RECYCLED PLASTIC FIBER REINFORCED HOT-MIX ASPHALT

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ABSTRACT

Various reinforcing methods are widely utilized to extend the performing life of Hot-Mix Asphalt especially in view of fatigue crack or rut resistance such as polymer modification of asphalt binder or stone mastic asphalt mixture. Although some strengthening effects of such solutions have been reported, those may not guarantee long-term toughness or fatigue resistance because modified asphalt mixture sometime results in too stiff binder to sustain hysteresis external loading in bending-beam or cyclic direct tensile tests set-up. In addition, high costs and difficulties in field works of them are usually pointed out as drawbacks to apply to fields frequently. A new recycled plastic fiber-reinforced Hot-Mix Asphalt is proposed to provide more effective reinforcements in structural enhancement and usefulness in cost-side. A small amount of recycled plastic fibers in Hot-Mix Asphalt leads significant increases in phenomenological toughness and fatigue life of mixtures compared to unreinforced Hot-Mix Asphalt mixtures as resulting from indirect tensile tests and four-point bending beam tests.

1. INTRODUCTION

In ancient times, natural resources such as rice straws or reeds have been utilized as reinforcing media for civil or housing structures. However, those are not widely used causing inconsistent durability and strength or quality assurance problems. After being developed synthetic polymers like plastics, some drawbacks in natural resources were overcome and adopted in civil structures with geosynthetics. Most of geosynthetics such as geogrid or geomembrane were made of Polypropylene (PP), Polyethylene (PE), Polyester, or Nylon and those were widely utilized in geotechnical area to reinforce backfill or slope [1].

In recent times, except fiber grids and woven or non-woven matrices of fiber, fibrillated micro or macro fibers are utilized in concrete structures to control micro or macro cracks. Enhancing toughness of fiber-reinforced mixtures is the main reason of mixing fibers. However, although there are some cases of mixing filament fibers with roadway pavement materials like concrete or HMA to expect toughening effect, most of applications of fibers is limited in concrete structures like buildings and bridges [2].

To date, hot-mix asphalt mixture with some amount of fibers such as Polyester, PP, glass fiber, or Nylon have been reported with some superior effects compared to plain HMA like toughness, indirect tensile strength, shear strength, or fracture energy; however, one of the representative effect among them is higher toughness, which is increasing fatigue life of a mixture, than the plain HMA did in a laboratory scale [2, 3, 4].

Most of fibers in previous studies are micro fibrillated fibers having thin and short dimension like less than 0.1 mm in thickness and 10 mm - 15 mm in length, and the extrusive manufacturing process for producing those fibers usually utilizes brand new resin chips such as PP, Nylon, or Polyester, those are not recycled materials.

On the other hand, utilizing thin-fibrillated fibers with HMA in most of previous studies address difficulties in mixing and compaction, serious one is that the balling of fibers during mixing HMA is a critical issue to solve. In other words, this means that the good dispersion of fibers in HMA should be verified before paving the fiber-treated HMA.

This study developed new macro fibers as reinforcing media for HMA. The unique dimension of the developed fiber is capable of having good dispersion and toughening effect, and utilizing recycled chips of PET (Polyethylene terephthalate) makes decreasing the unit price of fibers. Indirect tensile strength tests, indirect cyclic fatigue test, and four-point bending beam tests were performed to address enhanced mechanical properties of fiber reinforced HMA such as toughness and resistance to fatigue damage. Phenomenological results show that noticeable reinforcing effects on enhancing toughness and reducing fatigue damages. Such effects may result in greater stability and longer fatigue life of HMA compared to those of conventional HMA.

2. RECYCLED PET FIBER-REINFORCED HMA

HMA is a composite mixture consisting of aggregate and asphalt binder. Volumetric properties such as air void, VMA (Voids in Mineral aggregate), VFA (Voids Filled with Asphalt), and specific gravity are primal parameters to control the quality of HMA. Asphalt binder makes aggregates stick together and provides cohesive strength to the mixture. An aggregate gradation results in various sizes of aggregates depending on a sieve analysis. Target air void in a mixture design process is a main parameter to decide the aggregate gradation such as dense, open, uniform, fine, or coarse gradations.

Interlocking forces developing by aggregates' interaction and adequate effective asphalt are sources of resisting external traffic loading and reveal compressive strength of HMA. The uniaxial compressive strength of highly interlocked HMA is about 3,000-5,000 MPa in a room temperature. On the other hand, the indirect tensile strength of HMA is relatively low value ranged about 300-500 kPa depending on the temperature which is about one over ten of compressive strength [4, 5].

