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# RUGGEDNESS TESTING OF THE MORTAR-AGGREGATE RATIO PROCEDURE

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**Abstract**

The mortar aggregate ratio test determines the amount of sand to cementatious materials in a particular mortar batch. The test method procedures are presented in ASTM C 780, *Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry.* This report presented the results of testing to investigate the effects of critical steps of the testing procedure. The effects analysis following the procedure found in ASTM E 1169, called ruggedness testing, allows testing variables to be systematically changed. The resulting outcomes are observed.

**Key Words**

Mortar, quality assurance, statistical analysis, laboratory evaluation

## 1 Introduction

Quality control/quality assurance for field mortar is often misunderstood and, therefore, the provisions of ASTM C 780, *Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry* often are misapplied. The mortar-aggregate (M-A) ratio test of Annex A4 determines the ratio of cementitious materials to aggregate and this ratio can be used to verify the mortar proportions determined to prequalify the mortar under a laboratory evaluation, such as ASTM C 270. Confidence in the results of the M-A test method will increase its use and allow the masonry industry to recommend the M-A test and move away from alternate QA/QC methods that sometimes lead to erroneous results.

This study will identify the laboratory factors that affect the results of M-A ratio tests. These results will be used to address the development of proposals, if necessary, to revise ASTM C 780 Annex A4 to improve the test procedures.

## 2 Project Scope General

The project identified environmental factors, or test conditions, that influence the determination of the mortar-aggregate ratio of Annex A4 of ASTM C 780. The influence of these factors was studied using ruggedness testing according to the procedures found in ASTM E 1169, *Standard Guide for Conducting Ruggedness Tests*.

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A review of Annex A4 and Annex A5 was conducted to identify the factors that would affect the M-A ratio results, and these are shown in Table 1.

*Table 1 Factors that Affect the Calculated M-A Ratio.*

| ASTM C 780 Section | Test Condition | Condition Designation | States[1] | State Code | Comments |
|---|---|---|---|---|---|
| A4.3.1 | Alcohol concentration | A | 70 % (L) versus 90 % (H) | L vs. H | Hydration process |
| A4.3.2 | Board life[2] | B | Fresh (cone pen = 63±5) (F) versus old (cone pen = 35±5) (O) | F vs. O | Mortar sampling time |
| A4.3.2 | Mortar sample size | C | 500 g (S) versus 700 g (L) | S vs. L | Difficulty in wet sieving |
| A4.3.4 | Drying sample | D | Oven dry (OD) in sieve versus hot plate dry transferring sample to pan (HP) | OD vs. HP | Transferring wet sieved materials |
| No section | Testing time | E | 4 hours (S) versus 48 hours (L) | S vs. L | Lab may not get to this test for 2 days |
| A4.3.2 | Agitate time | F | None (N) versus full (F) | N vs. F | Sample not shaken to stop hydration process |
| A5.3.3 | Burning of deleterious materials | G | Flame sample (F) versus wash alcohol and sample through filter (NF) | F vs. NF | Weight of dry mortar |

(1) States refer to high versus low test conditions, for example small and large sample size.
(2) Fresh mortar and old mortar cone penetration requirement based on experience.

This table shows the relevant ASTM C 780 sections (note that Annex A4 refers to Annex A5 for the computation of mortar water content), the test condition under consideration, and the proposed state of the conditions, its associated code, and comments. For example, time of testing was identified because a situation could arise where the test is conducted two or more days after sampling (pick up mortar and sand samples Friday afternoon and test on Monday morning). Furthermore, Annex A4 does not specify the time period for a valid M-A test. This and the other associated test conditions were identified by a line-by-line review of Annex A4.

Once the test conditions are identified, the methodology provided in ASTM E 1169 was used to develop an experimental study of the effects. Briefly, this ASTM guide outlines ruggedness testing using systematic changes of the test factors and observing the size of the effect on the test method result. This systematic process follows a series of Plackett-Burnham (P-B) designs that determine the systematic factor changes. The P-B designs are implemented by defining a test run that varies the factor states like those listed in Table 1 above. Further, the statistics of the P-B designs require that the number of test runs, N, be a multiple of four and that the number of factors be N - 1. Hence, the table above lists seven factors that will require eight test runs where M-A ratio is calculated.

