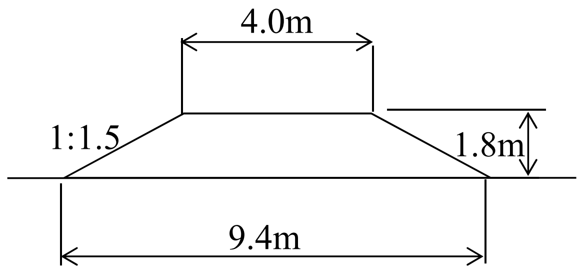

Figure 2. Embankment shape.

Table 1.Basic physical properties of embankment material.

Soil particle density ρ_s(g/cm^3)		2.546
Natural water content w_n (%)		67.91
Grain size distribution	≧ 2 mm (%)	23.8
	75 μm - 2 mm (%)	50.2
	≦ 75 μm (%)	26.0
Consistency limit		N.P.
Unified Classification System		GM
Maximum dry density ρ_{dmax} (g/cm^3)		0.989
Optimum moisture content w_{opt} (%)		53.2
Cone penetration index q_u (kN/m^2)		509
Coefficient of permeability k(m/sec)		4.51×10^{-7}
Frost susceptibility	Freezing rate (mm/h)	0.660
	Frost heave ratio (%)	116.6

Photo 1. Frozen soil.

Photo 2. Filling material.

Table 2.Construction conditions.

Embankment No.	*1*	*2, 3*	*4*
Construction season	Winter	Winter	Summer
Construction period	February 5, 2013	February 12-20, 2014	September 18-24, 2013
Embankment material	Non-frozen soil	Frozen soil	-
Basement layer	Yes	No	No

Survey method. Measurements shown in Table 3 that were taken at the locations shown in Fig. 3 were started for each embankment immediately after the completion of construction. These measurements were done for one year after construction completion; however, for embankments No. 2, No. 3, and No. 4, one item was measured for 3 years. The densities of embankments No. 1, No. 2, and No. 4 were measured by using the sand replacement method in which soil excavated from the embankment is replaced with a dry sand of known density. The density of embankment No. 2 immediately after construction was determined by using the drive-cylinder method, but only at the locations where this method was possible, because the large grain size of the frozen soil made it difficult to use a technique in which sand is poured.

Table 3. The details of investigated items.

Measuring item	*Measuring method*	*Number of measurements*	*Target embankment*	*Remarks*
Temperature in the soil	Automatic measurement by temperature sensor	1	1,2,3,4	Every 10cm
Temperature				Height of 1m above embankment surface
Height	Wooden mark	3	1	Crown
	Settlement plate	1	2,3,4	Mid and bottom
Cone penetration index	Cone penetrometer	2	2,3,4	Every 10cm
Density	Sand replacement method	3	1,2,4	Immediately after construction

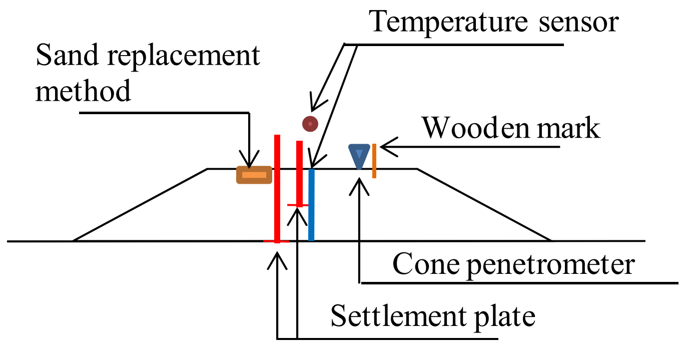

Figure 3. The measurement position of the embankment.

TEST RESULTS

Density of the embankments. The dry densities of the embankments immediately after construction are shown in Fig. 4. The dry densities of embankment No. 4, which was constructed during summer, are the highest. The next-highest dry densities are for embankment No. 1, which was constructed during winter from unfrozen soil. The densities of embankment No. 2, which was constructed during winter from frozen soil, are the lowest. Embankment No. 2, which was constructed from frozen soil, did not satisfy the compaction standard for embankments specified by the Hokkaido Regional Development Bureau, Ministry of Land, Infrastructure, Transport and

Tourism (See also Atsuko Sato, Takahiro Yamanashi, Teruyuki Suzuki and Shinichiro Kawabata - 2014.) The reason for the low dry density of the embankment constructed from frozen soil is thought to be that sufficient compaction was not possible for the frozen soil because the frozen soil blocks were not crushed under compaction of ordinary rolling pressure. The embankment constructed during winter from unfrozen soil satisfied the above-mentioned standards. Based on the above, the embankments constructed during winter were able to satisfy the construction standard values for embankments when unfrozen materials were used.

