Innovative Interlocking Concrete Pavement: Deflection Analysis and Urban Roadway Applications

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Abstract

This research focuses on developing and evaluating an innovative Interlocking Concrete Pavement (ICP) to address challenges in urban businesses and residential areas. Its unique shape distinguishes it from conventional interlocking pavements, making it suitable for urban traffic. Given the uncommon use and distinctive shape of ICPs in urban roadways, pavement surface deflection analysis is crucial for assessing the structural performance and serviceability of this pavement type. Deflection analysis evaluates the pavement's capacity to withstand heavy loads, maintain structural integrity, and demonstrate its performance advantages over traditional designs. The study presents a collaborative effort conducted by the Centre for Pavement and Transportation Technology (CPATT) at Waterloo University (UW), in partnership with Sidewalk Labs, a New York-based sibling company of Google located in Toronto. The primary objective of this study is to evaluate maximum pavement deflection under heavy truck loads and to determine the optimum pavement thickness using a 3D finite element method (FEM). ABAQUS was employed for this analysis, yielding a calculated maximum deflection of -2.1 µm, which is significantly lower than that of conventional interlocking pavements. The optimum pavement thickness was determined to be 20 cm. The results indicate that the proposed ICP exhibits superior deflection

performance under heavy repeated loads. Although the findings are promising, further studies, such as field tests and long-term performance assessments, are needed to confirm the pavement's structural integrity and durability under real-world traffic and environmental conditions. Additionally, the influence of other factors, like thermal effects and subgrade variations, should be investigated to fully integrate this pavement into urban infrastructure.

KEYWORDS: Interlocking concrete pavement (ICP), Deflection analysis, Finite element method (FEM), Sustainable pavement, ABAQUS

INTRODUCTION

Interlocking Concrete Pavements (ICPs) have traditionally been employed in low-speed, light-traffic applications such as pedestrian areas, parking lots, and plazas. Over the last three decades, countries such as Australia, Canada, England, the Netherlands, South Africa, and the United States have extensively studied the structural design of ICPs, leading to increased municipal applications, including city streets and crosswalks (Hein and Burak, 2007). However, the potential use of ICPs in urban roads, particularly in high-traffic environments like collectors and arterials, remains underexplored. To integrate ICPs into urban infrastructure, it is crucial to consider their structural performance, optimize design, and ensure long-term durability.

The proper construction of ICPs can yield excellent performance with minimal maintenance and reduced rehabilitation costs. Choosing suitable materials and designs for specific traffic conditions and environmental conditions significantly enhances pavement service life. Conversely, poorly selected materials, design errors, and improper construction can drastically shorten pavement longevity (Delatte, 2014). Additionally, ICPs require greater attention during site evaluation and construction, particularly for foundation preparation in areas with challenging soil conditions, such as high-clay-content subgrades that may require stabilization (Smith, 2006). Addressing these issues is essential for reducing construction errors and guaranteeing the long-term effectiveness of ICPs in urban settings.

Finite element analysis (FEA) has proven to be a robust tool for assessing pavement performance under various traffic loads, material types, and environmental conditions (Bugher et al., 2019). This method provides important insights into critical parameters such as stress, deflection, and thickness optimization. Recent developments focus on optimizing ICP dimensions and shapes, incorporating sustainable additives to enhance durability and mechanical performance, and refining structural design for urban applications. This study aims to bridge these gaps by analyzing the performance of a novel ICP design tailored for urban environments. Developed in collaboration with Sidewalk Labs, the proposed ICP incorporates larger, structurally enhanced concrete pavers designed for municipal use. Using ABAQUS software, finite element analysis was conducted to evaluate key performance metrics, including stress distribution, deflection, and pavement thickness. The findings provide critical insights into the structural integrity and service life of ICPs in high-traffic urban environments.

LITERATURE REVIEW

Analyzing stress and deformation in roadways under vehicle traffic loads is essential for designing pavements that can withstand long-term use and evaluate their performance under various traffic conditions (Zheng et al., 2012). In the early 1950s, Seddon introduced the integral transform method to calculate the stress distribution when pavements are subjected to pressure forces (Sneddon, 1952). Many

subsequent studies, including Kenney (1954) and Mathews (1958, 1959), employed analytical techniques to assess the stress and deformation of road structures under various loading conditions. However, as traffic and load volumes increased, these empirical models were no longer sufficient to fully capture the pavement behavior.

