Engineering Solid Mechanics (2018) 67-82

Contents lists available at GrowingScience

Engineering Solid Mechanics

homepage: www.GrowingScience.com/esm

Factors influencing stresses and movements in continuously reinforced concrete pavements – A review

M. M. Mirsayar[a*] and D. G. Zollinger

[a]*Texas A&M University, Zachry Department of Civil Engineering, College Station, TX 77843-313, USA*

A R T I C L E I N F O

Article history:
Received 6 June, 2017
Accepted 2 October 2017
Available online
3 October 2017

Keywords:
Stress
Continuously reinforced concrete pavements

A B S T R A C T

The use of cement concrete as a stronger and more durable material than asphalt concrete in construction of the pavements has been increased during the past decades. This review paper investigates the effect of various input variables for the design of continuously reinforced concrete pavements. A literature review is prepared based on the efforts performed by many researchers to investigate the effect of different factors including temperature change, shrinkage, material properties of the concrete, and concrete slab/ subbase bond properties on the displacements and stresses in the concrete slab. It is found that the important role of concrete slab/ subbase bond strength has not been investigated properly as compared to other input variables.

1. Introduction

Based on the structural performance, pavements can be classified into two categories: flexible pavements and rigid pavements. In flexible pavements, wheel loads are transferred by grain-to-grain contact of the aggregate through the granular structure. Since they are made of bituminous materials and aggregates, the flexural strength of the flexible pavements is less and they behave like a flexible plate. On the contrary, in rigid pavements which are made of cementitious materials and aggregates, wheel loads are transferred to sub-grade soil by flexural strength of the pavement and the pavement behaves like a rigid sheet. This review paper is aimed to address developments performed by the researchers on investigation of the different factors influencing stresses and displacements in rigid pavements which are used in many countries all around the world, especially the United States of America.

* Corresponding author.
E-mail addresses: mirmilad@tamu.edu (M. M. Mirsayar)

doi: 10.5267/j.esm.2017.10.002

Rigid pavements are made up of Portland cement concrete, and may or may not have a base course between the pavement and the subgrade. Rigid pavements tend to distribute the load over a relatively wide area of subgrade, and as a result, the major portion of the structural capacity is supplied by the concrete slab itself. They can be used for heavier traffic loads and can be constructed over relatively poor subgrade. There are four types of rigid pavements: Jointed plain concrete (JPC) pavement, jointed reinforced concrete (JRC) pavement, continuously reinforced concrete (CRC) pavement, and pre-stressed (PC) concrete pavement. JPC pavements are plain cement concrete pavements constructed with closely spaced contraction joints. Dowel bars or aggregate interlocks are usually employed for load transfer across pavement joints (joint spacing usually varies from 5 to 10m). In JRC, the reinforcements do not significantly improve the structural capacity, but can drastically increase the joint spacing (10 to 30m). Dowel bars are also used as load transfer in JRC pavements. CRC pavements are Portland cement concrete pavement with continuous longitudinal steel reinforcement and no intermediate transverse expansion or contraction joints. Instead, the pavement is allowed to crack in a random pattern and the cracks are held tightly closed by the steel reinforcement. In this review, it is particularly focused on models for prediction of the displacements in CRC pavements (Fig.1) rather than other rigid pavement types.

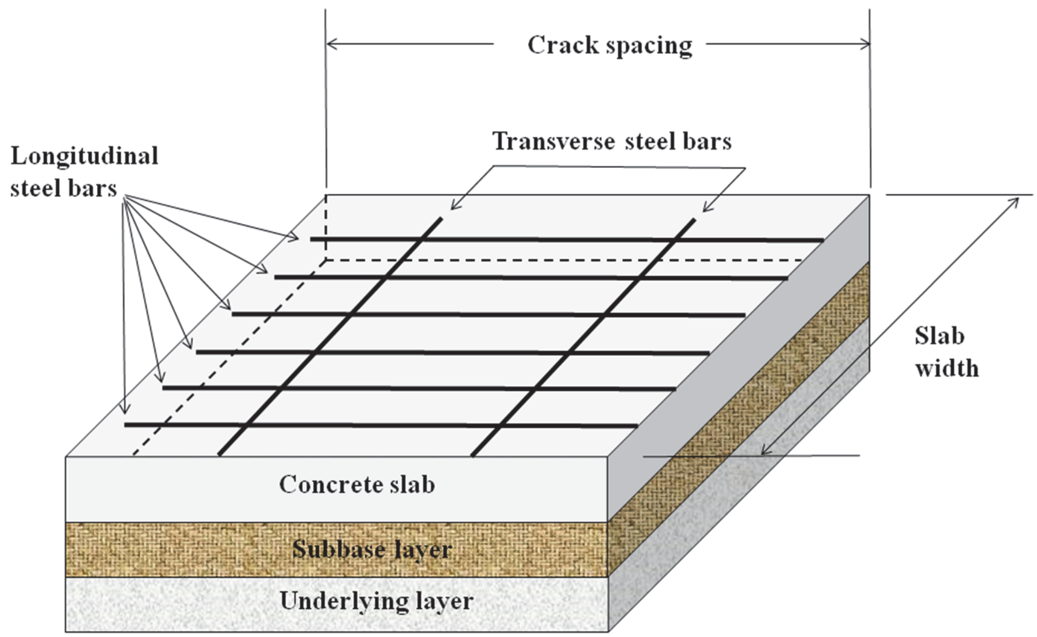

Fig. 1. General configuration of CRC pavement.

The first use of CRC pavements was in 1921 by the Bureau of Public Roads on Columbia Pike in Arlington, Virginia. Then, the first significant length of CRC pavements was constructed in the State of Indiana in 1938 (Highway Research Board, 1973). After that, a good performance of such projects (like the one in Illinois, California, and New Jersey around 1949) led to an increased interest in this design (AASHTO design guide, 1993). The use of CRC pavements was increased in the 1960s, 1970s, and 1980s during construction of the Interstate Highway System in the U.S. The use of CRC pavements in the U.S. was increased for more than 15,000 kilometers of equivalent two-lane pavement were in use or under contract at the end of 1971(Highway Research Board, 1973) and this amount is still increasing. Texas and Illinois, with dissimilar weather and environmental conditions, lead the nation in CRCP usage. Texas constructed its first section in Ft. Worth in 1951. From the 1960s on, Texas has constructed more CRC pavements than any other state, possibly more than all other states combined. Approximately 80 percent of current concrete paving projects let in Texas are CRC pavements. Illinois constructed its first CRC pavement in 1947 on U.S. 40 west of Vandalia. Based on the performance of this experimental project, Illinois began extensive construction of CRC pavements. Approximately two-thirds of the Illinois Interstate system was constructed with CRC pavements (Nam, 2005).

2. Factors affecting displacements in concrete slabs

There are many factors influencing displacements in concrete pavements. Among them we can mention temperature, moisture, material properties of the slab and subbase, and bond behavior between slab and subbase layer.

2.1. Temperature of the concrete slab

One of the primary sources of the stress in concrete slabs is thermal stress. In CRC pavements, the thermal stress depends on (1) the thermal properties in early ages which can be often characterized as heat of hydration and coefficient of thermal expansion; (2) the conditions at placement; (3) the environmental effects (ambient air temperature and solar radiations); (4) geometry of the structure.

The thermal stress field in concrete slabs is influenced by the boundary conditions of the slab. If a concrete slab is unrestrained, it expands and contracts during the early-age heating and the subsequent cooling process without stress development. However, concrete slabs are always restrained to some degree, either externally by adjoining structures or internally by different temperature in the components of the structure itself. Therefore, due to such imposed restraint conditions, temperature change results in compressive and/or tensile stresses in the concrete. Thus, a primary question would be, whether the induced thermal stresses lead to cracking or not (Cha, 1999).

