Open-graded Aggregate Base (OGAB) Controlling Subsurface Moisture Regime and Structural Stability from MnROAD Instrumentation Data

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ABSTRACT: Open-graded aggregate base courses have been increasingly used in Portland cement concrete (PCC) pavements as one of the effective strategies for improving subsurface drainage efficiency and thus pavement longevity. In addition to maintaining adequate permeability, these layers are also required to remain stable during pavement construction, performance period and future rehabilitation activities. In an effort to study subsurface drainage and stability of a new open-graded aggregate base material (OGAB Special) under construction, PCC pavement test sections (Cells 306 and 406) were constructed by the Minnesota Department of Transportation (MnDOT) on the 3.5-mile mainline interstate roadway segment at the MnROAD test facility in 2011. Both test cells consist of 6-in. thick PCC slab, 6-in. thick OGAB Special layer and 7-in. Class 5 (MnDOT traditional dense-graded) unbound aggregate underlain by clay subgrade. This paper presents the findings from analyzing field instrumentation data and Falling Weight Deflectometer (FWD) test results to assess the effectiveness of the OGAB Special layer in controlling subsurface moisture regime and providing structural stability. For comparison, field test data were also collected and analyzed from MnROAD Cells 38, 53, and 54 that are located in the low-volume roadway segment and consist of PCC slabs of similar thickness and traditional dense-graded base layers (Class 5 or 6) underlain by clay subgrade. It was concluded from analysis results that the OGAB Special layer cannot only reduce the subsurface moisture content significantly but also provide comparable structural stability, as compared to traditional dense-graded (Class 5/6) base layers.

INTRODUCTION

Moisture is a main cause of deterioration in Portland Cement Concrete (PCC) pavements (Cedergren 1994; Ceylan et al., 2013). For pavement foundation materials, excessive moisture within the pavement system could cause reduced strength (bearing capacity), increased material erosion and reduced hydraulic conductivity (Fredlund and Rahardjo, 1993; Lu and Likos, 2004). In cold winter climates like in Minnesota, this problem is magnified further by the risk of frost damage when water is present. To improve subsurface drainage efficiency and thus pavement longevity, placing a permeable base layer underneath PCC slabs, among others, has become a typical countermeasure. In Minnesota, two main permeable aggregate base (PAB) materials are currently used, i.e., stabilized and unbound. Hagen and Cochran (1996) demonstrated the effectiveness of a permeable asphalt-stabilized base in removing water within two hours after rainfall ended; furthermore, research at Minnesota's cold weather road research facility (MnROAD) and elsewhere has shown that concrete pavements built over well-draining aggregate base materials perform substantially better than those built over more traditional dense-graded bases (Akkari et al., 2012). In addition to maintaining adequate permeability, these layers are also required to remain stable during pavement construction, performance period and future rehabilitation activities. This is evidenced by the Minnesota Department of Transportation (MnDOT)'s use of open-graded aggregate base (OGAB) on many construction projects, which has added substantial construction costs due to stability issues (Akkari et al., 2012).

Much of the permeable base research has focused on its role as a subsurface drainage component as characterized by its porosity and permeability, while the structural behavior of permeable base has received much less attention. Diefenderfer et al. (2005) reported the use of the Falling Weight Deflectometer (FWD) as an effective tool in evaluating the performance of a drainage layer in pavements in Virginia as it contributes to the structure of the pavement system. Hall and Crovetti (2007) assessed the relative structural contributions of different base types in NCHRP Project 1-34D and indicated that it is not the drainability of the base layers but the stiffness that influenced deflection response, roughness, rutting, faulting, and cracking. Presently, there are few guidelines for structural analysis and design of permeable base. Tao et al. (2008) determined through laboratory testing an optimum gradation for unbound aggregates that are commonly used in Louisiana highways, which outperforms current Louisiana class II base gradation in terms of both structural stability and permeability. More recently, MnROAD tested a modified OGAB material (i.e., OGAB Special) which proved to be stable during construction, in addition to showing promising results for permeability of this material shown by preliminary test results (Akkari et al., 2012).

OBJECTIVES AND SCOPE

Conflicting findings have been reported in prior studies regarding the effectiveness of permeable bases. As a follow-up to the preliminary study outlined by Akkari et al. (2012), this paper is aimed to further examine the effectiveness of the OGAB Special layer that was experimented in PCC pavement sections at MnROAD, in terms of both permeability and structural stability in actual service. This is accomplished by two steps: first, analyze subsurface moisture contents measured using instrumented sensors under pavement sections constructed by the OGAB Special and traditional dense-graded layers; and second, evaluate the pavement structural capacity using the

FWD data for predicting the expected pavement life.