The FEM has become an indispensable tool in pavement design, as it enables more accurate simulations of pavement performance under various traffic conditions, material properties, and environmental factors. FEM allows for the detailed analysis of parameters like stress, strain, deflection, and thickness optimization, providing a deeper understanding of pavement performance (Bugher et al., 2019). This method is particularly useful for designing ICPs, which feature unique characteristics that depend on the materials, sub-layers, block shapes, and technological innovations employed. Researchers can enhance ICP design for better performance and durability in real-world conditions by analyzing these factors.
In 2016, Lin et al. developed a deflection prediction model for concrete block pavements. Their model included factors such as surface structure, block shapes, and structural patterns, alongside dynamic loading simulations using FEM (Lin et al., 2016). This model aimed to enhance the accuracy of deflection predictions for concrete pavements, particularly under repetitive loading from heavy traffic. Earlier studies also examined the behavior of interlocking concrete pavements under load repetition, focusing on the calculation of stress, strain, and deflection for concrete blocks subjected to repetitive loadings (Molenaar et al., 1965; Tabatabaie and Barenberg, 1978; Tayabji and Colley, 1983; Nishizawa et al., 1984). These studies established the importance of modeling jointed concrete pavements to better understand their long-term performance under traffic loads.

Research on ICPs has expanded to evaluate the effects of different design and material variables on the structural performance of pavements. For example, in 2014, Mampearachchi and Senadeera explored different block shapes and paving patterns using FEM to determine the optimal design for low- to medium-traffic conditions, with a focus on heavy trucks and buses. Their study identified stretcher and herringbone patterns, combined with uni-style block shapes, as the most effective configurations for optimal pavement performance (Mampearachchi and Senadeera, 2014). These configurations were found to improve stress distribution and deflection performance, ensuring the structural integrity of ICPs under heavy traffic conditions.

In a similar vein, Dhanushika and Peiris (2017) developed an FEM-based framework to determine the optimal dimensions for concrete blocks in road applications. Their findings demonstrated that specific block shapes and sizes can greatly lower stress and deflection, enhancing the overall structural performance of the pavement. This research underscored the importance of optimizing block dimensions to achieve the lowest possible stress and deflection, ensuring durability and long service life for ICPs in urban settings.

Di Mascio et al. (2019) investigated concrete blocks' stress-strain behavior, rutting, and fatigue performance in urban and local roads. This study specifically analyzed the performance of interlocking concrete block pavements under different wheel positions, block patterns, and bedding sand thicknesses. The results revealed that rectangular concrete blocks with plane-side surfaces, when used with a cement-treated base layer and granular unbound foundation, exhibited superior resistance to stress and fatigue, making them suitable for high-traffic environments. The use of hexagonal interlocking concrete pavers was also explored, showing promising results in terms of load distribution and long-term durability.
De Larrard et al. (2013) investigated the performance of impermeable equilateral hexagonal concrete pavers exposed to heavy traffic loads over nearly a year. They found that ICPs demonstrated satisfactory behavior with minimal cracking under truck loads, indicating the viability of hexagonal designs for urban

pavements. The equilateral hexagonal shape helped reduce the risk of angular failure under traffic loads, contributing to the long-term durability of the pavement Additionally, these pavers generated less noise than traditional pavements, providing environmental and social advantages. The innovative design addressed structural issues and contributed to more sustainable urban infrastructure by lowering noise pollution and enhancing construction efficiency.

The goal of sustainable pavement design is not only to meet structural, and traffic demands but also to address social, environmental, and economic concerns. Sustainable pavement solutions take into account factors like public safety, construction costs, vehicle operation, and maintenance, while also reducing environmental impacts such as energy use, greenhouse gas emissions, and stormwater runoff. Current developments have concentrated on researchers' efforts to create durable and ecologically friendly products using advanced materials and technology (Van Dam et al., 2015).

Concrete pavements, particularly those made from interlocking pavers, have been identified as a cost-effective and environmentally friendly alternative to traditional pavement solutions. These pavements offer the advantage of preserving the existing surface while reducing material use, thus lowering construction costs. Additionally, concrete pavements last longer and need less maintenance, which decreases the frequency of rehabilitation (TAC, 2013). Li et al. (2013) highlighted two major environmental issues heat islands and stormwater runoff that can be mitigated using permeable interlocking concrete pavements. Their study, conducted at the University of California Research Center (UCPRC), demonstrated that permeable pavements reduce solar radiation absorption, minimize heat island effects, and allow water to drain through the pavement surface, thereby reducing stormwater runoff. These benefits position ICPs as an ideal solution for urban areas facing environmental challenges such as heat islands and poor drainage (Li et al., 2013).

In summary, the literature reveals the significant potential of interlocking concrete pavements, particularly when optimized through FEM and other analytical techniques. From improving structural performance and deflection resistance to addressing environmental and economic challenges, the design and application of ICPs are evolving rapidly. The use of innovative block shapes, patterns, and materials is crucial to the continued advancement of this pavement type, and future studies should further explore the long-term behavior of ICPs under various traffic loads and environmental conditions.

RESEARCH METHOD AND MATERIALS

This study introduces a novel approach to urban roadway infrastructure by developing innovative ICPs designed to withstand high-traffic conditions while addressing sustainability, durability, and maintenance challenges.

Research methodology

The research methodology is outlined in Figure 1.

Materials

Basic Components

- Coarse Aggregates: Provide strength and stability.
- Fine Aggregates: Ensure proper compaction and density.