Due to the hydration of the fresh concrete, energy releases in the form of heat. Mixing Portland cement compounds with water leads to a rapid release of heat initially, which then drops down within about 10 to 20 minutes. This reaction probably represents the heat of the solution of sulfates and aluminates in the mixture (Mehta & Monteiro, 1993). The primary heat generation cycle starts a couple of hours after the cement compounds are mixed with water. Before that, concrete is in a plastic state and is relatively inactive chemically. A couple of hours after concrete is mixed with water, the peak of the primary cycle reaches its peak value. At this step, the major portion of the hydration products crystallizes from the solution of the mixture. This step includes the time of initial and/or final set of the concrete. As hydration products grow, they form a barrier to the infiltration of additional water; and when there is no room for further growth of crystals, or when hydration is theoretically completed the reaction drops down and may eventually stop (Mindess & Young, 1981; Nam, 2005). The rate of hydration is very sensitive to temperature, especially during the primary cycle (Mindess & Young, 1981; Nam, 2005). Therefore, the temperature condition during construction is an important factor affecting the rate of hydration.

The coefficient of thermal expansion (COTE) is also a key parameter affecting on the thermal stress distribution in concrete slabs. Like all composite materials, the COTE of concrete is influenced by a large number of factors that can be generally related to its major components: cement paste and aggregate. Primarily affected by the moisture content of the paste, the COTE of the paste varies significantly during the hydration process and will be stabilized thereafter. The thermal characteristics of concrete obviously affect the crack pattern in concrete slabs since thermally induced dimensional changes in the Portland cement concrete influence the formation of transverse cracks. The type of coarse aggregate also directly influences on COTE of concrete, because coarse aggregates form a large part of concrete by volume (McCullough et al., 1999).

The COTE of concrete is approximately equal to the volumetrically weighted average of the coefficients of its ingredients (Nam, 2005). In order to calculate the thermal strains and stresses of concrete slabs, the COTE of concrete is needed. The COTE of concrete is measured by many researchers so far (Nam et al., 2006; Byfors, 1980; ACI Committee. 517, 1980; Emborg, 1989). The COTE of concrete varies within $2.78 - 8.33 \times 106/^{o}F$, depending on aggregates, constituents and the moisture state of concrete (Byfors, 1980). It also has been reported in the literature that the COTE of concrete is slightly greater during heating than cooling and its value at early-ages is higher than that of mature concrete (Byfors, 1980; ACI Committee. 517, 1980; Emborg, 1989).

Environmental conditions also leads to temperature gradients in concrete slabs. High temperature in fresh concrete due to ambient air temperature and solar radiation may induce such undesirable effects as increased water demand, increased rate of setting, increased rate of slump loss, difficulties in controlling entrained air, increased tendency for plastic shrinkage cracking, and critical need for prompt curing (Nam, 2005). In hardened concrete, high temperature may lead to decreased strength, increased shrinkage, increased creep, decreased durability, and non-uniformity of surface (Kosmatka & Panarese, 1988; Samarai et al., 1983). Also, because the hydration of cement is a chemical process, a high ambient temperature will increase the rate at which the concrete hydrates. High solar radiation during construction may also significantly influence on increasing the concrete temperature as well as the rate of hydration. This expedited rate of hydration results in a higher and earlier peak concrete temperature during the construction day (Suh et al., 1992).

2.2. Concrete shrinkage

Since concrete is largely composed of water, the water transport and change in amount of water significantly influence in volume change of concrete. In other words, water-related shrinkage is a volumetric change caused by loss and movement of the water (i.e., change in the internal pore pressure caused by drying or self-desiccation). Drying of concrete is affected by the environmental conditions in which the relative humidity of the concrete attempts to equilibrate with the humidity of the surrounding environment. As the internal humidity strives to equilibrate with a lower environmental humidity, water is evacuated from the capillary pores which results in the development of tensile stresses. This tensile stress is attributed to the compressing the rigid skeleton of concrete which provides a partial explanation for the effect we commonly refer to as drying shrinkage. Shrinkage in concrete can be classified into the following types:

Plastic shrinkage is a term used for freshly poured concrete and manifests itself soon after the concrete is placed in the forms while the concrete is still in the plastic state. This type of shrinkage occurs when the rate of loss of water from the surface exceeds the rate at which the bleeding water is available. Environmental considerations including wind speed, solar effects, low relative humidity, and high temperature significantly influence the potential of plastic shrinkage cracking (Schaels & Hover, 1988). There are several ways suggested by researchers to prevent plastic shrinkage cracking such as limiting early-age evaporation through the use of plastic sheeting, mono-molecular films, water fogging, or wind breaks in conjunction with properly designed concrete mixtures. If proper curing is not provided, plastic shrinkage cracks could occur at a very early age of CRC pavements (Nam, 2005).

Drying shrinkage is by far the most common cause of shrinkage. The drying shrinkage of concrete is analogous to the mechanism of drying of timber specimen. The loss of free water contained in hardened concrete, does not result in any appreciable dimension change. It is the loss of water held in gel pores that causes the change in the volume. Under drying conditions, the gel water is lost progressively over a long time, as long as the concrete is kept in drying conditions. One of the most substantial factors influencing free shrinkage is the water to cement ratio (w/c). The w/c required for complete hydration is typically assumed to be approximately 0.42 depending on the amount of gel porosity that is assumed (Bažant & Najjar, 1971). The amount of water has a direct influence on the size and magnitude of the porosity (i.e., higher w/c pastes have higher porosity). Therefore, specimens with a lower w/c have a lower amount of pore water and consequently exhibit lower drying shrinkage. Currently, Texas Department of Transportation (TxDOT) limits the water-to-cement ratio to a maximum 0.45 for paving concrete (Nam, 2005). Gradation of the aggregates probably may not directly influence shrinkage (Neville, 1996), however, we may conclude that the use of larger aggregates might indirectly lead to a higher aggregate volume which exhibits lower free shrinkage since the aggregate is generally dimensionally stable. Aggregates with higher stiffness exhibit lower free shrinkage based on the same reasoning. The use of high porosity lightweight aggregate (LWA) has also been suggested as one method to minimize autogenous shrinkage (Lura et al., 2002; Zhutovsky et al., 2002). For this purpose, the LWA is saturated to various degrees before using and the aggregate acts as a water reservoir to supply water that counteracts the self-desiccation of the paste.

Autogenous shrinkage occurs in a conservative system, like sealed concrete (i.e., no moisture loss) without temperature change. This type of shrinkage primarily occurs as a result of chemical shrinkage which causes volume reduction due to the hydration reaction and self-desiccation.

Carbonation Shrinkage occurs when Carbon dioxide present in the atmosphere reacts in the presence of water with hydrated cement. Calcium hydroxide gets converted to calcium carbonate and also some other cement compounds are decomposed. Such a complete decomposition of calcium compound in hydrated cement is chemically possible even at the low pressure of carbon dioxide in normal atmosphere. Carbonation penetrates beyond the exposed surface of concrete very slowly.

2.3. Material properties

The material properties of the concrete slab, subbase layer and reinforcing steel significantly influences displacements in pavement structures. For concrete slab, the material properties of the concrete ingredients (cement past and aggregates) represents the effective modulus of the concrete. The stiffness and strength of each component influences crack pattern in a concrete slab and therefore are essential to be studied. The stiffness of each layer in a concrete pavement structure directly relates to the displacements in the structure. The effect of stiffness of layers on the displacement field in concrete slabs has been investigated by the researchers in the past (Polak & Vecchio 1993; Polak 1996; Zhang & Li, 2001). In the previous researches, the concrete slab and base layer are modelled as linear elastic plates connected by springs (Winkler foundation) and the displacements in the pavement is evaluated by plate theories (like Mindlin plate theory). However, the concept of using springs as interface elements brings many problems since such spring models does not represent de-bonding mechanism between layers in a sophisticated manner. The displacements in concrete slab are developed in either elastic deformations or de-bonding (permanent deformations). However, due to the complexity, a sophisticated model representing both de-bonding and deflections has not been developed yet.

