Alternative Concrete Masonry Unit

Sam Carnes & Teo Albers

Project Members

December 14, 2017

Dear Dr. Tuchscherer:

The team submits here with a proposal in support of a research project "Alternative Concrete Masonry Unit" to be performed under the direction of Northern Arizona University's capstone program.

Questions regarding any technical aspects of the proposal should directed to either Sam Carnes or Teo Albers.

Sam Carnes: sgc55@nau.edu

Teo Albers: tja224@nau.edu

Your consideration of the proposal is greatly appreciated.

Sincerely,

Sam Carnes

Teo Albers

Enclosure: Proposal

cc: Dr. Dianne McDonnell

NORTHERN ARIZONA UNIVERSITY

Alternative Concrete Masonry Unit

Final Proposal

CENE 476

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Teo Albers
Sam Carnes

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1.0 Research Goal & Background

1.1 Project Description

The goal of this project is to create an alternative building product. The alternative building product will be an insulated, dry-stacked modular block made from local materials (e.g. cinders, cement) and local waste products (e.g. fly ash, small-diameter timber) [1]. The new building product must be created in order to reach an insulation value of at least R-10 while meeting all necessary strength requirements [1]. Additionally the block will need to meet all modern design demands of building construction.

1.2 Project Background

In the current market insulated modular blocks made with wood fiber aggregate are limited. The blocks that are available are not structural and simply act as formwork intended to support the hydraulic pressure of grout. Additionally due to costs the availability of current blocks relies heavily on regional availability of the necessary materials. Existing systems are made of approximately 15% to 25% cement and 75% to 85% mineralized wood fibers [1]. At heights over 3 to 4 feet the blocks need to be braced out-of-plane in order to prevent shifting relative to one another. Structural properties, the requirement to grout, the need to brace out-of-plane, and the required insulation value of R-10 are all disadvantages of current modular blocks. Different materials and different ratios of cement to mineralized wood fibers could produce a better product with increased structural properties.

1.3 Stakeholders

The current stakeholders of this research include Dr. Tuchscherer whom is our team's client. Additional stakeholders include local brick manufacturers and local logging companies.

2.0 Research Methods

2.1 Material Study

2.1.1 Establish Baseline

A collection of existing concrete mixes will be gathered in order to create a baseline for further design mixes that will optimize wood fiber aggregate. Concrete mixes that will be collected include, quikrete, rapid set, and sika. The mixes will be tested for their compressive strength following the procedure outlined in ASTM C140 [8].

2.1.2 Small Diameter Timber Analysis
An analysis of the determination of the necessary steps needed to make the small diameter timber usable within a concrete mix. The team will reach out to David Autey, a timber scientist to discuss the necessary mineralization process that the small diameter timber must undergo before being used in a mix.

2.2 Prototyping

2.2.1 Material Collection
All materials will be gathered locally from the Flagstaff area. Small diameter timber will be obtained from Ribelin logging company while all cinders will be collected on site at cinder hills OHV area located in the Coconino National Forest 13 miles northeast of Flagstaff.

2.2.2 Design
A total of 48 prototypes will be constructed out of three different mix ratios. The mix ratios will be based off the results from the baseline study. Prototypes will be right circular cylinders measuring 8” in height and 4” in diameter per ASTM C470 [9].

2.3 Product Testing

2.3.1 Embodied Energy Study
An embodied energy study will be completed in order to define the insulative properties of the prototypes. The team will meet with Alan Francis a professor at NAU to discuss the appropriate insulative test required.

2.3.2 Compressive Strength
The Compressive strength of the dry stacked modular brick will be gauged following the procedures of ASTM C39 [10]. The test method consists of applying a compressive axial load to molded cylinders until failure occurs. The compressive strength is then calculated by dividing the maximum load by the cross sectional area of the prototype. The test specimens should be allowed at a minimum 28 days to fully cure and reach its ultimate strength, however the sample specimens are removed from the moisture tight container 48 hours prior to the 28th day of the curing cycle of the samples [10].

2.3.3 Tensile Strength
The tensile strength of the dry stacked modular bricks will be analyzed in accordance to ASTM C496 [11]. ASTM C496 is the testing method for the splitting tensile strength of cylindrical concrete specimens. The procedure includes applying a diametral compressive force along the length of a cylindrical concrete specimen until failure occurs [11]. To analysis the tensile strength the maximum load sustained by the specimen is divided by the appropriate geometrical factors.

2.3.4 Freeze-Thaw

The freeze-thaw capabilities of the team's dry stacked modular bricks will be most likely be in line with the ASTM-666 where the samples will be tested for the two most prevalent types of structural strength corrosion, internal micro cracking and surface scaling. Internal Cracking is seldom present in properly air sealed concrete, however if an unprotected dry stacked modular brick that has poor network it can theoretically lead to the ultimate failure of the dry stacked modular brick. Internal cracking takes place when a dry stack modular block has voids that are generally not filled with water but with air, however when the water seeps through the voids and freezes, internal stresses generated from the approximate 10% expansion in the waters volume as the water transitions from a liquid state to a solid. Surface scaling occurs when there is some sort of deicer (i.e. salt) present in the dry stacked modular brick. With the presence of salt, the evaporation process is much more time consuming which consequently will increase the degree of saturation for the dry stacked modular brick; since scaling is microscopic surface quality of the sample, its only influencer's is its water/cement ratio, curing techniques, as well as its final placement. The testing method that will be used to evaluate the freeze thaw characteristics of the specimens require that these said specimens be in a fully saturated state prior to being subjected to a highly intensive freeze thaw cycles. The cylinders will be subjected to 5-8 freeze thaw cycles per day with a total of 300 cycles at the conclusion of the freeze-thaw test. Currently the industry has two primary methods to expose samples to freeze thaw cycles. Method 1 has the samples to be both frozen and thawed out in water, while method 2 subjects it to a less severe freeze thaw cycle where the sample is frozen in the air and is thawed out in water. The controlled temperature range that is used for freeze-thaw test varies from 40F-0F; and the internal decline in strength can be measured by measuring the resulting change in length or the change in the samples modulus of Elasticity [6].

2.4 Feasibility Study

2.4.1 Block Lite Tour

The methods of research will have the team contact local flagstaff brick company Block Lite. The team hopes to receive a guided tour from the company Block Life in order to obtain a more in depth understanding of the company's manufacturing techniques and practices that have made them a successful company. The team will research the constructability of the modular block.

2.4.2 Current Available Options

Investigation of the techniques that the market currently practices for constructing their dry stacked modular bricks. The team will compile research on the process that is necessary in modern day brick manufacturing. The current modular blocks using small diameter timber on the market need to be braced when used as a stem wall. The team will research a strategy in where the modular block does not need to be braced and can be constructed simply using grout to place the blocks.