- Portland-Limestone Cement (PLC): Acts as the primary binding agent.
- Water: Facilitates hydration and workability.

Additional Components

- Slag: Enhances durability and reduces carbon footprint.
- Ground Glass Pozzolans: Improves mechanical properties and lowers permeability.
- Fibers: Reinforces tensile strength and mitigates cracking.
- Water-Reducing Admixtures: Improves workability and reduces water-cement ratio.

Modeling and simulation

Finite Element Modeling (FEM) was employed to simulate the ICP's structural performance using ABAQUS software. Key steps include:

1. ***Geometry and Meshing:***
   - Adopted a hexagonal interlocking pattern for efficient load distribution. The specific ICP design is illustrated in Figure 2, showcasing its modular, sustainable, and structural features.
   - Optimized mesh sizes to balance computational efficiency with accuracy.
2. ***Material Properties:***
   - Defined elastic modulus, Poisson's ratio, and density for all pavement layers.
   - Incorporated sustainable materials to reflect real-world applications.
3. ***Boundary Conditions and Loading***
   - Applied urban traffic loads (827.4 kPa tire pressure).
   - Defined boundary constraints to simulate realistic conditions.
4. ***Performance Evaluation****:*
   - Analyzed deflection behavior under heavy loads.
   - Verified results against laboratory tests to ensure reliability.
   - The meshing strategy for the finite element model is illustrated in Figure 3, showing the detailed honeycomb pattern and foundation discretization essential for accurate FEM analysis.

Table 1 summarizes the material and layer attributes used in the ABAQUS finite element model. Omidi's thesis provided the dataset (Omidi, 2021), including the elastic modulus (E) and Poisson's ratio (v) for each layer: concrete blocks, bedding sand, cement-treated base (CTB), recycled-aggregate subbase, and sand/gravel subgrade. The section model featured layers that were (200, 40, 150, and 200) mm thick. Rather than a Winkler foundation, the subgrade was modelled as a continuum layer. The Material → Elastic module was used to specify these parameters, which were then assigned to each part. When density data were not available, standard literature values were used to facilitate mass calculations as necessary. The 200 mm paver thickness was retained from the large-format, two-part hexagonal IFSTTAR design intended for heavy urban traffic applications. This thickness was evaluated as part of the proposed pavement system and was not selected through a comparative optimization of different block thicknesses. Therefore, the study does not suggest 200 mm as a universal optimum thickness for all ICP applications.

Based on the findings of Jessica Achebe (2022), the optimal mix design adopted in the present FEM was determined through an integrated assessment of environmental performance and structural properties. The chosen formulation, comprising 70% limestone cement (GUL), 20% slag, and 10% glass pozzolan, achieved a good balance between mechanical strength and energy efficiency. This mixture includes a significant amount of supplementary cementitious materials, helping to significantly reduce carbon emissions while still providing sufficient structural performance. For more details, please refer to Achebe's (2020) thesis.

Sustainability considerations

- The integration of eco-friendly materials such as slag and recycled aggregates reduces greenhouse gas emissions, and sustainable strategies encompass (Al-Bayati et al., 2016, Al-Bayati, 2019, Chhetri et al., 2024).
- Reduced Material Usage: Optimized thickness minimizes resource consumption.
- Environmental Impact: Incorporation of recycled materials and supplementary cementitious materials significantly lowers carbon emissions.
- Economic Benefits: Long-lasting pavements reduce maintenance costs.

RESULTS AND DISCUSSION

Optimal pavement thickness

An adequately designed ICPs must perform well under various geological, traffic, environmental, and operational conditions. The pavement thickness is critical for determining its structural capacity and service life. For urban roadways subjected to heavy traffic, the thickness must be greater than that of pavements for light-traffic areas, such as parking lots or sidewalks. Ensuring sufficient thickness reduces deflection and increases resistance to repetitive loads.

Different pavement thickness scenarios were analyzed FEM in ABAQUS. The results for deflection under varying thicknesses are summarized in Table 2. As shown, increasing thickness significantly reduces vertical displacement. However, diminishing returns are observed beyond a thickness of 20 cm, as the difference in deflection between 20 cm and 21 cm is minimal compared to the difference between 19 cm and 20 cm.

The Finite Element Modelling (FEM) results' curve-fitting analysis shown in Figure 4 indicates that a pavement thickness of 20 cm is optimal for balancing cost and effectiveness. Although thicker pavements of more than 20 cm do not considerably improve deflection reduction, they result in higher construction and material costs.

Deflection analysis

Deflection is a critical parameter for assessing the structural integrity of pavements under traffic loads. The maximum allowable deflection for urban road pavements is 3.8 mm based on guidelines from the "*Asphalt Overlays for Highway and Street Rehabilitation*" (MS-17) specification. The FEM analysis of the

proposed ICP indicates a maximum deflection of 0.0021 mm, significantly lower than the allowable limit, demonstrating the pavement's excellent performance.

