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Cellular Concrete: Engineering and Technological Advancement for Construction in Cold Climates

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Abstract: Construction in cold climates often requires the use of innovative products to achieve appropriate, cost-effective solutions to engineering problems. Applications utilizing cellular concrete include the thermal insulation and structural support of utilities, natural gas pipelines, building foundations, above-ground storage tanks, roadways, and slabs with in-floor heating. Cellular concrete is also used extensively for grouting and void filling because of its low cost and high flowability. In addition, large volume lightweight fill projects often use cellular concrete to reduce loading on underlying compressible soils and/or eliminate the potential for liquefaction during earthquakes.

The use of cellular concrete often results in significantly better performance, faster construction, and reduced cost when compared to alternative construction materials and methods. Properties, case studies and advantages of cellular concrete are presented herein.

1. Introduction

With the looming requirements to reduce greenhouse gas emissions, greater energy efficiency in the production and use of hydrocarbons will increase to levels not contemplated today. The need for thermal insulation will expand at a tremendous rate in the near future. For construction of water handling utilities, roads, homes, commercial and industrial facilities in cold to extremely cold environments, cellular concrete can be used to great benefit. Not only can cellular concrete meet thermal insulation needs, but also the strength, extreme fire resistance, durability and ease of application, even in very cold winter conditions, makes cellular concrete insulation a very attractive choice.

2. Cellular Concrete Defined

Cellular concrete, sometimes referred to as foam concrete, is a lightweight construction material consisting of Portland Cement, water, foaming agent, and compressed air. The foam is formulated to provide stability and inhibit draining (bleeding) of water. Pozzolans, such as flyash, and fibers are often added to the mix to customize compressive and flexural strengths. Cellular concrete typically contains no sand or aggregate.

By trapping air bubbles within the concrete, a lightweight, insulating material is formed. It has fireproofing, insulation, sound attenuation and energy absorbing characteristics. Cellular concrete is either cast-in-place or precast; however, most applications call for a cast-in-place material.

Cellular concrete may be produced with wet densities from 250 to 1,600 kg/m³, with most below-ground applications being placed at wet densities of 400 to 600 kg/m³. The relationship between density, strength, and thermal conductivity for this range is as follows:

Table 1 - Typical Cellular Concrete Physical Properties

Wet Density	28-Day Compressive Strength	Thermal Conductivity	R Value per Inch
(kg/m³)	(MPa)	(W/m/K)	(°F•ft²•hr/Btu)
400	0.71	0.075	2.0
450	0.84	0.080	1.8
500	1.14	0.086	1.7
550	1.51	0.092	1.6
600	1.98	0.097	1.5

Cellular concrete is more durable when compared to traditional insulating materials, especially when considering potential chemical / fire exposure such as in process facilities. Compressive strengths are typically greater than four times that of plastic foam insulations.

3. Product Applications

Cellular concrete is being used in a wide variety of applications because of its lightweight, insulating, fire resistant, chemical resistant, and structural properties. Some of the most common applications are further described in the following pages.

3.1. Insulation of Shallow Utilities

3.1.1 Background

Pipes carrying water are often insulated when they cannot be buried below frost penetration depth. The reasons for shallow burial may include conflicts with other utilities, maintenance considerations, change of grade, high groundwater level, or high cost of blasting through solid rock.

The amount and configuration of insulation will depend on several factors such as climatic conditions, depth of burial, width of trench, soil type, moisture content, water temperature and flow rate in the pipe. For instance, the depth of frost penetration is typically less for saturated soil versus that same soil in a dry condition because of the latent heat released during freezing of water.

At some sites, exposure to petrochemicals is a concern. Selection of an insulating material must take into account durability issues. For instance, a known limitation of plastic foam insulation is degradation when exposed to even small amounts of hydrocarbons.

