Structural Evaluation of Pervious Concrete on Cellular Lightweight Permeable Concrete (CLPC) Base

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Abstract

An evaluation was made of the structural capacity of pervious concrete pavement on Cellular Lightweight Permeable Concrete (CLPC) base. Included in the evaluation was structural testing using the Falling Weight Deflectometer (FWD) on this pavement, as well as on other pervious pavements with virgin aggregate and recycled concrete bases. FWD tests were also performed on a conventional concrete (PCC) pavement with stabilized base. Using the PCC pavement as a benchmark for acceptable structural capacity, the maximum FWD deflections and the deflection profiles of the different pavements were analyzed by comparing the deflection data among the various pervious pavements and the conventional concrete pavement.

Results of the evaluation indicated that the pervious concrete pavement on CLPC has equal structural capacity to that of the previous concrete on aggregate base, and a higher structural capacity to that on recycled concrete base. The results also showed that the structural capacity of pervious concrete on CLPC base is equivalent to the structural capacity of PCC pavement.

Evaluation of construction and the test results suggests that the use of Cellular Lightweight Permeable concrete (CLPC) will speed up base construction time; save on transportation, labor and material cost, aid in the dissipation of surface water that drains through the pervious layer; and provide adequate support to the pervious pavement to carry low to moderate traffic, including local truck traffic, in city streets.

Background

Pervious Concrete is a concrete mix with little or no sand in the mix. The pervious mix can be made in different colors and aggregate sizes to produce different surface textures. The void ratio may reach or exceed 25% to allow rapid drainage of surface water. Pervious pavement has been specified in parking areas and sidewalks to maximize permeable surfaces in commercial and residential developments to preserve land otherwise used for detention/retention ponds, and to support traffic loads from cars and small trucks. It provides a much cooler surface compared to asphalt and PCC pavements, especially during night time, thus reducing energy consumption for cooling and lighting. Pervious concrete has been used in Florida since that early 1980s for parking pavements, base layers beneath conventional concrete pavements, and as edgedrain material for concrete pavements.

In recent years the use of pervious concrete in the US and other countries has increased as a result of heightened awareness to the need for more sustainable and green infrastructure. However its use has been limited in most applications to parking areas and sidewalks used for housing and commercial developments and office buildings. There has been some reluctance to expand its use to streets and roads due insufficient information related to its structural capacity to carry mixed vehicular and truck traffic, long term permeability, and surface durability to resist raveling.

The primary factors affecting the structural capacity of pervious pavement include; thickness of the pervious pavement layers; mix design; placement and compaction effort and uniformity; stiffness of the base and subgrade layers; and confinement along the pavement edges. As long as higher stiffness and strength is achieved in a fairly drainable layer, pervious pavement can be successfully used in streets and roads subjected to light and moderate truck traffic.

Designing a thicker pervious layer will contribute to stiffer layer capable of carrying more and heavier traffic. However, the pervious concrete mix needs to be designed for higher strength to contribute to greater stiffness. This can be achieved by including a larger paste fraction, and possibly incorporating some sand in the mix. While losing some voids in the previous matrix, the mix will produce a stronger and stiffer layer.

Proper and uniform placement and Compaction of the pervious mix are important contributors to a stronger and stiffer pervious layer. This can best be achieved by using machines to place and compact the pervious layer. However, traditional manual placement and compaction can achieve fairly uniform strength and stiffness across the entire pavement, provided that a consistent mix is produced in every batch, and the use of reliable compaction equipment that imposes adequate and fairly uniform consolidation. Segregation and uncontrolled water content in the mix will introduce pockets of weakness and inconsistent compaction in the pavement. Proper curing will also achieve more durable surface that may resist aggregate raveling.

Another essential element to the success of pervious pavements for streets is properly designed and constructed stiff and drainable base layer. Stabilized granular materials, virgin aggregate and recycled concrete, and Cellular Lightweight Permeable Concrete (CLPC) are among the best base materials that provide proper stiffness and adequate draining capacity.

Confinement by the curb along the edges of the pervious pavement will add structural support to prevent damage to the edges and the entire pavement from the heavy truck wheels. The curb also reduces aggregate raveling along the edges of the pavement.

A study was initiated to evaluate the use pervious concrete pavement for streets as a green alternate to other types of pavements. Five test sections and a parking display area were constructed in Jacksonville, Florida using variable pervious pavement thickness on different base types. One major components of the study was to evaluate the structural capacity of pervious pavements on various base types using the Falling Weight Deflectometer. The focus of this report is on the evaluation of the structural capacity of pervious pavement on cellular permeable light weight concrete (CPLC) base compared to aggregate and recycled concrete bases, and to a conventional concrete pavement.