Figure 5 illustrates foundation's deformation contour along the Z-direction, revealing the deflection distribution under heavy loads. Maximum deformation occurs directly beneath the loaded concrete blocks. Figures 6 and 7 show deflection paths for the foundation and the concrete pavers, respectively. These paths emphasize the areas of maximum deflection, enabling specific enhancements.

Figure 8 provides a detailed view of the displacement of nodes along path-1 in the Z-direction. This visualization helps identify key deformation areas that need further investigation or design refinements.

Discussion

The results indicate that the proposed ICP design, with a thickness of 20 cm, effectively minimizes deflection under heavy urban traffic conditions. Compared to conventional designs, the innovative ICP demonstrated superior performance, attributed to its optimized geometry, material composition, and structural configuration.

The detailed node displacement analysis (Figure 8) reinforces the reliability of the FEM approach, showcasing the ability to pinpoint and address critical deformation zones. These insights can inform the improvement of material properties and structural designs, leading to better pavement performance.

This study highlights the importance of integrating finite element analysis in pavement design to achieve optimal structural performance. Further validation through field tests is recommended to corroborate the FEM results under real-world traffic and environmental conditions. Additionally, investigating the effects of thermal variations and subgrade properties would enhance the robustness of the design.

In conclusion, the proposed meets and exceeds urban roadways' structural requirements, offering a sustainable and durable solution for modern infrastructure challenges.

CONCLUSIONS

This study has presented the development and evaluation of an innovative Interlocking Concrete Pavement (ICP) designed for urban roadways subjected to heavy traffic. The finite element analysis conducted using ABAQUS confirmed the structural robustness of the design, with an optimal pavement thickness of 20 cm resulting in a maximum deflection of 0.0021 mm, well below the allowable limits. This result underscores the superior load-distribution properties of the proposed ICP, driven by its novel geometry and sustainable material composition.

The findings demonstrate that the proposed ICP design not only meets but exceeds the requirements for high-traffic urban roads, providing a sustainable and economically viable alternative to conventional pavement systems. While the FEM-based approach offers significant insights into deflection and stress behavior, the study highlights the importance of field validation to confirm long-term performance. Future

research should focus on environmental factors such as thermal variations, subgrade variability, and the effects of repetitive load cycles across long durations.

This research integrates advanced modelling techniques with innovative design and materials, such as slag, ground-glass pozzolans, reinforcing fibres, and water-reducing admixtures, advancing sustainable, high-performance pavement solutions for urban infrastructure.

Table 1. Inputs for materials and layers used in the FE model (Omidi, 2021).

Component	Section label	Thickness	Elastic modulus, E	Poisson's ratio, v
ICP concrete block (PLC 70%, Slag 20%, GP 10%, with RCA)	A	200 mm	17,000 MPa	0.19
Bedding sand (coarse)	B	40 mm	100 MPa	0.30
Cement-treated base (CTB)	C	150 mm	5,170 MPa	0.20
Recycled aggregate subbase (coarse)	D	200 mm	200 MPa	0.35
Subgrade (sand & gravel)	E	modeled thick / fixed base	60 MPa	0.40

Note: The thesis reports E and v for each layer; densities were defined in ABAQUS (dynamic implicit) but not tabulated in the thesis. If needed, typical values can be adopted (e.g., 2400 kg/m³ for concrete).

Table 2. FEM Results for different pavement thickness (Omidi, 2021).

Thickness of Pavement (m)	Results of FEM (m)
0.1600	0.0041
0.1700	0.0036
0.1800	0.0030
0.1900	0.0025
0.2000	0.0021
0.2100	0.0019
0.2200	0.0017

