INTRODUCTION

Construction 3D printing technology is an approach to building wall structures by means of a robotic system that extrudes layer-by-layer high viscosity materials based on cement, gypsum, geopolymer, or other binders. This approach is regarded as a promising and innovative construction method, with many 3D printed buildings around the world serving as examples. However, there is still no single well-documented standard of 3D printed structures that can be approved for residential construction, complying with international building codes and construction requirements.

This report introduces a special configuration of 3D printed structures, comparable to the well-documented and accepted method of reinforced concrete masonry unit (CMU) construction. By matching our 3D printed walls with the (CMU) wall all construction techniques employed in roofing, foundation, etc., can be the same as used for CMU.

CMU construction employs a pattern of concrete blocks conducive to 3D printing and well-documented construction techniques. CMUs comprise a significant percentage of the American residential foundation wall market and have a long history of above-grade residential use in Arizona, Florida, Texas, and other parts of the southern United States.

The goal of this document is to demonstrate structural similarity between 3D printed walls and CMU walls, which may serve as a possible simplification in the permitting process for 3D printed buildings.

This document is an independent research done by Apis Cor company. Information presented in the document is subject to ongoing evaluation, development, and acceptance by an appropriate approving agency.
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SECTION 1
SPECIFICATIONS OF 3D PRINTED WALL

This section introduces the design of a 3D printed wall that mimics a 2 1/4-hour fire rating masonry wall, constructed with 8x8x16 masonry blocks. Structural similarities of the proposed 3D printed wall and the CMU wall are shown in Figure 1. The physical parameters of the proposed 3D printed wall are displayed next to the minimum requirements for the equivalent CMU constructed wall in Table 1. Table 2 presents the material properties of a 3D printed wall.

Material tests were performed by Briggs Engineering and Testing and The University of Connecticut, in accordance with ASTM testing standards.

Wall formation. Cement-based 3D printing material is extruded using a robot arm to form the wall’s foundation, layer by layer. Reinforcement, bars, and mesh are installed manually concurrently with the 3D printing. Grout and concrete are cast manually into columns and bond beams.

Briggs Engineering & Testing is regularly audited and/or certified by the National Institute of Standards and Technology’s Cement and Concrete Laboratory (CCRL), the Nuclear Regulatory Commission (NRC), the Federal Aviation Administration (FAA), the US Army Corps of Engineers, the American Association of State Highway and Transportation Officials (AASHTO) and the New England Transportation Technician Certification Program (NETTCP). Briggs Engineering & Testing also licensed or pre-qualified by all applicable state agencies such as the Massachusetts Highway Department (MHD) and the Massachusetts Bay Transit Authority (MBTA). Our State Certified Materials Laboratory and testing equipment is current and state of the art.

The University of Connecticut - a top-ranked research institution, campuses across Connecticut, US built to inspire, the global community that is UConn Nation.

![Figure 1. Structural similarity between 3D printed wall and CMU wall.](image-url)
Figure 2a. Dimensions of wall segment
Table 1. Physical parameters of 1-hour rating 3D printed wall compared to masonry:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>3D printed wall</th>
<th>Minimum requirement for CMU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate type in wall material</td>
<td>siliceous gravel</td>
<td>accepted</td>
</tr>
<tr>
<td>Material</td>
<td>as lightweight masonry</td>
<td></td>
</tr>
<tr>
<td>Equivalent thickness</td>
<td>4.5 in.</td>
<td>2.8 in</td>
</tr>
<tr>
<td>Net Area compressive strength (ASTM C1314)</td>
<td>2,350 Psi <strong>comply</strong></td>
<td>2,000 Psi</td>
</tr>
<tr>
<td>Column size</td>
<td>8x10 inches</td>
<td>8x8 inches</td>
</tr>
<tr>
<td>Minimum cover for R/C columns</td>
<td>comply</td>
<td>The minimum required cover over the vertical reinforcement is 2 in. (51 mm).</td>
</tr>
<tr>
<td>Bar size</td>
<td>as required</td>
<td>as required</td>
</tr>
<tr>
<td>Bar placement in terms of corrosion protection</td>
<td>comply</td>
<td>Masonry exposed to weather or earth bars larger than No. 5 (M#16) …………2 in. (51 mm) No. 5 (M#16) bars or smaller…………………1½ in. (38 mm) Masonry not exposed to weather or earth … 1½ in. (38 mm)</td>
</tr>
<tr>
<td>Joint reinforcement</td>
<td>comply</td>
<td>½ inch (13 mm) from edge of internal wall % inch (16 mm) from edge of external wall</td>
</tr>
</tbody>
</table>

