Ready-Mixed Foamed Cellular Concrete as Engineered Backfill Material

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Conflict of Interest: Roberto Montemayor is the owner of a cellular concrete production and installation company (Concretos Protermic SA de CV) in Monterrey, Mexico.
1. ABSTRACT

Backfill materials can be excavated soils, granular materials, or cementitious flowable materials. Depending on the application, backfill materials require specific properties such as workability for placement, resistant to settlement, minimum strength, and durability. Backfill materials must distribute loads to reduce vertical and lateral pressures on adjacent or underlying infrastructure components as well as existing materials. Historically, backfill materials are susceptible to poor quality control, high material heterogeneity and segregation, erosion, and sometimes excessive strength. Foamed cellular concrete (FCC) offers an alternative engineered material that can achieve a specified density and compressive strength while still providing superior placement efficiency and durability relative to traditional backfill materials. The density of FCC ranges from 300 to 1800 kg/m$^3$ and is achieved by the incorporating a high volume but stable air system inside the cementitious paste. Likewise, the compressive strength of FCC can be tailored from 10 to 130 kg/cm$^2$. FCC can be batched using traditional ready-mix equipment and only requires cement, water, and a foaming agent. Admixtures are beneficial to improve workability and paste stability properties while maintaining a reasonable cost. Other benefits of FCC for backfill applications are self-compacting and self-leveling, lightweight for reducing overburden, pumpability, erosion resistant, and thermal insulating, which makes it attractive for utility and drainage trenches, void filling, support layer for pavement patching, and for filling abandoned conduits.
2. INTRODUCTION

Poor compaction, improper moisture content, and non-uniformity are common problems in backfill materials that lead to premature distresses or failure of pavements, utility cuts, trenches, retaining walls, and foundations. Backfills commonly apply inexpensive materials that are readily available, such as the in-situ soil materials, granular materials such as crushed aggregates or recycled materials, and flowable fills, i.e., controlled low strength materials (CLSM). Potential backfill materials should have consistent properties that allow proper compaction, quality control testing, and long-term stability and durability. Additionally, poor construction techniques such as inadequate equipment and construction processes could lead to early distress or failure even when using appropriate backfill materials.

Foamed cellular concrete (FCC) is an alternative cementitious backfill material that replaces traditional aggregates, soils, or CLSM with a cementitious paste with a high volume of air bubbles. FCC is a self-compacting, self-leveling, lightweight, and erosion resistant material that contains water, cement, and a foaming agent (Jinzhu et al., 2018). Furthermore, it can be produced in ready-mix concrete trucks consistently and its properties can be designed according to the project application and construction requirements. Figure 1 provides some examples of FCC applications and their benefits for roadways during new construction, rehabilitation, and maintenance.
This paper summarizes the main steps for production of FCC, the key properties of ready-mix cellular concrete materials for infrastructure backfill, and several civil engineering applications of FCC.

3. RESEARCH SIGNIFICANCE

Currently, the use of FCC for geotechnical-structural applications is mostly limited to large specialty projects because of the requirements for the batching and mixing systems as well as personnel training. The use of ready-mix concrete equipment to produce FCC is presented as an alternative and reliable option for infrastructure backfill applications.

4. FOAMED CELLULAR CONCRETE

Cellular lightweight concrete is a class of cementitious material whose fresh and hardened properties are primarily controlled by the quantity of air introduced into the paste. The density of cellular concrete usually ranges from 300 kg/m³ to 1800 kg/m³ and has been used for applications such as thermal insulation, dead load reduction, and lightweight fill (Raj et al., 2019). The two main types of cellular lightweight concrete are Autoclaved Aerated Concrete (AAC) and Foamed Cellular Concrete (FCC). Dr. Johan Axel Erickson from Sweden originally invented AAC, which consists of a blowing agent, such as aluminum oxide, to generate bubbles within the cement paste. This aerated concrete requires autoclave curing and thus, can only be applied to precast elements (Hebel Website, 2019). FCC emerged in the 1950s with the introduction of air-entraining agents (AEA). Surfactant molecules have a hydrophilic head and a hydrophobic tail (see Figure 2) and
reduce the surface tension of water, which allows stabilization of fine air bubbles in the cement paste (Torrans et al. 1968). With the introduction AEA technology, FCC can now be used for cast-in-place applications. Currently, FCC is primarily cast without coarse aggregates and most of the time without sand. Technically, it should be referred to as a mortar or paste, but it is known and commonly referred to as a type of “concrete,” i.e., foamed cellular concrete.

