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A Comprehensive Overview on Main Distress Mechanisms in Composite Pavements

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Abstract: Fatigue cracking of cement-treated bases, instability rutting, top-down cracking, shrinkage cracking, reflective cracking and thermal fatigue cracking have been identified as the most common distresses affecting the service life of composite pavements, which consist of an asphalt course on top of a cement-treated base. These distresses prevent composite pavements from being considered long-life pavements, which are defined as pavements in which the structural elements may last indefinitely. This paper analyzes different factors leading to the initiation and propagation of the distress mechanisms, as well as the material properties required to improve the long-term performance of composite pavements.

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***Key words**: Composite pavement; Cracking; Distress mechanism; Performance.*

Introduction

One of the major concerns in pavement engineering is that the service life of pavements is often shorter than initially expected. Distresses lead to frequent rehabilitation that increases the global cost of the sections, including the cost of the delay experienced by drivers in work zones. Furthermore, although a 20-year performance period is typically considered in pavement design, longer service lives are definitely interesting from the life-cycle cost perspective.

The Forum of European National Highway Research Laboratories (FEHRL) has studied the so called long-life pavements [1, 2]. A long-life pavement is defined as “a well-designed and well-constructed pavement where the structural elements last indefinitely provided that the designed maximum individual load and environmental conditions are not exceeded and that appropriate and timely surface maintenance is carried out” [2]. Long-life pavements have also been studied in Spain as one out of twelve tasks included in the Fenix Project, but the research mainly dealt with the effect of top-down cracking on the service life of flexible pavements.

COST-Transport [3] ranked the most commonly used long-term performance indicators according to the information provided by fifteen countries in the European Union. The results showed that surface cracking and rutting are the major distresses affecting composite pavements. Another research project on pavement design [4] also considers instability rutting and surface cracking as the major distresses, rather than consolidation rutting or fatigue cracking, which are typically considered in pavement design. It is known that the use of a cement-treated base (CTB) in composite pavements clearly decreases the tensile stresses within the asphalt layer, reducing or even eliminating fatigue cracking of asphalt concrete (AC). In addition, cement-treated bases spread the load over a larger area, so the vertical deformation on top of the subgrade is decreased and consolidation rutting is thus prevented.

Previous studies on service life of composite pavements have focused primarily on section thickness [2], but further understanding of distress mechanisms and required material properties are key issues to improve performance. Therefore, the goals of this paper are (1) to characterize the main distress mechanisms affecting the serviceability of composite pavements, and (2) to provide some material property guidelines to achieve an optimum long-term performance.

In addition to instability rutting and surface-initiated cracking, the paper analyzes other mechanisms such as fatigue cracking of cement-treated materials, shrinkage cracking, reflective cracking, and thermal fatigue cracking.

Distress Mechanisms

Fatigue Cracking of Cement-treated Materials

Fatigue cracking is a distress mechanism caused by the slow development of micro-cracking within the internal structure of a material when subjected to repeated loading that produces tensile stresses under the ultimate strength. With cement-treated materials, micro-cracking takes place on the links developed between mortar and aggregate during the cement hydration [5].

Previous research based on the heavy vehicle simulator (HVS) has shown that different phases can be distinguished in the behavior of cement-treated materials [6]:

- Phase 1 (Pre-cracked phase): After placement, fine transverse and block cracking occur because of shrinkage and environmental effects.
- Transition from phase 1 to phase 2: Traffic-induced micro-cracks appear when the tensile strain exceeds 25% of the failure strain (about 36 με).
- Phase 2 (Post-cracked phase): Tensile strain induced by traffic loading increases until the material reaches the failure strain (about 145 με).
- Phase 3 (Post-cemented phase): After failure, the material is

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broken down into small pieces and behaves like a granular layer.

According to these results, Parmeggiani [6] concluded that cement-treated materials, regardless of the elastic modulus, can avoid fatigue failure by remaining in the pre-cracked phase, provided that the maximum tensile strain does not exceed 36 με.