DESCRIPTION OF FIELD DATA ACQUIRED

Selection of PCC Pavement Test Sections at MnROAD

MnROAD is a pavement testing facility operated by MnDOT in Albertville, MN to build and instrument innovative pavement sections and monitor their behavior. As shown in Figure 1, it consists of two unique road segments: a 3.5-mile mainline interstate roadway carrying “live” traffic averaging 28,000 vehicles a day; and, a 2.5-mile closed-loop, low-volume roadway (LVR) carrying a controlled 5-axle tractor-semi-trailer to simulate conditions of rural roads. Note that pavement test sections at MnROAD are referred to as “Cells”.

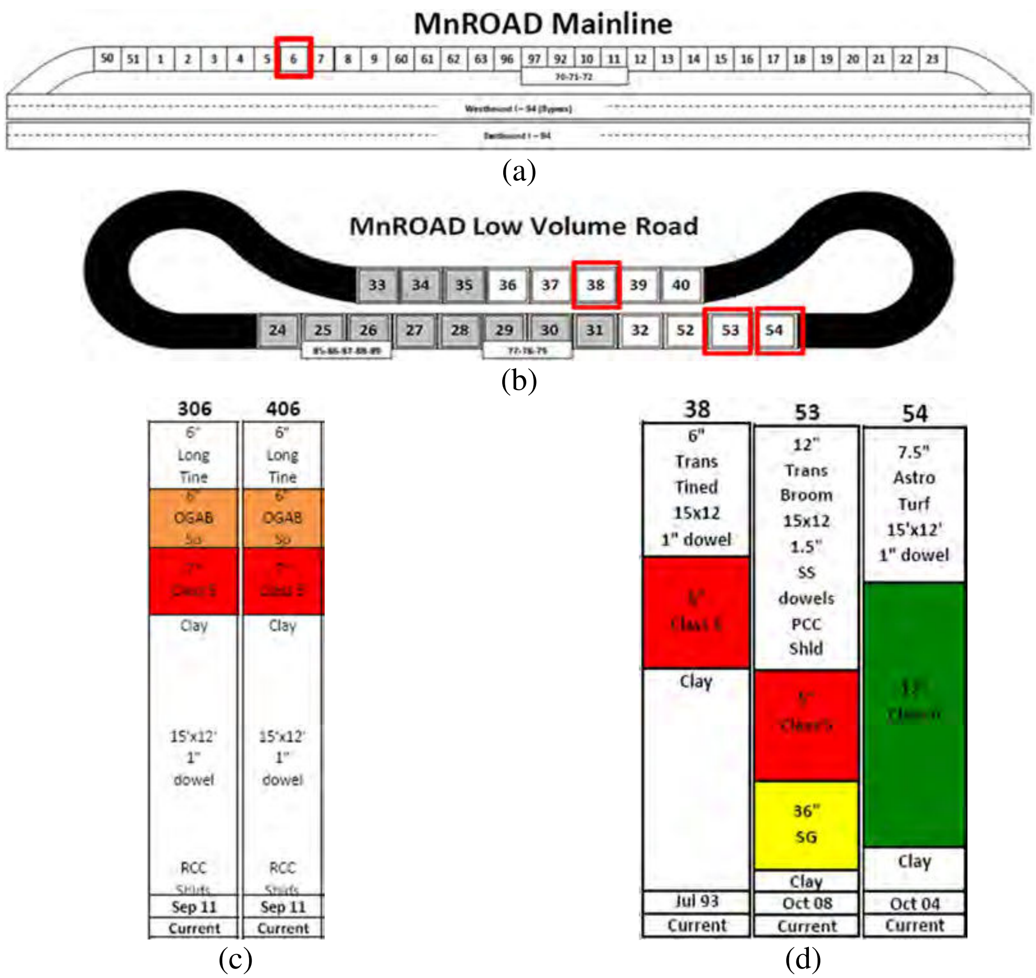


Figure 1. Layout of MnROAD (a) mainline and (b) low-volume road segments and pavement cross sections for (c) Cells 306 and 406 and (d) Cells 38, 53 and 54 (Courtesy of MnROAD Research Website: http://www.dot.state.mn.us/mnroad/).