HMA's mechanical properties are highly depending on temperatures such as low values at high temperatures and high values at low temperatures. Generally, critical tensile strain at the bottom of HMA in a pavement system is a primal performance criterion in a thickness design; it needs to increase the tensile strength of HMA to satisfy the criterion. Polymer modified asphalt binder may be a good alternative to increase the strength of HMA at high temperature and results in a good resistance to the rut damage.

A promising chemical technique for limiting HMA failures or enhancing physical properties of HMA is using polymer modified HMA exposed to severe climatic conditions and heavy-weight truck traffic. Although several advantages of polymer modified HMA have been reported, the polymer modified binder and mixture have not yet been characterized because of complexities in chemical and mechanical interactions between asphalt binder and polymer [6, 7, 8, 9].

Representatively, indirect tensile strength of polymer modified HMA exceeds at least about 1.4 times higher than the value of plain HMA depending on the level of modification while the price of the modified HMA is at least about 2.5 times higher than that of the plain HMA; however, strain energy after peak load in a low temperature of the polymer modified HMA is sometimes lower than the plain HMA does. This means that the modified HMA may result in too brittle in a low temperature and may experience sudden brittle fracture. Hence, the modified HMA may not provide a consistent improvement of long-term performance in a low temperature [9, 10].

This study did not focus on the modification of asphalt binder but addressed three dimensional reinforcement of HMA itself using plastic fibers with HMA. Phenomenological tests such as indirect tensile tests and four-point bending beam tests were performed to verify enhanced toughness and fatigue resistance of fiber reinforced HMA.

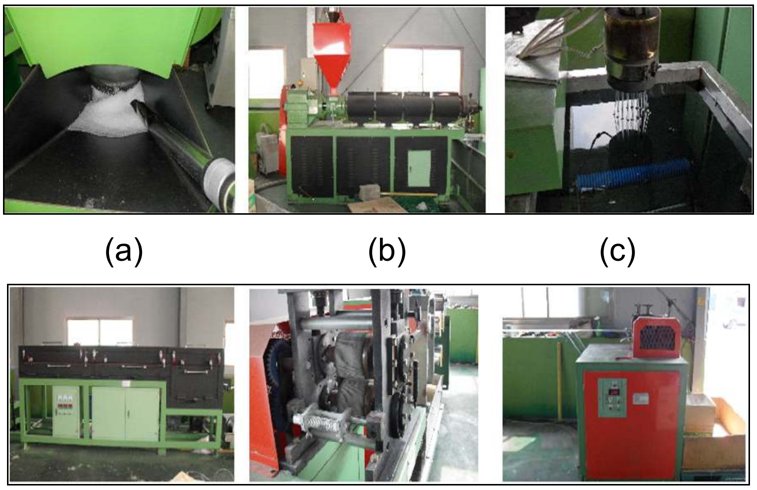
Whole processes to pave a roadway using the recycled PET fibers are showing like from Figures 1(a) to 1(e). Recycled PET chips were extracted out of discarded PET bottles, Figure 1(a). Local recycling manufacturers provided the recycled PET chips, Figure 1(b), and then produced PET fibers having a unique dimension like 30 mm (L) × 0.5-1 mm (W) × 0.5-1 mm (T), Figure 1(c).

Indirect tensile tests were performed to verify optimum fiber contents (OFC) through checking the variation of indirect tensile strength depending on arbitrarily selected fiber contents from 0.1% to 0.8% of mixture's weight; in addition, randomly dispersed fiber without any fiber's balling should be checked like PET fiber reinforced specimens after testing, Figure 1(d). Besides the laboratory tests, two field test sections in 50 m length each and one control section in 30 m length were constructed with several instrumentations such as pressure cells and I-type strain gauges in horizontal and longitudinal directions, Figure 5(e).

(a) (b) (c) (d) (e)

Figure 1 - (a) PET bottle, (b) Recycled PET chips (c) Recycled PET fiber (d) Fiber mixture, and (e) Fiber asphalt concrete test-bed

The detail processes from the recycled PET chip in Figure 1(a) to the recycled PET fibers are as follows: the melting temperature of recycled PET chip is about 250-260°C. All the chips are to be melting and shaping like long strings in the fiber extrusion unit at high temperature above 280 °C, Figure 2(b) and Figure 2(c). Extruded fibers need to be elongated several times to increase tensile strength of them, Figure 2(d). Number of elongation depends on the desirable tensile strength of a fiber maintaining at least ten times higher than the typical value of HMA like 300-500 kPa at 20 °C, the standardized number of elongation and modulus of fiber has not yet been defined though. The surface of fiber is shaped in the embossment unit, Figure 2(e). Embossed fibers then are to be cut for a desirable length depending on a maximum aggregate size of a HMA, Figure 2(f).