Table 2. Material properties of a 3D printed wall units

<table>
<thead>
<tr>
<th>Test</th>
<th>Value</th>
<th>Testing Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption</td>
<td>17.1 %</td>
<td>Briggs Engineering and Testing</td>
</tr>
<tr>
<td>Density material</td>
<td>101.3 lb/ft³</td>
<td>Briggs Engineering and Testing; University of Connecticut</td>
</tr>
<tr>
<td>Average compressive strength of material (kept in normal conditions) on 28 day (ASTM C39)</td>
<td>3,627 Psi</td>
<td>Briggs Engineering and Testing; University of Connecticut</td>
</tr>
<tr>
<td>Average compressive strength of material (kept in water) on 28 day (ASTM C39)</td>
<td>2,880 Psi</td>
<td>Briggs Engineering and Testing</td>
</tr>
<tr>
<td>NET area compressive strength test of hollow 3D printed wall unit (ASTM C1314)</td>
<td>2,350 Psi</td>
<td>Briggs Engineering and Testing; University of Connecticut</td>
</tr>
<tr>
<td>NET area compressive strength test of grouted 3D printed wall unit (ASTM C1314)</td>
<td>3,010 Psi</td>
<td>Briggs Engineering and Testing</td>
</tr>
<tr>
<td>3 point flexural test (Modulus of Rapture)</td>
<td>406 Psi</td>
<td>University of Connecticut</td>
</tr>
</tbody>
</table>
SECTION 2
MATERIAL TESTING

1. Material compressive strength.

Compressive strength testing was conducted for the 3D printed material, in accordance with standard ASTM C39 procedures. Although 3D printed structures are constructed in normal conditions, two series of material specimens were tested: specimens kept in normal conditions and specimens kept in water. Specimens were removed from the water storage immediately prior to testing.

Table 3 displays the average compressive strength of both specimens; Chart 1 demonstrates the development of compressive strength over time for samples kept in normal conditions; Chart 2 shows the development of compressive strength over time for samples kept in water and taken prior to the testing; and Figure 2 demonstrates the specimens before and after testing.

Table 3. Average compressive strength. Reports presented in Exhibit 1 and Exhibit 2.

<table>
<thead>
<tr>
<th>AGE</th>
<th>Kept in AIR</th>
<th>Kept in WATER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 sample</td>
<td>2 sample</td>
</tr>
<tr>
<td>1 day</td>
<td>420</td>
<td>380</td>
</tr>
<tr>
<td>2 days</td>
<td>1,230</td>
<td>1,240</td>
</tr>
<tr>
<td>7 days</td>
<td>2,150</td>
<td>2,360</td>
</tr>
<tr>
<td>28 days</td>
<td>3,590</td>
<td>3,510</td>
</tr>
<tr>
<td>90 days</td>
<td>3,890</td>
<td>4,160</td>
</tr>
</tbody>
</table>

Chart 1. Development of compressive strength over time for samples kept in normal conditions.
Chart 2. Development of compressive strength over time for samples kept in water.

Figure 3. Specimens before and after compressive strength testing.
2. NET area compressive strength of units

Hollow and grouted pieces sawed from a 3D printed wall structure were subject to compressive strength testing, according to standard ASTM C1314 procedures. The same test procedure was conducted with CMU blocks to compare the performance. Core fill grout from Spec Mix with strength of 3,000 Psi (ASTM C476) was used as grouting material. The test results are shown in Table 4. Figure 3 demonstrates the process of sawing the specimens from the 3D printed wall, Figure 4 and Figure 5 demonstrates the prototype of 3D printed wall as comparable to masonry, Figure 6 demonstrates specimens. Figure 7 demonstrates the hollow 3D printed specimen before and after the testing, Figure 8 and Figure 9 demonstrates 3D printed specimens and masonry units under the load.

Table 4. The report presented in Exhibits 3-5.

<table>
<thead>
<tr>
<th></th>
<th>3D printed</th>
<th>CMU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hollow units</td>
<td>2,495 Psi (average of 2 samples)</td>
<td>1,740 Psi</td>
</tr>
<tr>
<td>Grouted units</td>
<td>3,010 Psi</td>
<td>3,690 Psi</td>
</tr>
</tbody>
</table>

Fig.3 Sawing the specimens from the 3D printed wall

Fig.4 The prototype of 3D printed wall as comparable to masonry

Fig.5 The prototype of 3D printed wall as comparable to masonry
Fig. 6 Grouted and hollow specimens

Fig. 7 The hollow 3D printed wall’s sample before and after compressive strength test.

Fig. 8 The grouted (left) 3D printed wall’s unit and hollow (right) 3D printed wall’s unit after the test.
3. Absorption and density

Two material specimens with measurements of 4x3x16 in. were subject to absorption testing, according to the ASTM C642 procedure. The results of the testing are shown in Table 5.