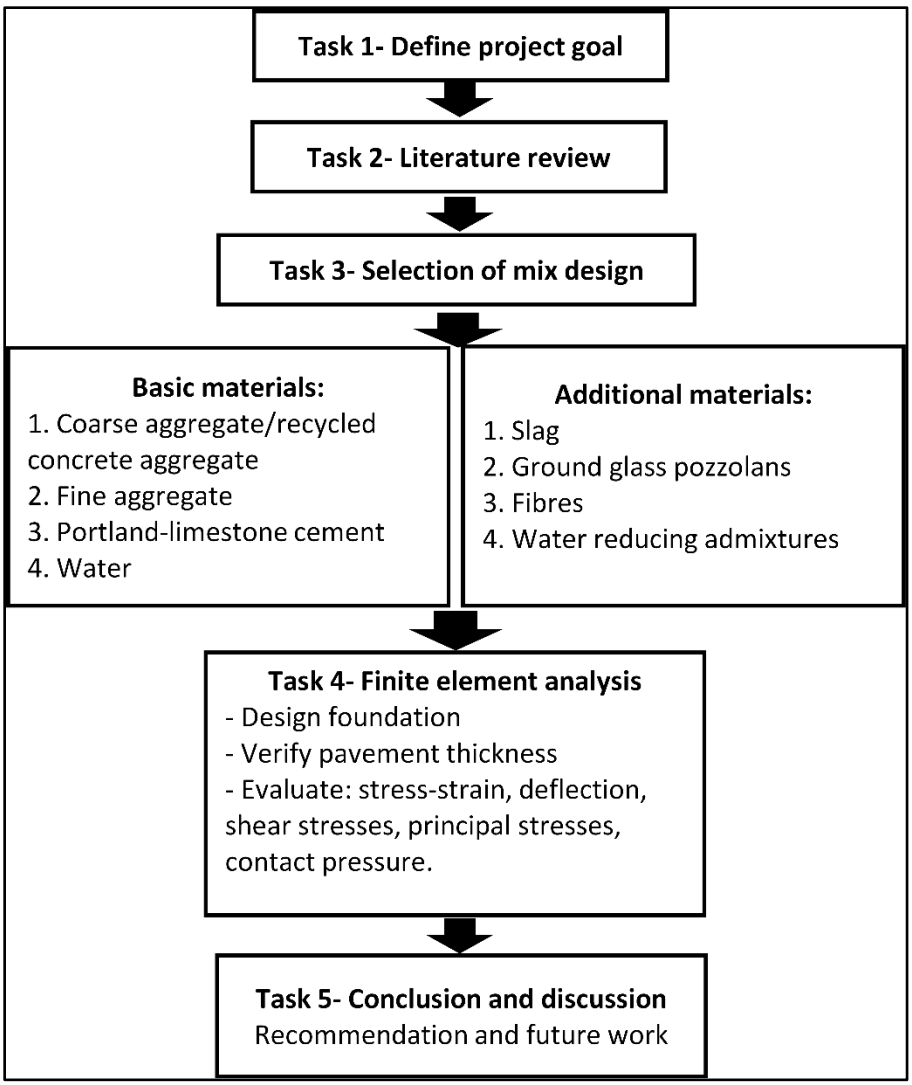

Figure 1. Research methodology.

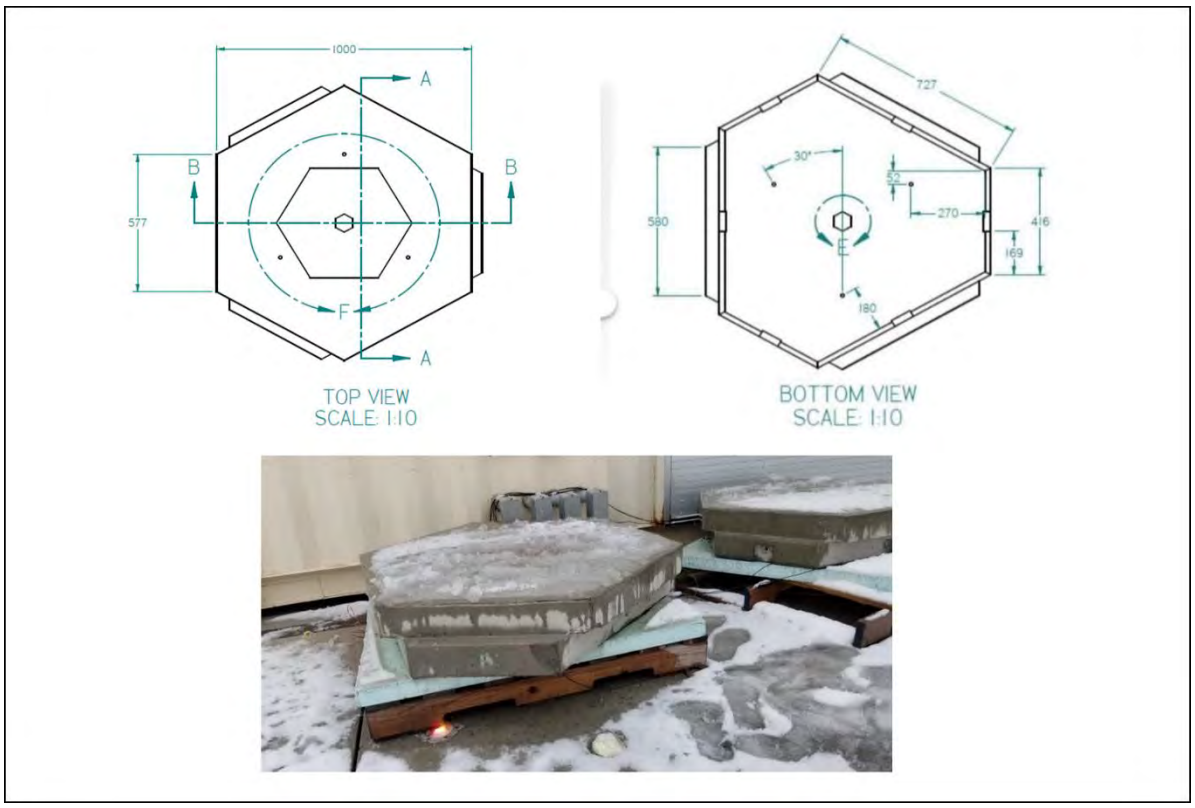

Figure 2. Innovative Interlocking Concrete Pavement Design alongside the concrete paver fabricated at Sidewalk Lab Toronto (Omidi, 2021).

