Water-Repellent Performance in Pozzolanic and Traditional Mortars

Herb Nordmeyer[1] and Paul R. Taylor[2]

[1]Project and Technology Manager, Technical Services Group, Headwaters Construction Materials, 5014 Callaghan Road, San Antonio, TX 78228; [2]Technical Services Group, Headwaters Construction Materials, 5014 Callaghan Road, San Antonio, TX 78228

KEY WORDS: water penetration, mortars, water repellents, admixtures, rate of absorption,

INTRODUCTION

Water penetrating through masonry walls can be a problem. To prevent it, there are several lines of defense. The first is to use masonry units and mortar which resist the penetration of water; a second is to use good workmanship to insure there are no voids through which water can pass; a third line of defense is weather-resistive barriers and flashing. This paper addresses only that part of the first line of defense that deals with mortar. More architects are specifying water-repellent admixtures to be added to masonry walls to reduce the water penetration through those walls. We have questioned how effective these admixtures are.

While other water-repellent admixtures have been studied, this paper is limited to one liquid admixture and the impact of that liquid admixture on five Type S mortar formulae.

The senior author has been involved in writing other papers about water-repellent admixtures which will be published at a future date:

> A paper by Nordmeyer and Hall concerning the impact of dry water-repellent admixtures on five mortar formulae.[1]
>
> A paper by Matthys and Nordmeyer concerning the impact of a liquid water-repellent admixture on three mortar formulae as it relates to moisture penetration using ASTM E 514 tests.[2]

This paper examines the impact of one liquid water-repellent admixture on 5 mortar formulae as it relates to rate of water absorption and moisture penetration using ASTM E 514 tests. The liquid water-repellent admixture tested is a well known commercial product. The admixture company's literature and MSDS state that it is "Mixture of Polymeric Dispersions in Water

MORTAR FORMULAE TESTED

Prior to the introduction of portland cement, most mortar was produced by slaking quick lime. With the introduction of portland cement in the late 1800s, portland/lime mortars were developed. In the 1920s, masonry cement was introduced. In the 1990s, mortar cement was introduced. Starting in the 1950s, masonry cement using a pozzolanic formula was developed, using natural volcanic ash, and was available in very limited portions of the United States. The senior author was a lab tech on a team that developed such a formula in the 1950s. In more recent years, masonry cement and mortar cement have been developed using fly ash, a reclaimed pozzolan. Its distribution is more general. Both authors are employed by a company that produces pozzolanic masonry and mortar cements in several locations across the United States.

Type S portland Cement/Hydrated Lime mortar is the standard by which many professionals judge all mortars; therefore this paper will use Type S portland Cement/Hydrated Lime mortars as a standard.

For this study, five Type S mortar formulae were selected for testing. They are listed in Table 1. In addition to a portland/lime blend and a traditional masonry cement, three formulae were included which used pozzolanic technology. Pozzolanic technology is well known in the production of concrete. In recent years pozzolanic technology has become more important in the production of masonry cements and stucco cements.[3]

All products are commercially available. The hydrated lime used was a dolomitic Type S hydrated lime.

Table 1 – Mortars Tested

ID	Type of Mortar	Hydrated Lime *	Fly Ash in Formula
I	Portland/Lime	17.5%	No
II	IP Cement/Lime	17.5%	Yes
III	Pozzolanic Mortar Cement	~15.0%	Yes
IV	Pozzolanic Mortar Cement	0.00%	Yes
V	Traditional Masonry Cement **	0.00%	No

* Percent by weight.

** The cement that is referred to as a traditional masonry cement (ID V) is produced by a portland cement company and is a milled blend of portland clinker, limestone, and other ingredients.

DESIGN OF THE STUDY

The study consisted of two parts. Each of the mortar formulae were tested in the San Antonio Lab, with and without water-repellent admixture, to determine

Water/cement ratio,

Water retention,
Air content, and
Rate of water absorption at
- 1 minute,
- 15 minutes,
- 1 hour,
- 4 hours, and
- 24 hours.

Several of the formulae with the water-repellent admixture were selected for further testing at the University of Texas at Arlington (UT – Arlington) to determine bond strength and water penetration through a masonry wall. Air content, water retention, and compressive strength were also determined at the UT – Arlington Laboratory. These results were compared with results from the data base that UT – Arlington has developed concerning portland cement/ lime blends and traditional masonry cement.

The rate-of-water absorption tests conducted at the San Antonio Lab in general followed the procedure outlined in ASTM C 1403 (Test Method for Rate of Water Absorption of Masonry Mortars).[4] The following variations of that test method were:

A blend of 20-30 sand and graded standard sand were used, rather than ASTM C 144 sand. This variation is allowed in Section 5.1.1 of ASTM C 1403.

