1.1 Introduction

Road infrastructure plays a vital role in the economic growth of a developing country like India. Government of India has identified road transportation as one of its priority sectors and accordingly formulated several ambitious road development programmes like *National Highway Development Project (NHDP*), *Pradhan Mantri Gram Sadak Yojana (PMGSY)* etc. Many State Governments have also taken up a number of road projects in the recent past. All these projects aim to provide new generation roads which are capable of handling the increasing number of vehicles with comfort, speed and safety.

Traditionally, most of the road pavements in India have been designed and constructed as bituminous pavements due to their low initial cost. However, compared to concrete pavements, bituminous pavements undergo faster deterioration when exposed to high traffic volumes and adverse moisture and temperature conditions and thus require recurring maintenance. Cement concrete pavements are being adopted nowadays for many new road projects in view of their distinct advantages over bituminous pavements. They are easy-to-maintain, durable, provide good riding surface and result in lower life cycle cost. Also, in city streets, drainage of water during the monsoon is generally poor and therefore, concrete road has become the obvious choice for many urban authorities in India.

Cement concrete pavements are being constructed in several hundreds of kilometers of the *Golden Quadrangle* and the *East-West* and *North-South Corridor Projects*. As the use of concrete for road construction is on the increase in India, it is necessary to have an improved understanding of the behavior of concrete pavements in order to enhance the rationality of the current design standards.

1.2 Structural Behavior of Concrete Pavement

A concrete pavement is generally made up of a cement concrete slab supported by a base and a subbase placed over compacted subgrade soil. These pavements are also termed as 'rigid pavements' because of the high rigidity and modulus value of concrete slab. Sometimes, for lower traffic volumes, the base layer is omitted and slabs are cast directly over granular subbases. The wheel load applied on the slab is distributed over a wider area of subgrade through these layers. Different types of transverse and longitudinal joints are provided to facilitate thermal expansion and contraction of the slab and to continue construction after a break. Dowel bars are usually provided across the transverse joints for load transfer and longitudinal joints are generally provided with tie bars for holding the slabs together. Load transfer across joints is possible through dowel bars, granular interlocking or by the combined action of both these mechanisms. Fig. 1.1 shows a schematic layout of a concrete pavement with dowel bars, tie bars and joints.

