RECALIBRATION OF THE UNIT STRENGTH METHOD FOR VERIFYING COMPLIANCE WITH THE SPECIFIED COMPRESSIVE STRENGTH OF CONCRETE MASONRY

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ABSTRACT

The unit strength table in the *Specification for Masonry Structures* (TMS 602/ACI 530.1/ASCE 6) allows users to designate specific combinations of mortar type and concrete masonry unit compressive strength to achieve minimum masonry assembly compressive strengths for design application. This table can also be used for inspection purposes when verifying the minimum specified compressive strength of masonry, f'_m, where the mortar type and unit compressive strength are known quantities. Compared to other options for verifying assembly compressive strength, the unit strength method can be easier and less expensive to implement. It is recognized, however, that the unit strength table is inherently conservative; providing assembly compressive strength values considerably lower than what would be expected for a given combination of unit strength and mortar type.

Drawing from a newly developed database of prism test data, this research investigation evaluates the correlation between unit strength, mortar type and assembly compressive strength. Based on this testing and analysis, a new unit/assembly compressive strength correlation is proposed that reflects not only contemporary materials and testing procedures, but unit compressive strength values that provide a more accurate assessment and predictor of assembly compressive strength for design application or field quality assurance.

KEYWORDS: specified compressive strength, prism testing, unit strength method, mortar type

INTRODUCTION

In accordance with the provisions of the 2012 *International Building Code* (IBC) [1] and the Masonry Standards Joint Committee (MSJC) *Building Code Requirements for Masonry Structures* (TMS 402/ACI 530/ASCE 5) [2], the minimum specified compressive strength of masonry, f'_m, is required to be verified for masonry structures designed using one of the engineering analyses methods. Verification of the minimum specified masonry compressive strength can be accomplished by one of three methods:

- Removing prisms from existing construction in accordance with ASTM C1532, *Standard Practice for Selection, Removal, and Shipment of Manufactured Masonry Units and Masonry Specimens from Existing Construction* [3] and testing in accordance with ASTM C1314, *Standard Test Method for Compressive Strength of Masonry Prisms* [4];

- Using the unit strength method: a standardized correlation between unit compressive strength, mortar type, and assembly compressive strength; or
- Construction and testing of prisms in accordance with ASTM C1314.

As illustrated in Table 1, the unit strength table in the *Specification for Masonry Structures* [5] allows users to designate specific combinations of mortar type and unit compressive strength to achieve minimum masonry assembly compressive strengths for design application; or for inspection purposes when verifying the minimum specified compressive strength of masonry, f'_m, where the mortar type and unit compressive strength are known quantities.

Table 1: Unit/Assembly Strength Correlation for Concrete Masonry

Net area compressive strength of concrete masonry units, MPa (lb/in.^{2})		Net area compressive strength of masonry[A], MPa (lb/in.^{2})
Type M or S Mortar	Type N Mortar	
---	13.10 (1,900)	9.31 (1,350)
13.10 (1,900)	14.82 (2,150)	10.34 (1,500)
19.31 (2,800)	21.03 (3,050)	13.79 (2,000)
25.86 (3,750)	27.92 (4,050)	17.24 (2,500)
33.10 (4,800)	36.20 (5,250)	20.69 (3,000)

[A] For units less than 4 in. (102 mm) in height, 85% of the values listed.

Compared to other options (prism construction or removal of prisms from existing construction), the unit strength method is often easier and less expensive to implement. It is recognized however, that the unit strength table is inherently conservative – and increasingly so at higher compressive strengths. There are tangible reasons for the inherent conservatism in the unit strength table method, including:

1) When originally introduced, the testing procedures and equipment used to develop the prism test data upon which the original unit strength table was based were considerably less refined than they are today. Changes introduced into ASTM C1314, which most notably include requiring stiffer/thicker bearing platens on testing equipment, produce more consistent, repeatable compressive strength results.
2) The predecessor to ASTM C1314 was ASTM E447, *Test Methods for Compressive Strength of Laboratory Constructed Masonry Prisms* [6]. Unlike ASTM C1314, ASTM E447 did not define, or provided various options for, the construction, curing and testing of masonry prisms. As a result, the same set of materials could produce prism test results that fluctuated considerably depending upon which variables were introduced during the construction and testing process.