Objective

The primary objective of the report is to evaluate Structural capacity of pervious concrete pavement on Cellular Lightweight Permeable Concrete base as compared to aggregate and recycled concrete bases as well as to conventional concrete pavement. This study is part of larger ongoing effort to evaluate the use of pervious concrete pavement for streets to carry low to moderate truck traffic.

Cellular Lightweight Permeable Concrete

Cellular Lightweight Permeable Concrete (CLPC) is light weight concrete produced by injecting a preformed foam into a cementitious slurry composed of cement slag and fly ash can be used as a cement replacement. The water to cement ratio is approximately 0.5. Injecting the foaming agent produces air bubbles that allow expansion of the cementitious paste volume by 300%.

The CLPC is pumped into the prepared area to build the base layer. The layer thickness can range from 4 inch to 6 inch (100 mm to 150 mm). The density of the mix after foam injection ranges from 30 pcf to 45 pcf (480 kg/m^3 to 720 kg/ m^3). The CLPC and can produce a minimum strength of 160 psi 1.1 Mpa. The open cell structure of CLPC and the additional detention capacity enable the storm water runoff to enter the native soil at a more controlled rate.

Pervious Pavement Test sections

Five pervious concrete test sections and a parking display were constructed at a testing facility inside the concrete batch plant of the Florida Roads and Materials (FRM) in Jacksonville, Florida. The test sections and parking display, and subsequent testing and evaluation were part of an overall plan to develop new applications for pervious concrete for streets and improve their performance in parking areas. The effort was a partnership among FRM, Cellular Concrete solutions, Pro-Crete Systems, Continental Cement, A-N Concrete and Global Sustainable Solutions. The work described in this report represents an important part of this extensive effort.

Design

The design of the parking display includes a 4 inch (100 mm) pervious concrete pavement placed on top of a 6 inch (150 mm) Cellular Lightweight Permeable Concrete (CLPC) and 6 inches of size 57 graded aggregate base layers, as shown in Figure 1. The pervious concrete was placed in three section using red, gray colored mixes on CLPC and tan colored mix on the aggregate base. Pervious concrete bricks were also used in the display to separate the sections. The display parking has been used to show to potential clients its esthetic features and demonstrate its ability to drain water in an efficient and timely manner.

The five test sections were designed as an 8 inch (200 mm) pervious concrete on three different base layers. Three sections of the pervious concrete were placed on 6 inch size 57 graded aggregate base. The fourth section was placed on 6 inch CLPC, and the fifth section had a 6 inch recycled aggregate base. The five sections were placed in sets of two and three sections, as shown in Figures 2 and 3. The PCC pavement which is used as a reference section is 10 inch (255 mm) thick conventional concrete pavement supported by at least 12 inch (300 mm) stabilized soil base.

Construction

The five test sections and the parking display were constructed in an open area inside the concrete batch plant facility of FRM. Pervious concrete and CLPC mixes were batched and prepared inside the plant.

Prior to construction, the site of the test sections was grubbed and compacted. Tests showed that the compaction achieved an average of 98% density. Concrete curbs were constructed along edges of the test sections prior to construction as shown in Figures 2 and 3. This was to provide edge support to the edge of the pervious concrete and increase its structural capacity.

Construction was completed in three stages. The Display parking area was constructed first. Three strips of 4 inch thick colored pervious concrete were constructed. Two strips were placed on 6 inch CLPC, and the third was placed on 6 inch size 57 aggregate (20 mm top size) base as shown in Figure 1.

The second stage included construction of two 12ft X 20 ft adjacent test sections (TS1 and TS2) as shown in Figure 2. In each test section, 8 inch pervious concrete was placed on 6 inch aggregate base. One of the test sections was cured conventionally using plastic sheet cover with intermittent water curing. The second test section was cured using Lithium Cure as will be explained below.

The third stage included three 20 ft X12 ft test sections (TS3, TS4 and TS5) as shown in Figure 3. The base layers for the test sections included CLPC (TS3), size 5 aggregate (TS4), and recycled concrete (TS5) materials, respectively, as shown in Figure 4. All base layers were 6 inches thick. Pervious concrete was placed as continuous pour on the three base layers. The thickness of the pervious pavement ranged from 8.5 to 10 inches . The pavement was cured using Lithium Cure.

The size 57 limestone aggregates for the base layers was transported to the construction site from a nearby aggregate terminal. The recycled concrete material was available onsite. The CLPC was produced on site as explained below.

Every aspect of the construction included a green and/or sustainable material or process, including mix design ingredients for the pervious concrete and CLPC; the use of recycled concrete material for base; and the use application of a more environmentally friendly Lithium Cure instead of plastic sheets.