The cubes were cured over water after demolding, rather than in a plastic bag.

The cubes were processed for the absorption test at 21 days of age, rather than 28 days of age.

Besides recording the rate of absorption for 15 minutes, 1 hour, 4 hours, and 24 hours, a rate of absorption at 1 minute, which is not specified in ASTM C 1403, was also recorded. The 1-minute absorption was included to give indication as to the initial rate of absorption when the formulae were used as a stucco scratch coat or brown coat.

The water retention and the air content were determined as per ASTM C 270.[5]

Testing at UT – Arlington was done according to the following procedures:

Mortar Cube Compressive Strength – ASTM C 270

Air Content of Plastic Mortar – ASTM C 270

Water Retention of Mortar – ASTM C 270

Flexural Bond Strength – ASTM C 1072 [6]

Water Penetration Resistance – ASTM E 514 [7]

The following variations to the test methods were made:

3-hole cored extruded standard modular red clay brick were used which matched the same blend and manufacturer used in earlier studies so comparison with the data base would be relevant.

The ASTM C 144 [8] sand should have 95% to 100% passing the 8-mesh sieve. The sand used had slightly less passing the 8-mesh sieve (Sample 1 – 93.5%, Sample 2 – 94.2%).

DATA DEVELOPED IN THE SAN ANTONIO LAB

Figure 1 illustrates the amount of water that was required to make the standard-sized laboratory batches in the San Antonio Lab. These data illustrate that in 4 out of the 5 cases, less water was required with the treated mortars. The reverse of the trend with Formula IV (pozzolanic masonry cement) may have been caused because the control mortar was made to a flow of 108% and the treated mortar was made to a flow of 112%.

Figure 1. Water demand with lab-mixed batches

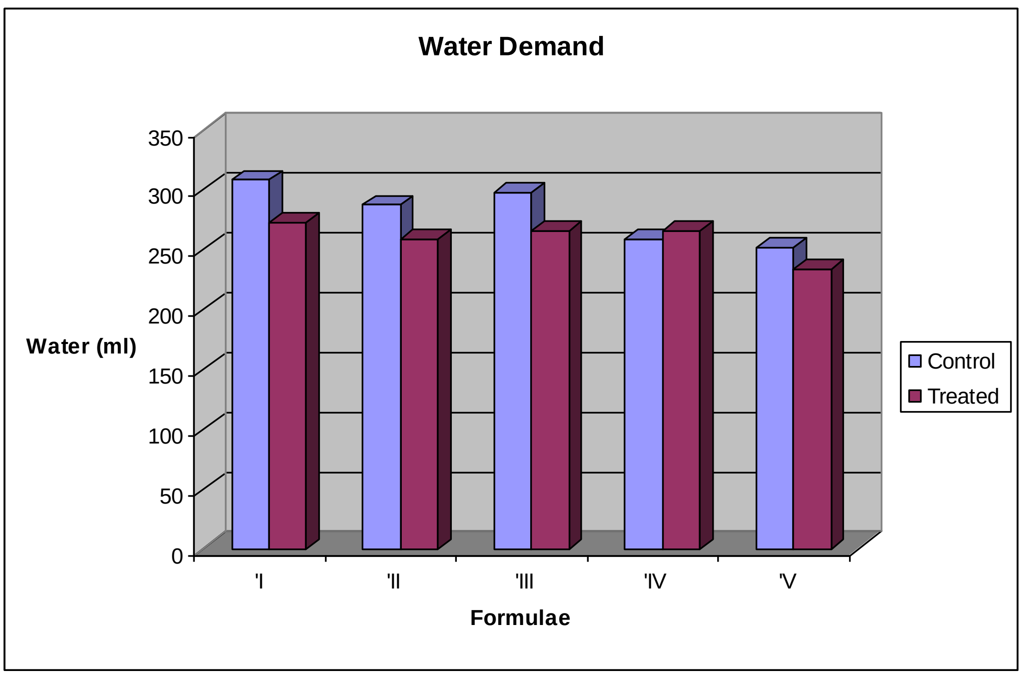


Table 2 presents data concerning water retention and air content of the different formulae that were tested.

Table 3 lists the results of the testing of water absorption and compares the impact of treatment. ASTM C 1384 [9] requires that for an admixture to be sold as a water-repelling admixture, it reduce the 24-hour rate of water absorption by 50% while maintaining a 28-day compressive strength of at-least 80% of the strength of the control. These data indicate that the liquid water-repelling admixture tested reduced the 24-hour rate of water absorption by 50% or more for Formulae II, III, and V.