3.1.2 Case Study – Insulation of Fire Water Pipes

Shallow bedrock and groundwater prevented the economical deep burial of over 500 lineal metres of fire water pipes at a site near Fort McMurray. In some cases, pipes were buried with less than 1m of soil cover. Typical frost depths for the Fort McMurray region range between 3 and 4 metres below grade, depending on the soil type, moisture conditions, and snow cover. Therefore, insulation was required to prevent the pipes from freezing.

A horizontal layer of cellular concrete was placed over top of the pipes. The insulation width and thickness was determined based on the depth below grade. The major advantage in using cellular concrete on this project was the speed of construction. Plastic foam boards typically require extensive labour and

personnel to install. Cellular concrete is a cast-in-place material; therefore, it conforms to any undulations in the excavation. Also, cellular concrete is much more durable than plastic foam because of its higher strength and resistance to hydrocarbons.



Figure 1. Picture of Fire Water Insulation near Fort McMurray.

3.2. Roadway Insulation and Structural Support

3.2.1 Background

Wet silty soils exhibit extensive heaving when they freeze – upwards of one-third metre was observed at some locations in Alberta. In the spring, the soil thaws from primarily the top of the frozen layer. Excess pore water is not allowed to drain from the upper thawed zone because the underlying frozen soil is impermeable. This results in near saturated conditions at the surface, which substantially reduces the roadway structural capacity. This can also cause the subgrade soil to migrate into the overlying granular subbase, especially when the road is subjected to heavy truck traffic. The safety, structural capacity, utility, and durability of such roadways are severely compromised.

The benefits of using cellular concrete for construction of roadways are:

- Insulating value - By utilizing cellular concrete within the roadway structure, pavement damage from frost heave and spring thaw are substantially reduced.
- Superior structural properties - Use of Cellular Concrete as a pavement subbase material creates an extremely rigid pavement structure, thus extending the life of the pavement and reducing maintenance costs.
- Less cost - Cellular concrete replaces both the insulating and granular subbase materials; therefore resulting in significant monetary savings.
- Ease of placement - Cellular concrete may be cast on a rough excavation. Cellular concrete can be placed and levelled to exactly the amount of thickness required.
- Reduced excavation - Cellular concrete typically replaces two to three times its thickness of granular subbase; therefore, less underlying soil needs to be excavated.
- Protection from adverse weather – Placement of cellular concrete can protect the subgrade soils from becoming softened and disturbed during rainfall.
- Reduced subgrade disturbance - Placement and compaction of granular soil can result in disturbance and weakening of the underlying subgrade soils. Cellular concrete is self-levelling; therefore, it requires no compaction or vibration.

3.2.2 Case Study – Insulating, Heavy Duty Road Base

Transit buses exert heavy loading due to the single rear axle. A bus-lane in Calgary with traffic volumes of up to 100 buses per hour had frost-heaved substantially and became virtually impassable. The sub-base of the road was saturated silty deposits, over 30 m in depth. The subgrade soil had a California Bearing Ratio (CBR) of 0.8%.

In 2000, the road was completely reconstructed with the following structure:

- Geotextile fabric,
- 50 mm of drainage rock (with subdrains beneath the curb & gutter),
- 200 mm of Cellular Concrete (wet density = 475 kg/m³),
- 150 mm of granular base course, and
- 125 mm of asphalt.

Since construction, the road has experienced no frost-heaving or distress to the pavement. A Benkelman Beam Deflection Test resulted in 0.012 inches of deflection, much less than the 0.035 inches allowed for such a road.

3.3. Resource Sector

3.3.1 General

Addressing cold weather, during construction and through ongoing operations, is a reoccurring theme in the resource sector. Winter activities are typically mandated by having to rely on the freezing of otherwise soft soils to support the transport of heavy equipment and facility components. Also, many resource projects are located in the North, and thermal insulation for human comfort or process requirements is necessary.