3.0 Project Management

3.1 Schedule

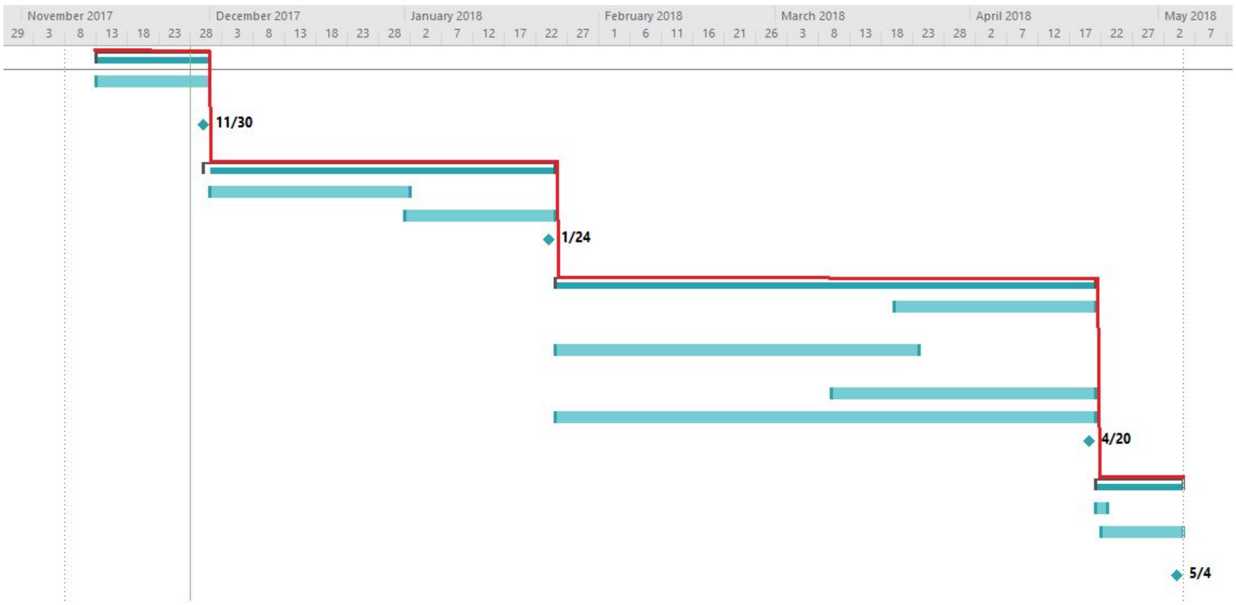
The project will be completed from the proposed plan over the course of 5 months. Table 1 lists the tasks anticipated to complete the project.

Table 1: Proposed Schedule

Material Study	**14 days**	**Mon 11/13/17**	**Thu 11/30/17**
Small Diameter Timber Analysis	14 days	Mon 11/13/17	Thu 11/30/17
Material Study Complete	0 days	Thu 11/30/17	Thu 11/30/17
Prototyping	**40 days**	**Thu 11/30/17**	**Wed 1/24/18**
Material Collection	22 days	Fri 12/1/17	Mon 1/1/18
Design	18 days	Mon 1/1/18	Wed 1/24/18
Prototyping Complete	0 days	Wed 1/24/18	Wed 1/24/18
Product Testing	**62 days**	**Thu 1/25/18**	**Fri 4/20/18**
Embodied Energy Study	24 days	Tue 3/20/18	Fri 4/20/18
Compressive Strength	42 days	Thu 1/25/18	Fri 3/23/18
Tensile Strength	31 days	Sat 3/10/18	Fri 4/20/18
Freeze-Thaw	62 days	Thu 1/25/18	Fri 4/20/18
Product Testing Complete	0 days	Fri 4/20/18	Fri 4/20/18
Feasibility Study	**11 days**	**Sat 4/21/18**	**Fri 5/4/18**
Block Lite Tour	2 days	Sat 4/21/18	Sun 4/22/18
Current Available Options	11 days	Sun 4/22/18	Fri 5/4/18
Feasibility Study Complete	**0 days**	**Fri 5/4/18**	**Fri 5/4/18**
Total Length of Project	**125 days**	**Mon 11/13/17**	**Fri 5/4/18**

Additionally the proposed gantt chart is presented below in Table 2. The critical path is highlighted in red within the gantt chart.

Table 2: Gantt Chart



Upon completion of the project the team will have demonstrated the feasibility of a new dry-stack modular block as well as analyzed the structural and insulative properties of at least three proposed prototypes.

4.0 Staffing and Cost of Engineering Services

4.1 Staffing

The project team will staff the research as follows in table 3 located below.

Table 3: Staffing

	Research Manager (RM)	Research Engineer (RE)	Lab Technician (LT)
Task	Time (hrs)		
2.1.1 Small Diameter Timber Analysis	10	25	0
2.2.1 Material Collection	12	32	0
2.2.2 Design	60	30	0
2.3.1 Embodied Energy Study	10	15	35
2.3.2 Compressive Strength	10	25	50
2.3.3 Tensile Strength	10	25	40
2.3.4 Freeze Thaw	10	30	60
2.4.1 Block Lite Tour	8	8	0
2.4.2 Current Available Options	10	15	0
Total Hours:	140	205	185
		Total:	530

4.2 Cost of Engineering Services

The cost breakdown of the project is located below in table 4. All personnel, equipment, and travel costs are included in the total cost of engineering services. All base pay rates include overhead and benefits using a x3 multiplier. The research cost estimate was determined by using the average base pay of civil engineers with 1-2 years field experience for their respective job descriptions.

Table 4: Cost Estimate Breakdown

Cost of Engineering Services				
	Personnel	Hours (hrs)	Base Pay ($/hr)*	Cost ($)
	RM	140	$150.00	$21,000.00
	RE	205	$90.00	$18,450.00
	LT	185	$60.00	$11,100.00
			Total:	$50,550.00
Equipment			Total:	$600.00
Travel			Total:	$25.00
			Total:	$51,175.00
*All base pay rates include overhead and benefits				

5.0 Project Deliverables

5.1 50% Report

A 50% report deliverable will be completed to ensure that the team is working towards the end goal and staying on schedule. The 50% report will contain all of the team's current research and developments up to the halfway point of the project. Additionally the report will go through a single draft process prior to its final submission in order to review the teams presented information.

5.2 Final Report

A final report will contain all of the research, developments, and findings that the team has made throughout the project's time frame. The team's final proposed modular block design will be presented within the final report.

5.3 Website

A website will be created to further summarize all necessary information for any parties interested in the project.

5.4 Presentation

The team's final deliverable will be a final presentation in front of several parties summarizing our findings and the team's final design proposal.

6.0 Project Limitations

6.1 Challenges

One of the challenges that the team will have is that typically brick manufacturers do not typically post their mix ratios for the public. At the most they typically only post their water cement ratio but other than that obtaining information will need to be obtained via a guided tour with one of the brick manufacturers. Other challenges that the team will face is that there is limited data on eco dry stacked modular bricks of having sufficient structural properties as well as having a correct R-value of 10.

6.2 Exclusions

Throughout the course of the project the team will refrain from doing an environmental assessment of the proposed design mix. Additionally the team will not research the available materials in any place other than Flagstaff, AZ. The team will not research the construction process that the modular blocks may be used for.

7.0 References

[1] R. Tuchscherer, "Wood FRC Block Concept", pp. 1-2, 2017.

[2] "Block-lite in Flagstaff, Az : Contact", *Block-Lite*, 2017. [Online]. Available: https://www.block-lite.com/contact.html. [Accessed: 18- Oct- 2017].

[3] “Go Brick”, *Go-Brick*, 2017,. [Online]. Available: http://www.gobrick.com/portals/25/docs/technical%20notes/tn9a.pdf. [Accessed: 18- Oct- 2017].http://www.gobrick.com/portals/25/docs/technical%20notes/tn9a.pdf

[4]http://ncma-br.org/pdfs/68/TEK%2018-01B5.pdf

[5]http://www.masonryinstitute.com/wp-content/uploads/MIW-Pocket-Guide.pdf

[6] ASTM C666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, Vol. 04.02.

[7] “A Procedure for Testing CMU mixes,” Cement, concrete, and Aggregates , vol 19

[8] ASTM C140/C140M, Standard Test Method for absorption in CMU

[9] ASTM C470 / C470M-15, Standard Specification for Molds for Forming Concrete Test Cylinders Vertically, ASTM International, West Conshohocken, PA, 2015, www.astm.org

[10] ASTM C39 / C39M-17b, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2017, www.astm.org

[11] ASTM C496 / C496M-17, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2017, www.astm.org

8.0 Appendix:

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DESIGNATION: C140/C140M - 17a

Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units

7 | Compressive Strength

7.1 Test Apparatus:

7.1.1 The testing machine shall have an accuracy of 1.0% over the anticipated load range. The upper platen shall be a spherically seated, hardened metal block firmly attached at the center of the upper head of the machine. The center of the sphere shall lie at the center of the surface held in its spherical seat but shall be free to turn in any direction, and its perimeter shall have at least 0.25 in. [6 mm] clearance from the head to accommodate specimens whose bearing surfaces are not parallel. The diameter of the upper platen (determined in accordance with Annex A8) shall be at least 6 in. [150 mm]. A hardened metal bearing plate may be used beneath the specimen to minimize wear of the lower platen of the machine.