Table 5. The report presented in Exhibit 6.

<table>
<thead>
<tr>
<th></th>
<th>Maximum Absorption, %</th>
<th>Density, dry, pcf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>16.8</td>
<td>101.6</td>
</tr>
<tr>
<td>Sample 2</td>
<td>17.3</td>
<td>101.0</td>
</tr>
<tr>
<td>Average</td>
<td><strong>17.1</strong></td>
<td><strong>101.3</strong></td>
</tr>
</tbody>
</table>

According to ASTM C90 units of 3D printed wall corresponds to Lightweight masonry units. Having average net area compressive strength as 2,495 Psi, units of 3D printed wall comply with minimum NET area compressive strength for Lightweight masonry which is 2,000 Psi.

4. 3-points flexural test

To check if 3D printed structures have cold joints, 3-points flexural test were conducted. 3 beams were sawed from a 3D printed wall, then the corrugated surface was sawed so that the specimens had straight surfaces for testing purposes. Meanwhile, 3 solid beams were cast with the same 3D printing mix design, to compare the results between the solid and 3D printed beams. Solid beams were tested at 28 days of age, and 3D printed beams were tested at 95 days of age. The test results are displayed in Table 6. Figures 10 - 14 demonstrate the preparation process of the specimens and testing process, Figures 15 demonstrates the cracking pattern for the printed beams and solid beams.

Table 6. Modulus of rapture. The report presented in Exhibit 7.

<table>
<thead>
<tr>
<th></th>
<th>3D printed</th>
<th>Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample 1</td>
<td>Sample 2</td>
</tr>
<tr>
<td>Value, MPa</td>
<td>2.56</td>
<td>2.67</td>
</tr>
</tbody>
</table>
Fig. 10  Sawing the 3D printed specimens

Fig.11  Casting the solid specimens

Fig. 12  The 3D printed specimens before and after sawing the corrugated surface

Fig. 13  The 3D printed and solid specimens ready for testing

Fig. 14  The 3D printed sample under the load
Fig. 15 A visual representation of the cracking pattern for the printed beams a) to c) and the solid beams d) to f).

Test results demonstrated that beams sawed from a 3D printed wall do not have cold joints.
SECTION 3
DESIGN

This section verifies the design similarities between a 3D printed wall and a 1-hour rating masonry wall assembled out of 8x8x16 in. concrete blocks. This section is based on the provision in Chapter 7 of the International Building Code (IBC) that governs materials and assemblies used for structural fire resistance.

1. Equivalent thickness

Equivalent thickness is essentially the solid thickness that would be obtained if the volume of concrete contained in a hollow unit were recast without core holes (see Figure 16).

Equivalent thickness of a 3D printed unit is 4.5 in. (see Figure 17), which complies with 2 1/4-hour fire resistance masonry unit made of material with siliceous gravel as an aggregate type, as shown in Table 7.

<table>
<thead>
<tr>
<th>Aggregate type in the concrete masonry unit</th>
<th>Minimum required equivalent thickness, in. (mm), for fire resistance rating, hours&lt;sup&gt;a,b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcareous or siliceous gravel</td>
<td>6.2 6.0 5.8 5.5 5.3 5.0 4.8 4.5 4.2 3.9 3.6 3.2 2.8 2.4 2.0</td>
</tr>
<tr>
<td>Limestone, cinders or unexpanded slag</td>
<td>5.9 5.7 5.5 5.2 5.0 4.8 4.5 4.3 4.0 3.7 3.4 3.1 2.7 2.3 1.9</td>
</tr>
<tr>
<td>Expanded clay, shale or slate</td>
<td>5.1 4.9 4.8 4.6 4.4 4.2 4.0 3.8 3.6 3.4 3.3 2.9 2.6 2.2 1.8</td>
</tr>
<tr>
<td>Expanded slag or pumice</td>
<td>4.7 4.5 4.4 4.2 4.0 3.8 3.6 3.4 3.2 3.0 2.7 2.5 2.1 1.9 1.5</td>
</tr>
</tbody>
</table>

<sup>a</sup> Fire resistance rating between the hourly fire resistance rating periods listed may be determined by linear interpolation based on the equivalent thickness value of the concrete masonry unit. The requirements of ASTM C55, ASTM C73, ASTM C90 or ASTM C744 (refs. 13, 14, 6, 15) shall apply. Include equivalent thickness of finishes where applicable: see section “Effects of Finishes on Fire Resistance Ratings.”

<sup>b</sup> Where combustible members are framed into the wall, the thickness of solid material between the end of each member and opposite wall face, or between members set in from opposite sides, must be at least 93% of thickness shown.