The net result was a database of prism compressive strengths with statistically high variability, which when codified into the existing unit strength method drove the lower bound correlation between unit, mortar, and prism to inappropriately conservative values. Even though testing expenses may be reduced through the use of the unit strength method, the inherent conservatism of the procedure results in indirect, but real costs because the full potential strength of a concrete masonry assembly is not realized. Nevertheless, because this data is conservative when applied to modern design standards, the unit strength approach has been maintained as a codified option.

The intent of this research investigation is to re-evaluate the correlation between unit and assembly compressive strength for concrete masonry using contemporary testing procedures and materials with the goal of recalibrating the existing unit strength method. A detailed discussion and analysis of this investigation is available in the public domain [7].

MATERIALS

All units used in this research consisted of hollow concrete masonry units having nominal dimensions of 200 x 200 x 400 mm (8 x 8 x 16 inch) and complied with the minimum requirements of ASTM C90, *Standard Specification for Loadbearing Concrete Masonry Units* [8]. Eight sets of units were used in this research with compressive strengths that ranged from approximately 13.8 MPa (2,000 lb/in.^{2}) to slightly more than 37.9 MPa (5,500 lb/in.^{2}). Although unit density is not considered to be an influential variable on the conclusions of this investigation, test specimens were constructed of lightweight, medium weight, and normal weight units with densities varying from 1,602 kg/m^3 (100.0 lb/ft^3) to 2,203 kg/m^3 (137.5 lb/ft^3) to capture the broadest range of intrinsic unit properties possible. The designations for the concrete masonry units used in this research are shown in Table 2.

Table 2: Unit Designations

Designation	Average Compressive Strength	Designation	Average Compressive Strength
U19	14.1 MPa (2,050 lb/in.^{2})	U40	28.3 MPa (4,110 lb/in.^{2})
U25	17.7 MPa (2,570 lb/in.^{2})	U45	31.3 MPa (4,540 lb/in.^{2})
U30	20.8 MPa (3,010 lb/in.^{2})	U50	35.0 MPa (5,080 lb/in.^{2})
U35	23.3 MPa (3,380 lb/in.^{2})	U55	38.0 MPa (5,510 lb/in.^{2})

Based upon past testing [9], mortar compressive strength is recognized as having a small, albeit measurable, influence on the resulting assembly compressive strength. Further, this influence generally tends to become more significant as the relative compressive strengths of the mortar and unit diverge. It is also conceivable that assembly compressive strength could be influenced by the type of cement used in the mortar. As such, this investigation included several different mortar formulations using both Type S and Type N mortars incorporating both portland cement/lime as well as masonry cement materials. To capture the range of compressive strengths for a given mortar type, mortar was batched by proportion as well as by property. Except for one mortar batch that fell just short of the minimum required compressive strength, each mortar formulation complied with the requirements of ASTM C270, *Standard Specification for Masonry Mortar* [10]. The non-complying mortar is not felt to have influenced the conclusions or recommendations of this investigation. The mortar designations used in this research are:

- PCL18 – Portland cement lime mortar having a compressive strength of 13.2 MPa (1,920 lb/in.^{2}) as determined in accordance with ASTM C270; targeting the minimum property requirements for a Type S mortar of 12.4 MPa (1,800 lb/in.^{2}).
- PCL7.5 – Portland cement lime mortar having a compressive strength of 4.8 MPa (700 lb/in.^{2}) as determined in accordance with ASTM C270; targeting the minimum property requirements for a Type N mortar of 5.2 MPa (750 lb/in.^{2}).
- MC18 – Masonry cement mortar having a compressive strength of 13.6 MPa (1,970 lb/in.^{2}) as determined in accordance with ASTM C270; targeting the minimum property requirements for a Type S mortar of 12.4 MPa (1,800 lb/in.^{2}).