Cellular Lightweight Permeable Concrete (CLPC) Base

A cement and slag slurry was used- for the- CLPC. The slurry was batched and then mixed inside a concrete truck. The mix design for the slurry was a 50/50 ratio of cement to slag with water to cement ratio of 0.5. The slurry was transported to the test section site where Cellular Concrete Solutions pre-formed foam was placed into the slurry with inline system by Pro-Crete, as shown in Figures 5. Since the foam increases the volume of the slurry by 300%, the use of inline system is more efficient than placing the foam directly inside the drum of the truck mixer. This reduces the number of trucks needed for a placement task, which reduces carbon emissions.

The CLPC was pumped on previously prepared and compacted subgrade for the parking display and TS3. At TS3, a 3-inch (75 mm) diameter rubber hose was used to build up a 6 inch thick

CLPC base as shown in Figure 6. It took about 15 minutes to build the 6 inch CLPC base in the test section. This is considered a very fast and efficient process to place a base layer that does not require any compaction or curing, this reduces labor cost. The wet density of the mix was 32 pcf (512 kg/m^3). The compressive strength that corresponds to a dry density of 28 pcf is estimated at 150 to160 psi according to data in the Technical Bulletin FC715-0702 of Cellular Concrete Solutions mix design chart.

Aggregate Base Layers

The other base layers used included 6 inch size 57 virgin aggregate, which was used in TS1, TS2 and TS4. In TS5 concrete recycled material was used as the base layer. The recycled material included all aggregate sizes including fines that were produced from the crushing of the parent concrete members. This may have affected the stiffness of the base and structural capacity of the pavement. Removing some of the fine material will provide better compaction and produce a stiffer base.

The pits for the four test sections were grubbed, compacted to 98% density, and graded prior to placement of the base material. The aggregate and recycled concrete base layers were placed and then compacted using a Wacker vibratory compactor. It should be noted, that during placement and compaction of the aggregate and concrete recycled material, the surface elevation of the base layers changed which caused variation in the pavement thicknesses in the respective test sections as compared to the original thickness design of 8 inches.

Pervious Concrete Pavement

The pervious concrete mix included a 660 lb/yd^3 (390 kg/ m^3) (blend cement and slag with water to cementitious ratio of 0.26. Size 89 graded limestone aggregate (10 mm top size) and used in the mix. In addition, small quantity of sand was added to the pervious mix to increase its strength. Air entraining and retarding admixtures were used to maintain proper flow and improve consistency.

The mix was batched in the truck mixers of FRM where the ingredients were mixed to proper consistency and flow. The truck mixers backed into the pits to discharge the pervious mix. The heavy wheels of the ready mix truck caused one to two inch ruts in both the aggregate and recycled concrete bases. The CLPC base layer exhibited less rutting as shown in Figure 7. This could have been avoided if the trucks had enough space along the side of the pits to discharge the pervious mix. It should be noted that the weight of the truck mixer was 67,000 lb. The weights on front single and back tandem axels were 22,000 lb and 45,000 lb respectively. Rutting of the base is expected under such concentrated heavy wheels.

The truck mixers discharged the pervious concrete mix as shown in Figure 8. The mix was spread manually and then compacted using a vibratory roller screed. A hand held roller was used to correct any imperfections in the finished surface.

Lithium Cure

Four of the five test sections were cured with Lithium cure. Test section one (TS1) and the parking display were cured with plastic sheet cover.

Lithium cure is a clear solution with Lithium Silicate as its main active ingredient. Lithium Silicate penetrates the paste surface and possibly engages in reaction with the hydrated products. A film is formed on the surface of the pervious concrete which preserves moisture and provides the necessary curing to the pervious concrete pavement without the need to supplement curing with a plastic sheet cover. Lithium cure was applied at an application rate was 200 ft^2/gal (5 m^2/Lit) as soon as the sheen disappeared from the surface. A hand held sprayer was used to spray the lithium cure as shown in Figure 9.

The use and evaluation of the Lithium Cure was an attempt to introduce additional “green” element to the construction of pervious concrete. Lithium Cure has no resin, is zero Volatile Organic Compounds (VOC) and is GreenGuard® product for indoor air quality. Use of lithium Cure will eliminate the need for plastic sheets to cure pervious concrete. This will save disposal cost and contribute to preserving landfill space.

Tests and Evaluations

The primary goal of the study was to elevate the application of pervious concrete pavements from parking areas and sidewalks to streets that can handle low to moderate mixed traffic including truck traffic. The evaluations and testing of the pervious sections at the FRM facility, using different base layers was a major effort to achieve that goal. The tests included structural testing of the pavements sections using the Falling Weight Deflectometer (FWD). The ultimate goal of testing is to develop pervious concrete pavement design charts for streets with the mixed traffic. The other evaluation was to visually assess the effectiveness of the pervious mixes, and impact of the construction techniques on the efficiency of the pavement in draining surface water in a timely manner.

