Pilot Program to Determine Appropriate Lambda Factors for Design of Reinforced Masonry with Lightweight Grout

TMS Annual Meeting
Denver, CO
October 13, 2022

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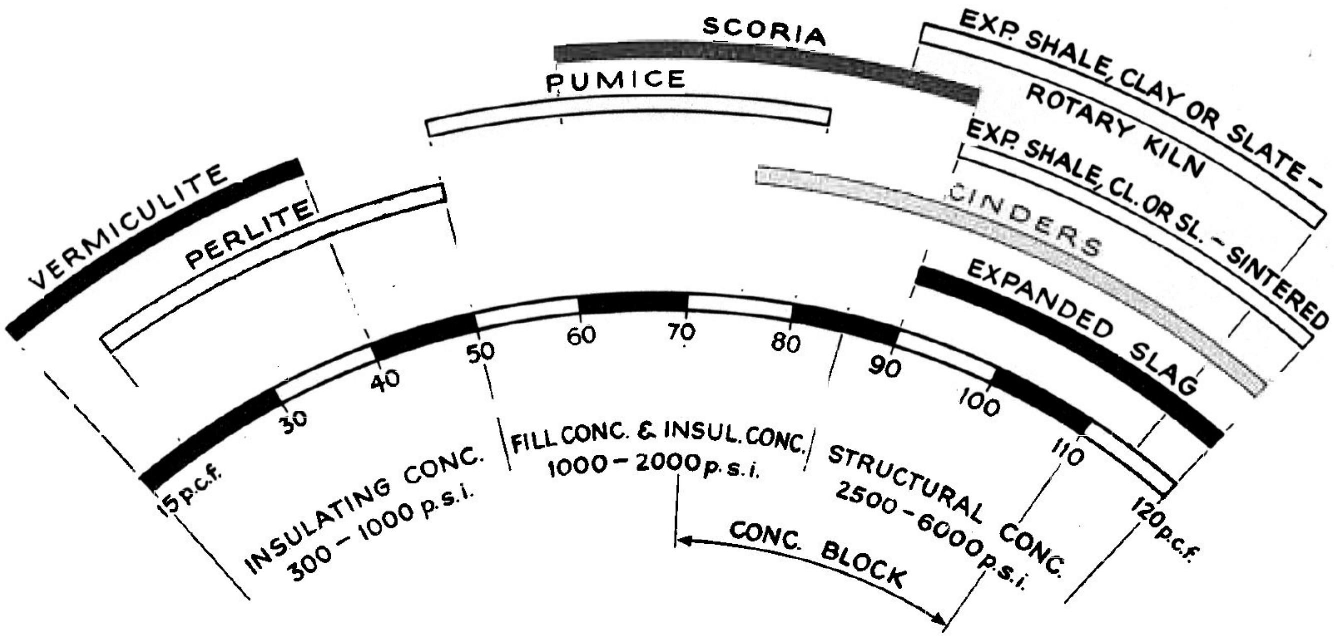
THE MASONRY SOCIETY

Outline

- Lightweight Aggregates
  - Performance Advantages
  - Considerations for Mixing Process
  - Current Design Process in ACI 318-19
- TMS 402/602 Research Need and Pilot Program Overview
- Pilot Program Results
  - Trial Mix Designs and Impact on ASTM C476
  - Anchor Bolt Testing
  - Diagonal Shear Strength Testing
  - Lap Splice Testing
- Ongoing Work and Next Steps

Lightweight Aggregates

Lighter; better insulating properties



WEIGHT SPECTRUM OF LIGHTWEIGHT CONCRETES

Higher strength

- Advantages
  - Weight reduction
  - Fire resistance
  - Thermal insulation
  - Sound insulation
  - Internal curing

Lightweight Aggregates

- Considerations for Mixing Process
  - Highly absorptive aggregates (requires 72 hr of presoaking, 24 hr draining, ASTM C127/C128)
  - Adjustment for free water content on day of mixing

Lightweight Aggregates

- ACI 318-19 Design Provisions
  - Reduction factor (Lambda) for design with lightweight concrete on properties governed by tensile, shear, and bond behavior
  - Updated in 2019 to be a function of equilibrium density

ACI 318-14

Table 19.2.4.2—Modification factor λ

Concrete	Composition of aggregates	λ
All-lightweight	Fine: ASTM C330 Coarse: ASTM C330	0.75
Lightweight, fine blend	Fine: Combination of ASTM C330 and C33 Coarse: ASTM C330	0.75 to 0.85[1]
Sand-lightweight	Fine: ASTM C33 Coarse: ASTM C330	0.85
Sand-lightweight, coarse blend	Fine: ASTM C33 Coarse: Combination of ASTM C330 and C33	0.85 to 1[2]
Normalweight	Fine: ASTM C33 Coarse: ASTM C33	1

ACI 318-19 Table 19.2.4.1 (a)

w_c, lb/ft³ (kg/m³)	**λ**
≤ 100 (1600)	0.75
$100 < w_c \le 135$ $(1600 < w_c \le 2160)$	$0.0075w_c$ $(0.00047w_c) \le 1.0$
> 135 (2160)	1.0

Research Need and Pilot Program

- Research Need
  - TMS 402-22, allows lightweight aggregate to be used in the production of concrete masonry units (CMU), it does not allow lightweight aggregate to be used for grout
- Pilot Program Objective
  - Conduct a small number of assessment tests across a variety of specimen types to quantify differences in performance between lightweight and normal weight grout and propose a preliminary lambda factor for lightweight grout.

Trial Mix Designs

Mix Designs to Meet Volume Requirement

ASTM C476 4.2.1.1

-Segregation observed

-Quality mixes were not obtained even after the use of superplasticizers and Viscosity Modifying Admixtures (VMAs)

-Minimum compressive strength criteria (2000 psi) fulfilled for expanded clay grout only

Volume Proportion	ASTM C476 Table 1	EC1	EC2	ES1	ES2
cement	**1**	1	1	1	1
fine aggregates	**2.25-3**	2.25	2.25	2.25	2.25
coarse aggregates	**1-2**	1	1	1	1
28-day compressive strength, (ksi (MPa))	**>2**	2.43	2.45	1.44	1.12
	(>14)	(16.75)	(16.89)	(9.93)	(7.72)

Trial Mix Designs

Mix Designs to Meet Volume Requirement

ASTM C476 4.2.1.1

-Segregation observed

-Quality mixes were not obtained even after the use of superplasticizers and Viscosity Modifying Admixtures (VMAs)

-Minimum compressive strength criteria (2000 psi) fulfilled for expanded clay grout only

Trial Mix Designs

Mix Designs to Meet Strength Requirement

ASTM C476 4.2.1.2

By Concrete Mix Design:

-Volume proportion (cement:fines:coarse): 1:1.08:1

-No segregation

-Minimum compressive strength criteria fulfilled

-Richer and less economical mix

- Used for anchor bolt tests and modulus of rupture tests

By Hand Batching:

- Volume proportion (cement:fines:coarse) 1:1.77:0.79

-No segregation

-Minimum compressive strength criteria fulfilled

-Leaner and economical mix

-Used for diagonal tensile strength tests and lap splice tests

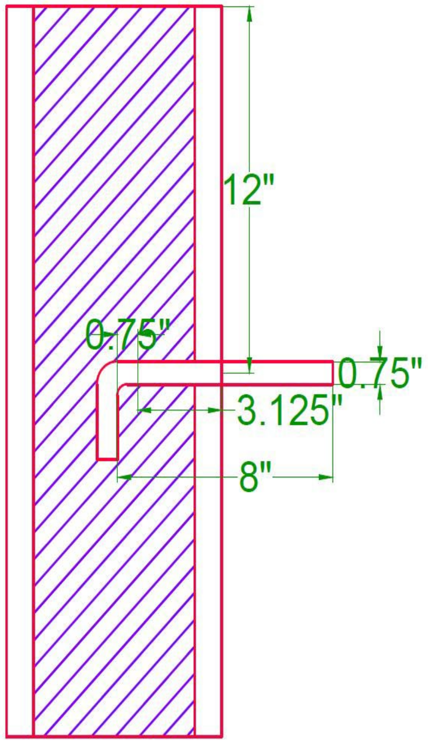
Implications for ASTM C476

- Recommend a separate section in the ASTM C476 standard for LW grout that does not reference the volume proportions of ASTM C476 Table 1 may be merited, in a manner similar to self-consolidating grout.
- Future work: develop a formal mix design procedure for lightweight grout

Anchor Bolt Testing

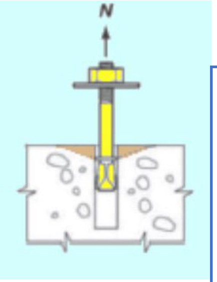
Tensile Test:

- Tests conducted in compliance with ASTM E488
- Six 24 in. X 24 in. walls for Expanded Clay (EC) grout and Expanded Slate (ES) grout each
- 3/4 in. L bolts used
- Around 15/16 in. holes drilled bisymmetrically
- 3.125 in. embedment depth



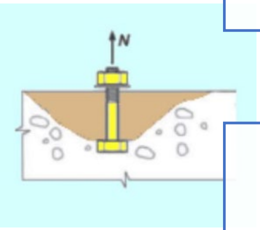
Section at X-X

Anchor Bolt Testing



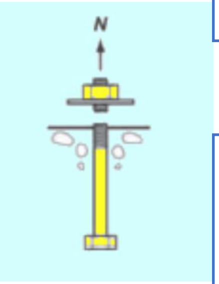
Anchor bolt pull out

- $B_{anp}=1.5f'_m e_b d_b+300\pi(l_b+e_b+d_b)d_b$ (lbf, in.)



Masonry breakout

- $B_{anb}=4A_{pt}\sqrt{f'_m}$ (lbf, in.)

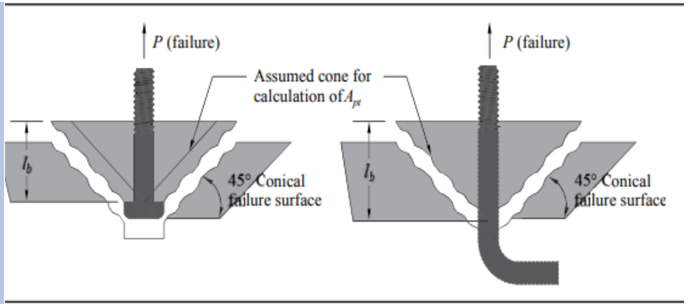


Steel yielding

- $B_{ans}=A_b f_y$ (lbf, in.)

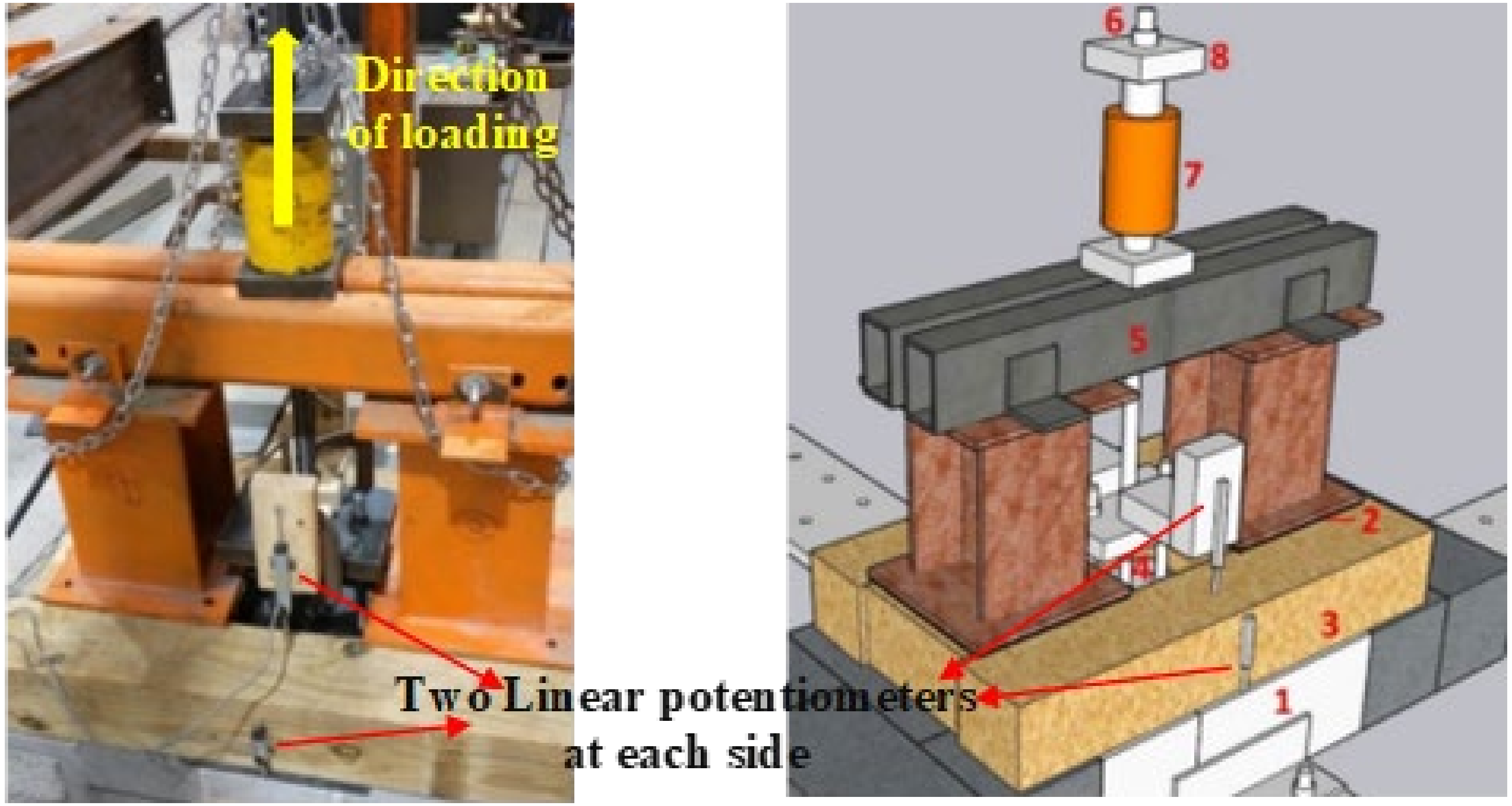
Specimen Design (TMS 402-16):