(a) (b) (c)

(d) (e) (f)

Figure 2 - Manufacturing PET fibers: (a) Recycled resin hopper, (b) Fiber extrusion unit (c) Extrusion nozzle and cooling, (d) Elongation unit, (e) Embossment unit, and (f) Fiber cutting unit

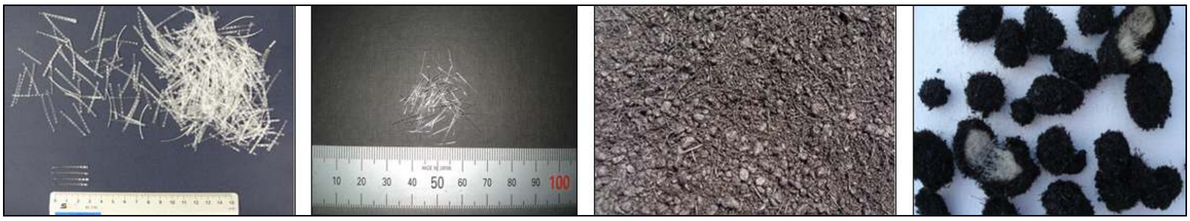
The dimension of the recycled PET fibers for a base layer is in Figure 3(a), 30 mm (L) × 0.5-1 mm (W) × 0.5-1 mm (T) in this study. Mechanical properties of the recycled PET fibers are as follows: the specific gravity of the recycled PET fiber is about 1.32, tensile strength is in range of 300-305 MPa in a room temperature, the elastic modulus in a room temperature is about 13 GPa, and the elongation is about 7.5 %. All the mechanical properties of the recycled PET fibers in this study are equivalent to typical values of a new PET fiber.

The recycled PET fibers, Figure 3(a), have several embossments on fiber's surface to increase surface frictional force and they have a deep longitudinal groove in the middle of the surface of each fiber to induce additional separation at the two-ends of each fiber while dry-mixing process with aggregates in an asphalt plant.

Adding a small amount of fibers into a plain HMA does not need any equipment to mix fibers with HMA except throwing a fiber-bag into a pug-mill during dry mixing process in a batch plant. Two shapes of fibers in this study are tested like recycled PET fibers of Figure 3(a) and thin conventional micro fibers of Figure 3(b) to show mixing and handling characteristics in a plant respectively.

The relative macro dimension comparing conventional fibers like the micro fiber which is less than 10 mm length and 0.1 mm thickness makes macro fibers in HMA free from fiber's balling at high mixing temperature above 180 °C and avoids difficulties of fiber's dispersion in HMA when using thin conventional micro fibers of Figure 3(b) like 10 mm (L) × 0.1-0.2 mm (W) × 0.1-0.2 mm (T).

Although any additional mixing process did not be provided without only the dry-mixing with aggregate about 20-30 seconds in the asphalt batch plant, the recycled PET fiber reinforced HMA after wet-mixing has shown, Figure 3(c), that good dispersion of fibers without any noticeable fiber's balling, while thin micro fibers were highly conglomerated causing not enough plant-mixing time and the easy entanglement of the micro fibers, Figure 3(d).

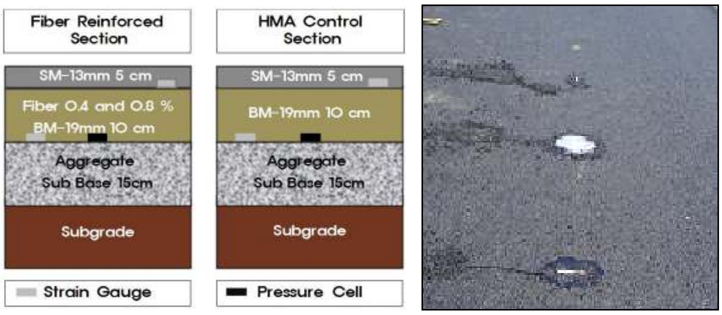


(a) (b) (c) (d)