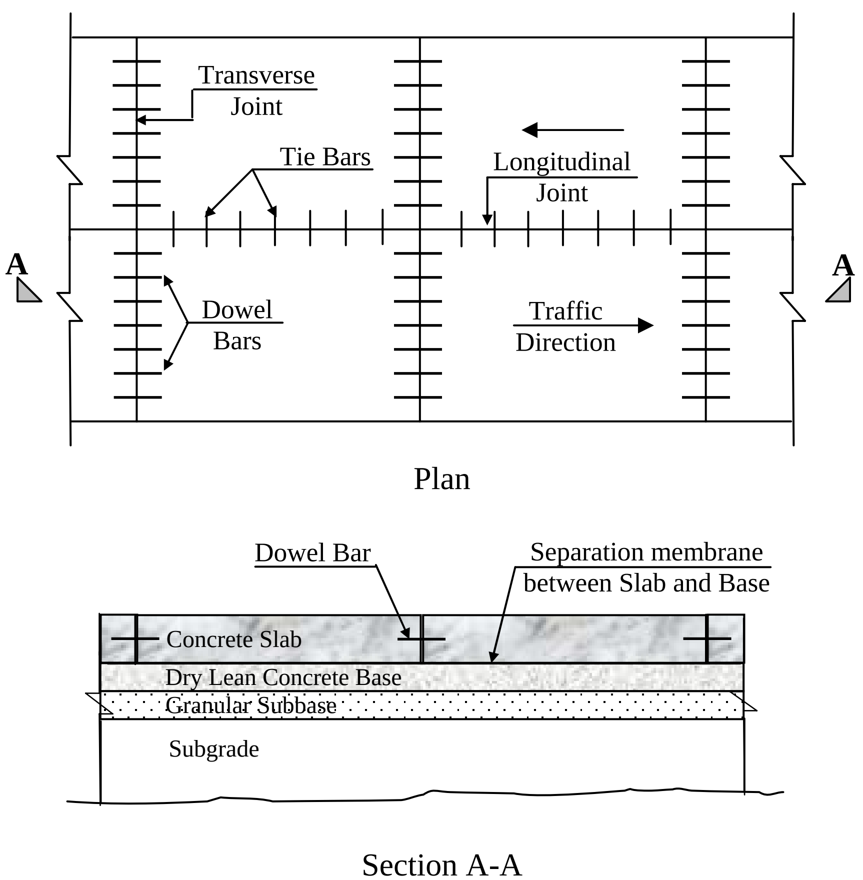

Fig. 1.1: Schematic Arrangement of Concrete Pavement Components

The structural response of jointed concrete pavement depends on subgrade characteristics, pavement material characteristics and climatic conditions. Climatic conditions mainly include daily and seasonal variations in temperature and changes in moisture gradient within the depth of concrete slab. The daily variation in temperature causes thermal gradients through the depth of concrete slab, while the seasonal variation results into different average temperatures of concrete slab. The concrete slab will tend to curl upward or downward when it is subjected to a positive and negative temperature variation within its depth. Due to its self weight and other restraints provided by foundation, dowel bars etc., the concrete slab is not allowed to curl freely, resulting in the development of curling stresses in the pavement. Due to uniform temperature rise or fall during seasonal variation in temperature, there is an overall expansion or contraction of the slab. The slab movements are restrained due to the friction between the slab and the foundation. This induces frictional stresses at the bottom fiber of the concrete pavement.

Moisture gradient in concrete slab also induces warping stresses. It depends on ambient relative humidity at the surface, free water in concrete and the moisture content of the subbase or subgrade. The effect of moisture is seasonal and remains constant for a long time, resulting in very small stress reversals and very low fatigue damage. However, the steady-state stresses due to moisture gradients are potentially very large and are usually additive with corner load related stresses. Also, the creep effect may reduce warping stresses (and built-in curling stresses) in the long run.

Pavement may undergo fatigue cracking due to repeated application of wheel loads along with temperature variation. Fatigue can cause both transverse cracking and longitudinal cracking. Transverse cracking initiates at the pavement edge midway between transverse joints, while longitudinal cracking initiates in the wheel path at transverse joints, usually at the wheel path nearest to the slab centerline. Faulting of doweled pavements is mainly due to crushing / spalling of concrete around the dowels under repeated wheel loading causing excessive bearing stress. Presence of water in soil, the rate at which it is ejected into the pavement, the erodibility of subbase material, the magnitude and number of load cycles, influence the degree of pumping and erosion in concrete pavements. Joint deterioration includes spalling and general breakup of concrete near the corners of the joints. Sometimes premature cracking occurs within the slabs due to temperature, shrinkage and moisture effect.

1.3 Motivation for the Work

Different guidelines are being followed for the analysis, design and construction of concrete pavements (*Portland Cement Association, 1984, American Association of State Highway and Transportation Officials, 1993, Indian Roads Congress, 2002 and Australian Pavement Design, 2004*). These guidelines are mostly based on empirical or semi-mechanistic approaches. The performance studies of certain road test results (Maryland Road Test, AASHO Road Test, 1962, Arlington Road Test etc.) were utilized in developing some of these existing design guidelines. The modes of distresses and the performance criteria adopted also vary from one design method to another.

For making judicious selection of an appropriate design or rehabilitation option for jointed concrete pavement, it is necessary to have a model that can be used for evaluation of various options in a rational manner. Any such model must have the capability to represent different components of concrete pavement realistically. Some of the issues that need to be addressed for the design of concrete pavement are: - multi-layer foundation system, mechanisms of load transfer across joints / cracks, consideration of temperature stresses etc.

A review of available literature indicates that significant improvements have been made over the last several decades in terms of analytical evaluation of jointed concrete pavements. Closed-form solutions (Westergaard, 1926a) have been used by many agencies to obtain critical stresses in concrete pavements. These solutions are based on certain simplifying assumptions like infinite slab in horizontal directions, full contact between slab and foundation, linear temperature variation. Some of the current design guidelines have been developed based on these closed-form solutions.