![Figure 2. Surfactant Molecules in Foamed Cellular Concrete](image)

The properties of cellular concrete are engineered to fulfill the project’s design and construction requirements through modification of the FCC’s density, foaming agents, and paste content.

**Density**

Density is the main parameter controlling the hardened properties of FCC as well as means of quality control and assurance. Figure 3 shows the relationship between the compressive strength and the density of FCC. Similar relationships have been established previously for thermal conductivity (Raj et al., 2019), impact resistance (He et al. 2019), and sound absorption (Stolz et al. 2018). Density of the FCC is controlled by increasing the volume of foam for a fixed set of constituents (cement, water, admixtures) and should always be verified onsite. Consistent field density measurements will result in a stable and homogeneous FCC placed at the construction site. High variability in the measured density could indicate instability in the foam system that will eventually lead to segregation, non-uniformity, and paste settlement.
Foaming agents

Foaming agents have similar appearance and texture to shaving cream and are added to the cementitious paste to incorporate the large volume of air bubbles that creates the foamed cellular concrete. Foaming agents can be natural, protein-based admixtures or synthetic-based admixtures (Raj et al. 2019). Protein-based admixtures are high molecular weight surfactants with excellent stability but are expensive and have limited compatibility with other chemical admixtures. The synthetic-based foaming agents are surfactants obtained from fatty acid derivatives with high foaming capabilities but lower stability. Nevertheless, synthetic-based foaming agents are significantly more economical and have a higher compatibility with other admixtures. Additionally, synthetic surfactants can be modified to create a high degree of connectivity between adjacent air bubbles in order to produce a highly permeable cellular concrete (Sutmoller et al. 2019).

Cementitious paste

The two parameters that control the workability and stability of the cementitious paste in FCC are the water/cement ratio (w/c ratio) and chemical admixtures. The cement paste needs to have the appropriate viscosity and cohesiveness to create and stabilize bubbles during the mixing, transiting, pumping, and placement process.
The w/c ratio plays an important role in the workability and stability of foamed concrete such that it is high enough to allow foam incorporation into the cement paste but low enough to prevent a loss in paste cohesiveness that could result in segregation and collapse of the FCC (Nambiar et al., 2008). When the paste viscosity and cohesiveness is not at the right balance in FCC systems, the “drainage” effect separates the liquid and air phases because of internal flow (Davis et al, 2012). Figure 4 shows an example of an unstable FCC sample, where, the cement paste (solids) settles on the bottom of the sample and the air bubbles float to the sample’s surface.

![Image](image_url)  
**Figure 4. Segregated Cellular Concrete**

Two helpful tests to determine the target workability of the FCC mix are the Marsh cone test and the flow cone test. The Marsh cone test evaluates the plastic viscosity of a liquid by recording the time taken for a specific volume to flow through an opening. For FCC, the recommended volume is 1 liter at an opening size of 12.5mm. The flow cone test provides a measurement of spreadability of a mix and should be tested according to the ASTM 230. FCC reference values for flow time are less than 20 seconds and a spread between 135mm and 240 mm with the flow cone test (Nambiar et al, 2008).

FCC can be produced with straight Portland cement, but chemical and mineral admixtures can significantly reduce the cost and dramatically improve the workability, stability, and final properties (Raj et al. 2019). Table 1 lists common admixtures used to improve the FCC properties.
Given there are interactions between various chemical and mineral admixtures with the cement paste, trial batches are required to verify the workability, bubble creation, and stability of the air system in FCC along with achieving the desired density and strength values.

Table 1 Foamed cellular concrete admixtures to improve workability, stability, and cost

<table>
<thead>
<tr>
<th>Admixture</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superplasticizer (Nambiar et al. 2008)</td>
<td>• Increase the workability of the mix with minimum segregation.</td>
</tr>
<tr>
<td></td>
<td>• Smaller dosages should be used to prevent strong repulsion between surfactant molecules.</td>
</tr>
<tr>
<td>Viscosity Modifier Admixtures (Davis et al. 2012)</td>
<td>• Improves the cohesion and plastic viscosity of the mix to minimize paste-foam segregation</td>
</tr>
<tr>
<td>Supplementary Cementitious Materials Fly-ash Type C</td>
<td>• Reduce the cost of cementitious materials.</td>
</tr>
<tr>
<td>Fly-ash Type F</td>
<td>• Reduce the heat of hydration</td>
</tr>
<tr>
<td>Blast furnace slag (Raj et al. 2019 and Nambiar et al. 2008)</td>
<td>• Increase compressive strength at 90 days</td>
</tr>
<tr>
<td></td>
<td>• Improves workability</td>
</tr>
<tr>
<td>Limestone Dust (Raj et al. 2019)</td>
<td>• Reduces the cost of mix</td>
</tr>
<tr>
<td></td>
<td>• Reduces shrinkage of paste</td>
</tr>
<tr>
<td>Sand (Davis et al. 2012)</td>
<td>• Good filler to increase FCC density</td>
</tr>
<tr>
<td></td>
<td>• Reduces the cost of the final mix</td>
</tr>
<tr>
<td></td>
<td>• Reduces shrinkage of paste</td>
</tr>
<tr>
<td>Fibers (American concrete institute, 2014)</td>
<td>• Increase cohesiveness of mix</td>
</tr>
<tr>
<td></td>
<td>• Reduce shrinkage cracks</td>
</tr>
<tr>
<td>Common chemical admixtures at ready-mixed concrete plants</td>
<td>• Accelerates or retards FCC setting times according to project needs.</td>
</tr>
</tbody>
</table>