3.3.2 Pipeline Insulation and Support

Hot oil or gas pipelines that cause thawing of underlying permafrost can be effectively insulated and supported using cellular concrete. In rocky conditions, cellular concrete padding can be used to protect pipe from damage during backfill and from rock falls. By providing a high performance bedding material to the pipeline, point stresses from differential movement of the pipeline can be virtually eliminated; therefore, the potential for stress corrosion cracking over time is substantially reduced. Also, above a pH of 9.4, steel can be passively protected from corrosion. The pH of cellular concrete can be formulated to be as high as 13.

Cellular concrete can play a multi-faceted role in pipeline insulation, padding, rigid-support and corrosion reduction. In cold weather, utilizing the high heat of hydration of cement can be beneficial for efficient construction.

3.3.3 Fire Protection

For resource production, processing and storage facilities, cellular concrete can be utilized for very effective fire protection. The fire resistance of cellular concrete is extremely high: better than ordinary concrete and in the order of ceramic, refractory materials. Cellular concrete can easily be pre-cast or poured around complicated shapes. At one-fifth the density of ordinary concrete, pre-fabricated pipe-racks and other modules can be transported and positioned more easily and with less expense.

3.3.4 Resource Roads

Cellular concrete road base material sometimes combined with geotextile fabrics and grids, can greatly improve constructability and durability of roads. The lightweight nature of cellular concrete can be utilized to 'float' roads over muskeg. With strength of up to three-times that of gravel, high load capacity can be obtained with cellular concrete base material. The insulation quality of cellular concrete can be used to prevent frost-heaving or protect underlying permafrost.

3.4. Above Ground Storage Tanks

3.4.1 Background

Above-ground welded steel storage tanks are commonly constructed on industrial sites for storage of a wide variety of fluids. These tanks can easily exceed 15m height and 30m in diameter; therefore, they exert a large load over a broad area. In petrochemical facilities, these tanks usually require a secondary containment liner be located underneath the tank. Many of these tanks operate at high temperature – therefore requiring insulation of the base to prevent damage to the liner and drying of the underlying soil – potentially resulting in excessive settlements. Cellular concrete commonly provides insulation, load reduction, and support for the tank in these situations.

3.4.2 Case Study – SAGD and Upgrader Tank Farms

Thirty tanks were constructed at a site in Northern Alberta. The operating temperature of these tanks ranged from 5 °C to 90 °C. The largest tank was 33.5 m in diameter and 17 m high. Without insulation, high temperatures would cause desiccation of the underlying soil, thus resulting in excessive tank settlements. Also, a high density polyethylene (HDPE) secondary containment liner was being placed beneath the tank. This liner was rated for a maximum sustained temperature of 60 °C.

For each tank, 100 mm of bedding sand was placed over top of the HDPE liner, followed by 475 mm of cellular concrete (wet density = 475 kg/m³) placed inside steel rings. This material was levelled to API-650 requirements. The above-ground storage tanks were placed directly on the cellular concrete.

This formulation of cellular concrete was the ideal balance between insulating value, strength, and cost. Typical insulating materials have extremely limited load bearing capacity. This often requires numerous structural layers to overcome these limitations, thus substantially increasing cost. The use of gravel to dissipate heat requires many metres of fill. Also, cellular concrete is produced onsite; therefore, transportation logistics and costs are substantially reduced in comparison to traditional insulating methods.

Many traditional tank bases incorporate a sand layer beneath the tank. During tank construction, this sand layer becomes disturbed. This often requires remedial activities such as grouting beneath the annular ring. Cellular concrete does not have this limitation since it remains in place during construction activities.



Figure 2. Cellular Concrete used for insulation below above ground storage tanks.

3.5. Frost Protected Shallow Foundations

3.5.1 Background

Under the *National Building Code of Canada* (National Research Council Canada, 1995), foundations must bear on soil below frost penetration depth. For heated structures with no insulation to limit heat from being wasted to the underlying soil, the bottom of the footings are typically placed 1.2 m below grade in the southern part of Canada, and increasing in depth towards the north—until regions of permafrost are reached. South of the permafrost, 3 to 4 m of annual frost is common. The cost of building deep foundations—or going less deep but allowing extensive heat loss to occur under the structure to prevent frost formation—can be high.

