Performance improvement of asphalt concretes using fiber reinforcement

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1. Introduction

Over the past decades, Thailand’s road network has suffered considerable deterioration in the figure of excessive permanent deformation and fatigue failure. The destruction of the durability of the Asphalt Concrete (AC) pavement is often due to the continuous and heavy traffic loading, which induces high shear and tensile stresses. These poor road conditions have resulted in the search by Thailand road authorities and practitioners for solutions in the form of alternative and superior pavement materials. The improvement of Hot Mix Asphalt (HMA) pavements to mitigate the premature deterioration of AC pavements includes the use of higher asphalt contents, and the inclusion of modifiers such as polymers, synthetic/crumb rubber, and fibers (Walied and Shane, 2014). The performance of AC pavements was found to be enhanced by fiber reinforcements (Nelson and Xinjun, 2014). Puzinauskas (1969) included natural asbestos fibers in asphalt mixtures to reinforce AC pavement. It was demonstrated that the fibers improved the low temperature cracking properties. Button and Hunter (1984) reported that the additional fibers increased flexible behavior and resistance to cracking failure. Maurer and Malasheskie (1988) indicated that a fiber reinforced AC pavement exhibited lower reflective cracking than a conventional AC pavement (without fiber).

A field investigation on the comparison of performance of AC stabilized with various fiber materials in a service life of 10 years demonstrated that the trial sections with fiber reinforcements had higher resistance to transverse and block cracking than other trial sections (Edgar, 1998). However, both the control section (without stabilization) and the fiber reinforced section were subjected to rutting, fatigue cracking, and raveling. McDaniel and Shah (2003) conducted field study on several different types of fiber reinforced AC mixes under a service life of about 10 years. It was reported that the fiber modified section

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ABSTRACT

This study reports on the laboratory performance, field performance and cost analysis of fiber-reinforced asphalt concrete (FR-AC) pavement using AC60/70 and polymer modified asphalt (PMA) as binders. The performance testing included indirect tensile resilient modulus, indirect tensile strength modulus, indirect tensile fatigue life, dynamic creep and wheel-tracker tests. Field trials of AC60/70 and PMA mixtures, were undertaken with and without fibers and the International Roughness Index, texture depth, and rutting of the mixtures were measured over time. The PMA + Fiber mixture exhibited the best performance among the materials tested. The performance of AC60/70 + Fiber mixture were comparable to PMA mixture. The improvement of both fatigue cracking and rutting were similar for AC60/70 + Fiber mixtures while the improvement of fatigue cracking was higher than rutting for the PMA mixtures. Since the performance of FR-AC was similar for both laboratory and plant mixed specimens, the laboratory mix design results can be used to interpret the field performance. The fiber reinforced AC60/70 mixture was found to be the most economical. The outcome of this research can be used as a guide, for establishing the specification of FR-AC pavement in Thailand and other countries using similar mix design.

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exhibited a good resistance against the longitudinal and transverse cracking.

Prowell (2000) investigated the field performance of a highway pavement using a Superpave mix design, reporting that the trial section reinforced with polypropylene and polyester fibers exhibited a better resistance in rutting and cracking than that trial section without fiber reinforcement. As a result, a lower rate of rutting/cracking was detected in any section after about 4 years of service. Kaloush (2008) and Kaloush et al. (2010) investigated fiber-reinforced asphalt mixes as a surface pavement material and benchmarked it with the performance of conventional mixes as a controlled material using sophisticated performance tests. It was concluded the fiber reinforcement can strengthen the resistance to the permanent deformation, fatigue- and thermal cracking, which are the main factors causing pavement distresses.

The influence of fiber reinforcement on the geotechnical properties of a dense-graded AC mixes followed the Marshall procedure was investigated by Bueno et al. (2003) under static and dynamic triaxial tests. The parameters of triaxial shear strength of the fibers-reinforced samples were found to be consistent with small variations. The recycled carpet fibers were used to increase the resistance to fatigue cracking and fracture energy of the asphalt specimen (Lee et al., 2005). It demonstrated that fiber reinforcements can enhance fracture energy and fatigue life of AC.

To the best of authors’ knowledge, the physical and mechanical advantages of fiber reinforced traditional AC and conventional PMA have been confirmed by several research works and the previous published authors’ work (Takaikaew et al., 2018) in only the laboratory testing phase. Therefore, this study would report on both laboratory and field performance and cost analysis of FR-AC pavement using two different binders namely AC60/70 and polymer modified asphalt (PMA). Moreover, the economic analysis based on cost of construction and the improvement of the overall performance were studied to evaluate the cost-effectiveness of using this concept for road construction. Four types of tested AC included conventional AC60/70 asphalt concrete as control mixture, PMA concrete, fiber reinforced AC60/70 asphalt concrete and fiber reinforced PMA concrete. These tested ACs were mixed in the laboratory and field plant as well as the performance tests of laboratory mixed FR-AC specimens and plant mixed FR-AC specimens were conducted to compare the mixing quality between laboratory and plant. The geotechnical tests included those related to the fatigue cracking failure, which are indirect tensile resilient modulus, indirect tensile strength modulus, indirect tensile fatigue life and those related to the rutting failure, which are dynamic creep and wheel-tracking. Two field trials were undertaken to investigate field performance of FR-AC, including International Roughness Index (IRI), texture depth and rutting.

The significant findings of this research will encourage the usage of fiber-reinforced AC as an economic and durable pavement surface for high traffic volume road. The research output can be used as a guideline for the development of code of practice and pavement standards in Thailand and other countries, when using a similar mix design method.