5. PRODUCTION OF READY-MIXED CELLULAR CONCRETE

The ready-mixed concrete industry has an extensive infrastructure of more than 5,000 ready mix plants across the United States (NRMCA, 2019). These concrete plants already have storage for the constituent materials, batching control systems, trucks for mixing and delivery, and quality control expertise that are ideal for the production and discharging of foamed cellular concrete.
Figure 5 provides a schematic of the production of FCC using a ready-mixed concrete plant and transit truck. The four primary steps in producing ready-mixed FCC are discussed next.

![Schematic of production steps](image)

**Figure 5. Production steps of ready-mixed foamed cellular concrete**

**Step 1: Prepare concrete equipment and constituent materials**

*Equipment:* Ready-mix truck, material storage, and batching system.

*Location:* Ready-mixed concrete plant

The constituent materials are stored at the concrete plant. The concrete mixing trucks should be clean and free of any concrete or drum water from previous batches. Small chemical residue from previous mixes can act as anti-foaming particles that reduce the volume and stability of the foamed concrete.

**Step 2: Batching and mixing of constituents**

*Equipment:* Ready-mix truck and batching system.

*Location:* Ready-mixed concrete plant

The controlled batching system should begin the discharging sequence with water, followed by sand (if applicable), and then cement with a discharge delay of 2 seconds between each material. The discharging rate should be adjusted so that the cement discharge finishes first, followed by sand (if applicable), and finally the water (CON-E-CO, 2011). This sequencing strategy avoids
paste coagulation or material adhesion to the mixer walls. If the batching system can only discharge sequentially, a good practice is to start with 80% of the mix water and after all the other materials have been added, finish with the remaining 20% of water.

**Step 3: Foaming**

*Equipment:* Foam generator  
*Location:* Construction site (ideal) or ready-mixed concrete plant

The foam generating equipment mixes pressurized air with a surfactant and water to create the foam. The equipment should be calibrated to achieve the desired foam density, which is typically 32 to 80 kg/m$^3$ (Raj et al, 2019). The process of creating the foam consists of first diluting the foaming surfactant in water according to the supplier specifications. The solution is then charged to the foam generator until a workable and stable foam is created. Next, the foam is added to the drum mixer and mixed with the cementitious paste until the mix is homogeneous and proper wet density is achieved. The foam generator should have controls for airflow, air pressure, and solution flow rate to maintain foam density consistency within ±10%. The generated foam can be charged at the ready-mixed concrete plant. However, it is preferable to add the foam at the construction site to maximize air system stability and trucks can be filled up to 30% more volume at the site, i.e., 7m$^3$ to 10m$^3$ total volume, without the risk of drum leakage.

**Step 4: Discharging FCC on site**

*Equipment:* Mortar pumps  
*Location:* Construction site

Once the foamed concrete has reached the specified wet density, it can be directly discharged from the ready-mix truck to the backfill location or pumped to the appropriate site location. Pumping of FCC can use a regular concrete or mortar pump. To ensure the quality of the mixture, pump setup, and pressure settings, the FCC wet density should be checked before and after the pumping to detect any changes in density.

**Quality Control Testing for Density**

The dry density of foamed concrete is the key parameter for achieving the desired performance properties for a particular infrastructure application. To ensure the specified FCC mix is being cast-in-place, the wet density should be tested on-site and compared to the calculated density based on the mix design constituents and proportions. ACI’s guide for low-density concrete describes the procedure for testing the wet density of the foamed concrete on-site. First, a known volume of foamed concrete is accurately weighed to obtain the measured wet density. The calculated or target wet density can be obtained using the following formula.
\[ \rho_w = \frac{S + W + A + F}{V} \]

where,
\(\rho_w\) = calculated wet density of foamed concrete (kg/m\(^3\))
\(S\) = dry weight of all solid materials (cement, fly ash, dry fillers, etc.) in kg
\(W\) = mixing water weight, kg
\(A\) = chemical admixture weight, kg
\(F\) = foam weight, kg
\(V\) = target volume, e.g., 1 m\(^3\)

The on-site, measured wet density should be in a range of ±10% of the target (calculated) wet density of the FCC mixture design. Periodic tests are recommended to ensure the desired wet density is achieved and to adjust the mixture for temperature, humidity, and transit time changes.