Structural Capacity

Three test sections, TS3, TS4 and TS5, were subjected to tuck loading after four days from applying the Lithium Cure. The traffic included concrete truck mixers of the FRM batch plant as shown in Figure 10. Close to 1,000 passes were made on the test tracks using empty and fully loaded trucks. It should be noted that each fully loaded and empty truck weighed 67,000 lb and 29,000 lb (30,000 and 13,000 kg) respectively. Also, in a fully loaded concrete truck, the steering and drive axles are loaded to 22,000 lbs and 45,000 lbs (9,900 and 20,000 kg), respectively.

Despite the heavy axle loads, no cracking was observed in any of the three test sections. It can be assumed that critical stresses were not reached to cause cracking. The good performance of the three test sections is attributed to a number of factors including, thickness of the pervious pavement, strength of the mix, stiffness of the base layers, and edge support along the curbs.

It was also encouraging to observe that very little aggregate raveling occurred on the pavement surface despite the heavy truck traffic. The pervious mix ingredients and strength, as well as adequate compaction may have reduced the raveling to a minimum.

Structural Testing Using the Falling Weight Deflectometer

Following the truck loading of the three test sections, the Falling Weight Deflectometer (FWD) was performed on the five test sections, the parking display and the 10 inch conventional concrete slab representing the pavement area of the batch plant.

The FWD is a non destructive testing machine used to evaluate the structural capacity of pavements for design and rehabilitation purposes. The testing unit includes a stack of load plates that are raised to different elevations and dropped on rubber buffers to generate various loading levels on a 12” (30 cm) load plate which is placed on the surface of the pavements. The FWD load ranges from 1,500 lbf to 27,000 lbf (7kN to120 kN). A total of 9 geophones are used to measure deflections from the FWD loads. The geophones are placed at the center of the load plate and at various distances starting at 8 inch (200 mm) to a maximum distance 60 inch (1,500 mm) from the plate. The maximum deflection is measured at the center of the load plate, and is a combined response of the pavement system including the surface and support layers. The outer geophones tend to measure the stiffness of the support layers.

Core samples were obtained from the five test sections to measure the true thickness of the pervious pavement prior to performing the FWD. The core thickness values are shown in Table 1. The thickness of the pavement of the parking was measured and confirmed to be 4 inches.

The FWD tests were performed at two points in each test section and parking strip and PCC slab. A typical FWD testing is shown in Figure 11. Average FWD impact loads of 30, 40, 53, and 65 kN or (7,500, 10,000, 12,000 and 16,250 lb), which correspond to 430, 570, 750 and 930 kpa (62, 83, 110 and 134 psi) pressure, were applied at each test point. Deflections were measured at 0, 200, 305, 460, 610, 915, 1,220, 1,525 and 1830 mm or (0, 8”, 12”, 18”, 24”, 36”, 48”, 60” and 72”) from the center of the load plate.

The stress and maximum deflections for the five test sections and PCC slab are shown in Figure 12. Typical the deflections for FWD 750 kpa loading are shown in Table 1 and Figures 13 and 14. The deflections trends were similar for all other FWD load levels.

The stress and deflection relationship was linear, which indicates intimate contact between the pervious pavement and the base as shown in Figure 12. The PCC slab has a slight deviation from the linear trend which is likely due to curling. The linear relationship indicates full base support which highlights the importance of providing a stiff base beneath the pervious pavement to produce greater structural capacity to carry heavier traffic loads. This may explain the good performance of the test sections under the limited but heavy truck loading.

FWD deflections is a reliable indicator of the structural capacity of a pavement system. A lower deflection generally indicates higher structural capacity. The maximum FWD deflections for TS4, with 10 inch (255 mm) pervious concrete and 6 inch (150 mm) aggregate base, were lower than those for the 10 inch PCC slab by 18% as shown in Tables 1 and 2 and Figure 15. The deflections of the 8.25 inch (210 mm) TS3 with the 6 inch CLPC base were 3% lower than the PCC slab. Based on these results, both test sections seem to have high structural capacity to carry truck traffic.

It is important to note that the 10” PCC pavement has performed well under the heavy truck mixer traffic. This fact demonstrates that pervious pavements on aggregate and CLPC bases will perform well under light to moderate truck traffic when designed with adequate thickness; proper base and edge support; well engineered pervious mix; and good construction practices.