The P-B design for N=8 is computed in ASTM E 1169 and will be used for this study. Using the factors in Table 1, Table 2 emerges as the P-B design for this project.

*Table 2 Experimental Design* [1]

| | Test Conditions | | | | | | |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G |
| 1a, b, c | H | O | L | HP | L | N | F |
| 2 a, b, c | L | O | L | OD | S | F | F |
| 3 a, b, c | L | F | L | OD | L | N | NF |
| 4 a, b, c | H | F | S | OD | L | F | F |
| 5 a, b, c | L | O | S | HP | L | F | NF |
| 6 a, b, c | H | F | L | HP | S | F | NF |
| 7 a, b, c | H | O | S | OD | S | N | NF |
| 8 a, b, c | L | F | S | HP | S | N | F |

[1] a, b, c – are three replicates for each 1-8 test runs

For example, test set number 1 has the following variables and this set will be replicated three times.

- 90 % alcohol concentration
- old mortar
- 700 g sample size
- hot plate drying
- 48 hours before testing
- no agitation
- flame the sample to burn off alcohol

Testing was conducted on one mortar type – Type S masonry cement. After all eight test runs, the effect of each condition was determined by using the methodology found in ASTM E 1169. For example, this identifies whether the board life of the mortar – condition B – has a large effect on the M-A ratio. Individual tests results will be presented first following the analysis of factor effects.

## 3 Test Results

The M-A ratio determines the amounts of cement and aggregate by introducing alcohol into a mortar sample to stop the hydration process. The mortar sample is weighed in various states – wet, oven dried, removal of alcohol, etc. – to determine the amount of dry mortar and dry aggregate.

Twenty-four individual M-A tests were conducted – eight test runs with three replicates per run – and the individual M-A were calculated and Table 3 lists the average M-A results. Further, Table 4 lists the average M-A ratio along with standard deviation and coefficient of variation. The descriptive statistics indicate that there is the influence of testing bias inherent in the results. A discussion of the procedure to determine test precision and bias is included at the end of this report.

Figure 1 shows the resulting M-A results for each individual test. Plotted as a dashed line in this figure is the actual M-A ratio for the mortar mix used for this analysis. Test runs 1 and 3 deviated from the actual M-A ratio of 3.2, due to the variation of factors. In particular, for test run 1, the sample was not agitated and tested at 48 hours. The test condition variables were not introduced one at a time, so the individual test runs cannot be used to conclude which factor had the greatest effect. Instead, the following P-B analysis will be used to investigate which factor had the most influence on the results.

*Table 3 Individual Results*

| Test Run | Test Condition(1) | | | | | | | Average M-A Ratio(2) |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | |
| 1 a, b, c | H | O | L | HP | L | N | F | 5.6 |
| 2 a, b, c | L | O | L | OD | S | F | F | 3.3 |
| 3 a, b, c | L | F | L | OD | L | N | NF | 5.7 |
| 4 a, b, c | H | F | S | OD | L | F | F | 3.4 |
| 5 a, b, c | L | O | S | HP | L | F | NF | 3.6 |
| 6 a, b, c | H | F | L | HP | S | F | NF | 3.4 |
| 7 a, b, c | H | O | S | OD | S | N | NF | 3.0 |
| 8 a, b, c | L | F | S | HP | S | N | F | 3.4 |

(1) See Table 1 for condition definition
(2) Average of three replicates

*Table 4 Descriptive Statistics*

| Test Run | Average M-A Ratio | Standard Deviation | COV (%) |
|---|---|---|---|
| 1 | 5.6 | 0.85 | 15.26 |
| 2 | 3.3 | 0.42 | 12.49 |
| 3 | 5.7 | 0.81 | 14.26 |
| 4 | 3.4 | 0.32 | 9.36 |
| 5 | 3.6 | 0.81 | 22.66 |
| 6 | 3.4 | 0.12 | 3.36 |
| 7 | 3.0 | 0.15 | 5.04 |
| 8 | 3.4 | 0.15 | 4.54 |