A less expensive frost protected foundation can be built using insulation laid horizontally around the perimeter of a structure with shallow footings. Further cost savings can be easily realized by providing adequate insulation under the floor of the structure. Cellular concrete insulation has been used for such shallow foundation / insulation systems. The density of cellular concrete typically used for this application is in the order of 475 kg/m^3 , with a compressive strength of 1.0 MPa and a thermal conductivity of 0.082 W/m.K. Once again, the support of cellular concrete insulation is better than fully compacted gravel. This means that the insulation can play a structural role in the foundation system, contributing to the economic efficiency. For many small to medium size structures, a thickened-edge-slab on top of the cellular concrete insulation is sufficient to complete the foundation.

If the building site is already frozen prior to construction, the shallow foundation can save significant cost and time by avoiding the cost and delay of ripping or thawing the entire building footprint, and then hoarding and heating poured concrete frost walls or grade beams. Modern glycol ground thawing equipment can be used to thaw narrow strips under only the perimeter of the building. After thawed strips just wide enough for the footings are prepared, the footings and perimeter shell of the building are erected. Then the ground on the inside of the insulated shell can be thawed very economically. Moreover, this method avoids much of the excavation work and the problem of obtaining unfrozen backfill material.

To satisfy the code requirement of obtaining bearing on moisture stable soil, the grade around the building should slope away at 2 % min., especially when building over clay (as always, all organic soil should also be removed prior to construction). This shallow foundation alternative can be especially useful when constructing in areas where high ground water may be encountered.

3.5.2 Case Study – Industrial Frost Protected Shallow Foundation

An owner/builder wanted to reduce construction and operating costs for a proposed manufacturing facility with in-floor heating.

A frost protected, shallow foundation was built by first removing the organic soil from the site, installing the plumbing services, and then placing a pad of cellular concrete (wet density = 475 kg/m^3) extending 1.2 m horizontally past the edge of the building. A thickened-edge, ordinary concrete slab on top of the cellular concrete insulation, completed the foundation.

The following reductions in cost were realized:

- Excavation - The only excavation required was to strip the topsoil and install the plumbing services.
- Heating costs - Thermal modelling predicted that the winter heating cost would be reduced by approximately 50%. The owner confirms that his heating fuel consumption is very low.
- Gravel costs - Gravel is normally required below a slab-on-grade; however, the cellular concrete provides support equivalent to two-to-three- times greater thickness in gravel, and satisfies all other code requirements.

3.6. Foundations on Permafrost

In permafrost areas, shallow foundation systems are generally the most economical, especially in situations where floor loads are high. Shallow foundations may be placed either at grade or on non-frost susceptible soil, such as a gravel pad: or cellular concrete when it is desirable to limit the impact of the structure on the underlying permafrost. Cellular concrete with a density of 475 kg/m^3 , compressive strength of 1.0 MPa, and thermal conductivity of 0.082 W/mK would typically be used for such an application. Once again, the cellular concrete not only provides insulation, but also superior bearing performance to granular material.

In areas where gravel is scarce, cellular concrete may be used as material for the entire building pad as it is non-frost susceptible. Structures may be elevated above the soil to form an air gap (using either shallow or deep foundation methods). Cellular concrete may be used in this instance to protect the underlying permafrost 'foundation' from seasonal frost effects and/or to provide a lightweight, insulating floor underlayment.

Subgrade cooling systems such as thermosyphons may also be used to reduce the thermal disturbance of the underlying permafrost. Typically, subgrade cooling systems consist of either passive or mechanical systems. Passive systems automatically begin to transfer heat out of the ground when the ambient air temperature falls below the ground temperature. These are typically charged with a refrigerant such as propane, carbon dioxide or ammonia. Mechanical systems require external power, and are generally comprised of either liquid or cold air refrigerant systems.