Both the aggregate and CLPC bases provided very good support to allow the pervious concrete pavement to carry truck traffic. However, CLPC offers advantages in construction and cost saving compared to the conventional aggregate base layers. The CLPC was mixed and prepared on site, and was pumped in place in a short period of time.

The structural capacity of the thinner test sections (TS1 and TS2) was 66% lower than that of the PCC pavement. However, with better compaction of the aggregate base, thinner pervious pavements will provide adequate structural capacity to carry light truck traffic and for streets and parking areas.

Based on the FWD results, the 4” (100 mm) thick pervious concrete design used in the parking display will not be adequate for street traffic. It is most suited for parking areas with light traffic or for sidewalks and recreation surfaces.

The FWD tests demonstrated that pervious concrete pavement can perform well under heavy traffic. However, raveling remains as a main area of concern in high speed traffic. Further research is needed to minimize raveling.

Permeability

No specific field test was conducted to determine the exact permeability values for the pervious concrete. However, the effectiveness of the pervious pavement to drain the water was verified. Water was discharged on the pervious surfaces as shown in Figure 16. The water disappeared inside the pervious system shortly after being discharged on the surface of the pervious pavement. This was a good indication that the parking display and the five test sections were draining surface water effectively.

One observation noted during construction was that over-compaction of the pervious concrete appeared to bring more paste to the surface. Additional paste tends to clog some of the surface voids and reduce drainability. A few surface areas exhibited lower percolation compared to the surrounding due to over compaction and clogging of surface voids. A better control of the mix design and consistency, and paying attention to compaction timing, pattern and energy will reduce clogging of surface voids.

Conclusions

1. When properly designed and constructed, pervious pavement can be used in streets with light to moderate truck traffic.
2. Based on FWD results, pervious pavement on 6 inch (150 mm) aggregate and Cellular Lightweight Porous Concrete (CLPC) bases provide better structural capacity than the conventional PCC pavement.
3. The CLPC has major advantages compared to the aggregate base. It is simple to prepare, has shorter construction time, and saves on slurry volume and cost to build the base layer.
4. Thickness of pervious concrete for streets with light to moderate truck traffic should not be less than 8 inches (200 mm).
5. Curbs must be used for pervious pavement in street applications to provide edge support and reduce raveling.

6. The thickness of pervious pavements in parking areas should range from 5” to 7” (125 mm to 175 mm).
7. Aggregate raveling will be a concern in high speed traffic or at curves in the streets. Action should be taken to increase the strength of the pervious mix and pavement compaction. This action may impact drainability but will vastly improve resistance to raveling.

Recommendations to Expand Roadway Applications of CLPC

1. Determine the structural capacity of 6”, 7” and10” pervious pavement on 6 inch CLPC. This will facilitate the development of design chart.
2. Determine QC test for field drainability of CLPC.
3. Establish a laboratory relationship and charts for density, strength and drainability of CLPC paving mixes.
4. Develop a field QC test to evaluate the strength of the in-place CLPC
5. Establish proper curing time for CLPC prior to overlaying with pervious concrete.

Table 1 - Average FWD Deflections (microns) for 750 kpa Stress

Section	Thickness – mm (inch)	Stress kPa (psi)	Force kN (lb)	Distance from FWD Load Plate mm (inch)								
				0	200 (8”)	305 (12”)	460 (18”)	610 (24”)	915 (36”)	1220 (48”)	1525 (60”)	1830 (72”)
PCC	**255 (10”)**	**750 (110)**	**53 (12,000)**	**170**	**162**	**161**	**152**	**145**	**124**	**104**	**88**	**73**
TS1	**195 (7.75”)**	**750**	**53**	**283**	**257**	**243**	**213**	**188**	**142**	**107**	**81**	**63**
TS2	**210 (8.25”)**	**750**	**53**	**284**	**259**	**248**	**221**	**197**	**151**	**114**	**87**	**69**
TS3	**210 (8.25”)**	**750**	**53**	**165**	**150**	**147**	**133**	**122**	**100**	**80**	**65**	**53**
TS4	**255 (10”)**	**750**	**53**	**139**	**128**	**125**	**116**	**108**	**91**	**76**	**63**	**52**
TS5	**255 (10”)**	**750**	**53**	**226**	**208**	**202**	**182**	**165**	**130**	**99**	**77**	**58**
PS1	**100 (4”)**	**750**	**53**	**825**	**650**	**557**	**417**	**321**	**182**	**108**	**67**	**54**
PS3	**100 (4”)**	**750**	**53**	**916**	**723**	**610**	**451**	**337**	**182**	**107**	**73**	**57**

1 mil = 25.4 microns

PCC – Conventional Concrete pavement

<u>Pervious pavement test section</u>
TS1 – Aggregate base & plastic sheet curing
TS2 – Aggregate base & Lithium Curing
TS3 – Cellular Lightweight Permeable Concrete Base
TS4 – Aggregate base
TS5 – Recycled concrete base