Table 2. Water Retention and Air Content
San Antonio Lab using 20-30 and graded standard sand

Formula	Water Retention		Air Content	
	Control	Treated	Control	Treated
	%	%	%	%
I	90	84	5.2	10.8
II	85	83	3.8	10.8
III	83	88	12.6	11.6
IV	93	88	15.3	10.3
V	88	79	11.5	10.0

Table 3. Results of Water Absorption Testing
San Antonio Lab using 20-30 and graded standard sand

Formula	1 min.	15 min.	1 hr.	4 hrs.	24 hrs.
		(gms/100 sq cm)			
I-Control	6.51	29.68	49.45	83.39	105.44
II-Control	7.94	20.31	35.53	65.53	99.94
III-Control	2.87	7.91	15.00	31.16	70.49
IV-Control	4.15	7.98	12.56	22.63	45.38
V-Control	10.00	20.50	28.68	56.89	81.80
		(gms/100 sq cm)			
I-Treated	2.44	11.16	18.72	33.09	63.01
II-Treated	2.05	5.39	7.98	13.87	25.85
III-Treated	2.09	3.68	6.28	12.75	28.52
IV-Treated	1.78	3.84	7.29	15.11	32.94
V-Treated	3.49	6.01	9.26	15.73	35.45
		(treated as % of control)			
I-Impact	37%	38%	38%	40%	60%
II-Impact	26%	27%	22%	21%	26%
III-Impact	73%	47%	42%	41%	40%
IV-Impact	43%	48%	58%	67%	73%
V-Impact	35%	29%	32%	28%	43%

Type S portland cement/hydrated lime mortar (Formula I) has been considered the standard of the industry for years. Table 3 illustrates that the untreated portland/lime has the highest 24-hour rate of water absorption of any of the formulae tested. To better illustrate the variations in the 24-hour rate of water absorption, the data in Table 3 has been rearranged and is presented in Table 4. Table 4 shows the 24-hour rate of water absorption in descending order for both the treated and untreated formulae and then shows the rates as percentages of the untreated Formula I. Untreated Formula IV had only 43% as much absorption as untreated Formula I. Treated Formulae II, III, and IV (those containing fly ash) had less than 31% of the 24-hour absorption of the untreated Formula I.

Figure 2 illustrates the 24-hour rate of absorption in graphic form, including that all treated mortars exhibited lower 24-hour rates of water absorption than their corresponding controls.

Table 4. 24-Hour Absorption Compared With Untreated Portland/Lime Mortar

Formula	24 hour	
	(gms/100 sq cm)	(as % of Formula I-Control)
I-Control	105.44	100%
II-Control	99.94	95%
V-Control	81.80	78%
III-Control	70.49	67%
I-Treated	63.01	60%
IV-Control	45.38	43%
V-Treated	35.45	34%
IV-Treated	32.94	31%
III-Treated	28.52	27%
II-Treated	25.85	25%

DATA DEVELOPED AT UT – ARLINGTON

Table 5 contains data concerning water retention and air content that were run in the UT – Arlington Lab. These data are different from the data in Table 2, in that the data in Table 2 was developed from samples tested with a blend of 20-30 sand and graded standard sand. The sand as introduced into the mix was dry. The samples covered by Table 5 were produced using ASTM C 144 sand, which is a different gradation and was in a loose, damp condition when introduced into the mix.

Table 6 furnishes 28-day compressive strengths for the different mortars. The columns labeled lab-mixed mortars refer to mortars mixed in the lab to a flow of 112% to 118%.

The columns labeled field-mixed mortars refer to mortars mixed in a field mortar mixer to a flow which is adequate for laying brick. In this case the flows measured between 133% and 140%.

