Prestressed Concrete Pavement: Design and Analysis

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ABSTRACT

To understand behavior patterns of prestressed concrete pavements it is helpful to first review those of conventional concrete pavement. In the past 15 years the possibility of using prestresssed concretefor highway and airfield pavement has become of increasing interest to egineers. Design investigation and limited testing of model and prototype slabs have indicated that prestressed pavements permit a more efficient use of construction material in terms of required pavement thickness. Prestressed pavement can be designed with fewer joints and with less probability of cracking than conventional rigid pavements, thereby promising extended pavement life and reduced maintenance requirement.

Keyword: - *Prestressed precast concrete pavement, Pavement*

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1. INTRODUCTION

In a developing nation like India, roads play a crucial role in connecting various regions, including remote areas that rely on nearby urban centers for their daily necessities. The pavement serves as the lifeline of any country. With the recent improvement in the lifestyles of people residing in urban areas, almost every household now owns vehicles such as cars, bikes, and scooters. Consequently, urban areas have experienced a sudden surge in traffic, making the construction and repair of roads increasingly challenging to manage.

As a result, rigid pavements have emerged as the preferred choice over bituminous pavements in urban areas due to their extended lifespan and reduced maintenance requirements. The durability and low maintenance characteristics of concrete pavements have made them increasingly popular. However, constructing rigid concrete pavements is a time-consuming process that often leads to significant traffic congestion during the construction phase.

Consequently, there has been a search for new concrete pavement technologies that can be constructed quickly without compromising the quality of the pavement.

1.1 General

During the construction of concrete pavements in India, two major challenges are encountered: substandard construction quality and lengthy construction periods. Achieving improved concreting quality in Cast-in-Place (CIP) pavements is practically unattainable due to fluctuations in climatic conditions and the inability to ensure consistent curing throughout the entire pavement stretch. This research aims to address these limitations by introducing the concept of Precast Concrete Pavement (PCP). PCP offers a solution to overcome these shortcomings by employing a construction procedure similar to that of CIP pavements. The base course required for PCP is prepared in the same manner as traditional concrete pavements. However, an additional leveling course is necessary just below the precast panels. These panels are constructed off-site and then placed directly on the prepared base. If the base is not properly levelled, it can lead to the generation of additional stress at that specific point.

The following are the primary distinctions between precast and CIP pavements:

a. Construction Process: The construction process for conventional pavements consists of several on-site steps. Precast concrete pavements, on the other hand, are built by manufacturing precast elements off-site, which reduces on-site construction time.

b. Quality Control: Precast concrete pavements undergo manufacturing in a factory-controlled environment, ensuring consistent quality and durability. On-site factors such as weather, traffic, and other environmental factors, on the other hand, can affect the quality of conventional pavements.
c. Cost: When compared to conventional pavements, precast concrete pavements can save up to 30% on construction costs. This is due to the fact that precast elements can be manufactured off-site, lowering on-site labour and material costs.
d. Durability: Precast concrete pavements are extremely durable, withstanding heavy loads as well as harsh weather conditions. As a result, they are appropriate for high-traffic areas such as highways, airports, and ports.

The utilization of precast panels in casting yards offers significant advantages in terms of maintaining their quality. These panels are manufactured in a controlled environment, ensuring optimal conditions for their production. Only after gaining full strength are they transported to the construction sites. As a result, the occurrence of early age cracks and other environmental distress factors is effectively eliminated. The second major issue associated with the lengthy construction period of Cast-in-Place (CIP) pavements can also be addressed through the implementation of Precast Concrete Pavement (PCP) technology. With PCP, as the panels are cast in yards and the base preparation takes place on-site, the overall construction period can be reduced by approximately 50% compared to CIP pavements. This particular feature of PCP provides several advantages, including the reduction of risks associated with traffic congestion, decreased user costs due to lower fuel consumption, ease of construction in remote areas where it may be challenging to provide all the necessary construction machinery, and faster repair and maintenance work in case of any issues with the precast panels..

