deposits continue to grow as long as there is a supply of soluble calcium salts available to dissolve in the mortar matrix.

Figure 2. Efflorescence at Masonry Flashing

Figure 3. Efflorescence on Stone Masonry Wall

Figure 4. Efflorescence on Brick Masonry Wall from Paver Setting Bed Behind Wall

Industry Requirements

Currently, there is no provision within the industry or code documents to limit the stiffness of masonry mortar. As previously mentioned, Section 2.1A of the MSJC Specification (ACI 530.1) requires mortar to conform to ASTM C270. However, while the requirements of C270 provide criteria for the required flow of masonry mortars for laboratory testing (110 +/- 5%), Note 4 of the standard specifically excludes this criterion from field-prepared mortars:

> *"…The properties of laboratory prepared mortar at a flow of 110 +/- 5%, as required by this specification, are intended to approximate the properties of field prepared mortar after it has been placed in use and the suction of the masonry units has been satisfied. The properties of field prepared mortar mixed with the greater quantity of water, prior to being placed in contact with the masonry units, will differ from the property requirements in Table 2. Therefore, the property requirements in Table 2 cannot be used as requirements for quality control of field prepared mortar. Test method C780 may be used for this purpose."*

Although previous editions of ACI 530.1 also referenced ASTM C780, "Standard Test Method for Preconstruction Testing and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry," for field quality control when required by the specifier, more recent editions do not reference this test standard at all. Instead, Section 3.7, "Field Quality Control," merely requires sampling and testing of grout and verification of the masonry compressive strength. No quality control measures of field-prepared mortars are required by the specification.

As stated in the introduction to ASTM C780,

> *"No attempt is made to claim or substantiate specific correlations between the measured properties and mortar performance in the masonry. However, data from these test methods can be combined with other information to form judgments about the quality of the masonry."*

Based on the language from ACI 530.1 and the associated language in ASTM C270 and C780, there are no prescribed limits set for the consistency of mortar used in the field. If the specifier does not specifically require testing in accordance with ASTM C780 and associated criteria limiting the stiffness permitted through testing of construction mortars, the use of dry-pack mortars is not specifically excluded.

While there are no prescriptive requirements for mortar consistency, there is information contained within the ASTM C780 standard and other industry sources that provide guidelines for acceptable mortar properties. The Brick Industry Association (BIA) Technical Notes on Brick Construction, Technical Notes 8, "Mortars for Brick Masonry," indicates that mortars for brick normally have initial flows in the range of 130 to 150% to produce a level of workability satisfactory to the mason. However, flow testing in accordance with ASTM C1437, "Flow of Hydraulic Cement Mortar," is generally too cumbersome to be used in the field and masonry units that are heavier than brick and having lower absorption rates, such as stone, require a stiffer consistency of mortar. ASTM C780 Annex A3, "Initial Consistency and Consistency Retention of Mortars for Unit Masonry or Board Life of Masonry Mortars Using a Modified Concrete Penetrometer," provides criteria for the initial and final penetration resistance for consistency of masonry mortar tested in the field. This test prescribes use of a commercially available, pocket-sized, concrete penetrometer with an attachable disk to increase the footprint over the test specimen. Section A3.7.1 of the standard indicates that mortar should be prepared with an initial penetration resistance of 0.94 +/- 0.05 psi for mortar to be used with brick sized units or 1.24 +/- 0.05 psi for mortar to be used with heavier units requiring less plastic mortars for proper bedment. Final penetration resistance values for brick sized and heavier units are 1.74 and 2.44 psi respectively. Consistencies exceeding the final penetration values are considered too stiff for use. While this test method is more conducive to field applications than the flow table, the final penetration resistance is intended as a limiting value with regard to board life and is not directly applicable as a limiting criterion for initial mortar consistency. Additionally, in the authors' experience, mortars mixed to the initial penetration resistance criteria listed in the C780 standard for heavier units with lower absorption properties are generally not stiff enough to support the units during placement. These criteria ultimately would need to be adjusted to account for these conditions for heavier natural stone or, potentially, heavy man-made masonry units.