In an effort to study subsurface drainage and stability of a new permeable base material (i.e., OGAB special) under construction, two PCC pavement test sections, Cells 306 and 406 (referred to together as Cell 6), were constructed on the mainline segment at MnROAD in 2011. Both test cells consist of 6-in. thick PCC slab, 6-in. thick OGAB special layer and 7-in. Class 5 unbound aggregate underlain by clay subgrade, as shown in Figure 1(c). According to MnDOT specifications for traditional dense-graded aggregate materials, Class 5 requires at least 10% crushed particles, whereas Class 6 requires at least 15% crushed particles. Three additional PCC cells of similar design that are constructed with traditional dense-graded base layers on the low-volume segment are selected, i.e., Cells 38, 53, and 54. As shown (not to scale) in Figure 1(d), Cell 38 is a 6.5 in. thick jointed plain concrete pavement (JPCP) with 1.0 in. dowels. It has a 5 in. thick Class 5 base and clay subgrade. Following the Minnesota High Performance Concrete Pavement (HPCP) design concept targeted for a 60-year service life, Cell 53 is a 12 in. thick JPCP with 1.5 in. dowels and consists of a 5 in. thick Class 5 base, a 36 in. thick Select Granular (SG) subbase and clay subgrade. A 7.5 in. thick JPCP with 1.0 in. dowels, Cell 54 consists of a 12 in. thick Class 6 base and clay subgrade. All three cells have 15 12 ft panels. The grain size measurements in Figure 2 show that the OGAB Special is coarser than typical MnDOT Class 5 aggregate and is approximately within the gradation band specified by MnDOT for unbound Permeable Aggregate Base (PAB). Based on limited extensive laboratory and field observations, the OGAB Special gradation used to achieve the drainable base in Cell 6 at MnROAD appears to provide stability and permeability during construction (Akkari et al., 2012).

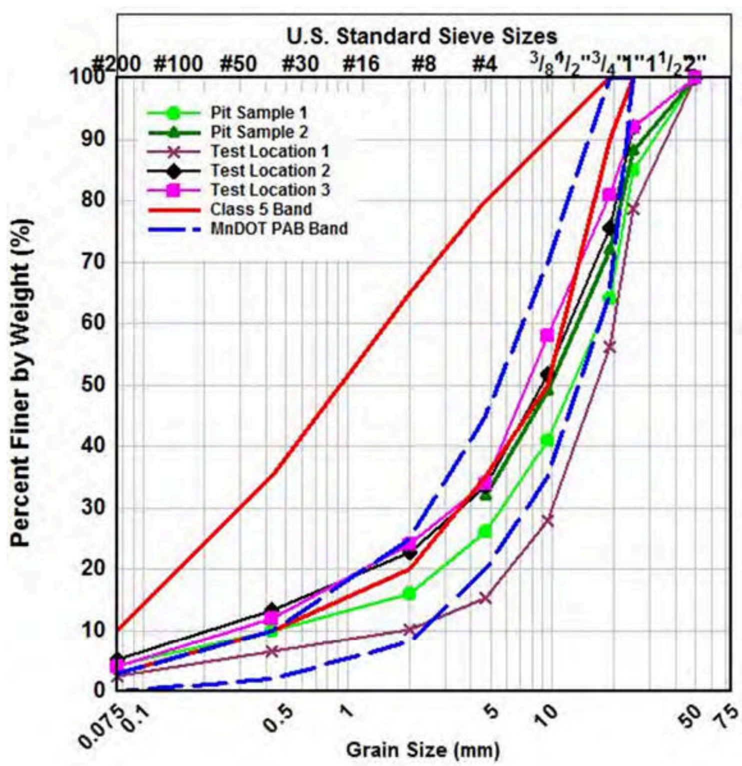


Figure 2. Grain size measurements of MnROAD Cell 6 OGAB Special in Relation to MnDOT Class 5 and Unbound Permeable Aggregate Base (PAB) Bands (graphed data provided by Akkari et al., 2012).

Field Instrumentation Data

To track the changes in the load and environmental response of a pavement structure over time, electronic sensors were installed during the initial construction of the test cells at MnROAD. These sensors measure variables such as temperature, moisture, strain, deflection, and frost depth in and under the pavement at certain intervals throughout the year (Johnson et al., 2008). Specifically, in addition to Time Domain Reflectometry, the Watermark (WM) 200-x sensors manufactured by the Irrometer® have been used to measure both soil moisture content and frost depth in base and subgrade layers. Those "WM" sensors measure change in electrical resistance due to changes in the soil moisture content. They are installed in a vertical stack of 7 sensors to capture the moisture content at various layers below the pavement surface. Data is automatically collected from each WM sensor every 15 minutes. The instrumentation layout of WM sensors in Cells 306, 38, and 53 is illustrated in Figure 3.