- MC7.5 – Masonry cement mortar having a compressive strength of 6.1 MPa (890 lb/in.^{2}) as determined in accordance with ASTM C270; targeting the minimum property requirements for a Type N mortar of 5.2 MPa (750 lb/in.^{2}).
- PCLS – Portland cement lime mortar batched to the leanest proportion requirements of Type S mortar in accordance with ASTM C270; having a measured compressive strength of 23.2 MPa (3,370 lb/in.^{2}).
- PCLN – Portland cement lime mortar batched to the leanest proportion requirements of Type N mortar in accordance with ASTM C270; having a measured compressive strength of 9.2 MPa (1,330 lb/in.^{2}).

While the majority of the tested prisms were hollow, some specimens were solidly grouted as a means of spot-checking the influence varying grout compressive strength had on the measured prism strength. The conclusions and recommendations offered in this paper are based solely on the results of the hollow prism test. A full discussion of the grouted prism testing is available in the full report of this investigation [7].

CONSTRUCTION AND TESTING

All prisms were constructed and tested in accordance with ASTM C1314 using two half-length concrete masonry units and containing one full-bed mortar joint that was struck flush upon completion of construction. Each set of prisms for a given mortar formulation were constructed on the same day from a single batch of mortar and allowed to cure at least 28 days prior to testing. The results of the prism testing are shown in Table 3.

In addition to the physical testing conducted as part of this investigation, NCMA Laboratory records were mined to obtain additional prism test data to supplement the information generated in this project. This supplemental data, which includes only prisms constructed with Type S mortar, is presented in Table 4. In all, 75 sets of prisms, consisting of 225 individual prisms, were analysed in this investigation.

Table 3: Prism Test Results

	Net Area Compressive Strength, MPa (lb/in^2)			
Prism Set ID	Prism 1	Prism 2	Prism 3	Average
U19-PCL18-H	15.9 (2,300)	17.1 (2,480)	17.9 (2,590)	17.0 (2,460)
U25-PCL18-H	18.3 (2,660)	19.6 (2,840)	17.9 (2,590)	18.6 (2,700)
U30-PCL18-H	23.6 (3,430)	21.6 (3,140)	23.5 (3,410)	23.0 (3,330)
U35-PCL18-H	21.1 (3,060)	21.4 (3,100)	19.0 (2,750)	20.5 (2,970)
U40-PCL18-H	24.9 (3,610)	22.9 (3,320)	22.8 (3,300)	23.5 (3,410)
U45-PCL18-H	23.4 (3,390)	23.0 (3,340)	24.9 (3,610)	23.8 (3,450)
U50-PCL18-H	23.3 (3,380)	24.1 (3,490)	23.8 (3,450)	23.7 (3,440)
U55-PCL18-H	27.9 (4,050)	29.9 (4,340)	29.6 (4,290)	29.2 (4,230)
U19-PCL7.5-H	15.2 (2,200)	16.1 (2,340)	14.1 (2,050)	15.2 (2,200)
U25-PCL7.5-H	17.0 (2,460)	18.2 (2,640)	17.4 (2,530)	17.5 (2,540)
U30-PCL7.5-H	20.3 (2,950)	20.2 (2,930)	21.3 (3,090)	20.6 (2,990)
U35-PCL7.5-H	17.1 (2,480)	18.6 (2,700)	16.2 (2,350)	17.3 (2,510)
U40-PCL7.5-H	24.5 (3,560)	20.9 (3,030)	21.5 (3,120)	22.3 (3,240)