To prevent the use of dry-pack mortars in masonry, the use of excessively stiff mortar materials should be prohibited. This is best accomplished by the development of minimum consistency criteria for all mortars and masonry units that would insure that the materials have adequate water content to achieve a sufficiently plastic consistency to provide optimum performance. The objective would be to reduce the amount of entrapped air in the mixture and reduce the permeability and porosity of the material. It should also provide more appropriate and consistent compressive and bond strength values and reduce the potential for water penetration and subsequent efflorescence formation on the masonry veneer.

Laboratory Testing

A preliminary laboratory testing program was developed by the authors to determine what effect the variation of water content in mortar mixtures would have on the fresh and hardened properties of the material. By establishing the observed workability of the material at different water contents and then determining at what point the mortar was negatively affected by a lack of moisture in the mixture, a threshold consistency of the material could be attained to limit the stiffness of the material used in the field.

Ten (10) laboratory mixtures of Type N portland cement-lime mortar (Type I portland cement and Type S hydrated lime) were developed and mixed in the laboratory with identical ratios of sand, cement, and lime. The water content was varied to prepare different mixture consistencies ranging from a dry-pack condition (Mixture A) to a relatively stiff masonry mortar. The water content, while not measured quantitatively, was related to the consistency of the freshly mixed mortar by measuring the flow and penetration resistance. Consistencies of all the mortars were generally stiffer than the documented industry initial flow and initial penetration resistance values in order to determine at what point the properties of the mortar would be negatively impacted at the extreme conditions. Two different aggregates were used in 5 each of the mixtures. Aggregate Type 1 was a natural sand that conformed to the gradation requirements of ASTM C144, “Standard Specification for Aggregate for Masonry Mortar.” Aggregate Type 2 was also a natural sand that was classified by the supplier as a “masonry sand” but was generally too fine to meet the gradation requirements of C144.

For each freshly mixed mortar, the flow was measured in accordance with ASTM C1437 and the penetration resistance was measured in accordance with ASTM C780 Annex A3. The results of two tests were compared to determine the relationship between the methods. Analysis of the data indicated that there was a strong correlation between both tests. Table 1 summarizes the data from the mortar flow and penetration resistance for the trial mixtures in the study and Figure 5 depicts the relationship between the tests.

Table 1. Mortar Flow and Penetration Resistance Test Results

Mixture Designation	Aggregate Type	Flow (%)	Penetration Resistance, psi (kPa)
A	1	1	Exceeded Device
B	2	11	Exceeded Device
C	1	17	Exceeded Device
D	2	33	Exceeded Device
E	2	40	6.31 (43.5)
F	2	53	4.19 (28.9)
G	1	53	5.63 (38.8)
H	2	64	3.47 (23.9)
J	1	66	3.57 (24.6)
K	1	76	1.97 (13.6)