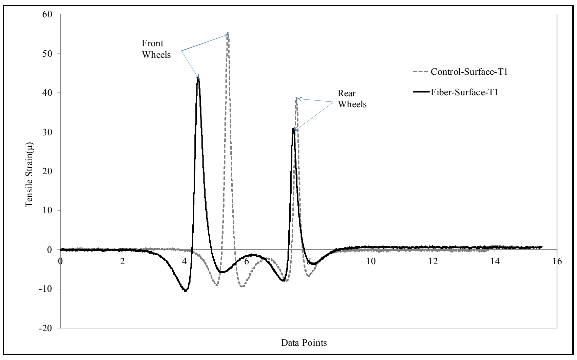
Figure 3 - (a) Thick recycled PET fibers, (b) Thin micro fibers, (c) Dispersion in mixtures, and (d) Thin micro fibers' balling

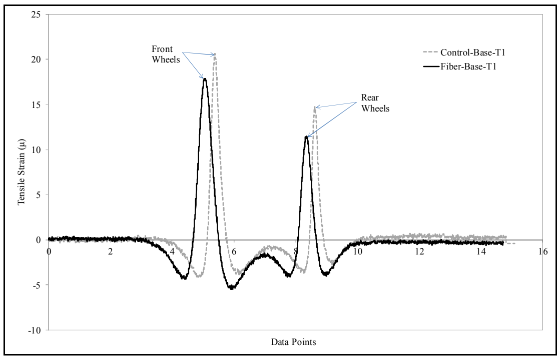
Authors expect that enhancing frictional force in the interface between aggregates and fibers through the several embossments, and increasing contact area of fiber with asphalt binder through additional separations at the two-ends of each fiber due to the longitudinal groove on the surface of recycled PET fiber, although further experiments need to verify those effects in mechanical or phenomenological test results in a future study.

Field performances in production and paving of the recycled PET reinforced HMA were investigated through test beds including several instrumentations: pressure cells and I-type strain gauges (KM-100B) were installed at the bottom of surface layer (5 cm) and the fiber reinforced base layer (10 cm), Figure 4(a).



(a)





(b) (c)

Figure 4 - (a) Instrumentation, (b) longitudinal strains at the bottom of surface layer, and (c) longitudinal strains at the bottom of base layer

Typical longitudinal strains in parallel to traffic loading direction were observed that compressive strains by approaching moving-loads to sensors were recorded first and then the maximum tensile strains were measured as the loading exists on the top of each sensor. Contact pressures were about 413 kPa underneath of front wheels and 275 kPa at rear wheels, and temperatures at surface and base layers were in between 7-10 °C.

All the peak responses in the fiber reinforced pavements are slightly lower than those of the plain HMA. Responses at the bottom of surface layers, Figure 4(a), were higher than responses at the bottom of the base layers, Figure 4(b), causing the shallow depth of the surface layer. Although the relative strain differences between fiber-reinforced pavements and plain HMA are not highly differentiated at these low temperature conditions, the toughening effect of fibers in HMA may contribute to lower peak strains in all cases.

However, analysis on chemical reactions between asphalt binder and fiber's surface could not be covered in this study because of chemical and mechanical complexities between them. Relative field performance tests due to cyclic loading could not be done causing lack of accelerated pavement testing system; hence, recycled PET fiber-reinforced HMA and plain HMA mixtures have been tested through laboratory tests such as four-point bending beam and indirect tensile tests representing relative performances of them.

3. MIXTURE CHARACTERIZATION

The objective of this study was to perform laboratory tests to characterize phenomenological behaviors of the fiber-reinforced HMA comparing to the plain HMA. Asphalt binder utilized in this study was PG 64-22 (AP5). All HMA mixtures both with-fibers and without-fibers were mixed according to mixture characteristics of Table 1 and aggregate gradations in Table 2. Asphalt content and number of gyrations are fixed to observe mechanical variations due to fiber contents such as 0.4 or 0.8% of mixture's weight. Fiber contents for an aggregate gradation were decided through indirect tensile strength and bending-beam fatigue tests result having maximum loading repetitions through a preliminary study.

Aggregate gradation for the surface mixture (SM-13mm) is fixed in dense gradation. Gradations for base mixtures (BM-19mm) varied in coarse, open, and dense grades to observe cyclic fatigue behaviors depending on aggregate gradations.