<sup>c</sup> Minimum required equivalent thickness corresponding to the hourly fire resistance rating for units made with a combination of aggregates shall be determined by linear interpolation based on the percent by volume of each aggregate used in the manufacture.
2. Column sizes

Masonry: for columns made with concrete having a specified compressive strength (f’c) of less than or equal to 12,000 Psi (82.7 MPa), the minimum dimensions shall comply with Table 722.2.4 of IBC:

Table 722.2.4 of IBC: MINIMUM DIMENSION OF CONCRETE COLUMNS (inches)

<table>
<thead>
<tr>
<th>TYPES OF CONCRETE</th>
<th>FIRE-RESISTANCE RATING (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Siliceous</td>
<td>8</td>
</tr>
<tr>
<td>Carbonate</td>
<td>8</td>
</tr>
<tr>
<td>Sand-lightweight</td>
<td>8</td>
</tr>
</tbody>
</table>

3D printed walls: Columns of 3D printed structures contain siliceous gravel as the aggregate type, whether constructed of concrete or 3D printed material. The overall dimensions of the columns in 3D printed walls are 8x10 in. Thus, columns of 3D printed structures comply with the requirements for a 1-hour fire resistance rating.

Reference: 722.2.4 of IBC

3. Minimum cover for R/C columns

Masonry: The minimum required cover over the vertical reinforcement is 2 in. (51 mm).

3D printed structures: Design of the 3D printed wall structure allows placement of the rebars in compliance with this section.

Reference: 722.2.4.2 of IBC

4. Bar size

Masonry: Typical single wythe walls correspond to a maximum bar size of No. 8, 9, and 11 for 8-, 10-, and 12- in. walls, respectively (M#25, 29 and 36 for 203-, 254- and 305-mm walls). In addition, the following limits apply:

a) maximum bar size is No. 11 (M#36);

b) the area of vertical reinforcement may not exceed 6% of the grout space area (i.e. about 1.26 in.\(^2\), 1.81 in.\(^2\), or 2.40 in.\(^2\) of vertical reinforcement for 8-, 10-, and 12-in. concrete masonry, respectively [815 mm\(^2\), 1,170 mm\(^2\), or 1,550 mm\(^2\) for 203-, 254- and 305-mm units, respectively]); and

c) for masonry designed using strength design procedures, the maximum bar size is No. 9 (M#29) and the maximum area of reinforcement is 4% of the cell area (i.e. about 0.84 in.\(^2\), 1.21 in.\(^2\), or 1.61 in.\(^2\) of vertical reinforcement for 8-, 10-, and 12-in. concrete masonry, respectively [545 mm\(^2\), 781 mm\(^2\), or 1,039 mm\(^2\) for 203-, 254-, and 305-mm units, respectively]).

3D printed structures: Design of the 3D printed wall structure allows selection of rebars in compliance with this section

Reference: “STEEL REINFORCEMENT FOR CONCRETE MASONRY” issued by National Concrete Masonry Association

https://ncma.org/resource/steel-reinforcement-for-concrete-masonry/
5. Corrosion

Masonry: A minimum amount of masonry covering the reinforcing bars is required to protect against steel corrosion. This masonry cover is measured from the nearest exterior masonry surface to the outermost surface of the reinforcement, and includes the thickness of masonry face shells, mortar, and grout. The following minimum cover requirements apply:

- Masonry exposed to weather or earth
  - bars larger than No. 5 (M#16) .........................2 in. (51 mm)
  - No. 5 (M#16) bars or smaller.......................1½ in. (38 mm)
  - Masonry not exposed to weather or earth … 1½ in. (38 mm)

3D printed structures: Design of the 3D printed wall structure allows placement of the rebars in compliance with this section.

Reference: “STEEL REINFORCEMENT FOR CONCRETE MASONRY” issued by National Concrete Masonry Association
https://ncma.org/resource/steel-reinforcement-for-concrete-masonry/

6. Joint reinforcement

Carbon steel can be protected from corrosion by coating the steel with zinc (galvanizing). The zinc protects in two ways: first, as a barrier separating the steel from oxygen and water; and second, during corrosion, the zinc is sacrificed before the steel is attacked. Increasing the zinc coating thickness improves the level of corrosion protection. Required levels of corrosion protection increase with the severity of exposure. When used in exterior walls or in interior walls exposed to a mean relative humidity of over 75%, carbon steel joint reinforcement must be hot-dip galvanized or epoxy-coated, or stainless-steel joint reinforcement must be used. When used in interior walls exposed to a mean relative humidity less than or equal to 75%, it can be mill galvanized, hot-dip galvanized, or stainless steel can be used. The corresponding minimum protection levels are:

- Mill galvanized—ASTM A 641 (ref. 16) 0.1 oz/ft² (0.031 kg/m²)
- Hot-dip galvanized—ASTM A 153 (ref. 17), Class B, 1.5 oz/ft² (458 g/m²)
- Epoxy-coated—ASTM A 884 (ref. 18) Class A, Type 1 ≥ 7 mils (175 µm) (ref. 3). Note that both the 2003 IBC and 2002 MSJC code incorrectly identify Class B, Type 2 epoxy coated joint reinforcement, which is not applicable for masonry construction.