PCP panels can be prestressed which can further enhance the performance of the pavement. Use of prestress makes it possible to reduce the thickness of PCP panels considerably, which in turn helps in optimum utilization of material. With decrease in thickness of PCP panels handling and transportation of panels becomes easy. As per literature, using prestress can reduce the thickness of PCP panel, thus leading to ease in handling and transportation of panel. With increasing popularity of concrete pavement and exponential growth of traffic in India study of these technology and suitability for Indian suburban region

1.2 Types of Precast Concrete Pavements

There are several types of precast concrete pavement systems, each designed for specific applications and construction requirements. Here are some of the most common types of precast concrete pavement:

a. Precast Concrete Slabs:

The most common type of precast concrete pavement system is the precast concrete slab. They are usually rectangular in shape and can be used for a variety of purposes such as highways, parking lots, and pedestrian walkways. Precast concrete slabs are built off-site and delivered to the job site for installation. They are usually pre-stressed in order to increase their strength and durability.

b. Precast Concrete Panels:

Similar to precast concrete slabs, precast concrete panels are typically larger in size and thickness. Airport runways, taxiways, and aprons, as well as port pavements, are common uses for them. Precast concrete panels are built off-site and delivered to the job site for installation. They are usually pre-stressed in order to increase their strength and durability.

c. Precast Concrete Blocks:

Precast concrete blocks are typically used for low-speed applications such as parking lots, pedestrian walkways, and bicycle paths. They come in a variety of shapes and sizes and can be arranged in a variety of patterns to create an aesthetically pleasing surface. Precast concrete blocks can also be used to build retaining walls and other landscaping features.

d. Precast Concrete Pavers:

Precast concrete pavers are similar to precast concrete blocks but thinner and are typically used for pedestrian walkways, patios, and landscaping applications. They come in a variety of shapes, sizes, and colours and can be arranged in various patterns to create an aesthetically pleasing surface.

e. Precast Concrete Bridge Decks:

Precast concrete bridge decks are used to build bridges and other elevated structures. They are built off-site and delivered to the construction site for installation. To increase strength and durability, precast concrete bridge decks are typically pre-stressed.

f. Prestressed Concrete Pavement:

A type of precast concrete pavement designed to withstand high tensile stresses is called prestressed concrete pavement. Prestressed concrete pavement is made with steel cables that are pre-tensioned or post-tensioned and embedded in the concrete to create a compressive force that counteracts the tensile stresses caused by traffic loads. This type of precast concrete pavement is frequently used for bridge decks and other applications requiring high tensile stresses

1.3 Applications of PCP

Precast concrete pavement is the construction technique that employs precast concrete slabs, panels or blocks that are manufactured off-site and transported to the construction site for installation. This pavement construction method has grown in popularity in recent years due to its numerous advantages, including cost savings, durability, quick installation, and sustainability. Precast concrete pavement systems can be used for a variety of purposes, including:

a. Highways:

Owing to their ability to withstand heavy loads and harsh weather conditions, precast concrete pavement systems are commonly used for highway construction. Precast concrete slabs can be manufactured off-site and transported to the job site for quick installation, reducing construction time and traffic disruptions.

b. Airports:

Since they can withstand heavy aircraft traffic, precast concrete pavement systems are commonly used for airport runways, taxiways, and aprons. Precast concrete slabs can be manufactured according to precisely defined specifications and installed quickly, reducing airport downtime.

c. Ports:

Knowing that they can withstand heavy container traffic and harsh marine environments, precast concrete pavement systems are used for port pavements. Precast concrete slabs can be intended to withstand the unique conditions of port operations, such as saltwater exposure and frequent heavy loads.

d. Parking Lots:

Due to the fact that they provide a stable and durable surface for vehicle traffic, precast concrete block pavements are commonly used for parking lots. Precast concrete blocks can be manufactured in a variety of sizes, shapes, and colours, allowing for customization to meet specific design requirements.

e. Pedestrian Walkways:

As they provide a safe and stable surface for foot traffic, precast concrete block pavements are also commonly used for pedestrian walkways. Precast concrete blocks can be developed with non-slip surfaces and arranged in a variety of patterns to improve their aesthetic appeal.