6. INFRASTRUCTURE BACKFILL APPLICATIONS

The high flowability and typical absence of fine aggregates in FCC make it a highly workable material that is easily pumped, requires minimal compaction energy, and readily fills voids and excavated areas. FCC’s self-compacting and self-leveling properties reduces the need for specialized labor and equipment to obtain a stable backfill material at a prescribed density. The ability of FCC to fill voids makes it a viable alternative to CLSM and granular materials, which consists of much coarser constituents. FCC is designed to have air bubbles smaller than just 1mm. Figure 6 shows a cut section under magnification for an FCC sample with a density of 600 kg/m\(^3\). To date, FCC has seen limited public sector infrastructure applications, e.g., backfill material for utility cuts and patching, lightweight fill, trench backfill, abandoned utility and pipe filling, etc. However, several key advantages of FCC over traditional CLSM are the greater control over the material’s density and strength and lower potential for segregation and subsidence.
Figure 6. Cut section of FCC sample with density of 600 kg/m$^3$.

**Slope failure backfill example**

In August of 2016, an unstable soil resulted in a slope failure in the foundation for a new building under construction in Monterrey, Mexico. The slope failure caused unsafe construction conditions, significant economic losses, and an unstable soil wall that risked further damage to the new and adjacent buildings as seen in the Figure 7 schematic. For repairing the slope, engineers recommended precast concrete panels for constructing a retaining wall to decrease costs as much as possible (see Figure 8). The retaining wall solution included using a lightweight material to fill the gap between the precast concrete wall and unstable soil volume (see Figure 9).

Figure 7. Project before landslide (left) and after landslide (right).
Figure 8. Precast concrete panels for retaining wall (Montemayor, 2017)

Figure 9. Void between unstable soil and precast concrete retaining wall (Montemayor, 2017)
FCC was selected because of its lightweight, strength, and stability and it could be easily pumped with a flexible hose. The FCC flow value was high in order to fill voids between the precast panels as well as the unevenness of the soil wall. Another advantage of FCC on an unstable soil wall is to avoid any soil displacement created by the vibration energy of the compaction equipment. As per ACI recommendation, the FCC was placed in lifts of 60 to 120cm (Figure 10) with 1 to 2 hours between lifts to avoid internal collapse or settlement of the FCC.

Figure 10. Completed retaining wall (left) and placement of FCC lift (right)

Overburden and other lateral pressure applications

In conjunction with roads and bridge construction, retaining walls, large fills and embankments, and trenches for drainage and utilities require backfill materials to limit overburden and lateral pressures on various infrastructure components. The density, water retention, and strength of the backfill material plays an important role in the earth pressures generated on the retaining walls, fill/embankments, pipes, culverts, and utility ducts. Table 2 shows a comparison of materials and select properties used for backfills. Three different foam concrete densities are presented in Table 2 with respect to other backfill materials. Like geofoams, FCC can significantly reduce vertical and lateral pressures especially as the required backfill depth increases while still maintaining a strength that is greater than compacted soil or granular materials.
Table 2 Summary of backfills materials and select properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Compressive Strength (kg/cm²)</th>
<th>Permeability</th>
<th>Overburden Pressure for 3-meter height (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foamed Concrete</td>
<td>300</td>
<td>4.8-8.6</td>
<td>Low or high depends on pore connectivity</td>
<td>900</td>
</tr>
<tr>
<td>Foamed Concrete</td>
<td>600</td>
<td>24.1-31.0</td>
<td>Low or high depends on pore connectivity</td>
<td>1,800</td>
</tr>
<tr>
<td>Foamed Concrete (ACI, 2014)</td>
<td>900</td>
<td>20-51.7</td>
<td>Low or high depends on pore connectivity</td>
<td>2,700</td>
</tr>
<tr>
<td>Granular Base (Bethelot, 2004)</td>
<td>2000</td>
<td>0</td>
<td>Medium to High</td>
<td>6,000</td>
</tr>
<tr>
<td>Compacted Soil (Zhu, nd)</td>
<td>1800</td>
<td>0.5-10</td>
<td>Low to Medium</td>
<td>5,400</td>
</tr>
<tr>
<td>Traditional CLSM (Kuo et al. 2018)</td>
<td>1800</td>
<td>20-120</td>
<td>Very Low</td>
<td>5,400</td>
</tr>
<tr>
<td>GeoFoams (EPS Molders, 2019)</td>
<td>45</td>
<td>5.17</td>
<td>N/A</td>
<td>135</td>
</tr>
</tbody>
</table>

