Guidelines for the design of semi-rigid long-life pavements

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Received 1 September 2015; received in revised form 12 March 2016; accepted 25 March 2016
Available online 29 March 2016

Abstract

Pavement distress leads to frequent rehabilitation that increases the global cost of pavement sections. A clear understanding of distress mechanisms is the cornerstone for extending pavement service life. The overall objective of this study was to provide guidance for the design of semi-rigid long-life pavements. The potential distress mechanisms in semi-rigid pavements were revisited in order to synthesize the primary factors affecting performance. One key observation from the literature was that, while thickness primarily controls fatigue cracking, material requirements are the primary factor governing other distress mechanisms. Semi-rigid sections proposed for the heaviest traffic conditions in Spain were analytically evaluated from the long-life perspective. Results showed that only some sections met the structural requirements to be considered long-life pavements; however, two of them were clearly overdesigned. In addition, thick asphalt lifts are used to delay the onset of reflective cracking, which is not a cost-effective approach. Findings from linear elastic analysis of alternative sections and observations on potential distress mechanisms led to establishment of guidelines for a more efficient design of semi-rigid long-life pavements. The established design concept integrated both layer thickness and material requirements.

Keywords: Long-life; Semi-rigid pavement; Distress mechanism; Design

1. Introduction

Pavement distress leads to frequent rehabilitation that increases the global cost of pavement sections, including the cost of the delay experienced by drivers in designated work zones. Frequent pavement rehabilitation is impractical and non-efficient, so longer service life is of great interest from the life-cycle cost perspective.

Evidence of the existence of long-life pavements have been reported across the world, including the United States and many countries in Europe [1–4]. 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” [5].

The European Long-Life Pavements Group (ELLPAG) of the Forum of European National Highway Research Laboratories (FEHRL) has arguably conducted the most comprehensive study on long-life pavements in Europe to date [5,6]. As far as semi-rigid pavements are concerned, the design concepts presented by ELLPAG primarily addressed requirements in terms of section thickness [5]. For the sake of clarity, a semi-rigid pavement is composed of one or more asphalt layers on a cement-treated base (Portland cement concrete bases are not included in this definition).

Traditionally, the pavement community has based most of its pavement design systems on the hypothesis that a thicker section results in better performance. Although it
is undeniable that thickness plays a major role in the fatigue cracking performance of semi-rigid sections, it does not necessarily follow that thickness is the primary factor in all pavement distresses. In fact, pavement distress may be governed by other factors such as environmental conditions, material properties or even construction deficiencies.

A clear understanding of the potential distress mechanisms is the cornerstone for extending pavement service life. As a result, primary factors affecting performance (e.g., layer thickness, material properties, etc.) can be integrated into a set of guidelines for a more effective design of semi-rigid long-life pavements.

2. Objectives

The overall objective of this study was to provide guidance for the design of semi-rigid long-life pavements. More specific objectives included:

1. To synthesize potential distress mechanisms in semi-rigid pavements and corresponding primary factors for improved performance.
2. To perform a structural analysis to determine whether the semi-rigid sections proposed for the heaviest traffic conditions in the Spanish pavement design guide may potentially be considered long-life pavements.
3. To propose a design concept for semi-rigid long-life pavements based on findings from (1) and (2).

3. Key observations on potential distress mechanisms in semi-rigid pavements

COST-Transport [7] ranked the most frequently used long-term pavement performance indicators based on the rating provided by fifteen countries in the European Union. The results showed that surface cracking and rutting were perceived as the major distresses in semi-rigid pavements. Another study [8] also suggested surface cracking and instability rutting as main distress mechanisms, rather than subgrade rutting or fatigue cracking, which are typically considered in pavement design. Besides surface-initiated cracking (top-down cracking and thermal fatigue cracking) and instability rutting, this paper reviewed fatigue cracking, shrinkage and reflective cracking of cement-treated materials. This section synthesizes the primary factors for improved performance associated with the aforementioned distress mechanisms. Further details on distress mechanisms in semi-rigid pavements can be found in prior research [9].