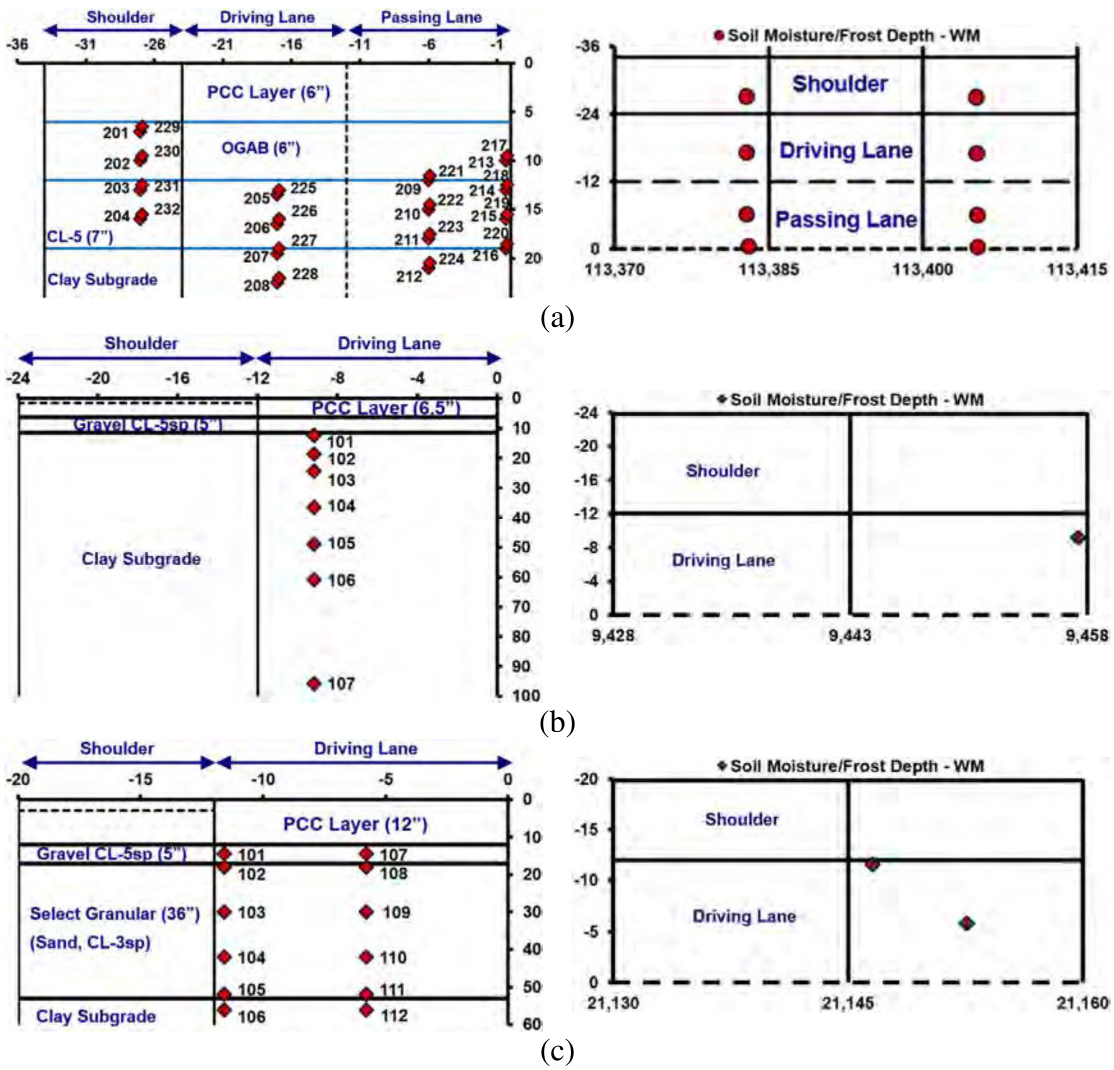


Figure 3. Instrumentation Layout of WM Sensors for MnROAD (a) Mainline Cell 306, (b) Low-volume Cell 38 and (c) Low-volume Cell 53.

Field FWD Data

The FWD device is designed to measure the load-deflection response of pavement systems subjected to an impulse load that simulates a passing wheel. The deflection basin captured by the geophone sensors (spaced at specific distances from the load plate) can be used to determine the strength of concrete pavement and back-calculate the moduli of PCC slabs (E_{PCC}) and underlying layers, e.g., the modulus of subgrade reaction k_s. The maximum deflection under the loading plate (D_0) and the deflection at the outermost sensor are indicators of overall pavement and subgrade stiffness, respectively (Barenberg and Petros, 1991). According to Suleiman et al. (2011), the E_{PCC} values are more strongly correlated to the FWD deflections near the load center than in the farther ones, whereas the opposite is true for k_s values. Several methodologies have been developed over the years to back-calculate the rigid pavement properties from measured FWD deflection basins and pavement layer thicknesses (Hall et al., 1997; Ceylan, 2002; Fwa and Setiadji, 2006).