2. Materials and specimen preparation

2.1. Aggregate and asphalt binders

Aggregates are the main ingredient for producing asphalt mixtures which are used to control the stresses and absorb energy on the AC road (Amir et al., 2012). Crushed limestone samples, complying with the specifications of Department of Highways (DOH), Thailand, were obtained from Khon Kaen Province, Thailand and used as the aggregate in this study. The aggregate was prepared by dividing into 4 bins: bin 1, bin 2, bind 3, and bin 4 with different sizes of <4.75 mm, <9.50 mm, <12.50 mm, and <19.00 mm, respectively. Figure 1 shows the grading curve of aggregate, which was comprised of 42% of maximum aggregate size 4.75 mm (Bin 1), 25% of maximum aggregate size 9.5 mm (Bin 2), 15% of maximum aggregate size 12.5 mm (Bin 3) and 18% of maximum aggregate size 19.0 mm (Bin 4). Its gradation distribution is within a gradation limit specified by DOH of Thailand [DH-S 204/200 (DOH 2000)]. The basic properties of aggregates compared with the DOH’s requirements are depicted in Table 1.

Two studied types of asphalt binders were used as the controlled mixtures in this research obtained from an asphalt refinery plant in Bangkok, Thailand. First binder was AC60/70 (asphalt cement penetration grade 60/70), which is the most practical used material for asphalt pavement in Thailand. Another one was polymer modified asphalt (PMA) binder. Both were tested to determine their properties for compliance with DOH requirements [DH-S 408/2532 (DOH 1989)]. The conventional rheological experiments were conducted to determine the asphalt properties including the Penetration at 25 °C, Ring and Ball (R&B) Softening Point, Specific Gravity, Viscosity at 135 °C and 165 °C, Flash Point, Elastic Recovery and Ductility tests. The rutting resistance parameter or dynamic shear (G’/sin δ) of AC60/70 and PMA binders were measured at 76 °C and 10 rad/s, in a form of control stress by Dynamic Shear Rheometer (DSR). The physical properties of PMA and AC60/70 compared with the standards were respectively summarized and are presented in Table 2 and Table 3.

2.2. Fiber reinforced asphalt concrete

A blend of synthetic polyolefin (tan-colored) and aramid (yellow-colored) fibers designed for HMA applications were studied. Polyolefin fibers are commonly utilized as reinforcing agents in concrete and asphalt concrete. Microstructural analysis using scanning electron microscope tool was carried out to examine the microstructure properties of studied mixtures in this research as shown in Figure 2. Table 4 indicates physical properties of polyolefin and aramid fibers.

2.3. Specimen preparation

In this paper, the HMA mix design followed Job Mix Formula was used to produce the AC mixtures, based on DOH specifications, which is equivalent to the Marshall mix design process. The aggregate was heated in an oven between 170 and 190 °C, which are about 20 °C higher than the mixing temperature (150 °C for AC60/70 and 170 °C for PMA). The additional fibers were then blended thoroughly with the aggregates. The melted asphalt binder at 150 °C for AC60/70 and 170 °C for PMA was blended with fiber-aggregate mixture to obtain the desired specimens. A recommended 0.05% fiber content (based on total mass of mixture) for the mix design was used in this study (Waleed and Shane, 2014). To produce the Marshall specimens, the hot mixtures from both laboratory mixing and plant mixing were compacted in a steel mold under 75 blows on each side. The diameter and height of the Marshall sample were 101.6 mm and 63.5 mm. The specimen preparation was undertaken at a temperature of 150 °C and 170 °C for AC60/70 and PMA, respectively. Four types of mixtures namely AC60/70, AC60/70 + Fiber, PMA, and PMA +...
Fiber were prepared to evaluate the mechanical characteristics of fiber reinforced asphalt mixtures. Based on Marshall method, all compacted mixtures were subject to the following tests: (a) Bulk Specific Gravity Determination, (b) Stability and Flow Test, and (c) Density and Voids Analysis. The Optimum Asphalt Content (OAC) was the mean value of asphalt content obtained at the maximum density, 4% air void, and maximum Marshall stability (Asphalt Institute, 1997). For each mix design, 3 samples were made at 4.5%, 5.0%, 5.5%, 6.0% and 6.5% asphalt content to determine OAC.

![Table 1. Basic properties of aggregates for job mix formula of asphalt concrete.](image)

| Property                          | AC 60/70 | PMA |
|-----------------------------------|----------|-----|
| Flakiness index (%)               | 35 maximum | 35 maximum |
| Elongation index (%)              | 35 maximum | 35 maximum |
| Asphalt absorption (%)            | N/A      | N/A |
| Los Angeles abrasion (%)          | 40 maximum | 40 maximum |
| Soundness (%) coarse/fine         | 9 maximum | 9 maximum |
| Sand equivalent (%)               | 50 minimum | 50 minimum |
| Asphalt content (%)              | 5.0 ± 0.3 | 5.0 ± 0.3 |
| Marshall density (g/cm³)         | 2.40-2.42 | 2.418 |
| Marshall air voids (%)           | 3.40-4.80 | 4.0 |
| Strength index (%)               | 75 minimum | 78.1 |
| Aggregate crushing value (%)     | -        | - |
| Aggregate impact value (%)       | -        | - |
| Polished stone value (%)         | -        | - |