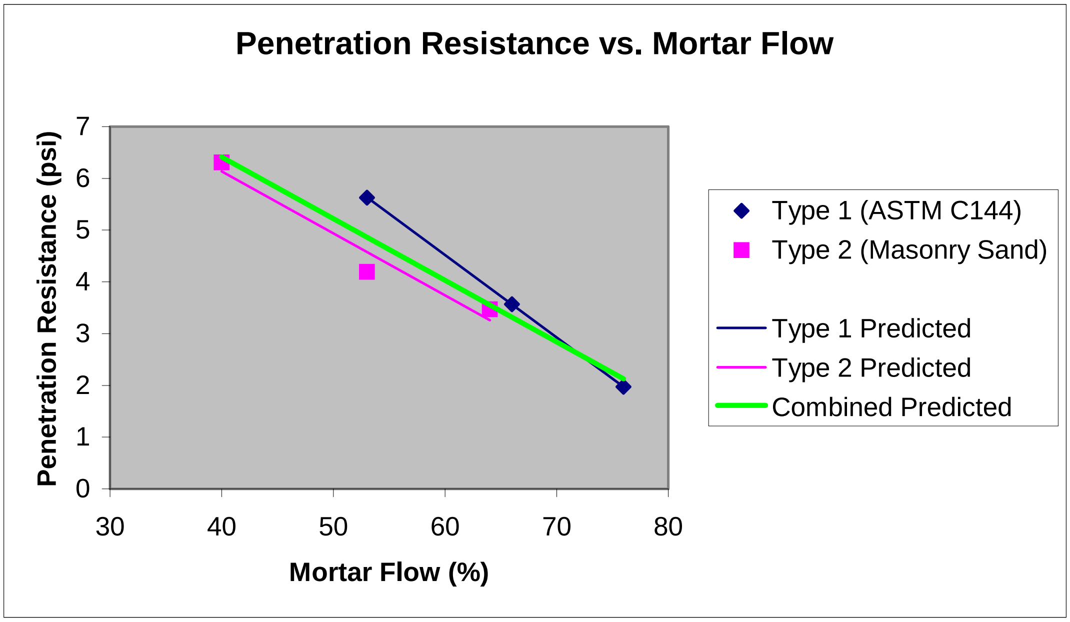

Figure 5. Mortar Flow vs. Penetration Resistance (1 psi = 6.89 kPa)

The relationship between the flow and penetration resistance testing proved to be reasonably linear within the working range of the penetrometer and the generally accepted workability range of the material tested. However, the relationship between the two tests is not valid at the extreme conditions. Very stiff mortars (including dry-pack consistency) with very low flow measurements exceed the capacity of the penetrometer. Mortar with excessively high flows, while measurable by both methods, would not be appropriately stiff to place masonry units in practice. Generally, the authors believe that for purposes of establishing limiting criteria, either method would be permissible for use. Of the two methods, the penetration resistance test offers the better alternative for field applications. Because the actual testing range of the device normally cannot exceed a penetration resistance greater than approximately 6.5 psi, the minimum water content for the mortar must be sufficient to yield a mortar capable of being tested in the field.

Each mortar mixture prepared in the laboratory was tested for compressive strength at 28 days in accordance with ASTM C780 Annex 7, "Compressive Strength of Molded Masonry Mortar Cylinders and Cubes." The average compressive strengths for each set of samples are summarized in Table 2. The results of the strength testing are separated into two groups, one for each of the two aggregates used in the mixtures. Graphical plots of the compressive strength data relative to the mortar flow results for both mix designs are summarized in Figure 6.

Table 2. Average 28-Day Compressive Strengths

Sample	Compressive Strength, psi (MPa)	Standard Deviation, psi (MPa)	Sample	Compressive Strength, psi (MPa)	Standard Deviation, psi (MPa)
A-1	1250 (8.62)	340 (2.34)	B-2	810 (5.58)	20 (0.14)
C-1	1530 (10.55)	170 (1.17)	D-2	870 (6.00)	15 (0.10)
G-1	1370 (9.45)	65 (0.45)	E-2	770 (5.31)	15 (0.10)
J-1	990 (6.83)	0	F-2	680 (4.69)	5 (0.03)
K-1	1020 (7.03)	65 (0.45)	H-2	710 (4.90)	15 (0.10)