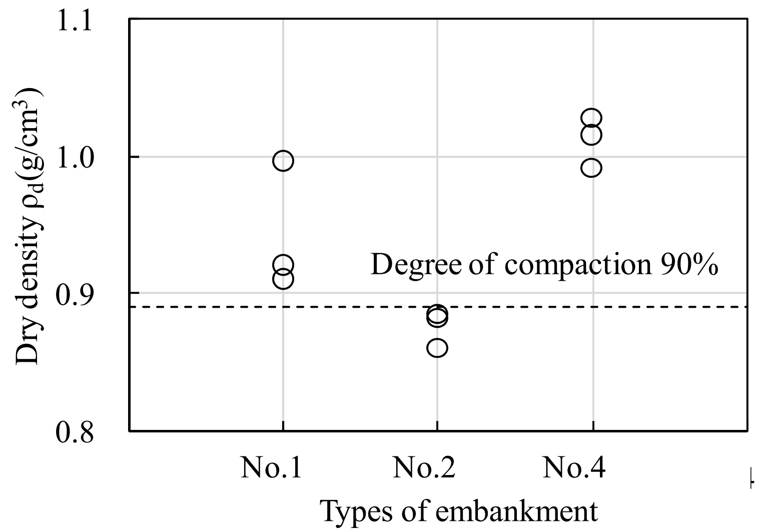

Figure 4. Dry densities of the embankments immediately after construction.

Freezing conditions of the embankments. The parts of the embankment body that froze were determined by using a sensor to measure the temperatures inside the embankments and by estimating the locations where the temperature was below 0°C. The freezing condition of each embankment after construction are shown in Fig. 5. In embankments No. 1 and No. 4, which were constructed from unfrozen material, the freezing progressed with time, and the embankments started to thaw from the surface around when the cumulative daily mean temperature was the lowest (i.e., at a time after which the average temperature started to rise above zero), and the embankments had completely thawed by early to mid April. The start of the thawing period for embankment No. 2, which was constructed during winter from frozen soil, was about the same as those of the other embankments; however, embankment No. 2 did not thaw completely until mid August.