U45-PCL7.5-H	22.4 (3,250)	21.1 (3,060)	19.3 (2,800)	21.0 (3,040)
U50-PCL7.5-H	22.1 (3,210)	20.4 (2,960)	21.9 (3,180)	21.5 (3,120)
U55-PCL7.5-H	25.9 (3,750)	22.8 (3,300)	24.6 (3,570)	24.4 (3,540)
U19-MC18-H	14.8 (2,140)	14.2 (2,060)	15.2 (2,200)	14.7 (2,130)
U35-MC18-H	20.6 (2,990)	22.1 (3,200)	19.8 (2,870)	20.8 (3,020)
U55-MC18-H	26.9 (3,900)	29.3 (4,250)	26.3 (3,820)	27.5 (3,990)
U19-MC7.5-H	13.7 (1,990)	13.4 (1,950)	13.9 (2,020)	13.7 (1,990)
U35-MC7.5-H	15.6 (2,260)	16.7 (2,420)	14.4 (2,090)	15.6 (2,260)
U55-MC7.5-H	25.4 (3,680)	22.9 (3,320)	24.3 (3,530)	24.2 (3,510)
U19-PCLS-H	16.5 (2,390)	15.2 (2,200)	15.8 (2,290)	15.8 (2,290)
U35-PCLS-H	21.1 (3,060)	21.4 (3,110)	20.1 (2,910)	20.9 (3,030)
U55-PCLS-H	31.0 (4,500)	29.9 (4,330)	31.9 (4,630)	31.0 (4,490)
U19-PCLN-H	16.3 (2,360)	15.3 (2,220)	14.8 (2,150)	15.4 (2,240)
U35-PCLN-H	17.7 (2,570)	17.0 (2,470)	17.0 (2,470)	17.2 (2,500)
U55-PCLN-H	27.2 (3,950)	28.3 (4,100)	28.7 (4,160)	28.1 (4,070)

Table 4: Additional Type S Data Points from NCMA Laboratory Projects

Average Unit Strength, MPa (lb/in.^{2})	Average Prism Strength, MPa (lb/in.^{2})	Average Unit Strength, MPa (lb/in.^{2})	Average Prism Strength, MPa (lb/in.^{2})
20.8 (3,020)	20.6 (2,980)	26.3 (3,820)	19.8 (2,870)
40.1 (5,810)	31.3 (4,540)	36.8 (5,330)	30.1 (4,360)
47.4 (6,880)	37.9 (5,490)	48.0 (6,960)	36.1 (5,230)
29.3 (4,250)	24.5 (3,550)	42.4 (6,150)	32.2 (4,670)
24.0 (3,480)	18.8 (2,720)	45.2 (6,550)	27.4 (3,980)
37.4 (5,430)	30.0 (4,350)	28.1 (4,070)	23.2 (3,360)
26.4 (3,830)	21.9 (3,180)	27.7 (4,010)	23.7 (3,440)
20.7 (3,000)	18.1 (2,620)	28.8 (4,170)	25.1 (3,640)
23.6 (3,420)	19.1 (2,770)	34.4 (4,990)	28.1 (4,080)
26.7 (3,870)	21.2 (3,070)	24.3 (3,530)	20.9 (3,030)
33.9 (4,920)	27.7 (4,020)	27.3 (3,960)	22.3 (3,240)
25.1 (3,640)	22.1 (3,210)	29.8 (4,320)	24.9 (3,610)
29.3 (4,250)	22.5 (3,260)	20.1 (2,920)	17.8 (2,580)
25.8 (3,740)	19.9 (2,880)	29.9 (4,330)	19.3 (2,800)
24.7 (3,580)	18.8 (2,730)	32.3 (4,680)	22.9 (3,320)
23.8 (3,450)	24.3 (3,530)	29.8 (4,320)	22.1 (3,200)
33.4 (4,840)	26.1 (3,780)	27.5 (3,990)	20.9 (3,030)
35.7 (5,170)	27.9 (4,040)	38.5 (5,590)	27.2 (3,950)
22.5 (3,260)	18.8 (2,730)	30.1 (4,360)	21.2 (3,080)
31.6 (4,580)	27.7 (4,020)	29.9 (4,340)	27.0 (3,920)
20.5 (2,970)	23.7 (3,440)		