Figure 2. 24-Hour Rate of Absorption

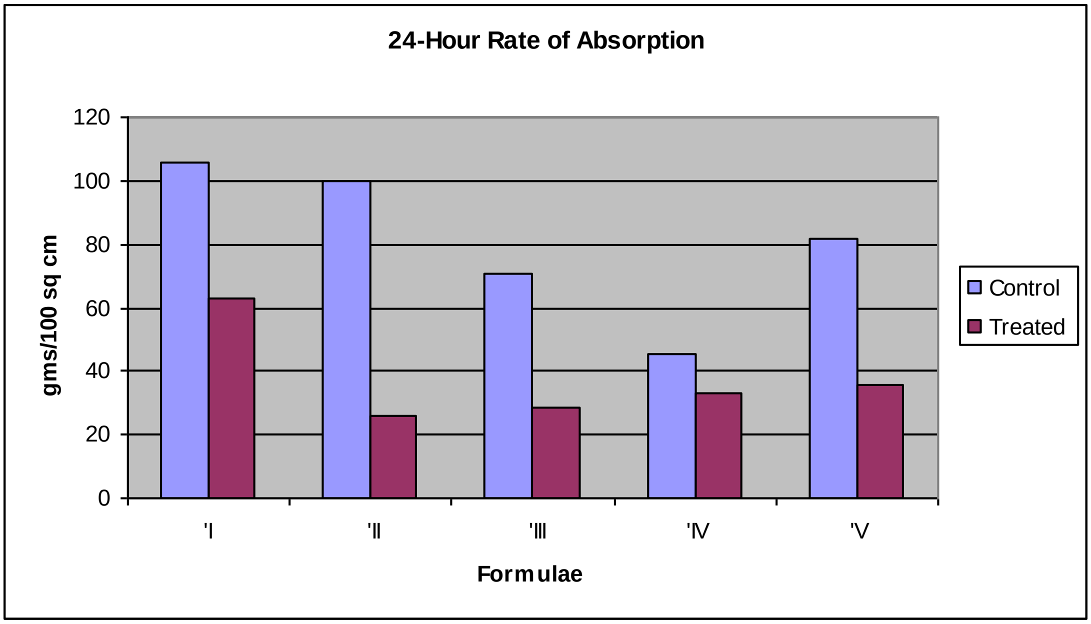


Table 5. Water Retention and Air Content
UT – Arlington Lab using ASTM C 144 sand

	Water Retention		Air Content	
Formula	Control	Treated	Control	Treated
	%	%	%	%
I	89	93	6.7	2.5
II		98		2.7
III				
IV		90		11.7
V	86		14.7	

Table 6. 28-Day Compressive Strength
UT – Arlington Lab using ASTM C 144 sand

	Lab-mixed mortar		Field-mixed mortar	
Formula	Control	Treated	Control	Treated
	(Mpa)	(Mpa)	(Mpa)	(Mpa)
I	18.0	23.2	9.3	10.5
II		17.3		7.4
III				
IV		19.4		6.8
V	21.4		12.9	

Table 7 gives the results of the ASTM E 514 testing. The test involves:

Building a masonry wall,

Attaching a testing chamber to it,

Attaching a method to collect water passing through the wall,

Developing near-hurricane conditions inside the test chamber, and

Collecting water that passes through the wall.

ASTM E-514 describes a 4-hour test. UT – Arlington personnel have traditionally continued the tests for 24 hours. Tests were run on three mortars and compared with information that was in the UT – Arlington Data Base concerning tests run on Type S portland/lime mortars and on Type S masonry cement mortars.

Table 7. Water Permeance Test
1.1 square meter test wall

			1.1 m^2 test wall			
Start	Stop		Test Data		Data Base	
		I-Treated	II-Treated	IV-Treated	I-Control	V-Control
(hr)	(hr)	(ml)	(ml)	(ml)	(ml)	(ml)
0	1	0	0	0		
1	2	0	0	8.2		
2	3	0	3.3	18.5		
3	4	0	4.5	32.8		
4	5	0	9.5	50.5		
5	6	0	16.5	72.7		
23	24	0	1.3	16	300	3500

Table 8 presents data related to the flexural bond strength tests that were performed at UT – Arlington according to ASTM C 1072 (Standard Test Method for Measurement of Masonry Flexural Bond Strength).

DISCUSSION

Many mortars formulated with pozzolanic technology develop strength slower than traditional mortars. Manufacturers of such mortars understand this late strength gain, but formulate their mortars to meet existing standards. Figure 3 depicts the growth in strength exhibited by one Type S masonry cement produced with pozzolanic technology and one Type S masonry cement produced by inter-grinding of portland cement clinker, limestone, and additives (traditional method). These test results are based on testing according to the requirements of ASTM C 91 (Standard Specification of Masonry Cement)[10]. With the masonry cement produced by the traditional method, a majority of the strength has been achieved by 28 days.

Table 8. Flexural Bond Strength

Formula	Bond (Mpa)	COV (%)
I-Control	0.72	0.16
I-Treated	0.79	0.18
II-Treated	0.78	0.14
IV-Treated	0.64	0.19
V-Control	0.30	0.17

With the continued growth in compressive strength, the possibility exists, but has not been tested by the authors, that rate of water absorption and flexural bond strength values may change with time as the various reactions are carried closer to completion. Both Thomson[11] and Meadowcroft[12] reported that when portland/lime mortars and portland/lime substitute mortars were tested for flexural bond strength at 28, 60, and 90 days, in most cases the flexural strength increased with age. Helmuth[13] reports that pozzolanic mortars are often more dense than high-portland mortars. This may account for the reason the pozzolanic mortars did not absorb as much water as the portland/lime mortars.