Combination of embedment length (3.125”) and diameter (3/4”) selected to minimize the value of masonry breakout failure among the failure types



Anchor Bolt Testing

Tensile Test Set Up:



(a) (b)

Typical Failure Pattern:

Anchor Bolt Testing

Tensile Test Results:

- Ratios presented use TMS 402-16 for $F_{predicted}$
- For the NW grout dataset [1], the specimens shown failed in masonry though the predicted failure mode was bolt yielding and the ratios of tested to predicted load (using f'_m) at failure were less than 1.0 for bar diameters greater than or equal to 16 mm (5/8 in.).
- Significantly higher tensile capacity for the ES grout, which was consistent with results of MOR tests.
- All tested/predicted equivalent to or better than NW dataset

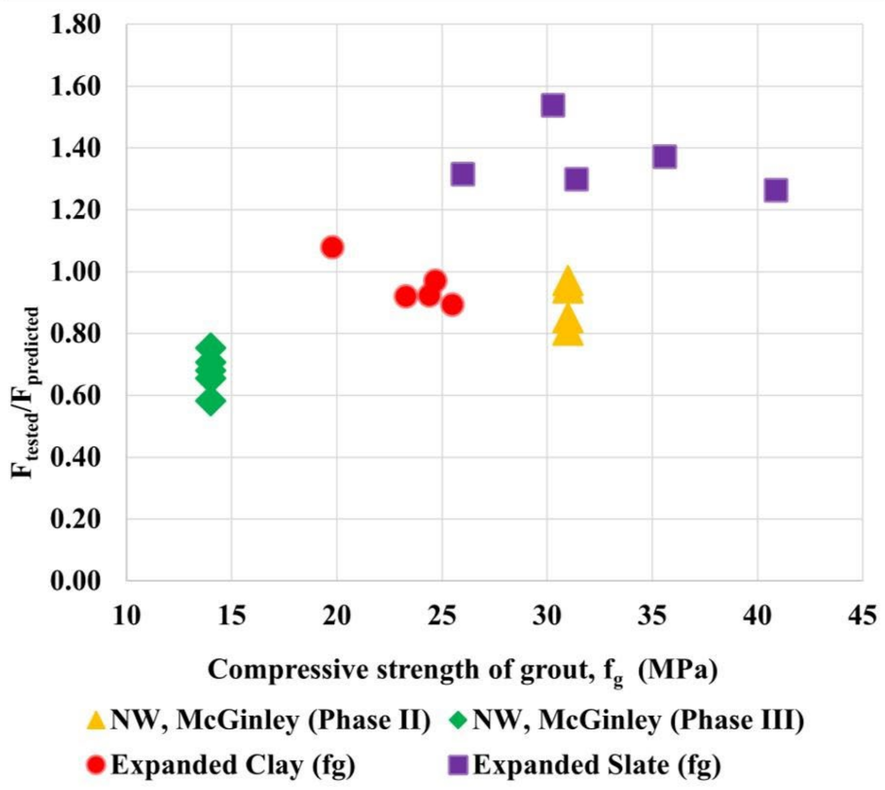
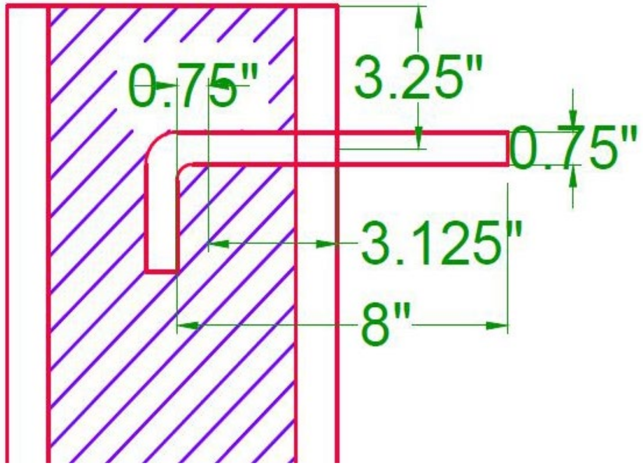


Figure 7- $F_{tested}/F_{predicted}$ vs Compressive strength of grout, f_g (MPa) for 19 mm anchor bolt tensile test specimens.

Anchor Bolt Testing

Shear Test:

- Tests conducted in compliance with ASTM E488
- Six 24 in. X 24 in. walls for Expanded Clay (EC) grout and Expanded Slate (ES) grout each
- 3/4 in. L bolts used
- Around 15/16 in. holes drilled at 3.25 in. distance from the top of the wall and symmetric along vertical axis
- 3.125 in. embedment depth



Anchor Bolt Testing

Masonry breakout

$$B_{vnb} = 4A_{pv}\sqrt{f'_m} \quad \text{(lbf, in.)}$$

Masonry crushing

$$B_{vnc} = 1750\sqrt[4]{f'_m A_b} \quad \text{(lbf, in.)}$$

Anchor pryout

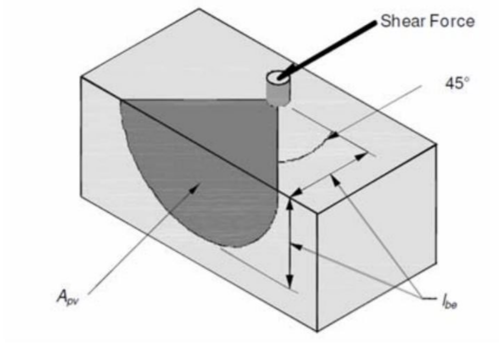
$$B_{vnpry} = 2.0B_{anb} = 8A_{pt}f'_m \quad \text{(lbf, in.)}$$

