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Evolution and locational variation of asphalt binder aging in long-life hot-mix asphalt pavements

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HIGHLIGHTS

- Asphalt binder continuously ages throughout the long-life HMA pavement structure.
- The type of asphalt mixture significantly affects binder aging rate.
- Aging rate decreases with pavement depth for the same type of asphalt mixture.
- Cross-sectional binder aging variation is insignificant.
- Asphalt at the bottom of pavement has access to oxygen at a reduced concentration.

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ABSTRACT

Understanding asphalt binder aging in long-life hot-mix asphalt (HMA) pavements is critically important for rational pavement design and construction practice. Using binder test data obtained at various times from a heavily trafficked 36-year-old HMA road pavement, the study examined the evolution of binder aging as well as variations in aging severity with pavement depth and cross-sectional location. Asphalt consistency, ductility, and temperature sensitivity were the parameters used to assess the status and the effects of binder aging. The influence of binder aging on the dynamic modulus (E^*) of asphalt concrete (AC) was also examined. It was found that asphalt binders continuously and severely age over time, irrespective of location in the pavement structure. This finding differs from the long-held HMA pavement design assumption. Test data also revealed that mixture type and pavement depth have statistically significant effects on binder aging, but the effect of cross-sectional location (wheel path vs. non-wheel path) is insignificant. Binder aging variations with pavement depth can be attributed to the temperature and oxygen content variations in the pavement structure. The age hardening of asphalt binder leads to an increase in E^*. This inevitably affects the load-induced response of the pavement and its durability. The findings are expected to assist in improving the design of long-life flexible pavements based on mechanistic–empirical principles.

1. Introduction

Reconstruction of highway pavements at the end of their service lives is not only costly, but also always creates negative social and environmental impacts. For heavily trafficked roads, the social and environmental costs of road closure for reconstruction purposes are so high that pavements with long service lives are usually desired. For instance, long-life pavements that last for at least 40 years are found to be the most economical solution for trunk roads in the United Kingdom [1]. The counterpart in the United States, known as a "perpetual pavement", is expected to last longer than 50 years without structural damage [2]. In Hong Kong, life-cycle cost analysis (LCCA) by the highway agency favors the use of long-life pavements on all carriageways because of the high traffic volume born by such roads and the high social costs associated with road closures. As a result, a new initiative has been taken in Hong Kong, by which all carriageway pavements are to be upgraded to the long-life standard (⩾40 years of design life). It is anticipated that the load-carrying layers of these pavements do not suffer cumulative structural damage or that damage would be so small that noticeable pavement distress within the design life would not result. Long-life HMA pavements can bring significant benefits to society if the promised performance can be delivered.

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Long-life (or perpetual-life) HMA pavement design has traditionally focused on both the control of load-induced tensile strain at the bottom of the asphalt concrete (AC) layers and the compressive strain at the top of subgrade [3]. A commonly used design standard is a tensile strain at the bottom of the AC of less than 70 uε and a compressive strain at the top of the subgrade of less than 200 uε [4]. Within these limits, neither bottom-up fatigue cracking nor subgrade rutting is expected to develop [4]. However, if these critical strains are exceeded, it does not necessarily imply that the pavement cannot achieve a "long life." Rather, the damage caused by traffic loads will accumulate over a period of time, as will pavement distress. The design life will then be a function of the end-of-the-life pavement distress thresholds, traffic loads, and the mechanistic responses of the pavement under the traffic loads and environmental factors. It is possible that the pavement life can be over 40 years under a combination of these factors even if the strain limits are exceeded. The performance life can be assessed using a mechanistic–empirical pavement analysis procedure such as the Mechanistic–Empirical Pavement Design Guide (ME-PDG) [7].