In general, FWD tests are performed on most of the MnROAD pavement cells multiple times each year to measure the unique seasonal response of a pavement layer or system to a dynamic load. As of May 2009, there are 10 sensors used and they are numbered and located according to Table 1. FWD tests at MnROAD have been done with the trailer facing in the direction of traffic loading for all PCC test cells after April 1998 (Izevbekhai and Rohne, 2008). Specifically, each test cell has approximately 40 test points that are routinely tested. Test points in PCC cells are in groups of 5, following a fixed pattern associated with panel position. Typically, five of these groups are tested in each PCC lane. At each test point, surface deflections are collected for one drop at each load level of 6,000, 9,000, and 12,000 lbs. Note that the radius of the load plate is 6 in. Figure 4 shows the diagram of the FWD test points for Cells 306 and 406, as well as for a typical low-volume roadway (LVR) cell. Other information recorded during FWD testing includes the air temperature and infrared pavement surface temperature.

FIELD DATA ANALYSIS

Impact of OGAB Special Layer on Subsurface Moisture Regime

The WM sensor data are analyzed for the effectiveness of the OGAB special layer as a subsurface drainage component. Figure 5 shows the variation with time of hourly electrical resistivity (indicator of in-situ moisture content) recorded by sensors in different layers at Cells 306 and 53 (see Figure 3). The precipitation information recorded by MnROAD weather station is also provided as a reference. It clearly shows that the use of OGAB Special layer in Cell 306 significantly reduced the in-situ moisture content levels in all pavement layers (especially in subgrade soil), as compared to Cell 53 with traditional dense-graded base layer. Sensors #207 and #208 placed atop and within clay subgrade in Cell 306 were further compared against sensors #102 and #108 placed atop the SG subbase in Cell 53. Figure 6(a) shows the variation of average daily electric resistivity with time. It becomes more evident that the OGAB special layer in Cell 306 is effective in reducing the subsurface moisture content and thus improving drainage efficiency. The coefficient of variation (COV), defined as the ratio of standard deviation to the mean, of average daily electric resistivity that varies with time is also shown in Figure 6(b) for both cells. Note that each of the dashed horizontal lines in Figure 6(b) represents the average COV level for the corresponding sensor. It shows that the use of the OGAB special layer resulted in much higher COV values of subsurface moisture content, which is expected as water can more easily penetrate through the OGAB special layer and make the subsurface moisture variation more susceptible to precipitation, if no other drainage options are used.