7.1.2 When the bearing area of the upper platen or lower platen is not sufficient to cover the area of the specimen, a single steel plate with a thickness equal to at least the distance from the edge of the platen to the most distant corner of the specimen shall be placed between the platen and the capped specimen. The length and width of the steel plate shall be at least 0.25 in. [6 mm] greater than the length and width of the units. See Annex A8 for information on determining the required minimum bearing plate thickness, t_{BP}. The provided bearing plate (when needed) shall have a thickness at least equal to the value of t_{BP} as determined in Annex A8.

7.1.3 The surfaces of the platen or plate intended for contact with the specimen shall have a hardness not less than HRC 60 (BHN 620). The surfaces of the platen and plate shall not depart from plane surfaces by more than 0.001 in. [0.025 mm] in any 6 in. [150 mm] dimension.

NOTE 7: Research has shown that thickness of bearing plates has a significant effect on the tested compressive strength of masonry units when the bearing area of the platen is not sufficient to cover the area of the specimen. Plate bending results in nonuniform stress distributions that can influence the failure mechanisms of the tested specimens. The magnitude of this effect is controlled by the stiffness of the plate, the size of the specimen tested, and the strength of the specimen. Tested compressive strengths will typically increase with increased plate thickness and with reduced distance to the furthest corner of the specimen. Some testing laboratories have limitations that limit the practicality of eliminating plate bending entirely. Therefore the plate thickness requirements in 7.1 are intended to provide an adequate level of accuracy in the compression test results so as to conform to the limits of practicality of the testing laboratory.

7.1.4 The testing machine shall be verified in accordance with Practices E4 at a frequency defined by Practice C1093.

7.2 Test Specimens:

7.2.1 Unless specified otherwise in the applicable annex, test three specimens in compression.

7.2.2 Unless specified otherwise in the applicable annex, specimens shall be full-sized units except when the units cannot be tested full-size due to specimen configuration or testing machine requirements. In these cases, reduce the specimen size in accordance with Annex A1.

7.2.3 After delivery to the laboratory, store compression specimens (unstacked and separated by not less than 0.5 in. [13mm] on all sides) continuously in air at a temperature of 75 15 F [24 8 C] and a relative humidity of less than 80% for not less than 48h. Alternatively, if compression results are required sooner, store units unstacked in the same environment described above with a current of air from an electric fan passing over them for a period of not less than 4 h. Continue passing air over the specimens until two successive weighings at intervals of 2h show an increment of loss not greater than 0.2% of the previously determined weight of the specimen and until no moisture or dampness is vis ble on any surface of the unit. Specimens shall not be subjected to oven-drying.

NOTE 8: In this test method, net area (other than certain solid units, see 9.5) is determined from specimens other than those subjected to compression testing. The compressive strength method is based on the assumption that units used for determining net volume (absorption specimens) have the same net volume as units used for compression testing. Sampled split face units, which have irregular surfaces, should be divided at the time they are sampled from the lot, such that the absorption test specimens have a net volume that is visually representative and a weight that is representative of the compression test specimens.

7.2.4 Where saw-cutting of test specimens is allowed or required by the standard or applicable annex, sawing shall be performed in an accurate, competent manner, subjecting the specimen to as little saw vibration as possible. Use a diamond saw blade of proper hardness. Following cutting, residue from the cutting operation shall be removed prior to continuing testing (see Note 9). If the specimen is wetted during sawing, allow the specimen to dry to equilibrium with laboratory air conditions before testing, using the procedures outlined in 7.2.3.

NOTE 9: For specimens cut with a wet saw, rinsing with clean water is typically sufficient for removing cutting residue. For specimens cut with a dry saw, brushing with a soft-bristle brush is typically sufficient for removing cutting residue.

7.2.5 If compression test specimens have been saw-cut from full-sized units and the net area of the compression test specimens can not be determined by 9.5.1, saw-cut an additional three units to the dimensions and configuration of the three compression test specimens. The average net area for the saw-cut compression specimens shall be taken as the average net area of the additional three saw-cut units calculated as required in 9.5. Calculated net volumes of saw-cut specimens shall not be used in calculating equivalent thickness.

7.3 Capping Cap test specimens in accordance with Practice C1552.

7.4 Compression Testing Procedure:

7.4.1 Position of Specimens Test specimens with the centroid of their bearing surfaces aligned vertically with the center of thrust of the spherically seated steel bearing block of the testing machine (Note 10). Except for special units intended for use with their cores in a horizontal direction, test all hollow concrete masonry units with their cores in a vertical direction. Test masonry units that are 100% solid and special hollow units intended for use with their hollow cores in a horizontal direction in the same direction as in service. Prior to testing each unit, ensure that the upper platen moves freely within its spherical seat to attain uniform seating during testing.

NOTE 10: For those masonry units that are symmetrical about an axis, the location of that axis can be determined geometrically by dividing the dimension perpendicular to that axis (but in the same plane) by two. For those masonry units that are nonsymmetrical about an axis, the location of that axis can be determined by balancing the masonry unit on a knife edge or a metal rod placed parallel to that axis. If a metal rod is used, the rod shall be straight, cylindrical (able to roll freely on a flat surface), have a diameter of not less than 0.25 in. [6 mm] and not more than 0.75 in. [19 mm], and its length shall be sufficient to extend past each end of the specimen when placed upon it. The metal rod shall be placed on a smooth, flat, level surface. Once determined, the centroidal axis shall be marked on the end of the unit using a pencil or marker having a marking width of not greater than 0.05 in. [1.5 mm]. A tamping rod used for consolidation of concrete and grout for slump tests performed in accordance with Test Method C143/C143M is often used as a balancing rod.

7.4.2 Moisture Condition of Specimens At the time the specimens are tested, they shall be free of visible moisture or dampness.

7.4.3 Speed of Testing Apply the load (up to one half of the expected maximum load) at any convenient rate, after which adjust the controls of the machine as required to give a uniform rate of travel of the moving head such that the remaining load is applied in not less than 1 nor more than 2 min. The results of the first specimen shall not be discarded so long as the actual loading time for the second half of the actual load is greater than 30 s.

NOTE 11: The allowance for a loading rate outside of 1 to 2 min for the first specimen acknowledges that the expected load may be different than the actual maximum load. The load rate for the remaining two specimens should be adjusted based on the first specimen results.

7.4.4 Maximum Load Record the maximum compressive load in pounds [newtons] as P_{max}.

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Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units

9 | Calculations

9.1 Absorption Calculate absorption as follows:

$$\text{Absorption, lb/ft}^3 = [(w_s - w_d)/(w_s - w_i)] \times 62.4 \quad (1)$$

$$[\text{Absorption, kg/m}^3 = [(w_s - w_d)/(w_s - w_i)] \times 1000]$$

$$\text{Absorption, \%} = [(w_s - w_d)/w_d] \times 100$$

where:

w_s	=	saturated weight of specimen, lb [kg],
w_i	=	immersed weight of specimen, lb [kg], and
w_d	=	oven-dry weight of specimen, lb [kg].

9.2 Moisture Content Calculate the moisture content of the unit at the time it is sampled (when w_r is measured) as follows:

$$\text{Moisture Content, \% of total absorption} = [(w_r - w_d)/(w_s - w_d)] \times 100 \quad (2)$$

where:

w_r	=	received weight of unit, lb [kg],
w_d	=	oven-dry weight of unit, lb [kg], and
w_s	=	saturated weight of unit, lb [kg].