Review of potential distress mechanisms in semi-rigid pavement showed that, while thickness plays a major role in fatigue cracking, material requirements are the primary factor governing other distress mechanisms. With respect to the surface course, the use of polymer-modified binder, a gradation more resistant to fracture, and a moderate air void content appear to improve the asphalt mixture performance in terms of top-down cracking [10–16]. In addition, asphalt binder with low aging susceptibility and moderate filler-to-binder ratio are required to minimize the potential for thermal fatigue cracking [17]. With these requirements, gap-graded mixtures appear to be a good option because of their moderate air void content and relatively high proportion of polymer-modified bituminous mortar. Also, gap-graded mixtures bring the advantage of high macrotexture for improved safety. Regarding the binder course, rough-textured aggregate, a shear resistant gradation, a relatively hard or a polymer-modified binder, and a relatively low air void content are required for adequate rutting resistance and waterproofness of the section [18–25]. A dense-graded mixture seems to potentially meet the requirements for the binder course. Furthermore, the cement-treated base should be designed to prevent fatigue cracking failure (main thickness requirement of the section) and reduce shrinkage effects. Shrinkage involves not only mix design factors such as cement type, aggregate type, water-to-cement ratio, and presence of admixtures, but also involves placement conditions such as curing and pre-cracking [26,27]. Finally, because of the presence of transverse joints in the cement-treated base, a mitigation treatment is required to control reflective cracking. Numerous interlayer systems such as stress/strain absorbing membrane interlayers (SAMI) or reinforcing systems have been tried to mitigate reflective cracking with a varying degree of success [26,28–30]. Experimental results have shown that steel net and glass-fiber geogrid seem to be more adequate for heavy traffic conditions, whereas chip seals, sand-asphalt and geotextiles may be used for low traffic volume [8]. Another approach to mitigate reflective cracking is the use of inverted pavement structures, which basically consists in incorporating a granular material, such as crushed stone or gravel-emulsion, between the asphalt surface and cement-treated base.

4. Structural analysis of semi-rigid sections

Layered theory [31] was used to determine the response (i.e., stresses and strains) of different semi-rigid pavement sections based on typical material properties used in Spain. All materials were assumed to be homogeneous, isotropic, and linearly elastic and were characterized by their elastic modulus and Poisson’s ratio.

4.1. Properties of pavement materials used in Spain

4.1.1. Asphalt mixtures

Hot-mix asphalt (HMA) used for surface course in Spain can be open-graded (PA), gap-graded (BBTM A and BBTM B) and dense-graded (AC S and AC D). AC S is usually employed as the binder course. When an additional asphalt layer is placed under the binder course, AC S is also considered the best option, although AC G may be also used. Table 1 presents the properties of the asphalt
mixtures used in Spain, where $E$ represents the elastic modulus and $v$ the Poisson’s ratio usually considered for pavement analysis.

4.1.2. Cement-treated materials used for base layer

Cement-treated bases (CTB) used in Spain include soil-cement (SC), gravel-cement (GC), high-resistance gravel cement (HRGC) and compacted lean concrete (CLC). The properties of these materials are shown in Table 2, in which $R_{c,7d}$ is the minimum compressive strength at 7 days, $R_{c,28d}$ is the minimum compressive strength at 28 days, $R_{c,LT}$ represents the long-term compressive strength, and $R_{F,LT}$ is the long-term flexural strength.

4.1.3. Subgrade materials

The subgrade may consist of the existing material or may include the use of selected natural soils or stabilized soils to increase bearing capacity. Stabilized soils result in higher structural capacity and lower moisture susceptibility than natural soils. Since the level of bending in a CTB is affected by the properties of the layer immediately underneath, stabilized soils are commonly introduced to improve the overall performance of semi-rigid sections. The properties of the stabilized materials used according to Spanish specifications are presented in Table 3. $CBR_{7d}$ corresponds to the California bearing ratio at 7 days of age.

4.2. Consideration of fatigue cracking in cement-treated materials

The resistance of cement-treated materials to fatigue cracking was analyzed by two distinct criteria identified in the literature: maximum tensile strain and maximum tensile stress. First, the maximum tensile strain was restricted to 36 με based on studies conducted by Parmeggiani [32]. Secondly, the maximum tensile stress was defined by the fatigue model proposed by the Eduardo Torroja Institute (Eq. (1)), which is considered to be valid for the cement-treated materials used in Spain [27]:

$$\frac{\sigma_t}{R_{F,LT}} = \gamma \cdot (1 - a \cdot \log N)$$  \hspace{1cm} (1)

where $\sigma_t$ is the maximum tensile stress supported by the material, $R_{F,LT}$ is the long-term flexural strength, $N$ is the number of load repetitions, $\gamma$ is a calibration factor, and $a$ is a fitting parameter. Typical values of 0.8 and 0.065 can be assumed for $\gamma$ and $a$, respectively [27].