![Table 2. Fundamental Properties and Standard used for Polymer Modified Asphalt.](image)

| Parameter measured                   | Test method | Results | Specification |
|--------------------------------------|-------------|---------|---------------|
| Penetration at 25 °C, 100g, 5 s,0.1 mm | TIS 1201-93 | 55      | 55-70         |
| Softening Point, Ring and Ball, °C    | TIS 1216-94 | 76.3    | 70 Min.       |
| Ductility at 13 °C, 5 cm/min, cm     | TIS 1202-93 | 128     | 55 Min.       |
| Elastic Recovery at 25 °C, 10 cm, %  | ASTM D6884-06 | 92.5    | 70 Min.       |
| Toughness, kg/cm                     | ASTM D5801-95 | 374    | 170 Min.      |
| Tenacity, kg.cm                      | ASTM D5801-95 | 291    | 100 Min.      |
| Brookfield Viscosity, shear rate 18.6 s-1, Spindle no.21 | ASTM D4402-06 | 1355  | 3000 Max.     |
| At 135 °C, m Pa.s                    | ASTM D5892-00 | 465    | 1000 Max.     |
| Storage Stability at 163 °C, 24 h.   | ASTM D5892-00 | 1.4    | 2 Max.        |
| Different in Softening Point, °C     | TIS 1216-94 | 1.02   | 1.00-1.05    |
| Density at 25 °C, g/cc               | ASTM D70-09e1 | 315    | 220 Min.     |
| Flash Point, Cleveland Open Cup, °C  | TIS 1182-94 | Over 100 | 100 Min.   |
| Solubility in Toluene, % wt.         | ASTM D5546-09 | 99.90  | 99.0 Min.    |
| Dynamic Shear, G'/sin δ at 76 °C, 10 rad/s, kPa. | AASHTO T5-98 | 2.3    | 1.0 Min.     |
| Weight Loss, % wt.                   | ASTM D2872-12 | 0.126  | 0.5 Max.     |

![Table 3. Fundamental Properties and Standard used for Asphalt Cement AC60-70.](image)

| Parameter measured                   | Test method | Results | Specification |
|--------------------------------------|-------------|---------|---------------|
| Penetration at 25 °C, 100g, 5 s,0.1 mm | DH-T 403/1975 | 69      | 60-70         |
| Flash Point (Cleveland Open Cup), °C  | DH-T 406/1976 | 282    | 232 Min.      |
| Softening Point, Ring and Ball, °C    | TIS 1216-94 | 47.8    | 45-55         |
| Ductility at 13 °C, 5 cm/min, cm     | DH-T 405/1976 | Over 100 | 100 Min.   |
| Solubility in Trichloroethylene, % wt. | DH-T 409/1977 | 99.85  | 99.0 Min.    |
| Thin Film Oven Test, 3.2 mm, 163 °C, 5 h. | DH-T 409/1977 | 0.05   | 0.8 Max.     |
| Loss on Heating, % wt.                | AASHTO T179 | 71.5    | 54 Min.       |
| Penetration of Residue, % of Original |             | Over 50 | 50 Min.       |
| Ductility of Residue at 25 °C, 5 cm/min,cm |             |         |               |

Fiber were prepared to evaluate the mechanical characteristics of fiber reinforced asphalt mixtures. Based on Marshall method, all compacted mixtures were subject to the following tests: (a) Bulk Specific Gravity Determination, (b) Stability and Flow Test, and (c) Density and Voids Analysis. The Optimum Asphalt Content (OAC) was the mean value of asphalt content obtained at the maximum density, 4% air void, and maximum Marshall stability (Asphalt Institute, 1997). For each mix design, 3 samples were made at 4.5%, 5.0%, 5.5%, 6.0% and 6.5% asphalt content to determine OAC and five specimens were prepared to determine the theoretical maximum density (TMD). The attained values were benchmarked with the requirements designated by DOH specification.

Since the lateral side of the specimens was not porous (Muniandy and Aburkaba, 2014), the bulk specific gravity (Gṁ) test was performed in...
accordance with ASTM D2726. The $G_{mb}$ was determined based on the following expression:

$$G_{mb} = \frac{A}{C - B}$$

where $A$, $B$, and $C$ are the mass of sample (g) in air, submerged in water, and in saturated surface dry condition, respectively.

A theoretical maximum specific gravity ($G_{mm}$) was measured based on AASHTO T209/ASTM D2041 and it can be determined using the following expression:

$$G_{mm} = \frac{W_c - W_b}{(W_c - W_a) - (W_d - W_b)}$$

where $W_a$ and $W_b$ are the mass of container (g) in air and in water, respectively; $W_c$, and $W_d$ are the mass of container and specimen (g) in air and water, respectively and $\gamma_w$ = Specific gravity of water (1 g/cm³).

The following equations were employed to determine the volumetric properties:

Air void or void in total mix,

$$VTM = 100 \left( 1 - \frac{G_{mb}}{G_{mm}} \right)$$

Voids in mineral aggregate

$$VMA = 100 \left[ 1 - \frac{G_{mb}(1 - Pb)}{G_{mb}} \right]$$

Voids filled with asphalt

$$VFA = 100 \left( \frac{VMA - VTM}{VMA} \right)$$

3. Performance tests on laboratory and plant mixed specimens

This research aims to investigate the mechanical characteristics of the FR-AC compared with conventional AC (without fiber-reinforcement) with different binders (AC60/70 and PMA) via laboratory and field studies. The mixing quality of FR-AC in both laboratory and plant was also investigated to examine the scale-impact on the geotechnical properties and performance of AC.

HMA mixtures are traditionally designed with their properties being evaluated in laboratory, but the designed mixtures were produced and constructed in the field using an asphalt mixing plant. The mechanical properties of the plant mixtures in a large batch might be different from the laboratory mixtures. The performance comparison of specimens mixed in laboratory and plant was then carried out to ensure that the laboratory mix design is applicable to the real construction.

The testing program included traditional (Marshall stability and flow, and indirect tensile strength) and performance tests. The performance tests included those simulating rutting (dynamic creep and wheel-tracking) due to excessive bearing stress on the AC pavement surface and fatigue cracking (indirect tensile resilient modulus, indirect tensile stiffness modulus, and indirect tensile fatigue) due to excessive tensile stress at the bottom of AC pavement.

3.1. Laboratory experimental program

3.1.1. Marshall stability and flow test

The Marshall stability and the flow assessments were undertaken on the mix design samples (101.6 mm in diameter and 63.5 mm in height) at various AC contents (4.5–6.5%) based on ASTM D1559 under a compressive loading (strain rate of 50.8 mm/min).

