Embodied Energy
of Concrete Masonry

Say Goodbye to f'_m = 1500 psi

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Photo by Elizabeth Young

Sustainability has risen to the top of the concerns for every industry. Masonry experts have done an excellent job promoting the sustainable characteristics of masonry. As structural engineers, we try to incorporate sustainability into our designs. However, that usually means specifying alternate materials for aggregates, supplementary cementitious materials (SCM) and additives. Personally, I have felt that options to increase the sustainability of my projects have been limited. However, structural engineers have the ability to make the greatest impact on sustainability by harnessing the embodied energy of concrete masonry. We need to use masonry as efficiently as we can with our designs.
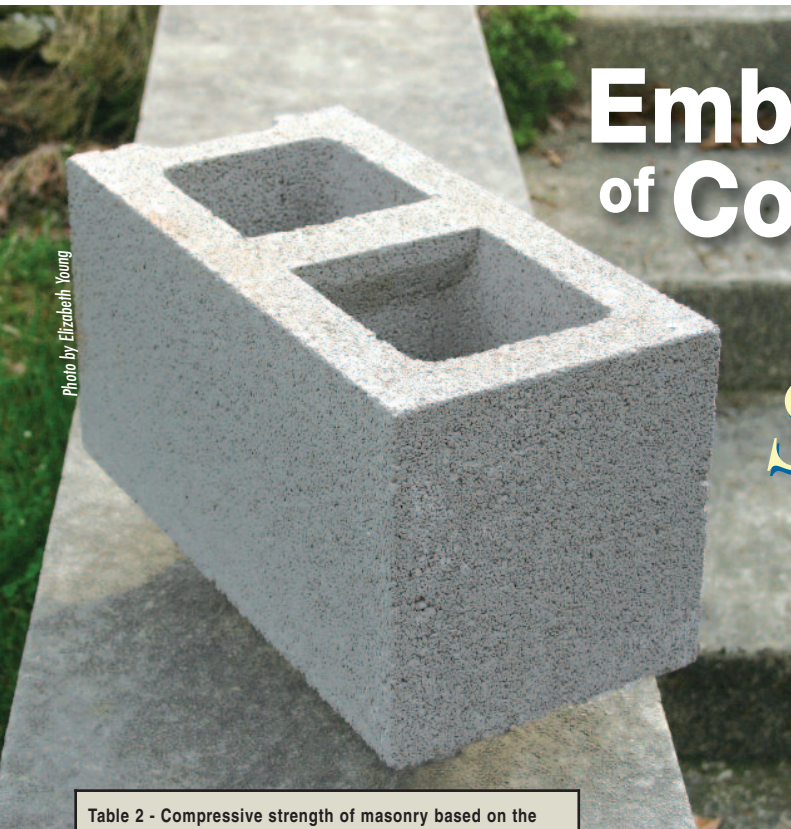
Table 2 - Compressive strength of masonry based on the compressive strength of concrete masonry units and type of mortar used in construction

Net area compressive strength of concrete masonry units, psi (MPa)		Net area compressive strength of masonry, psi[1] (MPa)
Type M or S mortar	Type N mortar	
—	1,900 (13.10)	1,350 (9.31)
1,900 (13.10)	2,150 (14.82)	1,500 (10.34)
2,800 (19.31)	3,050 (21.03)	2,000 (13.79)
3,750 (25.86)	4,050 (27.92)	2,500 (17.24)
4,800 (33.10)	5,250 (36.20)	3,000 (20.69)

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

Table 2 from TMS 602 illustrates the minimum strength for CMU allowed by ASTM C90, 1900 psi, combined with Type S mortar results in an f'_m of 1500 psi.

The *defacto* design strength used by many engineers is f'_m = 1500 psi. However, in many regions of the country, 1500 psi is an extremely conservative value based upon the concrete masonry units (CMU) available. Generally, f'_m equal to or greater than 2000 psi is easily achievable because higher strength units are the norm. Using masonry more efficiently will enhance the economic advantage of reinforced masonry and improve sustainability.

Unit Strength Method
The Unit Strength method is recognized by the masonry standard, *Specification for Masonry Structures* (TMS 602)[1] as one of two valid methods to verify the compressive strength of masonry. The Prism Test method involves a mason contractor constructing a prism, two CMU high with one mortar joint, then having the prism crushed by a testing firm. Both are acceptable for new construction. Unit Strength has

become the method most engineers seem to use, due to its simplicity and time savings.

Table 2 (TMS 602) illustrates the Unit Strength method for concrete masonry. This method requires the engineer to specify the minimum net area compressive strength of the masonry units and specify the type of mortar. From these two pieces of information, we arrive at a net compressive strength of the masonry (f'_m).