With the continued growth in compressive strength, with growing interest in green building, mortars and stuccos could be designed with lower initial compressive strength, but would exceed current 28-day requirements at 56 days or 90 days of age. This would allow more fly ash and less portland cement to be used and would slightly reduce the volume of carbon dioxide produced each year. Bargaheiser and Nordmeyer[14] addressed this issue at ASTM's 2006 Symposium on Masonry.

Table 6 lists 28-day compressive strength results. This data has been repackaged into Figure 4 to better illustrate a problem that regularly develops on job sites when attempts are made to test the mortar for compressive strength and use the Property Specification Table of ASTM C 270 as qualifying numbers. When testing mortar in the lab according to ASTM C 270, the flow is required to be 110% ± 5%. According to ASTM C 270 Property Specification Table, lab-mixed Type S mortars need to meet or exceed 12.4 MPa. According to ASTM C 270 Proportion Specification Table, there are no requirements to meet any compressive strength. When mortars are mixed in the lab, they are mixed to a lower flow than when mixed in the field. The lower flow of the lab-mixed mortars is an attempt to duplicate the field-mixed mortar after the brick have sucked water out of the mortar. Mortars mixed to a flow that is appropriate for laying brick (130% to 145%) are not required to meet any specific compressive strength. Feret's Law[15] addresses the impact of the absolute volume of cement, water, and air on compressive strength of concrete. The better-known Abram's Law addresses the impact of absolute volume of cement and water on compressive strength. The literature does not state whether these laws can be applied to mortar; however, it is noted that by increasing the flow (and thus the amount of water), the compressive strength has decreased.

Figure 3. Compressive Strength of Different Type S Masonry Cements

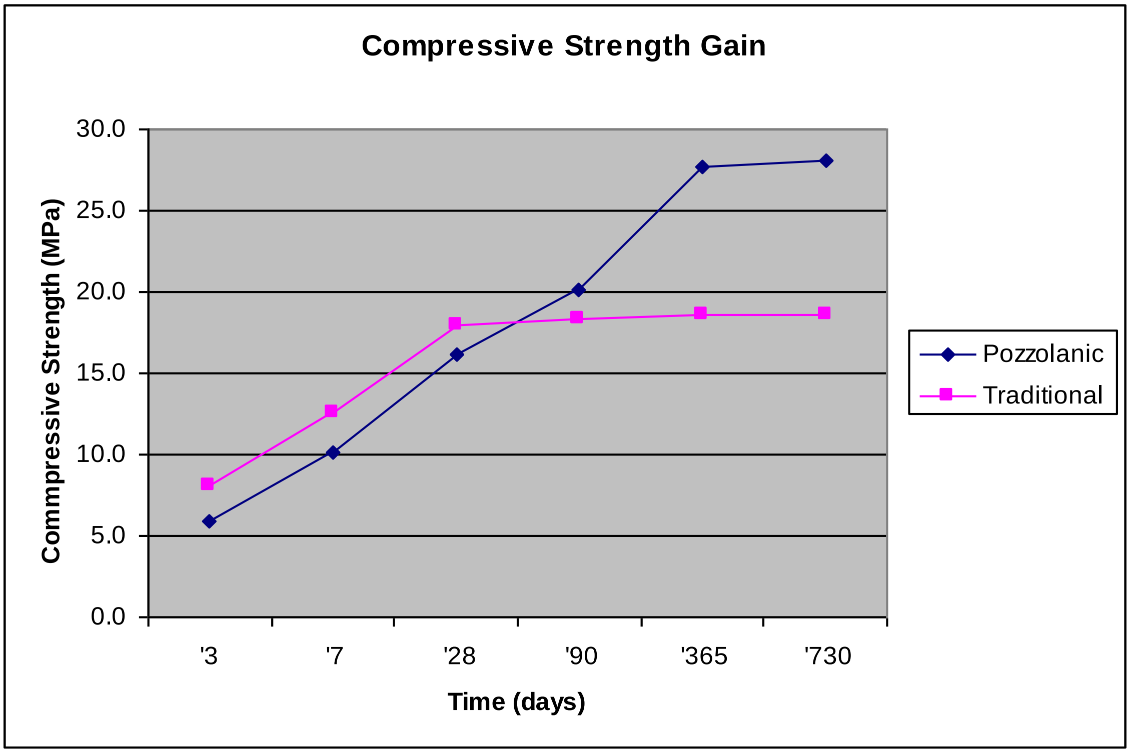


Table 8 lists data concerning flexural bond strength. It should be pointed out that ASTM C 270 does not have a requirement for flexural bond strength. ASTM C 1329 (Standard Specification for Mortar Cement) [16] has a requirement for a 28-day flexural bond strength of 0.7 MPa. That standard requires the test be performed:

With a standard concrete brick,
With mortar made with a blend of 20-30 sand and graded standard sand,
With a flow of 125% ± 5%, and
Assembly of the prisms follows a different procedure.