The Marshall stability is obtained once the material failed at the maximum loading while the flow value is the associated plastic flow of the sample. The average Marshall stability and flow values were reported from triplicate samples of each asphalt content, to ensure testing consistency.
3.1.2. Indirect tensile strength (ITS)

ITS test was conducted to measure the strength of asphalt mixes according to ASTM D6931 using a deformation rate of 50.8 mm/min at a temperature of 25 °C. The reported results are an average from three specimens. Eq. (6) was used to calculate the ITS of asphalt concrete,

\[
ITS = \frac{2P}{\pi D \Delta H}
\]

where \( P \) is the peak value of the applied vertical load; \( T \) is the average thickness of the sample; and \( D \) is the diameter of the sample.

3.1.3. Indirect tensile resilient modulus

Indirect tensile resilient modulus (\( M_r \)) of the studied asphalt mixtures were obtained from tensile testing at a temperature of 35 °C followed D4123-82 and AASHTO TP31-94. \( M_r \) is one of the major properties for pavement design and it is used as an indicator to describe the stiffness of the asphalt mixture. Higher value of \( M_r \) indicates stiffer mixtures, which results in higher load distribution ability. Eq. (7) is used to compute the \( M_r \):

\[
M_r = \frac{P(0.27 + \nu)}{(\Delta H)D}
\]

where \( P \) is the peak value of the applied vertical load (N), \( \Delta H \) is the average amount of the horizontal deformation obtained from the last 5 applications of the load pulse (mm), \( D \) is the average thickness of the sample (mm), and \( \nu \) is the Poisson’s ratio. Standard test conditions and requirements for \( M_r \) are summarized in Table 5.

3.1.4. Indirect tensile stiffness modulus (ITSM)

The stiffness modulus was obtained from the indirect tensile stiffness modulus (ITSM) test in accordance with BS-EN DD 213 (1993). The operations were started by selecting the target period from an initial stage of load application till it reached the peak one, which is known as a load pulse rise time. Meanwhile, the target horizontal deformation was also set. The computer was used to automatically calculate the number of conditioning pulses as well as the force that applied to the asphalt mixtures. The minor adjustment of the applied force can be performed based on the conditioning pulses tool. This adjustment is practically conducted in order to attest that the seat of the loading strips was properly placed on those mixtures; hence the specified horizontal deformation was attained. After the completion of the conditioning pulses, the system applied five load pulses. It generated the indirect movement on the horizontal diameter and the strain was calculated based on the known specimen’s diameter. The known cross-sectional area of the mixture and the measured applied force were then used to compute the applied stress. Thus, ITSM can be calculated based on these stress and strain values. The conditions and requirements for the ITSM test are summarized in Table 5.

3.1.5. Indirect tensile fatigue test (ITFT)

ITFT was performed using the 12.5 mm wide curved loading strip according to BS-EN12697-24: 2004. The samples were subjected to the controlled stress pulses in repetitive manner until it failed while its vertical deformation was recorded. The ITFT is obtained from the relationship between the accumulative vertical deformation versus an amount of load pulse (John maddison read, 1996).

To simulate an 80 km/h (50 mph) velocity of a vehicle running on the pavement, a frequency of 10 Hz was set for a haversine loading pulse. The loading and rest periods were 0.1 and 0.9 s, respectively. This experiment was carried out in an environmental chamber at 25 °C and the Poisson’s ratio value was 0.35. The conditions and requirements for ITFT are summarized in Table 5.

3.1.6. Dynamic creep test

The (confined/unconfined) dynamic creep test is widely performed to determine the resistance to rutting of the bitumen mixture. The unconfined dynamic creep test is the most practically employed to assess the deformation resistance of the mixture under repeated axial loading. Goetz and Wood (1957) indicated that the plastic strain of the mixture was induced by this form of loading, which is known as the main contribution to permanent deformation.

| Table 5. Standard tests conditions and requirements for laboratory experimental program. |
|---------------------------------------------------------------|
| **Experimental Program** | **Test Conditions** |
| **Indirect tensile resilient modulus (\( M_a \))** | |
| Test stress | 15% of ITS |
| Test duration | 150 cycles |
| Test cycle | Square wave pulse 1 s on, 1 s off |
| Test temperature | 35 °C |
| **Indirect tensile stiffness modulus (ITSM)** | |
| Horizontal strain | 0.005% of the specimen diameter |
| Rie time | 124 ms – equivalent to a frequency of 1.33 Hz |
| Specimen diameter | 102 mm |
| Specimen thickness | 64 mm |
| Test temperature | 35 °C |
| Poisson’s ratio | 0.40 for 35 °C |
| **Indirect tensile fatigue test (ITFT)** | |
| Target test stress | 300 kPa |
| Target rise time | 125 ms |
| Failure criteria | 9 mm vertical deformation |
| Test temperature | 25 °C |
| **Dynamic creep test** | |
| Conditioning stress | 10 kPa |
| Conditioning period | 30 s |
| Test Stress | 120 kPa |
| Test Duration | 1800 Pulses |
| Test cycle | square wave pulse 1 s on, 1 s off |
| Test temperature | 40 °C |
The load pulses of 1-s period followed by 1-s rest period were repeatedly applied to the asphalt mixtures. During the experiment, an accumulative permanent deformation of the mixes was measured. A correlation between axial strain and the quantity of load pulses was plotted in order to ascertain the potential rutting of the specimens.

For this study, the loading conditions were selected following the specification in (BSI 1996) DD226: 1996 for measuring the permanent deformation of the specimens. The test condition for the dynamic creep test is summarized in Table 5.

3.1.7. Wheel-tracker test

Life cycle assessment of the in-service asphalt pavements can be predicted by the permanent deformation (rutting) using the wheel-tracker test. Rutting is defined as an irreversible permanent residual strain generated by the applied load to the surface of AC. The repeated axle loadings create the tremendous accumulations of permanent strains and lead to pavement surface rutting (Alatalo et al. 2012; Moghaddam et al., 2014).