The permeability of the backfill is another important property to consider. Lateral pressures increase on infrastructure components and the shear resistance of the backfill material decreases as moisture content increases. Two ways to minimize earth pressures and loss in backfill strength are to collect and convey water before it infiltrates into the backfill or provide subsurface drainage to prevent water accumulation. Cellular concrete can be designed to produce low permeability through the addition of a closed-cell foaming agent. Alternatively, a more permeable FCC can be achieved with an open-cell foaming agent that will promote interconnectivity between the air system to allow water movement (Sutmoller et Al., 2019).

**Durability**

The durability of a backfill is defined as the ability of the material to continue to perform as intended when subjected to erosion, contamination, or changes in moisture and temperature. FCC offers improved protection against these factors compared to traditional compacted soil and granular materials.
Material erosion occurs when a hydraulic force from water flow or pressure, exceeds the local material capacity. Erosion action produces a loss of material (Service, 2006), which compromises the strength and stability of the backfill as well as the integrity of the infrastructure component. In streets and highways, the erosion of backfill material and subgrade can lead to subsidence, depressions, pavement cracking, and potholes. Depression, potholes, and sinkholes can also be created by significant subsurface erosion of backfill and soil material produced by leakage of water, sanitary, or stormwater pipes. On a recent highway near Mexico City, heavy rains and a poorly designed drainage system eroded the subgrade support of a highway, which resulted in a 5-meter deep sinkhole. The pavement did not show signs of deterioration and suddenly collapsed into a massive sinkhole that swallowed several cars, produced serious injuries, and compromised the serviceability of the road (Expansion, 2017). Even at lower densities, researchers have shown that FCC has superior erosion resistance compared to compacted soil (Li et al., 2018), and could have potentially slow down or prevented this severe erosion incident.

FCC has good erosion resistance, but it may be affected by contaminants (Jin Zhu et al., 2018). Hydrated cement paste is susceptible to chemical attacks that could be present in ocean water, sewer systems, stormwater drainage, atmospheric pollutants, or other industrial contaminants (Mindess et al., 2008). Chemical attacks are complex reactions, but they generally transform the hardened paste products and significantly reduce the bulk strength of the material. Similar to conventional concrete, FCC is susceptible to similar types of chemical attacks. Therefore, a thorough study must be conducted on the material performance for applications where contaminants are expected.

The porosity and saturation level of foam concrete is an important parameter to determine its durability in colder environments. Foam concrete has the advantage of very high air content that allows for the expansion of water and dissipation of hydraulic pressures. However, even high porosity materials can degrade under saturated conditions (Raj et al., 2019). One advantage of foamed concrete is that it provides very good thermal insulation, which minimizes rapid freezing or thawing. This thermal insulating property can protect utilities that are not below the frost line.

7. CONCLUSIONS

Foamed cellular concrete (FCC) is a class of cementitious materials that can be produced with different density, strength, and performance properties for a variety of infrastructure applications. FCC is made up of four main constituents: cement, water, foaming agent, and admixtures. The proportioning of these constituents achieves FCC with different densities and compressive strength as well as open or closed-cell cellular concretes. In addition, sand has been used to increase the density of FCC. The traditional batching system at ready-mixed concrete plants as well as transit
trucks can be used to produce and deliver the FCC material. One of the most important quality control measures is monitoring the wet density of FCC over time to ensure the specified material is placed as desired.

Ready-mixed cellular concrete technology is available now to produce, install, and control backfill material properties for a variety of infrastructure applications such as backfill for pavement patching, utility and trench backfill, fill/embankment material for roadway and bridges, and retaining wall backfill. The high workability, self-compacting, and self-leveling of FCC makes it a great choice for trenches and voids, abandoned utilities and ducts, and require less placement and compaction labor relative to traditional backfill materials. The relatively low unit weight and tailored porosity of FCC reduces the vertical and lateral pressures on the surrounding infrastructure components. Furthermore, its higher erosion resistance and thermal insulating capabilities relative to traditional backfill materials improve the protection in water conveyance systems and utilities especially in colder environments.
8. REFERENCES

American Concrete Institute. (2014). Guide for cellular concretes above 50 lb/ft³ (800 kg/m³). Farmington Hills, MI.