The existence of a fatigue limit on cement-treated materials is also supported by other researchers [7-12]. Portland Cement Association (PCA) [13] indicated that cement-treated materials may withstand an unlimited number of load applications for a ratio of tensile stress to flexural strength equal to or lower than 0.45. Spanish Centre for Research on Public Works (CEDEX) and Spanish Cement Institute (IECA) [14] also stated infinite number of load repetitions may be achieved if the maximum tensile stress does not exceed 40-50% of the flexural strength.

Therefore, two criteria have been established to prevent fatigue failure of cement-treated materials: maximum tensile strain and maximum tensile stress.

Instability Rutting

Instability rutting appears as a surface depression in the wheelpath and is characterized by a lateral displacement of material due to a poor rheology performance of the mixture (Fig. 1).

Analysis of measured tire contact stresses showed high shear stresses near the surface combined with low levels of confinement, which may explain the mechanism of instability rutting [15, 16]. Su et al. [17] also indicated that instability rutting is due to shear stresses developed within the asphalt concrete, especially in composite pavements where the asphalt surface absorbs the tangential deformations. Furthermore, Flintsch et al. [12] pointed out that the presence of a stiff base, which does not allow any significant vertical deformation to occur, causes the asphalt material to deform in order to absorb all the vertical strains. Thus, the stiffness of the base increases the potential for instability rutting and the subsequent rut depth.

Quanliang et al. [18] identified two stages on rutting formation. During the first stage, characterized by the viscous response of the asphalt material, deformation rapidly occurs due to the compaction produced by passing loads. During the second stage, the previous compaction increases rutting resistance and reduces the rate of deformation.

Regarding the location of the distress, Quanliang et al. [18] found that the deformation mainly takes place in the asphalt binder course, at a depth that ranges from 4 to 10 cm. Moreover, they observed that layer thickness was not a major factor. By contrast, mixture properties, temperature, and traffic (both magnitude and rate of application) had higher effect on permanent deformation.

Su et al. [19] studied the shear stress distribution with depth on composite pavements. They observed the maximum value consistently appeared at a depth of 6 cm, regardless of the load and tire pressure considered. In addition, they revealed that different thicknesses of asphalt layer, ranging from 10 cm to 30 cm, had little influence on maximum shear stress. Nonetheless, a poor bond between the asphalt layer and the cement-treated base can definitely increase the risk of rutting and slippage failure.

Fig. 1. Pavement with Severe Instability Rutting.

With respect to asphalt mixture composition, a research project on the effect of binder on rutting resistance showed that polymer-modified binders and relatively hard binders (less than 50 penetration units in the standard penetration test) decreased both the total deformation and the deformation rate measured on wheel-tracking tests [20]. The same study noted that crushed fine aggregate and rough-textured coarse aggregate increased the rutting resistance of asphalt mixtures. In order to reduce rutting susceptibility, a minimum air void content of 3% is recommended to avoid tender problems and a maximum air void content of 8% to assure a certain degree of interlocking among aggregate particles [21].

Top-down Cracking (TDC)

Top-down cracking (TDC) is a distress that initiates at the pavement surface and propagates downward through the asphalt course. It usually appears as longitudinal cracks, either in the wheelpath or near the edges. TDC can occur at an early stage, even the first year after construction [22], but initially it does not affect the structural capacity of the pavement. However, at an advanced stage, cracks provide a path for water, which clearly affects both the functional and structural properties of the pavement.

Svasdisant et al. [23] defined three different stages in TDC initiation and propagation. During the first stage, a single short longitudinal crack appears just outside the wheelpath. During the second stage, initial longitudinal cracks grow longer and new cracks develop parallel to and within 30 to 100 cm of the original crack. Finally, longitudinal cracks are connected by short transverse cracks.