Anchor yielding

$$B_{vns} = 0.6A_b f_y \quad \text{(lbf, in.)}$$

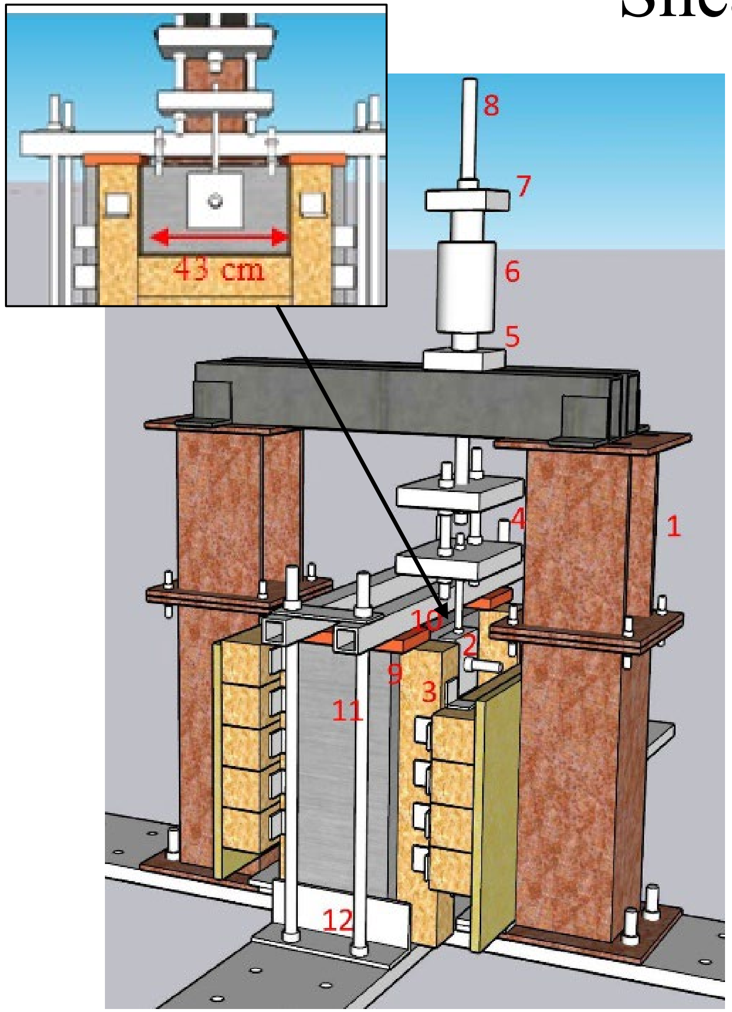
Specimen Design (TMS 402-16):

Combination of embedment length (3.125 in.), diameter (3/4 in.), anchor bolt edge distance (3.25 in.)selected to minimize the value of masonry breakout failure among the failure types



Anchor Bolt Testing

Shear Test Set Up:



Typical Failure Pattern:

Anchor Bolt Testing

Shear Test Results:

- Ratios presented use TMS 402-16 for $F_{predicted}$
- Anchor bolt shear tests in the LW specimens performed similar to the NW dataset of McGinley[1]
- Specimens had a tested to predicted ratio of < 1.0

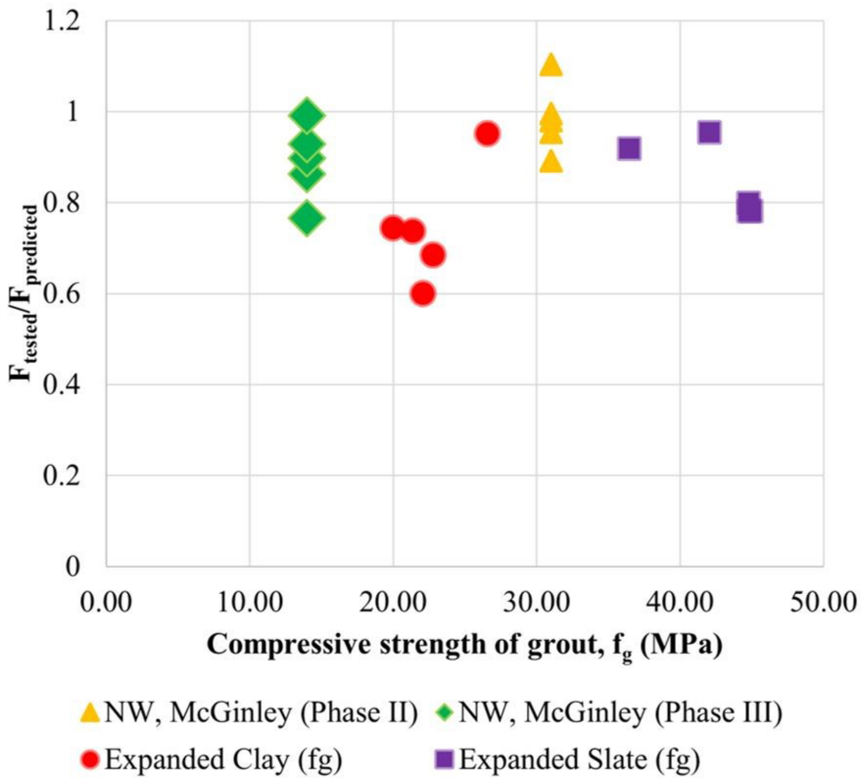


Figure 11- $F_{tested}/F_{predicted}$ vs Anchor Bolt Compressive strength of grout, f_g (Mpa) for Anchor Bolt Shear Test.