2.4. Bond behavior between concrete slab and subbase

The bond behavior between the Portland cement concrete slabs and the subbase layer significantly influences on the displacements in concrete slabs caused by environmental loading as well as the traffic loading. In addition, the bond behavior directly affects the cracking patterns in concrete slabs. Therefore, the study of bond behavior at the interface of the concrete slab and subbase layer is essential to improve our pavement design. In other words, an extension in the service life of rigid pavements, which represents a significant portion of the construction industry's efforts, can lead to enormous improvements in the life cycle costs and sustainability of our transportation system.

The bond strength of the Portland cement concrete/subbase has rarely been investigated by some researchers. A limited number of published works can be found in the literature for the shear strength and tensile strength of the Portland-cement concrete/asphalt concrete bonded joints, with and without interface cracks (Delcourt & Jasenski, 1994; Petersson & Silfwerbrand, 1993; Mack et al., 1997; Rasmussen & Rozycki, 2004; Sadd et al., 2008; Chabot et al., 2013; Tschegg et al., 2007; Jung et al., 2010; Pouteau et al., 20014; Mirsayar et al., 2016a; Tozzo et al., 2015). Chabot et al. (2013) conducted a set of experiments to investigate mixed mode interfacial fracture in asphalt concrete/ Portland cement concrete bonded joints. They used four point bend specimens for their fracture tests and obtained strain energy release rate under different loading and boundary conditions. Tschegg et al. (2007) dealt with the testing and assessment of the bond behavior and the crack resistance of asphalt-concrete interfaces tested at different temperatures. They conducted their tests at different pretreatments of the interface: without any treatment, using cement grout, using a combination of cement grout and synthetic dispersion, or using only synthetic dispersion. Pouteau et al. (2004) studied the fatigue life of a concrete layer bonded to an asphalt subbase. They presented an in situ experiment aiming to evaluate the growth of a defect at the interface of a CRC pavement bonded to an asphalt subbase under traffic loads. They also suggested a new laboratory test to study the initiation and the propagation of the crack at the interface. However, all previous works failed to obtain fracture toughness under different mixed mode conditions because of the limitations on the specimen geometry. The finite element simulation of the crack propagation at the interface of concrete slab and subbase has also rarely been investigated by the researchers (Mirsayar et al., 2016a; Tozzo et al., 2015). For instance, Mirsayar et al. (2016a) conducted a series of finite element simulations to investigate effect of subbase modulus and environmental loadings on the interface crack propagation between plain Portland cement concrete slabs and the subbase. However, they used a two dimensional model and did not considered the bond strength effects. Kim et al. (2003) conducted a series of finite element simulations to study bond behavior between the concrete slab and the base. They also performed a sensitivity analysis to investigate the effects of overlay and CRC pavement parameters, such as elastic modulus, thickness, coefficient of thermal expansion and percent reinforcement, on the interfacial shear and normal stresses. They have incorporated their mechanistic model into the HIPERBOND software developed for the FHWA. Totsky (1981) developed a model in which a multilayered system resting on subgrade was modelled as series of springs and plates where curling was analyzed iteratively. In this model, the springs that were in tension are removed as the pavement section curls allowing for the system to be reanalyzed for determining the equilibrium condition. The removal of the interfacial springs during the solution process represented the layer separation.

3. Slab movements

All Portland cement concrete slabs undergo shrinkage as the concrete ages. This volume change in concrete is very important to the engineer in the design of a concrete slab. This volume change is controlled by expansion joints and is restricted by the slab's boundary conditions. Therefore, the evaluation of slab's end movement is very important for design purposes.

In addition to the horizontal shrinkage of the concrete slab, the edges of the slab lift upwards due to the temperature and moisture gradient throughout the slab (Fig. 2). In a pavement structure, with respect to temperature, when the slab surface is cooler than the slab bottom, the surface tends to contract and curling the slab edges (or corners) upward as a result of negative temperature gradient through the slab thickness. On the other hand, the moisture gradient through the thickness induces an additional deformation in the concrete slab, called warping. Such factors are particularly prevalent during the curing stages of a concrete pavement affecting the potential for lift-off (the separation of slab from the subbase layer).

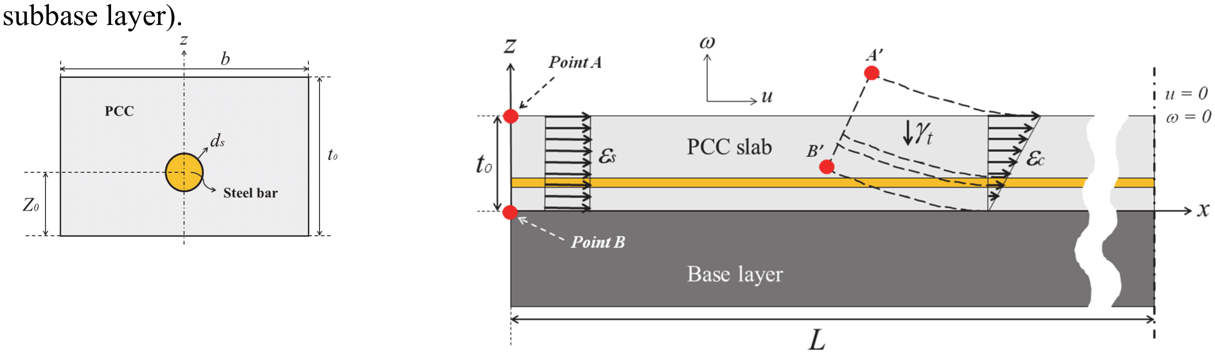

Fig. 2. 2D scheme of the end movement in a reinforced concrete slab due to shrinkage and temperature gradients

Lift-off is the first step towards erosion damage which is a distress type that threatens the sustainability of a concrete pavement. In a concrete slab, the lift-off is controlled by the net climatically induced contraction strain field, which takes into account both temperature and the moisture effects, the bond behavior between concrete slab and subbase, and the weight of the concrete slab. Such interaction causes a stress field throughout the slab which results in separation of the slab from the subbase.

In CRC pavement, the longitudinal reinforcement is continuous and each individual length of the reinforcing bar is welded end-to-end to each of its adjoining bars in the reinforcement grid. The steel keeps the cracks tightly closed maintaining the integrity of the aggregate interlock across the cracks. Over the years, the mechanism of the slab deformation due to such environmental effects has been investigated by many researchers. Palmer (1988) studied stress, strain and displacement field in CRCP. He calculated relative displacements between concrete slab and subgrade, and between concrete slab and reinforcing steel bar. However, he did not consider effect of lift-off on the slab end movement and did not take into account the effect of interface crack propagation.

McCullough and his colleagues (McCullough & Elkins, 1979; Mendoza-Diaz & McCullough, 1979) developed CRCP-11 program to design concrete pavement under different climatic conditions. The software was a sophisticated tool for pavement design considering predicted minimum concrete temperatures for the medium and long terms which allows a reasonable economical designs. Zhang (2012) studied the effects of base characteristics on curling stresses of CRCP under different types of base materials. He studied the effects of six typical bases on curling stresses of CRCP subjected to temperature variations using a 2D finite-element method. However, he used a simple friction model which is not a realistic bond behavior between the slab and base layer.

The lift-off in concrete slabs has been investigated by many researchers so far, by taking into consideration effects of curling and warping, together and separately (Westergaard, 1927; Tang et al., 1993; Bari & Zollinger, 2016; Jeong & Zollinger, 2006; Jeong et al., 2006; Bissonnette et al., 2007; Mohamed & Hansen, 1997; Rao & Roesler, 2005; Yu et al., 1998; Rao et al., 2001). A pioneering work has been done by Westergaard (1927) on the thermal stress field analysis in rigid slabs due to their curling. He presented a linear elastic solution for the slab curling assuming a linear temperature gradient through the slab thickness and an elastic Winkler foundation for the subgrade. Tang et al. (1993) suggested an analytical approach to evaluate stress and displacement distribution in a semi-infinite slab and in an infinitely-long slab of a finite width. They also considered the effect of gap that may occur under the concrete slab resulting from curling and proposed an approximate formula for the maximum stress in a finite slab. However, the net effects of curling and warping causes the lift-off in concrete slab pavements. In this regard, Bari and Zollinger (2016) proposed a new framework to model the effects of the concrete slab/subgrade interface for design purposes considering short- and long-term performance. They studied the effect of interfacial adhesion as well as the sliding friction on the interfacial resistance and the slab lift-off. However, in practice, cracks propagate at the interface of the concrete slab and subbase and none of the above models can present a sophisticated method to describe interface crack propagation mechanism.