TDC is a complex surface distress mode related to tensile and shear stresses associated with non-uniform tire stresses, interlayer slippage, thermal stresses, stiffness gradients, construction problems such as segregation, and premature asphalt binder hardening [24, 25]. Su et al. [19] also recognized that shear stresses play a major role on TDC; when the maximum shear stress is high enough, cracking may appear at the tire edge under repeated traffic loading.

Based on field and laboratory research, Svasdisant et al. [23] pointed out that top-down cracking is caused by high radial tensile stresses on the asphalt surface induced by a combination of traffic load, temperature gradients, asphalt binder hardening, and segregation of the mixture. According to Rolt [26], asphalt binder content, air voids, and mineral filler content had a statistically significant effect on the propagation rate of TDC. Nonetheless, their effect is relatively small compared to the effect of surface age hardening, especially in the top 2-3 mm [26]. Before excessive binder aging takes place, the kneading effect of vehicle loads during hot weather may reduce the damage on asphalt mixture. However, as the AC stiffness increases due to aging or temperature drops, that healing effect disappears and permanent cracks occur.

Thus, it can be concluded that top-down cracking is a distress related to the stresses developed at the pavement surface, the properties of the asphalt concrete (stiffness gradients and binder hardening), and placement conditions, especially segregation. The use of gradations more resistant to fracture and polymer-modified binders have shown improved performance in terms of top-down cracking [24, 27-29]. Additionally, placement conditions should be carefully considered to avoid cracking induced by segregation (Fig. 2).

Shrinkage Cracking

Shrinkage of cement-treated materials is characterized by a reduction in volume due to three different mechanisms: plastic shrinkage, drying shrinkage, and thermal shrinkage. Plastic shrinkage occurs when the rate of water removal from the surface of freshly placed concrete exceeds the rate at which bleed water rises to the surface. Drying shrinkage is caused by the loss of physically adsorbed water from the calcium silicate hydrate (C-S-H). Thermal shrinkage begins when the concrete cools down to the ambient temperature from the temperature peak caused by hydration heat.

The reduction in volume involves the development of tensile stresses that cause transverse cracks at regular intervals. Cracks reduce the ability to transfer load and originate stress concentrations near the joints, especially during cold weather as joint spacing increases. The following factors can be considered during mix design to reduce the effect of shrinkage in cement-treated materials [30]:

- Cements with moderate heat of hydration, high mineral admixture content, and medium to low ultimate strength are recommended.
- The cement content should be the lowest compatible with required strength and adequate mix homogeneity.
- Limestone aggregate has a relatively lower coefficient of thermal expansion (COE), decreasing the stresses induced by temperature changes.

During placement, other factors are known to affect the shrinkage of cement-treated materials: high temperature and dry environments increase the humidity loss; compaction humidity higher than optimum increases shrinkage; and a lag between the placement of the cement-treated base and the asphalt mixture on top will reduce the stresses developed at the interface of both materials.

Furthermore, curing and pre-cracking are two key issues regarding the control of shrinkage of cement-treated materials. Curing is intended to reduce the humidity gradient and, thus, to minimize the reduction in volume. Pre-cracking is used to control and reduce the spacing between naturally occurring transverse cracks. The creation of joints at a predetermined, shorter spacing decreases the joint opening and improves load transfer across the faces of the crack. Although many different pre-cracking techniques have been reported in the literature, field experience has shown that the creation of fresh transverse joints followed by the application of an emulsion is one of the most cost-effective methods on composite pavements.

Fig. 2. Top-down Cracking Associated with Segregation

Other alternatives to minimize the shrinkage of cement-treated materials include the use of expansive agents based on the formation of ettringite or calcium hydroxide, and shrinkage reduction admixtures (SRA), which produce a controlled expansion to mitigate the reduction in volume experienced by the material [31].