f. Bicycle:

Given that they provide a smooth and durable surface for bicycles, precast concrete pavement systems are also suitable for bicycle paths. Precast concrete slabs can be manufactured in a variety of sizes and shapes to meet specific design needs, such as accommodating curves and intersections.

g. Military Bases:

Owing to their durability and ability to withstand heavy military vehicles, precast concrete pavement systems are used in military bases. Precast concrete slabs can be designed to withstand blast and impact loads, making them suitable for military use.

h. Industrial Facilities:

Because of their ability to withstand heavy equipment and chemicals, precast concrete pavement systems are used in industrial facilities. Precast concrete slabs can be made with chemical-resistant coatings and designed to withstand heavy loads on frequently.

1.4 Objective of Research

The research on Finite Element (FE) analysis and design of precast concrete pavement aims to enhance our understanding of the behaviour of such pavements and develop design methods that ensure their long-term performance. FE analysis involves utilizing computational techniques and numerical methods to model and predict the complex structural behavior of precast concrete pavements. In comparison to traditional cast-in-place concrete pavement, precast concrete pavement is a relatively new technology that offers potential advantages such as faster construction, extended service life, and reduced maintenance costs. However, the design and analysis of precast concrete pavement present challenges due to their intricate nature, requiring a comprehensive comprehension of the behaviour of individual precast panels and their interaction with the supporting base layers.

The following are the specific objectives of research focusing on analysis and design of precast concrete pavement:

a. To create FE models of precast concrete pavement that are reliable and accurate enough to simulate the behaviour of individual panels, joints, and supporting layers.
b. To assess the performance of precast concrete pavement under a variety of loading and environmental conditions, such as traffic loading, and temperature changes,
c. To investigate the effect of various design parameters on the performance of precast concrete pavement, such as joint spacing, joint type, panel geometry, and material properties.
d. Identifying potential failure modes of precast concrete pavement under various loading and environmental conditions, as well as developing mitigation measures to improve long-term performance.
e. The performance of precast concrete pavement has to be compared to that of traditional cast-in-place concrete pavement and other alternative pavement systems.

Overall, the objective of the research is to improve the design and construction of precast concrete pavements, as well as to ensure their long-term performance and sustainability. The findings of such studies can be used to develop guidelines and standards for the use of precast concrete pavement in transportation infrastructure projects.

2. TESTING

Testing precast concrete pavement after placement is crucial to verify its compliance with design specifications and ensure its performance as intended. Several tests can be conducted to assess different aspects of the pavement:

Bonding Testing: Evaluating the bond between the precast concrete pavement panels and the subbase is essential for the structural integrity and durability of the pavement. Factors such as surface preparation, quality of bonding agents, and curing conditions can affect bonding. Proper construction practices and quality control measures should be followed to ensure consistent and reliable bonding.

Load Testing: Load testing is employed to assess the load-carrying capacity of the precast concrete pavement. It involves applying a known load to the pavement and measuring the resulting deflection response. Static load testing or dynamic load testing, using equipment like a falling weight deflectometer (FWD), can be used to perform this evaluation.

Load Transfer Efficiency: The effectiveness of the load transfer system within the precast concrete pavement can be assessed by calculating the deflection-based load transfer efficiency. This measure indicates how well the load is transferred between adjacent pavement panels, ensuring uniform distribution of the applied loads.These testing methods provide valuable insights into the performance and structural integrity of the precast concrete pavement, allowing for adjustments or improvements if necessary.

Fig. 3.1: Load Transfer Efficiency Calculation for Joints (Smith and Snyder, 2021)

To assess the pavement joints' capacity to transfer loads between adjacent panels, joint load transfer efficiency testing is employed. In this test, one panel is loaded, and the deflection reaction at the joint between the two panels is measured. Based on the amount of load transferred to the adjacent panel, the load transfer efficiency is determined using eq. xx.