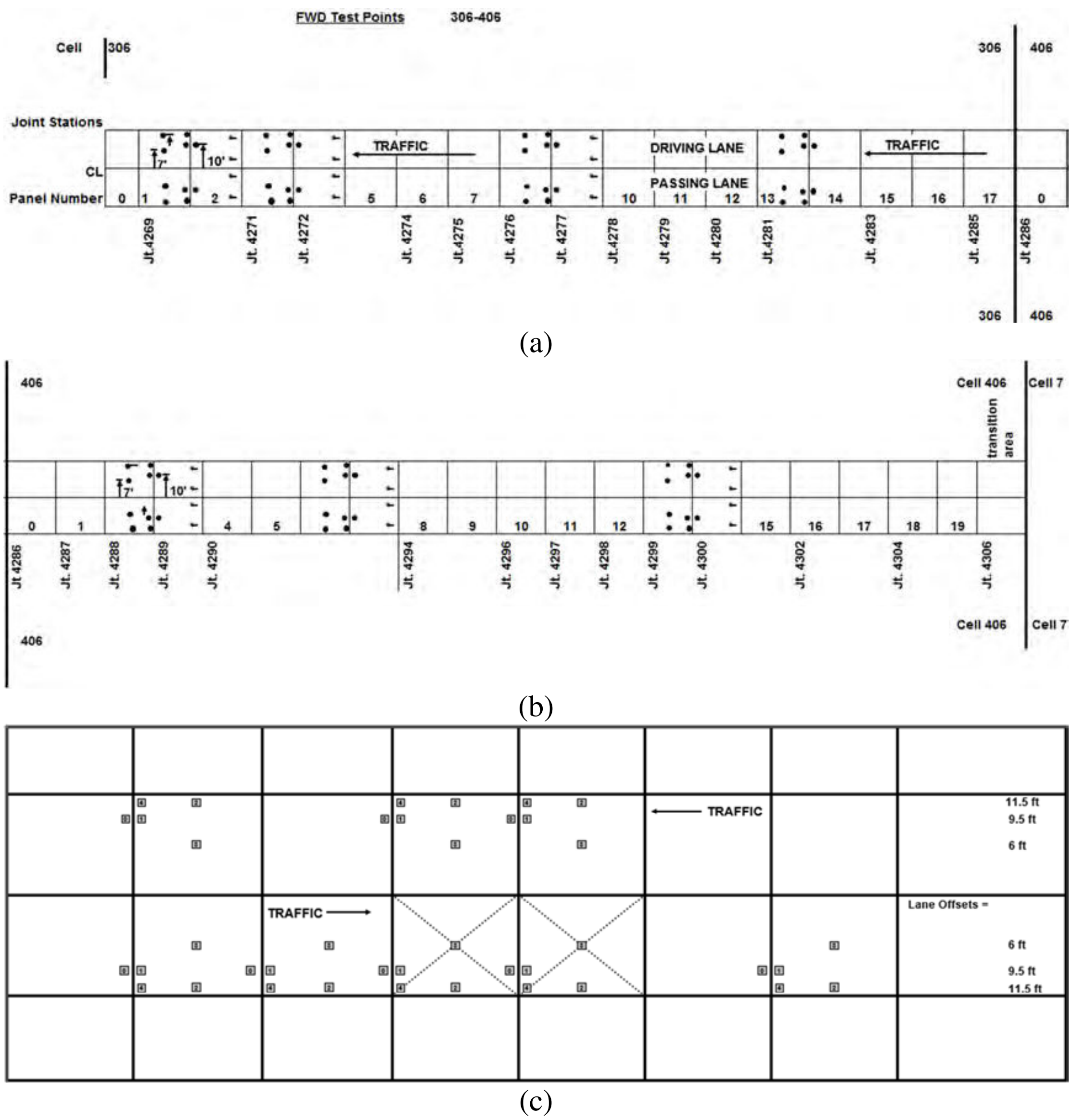


Figure 4. Diagram of FWD Test Points in (a) Cell 306, (b) Cell 406 and (c) a Typical Low-volume Roadway (LVR) Cell.

Table 1. Geophone Sensor Spacing for Each FWD Test at MnROAD

Sensor Number	1	2	3	4	5	6	7	8	9	10
Distance from center of load plate (in.)	0	8	12	18	24	36	48	60	72	-12

Note: 1 in. = 25.4 mm

It is worth mentioning that laboratory permeability testing was performed on thirteen samples of the OGAB Special material by closely following ASTM D2434-68 procedure (Constant Head). The resulting average value for the coefficient of permeability (k_{avg}) was reported as 19.3 ft/day, which is under the typical range for fine sand (2.83-28.3 ft/day) and is lower than what would be expected (Akkari et al., 2012). According to MnDOT specifications, permeable aggregate layers should have a permeability k of at least 300 ft/day, although a minimum value of 1,000 ft/day is desirable. This is probably because the only possible flow path for the water was clogged by finer particles seen washing to the bottom of the apparatus during the test, which is however less likely to occur in the field. In-situ permeability testing was also performed on August 17, 2011 at several different locations. The in-situ permeability k was found between 0.41 and 55 ft/day with an average of 23 ft/day (1ft/day=$3.53\ 10^{-4}$ cm/s). The permeability of Class 5 (dense-graded) base is about 0.4 ft/day, which is apparently much less than that of the OGAB Special in Cell 6.