NOTE 15: When determining the moisture content of a unit or set of units, the value determined is a measure of the water content of a unit based upon the received weight of the unit w_r. Thus, the moisture content calculation above is only applicable to the unit moisture content at the time the received weight, w_r, is obtained.

9.3 Density Calculate oven-dry density as follows:

$$\text{Density (D), lb/ft}^3 = [w_d / (w_s - w_i)] \times 62.4 \quad (3)$$

$$[\text{Density (D), kg/m}^3 = [w_d / (w_s - w_i)] \times 1000]$$

where:

w_d	=	oven-dry weight of specimen, lb [kg],
w_s	=	saturated weight of specimen, lb [kg], and
w_i	=	immersed weight of specimen, lb [kg].

9.4 Net Volume Calculate net volume as follows:

$$\text{Net Volume } (V_n)\text{, ft}^3 = w_d / D = (w_s - w_i) / 62.4 \quad (4)$$

$$[\text{Net Volume } (V_n)\text{, cm}^3 = (w_d / D) \times 10^6 = (w_s - w_i) \times 10^3]$$

where:

V_n	=	net volume of specimen, ft^3[cm^3],
w_d	=	oven-dry weight of specimen, lb [kg],
D	=	oven-dry density of specimen, lb/ft^3[kg/m^3].

W_s	=	saturated weight of specimen, lb [kg], and
W_i	=	immersed weight of specimen, lb [kg]

9.5 Average Net Area Calculate net area as follows:

$$\text{Average Net Area } (A_n), \text{ in.}^2 = (V_n \times 1728) / H \quad (5)$$

$$[\text{Average Net Area } (A_n), \text{ mm}^2 = (V_n \times 10^3) / H]$$

where:

V_n	=	net volume of specimen, ft^3[cm^3],
A_n	=	average net area of specimen, in.^{2}[mm^2], and
H	=	average height of specimen, in. [mm].

NOTE 16 In SI units, net volume is calculated in terms of cubic centimetres to be consistent with the reporting requirements of this standard. Net area, however, is calculated in terms of square millimetres in order to facilitate calculation of compressive strength in MPa which is defined as N/mm^2.

9.5.1 Except for irregularly shaped specimens, such as those with split surfaces, calculate the net area of coupons and those specimens whose net cross-sectional area in every plane parallel to the bearing surface is equal to the gross cross-sectional area measured in the same plane, as follows:

$$\text{Net Area } (A_n), \text{ in.}^2 [\text{mm}^2] = L \times W \quad (6)$$

where:

A_n	=	net area of coupon or specimen, in.^{2}[mm^2],
L	=	average length of coupon or specimen, in. [mm], and
W	=	average width of coupon or specimen, in. [mm].

9.6 Gross Area Calculate gross area of each specimen as follows:

$$\text{Gross Area } (A_g), \text{ in.}^2 [\text{mm}^2] = L \times W \quad (7)$$

where:

A_g	=	gross area of specimen, in.^{2}[mm^2],
L	=	average length of specimen, in. [mm], and
W	=	average width of specimen, in. [mm].

9.6.1 The gross cross-sectional area of a specimen is the total area of a section perpendicular to the direction of the load, including areas within cells and reentrant spaces, unless these spaces are to be occupied in the masonry by portions of adjacent masonry.

9.7 Compressive Strength:

9.7.1 Net Area Compressive Strength Calculate the net area compressive strength of the specimen as follows:

$$\text{Net Area Compressive Strength, psi } [\text{MPa}] = P_{max}/A_n \quad (8)$$

where:

P_{max}	=	maximum compressive load, lb [N], and
$A_{n,\,avg}$	=	average of the net area values determined for each of the three absorption specimens, in.^{2}[mm^2].

9.7.2 Gross Area Compressive Strength Calculate the gross area compressive strength of the specimen as follows:

$$\text{Gross Area Compressive Strength, psi } [\text{MPa}] = P_{max}/A_g \quad (9)$$

where:

P_{max}	=	maximum compressive load, lb [N], and
$A_{g,\,avg}$	=	average of the gross area values determined for each of the three specimens, in.^{2}[mm^2].

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Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units

8 | Absorption

8.1 Apparatus Unless specified otherwise in the appropriate annex, the following equipment shall be used:

8.1.1 Balance A balance readable and accurate to 0.1% of the weight of the smallest specimen tested. Balances shall be calibrated in accordance with Practice C1093.

8.1.2 Oven A ventilated oven of appropriate size capable of maintaining a uniform temperature of 230 9 F [110 5 C]. Ovens shall be verified in accordance with Practice C1093.

8.1.3 Timer A timer readable and accurate to 1 second. Timers shall be verified in accordance with Practice C1093. (See Note 12.)

NOTE 12: Recommended procedures for verifying timers can be found in NIST Special Publication 960-12 (2009): NIST Recommended Practice Guide Stopwatch and Timer Calibrations.

8.2 Test Specimens:

8.2.1 Unless specified otherwise in the applicable annex, test three specimens in absorption.

8.2.2 Unless specified otherwise in the applicable annex, tests shall be performed on full-sized units or specimens saw-cut from full-sized units. Calculated values for absorption and density of reduced-size absorption specimens shall be considered as representative of the whole unit.

8.2.2.1 When test specimens are saw-cut from full-sized units, the test specimen shall have an initial weight after cutting of no less than 20% of the initial received weight of the full-sized unit.

NOTE 13: When performing absorption tests on reduced-sized specimens, it is preferable to have a test specimen that is as large as practically possible and can be accommodated by laboratory equipment. This helps to reduce any location-specific variability from the absorption results.

8.3 Procedure:

8.3.1 Immerse the test specimens in water at a temperature of 60 to 80 F [15 to 27 C] for 24 to 28 h such that the top surfaces of the specimens are at least 6 in. [150mm] below the surface of the water. Specimens shall be separated from each other and from the bottom of the immersion tank by at least 0.125 in. [3 mm], using wire mesh, grating, or other spacers. The spacer shall not cover more than 10% of the area of the face that is in direct contact with the spacer (see Note 14).

NOTE 14: The intent of the requirement for spacer contact with the specimen surface is to limit the possibility of reduced absorption of water due to blockage by the spacer. In order to determine compliance, only the area of the surface of the specimen in contact with the spacer should be considered. For example, when a spacer is used between the bottom of the specimen and the bottom of the tank, only the area of the bottom of the unit should be used to determine the 10% limit (not the surface area of the entire specimen).

8.3.2 Weigh the specimens while suspended by a metal wire and completely submerged in water and record w_i (immersed weight).

8.3.3 Remove the specimens from water and allow to drain by placing them on a 0.375-in. [10-mm] or coarser wire mesh. While the specimen is draining and before weighing, remove visible surface water with a damp cloth. Weigh specimens 60 5s following removal from water. Record as w_s(saturated weight).

8.3.4 Subsequent to saturation, dry all specimens in a ventilated oven at 230 9 F [110 5 C] for not less than 24 h and until two successive weighings at intervals of 2 h show an increment of loss not greater than 0.2% of the last previously determined weight of the specimen. Record weight of dried specimens as w_d(oven-dry weight).