The Unit Strength table was derived from the results of over 329 prism tests (Figure SC-2) and was developed using outdated ASTM test methods to be overly conservative. It is not uncommon to perform prism tests in the field only to the find the actual f'_m is 25% to 30% higher than was obtained from the Unit Strength method. The National Concrete Masonry Association recognizes the conservatism in the Unit Strength method and has embarked on a research project to perform current testing procedures on the population of prisms and reassess Table 2. Initial results indicate that the f'_m can be increased while remaining conservative. However, until those results are published and accepted, we are left with the current Table 2 results.

How did we arrive at f'_m 1500 psi as the defacto standard? That comes from the Unit Strength method. ASTM C90, *Standard Specification for Loadbearing Concrete Masonry Units*[2], requires that CMU have a minimum strength of 1900 psi. Also, Type S mortar is commonly specified for structural masonry.

Using Table 2 with the Unit Strength method, the f'_m is 1500 psi.

Somehow, f'_m = 1500 psi became the standard for design. However, it's a conservative value.

Greater Strength CMU
Concrete masonry manufacturers throughout the US often produce to a higher standard than the minimum compressive strength listed in ASTM C90 (please verify specifics with your CMU manufacturer). CMU with a minimum strength of 3000 psi are common in many regions, especially in cold climate areas. Thus, the base price for many units already includes higher strength masonry. The higher strength is often used by manufacturers to provide a better mix for their molding process and to provide greater durability. So, while engineers may be specifying and designing with a minimum of 1900 psi units, they are likely getting units with a far higher strength on their projects. **Are you one of them?**

Using Table 2, the f'_m for 3000 psi units and Type S mortar would be 2105 psi (from linear interpolation). Compared to f'_m = 1500 psi, that's more than a 40% strength increase that goes unrealized. Compared to the structural steel industry, that's like designing for A36 (F_y 36 ksi) steel, but actually getting V50 (F_y 50 ksi) material. The unrealized capacity in that case is about 38%. Most engineers would not let that capacity slip away with steel, but are doing just that with masonry.

In several states, such as New York and Iowa, 2800 psi CMU are common and the industry in those states promotes f'_m = 2000 psi. This has created a greater awareness among engineers of higher strength units that can be produced. No longer do *masonry knowledgeable* engineers rely on f'_m = 1500 psi. They have learned to **first ask the manufacturers what they produce.**

Benefits from Increasing Strength
The benefits from increasing the f'_m should be obvious: sustainability and hidden economy in every design. Let's look at a few of the ways.

- Less grout required for partially grouted walls.
- Less reinforcement required for all walls.
- Reinforcement lap lengths reduced.
- Embedded anchors with greater capacities.

Several example designs illustrate potential for construction economy. The following examples are based upon Allowable Stress Design (ASD) methods and were prepared using the NCMA wall design software[3] and TMS 402[4]. The CMU has a density of 115 pcf. These design examples illustrate that increasing f'_m will provide greater economy because it will:

- Increase axial and flexural wall capacity.
- Increase capacity of shear walls.
- Decrease lap lengths for reinforcement splices.
- Increase flexural and shear capacity of masonry beams, columns and pilasters.
- Increase the stiffness of masonry elements by increasing the modulus of elasticity.
- Increase tension and shear capacities of embedments.
- Reduce reinforcement required. In many low seismic zones, typical spacing for vertical bars is 48" oc. That comes from 6t and 8" CMU (6 x 8=48"). Engineers need to take advantage of 6t with 12" CMU (6x12=72").

The examples also indicate that simply increasing designs to a minimum of f'_m = 2000 psi can improve the economy of masonry projects and thereby use the embodied energy of the masonry more fully.

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[1]*Specifications for Masonry Structures*, TMS 602-08/ACI-530-08/ASCE 5-08, The Masonry Society, Boulder CO

[2]*ASTM C90, Standard Specification for Loadbearing Concrete Masonry Units*, ASTM International, West Conshohocken PA

[3]*Structural Masonry Design System, Masonry 5.0.* National Concrete Masonry Association, Herndon VA

