Soft Soil Settlement Remediation and Roadway Elevation Increase with Permeable Low-Density Cellular Concrete (PLDCC)

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Abstract

This paper will address the feasibility of using permeable low-density cellular concrete (PLDCC) in soft soil remediation and roadway elevation applications. In this discussion, the paper will examine the case study of a project conducted at West Lake Eloise Drive in Winter Haven, Florida, and will also review and evaluate data from recent studies conducted at the University of Missouri - Kansas City related to the physical properties of PLDCC, including permeability, lightweight characteristics, compressive strength, and resistance to buoyancy. In its discussion of the West Lake Eloise Drive project, this paper will posit the effectiveness of 30-pcf (pounds per cubic foot) PLDCC in the remediation of settlement caused by soft soils as well as the proposed increase in elevation of roadways in areas that experience high water tables.

Introduction

Traditional techniques for the remediation of soft soil range from removal and replacement of poor materials to chemical stabilization or physical strengthening and have utilized a plethora of traditional backfill materials. Because of its unique physical characteristics, PLDCC provides a number of significant benefits in these applications, as can be seen in the highlighted West Lake Eloise Drive project.

Located between Lake Eloise and Lake Lulu, West Lake Eloise Drive in Winter Haven, Florida, is situated on low-level ground surrounded by water and marshes. West Lake Eloise Drive is designated as a collector road and carries approximately 4,000 vehicles a day. Figures 1 and 2 below (Madrid 2018) show maps of the site.

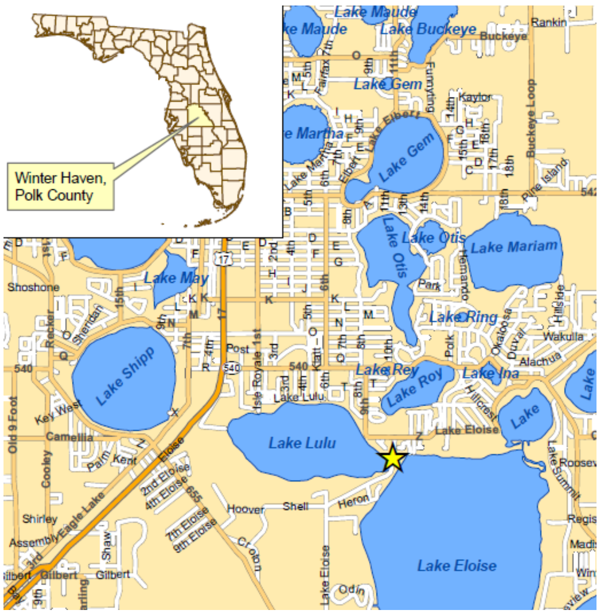


Figure 1 Site Map #1, West Lake Eloise Drive

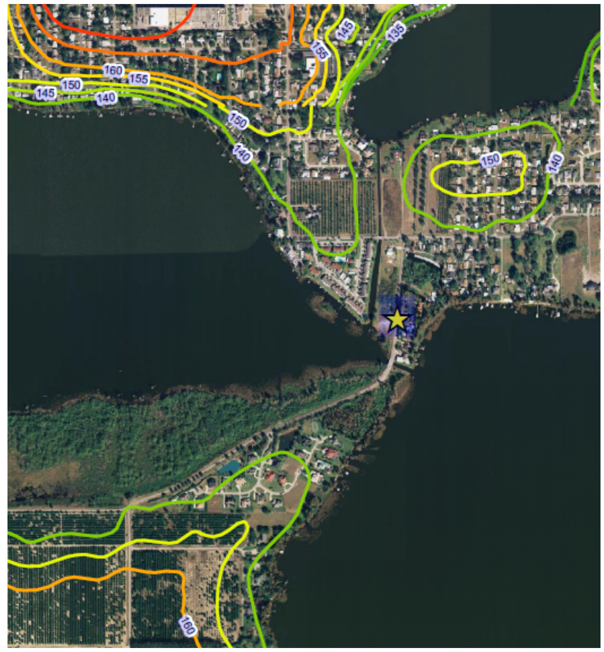


Figure 2 Site Map #2, West Lake Eloise Drive

Since being constructed in the 1940s, the roadway experienced continuous settlement with an estimated total settlement of more than four feet (at the worst location). The settlement occurred due to extremely soft, organic sub-soils consisting of peat and muck, which also led to seasonal flooding, road closures, and expensive maintenance and construction costs. During this time, approximately five layers of asphalt (with additional road base and fill soil layers) had been added to the roadway in attempts to mitigate the settlement and flooding issues. However, the weight of these additional layers caused further settlement. Figures 3 and 4 below (Aerix 2020) illustrate the extent of settlement and flooding that had occurred.