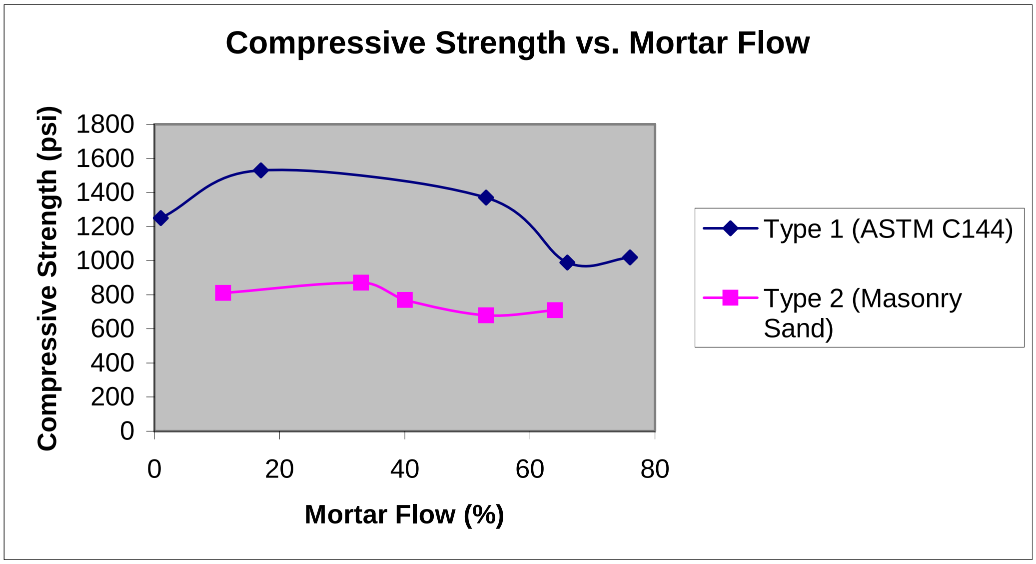

Figure 6. Average 28-Day Compressive Strengths Relative to Flow (100 psi = 0.69 MPa)

There was a significant difference in the overall strengths between the two aggregate types; however, the trends in the data were similar. The compressive strength, as anticipated, reflected a reduction in strength with increasing flow as well as a reduction in strength for the samples with the lowest flows. The reduction in the low flow material strength, as well as the increase in the standard deviations, likely reflects the inability to properly consolidate cylinders with very dry mortars and a reduction in properly hydrated cement due to inadequate water. Based on the graphical results, the optimum compressive strength would be in the flow range of 30 to 50. This corresponds to a penetration resistance of roughly 4 to 6 psi based on the penetrometer results. While the sample size of the materials tested in this study is relatively low, additional testing could be performed to refine the optimum compressive strength based on flow measurements and penetration resistance. It also should be noted that optimum compressive strength is not necessarily the most significant variable with regard to selecting a minimum water content and consistency for use in the field. Use of a mortar with a penetration resistance as high as 6 psi would result in a mortar with a significantly reduced board life and potentially a reduction in bond strength in absorptive masonry units.

Absorption testing was also conducted for each laboratory-mixed mortar based on the principles of ASTM C1403, “Standard Test Method for Rate of Water Absorption of Masonry Mortars.” The absorption was measured on 2" cube specimens at intervals of 15 minutes (initial absorption), 1 hour, 4 hours, and 24 hours (final absorption), and corresponding rates of absorption were calculated. The average rates of absorption for each set of specimens at each interval are given in Table 3. The distribution of water absorption with respect to time for each mortar is shown in Figure 7 and the initial rate of absorption versus flow is plotted in Figure 8.

Table 3. Average Rate of Absorption

Sample	Average Rate of Absorption, g/100 cm^2/min (lb/10 ft^2/min)			
	15 min	1 hr	4 hr	24 hr
A-1	7.561 (1.549)	0.011 (0.002)	0.000	0.000
B-2	1.497 (0.307)	0.377 (0.077)	0.183 (0.037)	0.032 (0.007)
C-1	3.273 (0.670)	0.546 (0.112)	0.134 (0.027)	0.009 (0.002)
D-2	1.763 (0.361)	0.457 (0.094)	0.207 (0.042)	0.022 (0.005)
E-2	1.772 (0.363)	0.400 (0.819)	0.140 (0.029)	0.015 (0.003)
F-2	2.477 (0.507)	0.585 (0.120)	0.344 (0.070)	0.007 (0.001)
G-1	2.198 (0.450)	0.553 (0.113)	0.256 (0.052)	0.014 (0.003)
H-2	1.976 (0.405)	0.555 (0.114)	0.278 (0.057)	0.016 (0.003)
J-1	2.229 (0.457)	0.592 (0.121)	0.275 (0.056)	0.022 (0.005)
K-1	2.415 (0.495)	0.643 (0.132)	0.307 (0.063)	0.015 (0.003)