Masonry: joint reinforcement must be placed so that longitudinal wires are embedded in mortar with a minimum cover of:

- ½ in. (13 mm) when not exposed to weather or earth
- ¾ in. (16 mm) when exposed to weather or earth.

3D printed structures: Design of the 3D printed wall structure allows placement of joint reinforcement in compliance with this section.

Reference: “STEEL REINFORCEMENT FOR CONCRETE MASONRY” issued by National Concrete Masonry Association
https://ncma.org/resource/steel-reinforcement-for-concrete-masonry/
SECTION 4
CONSTRUCTION SOLUTIONS

Having structural similarity between 3D printed walls and masonry walls proven, all construction techniques for 3D printed walls employed in roofing, foundation, etc., may be the same as used for CMU. Figures 18-21a demonstrates the following construction solutions: foundation, bond beam, installation a roof and lintels.
**Fig. 19 Bond Beam (CMU)**

- Bond Beam
- Vertical Reinforcement as required
- Horizontal Reinforcement as required
- Metal Lath, Mesh, or Wire Screen

**Fig. 19a Bond Beam (3D printed wall)**

- Bond Beam
- Vertical Reinforcement as required
- Horizontal Reinforcement as required
- Metal Lath, Mesh, or Wire Screen
Fig. 20 Lintels (CMU)

Fig. 20 Lintels (3D printed wall)
Fig. 21 Bond Beam and Roof (CMU)

Fig. 21a Bond Beam and Roof (3D printed wall)
Concrete Cylinder Field Test Results - Concrete Samples Fabricated and Tested per ASTM C-31, and C-39
Mortar Cubes Fabricated and Tested per ASTM C-109, Grout Prisms Fabricated and Tested per ASTM C-1019

The following is a report of laboratory test results for concrete cylinders, mortar cubes or grout prisms cast in the field. To correlate these results with field testing, simply match DATE CAST, and SET# with field inspection reports.

<table>
<thead>
<tr>
<th>SET #</th>
<th>SPECIMEN NUMBER</th>
<th>DATE CAST</th>
<th>DATE TESTED</th>
<th>AGE @ TEST</th>
<th>SIZE (in.)</th>
<th>TYPE</th>
<th>AREA (sq.in.)</th>
<th>DENSITY (lbs.cu.ft.)</th>
<th>MAX. LOAD (lbs.)</th>
<th>REQ'D COMPRESSIVE STRENGTH (psi)</th>
<th>TYPE OF FRACTURE (ASTM C39)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1A-AIR</td>
<td>8/7/19</td>
<td>8/8/19</td>
<td>24HR</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>2,990</td>
<td>420</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1B-AIR</td>
<td>8/7/19</td>
<td>8/8/19</td>
<td>24HR</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>2,700</td>
<td>380</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>1C-AIR</td>
<td>8/7/19</td>
<td>8/8/19</td>
<td>24HR</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>2,800</td>
<td>400</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>1A-WATER</td>
<td>8/7/19</td>
<td>8/8/19</td>
<td>24HR</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>2,980</td>
<td>420</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>1B-WATER</td>
<td>8/7/19</td>
<td>8/8/19</td>
<td>24HR</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>2,780</td>
<td>390</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>1C-WATER</td>
<td>8/7/19</td>
<td>8/8/19</td>
<td>24HR</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>2,700</td>
<td>380</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>1D-AIR</td>
<td>8/7/19</td>
<td>8/9/19</td>
<td>48HR</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>8,710</td>
<td>1,230</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>1E-AIR</td>
<td>8/7/19</td>
<td>8/9/19</td>
<td>48HR</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>8,800</td>
<td>1,240</td>
<td>5</td>
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<tr>
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<td>1F-AIR</td>
<td>8/7/19</td>
<td>8/9/19</td>
<td>48HR</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>8,620</td>
<td>1,220</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>1G-AIR</td>
<td>8/7/19</td>
<td>8/14/19</td>
<td>7DAY</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
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<td>8/14/19</td>
<td>7DAY</td>
<td>3.00</td>
<td>Cyl</td>
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<td>Cyl</td>
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<td>7DAY</td>
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<td>Cyl</td>
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<td>128.3</td>
<td>13,790</td>
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<td>1L-AIR</td>
<td>8/7/19</td>
<td>8/14/19</td>
<td>7DAY</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>13,090</td>
<td>1,850</td>
<td>5</td>
</tr>
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<td>1M-AIR</td>
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<td>11/5/19</td>
<td>90</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
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<td>21,400</td>
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<td>11/5/19</td>
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<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
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<td>2,790</td>
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<td>1O-AIR</td>
<td>8/7/19</td>
<td>11/5/19</td>
<td>90</td>
<td>3.00</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>19,900</td>
<td>2,820</td>
<td>5</td>
</tr>
</tbody>
</table>