As a result, the minimum of 0.7 MPa flexural bond strength listed in ASTM C 1329 has no relevance when compared with these data.

The 24-hour rate of absorption testing produced some interesting results.

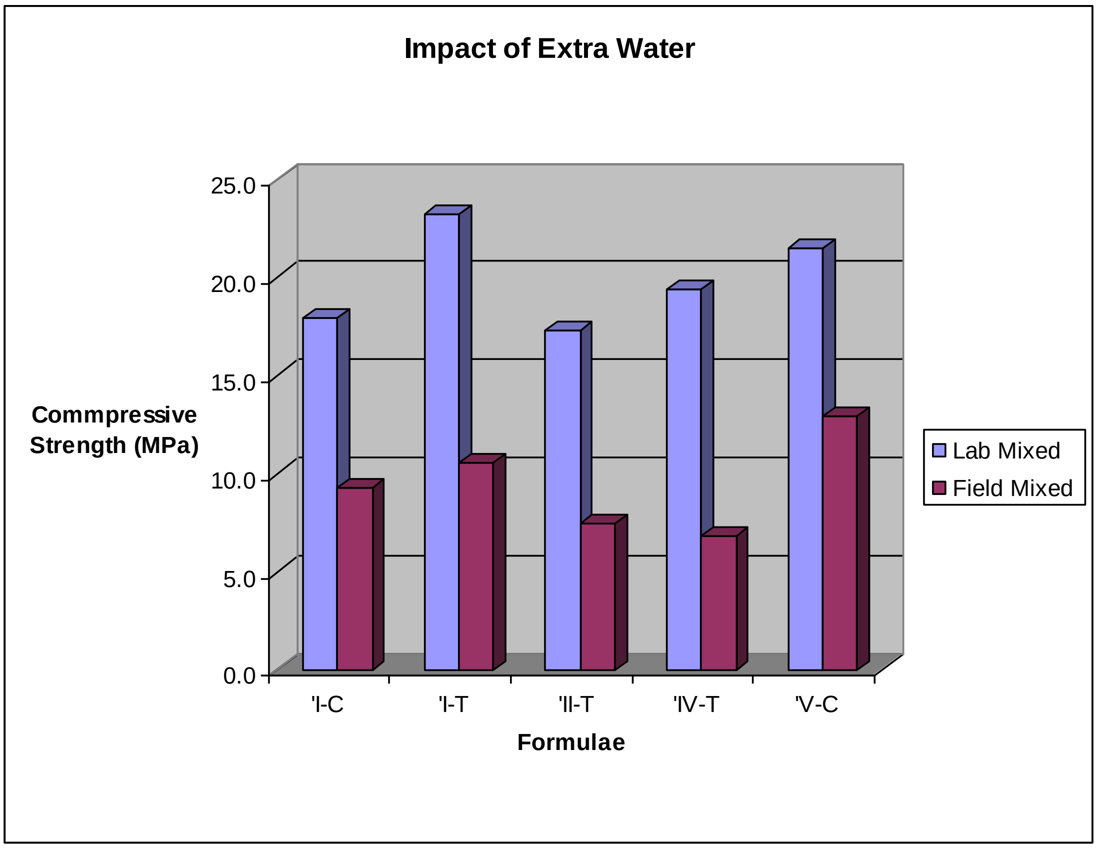
Formula I-Control (portland cement/lime mortar) is considered the standard of the industry; however, it had a higher 24-hour rate of absorption than any of the other treated or untreated mortars.

Formula IV-Control (pozzolanic masonry cement mortar) had a 24-hour rate of absorption that was only 43% that of Formula I-Control.

The liquid admixture, when dosed according to the manufacturer's recommendations, reduced the 24-hour rate of absorption to 26% to 73% of the values recorded for the control mortars. Obviously, different mortar formulae impact the functioning of the admixture. ASTM C 1384 requires that a water-repelling admixture reduce the 24-hour rate of water absorption by 50% while maintaining the 7- and 28-day compressive strengths at 80% or more of the control mortar.

Formulas II, III, and IV, when treated with the water-repellent admixture, reduced the rate of absorption to 25% to 31% of the rate found with the Formula I-Control.