Table 1 - Mixture characteristics

Mix type	Mix Design Data				
	Binder Type	Design AC (%)	Number of Gyration	G_{mm}	Fiber Contents (%)
Control	PG 64-22	5.2 ± 0.1	110	2.474	0.0
Fiber Mix	PG 64-22	5.2 ± 0.2	110	2.474	0.4 or 0.8

Table 2 - Aggregate gradation

Aggregate Gradation			Percent Passing (%)							
	Sieves		1"	0.75"	0.5"	0.375"	No.4	No.8	No. 30	No.200
	SM-13 mm		100.0	100.0	98.0	94.0	68.0	45.0	18.0	2.0
	BM-19mm	Coarse	100.0	94.5	77.3	59.7	31.9	24.1	12.3	3.0
		Open	100.0	98.5	89.8	63.8	26.0	18.5	9.6	2.8
		Dense	100.0	95.0	83.1	69.0	40.1	29.0	14.5	3.3

The close-up surface of recycled PET fiber-reinforced HMA for a base course of 19 mm coarse aggregate gradation are like Figure 5 and no noticeable fiber's balling in loose mixtures exists.

All test specimens were compacted using a gyratory compactor into 150 mm diameter mold. The mass of each specimen was calculated according to the target V_a like 6 percent, the volume of mold, and theoretical specific gravity of G_{mm}. Two specimens approximately 60 mm in height were cored and cut from the each compacted specimen for indirect tensile tests.

Figure 5 - Close-up surface of mono-strand fiber-reinforced HMA

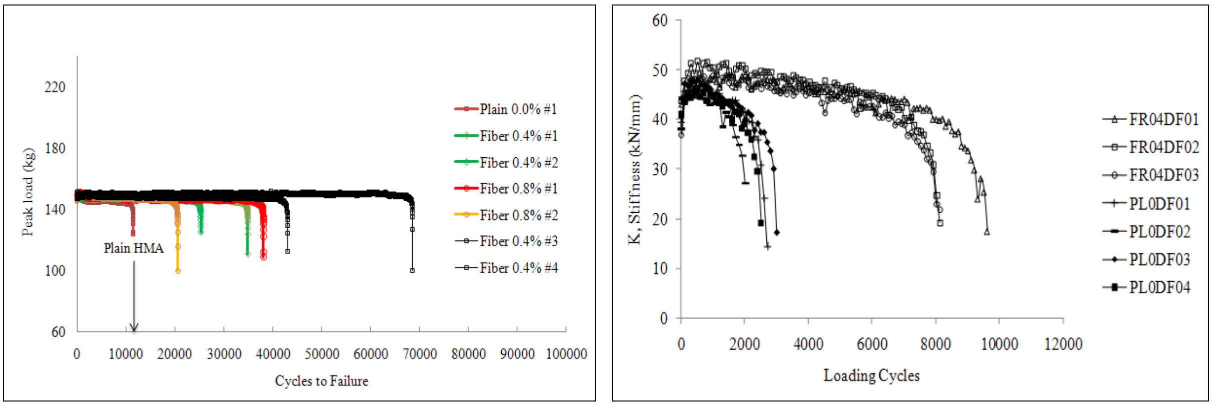
As for the fiber-reinforced HMA, although an available test or an analysis protocol regardless of fiber and binder interaction have not yet been developed in this research, HMA including fibers may expect better contribution to enhance the fatigue damage of HMA through conventional test protocols for HMA. Hence, Indirect cyclic loading fatigue tests, indirect toughness tests, and four point bending beam tests were performed to present relative characteristics upon the fiber reinforcement of HMA compared to plain

HMA mixtures, and enabled to observe physical properties such as toughness and fatigue life relatively between with and with fibers in HMA.

3.1 Indirect Tensile Loading Tests

Indirect tensile strength of HMA is a physical property that is widely utilized to evaluate relative tensile strength of HMA. A laboratory test protocol has been developed to determine tensile strength from indirect tensile test results [11].

This study applied cyclic loading pulse at 10 Hz of 1.5 kN to indirect cylindrical specimens at 25 °C for the 13 mm dense-graded HMA, Figure 6(a), to observe distinguishable indirect toughening effect between the PET fiber-reinforced specimen and the plain HMA. The 19 mm coarse-graded HMA is experienced the loading pulse at 10 Hz of 3.5 kN at 25 °C, Figure 6(b).



(a) (b)

Figure 6 - Indirect cyclic fatigue test results: (a) 13 mm Dense-graded HMA, (b) 19 mm coarse-graded HMA

As shown in Figure 6(a) for the 13 mm dense-graded HMA, the plain HMA failed after loading repetitions about 12,000 loading cycles, while the 0.4% and 0.8% PET fiber-reinforced HMA mixtures maintained loading cycles about 2 times to 7 times higher than the plain HMA did. Extending loading cycle up to fatigue failure would be caused by the toughening effect of fibers in HMA.