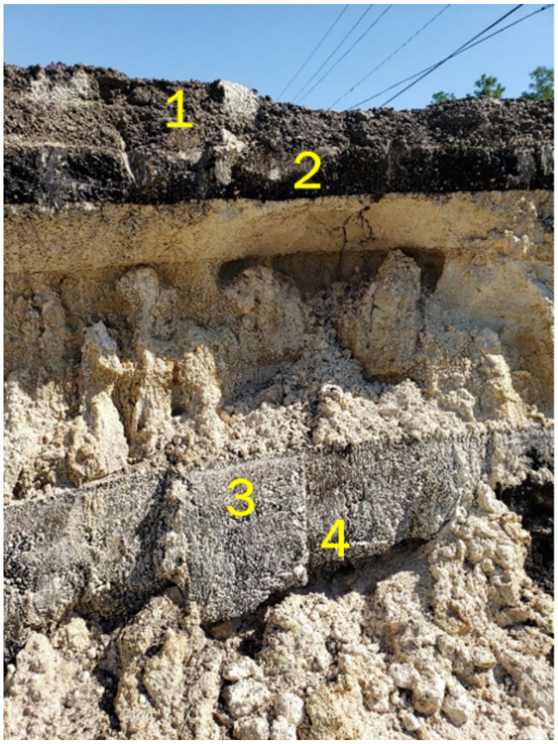


Figure 3 Existing and Prior Layers of Asphalt Ex. 1, West Lake Eloise Drive

Figure 4 Existing and Prior Layers of Asphalt Ex. 2, West Lake Eloise Drive

In 2017, Polk County decided that the roadway was in need of a more extensive evaluation and remediation. It was determined that the road needed to be at least one foot higher than its current elevation in order to eliminate flooding for all practical purposes. Adding more asphalt and increasing the embankment height using standard backfill materials, as had previously been done repeatedly, would have caused a new round of long-term settlement—it was estimated that one foot of new embankment height ultimately would have caused, at minimum, an additional six inches of settlement (and possibly more) based on the site's history. While the use of traditional backfill materials in this project would have increased the weight placed on the soft sub-soils and caused additional settlement, the lightweight, permeable characteristics of PLDCC presented a viable solution. The use of PLDCC would not only drastically reduce or eliminate future roadway settlement and facilitate the elevation of the roadway but would also address the high water table present on both sides of the roadway.

Project Considerations

PLDCC was chosen for West Lake Eloise Drive by Madrid Engineering Group, Inc. (Bartow, Florida) due to several unique project factors: the underlying soils of the roadway; the extremely high water table of the surrounding area; the need for a reduction in the load placed on surrounding soils to mitigate future settlement; the need for a higher roadway elevation; the need for a quick installation to avoid lengthy road closures; and the need for a highly permeable material that would facilitate a reduction in hydrostatic pressure (reduced buoyancy). While floodplain compensation would typically be required for this type of remediation project, the limited land and lack of right-of-way traffic within the Lake Eloise and Lake Lulu basins negated this option.

Prior to beginning any construction, Madrid Engineering conducted a soil survey map review, and found that, according to the Natural Resources Conservation Services (NRCS) Soil Survey reports, seasonal high water levels of an atypical depth were reported at this site. The NRCS defines seasonal high water as "a zone of saturation at the highest average depth during the wettest season that is at least six inches thick, persists for more than a few weeks, and is within six feet of the soil surface" (Madrid 2017). Through the completion of a comprehensive soil boring investigation of the site, Madrid Engineering found that the surrounding soil consisted of layered sand, peat, and muck soil types, including Arents-Urban land complex, Adamsville-Urban land complex, Samsula muck, and Hontoon muck. The boring test found layers of peat and organic silt up to 15 feet thick comprised of up to 90% organic material. The organic nature of these materials meant they were highly compressible and held an extremely high water content (with a much greater weight of water compared to solids). As the organic material continued to decay and shrink, the overlying soil and roadway began to settle. Based on these borings, it was clear that the compressible peat and muck were the cause of extensive settlement over time.