DISCUSSION AND ANALYSIS

Early analyses attempted to draw a single relationship between unit and prism compressive strength over the full range of test results, with the hope that a single expression could be generated instead of a more cumbersome table as currently used for the unit strength method. While simple to codify and apply, the results of such relationships had two distinct drawbacks:

1) At discrete locations across the spectrum of compressive strength results, there were instances where trend line or regression equations overestimated the resulting assembly/prism compressive strength that could not be easily corrected or accounted for using such direct relationships. Likewise, there were instances where such expressions would underestimate the assembly/prism compressive strength; thereby introducing a level of conservatism inappropriate for modern design application.
2) In expression form, it may imply a degree of precision that is unattainable in the field. While in reality a near limitless array of prism and/or unit compressive strength options are available, the tendency is to specify a masonry assembly compressive strength (f'_m values) in increments of 3.4 MPa (500 lb/in.^{2}) rather than a more specific compressive strength that is customized to each project's design variables. This created a secondary drawback associated with a single expression approach in that the predicted prism strengths resulting from the above expression would likely be rounded down to the nearest 3.4 MPa (500 lb/in.^{2}); fundamentally reintroducing the conservatism this research investigation set out to remove.

For these reasons, attempts to create a single relationship correlating unit to prism strength over the full spectrum of test data were abandoned. Instead, efforts were focused on developing relationships for specific subsets of material properties for both Type S and Type N mortars.

To simplify data analysis, the Type S and Type N mortar prism results were separated into discrete 3.4 MPa (500 lb/in.^{2}) ranges based on the measured compressive strength of the concrete masonry units. The beginning midpoint began at 13.8 MPa (2,000 lb/in.^{2}) and increased in 3.4 MPa (500 lb/in.^{2}) increments up to a maximum of 48.3 MPa (7,000 lb/in.^{2}). Each data set range included the test results for the units within +/-1.7 MPa (250 lb/in.^{2}) of the midpoint. For example, the dataset at 17.2 MPa (2,500 lb/in.^{2}) consists of the unit/prism test data where the unit compressive strength is between 15.5 MPa (2,250 lb/in.^{2}) and 19.0 MPa (2,750 lb/in.^{2}). The number of data points within each dataset range varied from a low of 3 to a maximum of 17. Given the limited number of data points in the high compressive strength range, coupled with the code-imposed limit [2] of 27.6 MPa (4,000 lb/in.^{2}) on the specified compressive strength of concrete masonry construction, subsequent analysis excluded all data points with a unit compressive strength in excess of 39.6 MPa (5,750 lb/in.^{2}), which corresponds to the midrange datasets of 41.4 MPa (6,000 lb/in.^{2}) and higher. As future needs dictate, additional research can be conducted to develop unit-to-prism compressive strength correlations, as well as corresponding design provisions, for high strength materials.

Each dataset range was statistically analyzed to find the 95% lower bound confidence interval assuming a normal distribution to take into account variances in the data. Because of the small sample size in each group ($N<30$), a t-series sampling distribution was used for the subsequent analysis. The results of these analyses are shown in Table 5 for the prisms constructed using Type S mortar and Table 6 for the prisms constructed using Type N mortar.

TYPE S MORTAR ANALYSIS

Table 5 shows the targeted masonry design strengths for each dataset range analyzed and the ratio of the 95% lower bound confidence interval to the targeted design masonry strength. Conceptually, the targeted masonry design strength, rounded in this analysis to the nearest 0.7 MPa (100 lb/in.^{2}) for practicality, would be the acceptable masonry assembly compressive strength used for design for the combination of unit compressive strength and mortar properties of each dataset. Ideally, the ratio of the 95% lower bound confidence interval to the targeted masonry design strength would be greater than or equal to 1.0 for conservative design application. For some discrete mortar type datasets, this ratio is less than 1.0; however, for the combined summary of all the Type S hollow prisms shown in Table 5, this ratio is at or above 1.0 for nearly all cases. The relatively low values of this ratio for discrete datasets within each mortar type category is a result of the very small number of data points within the dataset, which in turn yield artificially small lower bound compressive strengths compared to the more robust datasets inclusive of all Type S mortar prisms.