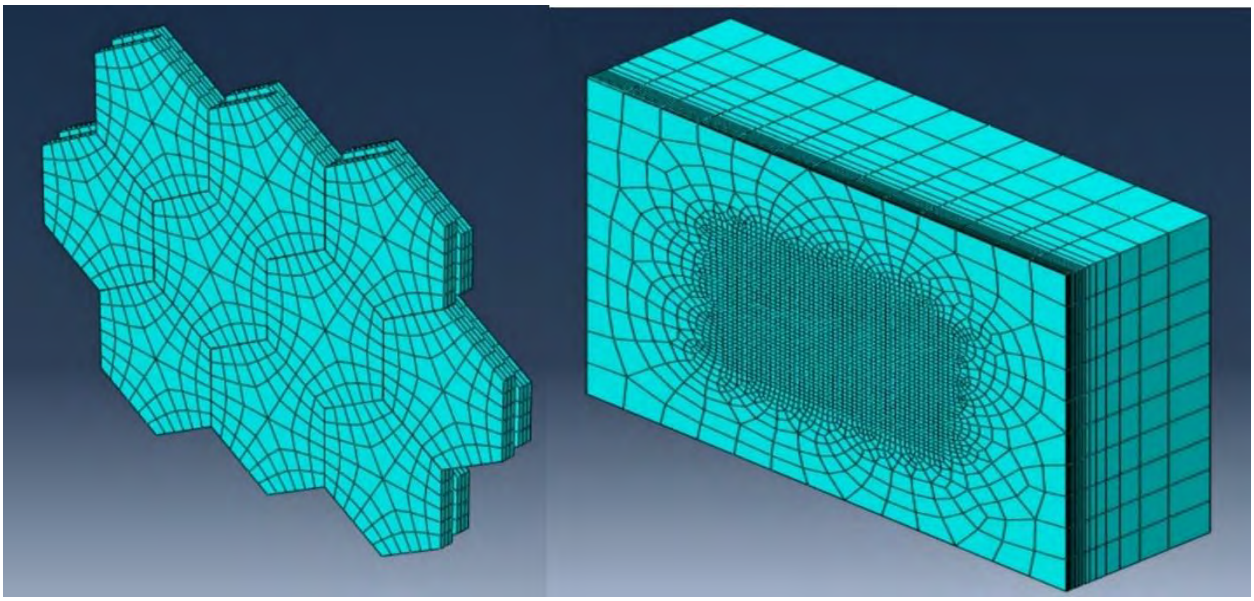

Figure 3. Mesh of honeycomb pattern and foundation illustrating the finite element discretization used in the modeling (Omidi, 2021).

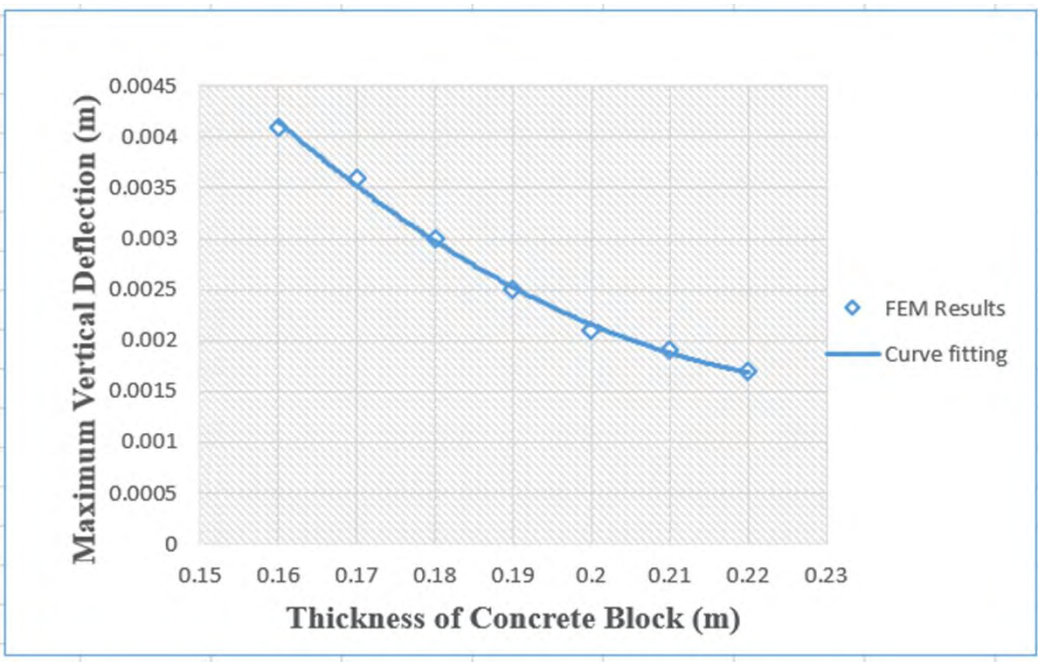

Figure 4. Deflection vs. Pavement Thickness (Omidi, 2021).