The rutting test was performed using a laboratory-scale wheel-tracker to simulate the movement of vehicles on the asphalt road. The wheel-tracker test was carried out based on BS-EN-12697-22 (BSI 2004) small size device procedures at the temperature of 60 °C. An in-house roller compactor was used to prepare the slab specimen with 500 mm length, 180 mm wide, and 100 mm in height following BS-EN-12697-33 (BSI 2004a). The average of at least 15 values of wheel passes: 1,000, 3,000, and 10,000 loading cycles was the reported as a rutting depth of the tested asphalt mixtures.

4. Field trial tests

The field trial tests were carried out to ensure that the quality of the construction and pavement materials used conformed with the specification requirements. The performance of pavement trials: control AC pavement and FR-AC pavement sections after years of traffic loading were investigated and compared. Three performance tests included International Roughness Index (IRI), rutting, and texture depth tests were conducted in this study. IRI is used to evaluate new pavement construction in which the penalties or bonus payments were determined based on smoothness (Sayers et al., 1986). The rutting tests were carried out by measuring transverse permanent deformations of the trial sections using a profilometer. The texture depth test was carried out by following the standard sand patch testing procedure in accordance with (ASTM, 2011) E965-96, 2011 and (BSI, 1990) 812-110, 1990.

The road trial constructions were constructed based on the asphalt pavement construction methods and the guideline of DOH, Thailand (DOH 1989). Two different road trials were constructed in collaboration with Bureau of Highways 10 (Suphunburi Province, DOH Thailand) and FORTA Corporation: Trial 1 Route No. 3086 in Kanchanaburi Province and Trial 2 Route No. 7 in Chonburi Province, Thailand. The aggregate was crushed limestone sourced from Khon Kaen Province, Thailand. The optimum of 5% asphalt content at 4% air void of the total mix by mass was used in this study.

The influence of fiber reinforcement on AC60/70 pavement was investigated in Trial 1, which was composed of a conventional AC60/70 section (without fiber) and a FR-AC60/70 (AC60/70 + Fiber) section (Figure 3a). Whereas the performance of conventional PMA mixture and fiber reinforced PMA mixture was compared in Trial 2, which composed of a PMA mixture (without fiber) section and an FPR-PMA (PMA + Fiber) section (Figure 3b). The traffic volume for Trial 1 and 2 was approximately 3 million vehicles and 106 million vehicles per year, respectively. The mix production at the asphalt plant and construction process are shown in Figure 4.

The job mix formula used to mix the aggregates and asphalt binders followed the Marshall mix design method. Similar to the laboratory mix processes, the aggregates were heated to 170 and 190 °C and then 0.05% fiber contents by the total mass of mixture were added. Based on the dry condition, the aggregates and fibers were thoroughly mixed for a duration of 10 s. The AC60/70 binder and PMA binder were respectively heated at 150 and 170 °C and mixed with those fiber-aggregate mixes to attain the well coated AC60/70 + Fiber mixture and PMA + Fiber mixture. The HMA mixtures were placed to the desired trial sections by asphalt paving machines. The asphalt emulsion prime coat was sprayed (about 0.4–0.6 l/m²) prior to HMA placement in order to improve the adhesion between the FR-AC layer and base course layer. Subsequently, the HMA mixtures were first compacted by road rollers (10–12 tons) and followed by second compaction using vibrating rollers (6–10 tons). The road pavements were finished by the final rolling using tandem rollers (6–10 tons) with two passes (one lap) at the surface temperature of about 50 °C to lessen the impact of initial rutting and the air void squash due to traffic effects.

5. Results and discussion

5.1. Laboratory performance test results

The results indicated the OAC was 5.0% of the total mix by mass. The results of the Marshall stability of all mixtures prepared in the laboratory and the plant are presented in Figure 5. All of the Marshall stability value in this study were higher than the minimum stability requirement (>8.2 kN) designated by the DOH, Thailand. The stability values of laboratory and plant mixed PMA specimens were 15.5 kN and 15.1 kN, respectively, which were remarkably higher than laboratory and plant AC60/70 mixtures (11.5 kN and 11.8 kN). For both laboratory and plant mixed specimens, the AC60/70 + Fiber specimens and PMA + Fiber specimens had greater stability values than the AC60/70 specimens and PMA specimens, respectively. This implied the role of fiber reinforcement on
the enhancement of Marshall stability. Although a similar trend was observed between the specimens mixed in laboratory and plant, the plant mixed AC60/70 + Fiber specimen (stability = 13.9 kN) had higher stability value than the laboratory mixed specimen (stability = 12.0 kN).

While the laboratory mixed PMA + Fiber specimen (stability = 15.5 kN) had similar stability value to the plant mixed PMA + Fiber specimen (stability = 15.0 kN).

Figure 6 presents ITS results of the laboratory and plant mixed specimens. ITS of the laboratory mixed samples was more or less the same as that of the plant mixed specimens, except the AC60/70 + Fiber specimens whereby the plant mixed specimens exhibited relatively higher ITS value (ITS = 489.3 kPa) than the laboratory mixed specimens (ITS = 435.3 kPa). For a particular asphalt binder, the specimens with fiber-reinforcement exhibited higher ITS values than the specimens without fiber-reinforcement (i.e., ITS of the laboratory mixed AC60/70 + Fiber specimen and AC6070 specimen was 435.3 kPa and 409.3 kPa, respectively and ITS of the laboratory mixed PMA + Fiber specimen and PMA specimen was 485.9 kPa and 471.2 kPa, respectively). This evidence proved that fiber-reinforcement did improve the ITS value of the conventional asphalt concrete. The previous research also revealed that the mechanical bonding between fiber and asphalt binder played a vital role in increasing the ITS value of hot mix asphalt mixtures (Bonica et al., 2016). Furthermore, the higher tensile strength of FR-AC mixtures attributes to the high resistance to crack propagation of an AC mixture.