This statistical reality becomes apparent for the 17.2 MPa (2,500 lb/in.^{2}) unit compressive strength dataset, which as shown in Table 5 has a confidence interval to targeted masonry design strength of 0.99 for combined datasets. Despite the large number of data points analyzed in this investigation that incorporated Type S mortar, this particular dataset only contained three prism test results in total, each of which was constructed using Type S portland-cement and lime mortar batched by property (PCL18). For this dataset, the compressive strength of each of these prisms was 18.3 MPa (2,660 lb/in.^{2}), 19.6 MPa (2,840 lb/in.^{2}), and 17.9 MPa (2,590 lb/in.^{2}), for an average compressive strength of 18.6 MPa (2,697 lb/in.^{2}). The variation in these test results, combined with the low number of data points, creates a 95% lower bound that is artificially low for this dataset. Although a judgment call, given that the targeted design strength of 17.2 MPa (2,500 lb/in.^{2}) is considerably lower than the average for this dataset, and no single data point is less than the targeted design strength, 17.2 MPa (2,500 lb/in.^{2}) appears to be a reasonable targeted design value, which would likely prove true if more data points were available for this dataset.

In considering the results shown in Table 5, one could argue that further refinement of the targeted masonry design compressive strength values could be achieved. For example, the targeted masonry design compressive strength value of 13.8 MPa (2,000 lb/in.^{2}) could be increased to 14.5 MPa (2,100 lb/in.^{2}), which would still be conservatively less than the 95% lower bound of 15.1 MPa (2,190 lb/in.^{2}) for this dataset. Given that this would result in a masonry assembly compressive strength larger than the compressive strength of the units used to construct the assembly, however, this may result in confusion or uncertainty in application. Likewise, one could argue that the 37.9 MPa (5,500 lb/in.^{2}) unit dataset range could increase the targeted design strength from 27.6 MPa (4,000 lb/in.^{2}) to 28.3 MPa (4,100 lb/in.^{2}) to more closely align with the statistically-derived lower bound compressive strength. The 27.6 MPa (4,000 lb/in.^{2}) targeted masonry design compressive strength was imposed here as this also corresponds to the upper limit on the specified compressive strength of concrete masonry currently stipulated by the strength design procedures of *Building Code Requirements for Masonry Structures* [2].

Table 5: Dataset Summary for All Type S Hollow Prism Data

Unit compressive strength dataset, MPa (lb/in.^{2})[A]	Average prism compressive strength, MPa (lb/in.^{2})	95% Lower bound confidence interval, MPa (lb/in.^{2})	Targeted masonry design compressive strength, MPa (lb/in.^{2})	Ratio of 95% confidence interval to targeted masonry design strength
13.8 (2,000)	15.8 (2,294)	15.1 (2,190)	13.8 (2,000)	1.09
17.2 (2,500)	18.6 (2,697)	17.1 (2,479)	17.2 (2,500)	0.99
20.7 (3,000)	20.9 (3,027)	18.8 (2,721)	18.6 (2,700)	1.01
24.1 (3,500)	20.6 (2,979)	19.9 (2,887)	19.3 (2,800)	1.03
27.6 (4,000)	22.8 (3,298)	22.0 (3,185)	21.4 (3,100)	1.03
31.0 (4,500)	23.7 (3,429)	22.2 (3,213)	22.1 (3,200)	1.00
34.5 (5,000)	25.9 (3,749)	24.3 (3,524)	24.8 (3,600)	0.98
37.9 (5,500)	29.2 (4,231)	28.3 (4,102)	27.6 (4,000)	1.03

[A]These values define the designations assigned to each data set, which corresponds to approximately the average compressive strength value of the units within the data set. The compressive strength of individual units within each data set may be slightly higher or lower than the data set designation.