4. Fracture criteria for bonded structures

The end movement of the concrete slab consists of both contraction shrinkage and slab lift – off. Such movement is accompanied with de-bonding of the slab from subgrade when the net induced climatically strain field in the concrete slab exceeds a critical value. In other words, this movement can be analyzed using an interfacial fracture model. The process of crack initiation and propagation at the interface of two dissimilar materials (He & Hutchinson, 1989; Hurd et al., 1995; Martin et al., 2001; Evans et al., 1990; Ayatollahi et al., 2010a; Mirsayar, 2014a; Fernlund & Spelt, 1994; Campilho et al., 2011; Álvarez et al., 2014; Fernlund et al., 1994) and in different engineering materials (Arabi et al., 2013; Ayatollahi et al., 2010b, 2011, 2013; Ayatollahi & Mirsayar, 2011; Mirsayar, 2013, 2014b,c, 2015a,b, 2017; Mirsayar & Samaei, 2013, 2014, 2015; Mousavi & Aliha 2016; Mohammad Aliha et al. 2017; Mirsayar et al., 2014, 2016b, 2017a,b; Mirsayar & Park, 2015, 2016a, 2016b; Mirsayar & Takabi, 2016; Razmi & Mirsayar, 2017) has widely been studied in the past. Depending on the bond strength, the mechanism of interfacial crack propagation can be classified into two types: strong interfaces, and weak interfaces. In strong interfaces, the crack kinks into the weaker material, and for weak bonds, the interface crack propagates through the interface. The fracture criteria for strong and weak interfaces are different from each other. For strong interfaces, fracture criteria deals with material properties of both bonded materials. However, for weak interfaces, the property of the bond is more important than mechanical properties of the each material. There are many published works in the literature by the previous researchers on the study of crack propagation at the strong interfaces. He and Hutchinson (1989), presented an energy based framework for crack propagation at the interface of two dissimilar elastic solids. Hurd et al. (1995) studied the mechanism of fracture at the strong interface of silicon and glass. They measured the mode I fracture toughness and kinking angles using a compact tension test specimen. Martinet al. (2001) carried out an asymptotic analysis to model the mechanism of deflection of a crack at an interface in a brittle bi-material system. Using the energy release rate concept, they found that in the case of a stationary crack impinging perpendicularly on the interface and submitted to progressive loading, the energy criterion depends on the elastic mismatch of the bi-material constituents and the ratio of the crack extensions in the deflected and the penetrated directions. Evans et al. (1990) studied fracture energy of a bi-material system and found that the fracture energy is not unique and usually exhibits values substantially larger than the thermodynamic work of adhesion. Mirsayar (2014a) recently proposed a new stress-based fracture criterion for crack kinking out of the interface which can be applied for bonded structures with strong interfaces. He found that not only the singular stress terms, but also the first non-singular stress term of the asymptotic series expansion influences on the fracture behavior of interface bonds.

One can also find a lot of published works in the literature for analysis of bond behavior of weak interfaces (Fernlund & Spelt, 1994; Campilho et al., 2011; Álvarez et al., 2014; Fernlund et al., 1994; Choupani, 2008; Nikbakht et al., 2009; Sharifi & Choupani, 2008). Fernlund and Spelt (1994) proposed a new jig for mixed mode fracture testing of adhesively bonded joints and conducted a set of fracture tests on different bonded structures to obtain their fracture toughness. Campilho et al. (2011) studied the ability of extended finite element method to predict the fracture behavior of thin layers of adhesive between stiff and compliant adherents. Choupani and his coworkers (Choupani, 2008; Nikbakht et al., 2009; Sharifi & Choupani, 2008) investigated the mixed mode crack propagation in adhesively bonded joints, made of various combination of the materials, experimentally.

The type of the specimen has always been an important factor for conducting research on the fracture properties of different materials. There are some important factors which are needed to be considered for choosing a fracture test specimen. A fracture test specimen should be: (1) manufactured easily, (2) should be able to be loaded easily, and (3) cover all loading configurations from pure mode I (opening mode) to pure mode II (sliding mode). However, many of the fracture tests proposed by the previous researchers are not able to cover all mixed mode conditions.

One can find several fracture test specimens in the literature such as compact tension (CT) specimen (Wagoner et al. 2005, Kim et al. 2014), wedge splitting (WS) test (Brühwiler et al., 1990; Issa et al., 2003), three point bend (3PB) specimen (Korte et al., 2014; Seitl et al., 2017; Aliha et al. 2017), four point bend (4PB) specimen (Munz et al., 1980; Razavi et al., 2017; Fakhri et al., 2017; Ayatollahi & Aliha 2011) , Brazilian disk (BD) specimen (Dai et al., 2015; Wei et al., 2015; Akbardoost et al., 2014; Ayatollahi & Aliha, 2009a), semicircular bend (SCB) specimen (Funatsu et al., 2014; Aliha et al., 2017; Wei et al., 2017ab; Ameri et al., 2012, 2016; Aliha & Fattahi Amirdehi, 2017), center cracked or notched ring specimen (Dehghany et al., 2017; Aliha et al., 2013), triangular bend (ECT) specimen (Aliha et al. 2013, 2016), edge notch disc bend (ENDB) specimen (Bahmani et al., 2017;

Tutluoglu & Keles, 2011; Aliha et al., 2015, 2016), Diagonally loaded square plate (DLSP) specimen (Ayatollahi & Aliha, 2009b), and double cantilever beam (DCB) specimen (Ranade et al., 2014; Lopes et al., 2016). Fig. 3 shows schematic representations for a number of aforementioned fracture test specimens. Some of them, like BD, DLSP and SCB specimens can cover form pure mode I to pure mode II conditions. However, for a bi-material system, we can rarely find a specimen in the literature satisfying all three conditions mentioned above for a proper fracture test specimen. To fill this gap, an effort has been performed recently by Mirsayar et al. (2017c). They proposed a new bi-material SCB specimen covering all mixed mode conditions on the interface bond from pure shear to pure tensile conditions as shown in Fig. 4.