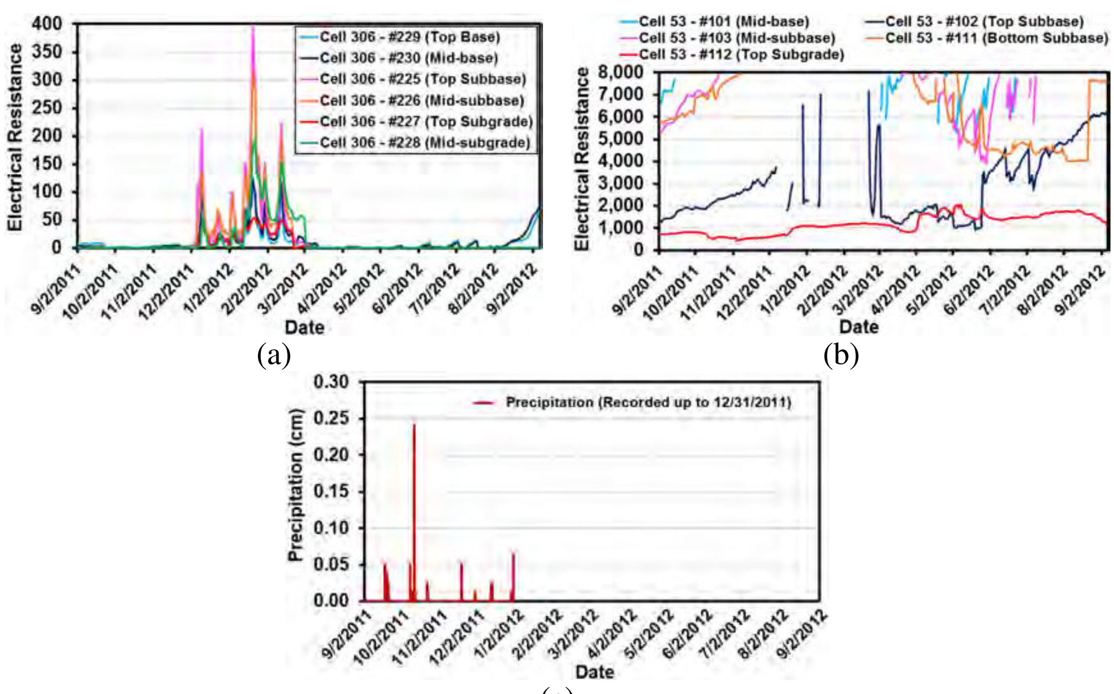
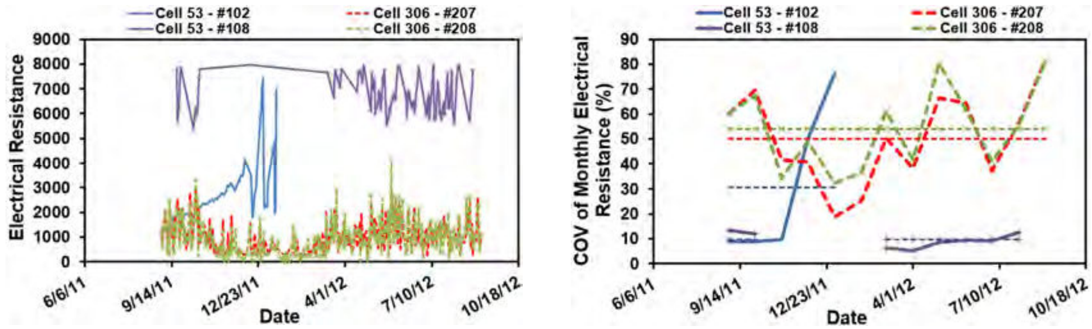


Figure 5. Hourly Electric Resistivity Measurements at Cells (a) 306 and (b) 53 and (c) Precipitation Data Recorded by the MnROAD Weather Station.



(a) (b)

Figure 6. Average Daily Electric Resistivity Measurements (a) and (b) Corresponding Coefficient of Variation (COV) Values at Cells 306 and 53.

Impact of OGAB Special Layer on Pavement Structural Capacity

The structural behavior of the OGAB Special layer in actual service compared to traditional dense-graded aggregate bases has not been investigated or reported yet; therefore, this section focuses on evaluating the structural behavior of Cell 6 with the OGAB Special layer compared with that of traditional concrete pavement systems, i.e., Cells 38 and 54. This is accomplished by comparing FWD test results. Those three cells share very similar geometry/configuration of PCC slabs and reinforcement details, as presented previously. To minimize the effect of potential thermal curling of the slab, only FWD measurements taken at similar time, air temperature and infrared surface temperature are selected for further comparison. This results in the selection of FWD measurements taken in early October when the air temperature and infrared surface temperature were about 14 °C and 20 °C, respectively. Note that the average PCC static modulus of elasticity (E_{PCC}) was reported as 5.5 10^6 psi for Cell 54 (Izevbekhai and Rohne, 2008) and 4.5 10^6 psi for Cell 38 (Vancura et al., 2011).

The center panel deflection basins measured from center points of several PCC slabs for Cells 306 and 54 at different FWD loading amplitudes are compared in Figure 7. The shape and magnitude of deflection basins in Figure 7 show that PCC slab #3 in Cell 306 yielded deflection response closely matching that of Cell 54, while slabs #8 and #13 in Cell 306 yielded weaker response compared to that of Cell 54. Considering the aforementioned similarity between Cells 306 and 54 (i.e., 6 in. vs. 7.5 in. slab thickness, 15 12 ft panels, 1.0 in. dowels, and clay subgrade), one may reasonably infer that the combination of 6-in. OGAB Special and 7-in. Class 5 in Cell 306 could exhibit structural behavior as strong as that of 12-in. Class 6 in Cell 54, provided that proper construction quality (e.g., uniformity) is achieved. Therefore, the structural capacity of the OGAB special layer in actual service could potentially compete with that of traditional Class 6 layer, not to mention its outperforming drainage efficiency. Those varying center panel deflection basins (measured at center points of different slabs) are then averaged and shown in Figure 8. It becomes more obvious that Cells 306 and 54 provided similar response, while Cell 38 provided the weakest response. This is expected because Cell 38 has the thinnest base layer (5-in. Class 5), which in turn further confirms the effectiveness of the OGAB Special layer in providing significant structural support.