TYPE N MORTAR ANALYSIS

The hollow unit prisms constructed with Type N mortar were analyzed in the same manner as the prism constructed using Type S mortar. Table 6 summarizes the average and 95% lower bound prism compressive strength values for each Type N dataset range. The significant difference between the Type S and Type N prism data is that additional laboratory data using Type N mortar was not available to supplement the test results of this investigation. As such, the following analysis is based on a limited number of test results.

Table 6: Dataset Summary for All Type N Hollow Prism Data

Unit compressive strength dataset, MPa (lb/in.^{2})	Average prism compressive strength, MPa (lb/in.^{2})	95% Lower bound confidence interval, MPa (lb/in.^{2})	Targeted masonry design compressive strength, MPa (lb/in.^{2})	Ratio of 95% confidence interval to targeted masonry design strength
13.8 (2,000)	14.8 (2,142)	14.1 (2,049)	13.8 (2,000)	1.02
17.2 (2,500)	17.5 (2,543)	16.5 (2,390)	17.2 (2,500)	0.96
20.7 (3,000)	20.6 (2,990)	19.6 (2,843)	17.9 (2,600)	1.09
24.1 (3,500)	16.7 (2,423)	16.0 (2,314)	17.9 (2,600)	0.89
27.6 (4,000)	22.3 (3,237)	19.0 (2,759)	17.9 (2,600)	1.06
31.0 (4,500)	21.0 (3,037)	18.3 (2,656)	17.9 (2,600)	1.02
34.5 (5,000)	21.5 (3,117)	19.9 (2,887)	17.9 (2,600)	1.11
37.9 (5,500)	25.6 (3,704)	24.2 (3,509)	17.9 (2,600)	1.35

In reviewing the summary of the Type N prism data shown in Table 6 it is immediately noticeable that the Type N prism data has considerable scatter in the results for unit compressive strengths above 20.7 MPa (3,000 lb/in.^{2}). Some of this relatively larger variation compared to the Type S prism data was to be expected given that there was no supplemental data from other sources to augment the Type N data. This observation alone, however, cannot fully explain the lack of trending and large scatter in the Type N mortar test results; indicating that some other contributing factor is influencing the results. Until such time as these factors and identified and understood it is recommended to limit the application of the unit strength method using Type N mortar to assembly compressive strength values of 17.9 MPa (2,600 lb/in.^{2}) or less as reflected in Tables 6. As more Type N prism test data becomes available, this recommendation should be revisited. Until such time, when concrete masonry design strength values in excess of 17.9 MPa (2,600 lb/in.^{2}) are desired with Type N mortar, either prism testing or removal of prism specimens from existing construction would need to be used to verify masonry compressive strength values.

CONCLUSIONS AND RECOMMENDATIONS

General observations from this investigation include:

- Current prism testing procedures produce significantly more consistent results compared to historical practices, which in turn permitted 95% lower bound confidence intervals to be established with less conservatism than current unit strength procedures.
- At the lower end of unit compressive strengths, the mortar type and compressive strength has little impact on the resulting prism compressive strength. The mortar type/strength does however begin to impact the measured prism compressive strength as the ratio of the unit-to-mortar compressive strength increases. As would be expected, higher strength units produce higher compressive strength prisms for both mortar types.
- Prisms constructed using mortar batched by proportion versus property produced prism compressive strengths that have slight, albeit measurable, differences of approximately +/- 7% across the range of unit compressive strengths tested in this project. This small difference, however, is not felt to warrant differentiating mortar batching procedures when applied to the unit strength method.
- At relatively high unit compressive strengths, prisms constructed using Type N mortar exhibited more variability between the average and 95% lower bound compressive strength when compared to their prism counterparts constructed using Type S mortar. As such, recommendations offered here propose limiting the application of the unit strength method for determining/verifying masonry design compressive strength using Type N mortar to 17.9 MPa (2,600 lb/in.^{2}) until more research becomes available that would explain whether the observations stemming from this investigation are unique, or if this is potentially a larger issue systemic to combinations of very high strength units and low strength mortars.
- The most significant observation from this research is what represents a statistical lower bound for concrete masonry assembly compressive strength. While historically the default value for the specified compressive strength of masonry in the U.S. has centered on 10.3 MPa (1,500 lb/in.^{2}), extrapolating the results of this research to unit compressive strength values of 13.1 MPa (1,900 lb/in.^{2}) shows that the weakest combination of permitted unit strength and mortar type can produce an assembly compressive strength of 13.7 MPa (2,000 lb/in.^{2}).