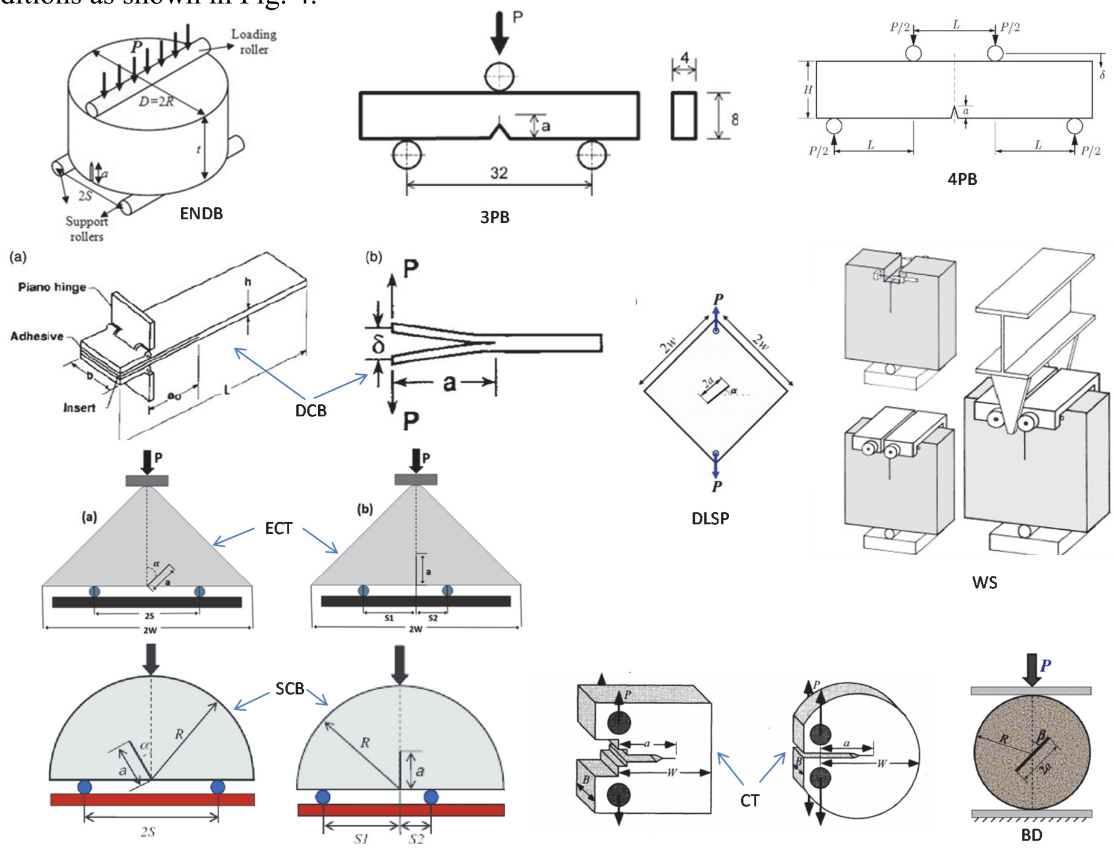

Fig. 3. Some test configurations proposed in the literature for fracture toughness study of different materials

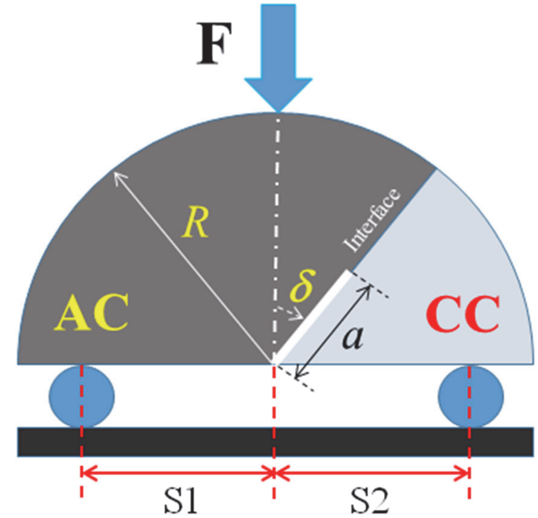

Fig. 4. Scheme of the developed SCB specimen made of asphalt concrete and Portland cement concrete, proposed by Mirsayar et al. (2017c)

5. Summary of the review

Among different factors affecting displacements and stress distribution in concrete slabs, the bond behavior between the concrete slab and the subbase layer has rarely been investigated. According to the field observations, a concrete slab on certain types of bases are bonded together and as a result, cracks initiate and propagate through the interface during the slab shrinkage. Edges and corners undergo interfacial sliding friction and possibly abrasive wearing due to each passing load which is a mechanism of erosive action leading to faulting. In the central portions of a slab, the interface is likely fully bonded either due to chemical adhesion or high frictional restraint or both. These conditions often exist in push-off or lab friction tests which have been common methods to measure the coefficient of friction but are frequently plagued by shear failure planes forming in the matrix of the subbase layer complicating the determination of the friction values (see Fig. 5a). The adhesive aspects of interfacial resistance have largely been thought to be a factor during construction where it has on occasion been the source of cracking problems. If the mechanical and/or adhesive resistance is too high initially, random cracking may be initiated at the bottom rather than the top of the slab during the early life of a jointed pavement – which is often a problem associated with the control of cracking during saw cutting operations since the notches are placed at the surface of the pavement. High bond resistance can also be a problem in CRC pavement construction (see Fig. 5b) but in a sense opposite of what happens in jointed pavement construction where cracking development is inhibited too much.

(a) (b)

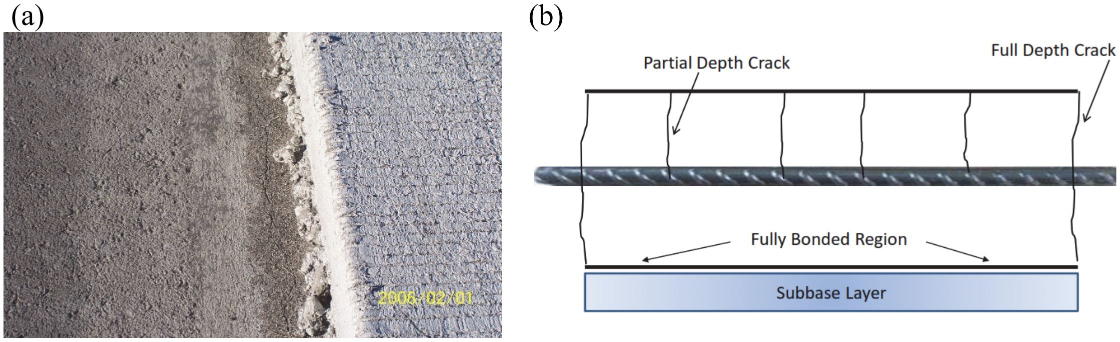

Fig. 5. (a) Example of shear failure below the slab/sub base interface (b) Partial-depth cracking in a longitudinal segment of CRC pavement.

Depending on the material properties of the subbase layer, the interface crack may kink into one of the materials (strong interface) or propagate through the interface (weak interface). Both cases could happen depending on the degree of bond between subbase and concrete slab. Recent studies indicate that the possibility of crack propagation through the interface increases at lower temperatures for a given concrete Mirsayar et al. (2017c). Also, the fracture criteria for evaluation of the interfacial crack propagation are different for weak and strong interfaces.

The previous methods for bond behavior assumes that slab and subgrade are sliding with respect to each other and do not take into account the effect of interface crack in their bond model. However, the cracks developed at the interface of subbase layer and concrete slab cause to the stress concentration which influences on the delamination behavior, and can be addressed by the interfacial fracture mechanics.

References

ACI Committee. 517. (1980). Accelerated curing of concrete at atmospheric pressure – State of the art. *ACI Materials Journal*, *6*, 429-48.

Akbardoost, J., Ayatollahi, M. R., Aliha, M. R. M., Pavier, M. J., & Smith, D. J. (2014). Size-dependent fracture behavior of Guiting limestone under mixed mode loading. *International Journal of Rock Mechanics and Mining Sciences*, *71*, 369-380.

Aliha, M. R. M., & Fattahi Amirdehi, H. R. (2017). Fracture toughness prediction using Weibull statistical method for asphalt mixtures containing different air void contents. *Fatigue & Fracture of Engineering Materials & Structures*, *40*(1), 55-68.

Aliha, M. R. M., Bahmani, A., & Akhondi, S. (2015). Numerical analysis of a new mixed mode I/III fracture test specimen. *Engineering Fracture Mechanics*, *134*, 95-110.

Aliha, M. R. M., Bahmani, A., & Akhondi, S. (2016). A novel test specimen for investigating the mixed mode I+ III fracture toughness of hot mix asphalt composites–Experimental and theoretical study. *International Journal of Solids and Structures*, *90*, 167-177.

Aliha, M. R. M., Hosseinpour, G. R., & Ayatollahi, M. R. (2013). Application of cracked triangular specimen subjected to three-point bending for investigating fracture behavior of rock materials. *Rock Mechanics and Rock Engineering*, *46*(5), 1023-1034.

Aliha, M. R. M., Mahdavi, E., & Ayatollahi, M. R. (2017). The influence of specimen type on tensile fracture toughness of rock materials. *Pure and Applied Geophysics*, *174*(3), 1237-1253.

Aliha, M. R. M., Pakzad, R., & Ayatollahi, M. R. (2013). Numerical analyses of a cracked straight-through flattened Brazilian disk specimen under mixed-mode loading. *Journal of Engineering Mechanics*, *140*(1), 219-224.