[4]*Building Code Requirements for Masonry Structures*, TMS 402-08/ACI-530.1-08/ASCE 6-08, The Masonry Society, Boulder CO
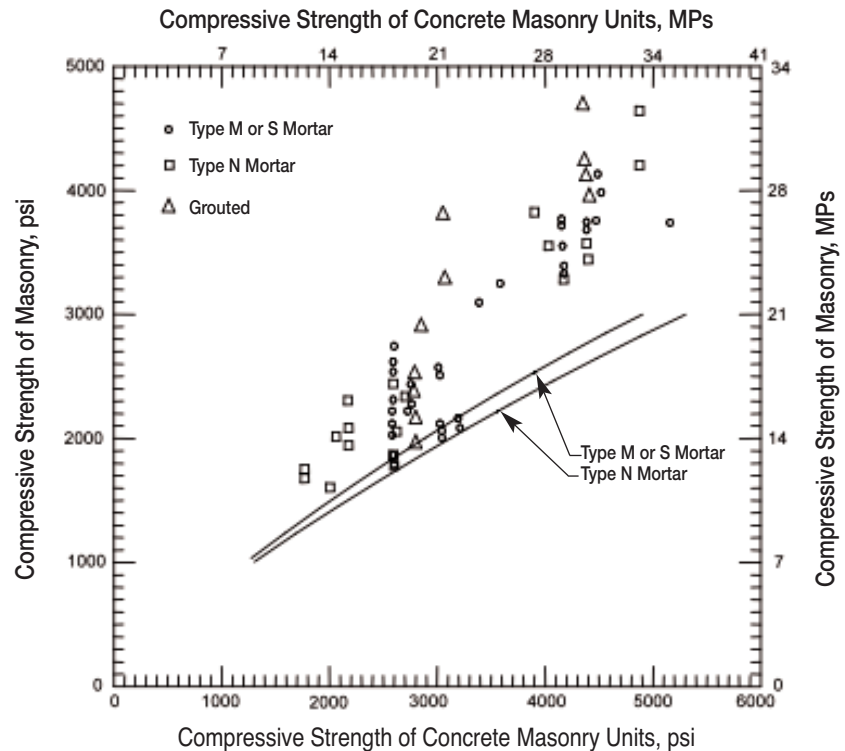
Figure SC-2 from TMS 602, used with permission of The Masonry Society

Examples - Results

Example LB1 - Loadbearing Wall: Determine grout and reinforcement
Wall: 8" CMU partially grouted, 20' high wall
Vertical load: 1500 lbs per foot live load applied 2" from wall centerline.
Lateral load: 25 psf

Results: f'_m = 1500 psi   #6 @ 16"
         f'_m = 2000 psi   #6 @ 32"
         f'_m = 2500 psi   #6 @ 40"

Example LB2 - Loadbearing Wall
Wall: 8" CMU partially grouted, 15' high wall
Vertical load: 1500 lbs per foot live load applied 2" from wall centerline.
Lateral load: 40 psf
Results: f'_m = 1500 psi   #6 @ 24"
         f'_m = 2000 psi   #6 @ 48"
         f'_m = 2500 psi   #6 @ 48"

Example LB3 - Loadbearing Wall
Wall: 8" CMU partially grouted, 15' high wall
Vertical load: 3500 lbs per foot live load applied 2" from wall centerline.
Lateral load: 40 psf

Results: f'_m = 1500 psi   #5 @ 24"
         f'_m = 2000 psi   #5 @ 48"
         f'_m = 2500 psi   #5 @ 56"

Loadbearing Wall Results
In each case, upgrading f'_m from 1500 psi to 2000 psi reduces the amount of grout and reinforcement by 50% for partially grouted walls. That's significant! For fully grouted walls, the reinforcement savings still remains. That's a tremendous improvement that often goes unrealized. Increasing to f'_m = 2500 psi provides additional savings for two of the examples. However, the incremental savings is not as dramatic as going from 1500 to 2000 psi.

Example SW1 - Shear Wall: Determine ASD capacity
Wall: 8" CMU wall partially grouted with #5 @ 24" oc vertically and standard joint reinforcement at 16" horizontally; 20' high and 20' long.

Vertical load: 150 kips live load (LL) applied uniformly along the wall (loadbearing shear wall).
Results: f'_m = 1500 psi $V_{capacity}$ = 50 kips
         f'_m = 2000 psi $V_{capacity}$ = 63 kips
         f'_m = 2500 psi $V_{capacity}$ = 73 kips

(kip=1000 lbs)

Example SW2 - Shear Wall
Wall: 8" CMU wall partially grouted with #5 @ 24" oc vertically and standard joint reinforcement at 16" horizontally; 20' high and 20' long.
Vertical load: 0 kips (non-loadbearing shear wall)
Results: f'_m = 1500 psi $V_{capacity}$ = 29 kips
         f'_m = 2000 psi $V_{capacity}$ = 30 kips
         f'_m = 2500 psi $V_{capacity}$ = 31 kips

Example SW3 - Shear Wall
Wall: 8" CMU wall fully grouted with #6 @ 8" oc vertically and standard joint reinforcement at 16" horizontally; 20' high and 12' long.

Vertical load: 140 kips live load applied uniformly along the wall (loadbearing shear wall).
Results: f'_m = 1500 psi $V_{capacity}$ = 32 kips
         f'_m = 2000 psi $V_{capacity}$ = 40 kips
         f'_m = 2500 psi $V_{capacity}$ = 47 kips

Shear Wall Results
In each case, upgrading f'_m from 1500 psi to 2000 psi increases shear capacity, particularly for loadbearing shear walls. The same is true for increasing up to 2500 psi. The non-loadbearing shear wall (SW2) was relatively unchanged for any change in f'_m. For these shear walls and loads given, the incremental increase in ASD Shear capacity is approximately the same for each increase of 500 psi in the f'_m.