$N$ was estimated based on an average daily truck traffic (ADTT) of 2000 heavy vehicles a day for the design lane and opening year, a truck factor of 0.8, an annual growth rate of 3%, and a minimum service life of 30 years. This resulted in about 30 million repetitions of the 128-kN single-axle design load (900 kPa tire pressure). For the computed value of $N$, Eq. (1) provides a ratio of tensile stress to long-term flexural strength of 0.4, which is consistent with the fatigue limit for cement-treated materials reported in the literature [21,27,33].

4.3. Analysis of current semi-rigid sections

The current Spanish pavement design guide offers a catalog of pavement sections based on the average daily truck traffic (ADTT) for the design lane and opening year, and the bearing capacity of the subgrade [34].

Table 1

Properties of asphalt mixtures used in Spain at 20 °C and 10 Hz.

<table>
<thead>
<tr>
<th>Asphalt mixture</th>
<th>Gradation</th>
<th>Air void content</th>
<th>$E$ (MPa)</th>
<th>$\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA</td>
<td>Open-graded</td>
<td>$\geq 20%$</td>
<td>3000–3500</td>
<td>0.35</td>
</tr>
<tr>
<td>BBTM B</td>
<td>Gap-graded</td>
<td>12–18%</td>
<td>3000–3500</td>
<td>0.35</td>
</tr>
<tr>
<td>BBTM A</td>
<td>Gap-graded</td>
<td>4–12%</td>
<td>3500–4000</td>
<td>0.35</td>
</tr>
<tr>
<td>AC D, AC S</td>
<td>Dense-graded</td>
<td>4–8%</td>
<td>6000–6500</td>
<td>0.33</td>
</tr>
<tr>
<td>AC G</td>
<td>Dense-graded</td>
<td>4–8%</td>
<td>5000–6000</td>
<td>0.33</td>
</tr>
<tr>
<td>AC S MAM*</td>
<td>Dense-graded</td>
<td>4–8%</td>
<td>11,000–12,000</td>
<td>0.30</td>
</tr>
</tbody>
</table>

* High-modulus asphalt concrete with type S gradation.

Table 2

Properties of cement-treated materials used in Spain (adapted from CEDEX and IECA [27]).

<table>
<thead>
<tr>
<th>CTB</th>
<th>Cement content (%)</th>
<th>$E$ (MPa)</th>
<th>$\nu$</th>
<th>$R_{c,7d}$ (MPa)</th>
<th>$R_{c,28d}$ (MPa)</th>
<th>$R_{c,LT}$ (MPa)</th>
<th>$R_{F,LT}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>3–7</td>
<td>5000–7000</td>
<td>0.25</td>
<td>$\geq 2.5$</td>
<td>$\geq 4$</td>
<td>4–8</td>
<td>0.9</td>
</tr>
<tr>
<td>GC</td>
<td>3.5–5</td>
<td>18,000–22,000</td>
<td>0.25</td>
<td>$\geq 4.5$</td>
<td>$\geq 8$</td>
<td>8–14</td>
<td>1.6</td>
</tr>
<tr>
<td>HRGC</td>
<td>5–7</td>
<td>22,000–28,000</td>
<td>0.25</td>
<td>$\geq 8$</td>
<td>$\geq 14$</td>
<td>14–22</td>
<td>2.0</td>
</tr>
<tr>
<td>CLC</td>
<td>5–10</td>
<td>28,000–32,000</td>
<td>0.20</td>
<td>$\geq 12$</td>
<td>$\geq 22$</td>
<td>22–35</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 3

Properties of stabilized soils used in Spain (adapted from CEDEX and IECA [27]).

<table>
<thead>
<tr>
<th>Type of stabilized soil</th>
<th>Binder type</th>
<th>Binder content</th>
<th>$CBR_{7d}$ (%)</th>
<th>$R_{c,7d}$ (MPa)</th>
<th>$R_{F,LT}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-EST1</td>
<td>Lime or cement</td>
<td>$\geq 2%$</td>
<td>$\geq 6$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>S-EST2</td>
<td>Lime or cement</td>
<td>$\geq 3%$</td>
<td>$\geq 12$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>S-EST3</td>
<td>Cement</td>
<td>$\geq 3%$</td>
<td>–</td>
<td>$\geq 1.5$</td>
<td>0.45</td>
</tr>
</tbody>
</table>
The semi-rigid sections proposed for the heaviest traffic conditions were studied to determine which sections meet the fatigue criteria. Fig. 1 shows the six sections analyzed, in which the numbers in the bar chart represent the thickness of each layer. Table 4 presents the traffic and subgrade conditions specified for the analyzed sections [34].