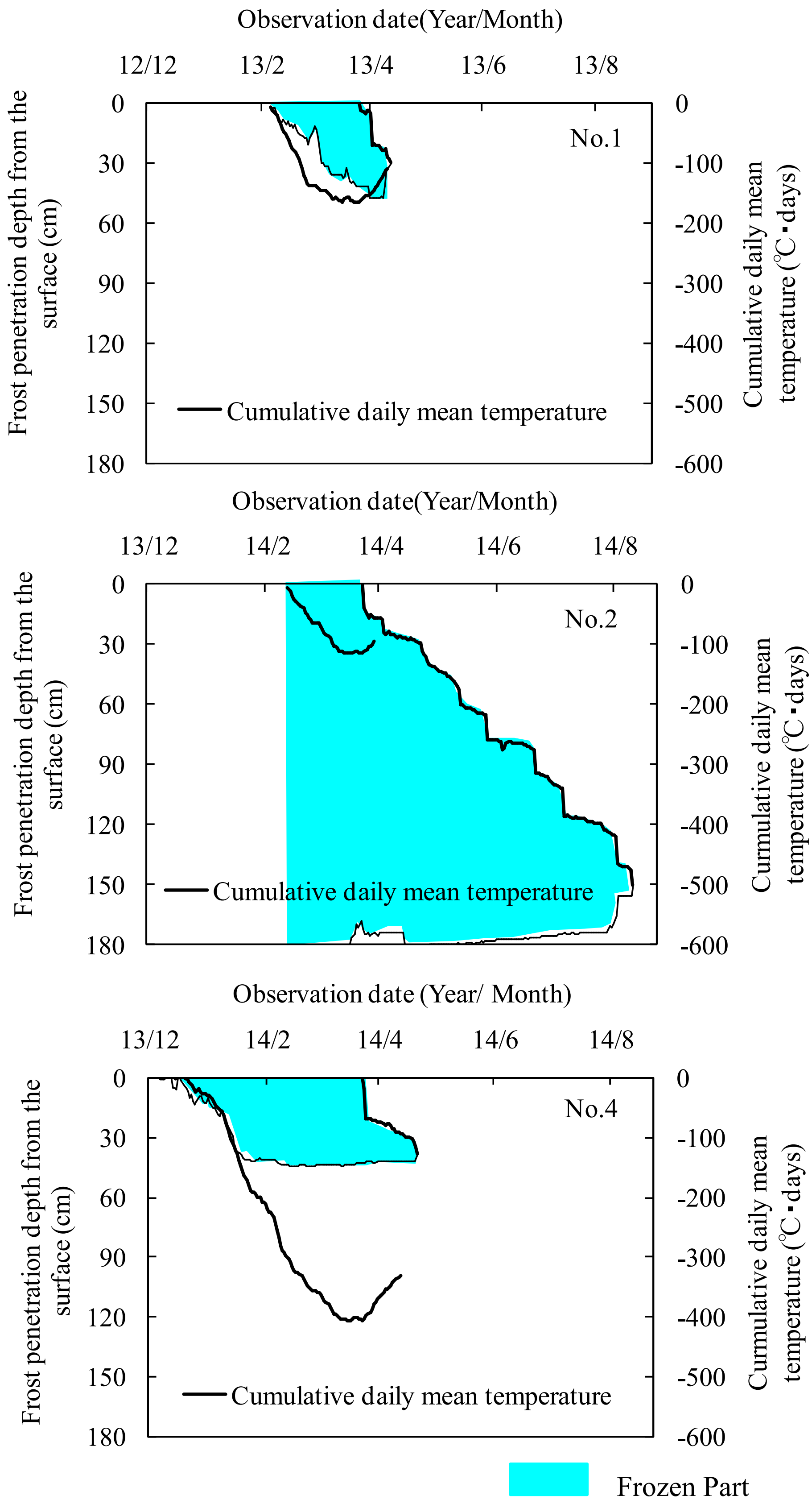

Figure 5. Frozen portion of embankment.

Subsidence of the embankment surface. The change in the crown height of embankment No. 1 and the changes in the difference between the mid height and the bottom height of embankments No. 2, No. 3, and No. 4 are shown in Fig. 6 as the subsidence of each embankment. Subsidence was measured for the 7 months after completion for embankment No. 1 and for the 3 years after completion for the other embankments. For embankment No. 4, almost no subsidence was observed during the observation period. The crown surface of embankment No. 1 deformed slightly, probably because construction was done during winter. No notable deformation was observed after the first minor deformation was found in early February. In contrast to the small deformation of embankment No. 1, embankments No. 2 and No. 3 were found to undergo ongoing subsidence from immediately after construction completion to long after that. Subsidence continued until mid October, which was 2 months after the embankment had completely thawed. A settlement plate was installed at the depth of 90 cm from the crown surface. Subsidence became great in July, when the thawing of frozen soil progressed to the depth of 90m. In embankment No. 2, there was less subsidence with the filling material than without the filling material; however, the effectiveness in terms of controlling subsidence when the filling material was used is small in the embankment constructed with frozen soil, where the subsidence is generally great.