Reflective Cracking

Reflective cracking is characterized by the appearance of a crack distribution on the pavement surface that resembles the existing crack or discontinuous pattern underneath. Differential movements between the cement-treated base and the asphalt layer have been identified as the major causes leading to the propagation of transverse cracks. However, these movements can be the result of three different mechanisms [30, 32]:

- Horizontal differential movements, usually referred to as thermally-induced reflective cracking. Temperature changes induce horizontal movements that produce stress concentrations at the cracking surroundings because of the friction between the base and the asphalt concrete.
- Vertical differential movements across cracks, commonly referred to as load-induced reflective cracking. Traffic loading depresses crack faces, resulting in shear-stress concentrations in the asphalt course.
- Upward curling of the slabs due to temperature drops results in tensile stresses at the surface of the AC that can lead to surface-initiated reflective cracking, especially under low temperatures, when the asphalt concrete becomes stiff and brittle.

Table 1 summarizes the causes, initiation and propagation modes, and factors affecting the three mechanisms of reflective cracking. As can be seen, shrinkage transverse cracks from cement-treated bases can appear on the surface of a composite pavement as a result of a bottom-up or top-down process (Fig. 3). Environmental and traffic conditions will define the dominant mechanism of reflective cracking, although some authors state that several mechanisms may occur at the same time [33].

Table 1. Summary of Mechanisms and Factors Affecting Reflective Cracking (Adapted from Von Quintus et al. [32]).

Mechanism	Cause	Initiation Mode	Propagation Mode	Propagation Direction	Factors
Horizontal Movement	Thermal-induced	Tension	Tension & Shear	Upward	Magnitude and Rate of Temperature Change, Material Properties
Vertical Movement	Load-induced	Shear	Shear	Upward	Wheel Load, Load Transfer Across the Crack, Differential Subgrade Support, Material Properties
Curling	Thermal-induced	Tension	Shear	Downward	Temperature Drop, Aging of HMA, Shrinkage Properties, Material Properties

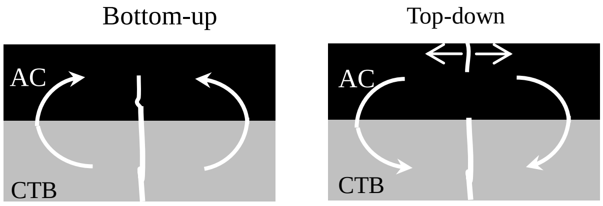

Fig. 3. Mechanisms of Reflective Cracking in Composite Pavements.

Fig. 4. Top-down Reflective Cracking [34].

Bottom-up Reflective Cracking

Theoretically, no bond between a cement-treated material and the asphalt concrete on top might prevent reflective cracking. Nevertheless, that would increase the tensile stresses within the asphalt course, leading to premature fatigue cracking. At the same time, water could circulate at the interface, reducing the structural capacity of the section.

When there is a good bond at the interface, transverse joints will propagate upward as clean cracks. Conversely, when the bond is poor, cracks tend to initially propagate through the horizontal interface until the asphalt course is completely debonded, and then they grow up vertically as multiple cracks.

Top-down Reflective Cracking

Nesnas and Nunn [34, 35] stated that reflective cracking in composite pavements can start at the surface (over the transverse joints) and propagate downward through the asphalt concrete (Fig. 4). The results showed that top-down reflective cracking is due to thermal cycles rather than traffic loading, since the same cracking patterns were observed in sections with and without traffic.

Properties of the surface course are considered to govern the initiation of this type of cracking [34, 35]. The higher coefficient of thermal expansion of asphalt concrete, the higher thermal gradient at the surface and, especially, the aging of the binder (increase in stiffness) increase the maximum tensile stress induced by temperature drops, which is what leads to cracking. The reduction of asphalt course thickness and a higher joint spacing of the cement treated base (CTB) were found to increase the maximum tensile stress at the surface.