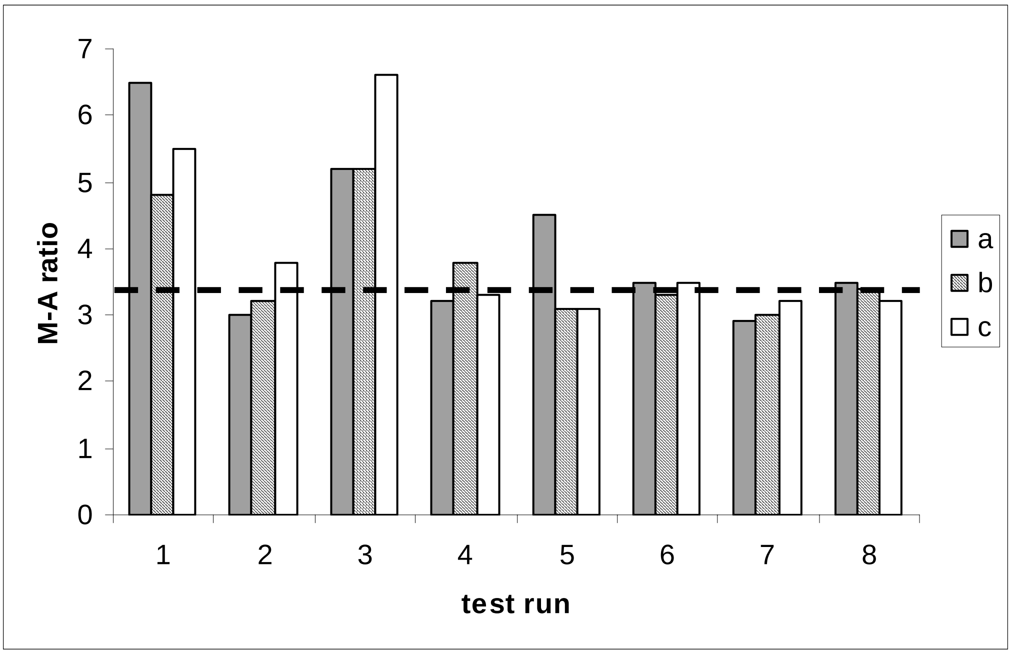


*Figure 1 Individual M-A Ratio Results*

## 4 Interpretation of Results

The effect of any factor, test conditions A–G, is calculated as the average measurement made at one level minus the average of the measurement at the other

level. For this study, levels are the condition states that were listed in Table 1. For example, the effect of test condition A would be calculated by averaging the M-A ratios for runs 1, 4, 6, and 7, minus the average for the M-A ratios for runs 2, 3, 5, 8. Details of the factor effect calculations are found in ASTM 1169. These calculations were done for the seven test conditions and three replicates. The condition effects are shown in Table 5.

*Table 5 Calculated Factor Effect for Replicates a, b, and c*

| Test condition | States | Effect Replicate a | Effect Replicate b | Effect Replicate c | Average Effect |
|---|---|---|---|---|---|
| Alcohol concentration | 70 % (L) and 90 % (H) | -0.025 | 0.000 | -0.300 | 0.108 |
| Board life | Fresh (cone pen = 63±5) (F) and old (cone pen = 35±5) (O) | 0.375 | -0.400 | -0.250 | 0.342 |
| Mortar sample size | 500 g (S) and 700 g (L) | 1.025 | 0.800 | 1.650 | 1.158 |
| Drying sample | Oven dry (OD) in sieve and hot plate dry transferring sample to pan (HP) | -0.925 | 0.150 | 0.400 | 0.492 |
| Testing time | 4 hours (S) versus 48 hours (L) | 1.625 | 1.000 | 1.200 | 1.275 |
| Agitate time | None (N) and full (F) | -0.975 | 1.000 | 1.200 | 1.058 |
| Burning of deleterious materials | Flame sample (F) and wash alcohol and sample through filter (NF) | -0.025 | -0.150 | 0.150 | 0.108 |