Remarks: ________________________________

APPROVED: ___________________________
The following is a report of laboratory test results for concrete cylinders, mortar cubes or grout prisms cast in the field. To correlate these results with field testing, simply match DATE CAST, and SET# with field inspection reports.

<table>
<thead>
<tr>
<th>SET #</th>
<th>SPECIMEN NUMBER</th>
<th>DATE CAST</th>
<th>DATE TESTED</th>
<th>AGE @ TEST</th>
<th>TYPE</th>
<th>AREA (sq.in.)</th>
<th>DENSITY (lbs.cu.ft.)</th>
<th>MAX. LOAD (lbs.)</th>
<th>REQ'D f'c</th>
<th>COMPR. STRENGTH (psi)</th>
<th>TYPE OF FRACTURE (ASTM C39)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1M-WATER</td>
<td>8/7/19</td>
<td>11/5/19</td>
<td>90</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>25,640</td>
<td>3,630</td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>1N-WATER</td>
<td>8/7/19</td>
<td>11/5/19</td>
<td>90</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>23,180</td>
<td>3,280</td>
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<td>1</td>
<td>10-WATER</td>
<td>8/7/19</td>
<td>11/5/19</td>
<td>90</td>
<td>Cyl</td>
<td>7.07</td>
<td>128.3</td>
<td>26,420</td>
<td>3,740</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
Compressive Strength Testing according to ASTM C39/C39M-18

August 15, 2019

ASSOC. PROF.: KAY WILLE
PH.D. CANDIDATE: D. HENDRIX
CIVIL AND ENVIRONMENTAL ENGINEERING DEPARTMENT, UNIVERSITY OF CONNECTICUT
ADVANCED CEMENTITIOUS MATERIALS AND COMPOSITES (ACMC) LABORATORY
PHONE: 860-486-2074
EMAIL: KAY.WILLE@UCONN.EDU

For Nikita Cheniuntai, CEO
Apis Cor Engineering LLC
4 Park Center Ct, Suite 200-A, Owings Mills, Baltimore, MD 21117

August 15, 2019
Test setup

The objective of this experimental investigation is testing the compressive strength of concrete which was provided by Apis Corporation. A servo-hydraulic load frame of 400,000 lb load capacity was used to carry out the test. Figure 1 shows the test setup located in the Structures Laboratory (FLC 115) at the University of Connecticut. In accordance with ASTM C39/C39M-18 three cylindrical concrete specimens (designated with no. 4, 5 and 7) with a diameter of 3 inches and a height of 6 inches were tested at a concrete of 28 days. The specimens before and after failure are shown in Figure 2.

Figure 1 Compressive Strength Test setup
Figure 2 Specimens before and after testing

Test results

Table 1 summarizes the compression test results. The average compressive strength and standard deviation based on the three samples tested is $3.28 \pm 0.19$ ksi or $21.93 \pm 0.76$ MPa.

Table 1 Compressive Strength Test Results

<table>
<thead>
<tr>
<th>Specimen no.</th>
<th>Maximum Compressive Load (kips)</th>
<th>Compressive Strength (ksi / MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>24.66</td>
<td>3.49 / 24.1</td>
</tr>
<tr>
<td>5</td>
<td>22.19</td>
<td>3.14 / 21.6</td>
</tr>
<tr>
<td>7</td>
<td>22.64</td>
<td>3.20 / 22.8</td>
</tr>
<tr>
<td>average</td>
<td></td>
<td><strong>$3.28 \pm 0.19 / 21.93 \pm 0.76$</strong></td>
</tr>
</tbody>
</table>
October 30, 2019

Apis Cor Engineering LLC
2 Bowdoin Street
Apt. 324
Everett, MA 02149

Attn: Nikita Cheiuntai

EVALUATION OF CONCRETE MASONRY UNITS
Apis Cor-Lab Testing

DATE RECEIVED  July 15, 2019

SPECIMEN  Two hollow 3D printed block samples made by the above referenced project and delivered to our Rockland facility for testing.

METHOD OF ANALYSIS  Sampling and Testing Concrete Masonry Units
          ASTM C 1314.