$\% LTE = \Delta\_UL/\Delta\_L$

Here LTE is the load transfer efficiency of the joint in percent, ΔL is the deflection at the center of the load plate and ΔUL is the deflection 6 inches from the joint on the unloaded side of the joint. Theoretically, LTE values range from zero (i.e., no deflection on the unloaded side) to hundred (i.e., equal deflections on both sides of the joint– see Fig. 3.1). In practise, LTE values rarely approach 0 and are usually slightly less than 100, though they can exceed 100 due to testing anomalies with specific pavement structures.

Non-destructive testing methods, such as Ground Penetrating Radar (GPR) and Ultrasonic Testing (UT), can be used to assess the quality of precast concrete pavements without causing damage to the pavement. These methods can be used to detect voids, delamination, and other flaws in the pavement's performance.

Surface texture is also assessed to determine the skid resistance and roughness of the pavement. This test involves measuring the surface texture of the pavement with a device such as a profilometer. For development perfectly skid resistant precast pavement without development of cracks formed due to tining with brooms can be avoided with use of reverse casting technology for manufacturing pavement with skid resistant marks.

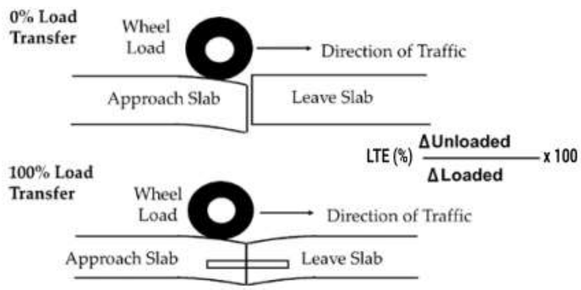

Fig. 1 Load Transfer Efficiency Calculation for Joints (Smith and Snyder, 2021)

3. ANALYSIS AND DESIGN

The Indian Road Congress (IRC) has published IRC 58-2015 guidelines for the design and analysis of concrete pavement in India. The guidelines provide recommendations for the design of concrete pavement based on the expected traffic load, environmental and climate conditions, and material properties. The following is a brief overview of the design and analysis of concrete pavement as per the IRC 58-2015:

a. It considers the expected traffic load, including the axle load, wheel load, and traffic volume over the design life of pavement. The traffic load is used to determine the thickness and strength of the pavement slab.

b. It considers the environmental and climate conditions of the area where the pavement will be constructed. Factors such as temperature, rainfall, and freeze-thaw cycles can affect the performance of the pavement.

c. It considers the alignment, grade, and cross slope of the pavement. The geometric design should be based on the expected traffic load and the environmental and climate conditions.

d. It considers the strength and stability of the subgrade on which the pavement will be constructed.

e. It specifies the properties and characteristics of the materials to be used, including the concrete mix design, reinforcement, and any other additives.

In the absence of design standards for PCP, design guidelines used for concrete pavement i.e. IRC 58-2015 is used. Vaitkus et. al. (2019) based on research concluded that design procedure of cast-in-place Jointed Plain Concrete Pavement (JPCP) is similar to Precast Concrete Pavements (PCP).