In case of the 19 mm coarse gradation for the base course of HMA, Figure 6(b), loading cycles up to fatigue failures of Plain HMA such as PL0DF01-PL0DF04 resulted in 2,000 to 3,000 cycles, while the PET fiber-reinforced HMA (FR04DF01-FR04DF03) maintained loading cycles up to 8,000 to 10,000 cycles about 4 times higher than those for the plain HMA. Toughness enhancements of fibers in the base course of HMA are also expected like the dense-gradation did.

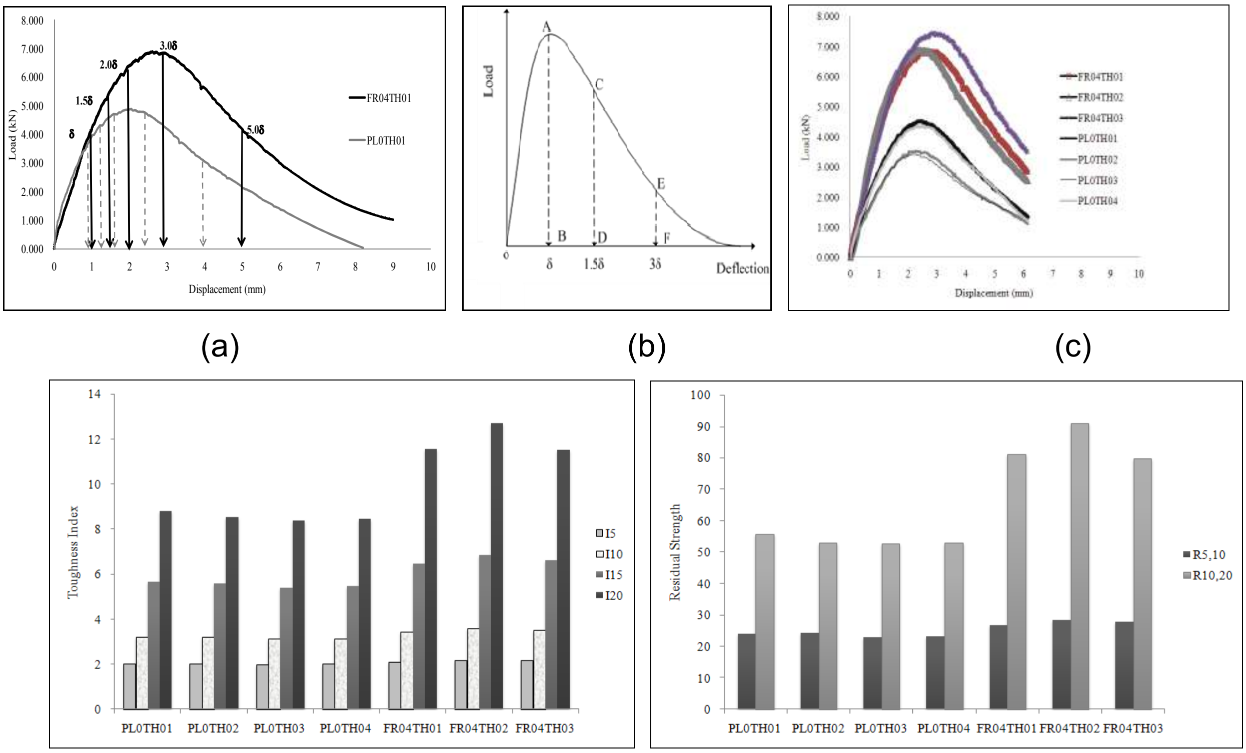
Besides the indirect cyclic fatigue behavior, it is commonly argued that the practical advantage of adding fibers into HMA is that, after initial failure or cracking, fibers could bridge fatigue damages and restrain mixtures from abrupt fracture of mixtures. To present toughness characteristics through indirect tensile tests, steady-state uniaxial loading rate of 0.2 mm/sec was applied to indirect specimens at 25 °C, and then load and deflection curves would be utilized to calculate toughness indices [2,3,4].

To distinguish toughness characteristics of all mixtures on the whole horizontal of indirect load and deflection curve by toughness indices, ASTM C1018 is referred to calculate toughness indices at different levels of deflection such as δ, 1.5δ, 2δ, 3δ and 5δ in Figure 7(a), where δ is vertical deflection. Toughness up to the δ represents the area under load and deflection curve that may be the storage energy recovering after removing load, although the point of δ is selected without any mechanical interpretation. Toughness indices such as I5, I10, and I20 in ASTM C1018 are the ratio between post-peak toughness and pre-peak toughness [12, 13, 14].