RESULTS

<table>
<thead>
<tr>
<th>Specimen#</th>
<th>Age at Test (days)</th>
<th>Gross Area, in²</th>
<th>Net Strength, psi</th>
<th>Max Load, in.</th>
<th>Corrected Strength, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>65</td>
<td>74.11</td>
<td>2640</td>
<td>195820</td>
<td>2070</td>
</tr>
</tbody>
</table>

Respectfully submitted,

BRIGGS ENGINEERING & TESTING
A Division of PK Associates, Inc.

Sean Skorohod
Director of Testing Services
Construction Technology Division
October 30, 2019

Apis Cor Engineering LLC
2 Bowdoin Street
Apt. 324
Everett, MA 02149

Attn: Nikita Cheiuntai

EVALUATION OF CONCRETE MASONRY UNITS
Apis Cor-Lab Testing

DATE RECEIVED  July 15, 2019

SPECIMEN  Two 3D printed blocks made by the above referenced project and delivered to our Rockland facility for testing.

METHOD OF ANALYSIS  Sampling and Testing Concrete Masonry Units ASTM C 1314.

<table>
<thead>
<tr>
<th>RESULTS</th>
<th>Specimen#</th>
<th>Age at Test (days)</th>
<th>Gross Area, in²</th>
<th>Net Strength, psi</th>
<th>Max Load, in.</th>
<th>Corrected Strength, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A (Hollow)</td>
<td>112</td>
<td>85.73</td>
<td>2060</td>
<td>176330</td>
<td>1520</td>
</tr>
<tr>
<td></td>
<td>B (Grouted)</td>
<td>112</td>
<td>88.94</td>
<td>3010</td>
<td>267790</td>
<td>2230</td>
</tr>
<tr>
<td></td>
<td>AVG</td>
<td></td>
<td>2540</td>
<td>AVG</td>
<td></td>
<td>1880</td>
</tr>
</tbody>
</table>

Respectfully submitted,

BRIGGS ENGINEERING & TESTING
A Division of PK Associates, Inc.

Sean Skorohod
Director of Testing Services
Construction Technology Division

www.briggsengineering.com
October 30, 2019

Apis Cor Engineering LLC
2 Bowdoin Street
Apt. 324
Everett, MA 02149

Attn: Nikita Cheiuntai

EVALUATION OF CONCRETE MASONRY UNITS
Apis Cor-Lab Testing

DATE RECEIVED
September 17, 2019

SPECIMEN
Two 8”x8”16” C.M.U. samples made by the the above referenced project and delivered to our Rockland facility for testing.

METHOD OF ANALYSIS
Sampling and Testing Concrete Masonry Units ASTM C 1314.

<table>
<thead>
<tr>
<th>RESULTS</th>
<th>Specimen#</th>
<th>Age at Test (days)</th>
<th>Gross Area, in²</th>
<th>Net Strength, psi</th>
<th>Max Load, in.</th>
<th>Corrected Strength, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Hollow)</td>
<td>36</td>
<td>69.86</td>
<td>1740</td>
<td>121530</td>
<td>1260</td>
<td></td>
</tr>
<tr>
<td>B (Grouted)</td>
<td>36</td>
<td>119.14</td>
<td>3690</td>
<td>439350</td>
<td>2660</td>
<td></td>
</tr>
</tbody>
</table>

**AVG.**

2720

**AVG.**

1960

REMARKS

Respectfully submitted,

BRIGGS ENGINEERING & TESTING
A Division of PK Associates, Inc.

Sean Skorohod
Director of Testing Services

www.briggsengineering.com
EVALUATION OF 3D PRINTED PRISMS

REFERENCE NUMBER  M-31069
DATE TESTED  October 22, 2019
SPECIMEN  Two 3D printed prisms made by and delivered to our Rockland
Laboratory by others.
METHOD OF ANALYSIS  Specific Gravity, Absorption, and Voids in Hardened
Concrete ASTM C642.

RESULTS

<table>
<thead>
<tr>
<th>Sample</th>
<th>Absorption after immersion, %</th>
<th>Absorption after immersion and boiling, %</th>
<th>Bulk density, dry (g/cc)</th>
<th>Bulk density after immersion, pcf</th>
<th>Bulk density after immersion and boiling, pcf</th>
<th>Apparent density (g/cc)</th>
<th>Volume of permeable pore space (voids), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.8</td>
<td>16.8</td>
<td>101.6</td>
<td>117.7</td>
<td>118.7</td>
<td>139.9</td>
<td>27.4</td>
</tr>
<tr>
<td>2</td>
<td>16.0</td>
<td>17.3</td>
<td>101.0</td>
<td>117.2</td>
<td>118.5</td>
<td>140.4</td>
<td>28.0</td>
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<tr>
<td>Average</td>
<td>15.9</td>
<td>17.1</td>
<td>101.3</td>
<td>117.4</td>
<td>118.6</td>
<td>140.1</td>
<td>27.7</td>
</tr>
</tbody>
</table>

If you have any questions or if I can be of further service, please contact me at your convenience. Respectfully submitted,

BRIGGS ENGINEERING & TESTING
A Division of PK Associates, Inc.