Many of the limitations of closed-form solutions are nowadays being addressed with the help of finite element method (FEM). Two-dimensional finite element models (Huang and Wang, 1973, Tabatabaie and Barenberg, 1980) were used extensively for the analysis of concrete pavement. However, in the recent past, three-dimensional models (William and Shoukry, 2001, Davids et al. 2003) are becoming increasingly popular because of their realistic representation of the pavement system and versatility in handling complex geometric and loading conditions. The intrinsic details of the pavement, like multi-layer foundation system, mechanisms of load transfer across joints and cracks and consideration of temperature stresses, can be understood more clearly with the help of a 3-D FE model.

An attempt has been made in this research study to develop a numerical model for analysis of jointed concrete pavements by addressing these issues. Finite element method was used for developing the numerical model. Laboratory and field investigations were conducted for obtaining typical input data about interface condition and on nonlinear temperature variation in the slab. Structural evaluation of in-service concrete pavements was carried out to validate the numerical model developed in the study. Some of the current design practices have been examined with the help of the numerical model and new guidelines have been proposed.

1.4 Objective of the Work

The broad objective of the present work is to evaluate the responses of jointed concrete pavements subjected to various traffic and temperature conditions relevant to Indian scenario. In order to achieve this objective, it is proposed to develop a three-dimensional finite element model for the analysis of jointed concrete pavement and to validate it with the experimental results available from literature and also by performing structural evaluation of an in-service concrete pavement. Using the validated numerical model, several design issues, like multi-layer foundation system, influence of interface condition, estimation of load transfer, and effect of non-linear temperature variation, have been examined. It is also proposed to carry out laboratory investigations to obtain certain input parameters for the numerical model. Keeping in view these objectives, available literature has been critically reviewed and the scope of the present work has been identified. The detailed literature review and the scope of the work are presented in Chapter 2.

1.5 Contributions from the Present Research Work

The major contributions of the present investigation are listed below.

- A three-dimensional finite element model has been developed for the analysis of jointed concrete pavement taking into consideration different features like multi-layer foundation system, different interface conditions, and load transfer mechanisms by dowel bar and aggregate interlocking systems through joints and / or cracks.
- Typical interface co-efficient of friction values have been recommended for different slab and base / subbase combinations. These can also be used for analysis and design of concrete pavements.
- Guidelines have been proposed for selecting the stiffness of the springs used to represent the aggregate interlocking mechanism in the finite element analysis of a jointed concrete pavement.
- A generalized expression has been proposed for estimating the load transfer efficiency (LTE) in a dowel-jointed concrete pavement. The expression is convenient for estimating the LTE in the backcalculation process instead of solving the FE based models.
- Relationships have been developed for estimating the load shared by different dowels in a group. These relationships are useful for the design of dowel bar system in a jointed concrete pavement.
- A generalized expression has been proposed for estimating the critical (edge) stress in the slab subjected to the combined action of axle loading and nonlinear positive temperature gradient. This ready-to-use equation can be utilized conveniently for the design of concrete pavement.
- The Fatigue Performance Model developed in the present study is an efficient tool for predicting the life of the pavement under cyclic loading.

1.6 Organization of the Thesis

The thesis is divided into eight chapters. The first chapter includes introduction, motivation for the work and the main objectives. A detailed literature review of various design methods and techniques adopted for modeling different components of concrete pavement are covered in the second chapter. The numerical modeling of concrete pavement and its validation with experimental works available in the literature are presented in the third chapter. In the fourth chapter, push-off tests carried out for evaluation of typical interface characteristics are described. The details of the field studies, performed on an in-service concrete pavement, are the contents of the fifth chapter. The sixth chapter includes the fatigue analysis of concrete pavement based on fracture mechanics approach. Several issues related to the design of concrete pavement are examined in the seventh chapter. The concluding chapter highlights the major outcome of the present work and also defines the scope for future research work. The references are given at the end of the thesis.