<u>Pervious Parking Display</u>
PS1- Cellular Lightweight Permeable Base
PS2 – Aggregate Base

Table 2 - Percent Difference in Structural capacity compared to PCC and Structural rankings

Section	Thickness mm (inch)	Difference in Structural PCC (%)	Structural capacity Ranking
PCC	255 (10")	0	3
TS4	255 (10")	18	1
TS3	210 (8.25")	3	2
TS5	255 (10")	-33	4
TS1	200 (7.75")	-66	5
TS2	210 (8.25")	-67	6
PS1	100 (4")	-385	7
PS3	100 (4")	-439	8

Figure 1 - Pervious Parking Display with CLPC and Aggregate bases

Figure 2 – Test Sections 1 (plastic sheet cure) and 2 (Lithium Cure) on aggregate base.

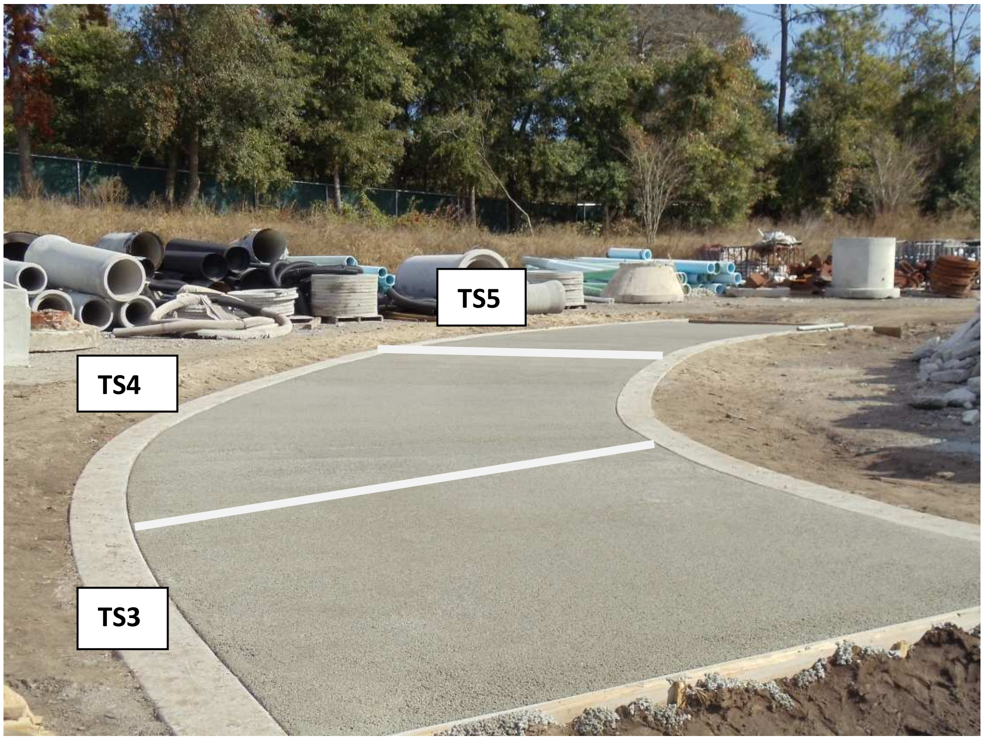

Figure 3 – Test sections 3, 4 and 5

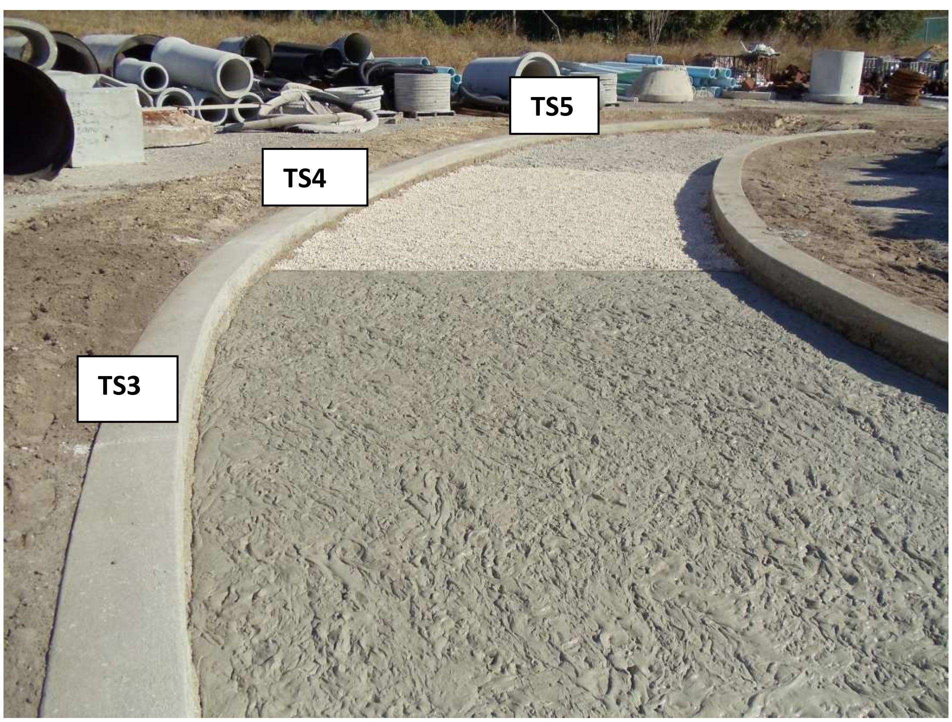

Figure 4 – CLPC, Aggregate and Recycled Concrete bases for Test Sections 3, 4 and 5

Figure 5 – Injection of Foam into the Cement-Slag Slurry to Form CLPC

Figure 6 – Pumping CLPC Base

Figure 7 – Ruts in Base Layers Caused by Heavy Truck Mixer

Figure 8 – Placement and Compaction of Pervious Pavement

Figure 9 – Spraying Surface with Lithium Cure

Figure 10 – Truck Loading on TS3, TS4 and TS5.