Figure 7 presents the test results of $M_R$ of both laboratory and plant mixed specimens. It illustrated that the plant mixed PMA + Fiber specimens had relatively higher $M_R$ value ($M_R = 3245.6$ MPa) than the laboratory mixed specimens ($M_R = 3005.0$ MPa), while the $M_R$ values of other laboratory and plant mixed specimens were similar. It is worth mentioning that the $M_R$ value of the AC60/70 + Fiber specimens (2352.0 MPa and 2305.5 MPa) was comparable to that of the PMA specimens (2352.0 MPa and 2361.0 MPa) and was remarkably higher than the control AC60/70 specimens (1542.2 MPa and 1675.2 MPa), mixed from laboratory and plant, respectively. In addition, the fiber-reinforcement can significantly enhance $M_R$ of the PMA mixture. It can be seen that the $M_R$ value of the plant and laboratory mixed PMA + Fiber specimens were respectively 3245.6 MPa and 3005.0 MPa, which were notably higher than the PMA specimens (without fiber) (2361.0 MPa and 2352.0 MPa).

The ITSM results of the laboratory and plant mixed specimens are presented in Figure 8. For both binders with and without fiber reinforcement, the ITSM values of the plant mixed specimens were slightly
greater than the laboratory mixed specimens. The PMA + Fiber samples indicated the highest ITSM values (i.e., 3125.2 MPa and 2935.0 MPa for plant and laboratory mixed specimens) and significantly higher than the control AC60/70 specimens (i.e., 1421.1 MPa and 1435.5 MPa for plant and laboratory mixed specimens). The ITSM value of the plant mixed AC60/70 + Fiber specimen was 1910.4 MPa and slightly higher than that of the laboratory mixed specimen of 1790.5 MPa. While the ITSM values of plant and laboratory mixed PMA specimens were 2113.1 MPa and 2010.0 MPa, respectively, which were about 10.6% and 12.3% higher than those of plant and laboratory mixed AC60/70 + Fiber specimens, respectively.

ITFT results of the laboratory and plant mixed specimens are shown in Figure 9. Fatigue life of asphalt mixtures is presented as the number of pulses at failure; the higher number of pulses indicates the longer service life of AC. Figure 9 indicates that the plant mixed specimens exhibited high fatigue life than the laboratory mixed specimens. For example, the fatigue life values of plant mixed AC60/70, AC60/70 + Fiber, and PMA + Fiber specimens were 107, 161, and 249, respectively, while the fatigue life values of laboratory mixed AC60/70, AC60/70 + Fiber, and PMA + Fiber specimens were 101, 137, and 220, respectively. However, the fatigue life values of the plant and laboratory mixed PMA specimens were more or less the same. Similar to the ITS, the fatigue life of AC60/70 + Fiber mixes was similar to that of PMA mixes, while the maximum value was obtained for PMA + Fiber specimens.

A permanent deformation from the dynamic creep test, which represented by an axial strain of all mixtures are shown in Figure 10. AC60/70 + Fiber, PMA, and PMA + Fiber specimens had respectively smaller axial strain than the controlled AC60/70 specimen. The permanent deformation of plant mixed and laboratory mixed specimens were more or less similar for all mixes. The accumulative permanent strains for FR-AC were low, which evidently revealed that its permanent deformations were enhanced when the number of cycles was high. In other words, the FR-AC had higher recoverable deformation than the unreinforced AC.

Figure 11 shows the rutting depths of the laboratory and plant mixed specimens at 10000 cycles. The rutting depth of the plant mixed specimens was slightly lower than the laboratory mixed specimens. For the plant mixed specimens, the rutting for AC60/70, AC60/70 + Fiber, PMA, and PMA + Fiber specimens were 6.53, 3.92, 3.91 and 2.51%, respectively. It was evident that the additional fibers can increase the rutting resistance of AC60/70 and PMA specimens by approximately 40% and 36% with, respectively. The rutting depths of the AC60/70 + Fiber specimens were comparable to the PMA specimens. This implied the potential use of fibers to improve the permanent deformation and rutting under high traffic load.

Overall, the performance in both fatigue cracking and rutting criteria of laboratory and plant mixed specimens is essentially the same. This implied that the mixing quality from both plant and laboratory is practically the same and the laboratory performance test results of the designed HMA can be used directly to interpret the field performance of the HMA pavement.

Brown et al. (1991) and Fitzgerald (2000) reported that fiber imparted the physical changes of asphalt mixture and improve its cohesive and tensile strength. Also, the fibers create a 3D reinforcement linkage in AC binder and lead to the dense matrix of the mixture (Putman and Amirkhanian (2004) and Tam and Bhatnagar, 2016). The FR-AC was thus capable to store more energy than traditional AC and hence the
improvement of $M_{R_b}$, fatigue life, ITSM, and rutting. It was observed that the performance of AC60/70 mixture is comparable with that of PMA mixture, having higher cost.

### 5.2. Field trial results

Trial 1 (AC60/70 and AC60/70 + Fiber) and Trial 2 (PMA and PMA + Fiber) were constructed in April 2013 and March 2015, respectively. The field trial measurement included International Roughness Index (IRI), texture depth and rutting. The field measurement on Trial 1 was carried out at 12 months (in April 2014), 15 months (in July 2014), and 18 months (in October 2014) after it was opened to traffic. While the field measurement on Trial 2 was carried out at three months (in June 2015), one year (in March 2016), and two years (in February 2017) after it was opened to traffic.