Average effects can be calculated from the magnitudes of the individual effect, and these are also listed in Table 5. The test condition with the largest effect was the time the test was conducted, average condition effect = 1.275, and it was observed that hydration did occur in the mortar samples stored in alcohol and tested at 48 hours. Figure 2 shows mortar in a 100 size sieve after 48 hours that was stored in 70% alcohol and not agitated. Mortar lumps formed in this sample and contributed to the increased amount of coarse material, leading to a higher calculated M-A ratio. Currently ASTM C 780 does not have guidance regarding the time to test the mortar sample. The test conditions that produced the next largest effects were sample size and agitation of the sample. The sample must be shaken in order to uniformly mix the mortar sample. When the sample is not shaken, mortar lumps formed (see Figure 2) increasing the M-A ratio. The size of the mortar sample affected the results because ASTM stipulates the use of 250 grams of alcohol. Therefore, there may not be enough

*Figure 2 Mortar Sample after 48-hour Storage in Alcohol*

alcohol available to stop the hydration process for the larger sample size, resulting in a high calculated effect as shown in Table 5. The method of sample drying and the age of the mortar sampled also affected the M-A ratio results.

ASTM E 1169 suggests the calculation of the “t-statistics” from the effects listed in Table 5, and then uses a Student’s t-distribution analysis to determine which effects are significant. ASTM E 1169 develops a methodology to estimate the standard deviation, *s*, from two sets of measurements and uses this to calculate the t-statistic. In this study, the set of measurements are the replicates a, b, and c. Therefore, the differences between replicates a and b, a and c, and b and c were used to calculate s and the resulting t-statistics.

Once the t-statistics are calculated, their values are compared to the t-distribution with seven degrees of freedom (number of test runs minus 1). For a 90% significant effect, the t-statistic needs to be greater than 1.895; for 95% significant, 2.365; and 99% significance, 3.499 [see The Civil Engineering Handbook, W.F. Chen, Editor-in-Chief, CRC Press, 1995]. From this analysis, Table 6 lists the effects that are significant for the replicate pairs.

The most significant effects are the size of the mortar sample, time of testing, and agitation of the mortar sample. These test conditions can be addressed within ASTM C 270 by stipulating these conditions.

*Table 6 Effect Analysis Using Student’s t-distribution*

| Replicates | 90% Significant Effect | 95% Significant Effect | 99% Significant Effect |
|---|---|---|---|
| a and b | Testing time<br>Mortar sample size | Testing time | |
| b and c | Mortar sample size<br>Testing time<br>Agitate time | Mortar sample size<br>Testing time<br>Agitate time | Mortar sample size<br>Testing time<br>Agitate time |
| a and c | Mortar sample size<br>Testing time | Mortar sample size<br>Testing time | |

## 4.1 Analysis of Mortar Testing Time

The effect of mortar testing time was investigated further to see if the test time could be extended further than 4 hours, but less than 48 hours. To do this, three M-A ratio tests were conducted at 4, 8, and 24 hours with each M-A test having three replicates. Furthermore, the other test conditions were held constant and were set to the condition states shown in Table 7 below. The other states were chosen based on the observations in this report as those most favorable to conduct an accurate M-A test. In fact, these test conditions repeat the states that were done for test run number 4 discussed above.

*Table 7 Variables Used in the M-A Ratio Tests*

| Test condition | A Alcohol | B Board Life | C Sample Size | D Drying Sample | E Testing Time | F Agitate Time | G Burn |
|---|---|---|---|---|---|---|---|
| States | 90% | fresh mortar cone pen (63+-5) | 500 gm | in sieve oven dry | 4, 8, and 24 hrs before testing | Full agitation | Flame sample to burn off alcohol |
| Code | H | F | S | OD | S | F | F |