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Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units

A1 | TEST PROCEDURES FOR CONCRETE MASONRY UNITS

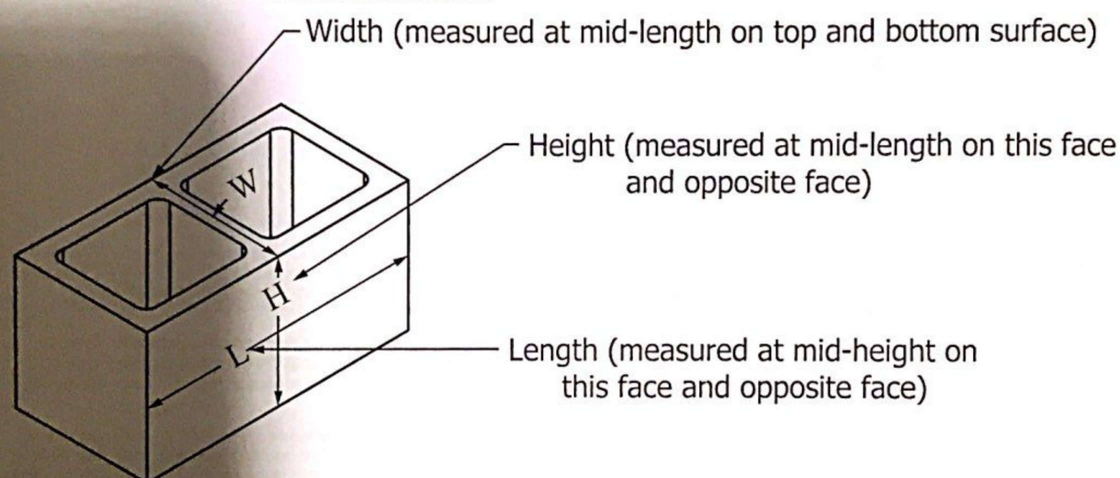
A1.1 Scope

A1.1.1 This annex includes testing requirements that are particular for concrete masonry units that are manufactured for compliance with the following unit specifications: C90, C129.

A1.2 Measurement

A1.2.1 For each unit, measure and record the following to the nearest division required to be reported (see Fig. A1.1):

FIG. A1.1 Diagram Showing Location of Measurements for CMU



(1) Width (*W*) at mid-length across the top and bottom bearing surfaces. Average the two recorded values to determine the width of the specimen.

(2) Height (*H*) at mid-length on each face. Average the two recorded values to determin the height of the specimen.

(3) Length (*L*) at mid-height on each face. Average the two recorded values to determine the length of the specimen.

A1.2.2 For each unit, measure the face shell thicknesses (t_{fs}) at the thinnest point 0.50 in. [13 mm] down from the top surface of the unit as manufactured (typically the bottom surface of the unit as laid) and record to the nearest division required to be reported. Disregard grooves, scores, and similar details in the face shell thickness measurements.

A1.2.3 For each unit, when the thinnest point of opposite face shells differ in thickness by less than 0.125 in. [3 mm], calculate the minimum face shell thickness by averaging the recorded measurements. When the thinnest points differ by more than 0.125 in. [3 mm], the minimum face shell thickness shall be taken as the smaller of the two recorded measurements.

A1.2.4 For each unit, measure the web thickness (t_w) at the minimum thickness of each web to the nearest 0.01in. [0.25mm].

A1.2.5 For each unit, determine the minimum web area using one of the following methods:

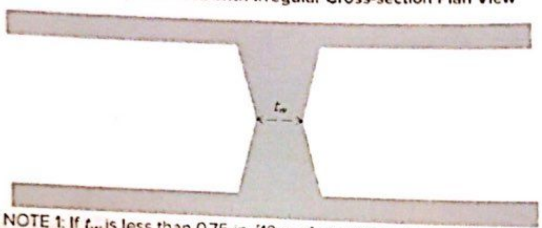
A1.2.5.1 For units with rectangular webs, measure the web height (t_h) at the minimum height of each web to the nearest 0.1 in. [2.5 mm]. For each unit, calculate the minimum web area for each web (A_w) by multiplying the minimum web thickness (t_w) and minimum web height (t_h) for measured web dimensions of 0.75 in. [19 mm] or greater. For each unit, calculate the total minimum web area (A_{wt}) by summing the web area (A_w) of each web.

A1.2.5.2 For units with webs that are not rectangular, disregard portions of the web that have a thickness of less than 0.75 in. [19 mm]. Make necessary measurements to determine the web area of each web at the minimum area based on the configuration of the web (see Note A1.2). For each unit, calculate the total minimum web area (A_{wt}) by summing the web area (A_w) of each web.

NOTE A1.1: Webs with minimum heights over their entire length or thickness over their entire height of less than 0.75 in. [19 mm] do not typically contribute to the unit s structural stability. Such webs should not be included in the minimum web area calculation. When a web has a portion that is less than 0.75 in. [19 mm] in thickness, the web area should be determined based only on the portions of the web that are larger than 0.75 in. [19 mm] in thickness. See Fig. A1.2 and Fig. A1.3.

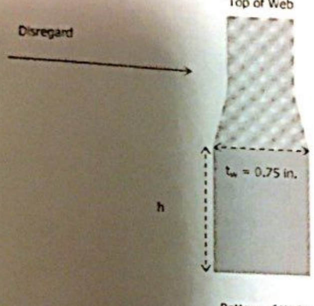
NOTE A1.2 It can be difficult on some units to access the minimum web area. If necessary, the unit can be saw-cut along the length at the minimum area to facilitate measurements. Fig. A1.3 shows an example of a non-rectangular web, where the upper portion would be discarded from the measurement because it is less than 0.75 in. [19 mm] in thickness, and the lower portion would be used to determine web area because it is greater 0.75 in. [19 mm] in thickness.

FIG. A1.2 Example of Web with Irregular Cross-section Plan View



NOTE 1: If t_w is less than 0.75 in. [19 mm] over the entire height of the web, disregard entire area of that web when determining minimum web area.

FIG. A1.3 Example of Irregular Web Area Calculation Section View



NOTE 1: Web Area = $t_w * h$

A1.3 Compressive Strength Testing

A1.3.1 Test Specimens Specimens shall be full-sized units unless full-size units cannot be tested due to specimen configuration or testing machine requirements. When necessary, modify specimens as required in A1.3.1.1 through A1.3.1.3.

A1.3.1.1 Unsupported projections having a length greater than the thickness of the projection shall be removed by saw-cutting. For units with recessed webs, the face shell projecting above the web shall be removed by saw-cutting to provide a full bearing surface over the net cross section of the unit. Where the resulting unit height would be reduced by more than one-third of the original unit height, the unit shall be coupon tested in accordance with A1.3.1.3.

A1.3.1.2 When compression testing full-sized units that are too large for the test machine's bearing block and platens or are beyond the load capacity of the test machine, saw-cut the units to properly size them to conform to the capabilities of the testing machine. The resulting specimen shall have no face shell projections or irregular webs and shall be fully enclosed in a four-sided cell or cells. The compressive strength of the segment shall be considered to be the compressive strength of the whole unit.

A1.3.1.3 When compression testing units of unusual size and shape where a suitable reduced-size specimen in accordance with A1.3.1.2 cannot be obtained, (see Note A1.3 and Note A1.4), the specimens shall be saw-cut to remove any face shell projections. The resulting specimen shall be a cell or cells containing four sides that will ensure a 100% bearing surface. Where saw-cutting will not result in an enclosed four-sided unit, the specimen shall be a coupon cut from a face shell of each unit. The coupon shall be cut from the unit such that the coupon height dimension is in the same direction as the unit s height dimension. The compressive strength of the coupon shall be the net area compressive strength of the whole unit. The coupon size shall conform with the following:

(1) Aspect ratio (height divided by width, H_s/W_s) of 2.0 0.1 before capping.

(2) Length to width ratio ((L_s/W_s) of 4.0 0.1.

(3) Coupon width shall be equal to the face shell thickness and shall not be less than 0.75 in. [19 mm].

(4) Coupon dimensions shall not differ by more than 0.125 in. [3 mm] from targeted dimensions.

A1.3.1.4 If a coupon complying with to A1.3.1.3 is used for compressive strength testing, measure the coupons in accordance with A1.3.2.

A1.3.2 Coupon Measurement Coupon measurements shall be performed to the nearest 0.01 in. [0.25 mm] using a measurement device readable and accurate to 0.01 in. [0.25 mm]. Measurements shall be taken as follows:

A1.3.2.1 Width Measure and record the width of the coupon (W_s) across the top and bottom surfaces at mid-length. Average the two recorded values to determine the width of the coupon.