The semi-rigid sections proposed for the heaviest traffic conditions were studied to determine which sections meet the fatigue criteria. Fig. 1 shows the six sections analyzed, in which the numbers in the bar chart represent the thickness of each layer. Table 4 presents the traffic and subgrade conditions specified for the analyzed sections [34].

Based on a multi-layer linear elastic analysis, it was found that sections 4 and 6 did not meet the fatigue limit of cement-treated materials. Conversely, sections 1, 2, 3 and 5 could potentially withstand unlimited number of repetitions. However, the cement-treated materials in sections 1 and 3 work far below their fatigue limit (i.e., they are clearly overdesigned), so a more efficient design is of particular interest.

It is worth to mention that sections similar to those used in Spain are commonly employed in other European countries. FEHRL [5] reported that semi-rigid sections for heavily trafficked conditions in Europe are made of a relatively thick asphalt layer (17–30 cm) on 20–30 cm of CTB. Only France has extensively used semi-rigid pavements with a thin asphalt surface (≤8 cm) by virtue of pre-cracking and introduction of a reflective cracking mitigation treatment.

4.4. New design proposal

Analysis of the Spanish semi-rigid designs proposed for the heaviest traffic conditions showed that cement-treated bases are overdesigned in some sections. In addition, thick asphalt lifts (at least 15 cm) are used in Spain for the purpose of delaying the onset of reflective cracking. The same approach has been reported in most European countries [5]. However, increase of asphalt layer thickness has been demonstrated to be ineffective not only from the standpoint of reflective cracking mitigation, but also from an economic point of view [28,35]. Therefore, a more effective design of semi-rigid long-life pavements was evaluated in this study.

The proposed approach consisted in reducing the thickness of the asphalt lift to 10 cm, which is assumed to be enough for providing adequate functional characteristics while diminishing the effect of temperature changes on the CTB. Then, two different reflective cracking mitigation treatments were selected based on findings from Section 3: a thin interlayer system (IS) and a gravel-emulsion (GE). Finally, CTB was considered the primary structural element of the section and, thereby, responsible for carrying the load. The thickness of the CTB (SC, GC, HRGC and CLC) was determined through linear elastic analysis so that fatigue criteria were satisfied (i.e., maximum tensile strain ≤36 με and maximum tensile stress ≤40% RfLT).

Four different section types were analyzed for each CTB:

- Type I, section composed of 10 cm HMA + IS + CTB.
- Type II, section composed of 10 cm HMA + 8 cm GE + CTB.
- Type III, section composed of 10 cm HMA + IS + CTB + 20 cm SC.
- Type IV, section composed of 10 cm HMA + 8 cm GE + CTB + 20 cm SC.

Additional design considerations were as follows:

- The subgrade consisted of a natural soil with a minimum CBR of 3%, a 30-cm lift of additional soil with a minimum CBR of 10%, and 30 cm of cement-stabilized subbase type S-EST3 (Table 3), which is a frequent design for Spanish highways.
- The structural contribution of GE was taken into account in terms of $E$ (3000 MPa) and $v$ (0.35), whereas the effect of IS was not included in the analysis.
- The asphalt lift was comprised of 3 cm of BBTM A on top of 7 cm of AC S (Table 1).

One of the limitations of layered theory is that the transverse joints of cement-treated materials cannot be considered. Although the presence of joints creates a discontinuous system, an opening up to 3 mm is reported to provide adequate load transfer across the faces of the crack [36,37].

5. Results and discussion

Fig. 2 shows the sections obtained as a result of the linear elastic analysis conducted, in which CTB thickness was computed to meet fatigue criteria. The label for each section includes the name of the main structural CTB.
The thickness of the HRGC sections was similar to that of the sections with CLC, despite the higher elastic modulus of CLC. The reason is that neither the tensile stress nor the tensile strain at the bottom of the CLC was found to be critical, so the thickness of the layer was defined by the critical stress and strain in the underlying cement-stabilized subbase. In other words, CLC worked far below its fatigue limit. Since CLC has higher shrinkage tendency than HRGC and does not represent any significant reduction in layer thickness, sections containing HRGC are considered a better choice.

Like CLC, the responses of the SC layer in sections type III and IV were not critical and its thickness was based only on minimum construction requirements. It was found that the presence of a stabilized subbase rendered the SC layer useless, and it would simply increase the cost of sections type III and IV.