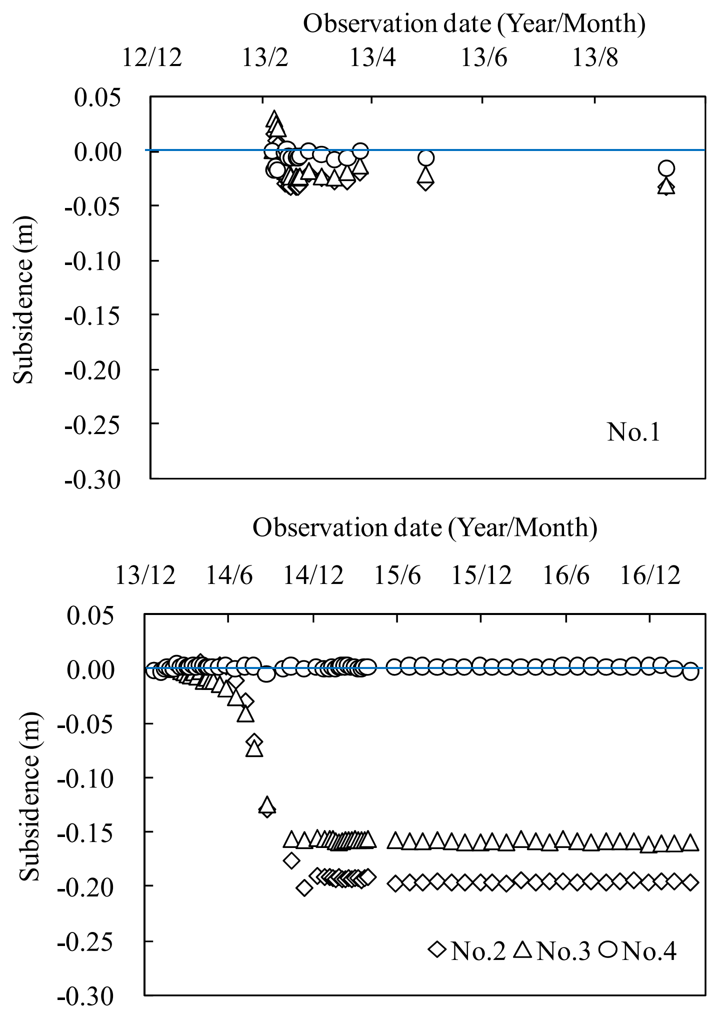

Figure 6. Subsidence of embankment.

Cone penetration index of the embankments. To clarify the relationship between the time elapsed and embankment strength, cone penetration indexes were determined for the crown surface and inside the embankment. For embankments No. 1 and No. 4, all cone penetration indexes for the crown surface measured at construction completion through early November corresponded to the evaluation "penetration impossible", which is understood to mean that the strength of the embankments was sufficient and constant. Fig. 7 shows the cone penetration indexes and measurement dates for embankment No. 3. The cone penetration indexes for embankment No. 3 immediately after construction completion corresponded to the evaluation “penetration impossible” because this embankment was constructed from frozen soil and the strength of the frozen material was high. The workability was good for this embankment. However, the cone penetration index for the crown surface of embankment No. 3 in early May, when the embankment had completely thawed, was about 150kN/m^2, and the embankment crown was too soft to walk on. The cone penetration indexes gradually became high with time after that, and they were about 800kN/m^2 in late August. It is thought that after some time, the cone penetration index of the embankment crown increased because of compaction from repeated rainfall and drying. The cone penetration index inside the embankment was measured at the depth of 20cm to 40 cm from the crown surface. The cone penetration index at this depth did not change noticeably over time and was about 200 - 500kN/m^2. The strength of the crown surface of the embankment constructed from frozen soil became high with time; however, the strength inside the embankment remained low, which showed the impossibility of securing the stability of the embankment. The inside of the embankment is thought to have had cavities after the frozen soil thawed and the density of the soil became low, which was indicated in the low strength of the embankment.

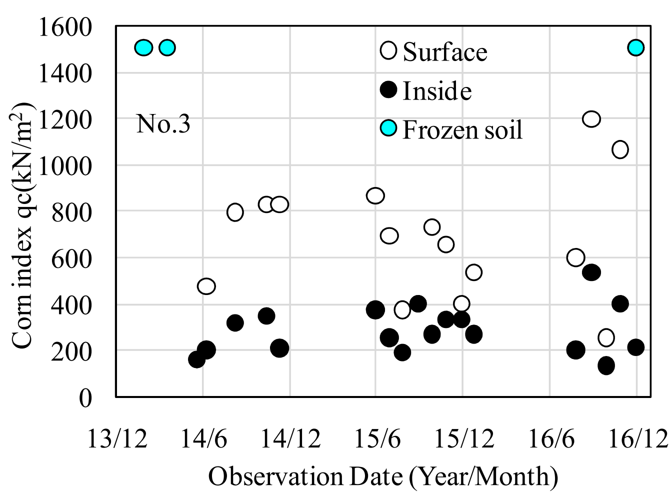

Figure 7. Cone penetration indexes

SUMMARY

In this study, the authors constructed four types of embankments from the same type of soil. These were an embankment constructed with unfrozen soil and embankments constructed with frozen soil (with filling and without filling) during winter, and an embankment constructed during summer. The quality, deformation, and strength of these embankments were compared. The comparison revealed the following.