Figures 5 and 6 below (Aerix 2020) show a sample of the testing completed in Madrid Engineering's boring test.

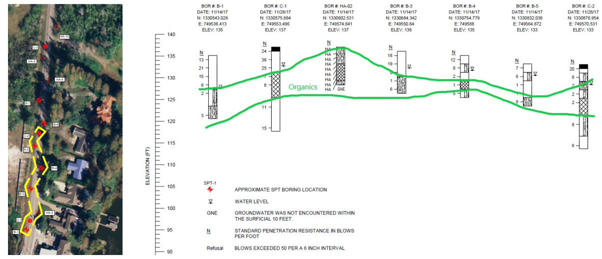


Figure 5 Boring Test Ex. 1, West Lake Eloise Drive

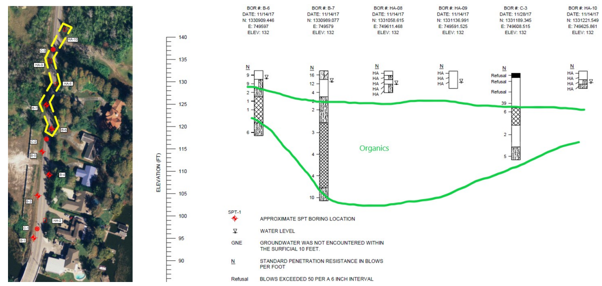


Figure 6 Boring Test Ex. 2, West Lake Eloise Drive

A surcharge to compress the underlying organics was considered but rejected because it would have taken several months to complete and the temporary embankment would have cut off the residents living adjacent to the road. This meant that lightweight fill was the only practical alternative to effectively increase the elevation of the road and prevent future flooding. Although there are several lightweight fill materials available on the market, PLDCC was chosen for this application because of its unique combination of engineering features and its price point. The following section of this paper further discusses the engineering characteristics of PLDCC.

Characteristics of Permeable Low-Density Cellular Concrete

There are a number of characteristics that made PLDCC an ideal solution for the West Lake Eloise Drive project. This paper will discuss those particular benefits as well as the characteristics that make PLDCC unique from other types of cellular concrete or flowable fill materials that traditionally might have been utilized on this type of project.

According to the ACI 523 Guide for Cast-in-Place Low-Density Cellular Concrete, LDCC is defined as "concrete made with hydraulic cement, water, and preformed foam to form a hardened material having an oven-dry density of 50 lb/ft^3 (800 kg/m^3) or less" (ACI 523.1R-06) (Aerix 2019).

While non-permeable low-density cellular concrete (LDCC) has been around since the 1940s, *permeable* low-density cellular concrete (PLDCC) is a relatively new innovation, coming to the forefront in the early 2000s. The unique characteristic of PLDCC, in comparison to its non-permeable counterparts, is that the bubbles used to produce the lightweight structure also link and allow retention and transmission of water at or above that of the native soil. It is because of its unique, permeable nature that PLDCC provides a compressive strength, stability, and flexibility unmatched by traditional fill materials (Aerix 2019).

Compressive Strength and Density

Compared to traditional backfill materials, PLDCC features a relatively high compressive strength. Due to the fact that it is manufactured with a foam generator, PLDCC contains air cells that can withstand the mixing and pumping inherent in the application process and even at a 30-pcf (481 kg/m^3) density, hardened PLDCC achieves a compressive strength that exceeds that of traditionally compacted backfill (Aerix 2019).