Sean P. Skorohod
Director of Testing Services
Construction Technology Division

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100 Weymouth Street - Unit C-2
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Cumberland, RI 02864
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28
Flexural Strength of Concrete Using Simple Beam with Center-Point Loading according to ASTM C293/C293M

November 6, 2019

ASSOC. PROF.: KAY WILLE
PH.D. CANDIDATE: D. HENDRIX

UNIVERSITY OF CONNECTICUT
ADVANCED CEMENTITIOUS MATERIALS AND COMPOSITES (ACMC) LABORATORY
PHONE: 860-486-2074
EMAIL: KAY.WILLE@UCONN.EDU
Flexural Strength of Concrete Using Simple Beam with Center-Point Loading according to ASTM C293/C293M
Advanced Cementitious Materials and Composites (ACMC) Laboratory
University of Connecticut

November 6th, 2019

Test setup

The objective of the experimental investigation is testing the flexural strength of six concrete specimens provided by Apis Cor Engineering LLC according to ASTM C293/C293M-16. Following ASTM C293/C293M-16 procedure the specimens were aligned such that the span was 7 inches and the load was applied in the center of the span. The loading rate was 1 mm/min.

Test conditions - Summary

- Following ASTM C293/C293M-16
- Span: 7 inches
- Loading rate: 1 mm/min

Test results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>Max Load (N)</th>
<th>Displacement at max (mm)</th>
<th>Max Moment (Nm)</th>
<th>Moment of Inertia (mm$^4$)</th>
<th>Modulus of Rupture (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printed 1</td>
<td>33.5</td>
<td>33.2</td>
<td>357</td>
<td>1.11</td>
<td>15.89</td>
<td>104061</td>
<td>2.56</td>
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<tr>
<td>Printed 2</td>
<td>33.5</td>
<td>33.4</td>
<td>375</td>
<td>0.44</td>
<td>16.67</td>
<td>104562</td>
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<tr>
<td>Printed 3</td>
<td>33.3</td>
<td>33.4</td>
<td>437</td>
<td>0.31</td>
<td>19.44</td>
<td>102285</td>
<td>3.16</td>
</tr>
<tr>
<td>Avg. printed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.80 ± 0.32</td>
<td></td>
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<tr>
<td>Cast 1</td>
<td>32.7</td>
<td>32.9</td>
<td>329</td>
<td>0.60</td>
<td>14.62</td>
<td>96128</td>
<td>2.49</td>
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<tr>
<td>Cast 2</td>
<td>31.7</td>
<td>33.0</td>
<td>575</td>
<td>0.50</td>
<td>25.56</td>
<td>87242</td>
<td>4.64</td>
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<tr>
<td>Cast 3</td>
<td>32.4</td>
<td>32.8</td>
<td>632</td>
<td>0.53</td>
<td>28.08</td>
<td>92694</td>
<td>4.90</td>
</tr>
<tr>
<td>Avg. cast</td>
<td>32.4</td>
<td>32.8</td>
<td>632</td>
<td>0.53</td>
<td>28.08</td>
<td>92694</td>
<td>4.01 ± 1.32</td>
</tr>
</tbody>
</table>

The height and width were an average of two locations measured on each beam. The maximum load was recorded by a calibrated load cell during testing. The displacement of the beams was measured by the crosshead displacement of the test machine. The maximum moment is defined as

$$\text{Max Load} \times \frac{\text{Span}}{4}$$  \hspace{1cm} (1)
The moment of inertia is defined as

\[ \frac{1}{12} \times \text{Height}^3 \times \text{Width} \]  

(2)

The modulus of rupture is defined as

\[ \text{Moment} \times \frac{\text{Height}}{2} \times \frac{1}{\text{Moment of Inertia}} \]  

(3)

The load vs displacement is reported below in Figure 1 for the printed beams and Figure 2 for the cast beams.

![Graph showing load vs displacement for printed beams.](image)

Figure 1 Load vs displacement for printed beams
A visual representation of the cracking pattern for the printed beams and the cast beams is shown in Figure 3 a-c) and d-f) respectively. No preferred cracking between the printed layers could be observed. The cracking pattern of the printed beams was similar to the pattern of the cast beams.

Figure 2 Load vs displacement for cast beams

![Graph showing Load vs Displacement for cast beams](image-url)
Figure 3 A visual representation of the cracking pattern for the printed beams a) to c) and the cast beams d) to f).