Figure 11 – FWD testing of the Pervious Test Sections

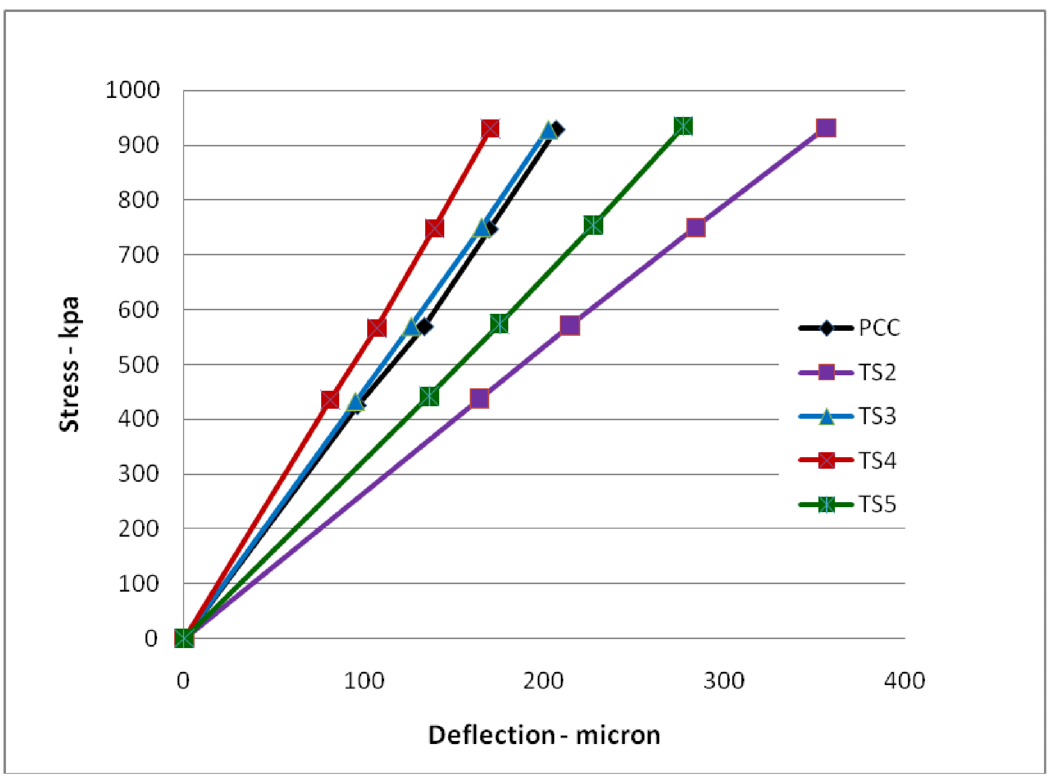

Figure 12 – FWD Stress vs. Deflections at the Load plate

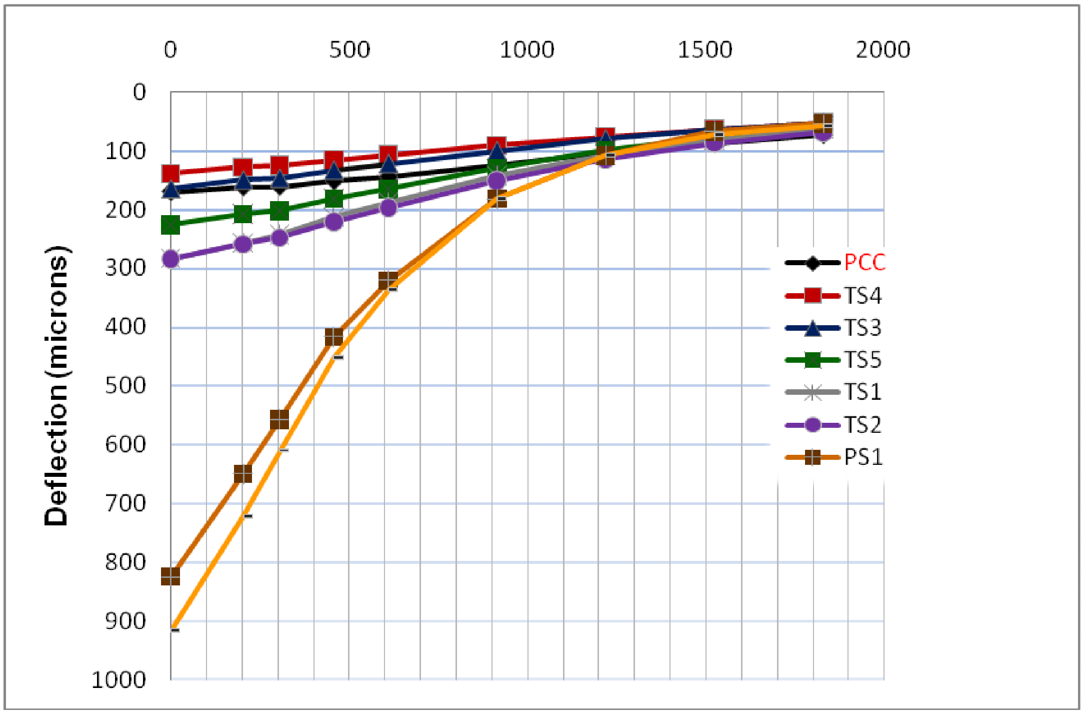

Figure 13 - FWD Deflections of Pervious Test Sections and Parking Display