In addition, to evaluate the toughness behavior between the plain and the PET fiber-reinforced HMA, toughness indices and residual strength parameters in ASTM C1018 were referred according to the following form:

$$R_{5,10} = \frac{100}{n-m}(I_{10} - I_5) \tag{1}$$

where R = residual strength parameter, toughness indices $I_5 = Area$ OACD / $Area$ OAB, $I_{10} = Area$ OAEF / $Area$ OAB in Figure 7(b), n=10, m=5 indicial parameters.



(a) (b) (c)

(d) (e)

Figure 7 - (a) Deflection parameters, (b) Conceptual diagram, (c) Indirect toughness test results, (d) Toughness indices, (e) Residual strength indices

Load and displacement curves are highly differentiated between the plain HMA (PL0TH01-PL0TH04) and the recycled PET fiber-reinforced HMA (FR04TH01-FR04TH03) in Figure 7(c). Toughness indices until pre-peak such as I5 and I10 in Figure 7(d) represent slight differences among specimens; however, post-peak toughness indices such as I15 and I20 of the recycled PET fiber-reinforced HMA are distinguishably higher than those of the plain HMA, the maximum difference in I20 between them results in 1.5 times higher than the value of plain HMA, FR04TH02 and PL0TH03 in Figure 7(d). The residual strength index of R10,20 after peak load of fiber-reinforced HMA are also greater than the pain HMA about 1.7 times higher than that of plain HMA, Figure 7(e).

Higher toughness indices of the recycled PET fiber-reinforced HMA comparing to the plain HMA represent that the load carrying capacity may prolong the performance life of HMA with the effect of fibers' bridging across aggregates or damaged area.

3.2 Flexural Beam Fatigue Tests

According to indirect test results, fibers in mixtures may enhance the damage resistance of HMA. Not a significant improvement in toughness prior to the peak-load may cause that the bridging or toughening effect may engage after some micro damage exists in a mixture. Therefore, it would be more explainable to evaluate the performance of fiber reinforcement in HMA that is based on energy absorption in whole horizontal of load and deflection responses during cyclic loads, since toughness indices only explain the toughening behavior within a relatively short time period about 30 to 40 seconds under static loading condition.

To propose more explainable phenomenological fatigue behaviors of HMA covering the whole range of fatigue behaviors such as primary, secondary, and tertiary stages considering the bridging effect of fibers in HMA, an alternative test based on the four-point bending beam fatigue test (4PB) were performed. The dissipated energy per unit volume per cycle or period was derived from the total potential energy per loading cycle like Equation 2 as follows:

$$\therefore\ W_i = Dissipated\quad Energy\ \ (DE) = \pi\hat{\varepsilon}^2 E''(w) = \pi\hat{\varepsilon}^2 \left|E^*\right| \sin\delta = \pi\hat{\varepsilon}_i\sigma_i \sin\delta_i \tag{2}$$

where W_i = dissipated energy at load cycle i, σ_i = stress amplitude at load cycle i, *DE* = dissipated energy per cycle, $\hat{\varepsilon}_i$ = strain amplitude at load cycle i, and δ_i = phase angle between stress and strain wave signals.
The dissipated energy per cycle is computed by using Equation 2. Then, the ratio of dissipated energy change (RDEC) per 100 cycle-intervals was calculated by Equation 3 [15]:

$$RDEC_a = \left|\frac{DE_a - DE_b}{DE_a \times (b-a)}\right| \tag{3}$$

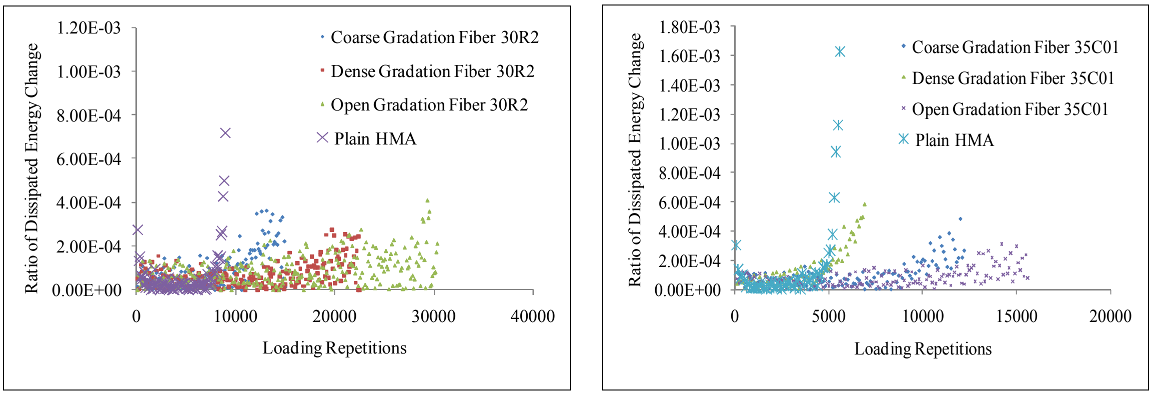
where RDEC = the ratio of dissipated energy change, a and b = loading cycles, 100 cyclic interval; and DE = dissipated energy during a loading cycle a and b, respectively.