Álvarez, D., Blackman, B. R. K., Guild, F. J., & Kinloch, A. J. (2014). Mode I fracture in adhesively-bonded joints: A mesh-size independent modelling approach using cohesive elements. *Engineering Fracture Mechanics, 115*, 73-95.

Ameri, M., Mansourian, A., Pirmohammad, S., Aliha, M. R. M., & Ayatollahi, M. R. (2012). Mixed mode fracture resistance of asphalt concrete mixtures. *Engineering Fracture Mechanics*, *93*, 153-167.

Ameri, M., Nowbakht, S., Molayem, M., & Aliha, M. R. M. (2016). Investigation of fatigue and fracture properties of asphalt mixtures modified with carbon nanotubes. *Fatigue & Fracture of Engineering Materials & Structures*, *39*(7), 896-906.

American Association of State Highway, & Transportation Officials. (1993). AASHTO Guide for Design of Pavement Structures, 1993 (Vol. 1). AASHTO.

Arabi, H., Mirsayar, M. M., Samaei, A. T., & Darandeh, M. (2013). Study of characteristic equation of the elastic stress field near bimaterial notches. *Strength of Materials, 45*(5), 598-606.

Ayatollahi, M. R., & Aliha, M. R. M. (2008). On the use of Brazilian disc specimen for calculating mixed mode I–II fracture toughness of rock materials. *Engineering Fracture Mechanics*, *75*(16), 4631-4641.

Ayatollahi, M. R., & Aliha, M. R. M. (2009a). Mixed mode fracture in soda lime glass analyzed by using the generalized MTS criterion. *International Journal of Solids and Structures*, *46*(2), 311-321.

Ayatollahi, M. R., & Aliha, M. R. M. (2009b). Analysis of a new specimen for mixed mode fracture tests on brittle materials. *Engineering Fracture Mechanics*, *76*(11), 1563-1573.

Ayatollahi, M. R., & Aliha, M. R. M. (2011). On the use of an anti-symmetric four-point bend specimen for mode II fracture experiments. *Fatigue & Fracture of Engineering Materials & Structures*, *34*(11), 898-907.

Ayatollahi, M. R., & Mirsayar, M. M. (2011). Kinking angles for interface cracks. *Procedia Engineering, 10*, 325-329.

Ayatollahi, M. R., Dehghany, M., & Mirsayar, M. M. (2013). A comprehensive photoelastic study for mode I sharp V-notches. *European Journal of Mechanics-A/Solids, 37*, 216-230.

Ayatollahi, M. R., Mirsayar, M. M., & Dehghany, M. (2011). Experimental determination of stress field parameters in bi-material notches using photoelasticity. *Materials & Design, 32*(10), 4901-4908.

Ayatollahi, M. R., Mirsayar, M. M., & Nejati, M. (2010a). Evaluation of first non-singular stress term in bi-material notches. *Computational Materials Science, 50*(2), 752-760.

Ayatollahi, M. R., Nejati, M., & Mirsayar, M. M. (2010b). An overdeterministic method for stress analysis of bi-material corners and interface cracks using finite element method. In Proceedings of the 9th Conference of Iranian Aerospace Society, Tehran, Iran.

Bahmani, A., Aliha, M. R. M., & Berto, F. (2017). Investigation of fracture toughness for a polycrystalline graphite under combined tensile-tear deformation. *Theoretical and Applied Fracture Mechanics*. To appear.

Bari, M. E., & Zollinger, D. G. (2016). New concepts for the assessment of concrete slab interfacial effects in pavement design and analysis. *International Journal of Pavement Engineering, 17*(3), 233-244.

Bažant, Z. P., & Najjar, L. J. (1971). Drying of concrete as a nonlinear diffusion problem. *Cement and Concrete Research, 1*(5), 461-473.

Bissonnette, B., Attiogbe, E. K., Miltenberger, M. A., & Fortin, C. (2007). Drying shrinkage, curling, and joint opening of slabs-on-ground. *ACI Materials Journal, 104*(3), 259-267.

Brühwiler, E., & Wittmann, F. H. (1990). The wedge splitting test, a new method of performing stable fracture mechanics tests. *Engineering Fracture Mechanics*, *35*(1-3), 117-125.

Byfors, J. (1980), Plain concrete at early-ages. Sweden: Swedish Cement and Concrete Research Institute. Report # FO 3:8.

Campilho, R. D. S. G., Banea, M. D., Chaves, F. J. P., & Da Silva, L. F. M. (2011). eXtended Finite Element Method for fracture characterization of adhesive joints in pure mode I. *Computational Materials Science, 50*(4), 1543-1549.

Cha, S. W. (1999). Modeling of hydration process and analysis of thermal and hygral stresses in hardening concrete. Seoul National University, Seoul, Korea.

Chabot, A., Hun, M., & Hammoum, F. (2013). Mechanical analysis of a mixed mode debonding test for "composite" pavements. *Construction and Building Materials, 40*, 1076-1087.

Choupani, N. (2008). Mixed-mode cohesive fracture of adhesive joints: Experimental and numerical studies. *Engineering Fracture Mechanics, 75*(15), 4363-4382.

Dai, F., Wei, M. D., Xu, N. W., Ma, Y., & Yang, D. S. (2015). Numerical assessment of the progressive rock fracture mechanism of cracked chevron notched Brazilian disc specimens. *Rock Mechanics and Rock Engineering*, *48*(2), 463-479.

Dehghany, M., Saeidi Googarchin, H., & Aliha, M. R. M. (2017). The role of first non-singular stress terms in mixed mode brittle fracture of V-notched components: an experimental study. *Fatigue & Fracture of Engineering Materials & Structures*, *40*(4), 623-641.

Delcourt, C., & Jasenski, A. (1994). First application of a concrete overlay on a bitumen-paved motorway in Belgium. *In the Proceedings of the 7th International Symposium on Concrete Roads, 2*(3), 15-20.

Emborg, M. (1989). Thermal stresses in concrete structures at early ages (Doctoral dissertation, Luleå tekniska universitet).

Evans, A. G., Rühle, M., Dalgleish, B. J., & Charalambides, P. G. (1990). The fracture energy of bimaterial interfaces. *Materials Science and Engineering: A, 126*(1-2), 53-64.

Fakhri, M., Amoosoltani, E., & Aliha, M. R. M. (2017). Crack behavior analysis of roller compacted concrete mixtures containing reclaimed asphalt pavement and crumb rubber. *Engineering Fracture Mechanics*, *180*, 43-59.

Fernlund, G., & Spelt, J. K. (1994). Mixed-mode fracture characterization of adhesive joints. *Composites Science and Technology, 50*(4), 441-449.

Fernlund, G., Papini, M., McCammond, D., & Spelt, J. K. (1994). Fracture load predictions for adhesive joints. *Composites Science and Technology, 51*(4), 587-600.

Funatsu, T., Kuruppu, M., & Matsui, K. (2014). Effects of temperature and confining pressure on mixed-mode (I–II) and mode II fracture toughness of Kimachi sandstone. *International Journal of Rock Mechanics and Mining Sciences*, *67*, 1-8.

He, M. Y., & Hutchinson, J. W. (1989). Kinking of a crack out of an interface. *Journal of Applied Mechanics, 56*(2), 270-278.

Highway Research Board. Continuously Reinforced Concrete Pavement (1973). National Cooperative Highway Research Program Synthesis of Highway Practice 16, Washington D.C.

Hurd, D. S., Caretta, R., & Gerberich, W. W. (1995). An experimental fracture mechanics study of a strong interface: The silicon/glass anodic bond. *Journal of Materials Research, 10*(2), 387-400.

Issa, M. A., Issa, M. A., Islam, M. S., & Chudnovsky, A. (2003). Fractal dimension—a measure of fracture roughness and toughness of concrete. *Engineering Fracture Mechanics*, *70*(1), 125-137.

Jeong, J. H., & Zollinger, D. (2004). Early-age curling and warping behavior: insights from a fully instrumented test-slab system. *Transportation Research Record: Journal of the Transportation Research Board*, (1896), 66-74.