Reflective Cracking Mitigation Techniques

The traditional approach to delay reflective cracking in composite pavements consists of increasing the thickness of the asphalt course on top of cement-treated materials. However, the general “rule of thumb” states that reflective cracking propagates at a rate of 25 mm per year [33, 36], so increasing the thickness of the asphalt layer has been demonstrated to be the least cost-effective technique [32]. As a result, numerous techniques such as stress absorbing membrane interlayers (SAMI) [33, 37-40], geosynthetics [36, 41-43], steel nets [44, 45], modified binders [46, 47], and specifically designed tack coats [48] have been tried to mitigate reflective cracking with varying degree of success.

Based on the classification previously proposed by Button and Lytton [42], Von Quintus et al. [32] defined five categories of mitigation techniques for reflective cracking: modify/strengthen existing asphalt surface, overlay layer/mixture modification, stress or strain relieving interlayer, reinforcement of asphalt overlays, and crack control method. For each category, Table 2 presents the most common mitigation treatments reported in the literature.

According to the extensive research on mitigation techniques for reflective cracking conducted by Von Quintus et al. [32], the following characteristics about mitigation treatments and their performance can be pointed out:

- The modification and strengthening treatments are used to remove the cracks in the existing pavement surface or adjust the joint condition of the pavement prior to the placement of an overlay.
- As previously mentioned, increasing the asphalt overlay thickness is considered the least cost-effective alternative to delay reflective cracking. However, mixture modification can improve the fracture resistance of the overlay, which does not prevent reflective cracking from occurring, but does reduce the

Table 2. Mitigation Treatments for Reflective Cracking (Adapted from Von Quintus et al. [32]).

Category	Mitigation Treatments
1. Modify/Strengthen Existing Asphalt Surface	Mill & Replace Asphalt Layer
	Hot in place Recycling
	Heater Scarification
	Full depth Reclamation
2. Overlay Layer/Mixture Modification	Thick Asphalt Layers
	Soft or Low Viscosity Asphalt
	Modified Asphalt (Polymers, Rubber)
	Specialty Mixtures (Such as Stone Mastic Asphalt)
3. Stress or Strain Relieving Interlayer	
a) Stress Absorbing Membrane Interlayer (SAMI)	− Chip Seals
	− Sand asphalt
	− Interlayer Stress Absorbing Composite (ISAC)
	− Highly Polymer Modified Asphalt Emulsion (PMAE)
	− HMA Interlayer with Material Modification: Soft Asphalt, Asphalt-rubber, Polymer-Modified
	− Thick Asphalt-rubber Membrane + Non-woven Fabric
b) Cushion or Crack Relief Layers	− Open-graded HMA Mixture (25-30% Air Voids) with a Nominal Maximum Aggregate about 25 mm
	− Unbound Aggregate/Crushed Stone Material
c) Bond Breaker Interlayer	− Sand/Stone Dust
	− Wax and Roofing Paper
4. Reinforcement of Asphalt Overlays	− Steel Reinforcement
	− Geosynthetics: Fabrics, Geogrids, Composites
5. Crack Control Method	− Saw and Seal Joints

severity of reflective cracks. Mixture modification is considered a good option in combination with other mitigation techniques.

- Stress and strain relieving interlayers are relatively low-stiffness systems that dissipate energy by deforming horizontally or vertically. Three different systems are included in this category: SAMI, cushion or crack relief layers, and bond breaker interlayers. SAMIs are thin treatments (less than 50 mm in thickness) of relatively impermeable material which do not increase the structural capacity of the section (not indicated for traffic-induced reflective cracking), but dissipate large horizontal movements. Cushion or crack relief layers increase the structural capacity and absorb or dissipate both horizontal and vertical differential movements, so they mitigate reflected cracks caused by the three mechanisms. Bond breaker interlayers reduce stress concentration by preventing bond, but have low success.
- Reinforcement of asphalt overlays includes the installation of a stiffer material to improve the tensile response of the asphalt concrete. It distributes the stresses caused by differential horizontal and vertical movements, decreasing the potential for reflective cracking caused by all mechanisms. It will not prevent reflective cracks from occurring when large differential vertical movement exists, but helps keep the reflective crack tight.
- Crack control methods control the severity of reflective cracks by sawing and sealing the asphalt overlay above joints in the cement-treated base, but do not prevent or delay reflective cracks.