Anchor Bolt Testing

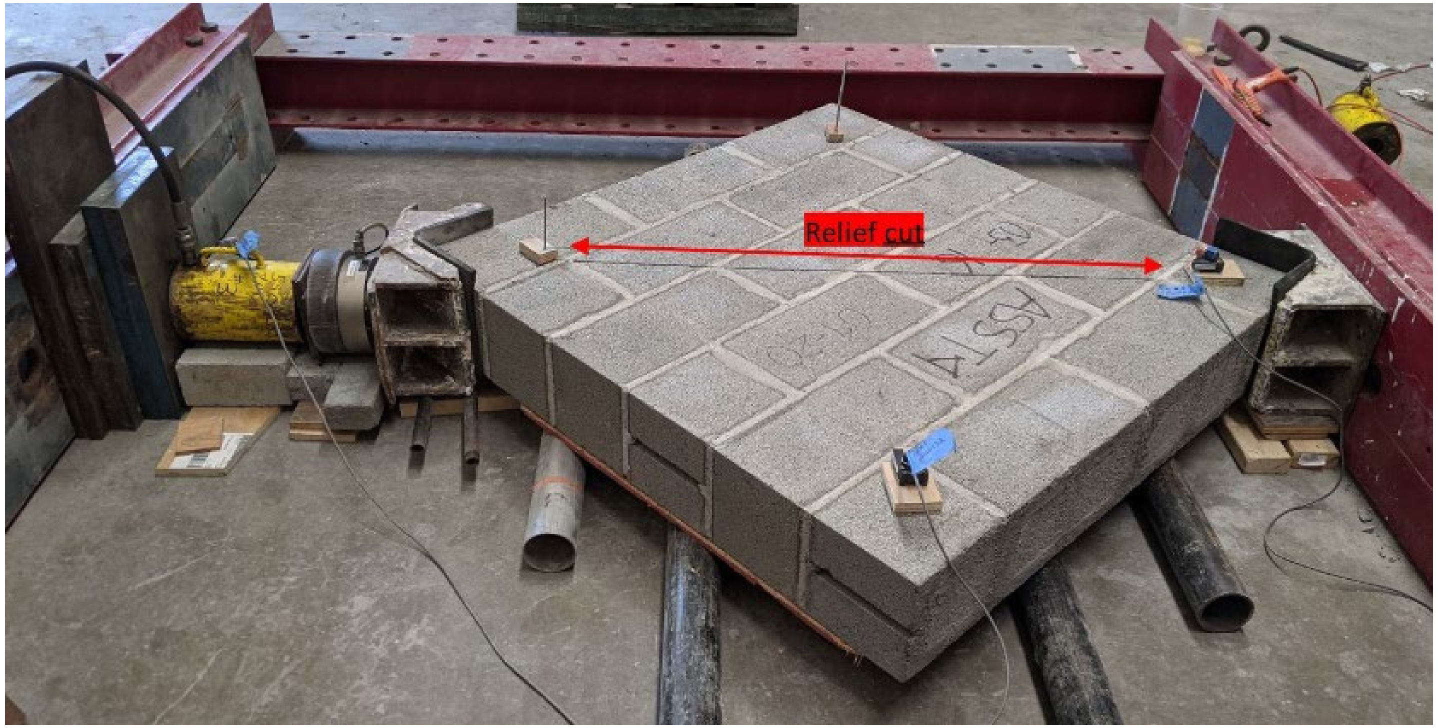
Summary:

- Lambda factor for tensile capacity may not be needed as all tested/predicted ratios were better than the NW dataset and generally close to or greater than 1. However, additional testing with smaller bar sizes should be conducted.
- Lambda factor for shear capacity may be needed as all tested/predicted ratios were slightly lower than the NW dataset. However, additional testing with smaller bar sizes should be conducted to determine the exact reduction factor or if the differences continue to remain small between LW and NW specimens.

Diagonal Shear Strength Testing

Test Set Up:

- ASTM E519
- Three 48 in. X 48 in. walls per grout type (Expanded Clay, Expanded Slate, Normal weight)
- Relief cut was made because the specimens were stronger than anticipated and also helped isolate grout behavior



Diagonal Shear Strength Testing

- Calculation of Average Shear Strength and Predicted Shear Strength

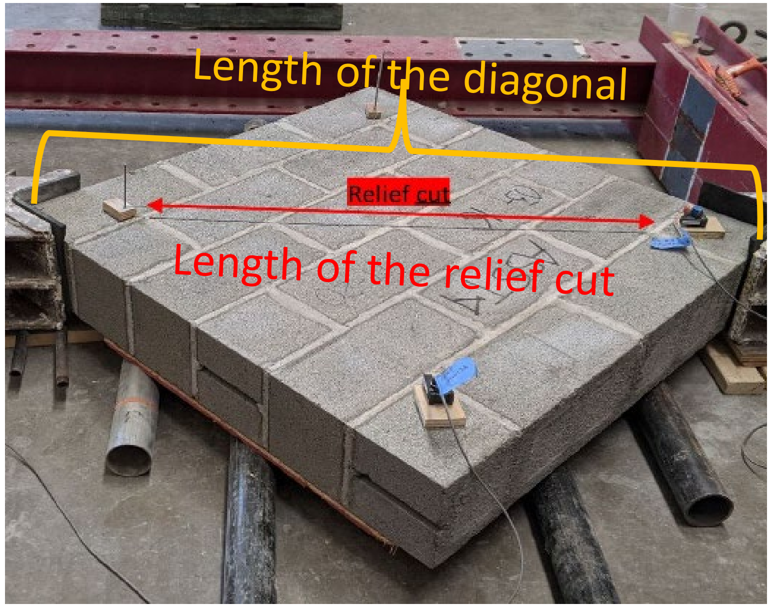
Average Shear Area = Length of the diagonal * Thickness excluding relief cut

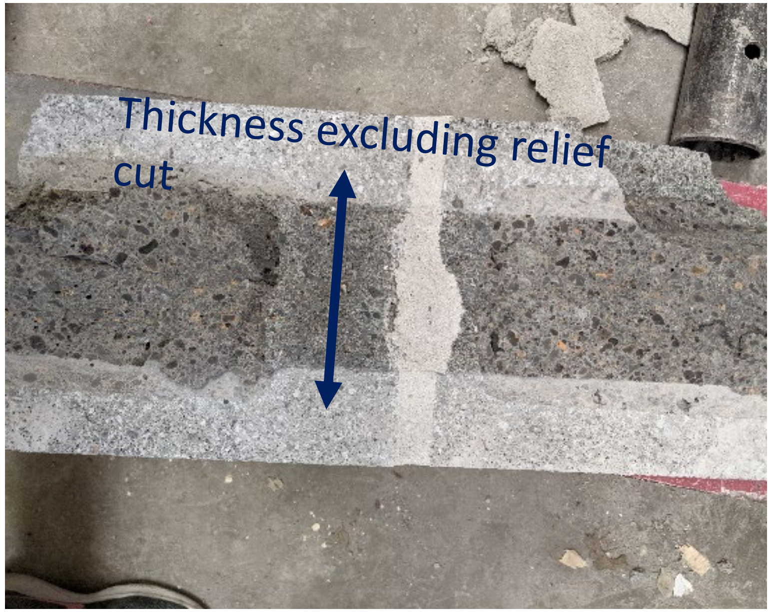
Average Strength= Tested Load/Average Area

Predicted Strength TMS 402/602-16 equations 9.2.6.1(a&b): Minimum of

$3.8\sqrt{f_g}$ psi

300 psi





Diagonal Shear Strength Testing

Calculation of Suggested Lambda:

- Selected such that the ratios $\tau_{avg}/(\lambda^*\tau_{predicted})$ were approximately equivalent to that for the NW specimens.