The various mechanistic and empirical models in ME-PDG are dependent on the assumptions of material property changes with time. Currently, it is assumed that asphalt binder aging and the resultant mixture hardening only take place at the pavement surface. This assumption is based on the findings of several early studies [5,6]. Recent evidence in the US, however, suggests that binder aging may also take place at greater pavement depths [8–10]. Several research findings on asphalt binder aging with time are summarized in Table 1. As shown in the table, contradictory results were reported. In addition, the research findings may not be applicable to long-life asphalt pavements due to several reasons: (1) None of the pavements in the studies are even close to long life, (2) the pavements are much thinner than the typical long-life pavement, (3) detailed layer-by-layer comparisons of aging status are missing, (4) historical binder test data for longitudinal comparison is unavailable, and (5) statistical significance test results are not reported. Moreover, some of the field samples used in the studies were exposed in an environment without air conditioning for a long time (e.g., over 10 years) [8]. The likelihood of further aging may make the samples different than those freshly obtained from the field.

If binder aging is limited to the pavement surface, a long-life pavement can be achieved with an adequate thickness design and timely maintenance activities such as resurfacing. Conversely, if severe binder aging occurs deeper within the pavement, it will change the stiffness and fatigue resistance of those layers. This further leads to the change of mechanistic responses and performance of the pavement structure under traffic loads. Therefore, knowledge of the characteristics and effects of asphalt oxidative aging in long-life HMA pavements is critically important for the development of appropriate design, construction, and preservation strategies.

The purpose of the research is to identify asphalt aging characteristics in HMA pavements that are close to "long-life" status with particular focus on: (1) the evolution of binder aging over time, (2) the variations of binder aging with pavement depth and location, (3) the effect of binder aging on the HMA's dynamic modulus (E^*), which is a fundamental property of the HMA mixture, and (4) factors that potentially affect binder aging in a pavement structure. The answers to these questions are also important for the design of conventional HMA pavements.

2. Research method

2.1. Pavement samples used for analysis

The HMA pavement sample cores used in this study were obtained from Tuen Mun Road in Hong Kong. Tuen Mun Road, with a total of six lanes, is one of the most heavily trafficked expressways in Hong Kong. The first phase (3 lanes Eastbound) was opened to traffic in 1977, with the second phase opened a few years later. The asphalt layers consist of a 30 mm open-graded friction course (OGFC), 40 mm wearing course (WC), 60 mm base course (BC), and 150 mm roadbase (RB). Since the initial construction, several resurfacing operations have occurred in various locations, but the BC and RB layers have never been replaced. The road is currently under reconstruction mainly for realignment purposes and the addition of shoulders (Fig. 1). Although fatigue cracking has started to appear at certain locations, pavement conditions for the majority of the road are still good, as shown in Fig. 1. There is confidence that the pavement can last for another 4 years in a generally good condition and hence literally meet the "long-life" definition. Therefore, the road was selected for the study of binder aging characteristics.

2.2. Analysis of historical data

In addition to its long service life, a further advantage of this road for analysis is the availability of test data of the original binder as well as the extracted binder after 8 years of road usage. The data, resulting from collaborative research with the Hong Kong highway agency in the 1980s, was published in a landmark paper by Mcleod [11]. Although the test methods and parameters used at that time are different from those used today, established equations are available for converting the test results obtained at different times to equivalent values for comparison purposes. Hence, the evolution of the asphalt binder during the whole lifecycle can be examined.

2.3. Asphalt sample preparation

Six sample cores of 100 mm diameter were taken from the road for analysis. The sampling locations are shown in Fig. 2. At each longitudinal location, samples were taken at wheel path and non-wheel path locations, respectively. The cores were immediately placed in glass jars, which were subsequently filled with nitrogen gas and sealed to preclude further contact with air. The cores were then cut into six slices, including the OGFC,

Table 1
Change of binder aging with pavement depth reported in existing literature.

Aging pattern shown from field studies	Data source	Existing literature
Aging greatly diminished within the top 25–39 mm of pavement surface	Material master database from various studies	Coons and Wright [5]
Aging can be neglected below the top 38 mm of pavement surface	Georgia, US	Mirza and Witczak [6]
Pavements oxidize at uniform rates with depth	Texas, US	Glover et al. [8] and Al-Azri et al. [9]
Aging in colder regions is slower than that in warmer regions; Aging severity initially decreases with pavement depth but increases towards the pavement bottom	Texas and Minnesota, US	Woo et al. [10]