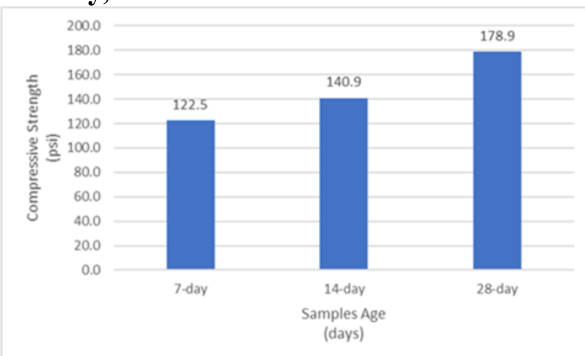
Table 1 below (ACI 2013) provides ranges of strength and density for typical cellular concrete materials. Of the mixtures shown, each contains a volume comprised of 70% to 75% foam (30 pcf [481 kg/m^3]), with compressive strength equal to or exceeding that of compacted soil. It is this mixture of high compressive strength and lightweight characteristics that make PLDCC an effective solution for soil remediation applications such as the West Lake Eloise Drive project.

Table 1 Cellular Concrete Material Strength and Density

Oven-Dry Density		Usual Range of Compressive Strength at 28 Days		Modulus of Elasticity	
lb/ft^3	kg/m^3	psi	MPa	10^3 psi	GPa
20 to 25	320 to 400	70 to 125	0.48 to 0.86	30 to 52	0.21 to 0.36
25 to 30	400 to 480	125 to 225	0.86 to 1.55	52 to 89	0.36 to 0.61
30 to 35	480 to 560	225 to 350	1.55 to 2.41	89 to 135	0.61 to 0.93
35 to 40	560 to 640	350 to 450	2.41 to 3.10	135 to 183	0.93 to 1.26
40 to 50	640 to 800	450 to 750	3.10 to 5.17	183 to 320	1.26 to 2.21

Table 2 below (CellFill 2020, WH-C495) shows the specific compressive strength and density of the PLDCC material utilized on the West Lake Eloise Drive project.

Table 2 PLDCC Material Strength and Density, West Lake Eloise Drive



Permeability

The coalesced cellular chemical structure of the foam concentrate in PLDCC mixtures make it highly permeable when compared to non-permeable LDCC, soil, or other traditional fill materials. (Refer to Table 3 below [Aerix 2019] for the rates of soil permeability, which range from 10^2 to 10^{-9} cm/sec.) Table 3 also notes the permeability rates of traditional fill materials, such as sand and clay, which generally range from 10^{-3} to 10^{-7} cm/sec. In contrast, PLDCC has a *minimum* permeability rate of 10^{-3} cm/sec (Aerix 2019).

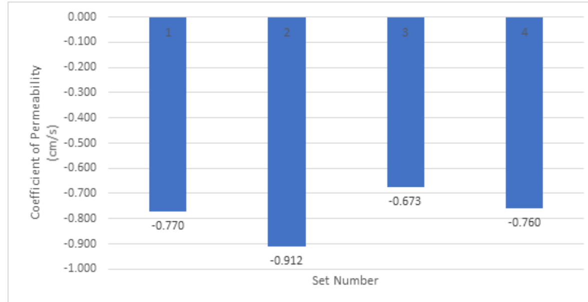
Table 3 Permeability of Backfill Materials

Coefficient of Permeability k (cm/sec) (log scale)

	10^{2} · 10^{1}	1.0 · 10^{-1} · 10^{-2}	10^{-3} · 10^{-4} · 10^{-5} · 10^{-6}	10^{-7} · 10^{-8} · 10^{-9}
Drainage	Good		Poor	Practically Impermeable
Backfill types	Clean gravel	Clean sands, clean sand and gravel mixture, **PLDCC**	Very fine, sand, organic and inorganic silts, mixtures of sand silt and clay, glacial till, stratified clay, **LDCC**	"Impermeable" soils, e.g., homogenous clays below zone of weathering

Graph 1 below (CellFill 2020, WH-D2434) highlights the permeability of the PLDCC samples tested at the West Lake Eloise Drive project.