1) The embankments constructed from frozen soil were found to have good workability, with high cone penetration indexes immediately after construction; however, the density was very low and did not satisfy the standard compaction value.
2) The deformation with thawing was small for the embankment constructed during winter from unfrozen soil. The deformation with thawing was great for the embankment constructed during winter from frozen soil. The time required for the deformation to end after the completion of thawing was long for this type of embankment. Deformation in the embankment constructed from frozen soil continued about 2 months after the frozen soil had completely thawed.
3) The strength of the crown surface of the embankment constructed from frozen soil increased to a certain degree; however, there were several locations within the embankment that had low strength even 3 years after construction completion.
4) It was found that, for embankments constructed during winter, sufficient quality was secured and the deformation after completion was small when the embankment was constructed from unfrozen material. And it was found to be difficult to secure the required quality for embankments constructed from frozen soil, and the strength of such embankments was so low that deformation occurred after construction completion.

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Numerical Modeling of Electrically Conductive Pavement Systems

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Abstract

Confronting snowfall at airports is a long-standing challenge for the aviation industry. To address these concerns, electrically conductive portland cement concrete (ECON) is currently a focus in pavement design. This method applies a potential difference to a surface or near-surface conductive concrete layer, heating the pavement to melt the snow. Due to the complex nature of performance measurements, most studies use experimental methods to examine the ability to remove accumulated snow. However, these methods are resource intensive. This study addresses this challenge through the development of an experimentally-validated 3D finite element (FE) model of ECON for evaluating its thermal performance. Predicted surface temperatures of the FE model are consistent with the data, indicating that a FE model is a promising method for feasibility studies and control strategy development.

INTRODUCTION

The removal of snow and ice is a necessary effort for airports located in cold regions with periodic snow and ice events in the winter seasons. The commonly-used methods for snow and ice removal are mainly through the use of vehicles and other snow plowing equipment, and melting the snow and ice using chemicals. Although these conventional methods are applied widely, they are time-consuming, resulting in delays and airplane accidents at the airports (Anand et al. 2014; Shen 2015). Moreover, in the case of the use of chemicals, the lifetime of the pavement is reduced, resulting in higher maintenance and rehabilitation costs. Therefore, there is a growing number of studies on alternative snow/ice removal methods. One alternative method is the use of heated pavement systems (Anand et al. 2014).

Several studies have been conducted on heated pavement systems (Pan et al. 2014, 2015; Shen 2015; Tuan 2004; Won et al. 2014). There are several types of heated pavement systems including: i) infrared heating, ii) electrical heaters imbedded in pavement, iii) hydronic heating by circulating hot water through pipes imbedded in pavement, iv) electrically conductive concrete and asphalt (Ceylan et al. 2014; Tuan 2004). Electrically conductive concrete (ECON) is the most recently developed heated pavement system technology. ECON is produced by adding electrically conductive material, such as steel shavings (Tuan 2004) or carbon fibers (Abdualla et al. 2017) to the concrete mix. The addition of these materials enables the pavement system to act like a resistor which heats up when an electrical potential difference is applied. The current study focuses on numerical modeling of electrically conductive concretes.

ECON's performance depends on the climatic conditions. Since conducting experimental research for every climatic conditions is costly, having a reliable numerical model for assessing the system response under different conditions would be extremely valuable. Previously there have only been two known studies on the numerical modeling of ECON systems (Abdualla et al. 2017; Tuan 2004). Tuan et al. (Tuan 2004), studied the experimental performance of ECON produced using steel shavings and also made a simplified FE model of ECON. This FE model could anticipate that the ECON temperature increases by applying electrical potential difference, however the consistency of the predicted temperature values with the experimentally-measured values was not reported. In the second study, Hesham et al. (Abdualla et al. 2017), developed an FE model of a single ECON layer. The ECON was produced by adding carbon fibers to the concrete mix. Hesham et al. reported that the temperature values predicted by the model at the middle of the ECON surface were consistent with the laboratory experimental temperature measurements over time. Given that ECON is highly complex, additional research is needed to develop a more comprehensive FE model of ECON, which includes all the pavement layers, enabling a more detailed understanding of ECON performance in a physics-based model that can, through validation, help to predict the pavement performance in a variety of conditions.