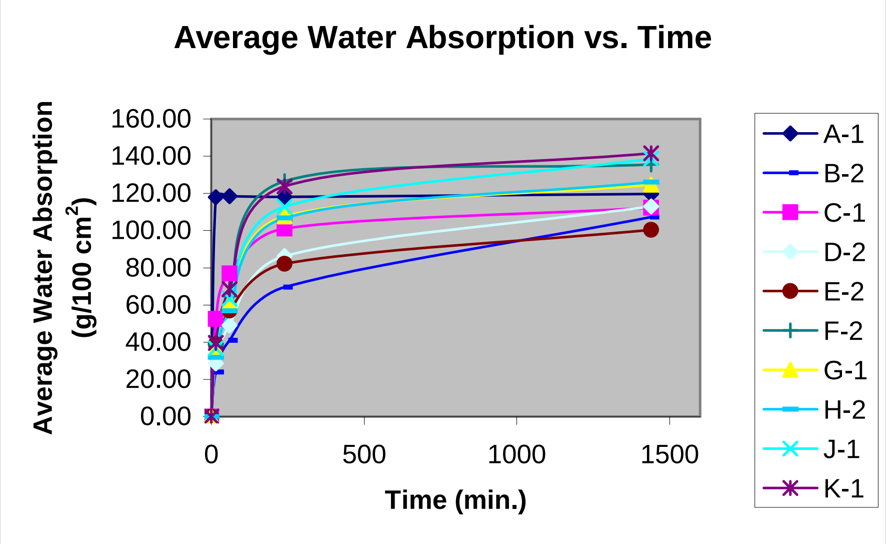

Figure 7. Average Water Absorption vs. Time (1 g/100 cm^2 = 0.20 lb/10 ft^2)

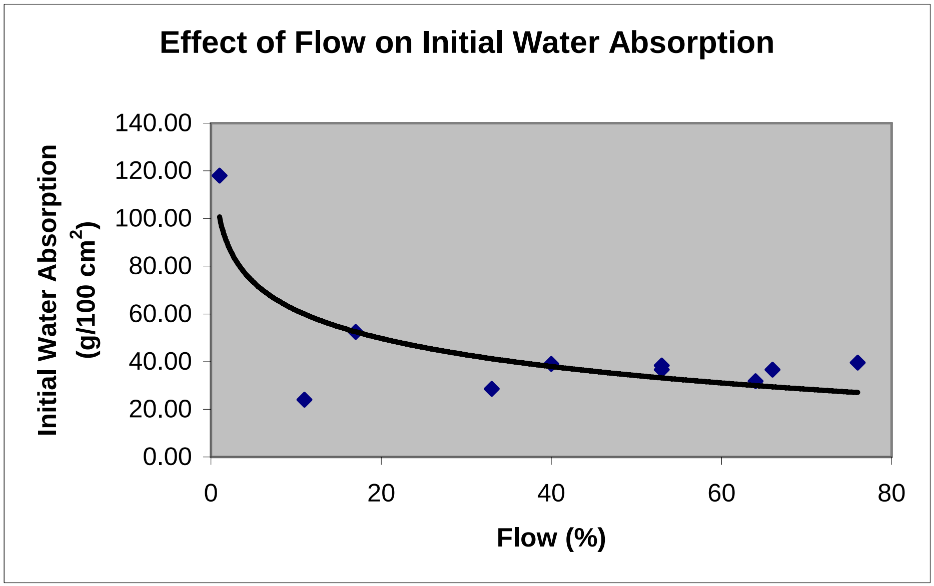

Figure 8. Effect of Flow of Fresh Mortar on Initial Water Absorption (1 g/100 cm^2 = 0.20 lb/10 ft^2)

Although the overall final water absorption did not differ greatly between the mixtures, the most significant trend observed in the data is the substantial increase in the initial absorption for the dry-pack specimen (Mixture A), illustrated by Figures 7 and 8. Virtually all of the water absorbed during the test occurred in the first 15 minutes of the test. This phenomenon is caused by the associated increase in the capillary suction on the surface of the specimen from the network of entrapped air voids in the sample. In practice, the presence of a dry-pack mortar between masonry units would result in a drastic increase in the rate of water penetration through the masonry assembly during relatively short duration rain events. The remainder of the data varied significantly, but in general, materials with a flow greater than 50 and an approximate corresponding penetration resistance of 5 psi provided the most consistent absorption values for the mortars tested.

In addition to the mortar absorption testing, standing head permeability testing was performed on a 3” diameter by approximately 4” high cylinder for each of the laboratory-mixed mortars. These cylinders were cast by pressing the mortar into the mold by hand using moderate force in order to approximate the conditions of the mortar as used during construction. After curing in laboratory air for 28 days, the bottom of the mold was sawn off and water was applied to the top surface of the specimen with a static head of approximately 1” for 20 minutes. The time between the application of the water and the point at which water materialized on the bottom surface of the specimen was recorded. The water penetrating through the sample for the duration of the test was collected and weighed to determine an overall permeability rate. Of the 10 specimens tested, only the dry-pack specimen (A-1) resulted in a measurable permeability of 0.31 $l/hr/in^2$. Water was observed on the bottom of the specimen after approximately 60 seconds. The remainder of the specimens, while absorbing some moisture over the 20-minute test period, did not permit active water penetration.