Graph 1 Permeability of PLDCC, West Lake Eloise Drive

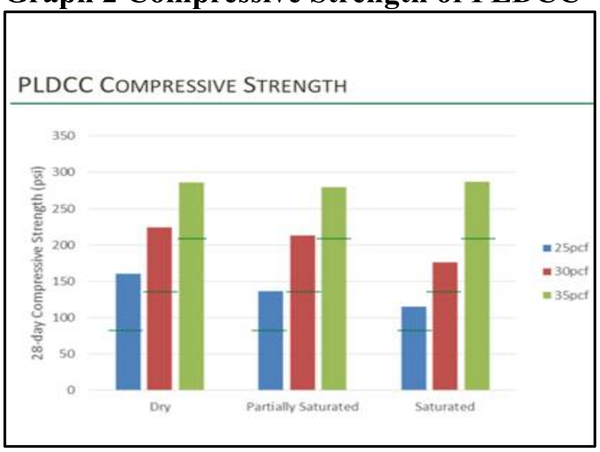


The use of PLDCC at West Lake Eloise Drive provided a unique advantage in facilitating the creation and maintenance of equilibrium between the water levels of the lakes on opposite sides of the roadway. The permeable nature of PLDCC meant that its replacement of the soft soils underneath the roadway would enable water from both sides of the road to filter through, which would reduce buoyancy and eliminate the potential for the PLDCC material to lift out of the ground. (It should be noted that the PLDCC used on this project has a lower density than water and, if not permeable, would have a much greater buoyancy force in high water conditions.) Additionally, the permeable nature of the PLDCC eliminated the need for the placement of cross-drains to equalize the water level between the lakes. Figure 7 below (Aerix 2020) shows this bi-directional movement of water through the PLDCC beneath the roadway.

Figure 7 Water Filtration through PLDCC, West Lake Eloise Drive

It is also important to note that the permeable properties of PLDCC do not negatively affect its compressive strength. With some permeable materials, permeability can reduce compressive strength as the material becomes more saturated. That is not the case with PLDCC, which maintains its compressive strength over time and through various levels of saturation, as is evident in Graph 2 below. The compressive strength of the PLDCC tested in this ASTM 28-day compressive strength study (UMKC 2018) remains constant when the material is dry, partially saturated, and fully saturated. Testing in this study was completed per ASTM C495/ C495M-12 Standard Test Method for Compressive Strength of Lightweight Insulating Concrete. The horizontal lines on the chart indicate the average ASTM strength requirement, which is exceeded in every case (Aerix 2019).

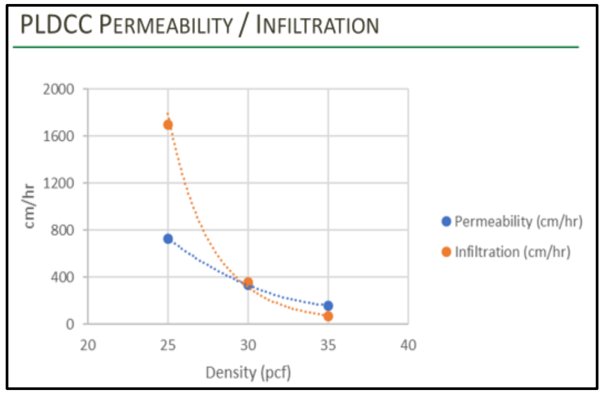
Graph 2 Compressive Strength of PLDCC



Hydrostatic Pressure and Buoyancy Reduction

The permeable characteristics of PLDCC can also contribute to significant reduction in below-grade hydrostatic pressure. Hydrostatic pressure decreases relative to the infiltration rate, which decreases relative to the permeability of the below-grade fill product. The permeability rate directly correlates to the infiltration rate of PLDCC, which reduces the potential for hydrostatic pressure. Graph 3 below (UMKC 2018) demonstrates this characteristic of PLDCC (Aerix 2019).

Graph 3 PLDCC Permeability and Infiltration Characteristics



This reduction in hydrostatic pressure leads to a reduction in buoyancy, which for the West Lake Eloise Drive project was an essential characteristic. The permeability of the 30-pcf PLDCC utilized in this project reduced potential buoyancy by providing 50% infiltration of water at 31.2 pcf. Figure 8 below (Aerix 2020) shows a unique typical section of the Lake Eloise project.