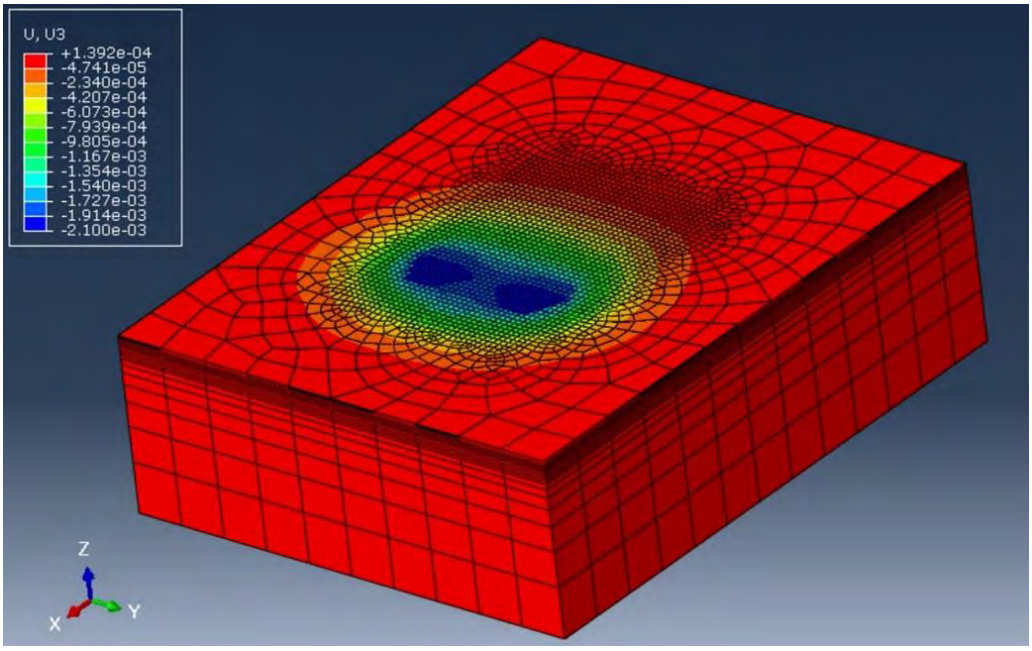

Figure 5. The deformation of the foundation in Z direction (Omidi, 2021).

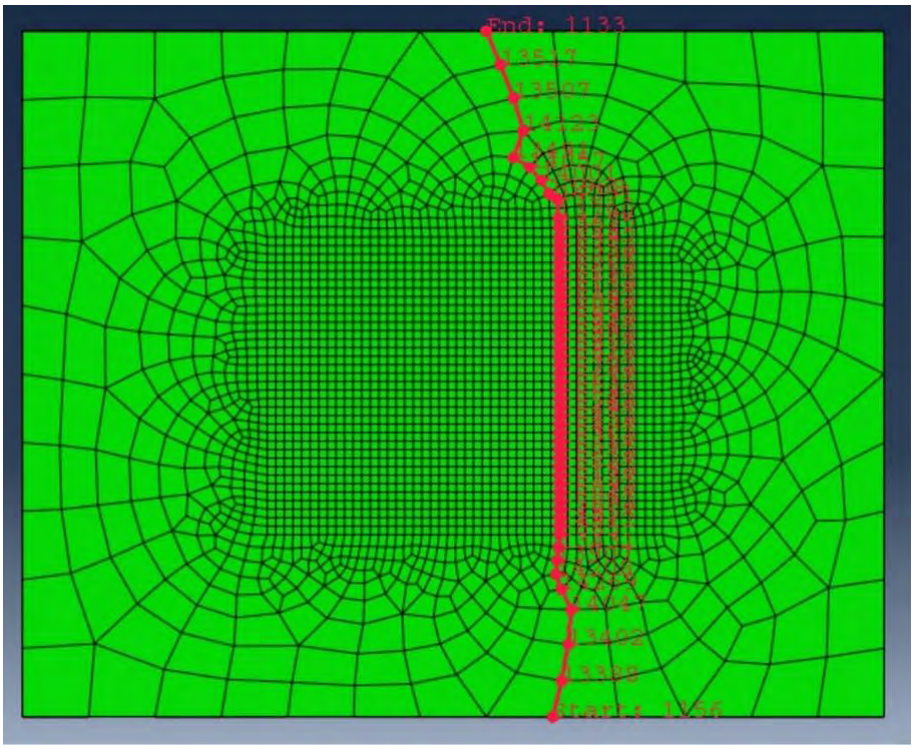

Figure 6. Deflection path in foundation (Omidi, 2021).