Figure 4. Impact of Extra Water



Results from the ASTM E 514 testing produced results that were not in line with the results produced by the 24-hour rate of water absorption, which is a qualifying test for water-repelling admixtures.

The ASTM E 514 test is a 4-hour test where a 1.1 square meter wall is exposed to near-hurricane conditions. There are no pass or fail criteria. These conditions are developed by spraying the wall inside a test chamber with water and maintaining air pressure to simulate the wind conditions. The 4-hour time was established because seldom do the high wind and heavy rain conditions of the test last for more than 4 hours. Tests conducted at UT – Arlington are normally run for 24 hours. The extended time allows observations concerning the wall that are not normally observed during a 4-hour test. One of those observations is that with masonry cement mortar, the rate of leakage remains constant or goes up after the wall is fully saturated, and with portland/lime mortar, the rate of leakage tends to be reduced after the wall is fully saturated. These results tend to confirm the common claim that portland/lime mortars exhibit autogenous healing. The claim of autogenous healing is often related to the actions of the hydrated lime in the portland/lime mortar.

Data concerning Formula I-Control and Formula V-Control come from the UT – Arlington Data Base and are averages of a number of tests of Type S mortars that have been conducted over the years. These data indicate that the average masonry cement mortar wall tested passes 11.7 times as much water between the 23rd and the 24th hour of testing as the average portland/lime mortar.

Formula IV-Treated (pozzolanic masonry cement) passed 72.7 milliliters of water between hours 5 and 6, but the rate had dropped to 16.0 milliliters of water between hours 23 and 24. This indicates that the wall is becoming more water-resistant with time. The manufacturer reports that the pozzolanic masonry cement that was used to produce Formula IV did not contain hydrated lime. This rate of water flow is 5.3% of the rate from the Formula I-Control that is considered the standard of the industry.

Formula II-Treated (1P cement/lime) passed 16.5 milliliters of water between hours 5 and 6, but the rate had dropped to 1.3 milliliters of water between hours 23 and 24. As with Formula IV-Treated, this indicates that the wall is becoming more water resistant with time. This rate of water flow is 0.4% of the rate from the Formula I-Control.

Formula 1-Treated (portland/lime) did not pass any water during the 24 hours of the test. Without any rate of flow, percentages cannot be calculated.

Adding the water-repellent admixture to Formula I increased the 28-day flexural bond strength by 10%. There is not enough data to indicate why this increase occurred, but it is noted that the treated mortar required less water to produce equal flow (better water-cement ratio), and the compressive strength for Formula I-Treated was higher than for Formula 1-Control. Data is not available to indicate whether treatment increased the flexural bond strength with the other formulae.

Flexural bond strength for all mortars tested, both control and treated, was from 2.1 to 2.6 times as high as for Formula V-Control (traditional masonry cement).

These data indicate that 24-hour rate of water absorption is not an indicator as to how much a masonry wall will leak.

The UT – Arlington Data Base listed an average leakage through walls Type S portland cement/hydrated lime mortar of 300 ml per hour between the hours 23 and 24 of the test. Meadowcroft reported ASTM E 514 tests run on portland cement/hydrated lime by the Construction Technology Laboratories, Inc., in Skokie, Ill., showed a leakage through walls ranging from 0 to 0.68 liters (680 ml) per hour. Matthys[17] reported only a few milliliters of water passing through a Type N portland cement/hydrated lime mortar. These data tend to validate the values reported from the Data Base.

Water flows through 1.1 square meter ASTM E 514 test panels of less than 30 ml per hour should be considered insignificant since that is 10% of the flow through walls built using portland/lime mortar, which is considered the standard of the industry.

Observation of ASTM E 514 tests indicates that in a leaky wall, much of the flow passes through hairline cracks at the mortar/brick interface. 24-hour rate of water absorption of a mortar is not related to the number of hairline cracks that might be present.

Treating Formula I increased the flexural bond strength and lowered the flow of water through the wall. The increased bond strength may have been caused by more extent of bond, which would translate into a higher extent of bond.

CONCLUSIONS

Mixing mortar to a flow appropriate for laying brick will reduce the compressive strength when compared to mortars mixed to a flow of 110% $\pm$ 5%.

The water-repellent admixture increased the flexural bond strength of portland/lime mortar, but there is not sufficient testing to state whether it will increase the flexural bond strength of other mortars.

The 24-hour rate of water absorption without water-repellent admixture varied widely between mortar formulae.

The impact of the water-repellent admixture on the 24-hour rate of water absorption varied widely between the mortar formulae.

24-hour rate of absorption is a poor indicator of performance of a mortar when tested according to ASTM E 514.