Thermal analysis for structures on permafrost is typically more intensive than for foundations in non-permafrost areas; therefore, finite element software programs are commonly used to model the combined effect of climate, building temperature, cellular concrete insulation configurations and subsurface cooling systems on the ground temperature regime.

3.7. Grouting and Void Filling

3.7.1 Introduction

The flowability of cellular concrete makes it an ideal material for filling irregular voids below ground. Typical injection pressures are less than 34 kPa (5 psi), which is much lower than traditional grouts. Cellular concrete is a compressible fluid; therefore, it can be placed under slight pressure during hydration to ensure complete filling of the void. If needed, cellular concrete grouts may be easily re-excavated.

Grouting and void filling applications for cellular concrete include:

- Abandoned pipes – Most municipalities will grout filled pipes abandoned beneath roadways. This is done to prevent potential subsidence of the roadway and reduce the risk of migration of contaminants, should a spill occur in the future.
- Soil cavities beneath roadways / rail lines – Tunnelling operations often cause voids to form in the soil adjacent to the casing. These voids must be filled to prevent settlement of the overlying structures.
- Voids beneath concrete slabs – Often, voids will form beneath concrete slabs-on-grade or roadways because of improper soil compaction, erosion, or use of frozen backfill soil. Traditional grouting methods cannot adequately fill these voids without coring several injection sites.

3.7.2 Case Study – Grouting Abandoned Utilities

Several water and sewer mains ranging from 200 mm to 1200 mm diameter with lengths of up to 270 m were abandoned beneath a roadway and proposed bridge structure at 50th Avenue and Crowchild Trail in Calgary, Alberta. Over time, the pipes could collapse and cause subsidence of the overlying structures. Also, if a contaminant spill were to occur, hazardous liquids could migrate along the pipes. The City of Calgary required that the abandoned pipes be filled with grout or completely removed.

Complete removal of the utilities was determined to be too costly and disruptive to traffic; therefore, cellular concrete (wet density = 475 kg/m³) was used to fill the abandoned water and sewer mains. Soil was placed at either end of the pipes to act as bulkheads and cellular concrete was pumped through 75 mm diameter injection pipes. Typically, cellular concrete was pumped from only one end of the abandoned pipes. Once cellular concrete was observed at the opposite end of the pipe, pumping was ceased. In this way, filling of the entire pipe was ensured.

3.7.3 Case Study – Void Fill

An existing power plant in Medicine Hat, Alberta was being changed from a traditional boiler fired plant to a combined cycle system. A surge tank was to be placed on the existing floor; however, plans were not available for the building; therefore, the piles, grade beam and structural slab were of unknown capacity. Also, holes cored in the concrete slab revealed a large void beneath nearly the entire slab. Soil testing indicated that the soil beneath the slab had a low bearing capacity.

The void beneath the slab was grouted with 500 kg/m³ Cellular Concrete. Because of the flowability that can be obtained with cellular concrete, only a single injection hole was required to completely fill the void. The structural slab was then cut away from the grade beam, so that it rested directly on the underlying cellular concrete. The cells were filled with the Cellular Concrete. The thickness was up to 3 m in some areas, placed in one pour. A 150 mm thick reinforced concrete pad was placed on top of the cellular concrete. The surge tank was placed on top of the slab.

In this way, the surge tank will bear its weight on the concrete and underlying soil, not on the existing piles of unknown capacity.

The alternative was to demolish this portion of the building and reconstruct the piles. Compared to this option, the cost of the project was reduced by approximately \$50,000 and saved roughly three months on the construction schedule.

If full density grout were used to fill the cavity beneath the slab, many more injection points would have been required. Also, full density grout would have added too much weight to the underlying weak soil.

3.8. Cold Weather Construction Material

The insulating nature of cellular concrete, combined with a significant amount of heat that can be generated within the material by the hydration reaction can be utilized to allow placing in extreme cold. In some cases the material can even be placed against frozen ground.