Additionally, the discrepancy of deflection basins between driving and passing lanes (Cell 306) or between inside and outside lanes (Cell 54) reflects the spatial variability of the overall PCC pavement stiffness. PCC slabs #3 and #13 in Cell 306 exhibited trivial discrepancy compared to slab #8, indicating much more uniform PCC modulus and slab support from underlying aggregate base. The same applies to slab #11 in Cell 54 compared to slabs #2 and #7. This implies that careful attention should be paid to construction quality by implementing proper QC/QA procedures.

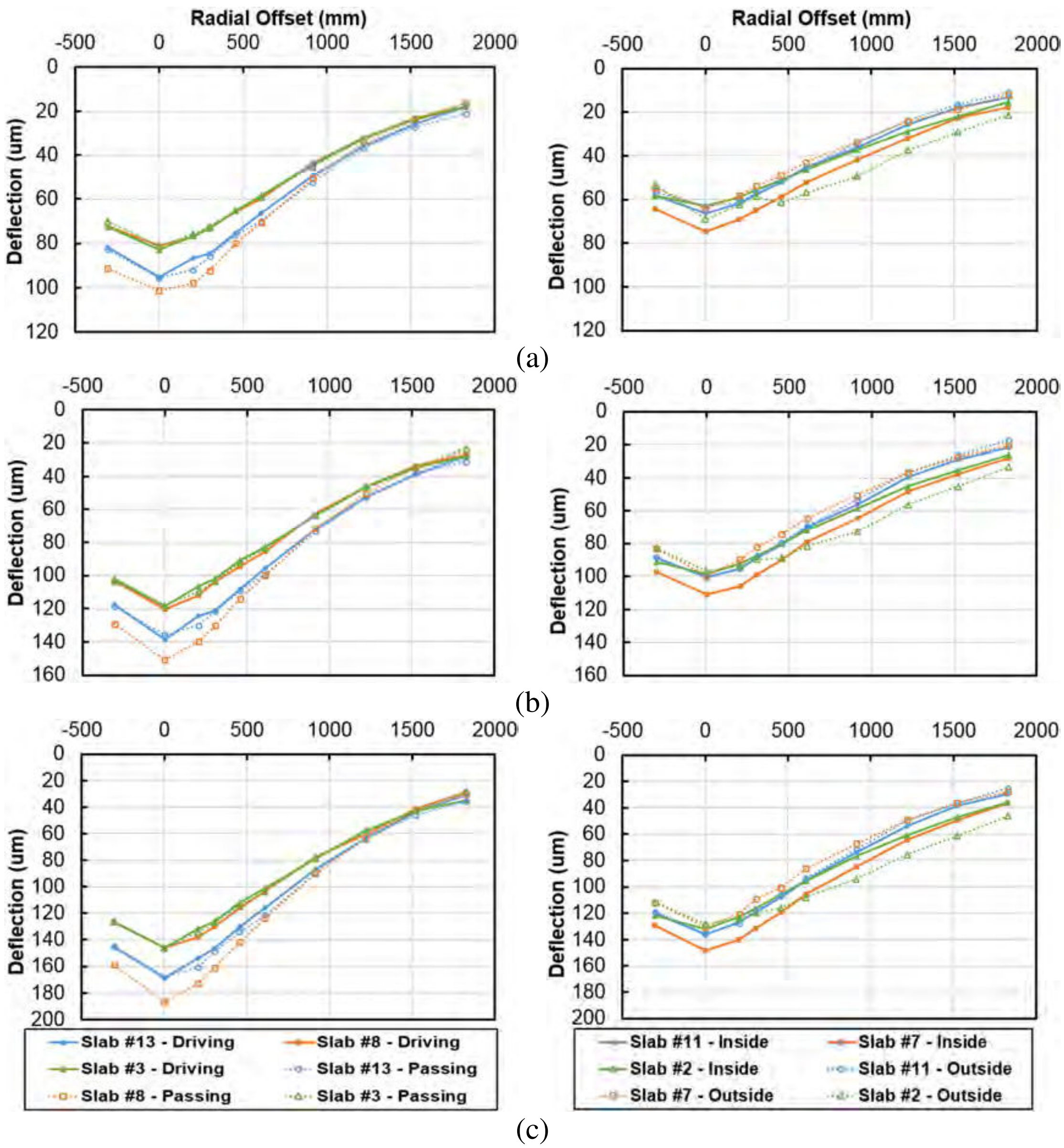


Figure 7. Center Panel FWD Deflection Basins Measured for Cells 306 (left) and 54 (right) at Applied Loads of (a) 6,000, (b) 9,000 and (c) 12,000 lbs.