Example MB1 - Masonry Beam
Beam: 8" CMU; three courses high grouted solid; joint reinforcement at 16" oc. Reinforcement in bottom of beam: 1- #4
Span: 4'-8"
Results: f'_m = 1500 psi   LL = 3.4 kips/ft
         f'_m = 2000 psi   LL = 4.1 kips/ft
         f'_m = 2500 psi   LL = 4.3 kips/ft

Example MB2 - Masonry Beam
Beam: 8" CMU; three courses high grouted solid; joint reinforcement at 16" oc. Reinforcement in bottom of beam: 1-#5; no shear reinforcement.
Span: 8'-8"
Results: f'_m = 1500 psi   LL = 2.1 kips/ft
         f'_m = 2000 psi   LL = 3.2 kips/ft
         f'_m = 2500 psi   LL = 3.5 kips/ft

Masonry Beam Results
In each case, upgrading f'_m from 1500 psi to 2000 psi increases the moment capacity of beams. The same is true for increasing up to 2500 psi except the incremental above 2000 psi is not as effective.

Example SP - Reinforcement Splice Lengths from TMS 402
f'_m = 1500 psi   Calculated length is taken as 100%
f'_m = 2000 psi   Reduces calculated length by 15%
f'_m = 2500 psi   Reduces calculated length by 24%

Splice Length Results
In TMS 402, splice lengths are related to the $(f'_m)^{-1/2}$ from the formula $l_d = 0.13\, d_b^2 f_y \gamma / K \sqrt{f'_m}$ (Eq. 2-12, TMS 402). Increasing f'_m reduces splice lengths.

For state building codes based upon the International Building Code (IBC)[5], splice lengths are based upon bar diameter. For those codes, there is no reduction in splice lengths due to increasing f'_m.

Example - Modulus of Elasticity ($Em = 900\, f'm$)
f'_m = 1500 psi E_m = 1.35 x 10^6 psi
f'_m = 2000 psi E_m = 1.80 x 10^6 psi (33% increase)
f'_m = 2500 psi E_m = 2.25 x 10^6 psi (67% increase)

Modulus of Elasticity Results
Modulus is directly related to f'_m. Thus, the E_m increases proportionally and increases the stiffness of the masonry element.

Example EM1 - Tension capacity of embedments ($B_{ab} = 1.25\, A_{pt}\, (f'm)^{1/2}$ from TMS 402, Eq. 2-1 and 2-3)
f'_m = 1500 psi B_{ab} is calculated as 100%
f'_m = 2000 psi   Increases calculated B_{ab} by 15%
f'_m = 2500 psi   Increases calculated B_{ab} by 24%

Example EM2 - Shear capacity of embedments ($B_{vc} = 350\, (f'm\, A_b)^{1/4}$ from TMS 402, Eq. 2-7)
f'_m = 1500 psi B_{vc} is calculated as 100%
f'_m = 2000 psi   Increases calculated B_{vc} by 7%
f'_m = 2500 psi   Increases calculated B_{vc} by 14%

Example EM3 - Shear capacity of embedments (B_{vb} from TMS 402, Eq. 2-6 and B_{vpry} from TMS 402, Eq. 2-8)
f'_m = 1500 psi B_{vb} and B_{vpry} are calculated as 100%
f'_m = 2000 psi   Increases calculated B_{vb} and B_{vpry} by 7%
f'_m = 2500 psi   Increases calculated B_{vc} and B_{vpry} by 14%

Embedment Capacity Results
In all cases, embedment capacities for shear and tension governed by the masonry increase with increasing f'_m.

[5] *2009 International Building Code*, International Code Council, 500 New Jersey Avenue NW, 6th Floor, Washington DC 20001

Sustainability. Good Economics

Whether you justify it as sustainability or good economics, the embodied energy of CMU needs to be captured along with the economy that comes with it. Clearly, increasing your f'_m to 2000 psi, as a design minimum, will improve capacities for the same amount of material, decrease required amount of wall grouting, and reduce the amount of reinforcement in partially grouted walls. Isn't that sustainability?

CMU manufacturers should publish their minimum unit strength, the higher strengths they offer and the results of prism tests using their units. Engineers should demand this information. Engineers may even find through prism test results that a minimum f'_m greater than 2000 psi is available regionally; all without an increase in unit cost. It's been there all the time and not used.

Let's say goodbye to $f'_m = 1500$ psi and switch to $f'_m = 2000$ psi as a minimum to make those designs more economical. It's one of the most truly sustainable decisions an engineer can make. ▥

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