- To fully capitalize on this last point, setting the lower bound unit compressive strength value at 13.8 MPa (2,000 lb/in.^{2}) in the recalibrated unit strength table subsequently creates a secondary question of whether the minimum average compressive strength of concrete masonry unit complying with ASTM C90 should concurrently be increased as well. Increasing the minimum average unit compressive strength from 13.1 MPa (1,900 lb/in.^{2}) to 13.8 MPa (2,000 lb/in.^{2}) would considerably simplify design and specification criteria as any "ASTM C90 compliant" concrete masonry unit would in turn produce a minimum specified compressive strength of 13.8 MPa (2,000 lb/in.^{2}).

Table 7: Compressive strength of masonry based on the compressive strength of concrete masonry units and type of mortar used in construction

Net area compressive strength of concrete masonry units, lb/in.^{2} (MPa)	Net area compressive strength of masonry, lb/in.^{2} (MPa)	
	Type M or S Mortar[1]	Type N Mortar[1]
2,000 (13.8)	2,000 (13.8)	2,000 (13.8)
2,500 (17.2)	2,500 (17.2)	2,500 (17.2)
3,000 (20.7)	2,700 (18.6)	2,600 (17.9)
3,500 (24.1)	2,800 (19.3)	-
4,000 (27.6)	3,100 (21.4)	-
4,500 (31.0)	3,200 (22.1)	-
5,000 (34.5)	3,600 (24.8)	-
5,500 (37.9)	4,000 (27.6)	-

[1]For units of less than 4 in. (102 mm) height, 85 percent of the values listed.

Combining the results from Tables 5 and 6 for the prisms constructed with Type S and Type N mortars produces Table 7, which in turn is recommended for adopting into existing building codes and standards. Additional comments related to Table 7 include:

- Footnote 1 of Table 7 is carried over from existing unit strength procedures and is intended to capture the apparent increase in the compressive strength of units having a low aspect ratio. The resulting strength and performance of assemblies constructed using reduced height units, however, would remain unchanged.
- As with current unit strength procedures, the results of this testing investigation support the linear interpolation of intermediate compressive strength values. Extrapolation of compressive strength values beyond those listed in Table 7 should not be permitted.
- Although this investigation did not test or analyze any prisms constructed using Type M mortar, it is felt to be conservative as well as historically consistent with past unit strength practices to apply the results of the Type S mortar specimens to analogous construction incorporating Type M mortar.
- Although this investigation included unit compressive strengths well above 37.9 MPa (5,500 lb/in.^{2}), an upper limit of 27.6 MPa (4,000 lb/in.^{2}) is proposed to align with existing strength design limits on the maximum specified compressive strength of concrete masonry.
- The upper limit of 2,600 lb/in.^{2} (17.9 MPa) imposed by Table 7 for masonry constructed using Type N mortar should not be construed as an absolute limit on masonry

compressive strength constructed using Type N mortar; but rather a reflection of the limited and relatively variable data currently available. When masonry compressive strengths above of 2,600 lb/in.^{2} (17.9 MPa) are desired with Type N mortar, prism testing would be necessary.

- This investigation, like the original leading to the developing of the first unit strength table, focused only on the performance of concrete masonry units complying with ASTM C90. Nevertheless, the existing codified unit strength table is applicable to concrete masonry units complying with ASTM C55, *Standard Specification for Concrete Building Brick* [11] and ASTM C1634, *Standard Specification for Concrete Facing Brick* [12], which were not considered in this study. Future research projects could focus on verifying the application of the proposed recalibrated unit strength table to units complying with ASTM C55 and ASTM C1634.

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