Jeong, J. H., Lee, J. H., Suh, Y. C., & Zollinger, D. (2006). Effect of slab curling on movement and load transfer capacity of saw-cut joints. *Transportation Research Record: Journal of the Transportation Research Board,* (1947), 69-78.

Jung, Y., Zollinger, D., & Wimsatt, A. (2010). Test method and model development of subbase erosion for concrete pavement design. *Transportation Research Record: Journal of the Transportation Research Board*, (2154), 22-31.

Kim, S. H., Kim, S. Y., Shen, T., Park, K. T., Kim, I. H., Koo, J. M., & Seok, C. S. (2014). Fracture toughness of SA 508 GR. 1A nuclear piping using compact tension (CT) and large curved CT specimen. *International Journal of Advances in Science and Technology*, 142-146.

Kim, S. M., Kim Nelson, P., Ruiz, M., Otto Rasmussen, R., & Turner, D. (2003). Early-age behavior of concrete overlays on continuously reinforced concrete pavements. *Transportation Research Record: Journal of the Transportation Research Board*, (1823), 80-92.

Korte, S., Boel, V., De Corte, W., & De Schutter, G. (2014). Static and fatigue fracture mechanics properties of self-compacting concrete using three-point bending tests and wedge-splitting tests. *Construction and Building Materials*, *57*, 1-8.

Kosmatka, S.H., & Panarese, W.C. (1988). Design and control of concrete mixtures. Illinois, USA: Portland Cement Association.

Lopes, R. M., Campilho, R. D. S. G., da Silva, F. J. G., & Faneco, T. M. S. (2016). Comparative evaluation of the Double-Cantilever Beam and Tapered Double-Cantilever Beam tests for estimation of the tensile fracture toughness of adhesive joints. *International Journal of Adhesion and Adhesives*, *67*, 103-111.

Lura, P., Van Breugel, K., & Maruyama, I. (2002). Autogenous and Drying Shrinkage of High-Strength Lightweight Aggregate Concrete at Early Ages–The Effect of Specimen Size. In PRO 23: Early Age Cracking in Cementitious Systems—EAC'01, *Proceedings of the International RILEM Conference* (pp. 335-342).

Mack, J.W., Wu, C.L., Tarr, S.M., & Refai, T. (1997). Model development and interim design procedure guidelines for ultra-thin whitetopping pavements. *Proceedings of the 6th international conference on concrete pavement design and rehabilitation, Indianapolis*, USA. 231–54.

Martin, E., Leguillon, D., & Lacroix, C. (2001). A revisited criterion for crack deflection at an interface in a brittle bimaterial. *Composites Science and Technology, 61*(12), 1671-1679.

McCullough, B.F., & Elkins, G.E. (1979). CRC pavement design manual. Austin Research Engineers, Inc. Prepared for the Associated Reinforced Bar Producers−CRSI. Austin, Texas.

McCullough, B.F., Zolinger, D., & Dossey, T. (1999). Evaluation of the performance of Texas pavements made with different coarse aggregates. Center for Transportation Research, The University of Texas at Austin, Report # 3925-1.

Mehta, P.K., & Monteiro, P.J.M. (1993). Concrete: Microstructure, properties, and materials. Second Edition, the McGraw-Hill Companies, Inc.

Mendoza-Diaz, A., & McCullough, B.F. (1983). Design charts for the design of HMAC overlays on PCC pavements to prevent reflection cracking. Center for Transportation Research, The University of Texas at Austin, Research Report # 249-6.

Mindess, S., & Young, J.F. (1981) *Concrete*. New Jersey, USA: Prentice-Hall Inc.

Mirsayar, M. (2013). Calculation of stress intensity factors for an interfacial notch of a bi-material joint using photoelasticity. *Engineering Solid Mechanics, 1*(4), 149-153.

Mirsayar, M. (2014b). A new mixed mode fracture test specimen covering positive and negative values of T-stress. *Engineering Solid Mechanics, 2*(2), 67-72.
Mirsayar, M. (2014c). A modified maximum tangential stress criterion for determination of the fracture toughness in bi-material notches–Part 1: Theory. *Engineering Solid Mechanics, 2*(4), 277-282.
Mirsayar, M. M. (2014a). On fracture of kinked interface cracks–The role of T-stress. *Materials & Design, 61*, 117-123.
Mirsayar, M. M. (2015a). Mixed mode fracture analysis using extended maximum tangential strain criterion. *Materials & Design, 86*, 941-947.
Mirsayar, M. M. (2015b). Three dimensional investigation of mode I stress intensity factor variations in crack front using finite element method. *American Journal of Engineering and Applied Sciences, 8*(1), 11.
Mirsayar, M. M., & Park, P. (2015). The role of T-stress on kinking angle of interface cracks. *Materials & Design, 80*, 12-19.
Mirsayar, M. M., & Park, P. (2016a). Modified maximum tangential stress criterion for fracture behavior of zirconia/veneer interfaces. *Journal of the Mechanical Behavior of Biomedical Materials, 59*, 236-240.
Mirsayar, M. M., & Park, P. (2016b). Mixed mode brittle fracture analysis of high strength cement mortar using strain-based criteria. *Theoretical and Applied Fracture Mechanics, 86*, 233-238.
Mirsayar, M. M., Aliha, M. R. M., & Samaei, A. T. (2014). On fracture initiation angle near bi-material notches–Effects of first non-singular stress term. *Engineering fracture mechanics, 119*, 124-131.
Mirsayar, M. M., Berto, F., Aliha, M. R. M., & Park, P. (2016b). Strain-based criteria for mixed-mode fracture of polycrystalline graphite. *Engineering Fracture Mechanics, 156*, 114-123.
Mirsayar, M. M., Huang, K., & Zollinger, D. G. (2016a). New approach to determining concrete slab lift-off by use of interfacial fracture mechanics concepts. *Transportation Research Record: Journal of the Transportation Research Board, 2590*, 10-17.
Mirsayar, M. M., Joneidi, V. A., Petrescu, R. V. V., Petrescu, F. I. T., & Berto, F. (2017a). Extended MTSN criterion for fracture analysis of soda lime glass. *Engineering Fracture Mechanics, 178*, 50-59.
Mirsayar, M. M., Razmi, A., & Berto, F. (2017b). Tangential strain-based criteria for mixed-mode I/II fracture toughness of cement concrete. *Fatigue & Fracture of Engineering Materials & Structures*.
Mirsayar, M., & Samaei, A. (2013). Photoelastic study of bi-material notches: Effect of mismatch parameters. *Engineering Solid Mechanics, 1*(1), 21-26.
Mirsayar, M., & Samaei, A. (2014). Application of maximum tangential stress criterion in determination of fracture initiation angles of silicon/glass anodic bonds. *Engineering Solid Mechanics, 2*(3), 145-150.
Mirsayar, M., & Samaei, A. (2015). A finite element study on the fracture initiation at the zirconia/veneer interface: An application in dental materials. *Engineering Solid Mechanics, 3*(4), 207-214.
Mirsayar, M., & Takabi, B. (2016). Fracture of underwater notched structures. *Engineering Solid Mechanics, 4*(2), 43-52.
Mirsayar, M., Shi, X., & Zollinger, D. (2017c). Evaluation of interfacial bond strength between Portland cement concrete and asphalt concrete layers using bi-material SCB test specimen. *Engineering Solid Mechanics, 5*(4), 293-306.
Mirsayar, M.M. (2017). On fracture analysis of dental restorative materials under combined tensileshear loading, *Theoretical and Applied Fracture Mechanics*, doi: http://dx.doi.org/10.1016/j.tafmec. 2017.07.020
Mohamed, A., & Hansen, W. (1997). Effect of nonlinear temperature gradient on curling stress in concrete pavements. Transportation Research Record: *Journal of the Transportation Research Board, 1568*, 65-71.
Mohammad Aliha, M. R., Fotouhi, Y., & Berto, F. (2017). Experimental notched fracture resistance study for the interface of Al–Cu bimetal joints welded by friction stir welding. *Proceedings of the*

Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 0954405416688935.