The permeability testing indicated that the mortar is significantly and negatively impacted by a severe reduction in the overall water content of the mortar although more workable mixtures had little effect on permeability. The network of interconnected voids permits the passage of water into and through the dry-pack more easily than a standard mortar that is mixed with enough water to reach a plastic consistency. As with the mortar absorption, the permeability has a direct influence on the water penetration resistance of masonry walls. The increase in mortar permeability increases the overall permeability of the assembly and permits water to migrate into the collar joint and filter down into the wall system. The flow of water through the dry-pack then can dissolve the calcium salts in the pore network resulting in efflorescence. Based on the permeability testing, any mortar with a consistency that is within the testing range of the penetrometer would provide a significant reduction of the permeability of the material.

Conclusions

The practice by masons of using excessively dry mortar materials in bed and collar joints, while not specifically prohibited by the code, can result in severe efflorescence problems and other detrimental effects on masonry cladding systems. To prevent the use of these types of materials, a lower bound water content must be specified to insure that the mortar reaches a plastic consistency that reduces the quantity of entrapped air voids and unhydrated cement in the material. A simple and effective method of evaluating the properties of the mortar is to determine the penetration resistance of the material prior to use. Testing performed in this study indicated that the device provides a reasonably linear correlation to the laboratory flow test that is normally used to equate water content to the workability of the materials. According to the limited preliminary evaluation performed by the authors, a maximum penetration resistance of approximately 4 psi would be sufficient to provide consistent and suitable hardened properties of the mortar including absorption, permeability, and compressive strength. While this value is greater than the final penetration resistance of 2.44 psi listed in the ASTM C780 Annex A3 for heavier units, it appears to be appropriate as an upper bound for heavy masonry with low absorption properties. Slightly stiffer mixtures (up to 5 psi) would yield adequate performance for hardened properties; however, in practice, such mixtures would likely yield insufficient board life to retain the mortar characteristics during the construction of the masonry and potentially could result in a reduction in bond strength, particularly with absorptive masonry units.

Additional testing is warranted to further refine this minimum threshold value for application to a wide range of masonry construction. Although not considered within this study, the influence of the consistency of the mortar on the bond strength to the masonry units should also be considered for masonry units with differing absorption properties when establishing the limiting criteria for the code. The criteria should also be refined to account for variations in cement types and contents, aggregates, and other components of masonry mortars.

References

American Society for Testing and Materials International 2001: “Standard Test Method for Flow of Hydraulic Cement Mortar,” ASTM C1437-01, 2001, American Society for Testing and Materials International, West Conshohocken, PA, USA.

American Society for Testing and Materials International 2002: “Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry,” ASTM C780-02, 2002, American Society for Testing and Materials International, West Conshohocken, PA, USA.

American Concrete Institute 2005: “Specification for Masonry Structures,” ACI 530.1-05/ASCE 6-05/TMS 602-05, 2005, American Concrete Institute, Farmington Hills, MI, USA.

American Society for Testing and Materials International 2005: “Standard Specification for Mortar for Unit Masonry,” ASTM C270-05, 2005, American Society for Testing and Materials International, West Conshohocken, PA, USA.

American Society for Testing and Materials International 2004: “Standard Specification for Aggregate for Masonry Mortar,” ASTM C144-04, 2004, American Society for Testing and Materials International, West Conshohocken, PA, USA.

American Society for Testing and Materials International 2000: “Standard Test Method for Rate of Water Absorption of Masonry Mortars,” ASTM C1403-00, 2000, American Society for Testing and Materials International, West Conshohocken, PA, USA.

The Brick Industry Association 2003: “Technical Notes 8 – Mortars for Brick Masonry,” BIA Technical Notes on Brick Construction, Revised 2003, The Brick Industry Association, Reston, VA, USA.