The objective of the current study is to build upon the existing literature to create a numerical model of ECON and pavement layers which is capable of estimating the temperature increase inside the ECON system based on the climatic conditions and system parameters including material properties and the applied electrical potential difference. To this end, an FE model of ECON, which is capable of considering electrical, thermal and structural loads and responses is produced in ANSYS (ANSYS Inc. 2017). This model is based on a full-scale ECON system test slab constructed at Des Moines International Airport (DSM), in the U.S. in Iowa. It includes an ECON layer with conventional concrete and subgrade layers underneath. The accuracy of the model results are compared with the measured temperature values of the ECON system at DSM. The ECON system at DSM consists of two 3.8 m by 4.6 m (12.5 by 15 ft) slabs with 6 electrodes embedded in each slab to provide the electrical potential difference. Electrodes are stainless steel angles and the actual potential difference applied to each pair of electrodes is approximately 210 V. The thickness of ECON layer is 9 cm (3.5 in) which is overlaid on a conventional Portland cement concrete layer of 10 cm (4 in) and a P-209 coarse aggregate base of 20 cm (8 in).

In the remainder of this paper, the methodology of developing the FE model and model updating method is explained and material properties for each layer is discussed. Results of the temperature increase from the model are reported and compared with the actual temperature measurements under the same climate conditions.

METHODOLOGY

In this study, transient thermal analysis in ANSYS is used to model the ECON slabs constructed at DSM international airport for studying the heating performance of the system. As shown in Figure 1, the modeled heated pavement system consists of two ECON slabs each with six electrodes. The elements used for modeling the system are SOLID5 element type for ECON, conventional concrete layer and subgrade, and PLANE13 element type for steel electrodes placed in the body of ECON layer. Both SOLID5 and PLANE13 are capable of handling electrical, thermal and structural loads and responses which are the requirements for the ECON model, thus higher order element types are not needed. Moreover, they are compatible and can be integrated and used in the same model. There are a total of 1,962 elements in the model, including smaller elements where the mesh size is finer for the electrodes because of their higher aspect ratio. The average size of the elements is approximately 65×65×65 cm^3 for subgrade and can be as small as 5×5×5 cm^3 for elements close to electrodes. The meshed model and the elements are shown in Figure 2.

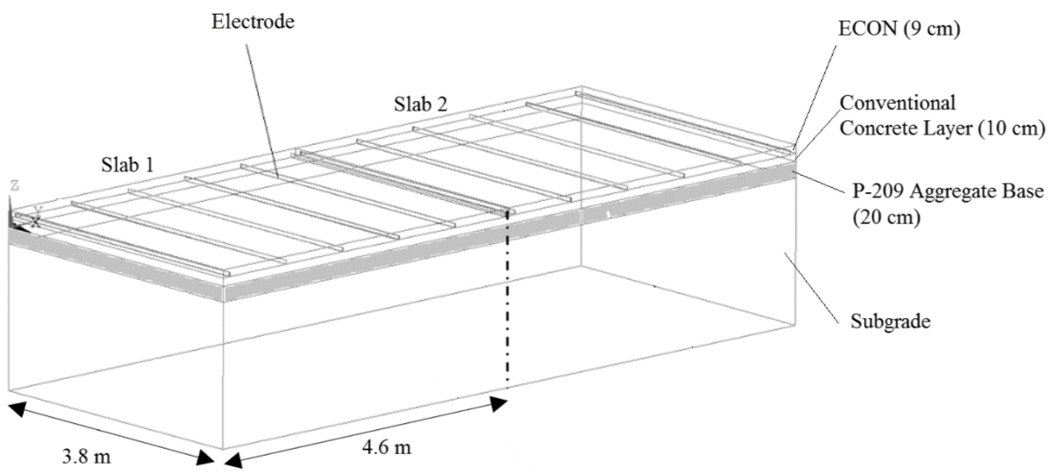

Figure 1. Finite element model of the ECON slabs constructed at Des Moines International Airport

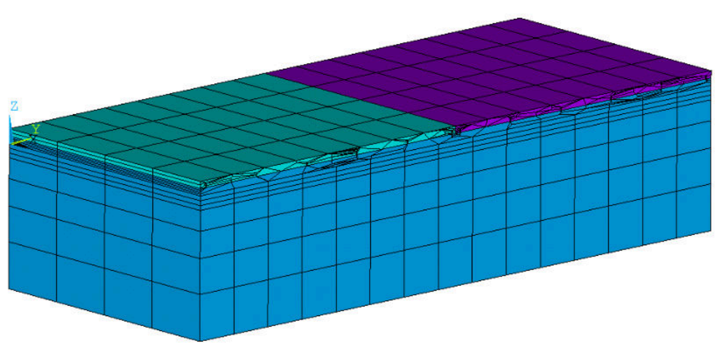

Figure 2. Elements of the FE model of ECON system