Table 6 demonstrates the results of IRI, texture depth and rutting of Trial 1 on AC60/70 and AC60/70 + Fiber sections. IRI values of both sections exhibited the good performance of lower than 2.5, which is specified by Department of Highway of Thailand. It was evident that AC60/70 + Fiber section had lower IRI than AC60/70 section. The field measured rutting was consistent with the laboratory measured one; the rutting of AC60/70 + Fiber section was lower than that of AC60/70 section. These results clearly demonstrated that the fiber-reinforcement can enhance the resistance to permanent deformation of AC60/70 pavement due to real repeated traffic loading (3 million vehicles per year).

Table 7 demonstrates the results of IRI, texture depth and rutting of Trial 2 on AC60/70 and AC60/70 + Fiber sections. IRI values of both sections were lower than that PMA section under the same high traffic volume. Furthermore, the rutting of PMA + Fiber section was lower than PMA section (without fiber). The rutting in Trial 2 (PMA mixtures) was lower than that in Trial 1 (AC60/70/70 mixtures) even though the traffic volume (106 million of vehicles per year) of Trial 2 was significantly higher than that of Trial 1 (3 million of vehicles per year) and the service time of Trial 2 was longer than that of Trial 1. For example, the rutting of AC60/70 section and AC60/70 + Fiber section were 1.92 mm and 1.43 mm, respectively after 18 months opened to traffic, while the rutting of PMA section and PMA + Fiber section were 1.42 mm and 1.32 mm after 24 months opened to traffic. This indicated that PMA mixtures exhibited greater endurance to permanent deformation than AC60/70 mixture although the cost of PMA mixture was higher.

On the other hand, the texture depths of both AC60/70 section and AC60/70 + Fiber section in Trial 1 were more or less the same at each time of field measurement. Similar texture depths were also recorded for the PMA section and PMA + Fiber section in trial 2. The texture depth is directly related to skid resistance of AC pavement, which represents the road safety condition (Siriphun et al., 2016, 2019). This implied that the fiber-reinforcement insignificantly improved the skid resistance of AC pavement.

The performance improvement (fatigue cracking and rutting criteria) of AC60/70 + Fiber, PMA and PMA + Fiber specimens compared with control AC60/70 specimen is shown in Figure 12. The overall fatigue cracking improvement was indicated as a mean value of percent improvement of $M_{R_b}$, ITSM, and ITFT, while the overall rutting improvement was indicated as a mean value of percent improvement of

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**Table 6. The results of IRI, texture depth and rutting of AC60/70 mixtures and AC60/70 + Fiber mixtures.**

| Date          | Station | Surface Type | IRI (m/km) | Texture Depth (mm) | Rutting (mm) |
|---------------|---------|--------------|------------|--------------------|--------------|
| April 27, 2014| 40 + 325–40 + 475 | AC60/70      | 2.21       | 0.59               | 1.16         |
|               | 40 + 525–40 + 675 | AC60/70      | 1.95       | 0.60               | 1.02         |
| July 31, 2014 | 40 + 325–40 + 475 | AC60/70      | 1.78       | 0.62               | 1.90         |
|               | 40 + 525–40 + 675 | AC60/70 + Fiber | 1.79      | 0.58               | 1.21         |
| October 10, 2014 | 40 + 325–40 + 475 | AC60/70      | 1.82       | 0.55               | 1.92         |
|               | 40 + 525–40 + 675 | AC60/70 + Fiber | 1.78      | 0.57               | 1.43         |

**Table 7. The results of IRI, texture depth and rutting of PMA mixtures and PMA + Fiber mixtures.**

| Date          | Station | Surface Type | IRI (m/km) | Texture Depth (mm) | Rutting (mm) |
|---------------|---------|--------------|------------|--------------------|--------------|
| June 27, 2015 | 14 + 625–14 + 815 | PMA         | 1.56       | 0.70               | 0.66         |
|               | 14 + 815–15 + 015 | PMA + Fiber  | 1.37       | 0.73               | 0.56         |
| March 3, 2016 | 14 + 625–14 + 815 | PMA         | 1.82       | 0.66               | 1.19         |
|               | 14 + 815–15 + 015 | PMA + Fiber  | 1.39       | 0.67               | 1.15         |
| February 21, 2017 | 14 + 625–14 + 815 | PMA         | 1.89       | 0.33               | 1.42         |
|               | 14 + 815–15 + 015 | PMA + Fiber  | 1.85       | 0.33               | 1.32         |

Figure 12. Overall improvement of fatigue cracking and rutting criteria of various types of asphalt mixtures compared with control AC60/70 mixtures: (a) mixed from laboratory and (b) mixed from plant.
dynamic creep (performance deformation) and rutting. It clearly confirmed the overall fatigue cracking improvements of PMA + Fiber specimens were the highest (about 106%–116% for laboratory and plant mixed specimens), while its overall rutting improvement were about 50% and 55% for laboratory and plant mixed specimens, respectively (see Figure 12a and b). In other words, for PMA, the fiber-reinforcement had higher potential in improving the fatigue cracking resistance than the rutting resistance. The same is not true for AC60/70 mixtures, the improvement in fatigue cracking and rutting for AC60/70 + Fiber specimens was similar, i.e., 30% for fatigue cracking and 21% for rutting and 41% for fatigue cracking and 32% for rutting, for the laboratory and plant mixed specimens, respectively. In other words, the fiber-reinforcement almost equally contributed to the fatigue cracking and rutting improvement for the AC60/70 mixtures.