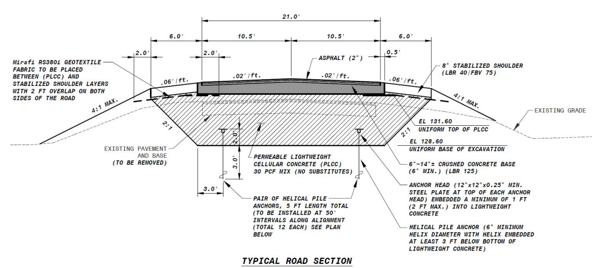


Figure 8 Typical Section, West Lake Eloise Drive

Madrid Engineering's calculations evidenced a 50% reduction in buoyancy for the PLDCC when saturated, which meant that a minimal amount of weight (pavement) would be required to be placed on top of the PLDCC to prevent the material from floating. If a non-permeable material had been used, significantly more weight (soil and pavement) would have been required.

Buoyancy "pressure" is assumed to be the density of water (62.4 pcf) minus the density of the PLDCC (30 pcf) times the saturated thickness at the design water level. For this project, an assumed 50% reduction in buoyancy resulted in the calculation of 62.4 pcf minus 30 pcf divided by two and multiplied by the saturated thickness. This assumed buoyancy must be balanced or exceeded by the weight or pressure of the unsaturated fill and pavement section existing above the design water level. Saturated density tests performed on samples of the PLDCC used on the project site reported a saturated density ranging between 60.3 pcf and 62.2 pcf on material that had been soaked in water for a period of one week.

West Lake Eloise Drive Application

The remediation of West Lake Eloise Drive began with dewatering the jobsite, which involved the placement of well pipes along the 470-foot-long portion of roadway. The well pipes were driven twelve feet underground and spaced six feet apart along both sides of the roadway. While dewatering was in process, the roadway was excavated and all existing material was removed, including many layers of sand, road base, and asphalt. The extreme settlement of the roadway was evident during the excavation in the fact that two-thirds of the excavation, toward the center of the roadway, terminated within an existing asphalt layer while outer portions of the excavation terminated in sand and limerock road base at the north end and exposed peat at the south end.

Once the excavation was complete, the PLDCC was pumped into the three-foot-deep excavated area at a rate of 160 cubic yards per hour. A total of just over 1,400 cubic yards of PLDCC was used at an approximate average thickness of 2.8 feet. Prior to pumping, helical anchors were placed in the excavation area to prevent any potential uplift that could occur during the construction phase in the case of a high-water event. Madrid Engineering completed pilot hole cores in the asphalt pavement at the bottom of the excavation to facilitate helical anchor installation and noted that pavement thickness at the bottom of the excavation ranged up to 18 inches (indicating the magnitude of previous settlement). The PLDCC was placed in a single lift in just nine hours over a two-day span, enabling construction to be completed much more quickly than would have been possible with the use of a traditional fill material. After the PLDCC was placed and fully cured, about eight inches of the crushed concrete road base was compacted, and a two-inch layer of asphalt base was placed on top. Figure 9 below (Aerix 2020) shows the completed roadway.

Figure 9 West Lake Eloise Drive, Completed

As can be seen in Figure 10 below (Aerix 2020), the placement of PLDCC, due to its permeability and lightweight characteristics, enabled both the mitigation of the site's water table and the effective elevation of the road grade by one-and-a-half feet.