A1.3.2.2 Height Measure and record the height of the coupon (H_s) at mid-length on each face. Average the two recorded values to determine the height of the coupon.

A1.3.2.3 Length Measure and record the length of the coupon (L_s) at mid-height of each face. Average the two recorded values to determine the length of the coupon

NOTE A1.3 Examples of units having unusual size or shape include, but are not limited to, bond beam units, open end units, and pilaster units.

NOTE A1.4 A full-size unit should be tested if feasible. If that is not feasible, then a reduced-size unit should be tested. If it is not feasible to test a full-size or reduced-size unit, then a coupon should be tested.

A1.3.3 Testing Cap and test specimens in accordance with 7.3 and 7.4.

A1.4 Absorption Testing

A1.4.1 Apparatus Absorption testing apparatus shall comply with 8.1.

A1.4.2 Test Specimens Specimens shall be full-size or reduced-size specimens in accordance with 8.2 except as modified in A1.4.2.1.

A1.4.2.1 Tests shall be performed on full-size units when test results are to be used to determine moisture content in accordance with 9.2 or equivalent thickness in accordance with A1.5.3.

A1.4.3 Testing Perform absorption tests in accordance with 8.3.

A1.5 Calculations

A1.5.1 Calculate absorption, moisture content, density, average net area, and net area compressive strength in accordance with Section 9.

A1.5.2 Normalized Web Area Calculate the normalized web area (A_{wn}) of each unit by dividing the total minimum web area (A_{wt}) by the nominal length and height of the unit as follows:

$$A_{wn}(\text{in.}^2/\text{ft}^2) = \frac{A_{wt}}{(L_n \times H_n)} \times 144 \qquad \text{(A1.1)}$$

$$\left[A_{wn}\ (\text{mm}^2/\text{m}^2) = \frac{A_{wt}}{(L_n \times H_n)} \times 10^6\right]$$

where:

A_{wn}	=	normalized web area, in.^{2}/ft^2 [mm^2/m^2],
A_{wt}	=	total minimum web area, in.^{2} [mm^2] (see A1.2.5),
L_n	=	nominal length of unit, in. [mm], and
H_n	=	nominal height of unit, in. [mm].

NOTE A1.5: Minimum web area does not apply to the portion of the unit to be filled with grout. The portion of the unit to be filled with grout should be deducted from the calculation of the normalized web area.

A1.5.3 Equivalent Thickness Equivalent thickness for concrete masonry is defined as the average thickness of solid material in the unit and is calculated as follows:

$$T_e,\ \text{in.} = (V_n / (L \times H)) \times 1728 \qquad \text{(A1.2)}$$

$$[T_e,\ \text{mm} = (V_n / (L \times H))]$$

where:

T_e	=	equivalent thickness, in. [mm],
V_n	=	average net volume of full-size units, ft^3[mm^3] (see 9.5),
L	=	average length of full-size units, in. [mm] (see A1.2.1), and
H	=	average height of full-size units, in. [mm] (see A1.2.1).

A1.5.3.1 Equivalent thickness shall only be calculated and reported for full-size concrete masonry units.

A1.5.4 Percent Solid Calculate the percent solid as follows:

$$\text{Percent solid, ft}^3\ (\%) = \left(\frac{(V_n \times 1728)}{(L \times W \times H)}\right) \times 100 \qquad \text{(A1.3)}$$

$$\left[\text{Percent solid, mm}^3\ (\%) = \left(\frac{V_n}{(L \times W \times H)}\right) \times 100\right]$$

where:

V_n	=	net volume of specimen, ft^3[mm^3] (see 9.5),
L	=	average length of specimen, in. [mm] (see A1.2.1),
W	=	average width of specimen, in. [mm] (see A1.2.1), and
H	=	average height of specimen, in. [mm] (see A1.2.1).

NOTE A1.6 This calculation determines the percentage of concrete in the gross volume of the unit. It is a useful reference value, but it is not a requirement of unit specifications. This value is not comparable to the definition of a solid unit in C90 and C129, which refers to the net cross-sectional area of every plane parallel to the bearing surface relative to the gross cross-sectional area of the same plane.

A1.5.5 Maximum Variation from Specified Dimensions:

A1.5.5.1 Determine the variation from each specified dimension by calculating the average width, height, and length of each specimen and comparing each average to the respective specified dimension, resulting in three variation results for each unit and nine results for a set of units. Determine the maximum variation for the set by identifying the maximum of the nine values.

A1.5.5.2 Specified dimensions shall be obtained from the unit manufacturer.

A1.6 Report

A1.6.1 Test reports shall include all of the information in Sections 10.2, 10.3, and the following:

A1.6.1.1 The minimum face shell thickness to the nearest 0.01 in. [0.25 mm] separately for each specimen and as the average for the three specimens tested.

A1.6.1.2 The minimum web thickness to the nearest 0.01 in. [0.25 mm] separately for each specimen and as the average for the three specimens tested.

A1.6.1.3 The normalized web area to the nearest 0.1in.^{2}/ft^2[500mm^2/m^2] as the average for the three specimens tested.

A1.6.1.4 The equivalent thickness to the nearest 0.1 in. [2.5 mm] as the average for the three specimens tested.

A1.6.1.5 The percent solid results to the nearest 0.1% separately for each specimen and as the average for the three specimens tested.

A1.6.1.6 Maximum variation from specified dimensions to the nearest 0.1 in. [2.5 mm] for the set of specimens tested.

A1.6.1.7 The gross area to the nearest 0.1 in.^{2} [50 mm^2] separately for each specimen and as the average for the three specimens tested.

A1.6.1.8 The gross area compressive strength to the nearest 10 psi [0.1 MPa] separately for each specimen and as the average for the three specimens tested.

A1.6.1.9 The net volume to the nearest 0.01 ft^3 [250 cm^3] separately for each specimen and as the average for the three specimens tested.

Eric R. Berg[1] and John A. Neal[1]

A Procedure for Testing Concrete Masonry Unit (CMU) Mixes

REFERENCE: Berg, E. R. and Neal, J. A., **"A Procedure for Testing Concrete Masonry Unit (CMU) Mixes,"** *Cement, Concrete, and Aggregates*, CCAGDP, Vol. 19, No. 1, 1997, pp. 3–7.

ABSTRACT: A laboratory method for the evaluation of concrete masonry unit (CMU) mix designs is proposed. The zero slump requirement and the unique method of molding CMU using simultaneous vibration and compression on an automated assembly line basis make CMU mix design a unique subset of concrete mix design. The compression and vibration of a block machine is simulated by the use of a drop hammer to compact the test specimens. The different compaction methods are equated by modifying the height of the hammer drop or the number of drops to obtain the same density as that obtained from the production block machine. The volumetric fill method of a production machine is replaced with weighing the mix placed in each mold prior to compaction to provide a uniform amount of material. Numerous batches can be made quickly in a laboratory using small amounts of material on a cost-effective basis. Two-inch (50-mm) cubes for strength testing based upon modified ASTM C 109 (Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50-mm Cube Specimens)) procedures, and 1-in. (25-mm) square bars for change of length testing based upon modified ASTM C 157 (Test Method for Length Change of Hardened Hydraulic-Cement Mortars and Concrete) procedures can both be made using standard molds and testing equipment.

KEYWORDS: concrete, masonry, mix design, testing

Normal concrete is a flowable mixture cast in a form. Consolidation of the mix is usually accomplished by internal vibration without external pressure on the concrete. A concrete masonry unit (CMU) mix is compacted in molds with simultaneous external vibration and pressure and then immediately removed from the molds. Although there are several manufacturers of CMU producing machinery for the North American market, the processes of making CMU are all basically the same. The requirements for a zero slump mix and the unique method of molding CMU on an automated assembly-line basis make CMU mix design a unique subset of concrete mix design.