Specimen	$\tau_{avg}/\tau_{predicted}$	λ	$\tau_{avg}/(\lambda^*\tau_{predicted})$
NDST1	1.85	1	1.85
NDST2	1.61	1	1.61
NDST3	1.57	1	1.57
average	**1.68**		**1.68**

Specimen	$\tau_{avg}/\tau_{predicted}$	λ	$\tau_{avg}/(\lambda^*\tau_{predicted})$
ECST1	1.42	0.7	2.03
ECST2	1.09	0.7	1.56
ECST4	1.09	0.7	1.56
average	**1.20**		**1.71**
ESST1	1.55	0.85	1.82
ESST2	1.40	0.85	1.65
ESST3	1.30	0.85	1.53
average	**1.42**		**1.67**

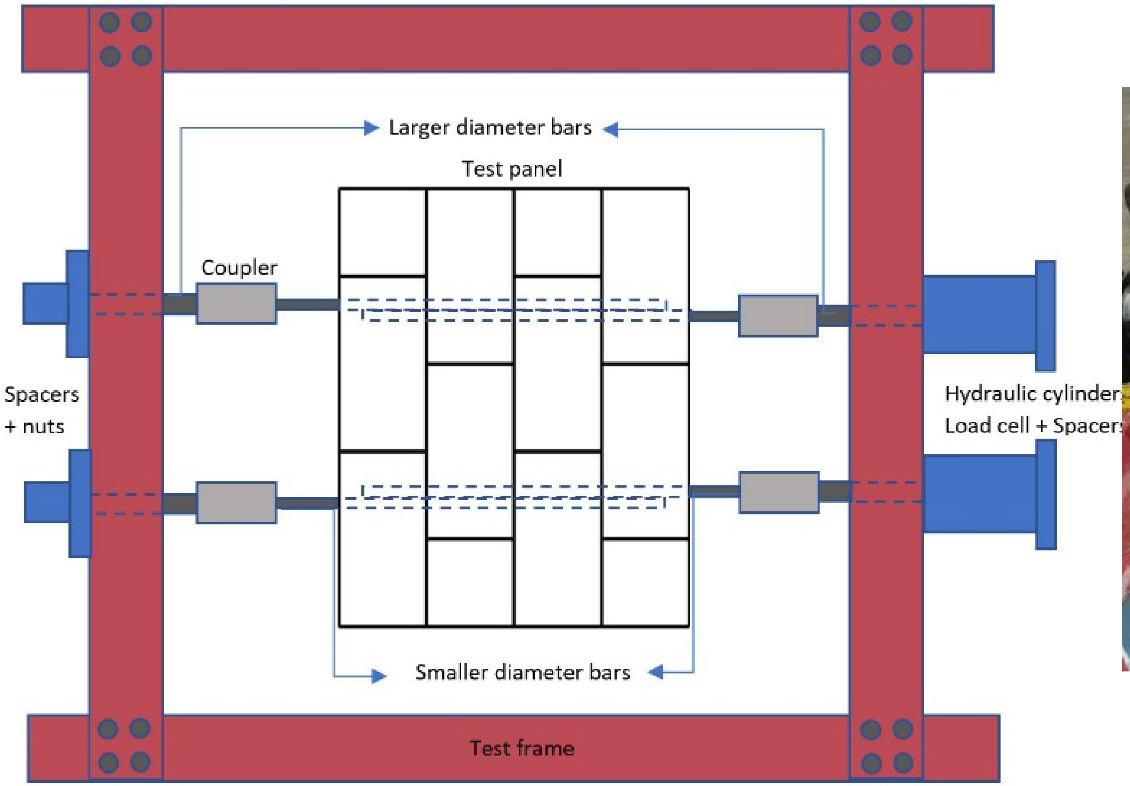
Anchor Bolt Testing

Summary:

- A lambda factor of 0.7 was required for the EC specimens and a lambda factor of 0.85 was required for the ES specimens
- Indicates a density-based lambda factor may be desirable

Lap Splice Testing

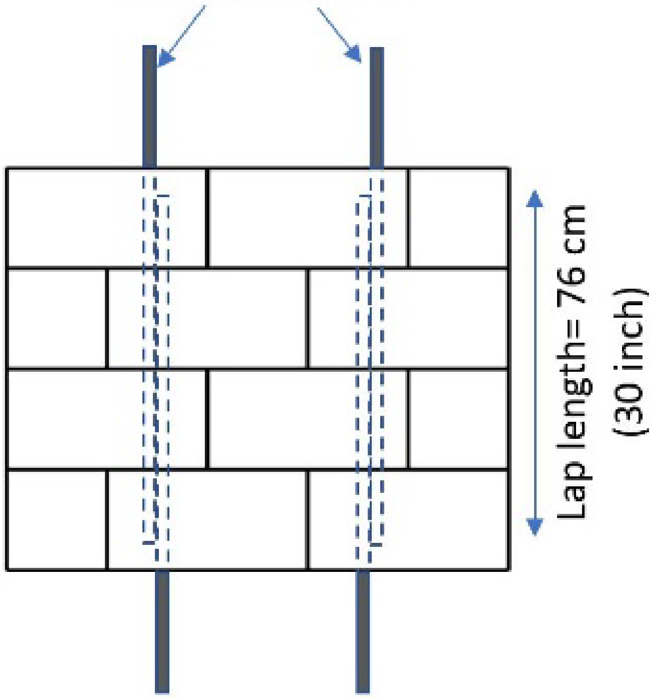
Test Set Up:

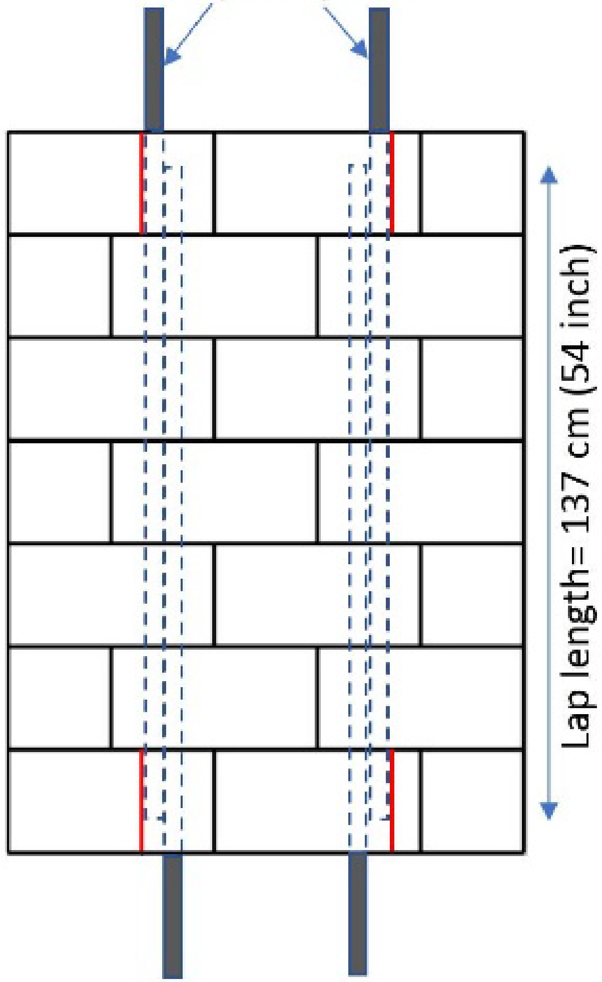


Lap Splice Testing

Specimen Design:

- Three of each arrangement shown tested with both EC and ES grout
- Lap length was 137 cm (54 in.) for No. 7 bar specimens; after relief cut lap length reduced to 40 in. (102 cm)





Lap Splice Testing

LW grout had 37% higher RMSE value than NW dataset

Results:

- Capacity of specimens was predicted using the regression equation of a study from NCMA 1999 [2] that utilized the same testing set up for NW assemblies.
- RMSE was calculated for several datasets of NW specimens and our LW specimens and compared to the equation from [2]

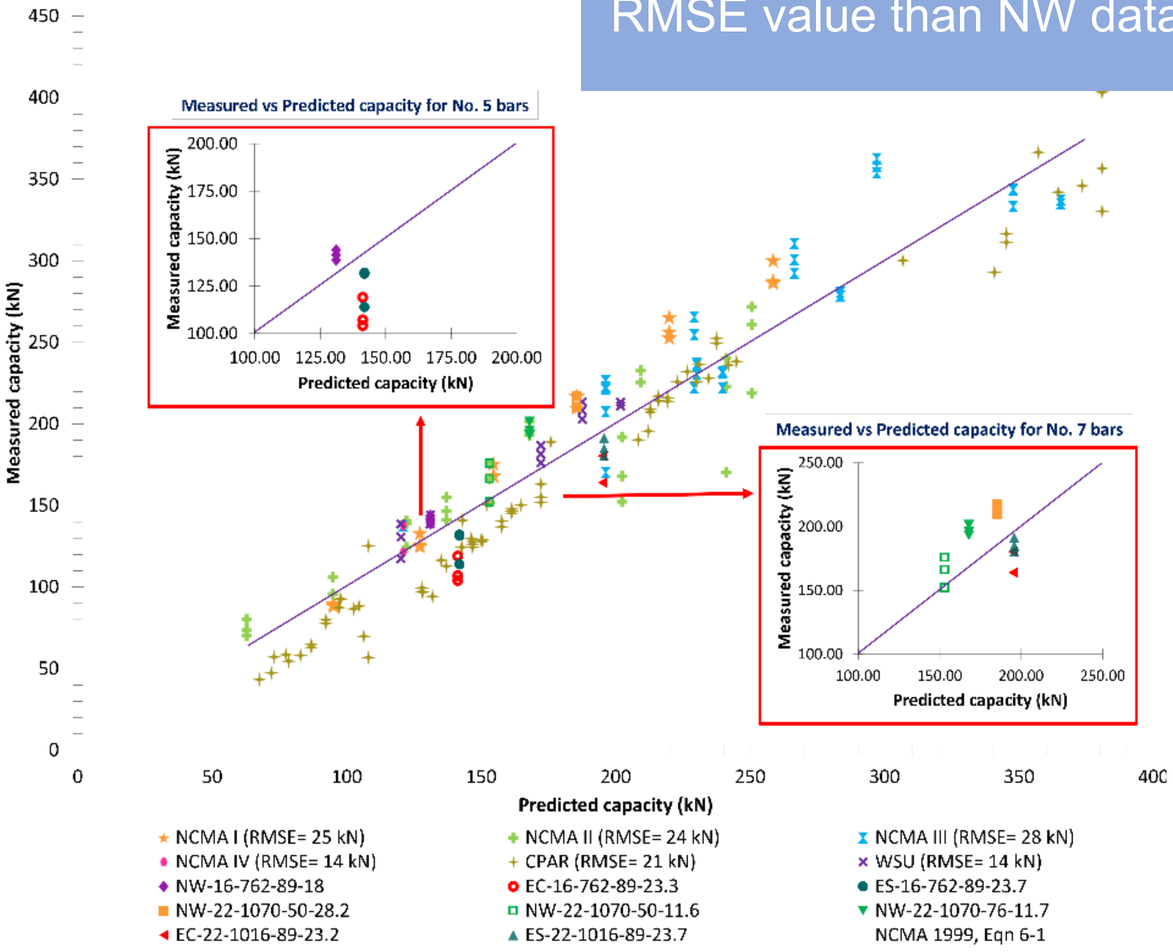


Fig. 7. Measured Capacity vs Predicted Capacity

Lap Splice Testing

Results:

- The tested lap splices were compared to their closest match in configuration from the normal weight data set
- Designations: Type of aggregate-Bar size-Development length-Clear cover- Masonry strength

Aggregate Type	Diameter, d_b , mm (in)	Development Length, l_d , mm (in)	Clear Cover, c_{cl} , mm (in)	Compressive Strength of Masonry, f'_m , Mpa (ksi)	Mean Tested Lap Splice Strength, F_{tested} , kN (kips)	Predicted Lap Splice Strength, $F_{predicted}$, kN (kips)
EC-16-762-89-23.3	16 (0.625)	762 (30)	89 (3.5)	23.3 (3.38)	110 (24.8)	141 (31.7)
ES-16-762-89-23.7	16 (0.625)	762 (30)	89 (3.5)	23.7 (3.44)	126 (28.3)	142 (31.9)
NW-16-762-89-18	16 (0.625)	762 (30)	89 (3.5)	18.0 (2.61)	141 (31.8)	131 (29.5)
EC-22-1016-89-23.3	22 (0.875)	1016 (40)	89 (3.5)	23.3 (3.38)	159 (35.7)	195 (43.8)
ES-22-1016-89-23.7	22 (0.875)	1016 (40)	89 (3.5)	23.7 (3.44)	186 (41.7)	196 (44.0)
NW-22-1016-51-11.7	22 (0.875)	1016 (40)	51 (2)	11.7 (1.70)	165 (37.1)	153 (34.4)