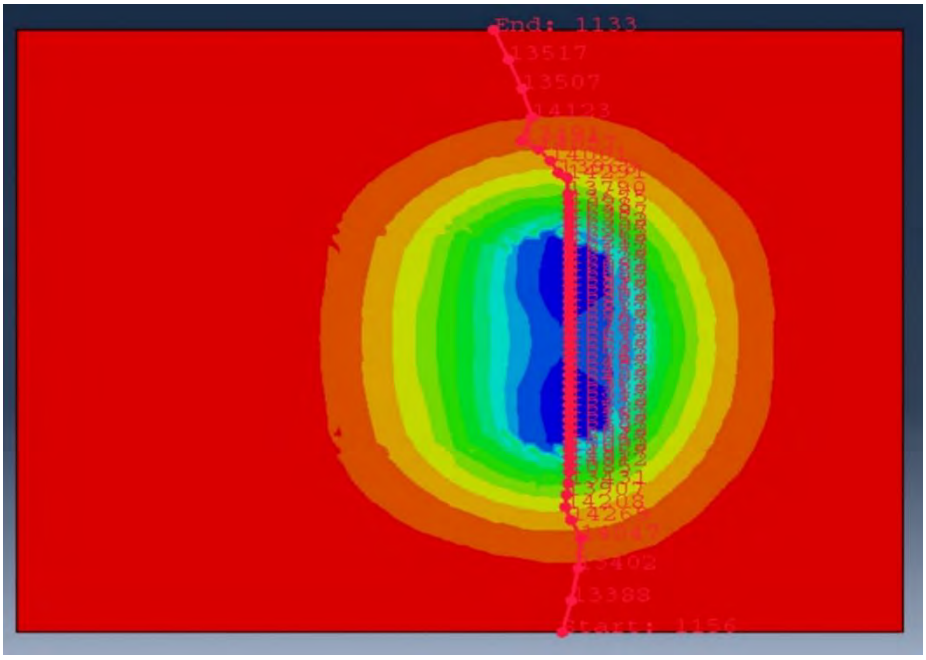

Figure 7. Deflection path in concrete pavers (Omidi, 2021).

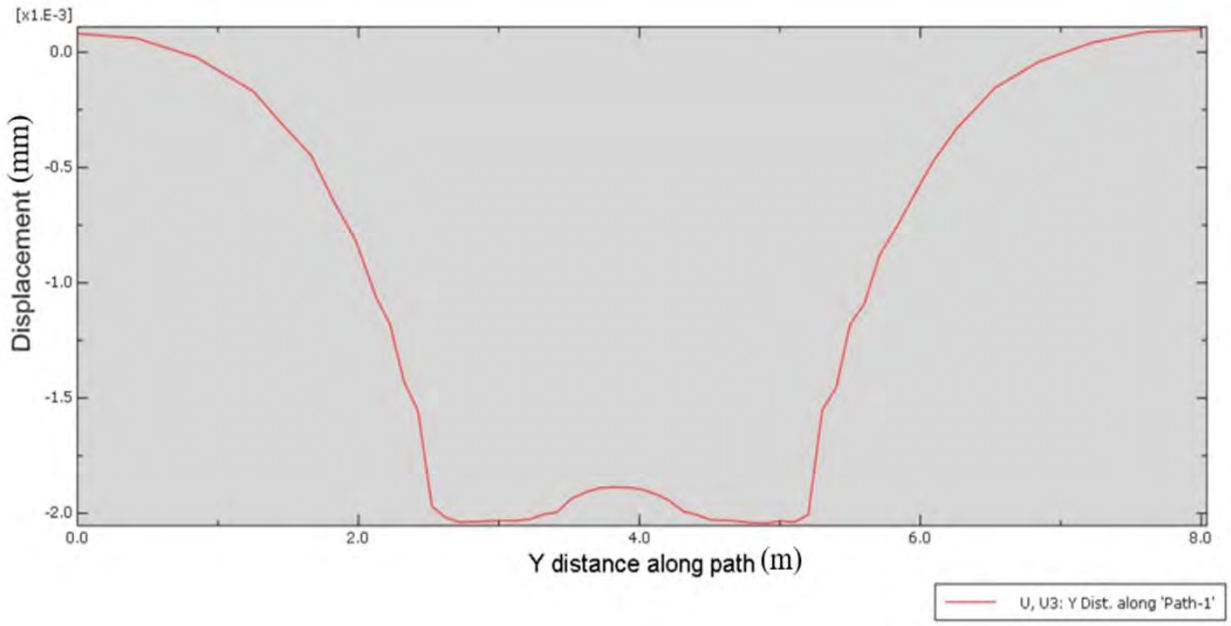

Figure 8. The Z-direction displacement of the nodes in path-1 (Omidi, 2021).

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