Portland cement/hydrated lime mortar, 1P cement/hydrated lime mortar, and pozzolanic-masonry cement mortar tested according to the ASTM E 514 test, exhibited insignificant leakage through the masonry wall.

RECOMMENDATIONS

The study should be continued to determine the impact of the liquid water repellent tested on leakage through walls produced with traditional masonry cement mortars.

The study should be continued to determine the impact of other liquid water repellents on leakage through walls produced by different mortar formulae.

ASTM Committee C 12 should review this paper and determine whether guidance should be included in ASTM C 270 on the selection of liquid water repellents or whether further study should occur prior to making that decision.

Personnel within the fly ash industry should encourage producers of mortars, stuccos, and masonry cements to utilize pozzolanic technology

REFERENCES

[1] Nordmeyer, Herb and Pam Hall, Variations in the Activity of Dry-Powder Water-Repellent Mortar Admixtures with Different Mortar Formulae. Presented at the ASTM Symposium on Masonry, Toronto, Canada, June, 2007.

[2] Matthys, John H., and Herb Nordmeyer, Type S Masonry Mortars Modified with Liquid Water Repellent. Presented at the 10th North American Masonry Conference, The Masonry Society, St Louis, MO, June, 2007.

[3] Nordmeyer, D. Herbert, "High Pozzolan Mortars and Stuccos," *Masonry: Opportunities for the 21st Century*, *ASTM STP 1432*, D. Throop and R. E. Klingner, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2003.

[4] ASTM C 1403, "Standard Test Method for Rate of Water Absorption of Masonry Mortars," ASTM International. For referenced ASTM standards, visit the ASTM website, www.astm.org. For Annual Book of ASTM Standards volume information, refer to the Standard's Document Summary page on the ASTM website.

[5] ASTM C 270, "Standard Specification for Mortar for Unit Masonry," ASTM International. For referenced ASTM standards, visit the ASTM website, www.astm.org. For Annual Book of ASTM Standards volume information, refer to the Standard's Document Summary page on the ASTM website.

[6] ASTM C 1072, "Standard Test Method for Measurement of Masonry Flexural Bond Strength", ASTM International. For referenced ASTM standards, visit the ASTM website, www.astm.org. For Annual Book of ASTM Standards volume information, refer to the Standard's Document Summary page on the ASTM website.

[7] ASTM E 514, "Standard Test Method for Water Penetration and Leakage Through Masonry," ASTM International. For referenced ASTM standards, visit the ASTM website, www.astm.org. For Annual Book of ASTM Standards volume information, refer to the Standard's Document Summary page on the ASTM website.

[8] ASTM C 144, "Standard Specification for Aggregate for Masonry Mortar," ASTM International. For referenced ASTM standards, visit the ASTM website, www.astm.org. For Annual Book of ASTM Standards volume information, refer to the Standard's Document Summary page on the ASTM website.

[9] ASTM C 1384, "Standard Specification for Admixtures for Masonry Mortar," ASTM International. For referenced ASTM standards, visit the ASTM website, www.astm.org. For Annual Book of ASTM Standards volume information, refer to the Standard's Document Summary page on the ASTM website.

[10] ASTM C 91, "Standard Specification for Masonry Cement," ASTM International. For referenced ASTM standards, visit the ASTM website, www.astm.org. For Annual Book of ASTM Standards volume information, refer to the Standard's Document Summary page on the ASTM website.

[11] Thompson, Margaret, "Can Lime Be Replaced? Saying It Replaces Lime Doesn't Make it Lime," *Masonry Construction*, Vol. 13, No. 3, March 2000, pp. 29-32.

[12] Meadowcroft, Charles D., "Can Lime be Replaced? Lime Alternates Are Not And Do Not Want To Be Lime!," *Masonry Construction*, Vol. 13, No. 3, March 2000, pp. 29-33.

[13] Helmuth, Richard, Fly Ash in Cement and Concrete, 203 pp., Portland Cement Association, 1987, pp. 117-120.

[14] Bargaheiser, Keith and Herb Nordmeyer, Greening of Mortars With Pozzolans. Presented at the ASTM Symposium on Masonry, Toronto, Canada, June, 2007.

[15] F. M. Lea, *The Chemistry of Cement and Concrete*, Chemical Publishing Company, Inc., 3rd edition, 1971, pp. 391-392.

[16] ASTM C 1329, "Standard Specification for Mortar Cement," ASTM International. For referenced ASTM standards, visit the ASTM website, www.astm.org. For Annual Book of ASTM Standards volume information, refer to the Standard's Document Summary page on the ASTM website.

[17] Matthys, John, "Masonry Mortar Investigation," Report to Best Masonry & Tool Supply, San Antonio, Texas, 1997.