An accepted laboratory method of testing mix designs for concrete masonry units (CMU) does not exist as the ability to duplicate the consolidation method of CMU manufacturing in the laboratory has not been developed. Previous experiments with CMU mix design not involving actual production machinery have used different consolidation techniques, uncontrolled or fixed compaction efforts and no calibration of compaction effort to that available from production machinery (Niak et al. 1996; Amiri et al. 1994; Black and Cunningham 1991; Roethal and Breslin 1990). Current testing of CMU mixes typically requires the use of production machinery to make full-size CMU with minimum batch sizes of about 1000 lbs (455 kg). The location of a production CMU machine, the availability of time on a production line, and the large amount of material required per batch make CMU mix design testing very expensive and difficult.

[1]Lecturer and associate professor, respectively, State University of New York at Buffalo, Civil Engineering Department, Ketter Hall, Amherst, NY 14260.

Research Significance

The proposed method provides a method to conduct mix design testing for CMU in a laboratory setting using small amounts of material. The manufactured test specimens, 2-in. (50.8-mm) cubes and 1- by 1- by 11.25-in. (25.4- by 25.4- by 285.7-mm) bars are standard shapes and use common cement/concrete molds and test equipment. Throughout the development of the test method, an effort was made to use existing equipment to minimize the cost and to use and/or modify appropriate ASTM standards and methods where ever practical. The method allows for a cost-effective method of evaluating mix design parameters particularly when one ingredient at different mix percentages or multiple variables will be tested.

CMU Production Overview

After batch mixing, wet CMU mix is dropped into the feed hopper of a CMU machine. A feed drawer is used to laterally transfer material onto the top of the CMU mold assembly. The material is then compacted into the molds using simultaneous vertical pressure and aggressive vibration of the entire mold. Excess material is deliberately kept in the upper part of the mold box and the machine is adjusted as required for correct mold filling. While the machinery places a consistent amount of material in the mold, the actual amount of material is not metered or documented. Upon completion of the compaction cycle, the CMU are lowered from the mold on a steel plate and moved by a conveyor to a curing operation. This cycle is completed 6 to 9 times a minute. A successful CMU mix must be highly compactible by the CMU machine's compaction method, not adhere to the molds or contact surfaces of the CMU machine, and be stiff enough so the formed CMU does not slump or deform when removed from the mold. These requirements result in a "zero slump" mix that does not contain sufficient cement paste to adhere to contact surfaces. As a result, the water and paste contents are below the level for the highest compaction and strength. Unlike "normal" concrete where reducing the water content improves the strength, the strength of a usable CMU mix is improved by the addition of water. Too much water will make the mix stick to mold surfaces and create

NOTE A1.6 This calculat...

problems of removal from the mold. The optimum water content is generally defined as the highest amount that allows for proper movement of the mix through the machine.

The adjustments available to a producer in the compaction method used on CMU machinery in North America are limited. The largest adjustment would be to change the rotating weights on the vibrator shafts, requiring at least 1 h and the removal of the mold from the machine. Normally, a producer will determine the optimum weights to use with his most common aggregates and then use those same weights for all production including the use of different aggregates. The vibration frequency of the mold box and the vertical compaction force are not adjusted by a producer. The time of vibration can be adjusted; however, most producers minimize the vibration time to maximize production speed. Overall, the compaction effort has little adjustment and timing adjustments made by a producer for height control of the molded CMU have little effect on the compaction effort. Most producers, when faced with a consolidation problem, will change the mix design and not change the machinery.

Equipment and Molds

There is no accepted method of duplicating the manufacturing process of CMU in a laboratory. Specifically, the vibration compaction method of a production CMU machine is the most difficult part of the process to recreate in a laboratory. The proposed test method uses a drop hammer to compact specimens. This provides compaction pressure with impact vibration. It also allows the compaction effort to be a measurable and repeatable quantity. A Pine Instrument Company Model PMC-4 compactor, designed for compacting asphaltic concrete samples for the Marshall method of mix design was modified to create the drop hammer (Fig. 1). The height of the hammer drop, the hammer weight, and the number of repetitions can be easily modified to vary the compaction effort. The movable hammer frame was constructed using 1-in. (25-mm) steel plate that used linear bearings to keep the hammer in vertical alignment (Fig. 2). Guides were installed in the bottom plate of the hammer frame for accurate placement of the molds. A different hammer face of solid steel was developed for each mold with a simple attachment method to the hammer frame using bolts and alignment pins. The hammer faces were undersized by 0.060 in. (1.5 mm) on all sides to allow for minor alignment differences between the molds, guarantee free movement of the hammer, and prevent the hammer from hitting the top of the mold or collar. The total hammer assembly weighed about 49 lbs (22 kg).

For the purpose of obtaining basic properties of the hardened concrete mixes, two different molds were developed for use with the drop hammer compaction equipment. Two-inch concrete cubes were made in three cube molds for compressive strength testing. Bars measuring 1- by 1- by 11.25-in. (25- by 25- by 286-mm) were made in two bar molds for change of length measurements.

The 2-in. cube molds were brass molds that conformed to Test Method for Compressive Strength of Hydraulic Cement Mortars (ASTM C 109). A collar for the top of the mold using 0.125-in. (3-mm) steel plate was devised to hold the concrete mix for each cube as the loose volume of the mix is more than the compacted volume (Fig. 3). The sides of the collar were 1-in. (25 mm) high and on a 16-degree taper. The bottom of the collar matched the alignment of the brass mold, providing an additional 0.125-in. (3-mm) height. This accommodated minor height differences in the compacted cubes.

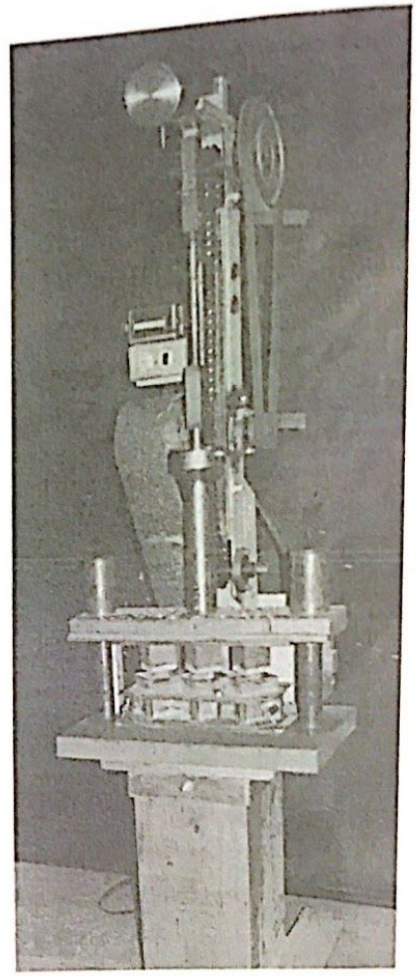


FIG. 1—*Modified Pine Instrument Company PMC-4 compactor with installed drop hammer frame.*

The 1- by 1- by 11.25-in. (25- by 25- by 286-mm) bar molds were steel molds that conformed to Specification for Apparatus for Use in Measurement of Length Change of Hardened Cement Paste, Mortar, and Concrete (ASTM C 490). The molds were modified by installing a 0.125-in. (3-mm) deep groove in the mold bottom plate to prevent movement of the mold side bars during compaction and the height of the mold side bars was increased to retain a net 1-in. height. Again, a collar was devised for the bar mold to contain the loose mix, using the same material and a similar assembly as for the 2-in. (50-mm) cubes (Fig. 4).