The information presented above provides an overview on the most commonly used mitigation treatments, and their application based on performance analysis. Further details on material selection and construction techniques can be found in selected references [32, 49].

For the purpose of minimizing the reflection of transverse joints in composite pavements, experimental results have shown that steel net and glass-fiber geogrids are more adequate for heavy traffic conditions, whereas chip seals, sand-asphalt or geotextiles may be used for low traffic volumes [4]. It should be noted that the effectiveness of the treatment depends on an appropriate selection based on the mechanism dominating the distress mode.

Finally, it should be noted that the layer placed immediately above the mitigation system must be kept bonded to ensure the overall performance of the section and provide a good barrier against water infiltration. Water can promote debonding problems as well as pumping under cement-treated bases, which clearly diminish the performance of the pavement section.

Thermal Fatigue Cracking

Thermal fatigue cracking appears as transverse cracks on the pavement surface that propagate downward. It is caused by the accumulation of low tensile strains due to daily temperature variations. Perez and Del Val [50] reported that below 25℃ the coefficient of thermal contraction of asphalt concrete is greater than the coefficient of thermal expansion, so some deformation is accumulated after each thermal cycle. Above 25℃ strains are relaxed due to a higher coefficient of thermal expansion and the viscoelastic response of asphalt concrete.

Therefore, when temperature ranges from -7℃ to 25℃, the accumulation of tensile strain in each thermal cycle leads to cracking if the failure strain at low temperature is reached [50]. Asphalt binder hardening and high filler to asphalt ratios considerably decrease the number of cycles that the mixture can withstand before failure.

Rare Distresses

Warping on composite pavements is defined as the displacement of the cement-treated base out of the horizontal plane due to excessive compression stresses. These high stresses are primarily related to high temperature, low humidity, and highly expansive soils. High cement contents, aggregate with a high coefficient of thermal expansion, and excessive exposure of the cement-treated material without the insulation provided by the asphalt concrete have also been pointed out as potential causes of warping.

Moreover, chemical reactions, such as aggregate-alkali reactivity or sulfate attack, can lead to the disintegration of the cement-treated materials [51]. Nonetheless, this type of distress rarely occurs in pavement engineering due to the level of control on material specifications and subgrade properties.

Conclusions

The design of long-life pavements requires elimination of any structural distress during the service life of the section. Fatigue cracking of cement-treated bases, instability rutting, top-down cracking, shrinkage cracking, reflective cracking, and thermal fatigue cracking have been addressed as the major distresses reducing the overall performance of composite pavements. In order to mitigate these distresses, the main factors affecting the mechanisms and the required material properties have been studied, resulting in the following conclusions:

- First of all, the surface course plays a major role on several identified distresses. Asphalt mixtures with low aging susceptibility and good fracture resistance help reduce surface-initiated cracking. This can be achieved by using polymer-modified binders and gradations more resistant to fracture, along with avoiding high air void contents. In addition, low aging-susceptibility binders and moderate filler to binder ratios improve the thermal fatigue resistance of asphalt concrete.
- Secondly, the binder course is responsible for permanent deformation resistance as well as waterproofing of cement-treated materials. Asphalt mixtures with a percentage of air voids within 3-8% and crushed aggregates, especially the sand fraction, improve the performance of the binder course.
- Thirdly, a mitigation technique should be incorporated on top of the cement-treated base in order to minimize the reflection of the transverse joints induced to control shrinkage.
- Finally, cement-treated materials are responsible for the structural capacity of composite pavements, so fatigue cracking should be considered in their design. In addition, minimizing the effect of shrinkage is a critical issue on the performance of cement treated bases, which involves not only mix design factors but also placement conditions such as curing and pre-cracking.

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