Figure 14 - FWD Deflections of Pervious Test sections and PCC Pavement

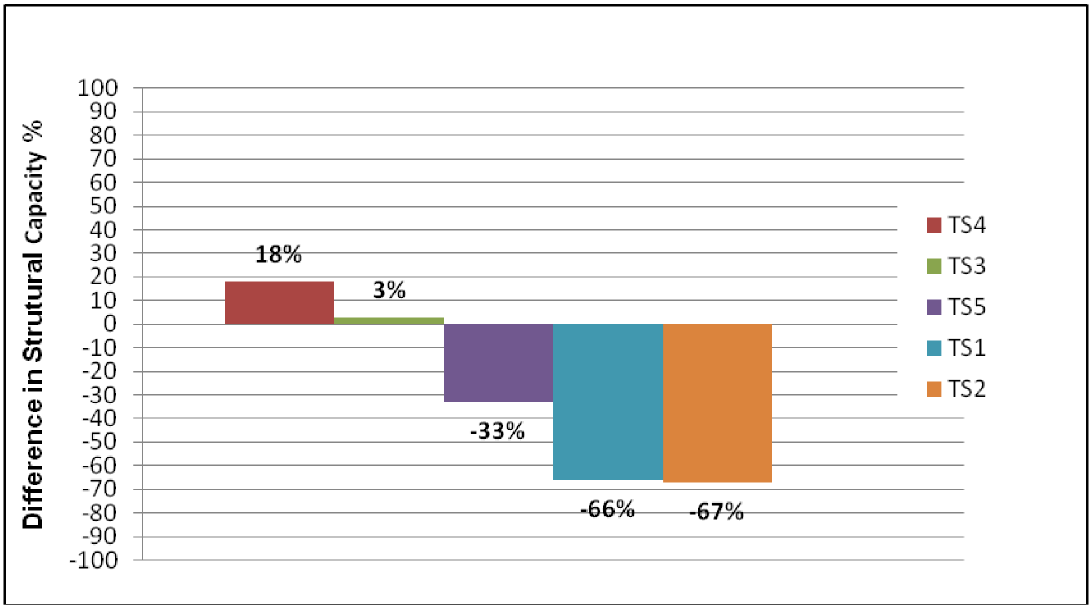

Figure 15 - Percent Difference in Structural Capacity as Related to Conventional PCC

Figure 16 –Testing Drainability of Pervious concrete