Thus, it is feasible to eliminate CLC sections as well as sections type III and IV since they do not represent any advantage in design with respect to the other sections. It should be pointed out that the remaining sections in Fig. 2 (SC-I, GC-I, HRGC-I, SC-II, GC-II, HRGC-II) are, on average, 14 cm thinner than the potential semi-rigid long-life sections identified in the Spanish design guide (sections 1, 2, 3 and 5 in Fig. 1).

These findings from multi-layer linear elastic analyses were combined with material requirements from a review of potential distress mechanisms (Section 3) to establish guidelines for a more effective design of semi-rigid long-life pavements. These guidelines are illustrated in Fig. 3 and described as follows:

- The surface course should be fracture resistant and have low aging susceptibility. Since this layer is in direct contact with vehicle tires, adequate functional characteristics are always desired. With these requirements, gap-graded friction courses seem to be a good option because of their moderate air void content, relatively high proportion of polymer-modified bituminous mortar and higher macrotexture.
- The binder course should provide adequate rutting resistance and waterproofness of the CTB. Dense-graded mixtures (relatively low air void content) with improved shear resistance (a primary network of large interactive particles) and rough-textured (crushed) aggregate are recommended.
- A reflective cracking mitigation treatment should be introduced between the asphalt binder course and the CTB.
- Regarding the CTB, two priorities are to be emphasized. First, the CTB is considered the primary structural element of the section and, thereby, its thickness should be determined to prevent fatigue failure. Secondly, reduction of shrinkage susceptibility requires consideration of mix design factors, such as cement type, aggregate type, water-to-cement ratio and use of admixtures, as well as placement conditions (curing and pre-cracking).
- Finally, a cement-stabilized subbase is recommended to reduce moisture susceptibility and increase bearing capacity.
6. Summary and conclusions

A clear understanding of the potential distress mechanisms and corresponding primary factors is the cornerstone of effective design of long-life pavements. Surface-initiated cracking (top-down cracking and thermal fatigue cracking), instability rutting, fatigue cracking of cement-treated materials, shrinkage cracking and reflective cracking were revisited as potential distress mechanisms affecting the performance of semi-rigid pavements. One key observation was that, while thickness primarily controls fatigue cracking, material requirements are the primary factor governing other distress mechanisms.

The analysis of the semi-rigid sections proposed in the Spanish pavement design guide for the heaviest traffic conditions showed that only four sections met the structural requirements to be considered long-life pavements. However, two of them were overdesigned. Furthermore, thick asphalt lifts are used in Spain to delay the onset of reflective cracking. This same approach has been reported in many other European countries, which is not a cost-effective alternative.

The previous analysis was used as the basis to propose alternative designs for semi-rigid long-life pavements. Alternative designs consisted in reducing the thickness of the asphalt layer to 10 cm in combination with the introduction of a reflective cracking mitigation treatment. The following findings were made:

- The use of compacted lean concrete (CLC) barely reduced base thickness as compared to high-resistance gravel cement (HRGC). Conversely, CLC has a higher tendency to shrink, so the use of HRGC is considered a better choice.
- The presence of a cement-stabilized subbase rendered the soil-cement (SC) layer underneath the main cement-treated base (CTB) useless.
- CTB thickness of selected alternative designs (SC-I, GC-I, HRGC-I, SC-II, GC-II, HRGC-II) ranged from a minimum of 24 cm for HRGC to a maximum of 41 cm for SC, based on typical materials used in Spain.
- Selected alternative designs were, on average, 14 cm thinner than the potential semi-rigid long-life sections identified in the Spanish pavement design guide.

Key observations on potential distress mechanisms and findings from multi-layer linear elastic analyses led to the establishment of guidelines for a more effective design of semi-rigid long-life pavements. Conclusions drawn in this study support the idea that the design of semi-rigid long-life pavements goes beyond simply defining layer thickness. Special emphasis should be placed on material requirements and the simultaneous consideration of both tensile strain and tensile stress as fatigue cracking failure criteria for determination of CTB thickness. It is important to note that the only thickness defined to prevent fatigue failure of the section was that for the CTB. CTB thickness was calculated for typical materials used in Spain. Although material properties may be different in other countries, the approach described in this study is intended to be applicable to any other country.

Acknowledgements

This paper describes one of the activities developed during the Fenix Project (www.proyectofenix.es), which was accomplished with the financial support provided by the Centre for the Development of Industrial Technology (CDTI) of the Spanish Government. Authors thank all public and private companies that have taken part in the project, as well as the researchers that have collaborated to its development.

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