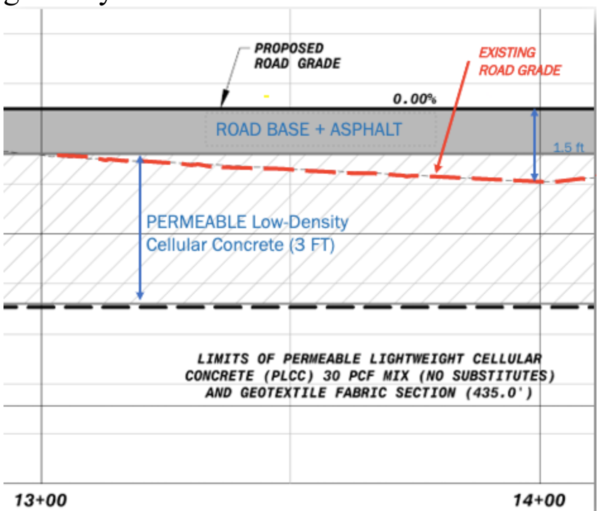


Figure 10 Typical Profile, West Lake Eloise Drive

Replacing the existing soils with PLDCC ultimately reduced the weight (pressure) placed on underlying organic soils by approximately 120 psf while allowing the embankment to increase in height by one-and-a-half feet. Removing the embankment soils and pavement removed approximately 330 psf (or more) of weight being placed on underlying soils, and placing approximately three feet of 30-pcf PLDCC and a layer of asphalt added only 210 psf. This meant that the new, remediated roadway placed only 210 psf of weight on underlying soils compared to the 330 psf (all values approximate) placed by the previous roadway.

Prior to the placement of PLDCC, the tops of the helical anchors were surveyed to be equal to the design height of the top of the PLDCC. However, at the start of the PLDCC placement, it was noted that the elevations at the base of the excavation appeared to be higher than the contractor previously thought, which meant that only about 2.5 to 2.7 feet (instead of the designed three feet) of PLDCC would need to be installed to meet the tops of the anchors. The decision was made to place about two inches of additional PLDCC above the tops of the anchors to ensure that enough lightweight material was in place to unload the area from its final loadings and that future settlements remained within expectations. Once the final crushed-concrete base layer was placed in preparation for the asphalt, the crews from Hubbard Construction surveyed the base and determined that it was on grade. However, by the end of these operations, some additional settlement was noticed and became cause for concern.

After additional investigation and discussions, the engineer concluded that the ground heave and later settlement were not long-term consolidation but rather rapid movement of the underlying peat, which had been unloaded and reloaded within a few days' time. This submerged peat layer has an extremely high water content, which causes it to act more as a fluid than a solid material. This type of movement is an immediate response to the loading and unloading of the roadway. In other words, when the excavation occurred, the underlying soft peat was unloaded and the base of the excavation heaved to its natural unloaded state. When the PLDCC and road base were placed, it moved back toward its natural loaded state. This type of movement occurs very rapidly and is different from compressive settlement, which occurs more slowly when water is squeezed out of the soil. This movement explains why the bottom of the excavation was about three inches higher than it was supposed to be at the start of the PLDCC placement. Due to the additional minor movement anticipated with the asphalt installation and final grading of the roadway, it was determined that the as-built survey would be completed at least two days after construction was finished. This as-built survey would serve as a baseline for annual monitoring of any additional settlement that might occur. While the initial cost of using PLDCC was higher than traditional remediation methods, Polk County expects that its use will reduce long-term maintenance costs for the roadway.

Summary and Conclusion

As evidenced by its unique physical characteristics—including high permeability, high compressive strength, resistance to buoyancy, and light weight—and its effective use in the West Lake Eloise Drive project, PLDCC is an ideal solution for soft soil remediation and roadway elevation applications, particularly in areas that experience high water tables.

One of the unique challenges in these types of applications, as noted in the West Lake Eloise Drive project, is that soft soils with an extremely high water content experience almost immediate heave during excavation, followed by a reverse settlement when final soil loads are placed. This means that the elevation levels measured between these steps in the process must account for this movement in order to ensure that the final grade elevation matches the proposed elevation. On these projects, particular care should be taken to avoid as much additional weight as possible—weight caused by either fill material or pavement—as this weight can further exacerbate soil and roadway settlement. For example, in the West Lake Eloise Drive project, if this movement wasn't taken into consideration, the mistake could have been made to install significantly less PLDCC, which would have resulted in reduced unloading of the soil and additional longer-term settlement.

When these essential factors are taken into consideration, 30-pcf PLDCC can be extremely effective in not only remediating settlement of soft soils but also enabling roadway elevation. Additionally, due to its resistance to buoyancy and high permeability, PLDCC effectively reduces hydrostatic pressure while facilitating water filtration, making it ideal for areas that experience high water tables.

Acknowledgements

This paper relies on research completed and data gathered by a number of industry professionals who must be acknowledged. These individuals include John Kevern at University of Missouri, Kansas City as well as the entire team at Hubbard Construction working on the West Lake Eloise Drive project.

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