Procedure

Although CMU mixes are very dry with zero slump, the batching and mixing of CMU mixtures is relatively straight forward. Mixers

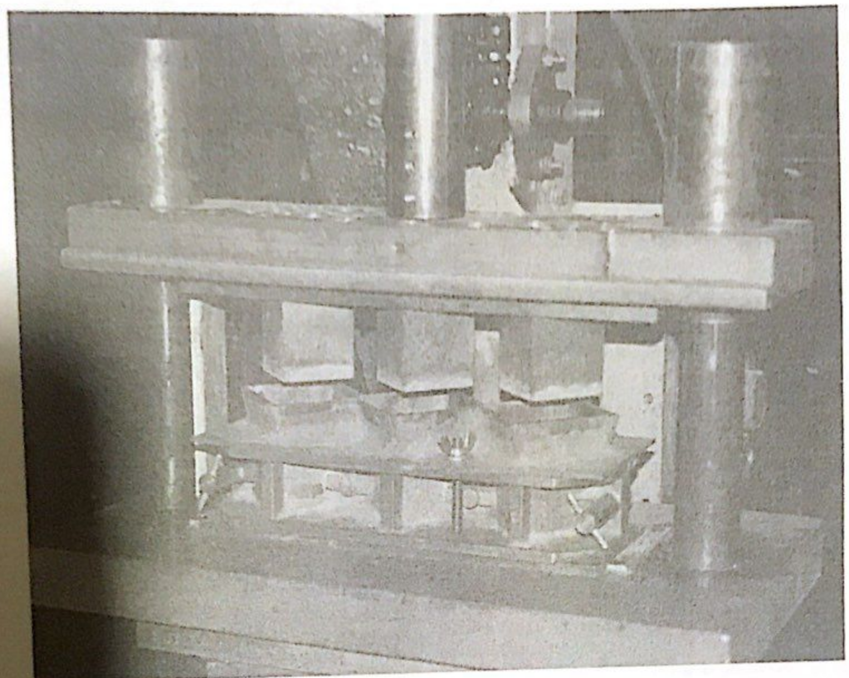


FIG. 2—*Drop hammer frame with 2-in. (50-mm) mold.*

FIG. 3—*Two-in. (50-mm) cube mold with collar installed.*

FIG. 4—*One-in. (25-mm) bar mold with collar installed.*

that conform to Method of Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency (ASTM C 305) for mortar mixing can be used for CMU mixes and ingredients can be batched by weight. The following steps outline a procedure for mixing, filling, and compacting specimens.

1. The mixing procedure as outlined in ASTM C 305 is used with the following changes:
   (a) Only the slow mixer speed is used.
   (b) The mixing time after the addition of the aggregate is 5 min, including the rest period of 90 s. Optionally, a more accurate simulation of production operations would be to adjust the total cycle time to that of the actual production mixer used by a producer. Most producers use a total mixing time of 5 to 6 min.
2. The material required to fill each mold cavity is weighed separately into transfer containers, three for 2-in. (50-mm) cubes or two for 1-in. (25-mm) bars. The amount of material is based upon the anticipated compacted density in the respective mold, measured to the nearest gram and adjusted for succeeding molds if the compacted height is not correct. Based upon a volumetric ratio, a bar mold will use 140% more material than a 2-in. (50-mm) cube.
3. With the mold collar installed, approximately $^1/_2$ of the mixture is placed in each mold cavity. Each half-filled mold cavity is then consolidated as per ASTM C 109 for the 2-in. (50-mm) cubes and Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete (ASTM C 157) for the 1-in. (25-mm) bar molds. For the bars, attention should be given to

the ends of the molds to ensure the measurement studs are surrounded with compacted material.

4. The remainder of the mixture is placed into each mold cavity. The material should be loosely spread out along the length of the 1-in. (25-mm) bar mold.

5. The filled mold is installed in the hammer frame and compacted by the drop hammer.

6. After a 2-h rest period, the samples are removed from the molds and cured. The cubes are completely removed from the molds. The end and side bars of the 1-in. bars should be removed and the bars with the gage stud holder left on the mold bottom plate for curing. After 24 h, the bars are removed from the bottom plate and the gage stud holders removed from the bars.

Correlation to Full Size CMU Production

The zero slump nature of a CMU mix makes consolidation a key aspect of the manufacturing process. Workability can be considered as a measure of a concrete mix's ability to minimize voids with a given amount of compaction effort. This reduction in voids increases both the density and strength of the hardened concrete. Workability is difficult to quantify and is a complex phenomena influenced by the type of aggregate, aggregate size gradation, amount of cement and pozzolons, water content, and admixtures, such as plasticizers. Density of a concrete is an accepted indirect measurement tool for workability as it is easily measured and has a direct relationship to strength for a given mix design (Neville 1981). Density was chosen as the parameter to correlate laboratory specimens to full-size production CMU, as the net effect of consolidation is the primary concern for hardened concrete.

Using a standard mix design and aggregate provided by a local CMU producer for standard CMU, an initial calibration was developed between the amount of compaction effort expended by the drop hammer and the density of 2-in. (50-mm) cubes after a 3-day moist cure. The compaction effort was quantified as the number of hammer drops times the height of the drop as an approximation of the energy expended. Figures 5 and 6 illustrate the density and 3-day compressive strength results, respectively, for two different drop heights. The local producer's density of 133.5 lb/ft^3 (2139 kg/m^3) using the same mix design is within the range of density obtained by the drop hammer, as

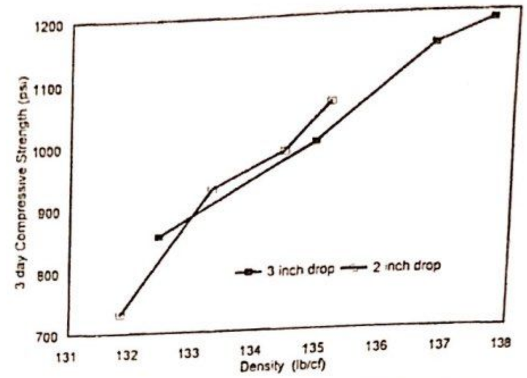


FIG. 6—*3-day compressive strength results of calibration test.*

shown in Fig. 5. This equivalent compaction effort would then be used for subsequent testing of the mix designs. Figure 7 is a plot of the 3-day compressive strength versus density of two calibration runs of the same mix design. The straight line is a linear least squares regression with an $R^2 = 0.91$.

For any particular mix design to be tested, the equivalent compaction effort for the drop hammer can be determined by comparing the density of the laboratory cubes to that of full-size standard CMU. Assuming the same specific gravities of ingredients, a reduction in density would indicate a reduction in workability and strength. Different aggregates and mix designs will have different target densities. A calibration run will be required for each target production machine using an existing mix design.

Comparison of Compressive Strengths

The effect of specimen size on indicated strength of concrete has been well documented. A. M. Neville (1981) illustrated a linear relationship between different sizes of cubes and the reported relative compressive strength. If an 8-in. (203 mm) solid cube is used to represent full-size CMU, Neville indicated a 12% lower value for the 8-in. (203-mm) cubes when compared to 2-in. (50 mm) cubes.

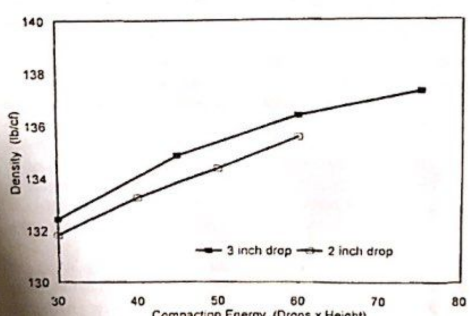


FIG. 5—*Relationship of compacted density to compaction effort for calibration test.*

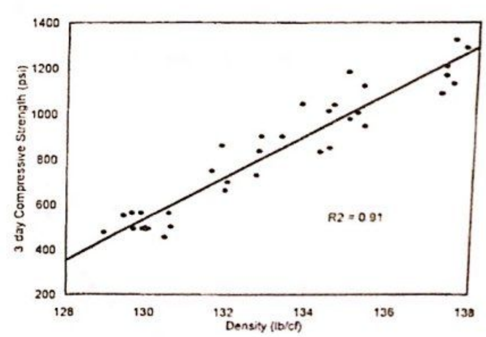


FIG. 7—*3-day compressive strength relationship to density for individual cubes of trial mixes.*