*Table 8 M-A Test Results at Different Test Times*

| Replicate | 4 hours | 8 hours | 24 hours | 48 hours [(1)] |
|---|---|---|---|---|
| a | 3.4 | 3.0 | 3.4 | 3.2 |
| b | 3.5 | 3.4 | 3.4 | 3.4 |
| c | 3.3 | 3.4 | 3.4 | 3.3 |
| average | 3.4 | 3.3 | 3.4 | 3.4 |
| Standard deviation | 0.10 | 0.23 | 0.00 | 0.32 |
| COV | 2.9% | 7.1% | 0.0% | 9.4% |

[(1)] Results from test run 4

Table 8 shows the results of the M-A tests at the different testing times including the results from test run number 4 presented previously. Good agreement was observed between all the test runs. Testing time was shown to be one of the critical factors, therefore it cannot be simply stated that the testing can be done at 48 hours as Table 8 would indicate. In fact, all Table 8 indicates is, if the test factors of Table 7 are maintained at their best states, the testing can be done at 48 hours with no degradation of the results. Therefore, more testing is needed to understand the variance due to testing time.

## 4.2 Revisions to ASTM C 780 Annex A4

Annexes A4 and A5 of ASTM C 780 provide the provisions of the M-A test method. From the results of this study, Table 9 was developed to summarize proposed changes to the test method. This study only reviewed Annexes A4 and A5; therefore, any changes to the Annex sections must be coordinated with the provisions in the main body of ASTM C 780. Further, Annex A5 duplicates some of the language contained in Annex A4. Consequently, changes to Annex A4 must be coordinated with the provisions of Annex A5 to avoid conflicting language.

*Table 9 Proposed Revisions to ASTM C 780*

| ASTM C 780 Section | Test condition | States | Current ASTM C 780 Language | Suggested Change |
|---|---|---|---|---|
| A4.3.1 | Alcohol concentration | 70% (L) and 90% (H) | None | None needed – alcohol concentration did not produce significant effect |
| A4.3.2 | Board life | Fresh (cone pen = 63±5) (F) and old (cone pen = 35±5) (O) | None | Add requirement to sample fresh mortar |
| A4.3.2 | Mortar sample size | 500 g (S) and 700 g (L) | Sample size between 500 to 700 g | Stipulate 500 g sample |
| A4.3.4 | Drying sample | Oven dry (OD) in sieve and hot plate dry transferring sample to pan (HP) | Requires oven dry | None |
| No section | Testing time | 4 hours (S) versus 48 hours (L) | None | Require that testing be conducted within 4 hours of sampling mortar |
| A4.3.2 | Agitate time | None (N) and full (F) | Requires agitation | None |
| A5.3.3 | Burning of deleterious materials | Flame sample (F) and wash alcohol and sample through filter (NF) | Requires flame sample to burn off alcohol | None |

## 5.0 Conclusion

The mortar aggregate ratio test determines the amount of sand to cementitious materials in a particular mortar batch. The test method procedures are presented in ASTM C 780. This report presented the results of testing to investigate the effects of critical steps of the testing procedure. The effects analysis following the procedure found in ASTM E 1169, called ruggedness testing, allows testing variables to be systematically changed. The resulting outcomes are observed.

Critical steps that were identified as causing the largest effects were: the time to conduct testing, the size (weight) of the mortar sample, and the agitation of the sample. It was recommended that the provisions of ASTM C 780 that govern these steps of the testing procedure be changed immediately. To a smaller degree, other test conditions also were found to affect the outcome of the M-A, i.e.: the sampling of fresh mortar and drying the sample in an oven. Changing these steps should be considered carefully before revising the test procedure. For example, the practicality of requiring fresh mortar may be difficult to enforce or accomplish on a jobsite.

Ruggedness testing identifies the effects of critical steps of a laboratory procedure. To further investigate the M-A ratio test procedure, an interlaboratory study (ILS) is required to determine the accuracy of the method. An ILS involves approximately 30 laboratories conducting the M-A procedure on the same sample. Then, statistical calculations conducted on results can determine precision and bias. The ILS procedures are found in ASTM E 691, *Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test.* The ASTM E 691 practice describes the techniques for planning, conducting, and analyzing the results of the ILS.

## References


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