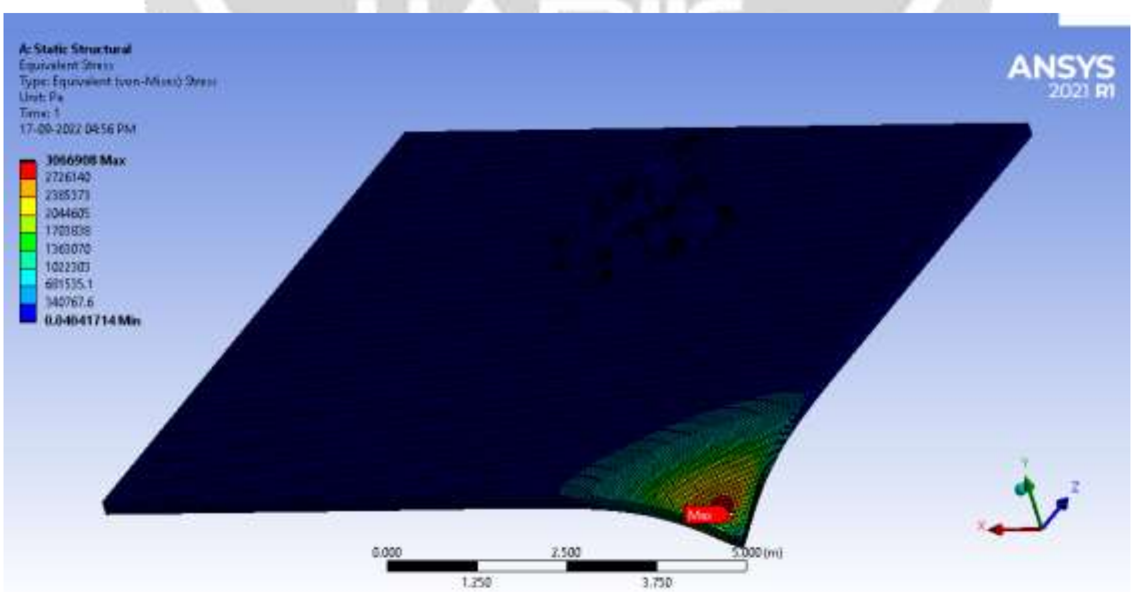

Fig.2 Stress Intensity Contour for Corner Loading of 100 kN Single Wheel Loa

4. OBSERVATION

In the present study, various guidelines for design of concrete pavement has been studied. Finite element model for concrete pavement without shoulder and for widened outer lane has been developed. Later the effect of change in size of pavement panel was studied. This models were used to study the effect of different design parameters on critical stresses. Also, existing PPCP pavement and newly developed trial stretch of Reverse Casted pavement was tested. Critical observations made from the study are presented below.

4.1.1 Observation on Analysis with existing Design Codes:

a. The model developed as per PCA (1984) guidelines subjected to axle loads as per the same, developed stresses which were in good agreement with formula proposed in guidelines.

b. The critical stresses calculated using IRC 58-2002 does not match with analysis results but are higher than them.

c. The critical stresses calculated approximately match with charts or regression equations proposed in IRC 58-2015, but they are slightly higher for some subgrade modulus values and lower for other values than that calculated using equation or charts.

d. The critical stresses calculated using regression equations of IRC 58-2015 does not match with charts provided in same guideline. Thus regression equations needs some modifications.

e. The critical stresses calculated for subgrade modulus of 79.9 MPa/m and 80.1 MPa/m using regression equation differ by up to 15% . Similarly, stresses differ by up to 20 % for 149.9 MPa/m and 150.1 MPa/m subgrade modulus. Thus modification are greatly required to avoid such discontinuity in results.

f. All the design guidelines are based on thickness design criteria, considering particular size of panel as reference. Thus design guidelines are needed to be modified to care of size effect of pavement.

4.1.2 Observation on Parametric Analysis

a. The study of effect of change in panel size carried out suggested that there is significant effect of panel size on critical stresses developed only due axle load .

b. The critical stresses developed due to axle load decreased by upto 80 % with decreasing size of panel from 4.5 m to 2.5 m.

4.1.3 Observation on Modified Stress Coefficient Equations

a. The modified stress coefficient equation can be used to determine maximum flexural stresses developed under axle loads, with effect of size of panel also taken into account.

b. The method gives accurate and comparable results with that of FE results for different panel sizes.

c. These method uses radius of relative stiffness for stress calculation. Therefore, there is no restraint for using particular modulus of elasticity or poissons ratio and hence more realistic and accurate results can be calculated.

5. CONCLUSIONS

a. The design of concrete pavement as per IRC 58-2015 have become more convenient and easy with creation of input dialog box and output message box

b. Existing design codes have a drawback that they are only for thickness design of concrete pavements. Thus an attempt has been made in this research to include effect of size in design methodology for calculation of maximum flexural stresses.

c. Modified Stress Coefficient Equation of Simplified Approach give accurate results for maximum flexural stresses, considering effect of change in size of panel, subgrade modulus, modulus of elasticity, and poissons ratio.

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