One of the keys to the cold weather success of cellular concrete is the high air content—as much as 75%. If cement, sand and gravel are stored in the cold, it takes approximately five-times as much heat to bring the materials to make ordinary concrete up to 5°C versus the materials to make cellular concrete. Then, as the cement generates heat, during the hydration reaction, the temperature gain within the material is dramatically accelerated in cellular concrete. The hydration reaction is exothermic—the evolution of heat raises the temperature, and the higher the temperature the faster the reaction proceeds, generating additional heat. Since cellular concrete typically has just one-fifth of the density of ordinary concrete, the temperature rise within cellular concrete will be five-times faster than for ordinary concrete. Also, the thermal conductivity of cellular concrete is approximately one-fifth that of ordinary concrete; therefore, the heat generated within cellular concrete is not carried away as readily is in ordinary concrete.

Cellular concrete is frequently placed in cold temperatures, with no more provision than placing insulating tarps over the material. When using cellular concrete as an insulating backfill material over a shallow water main, with air temperatures ranging from –15 to –25°C, compressive strength at 3 days in the field was equivalent to standard cylinder strength at 28 days in the laboratory.

When compressive strength between 1 and 5 MPa is all that is required, cellular concrete can save the cost of providing heat to cold weather construction.

3.9. Lightweight Fills

3.9.1 Background

The density of cellular concrete is typically in the order of 25% the density of soil or 20% the density of ordinary concrete. Therefore, Cellular Concrete can be used to reduce loading on compressible soils. Cellular Concrete will not liquefy during an earthquake, and it will not settle over time like standard soil backfill. Cellular concrete forms a rigid, free-standing body; therefore, it does not place lateral load on adjacent structures.

3.9.2 Case Study – Lightweight Fill (The Netherlands)

New shipping transfer stations were constructed on part of the country's river canal system. The stations were constructed on existing soft soil slopes by installing steel sheet piles for the quay wall and backfilling with cellular concrete to limit lateral loads on the quay and reduce future settlement of the terminal platform. The volume of cellular concrete utilized was approximately 3,000 cubic metres. The wet (cast) density was 475 kg/m³.



Figure 3. Picture of Lightweight Fill Project in The Netherlands.

3.10. Other Applications

Cellular concrete is used extensively for other geotechnical and structural engineering applications, as listed below.

- Energy absorption – Crash barriers are commonly constructed using cellular concrete. In fact, horizontal layers of cellular concrete are used to arrest passenger planes that overshoot the runway at various U.S. airports.
- Mine Backfill – Cellular concrete is commonly used to backfill abandoned mines to mitigate subsidence at the ground surface and/or prevent access by humans/wildlife to dangerous sections. (Boughrarou et al, 2005)
- Utility trench reinstatement - Cellular concrete does not settle over time, and its structural capacity is higher than gravel. If required, cellular concrete can be easily re-excavated. Therefore, cellular concrete is an ideal solution to the problem of trench reinstatement, especially where:
 - Compaction testing cannot be conducted due to safety reasons. Without compaction testing, compliance with specifications cannot be verified. For instance, cellular concrete is used extensively in Great Britain to avoid compaction and inspection issues during trench reinstatement (Jones et al, 2005). Quality assurance samples are safely taken above the excavation.
 - Close proximity of shallow utilities including gas, electrical, and fibre-optic lines prevent adequate compaction.
 - Compaction cannot physically be conducted. Because of its extreme flowability, cellular concrete fills small voids where regular compaction methods are impossible or impractical.

4. Summary

Cellular concrete provides improved methods of construction for shallow utility insulation, pipeline and tank support / insulation, frost protected shallow foundations, foundations on permafrost, grouting voids below ground, lightweight backfill, mine backfill, and energy absorption.

Typically, the use of cellular concrete results in a less expensive initial construction cost, and substantially reduced maintenance costs when compared to traditional construction methodologies. Often, much time is saved from the construction schedule.

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