An economic benefit analysis was carried out by comparing both overall fatigue cracking and rutting improvement of AC pavements with its percent increase in construction cost (USD/m²) (see Table 8). According to Comptroller General's Department, Thailand, the construction cost (USD/m²) of AC60/70 mixture for 50 mm thickness (typical in Thailand) in 2020, AC60/70 + Fiber mixture, PMA mixture, and PMA + Fiber mixture were 7.56, 8.29, 11.55, and 12.70, respectively. For a particular type of asphalt, the construction cost of fiber mixtures increases by 10% per unit when benchmarked with the unreinforced samples (i.e., construction cost of AC60/70 + Fiber mixture and PMA + Fiber mixtures was 10% greater than AC60/70 mixtures and PMA mixture). However, the percent increase of construction cost of AC60/70 + Fiber mixture, PMA mixture, and PMA + Fiber pavement were respectively 9.65%, 52.67%, and 67.94% when compared with the construction cost of control AC60/70 pavement. It is apparent that although the overall performance improvement of PMA mixture and PMA + Fiber mixture were high, its percent increase of construction cost was also high. The 53% increase in construction cost of PMA pavement can have its overall fatigue cracking and rutting improvement of 38% and 35% (data from plant mixing). While only 10% increase of construction cost of AC60/70 + Fiber pavement can have the overall improvement cracking and rutting improvement of 35% and 32% (data from plant mixing). This indicated the economic benefit of using the AC60/70 + Fiber pavement over PMA pavement. To illustrate the benefit of AC60/70 + Fiber pavement, the ratio of overall fatigue cracking and rutting performance per 1% of cost increase of all studied asphalt mixtures were compared with the controlled AC60/70 mixtures. In other words, based on the performance and construction cost of AC60/70 mixtures, the ratio of overall fatigue cracking improvement to 1% of construction cost increase of AC60/70 + Fiber mixture, PMA mixture, and PMA + Fiber mixture were 2.50% and 3.67%, 0.76% and 0.72%, and 1.23% and 1.36% respectively, for the laboratory and plant mixed specimens. Similarly, the ratio of overall rutting improvement to 1% of construction cost increase of AC60/70 + Fiber mixture, PMA mixture, and PMA + Fiber mixture were 2.24% and 3.27%, 0.62% and 0.67%, and 0.73% and 0.80%, for the laboratory and plant mixed specimens, respectively.

### 6. Conclusions

The laboratory and field tests were undertaken to examine the performance of fiber-reinforced conventional AC60/70 mixture and PMA mixture. Four asphalt mixtures: AC60/70 mixture, AC60/70 + Fiber mixture, PMA mixture, and PMA + Fiber mixture were prepared using the Marshall method, which followed the specification of DOH, Thailand. The mixing quality of FR-AC in both laboratory and plant was also investigated to examine the scale-impact on the geotechnical properties and characteristics of AC. Two field trials were constructed to study the effect of fiber reinforcement on AC60/70 mixture and PMA mixture. The field measurement included International Roughness Index (IRI), texture depth, and rutting. Finally, an economic benefit analysis was performed based on the two criteria: overall fatigue cracking improvement and overall rutting improvement when compared with the performance of AC60/70 mixture. The main conclusion of the current study can be drawn as follows:

1. An overall performance in both fatigue cracking and rutting criteria of laboratory and plant mixed specimens is principally the same. This indicated that the mixing quality from both laboratory and plant is comparable. In other words, the laboratory performance test results of the designed HMA can be used to estimate the field performance of the hot mixed asphalt pavement. The laboratory and field trial test results evidently proved that the fiber-reinforcement can enhance both overall fatigue cracking and rutting criteria improvement of the controled AC60/70 mixtures and PMA specimens. It contributes to the development of a 3D reinforcement system in asphalt binder, which lead to the dense and strong matrixes of the fiber reinforced AC mixtures.

2. The field trial tests were performed after years of opening to traffic and the field measurement indicated that all studied AC sections exhibited very good performance as their IRI values were lower than 2.5, which is specified by DOH, Thailand. The fiber-reinforced sections exhibited lower IRI and rutting than the unreinforced sections. This implied that fiber-reinforcement can improve the resistance of the permanent deformation of conventional AC mixtures and PMA mixtures. However, the texture depth measurement, an indicator of skid-resistance of AC pavement, indicated insignificant difference between AC60/70 mixture and AC60/70 + Fiber mixture as well as PMA mixture and PMA + Fiber mixture. This implied that the fiber-reinforcement insignificantly improved the skid-resistance of AC pavement.

3. It is worth mentioning that the AC60/70 + Fiber mixture and PMA mixture had practically the same overall improvement in both the fatigue cracking and rutting criteria. Whereas, the overall fatigue cracking improvement of PMA + Fiber mixture of 92% was significantly higher than the overall rutting improvement of 50%. This implied that fiber-reinforcement in PMA mixture had higher potential in improving fatigue cracking resistance than rutting resistance.
4. Based on the economic benefit analysis of AC pavement using the construction cost of AC60/70 pavement as a reference, the increase in construction cost of AC60/70 + Fiber, PMA, and PMA + Fiber pavement was about 10%, 53%, and 68%. The cost effectiveness of AC60/70 + Fiber pavement was clearly evident once the overall fatigue cracking and rutting improvement was analyzed taking the construction cost into account. The ratios of overall fatigue cracking improvement to one percent of cost increase of AC60/70 + Fiber, PMA, and PMA + Fiber pavements were approximately 3%, 0.75%, and 1.3%, respectively. While the ratios of overall rutting improvement to one percent of cost increase of AC60/70 + Fiber, PMA, and PMA + Fiber pavements were approximately 2.7%, 0.67%, and 0.76%, respectively.

The present laboratory and field trial studies confirmed the potential and efficient utility of fiber-reinforcement to improve the engineering properties and performance of traditional AC pavement in Thailand. For further research, a life cycle costing analysis directs engineering properties and performance of traditional AC pavement using fiber-reinforcement using a similar mix design method.

Declarations

Author contribution statement

Thaworn Takaikaew: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Menglim Hoy, Jitwadee Horpibulsuk: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Suksun Horpibulsuk: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Arul Arulrajah, Alireza Mohammadiina: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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