Lap Splice Testing

Calculation of Suggested Lambda

Aggregate Type	Mean Tested Axial Stress, $(\sigma_a)_{tested}$, Mpa (ksi)	Predicted Axial Stress, $(\sigma_a)_{predicted}$ MPa (ksi)	Tested/ Predicted	λ	Tested/ (λ*Predicted)
NW-16-762-89-18	**717 (104)**	**663 (96.1)**	**1.08**	**1**	**1.08**
COV (%)	1.89				
EC-16-762-89-23.3	558 (80.9)	717 (104)	0.78	0.75	1.04
COV (%)	7.16				
ES-16-762-89-23.7	636 (92.3)	717 (104)	0.89	0.85	1.11
COV (%)	8.22				
NW-22-1016-89-11.7	**425 (61.7)**	**395 (57.3)**	**1.08**	**1**	**1.08**
COV (%)	7.24				
EC-22-1016-89-23.3	410 (59.4)	503 (72.9)	0.81	0.75	1.09
COV (%)	5.38				
ES-22-1016-89-23.7	478 (69.4)	505 (73.2)	0.95	0.85	1.12
COV (%)	2.97				

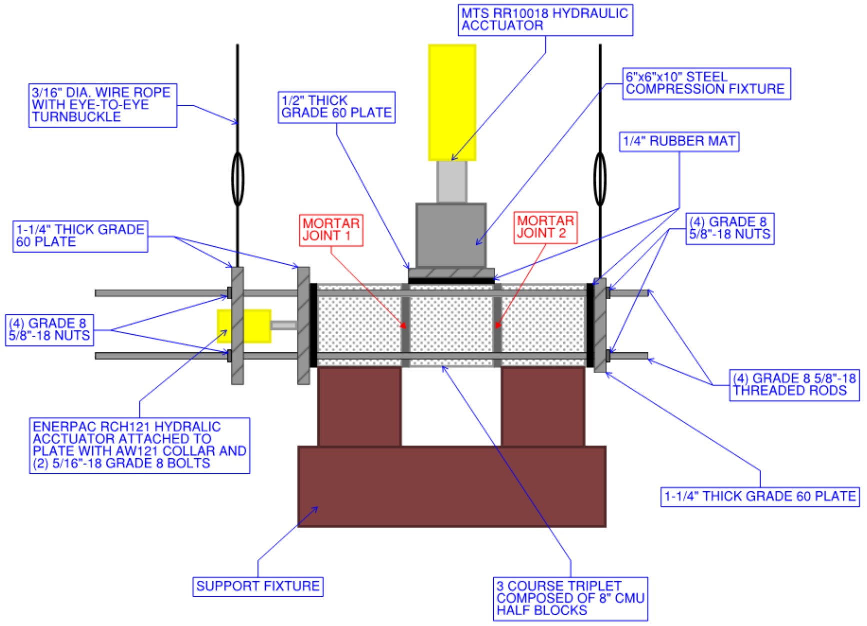
Lap Splice Testing

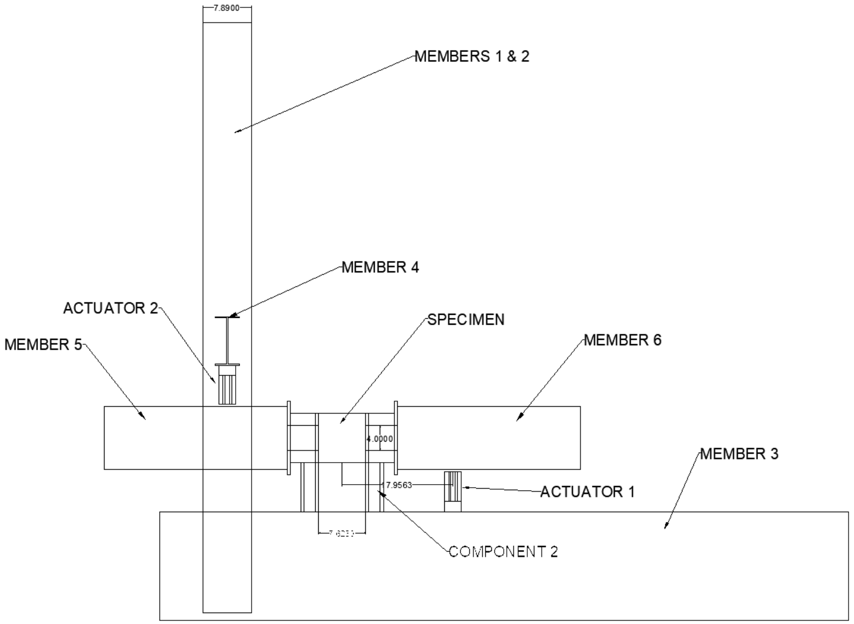
Summary:

- A lambda factor of 0.75 was required for the EC specimens and a lambda factor of 0.85 was required for the ES specimens
- Indicates a density-based lambda factor may be desirable

Ongoing Work

- Shear triplet testing and bond wrench testing
- Equilibrium density measurements for all mix designs





Next Steps

- Formulate a proposed equation for lambda factor as a function of equilibrium density
- Repeat anchor bolt testing across additional bar sizes to confirm trends
- Investigate other LW aggregate types (shale)
- Partner with other schools/labs for independent verification of proposed lambda factor

Thank you

- Students: Rumi Shrestha, Hannah Kessler, Ben Hiner, Cooper Banks
- NCMA: Jason Thompson
- Mix Design Collaborator: Dr. Prasad Rangaraju (Clemson)

- Sponsors: NCMA, ESCSI, General Shale, Arcosa, Stalite

References

[1] McGinley W. "Capacity of anchor bolts in concrete masonry." Report Phase IV. North Carolina A & T State University, 2004.

[2] National Concrete Masonry Association. "Evaluation of minimum reinforcing bar splice criteria for hollow clay brick and hollow concrete block masonry." 1999.

For further Information about the studies presented:

- Shrestha, R., Redmond, L., and Thompson, J., "Diagonal Tensile Strength and Lap Splice Behavior of Concrete Masonry Assemblies with Lightweight Grout," *Construction and Building Materials*, 344, 2022.
- Shrestha, R., Kessler, H., Redmond, L, and Rangaraju, P., "Behavior of Anchor Bolts in Concrete Masonry with Lightweight Grout," *The ACI Materials Journal* (published online Sept 2022).
- Shrestha, R., Redmond, L., Thompson, J., and Rangaraju, P., "Investigation of Mix Designs for Lightweight Grout per ASTM C476," *The Masonry Society Journal* (accepted, pending editorial revision).