Mousavi, A., & Aliha, M. (2016). Determination of fracture parameters for a bi-material center cracked plate subjected to biaxial loading using FEOD method. *Engineering Solid Mechanics*, *4*(3), 117-124.

Munz, D. G., Shannon, J. L., & Bubsey, R. T. (1980). Fracture toughness calculation from maximum load in four point bend tests of chevron notch specimens. *International Journal of Fracture*, *16*(3), R137-R141.

Nam, J. H., Kim, S. M., & Won, M. (2006). Measurement and analysis of early-age concrete strains and stresses: continuously reinforced concrete pavement under environmental loading. *Transportation Research Record: Journal of the Transportation Research Board, 1947*, 79-90.

Nam, J.H. (2005). Early-age behavior of CRCP and its implications for long-term performance (Doctoral dissertation). Austin, Texas: University of Texas at Austin.

Neville, A.M. (1996). Properties of concrete. Essex, UK: Addison Wesley Longman.

Nikbakht, M., Choupani, N., & Hosseini, S. R. (2009). 2D and 3D interlaminar fracture assessment under mixed-mode loading conditions. *Materials Science and Engineering: A, 516*(1), 162-168.

Palmer, R. P. (1988). A mechanistic model for the prediction of stresses, strains, and displacements in continuously reinforced concrete pavements (Doctoral dissertation, Texas A&M University).

Petersson, O., & Silfwerbrand, J. (1993). Thin concrete overlays on old asphalt roads. *Proceedings of the 5th International conference on concrete pavement design and rehabilitation*, USA: Purdue University. 241–6.

Polak, M. A. (1996). Effective stiffness model for reinforced concrete slabs. *Journal of Structural Engineering, 122*(9), 1025-1030.

Polak, M. A., & Vecchio, F. J. (1993). Nonlinear analysis of reinforced-concrete shells. *Journal of Structural Engineering, 119*(12), 3439-3462.

Pouteau, B., Balay, J.M., Chabot, A., & Larrard, F.D. (2004). Fatigue test and mechanical study of adhesion between concrete and asphalt. *9th International Symposium on Concrete Roads*, Istanbul, Turkey.

Ranade, S. R., Guan, Y., Ohanehi, D. C., Dillard, J. G., Batra, R. C., & Dillard, D. A. (2014). A tapered bondline thickness double cantilever beam (DCB) specimen geometry for combinatorial fracture studies of adhesive bonds. *International Journal of Adhesion and Adhesives*, *55*, 155-160.

Rao, C., Barenberg, E.J., Snyder, M.B., & Schmidt, S. (2001). Effects of temperature and moisture on the response of jointed concrete pavements. Seventh International Conference on Concrete Pavements. *The Use of Concrete in Developing Long-Lasting Pavement Solutions for the 21st Century*. 23-38.

Rao, S., & Roesler, J. R. (2005). Characterizing effective built-in curling from concrete pavement field measurements. *Journal of Transportation Engineering, 131*(4), 320-327.

Rasmussen, R. O., & Rozycki, D. K. (2004). Thin and ultra thin whitetopping–A synthesis of highway practice, NCHRP Synthesis 338. Transportation Research Board.

Razavi, S. M. J., Aliha, M. R. M., & Berto, F. (2017). Application of an average strain energy density criterion to obtain the mixed mode fracture load of granite rock tested with the cracked asymmetric four-point bend specimens. *Theoretical and Applied Fracture Mechanics*.

Razmi, A., & Mirsayar, M. M. (2017). On the mixed mode I/II fracture properties of jute fiber-reinforced concrete. *Construction and Building Materials, 148*, 512-520.

Sadd, M., Shukla, A., Subramaniam, V.K., & Lee, K.W. (2008). Determination of interfacial bond behavior of composite concrete-asphalt pavement systems. US Department of Transportation. Report # FHWA-RIDOT-RTD-08-1.

Samarai, M., Popovics, S., & Malhotra, V. M. (1983). Effect of High Temperatures on the Properties of Hardened concrete. *Transportation Research Record, 924*, 50-56.

Seitl, S., Ríos, J. D., & Cifuentes, H. (2017). Comparison of fracture toughness values of normal and high strength concrete determined by three point bend and modified disk-shaped compact tension specimens. *Fracture and Structural Integrity*, *42*, 56-65.

Shaeles, C. A., & Hover, K. C. (1988). Influence of mix proportions and construction operations on plastic shrinkage cracking in thin slabs. *Materials Journal, 85*(6), 495-504.

Sharifi, S., & Choupani, N. (2008). Stress analysis of adhesively bonded double-lap joints subjected to combined loading. *World Academy of Science, Engineering and Technology, 41*(17), 758-763.

Suh, Y.C., Hankins, K., & McCullough, B.F. (1992). Early-age behavior of continuously reinforced concrete pavement and calibration of the failure prediction model in the CRCP-7 Program. Center for Transportation Research, The University of Texas at Austin, Report # 1244-3.

Tang, T., Zollinger, D. G., & Senadheera, S. (1993). Analysis of concave curling in concrete slabs. *Journal of Transportation Engineering, 119*(4), 618-633.

Totsky, O.N. (1981). Behavior of multi-layered plates on Winkler foundation (in Russian). Moscow: Stroitel'naya Mekhanika I Raschet Sooruzhenii. 6, 54-58.

Tozzo, C., D'Andrea, A., & Al-Qadi, I. L. (2015). Prediction of fatigue failure at asphalt concrete layer interface from monotonic testing. *Transportation Research Record: Journal of the Transportation Research Board, 2507*, 50-56.

Tschegg, E. K., Macht, J., Jamek, M., & Steigenberger, J. (2007). Mechanical and fracture-mechanical properties of asphalt-concrete interfaces. *ACI materials journal, 104*(5), 474-480.

Tutluoglu, L., & Keles, C. (2011). Mode I fracture toughness determination with straight notched disk bending method. *International Journal of Rock Mechanics and Mining Sciences*, *48*(8), 1248-1261.

Wei, M. D., Dai, F., Xu, N. W., Xu, Y., & Xia, K. (2015). Three-dimensional numerical evaluation of the progressive fracture mechanism of cracked chevron notched semi-circular bend rock specimens. *Engineering Fracture Mechanics*, *134*, 286-303.

Wei, M. D., Dai, F., Xu, N. W., Liu, Y., & Zhao, T. (2017b). Fracture prediction of rocks under mode I and mode II loading using the generalized maximum tangential strain criterion. *Engineering Fracture Mechanics*. To appear.

Wei, M. D., Dai, F., Xu, N. W., Zhao, T., & Liu, Y. (2017a). An experimental and theoretical assessment of semi-circular bend specimens with chevron and straight-through notches for mode I fracture toughness testing of rocks. *International Journal of Rock Mechanics and Mining Sciences*, *99*, 28-38.

Westergaard, H.M. (1927). Analysis of stresses in concrete pavements due to variations of temperature. *Proceedings of the Sixth Annual Meeting of the Highway Research Board*, *6*, 201-215.

Yu, H., Khazanovich, L., Darter, M., & Ardani, A. (1998). Analysis of concrete pavement responses to temperature and wheel loads measured from intrumented slabs. *Transportation Research Record: Journal of the Transportation Research Board, 1639*, 94-101.

Zhang, J., & Li, V. C. (2001). Influence of supporting base characteristics on shrinkage-induced stresses in concrete pavements. *Journal of Transportation Engineering, 127*(6), 455-462.

Zhang, X. (2012). Effects of base characteristics on curling stresses of continuously reinforced concrete pavements. In CICTP 2012: Multimodal Transportation Systems—Convenient, Safe, Cost-Effective, Efficient (pp. 3169-3174).

Zhutovsky, S., Kovler, K., & Bentur, A. (2002). Efficiency of lightweight aggregates for internal curing of high strength concrete to eliminate autogenous shrinkage. *Materials and Structures, 35*(2), 97-101.