The 4PB specimen is repeatedly loaded in different displacement-controlled modes resulting in peak-to-peak strain levels such as 1000 $\mu\varepsilon$ and 1500 $\mu\varepsilon$. Completely reversed sinusoidal loading pulse at 25 °C was applied to all specimens until fatigue failure occurred, as used in this study. The test fixture and the PET fiber-reinforced specimen after fatigue failure are like Figures 8(a) and 8(b) respectively.

(a) (b)

Figure 8 - (a) Four-point bending beam fixture, (b) Mono-strand fiber-reinforced specimen after failure

All specimens in Figures 9(a) and 9(b) are made in same conditions such as binder grade, mixing, and compaction conditions except fiber's contents like 0.4% of specimen’s weight. Three different aggregate gradations such as coarse, dense, and open were utilized to observe the sensitivity of aggregate gradation. RDECs in all cases of PET fiber-reinforced specimens maintain longer loading repetitions until fatigue failure occurs than the plain HMA does.



(a) (b)

Figure 9 - Bending beam fatigue test: (a) Strain level 1,000 $\mu\varepsilon$ at 25 °C, (b) Strain level 1,500 $\mu\varepsilon$ at 25 °C

In addition, it is worth noting that the RDEC in open aggregate gradation shows the longest RDEC horizontal than others, although the RDEC sensitivity due to aggregates’ gradations is a primal issue to address within this study. This may mean that the fiber-reinforced HMA is more adaptable to relatively high air-void condition but relatively uniform size of void than low air-void mixture in a dense gradation, even though further tests need to be done to verify gradation sensitivity more extensively.

The RDEC of PET fiber-reinforced HMA maintain relatively longer steady-state or constant rate of energy change than those for the plain HMA due to the bridging effect of fibers in HMA, Figures 9(a) and 9(b). Although fatigue damages may relate to asphalt binder's quality, aggregate type and gradation, or mix design, fatigue performance with fibers are superior to that of the plain HMA.

The RDEC for the plain and PET fiber-reinforced HMA are plotted versus the number of loading cycles in Figures 9(a) and 9(b) to distinguish mixture's fatigue behaviors in different loading amplitudes. It represents that initial rapid changes of RDEC during the primary stage of loading cycles until the initial softening is completed. Following the primary stage, the curve remains relatively constant level of RDEC indicating stable fatigue damage resistance as a secondary stage of fatigue horizontal. Upon failure, the RDEC increases again, and a much greater portion of the dissipated energy capacity of a specimen may be converted to fatigue damage representing the tertiary stage shown in Figures 9(a) and 9(b).

While the tertiary stage starts around 8,000 loading repetitions for the plain HMA in dense gradation under 1,000 $\mu\varepsilon$ of peak-to peak strain, Figure 9(a), recycled PET fiber-reinforced specimens in dense, coarse, and open aggregate gradations maintain the secondary stage up to the 1.5 to 3 times higher loading repetitions than those of the plain HMA.

In case of 1,500 peak-to-peak $\mu\varepsilon$ level, Figure 9(b), loading repetitions up to the point of tertiary stage for the fiber-reinforced HMA in open gradation is about maximum 3 times longer than that of the plain HMA. The toughening effect of fibers in HMA is the cause of extending fatigue life, even though more tests in different temperatures or mixture types need to be done at this point.

4. CONCLUSION

Polymer modifications are widely utilized in HMA pavement to enhance the structural integrity of HMA. However, the modification of binder for a surface mixture may result in too stiff binder depending on its level of modification so that long-term fatigue damage potential may be more susceptible to temperature changes even compared to the unmodified HMA. This may not guarantee superiority in long-term toughness or fatigue resistance of the polymer modified HMA causing too stiff binder.

In view of compressive and shear strengths of hot-mix asphalt mixtures may be induced by interlocking forces of aggregates, use of modified binder enhancing the tensile property of a mixture with a high cost of polymer should be limited for a place where needs stiff binder in higher tensile strength than that of the plain HMA; e.g., intersections, bridge abutments, and bus-stop area.

To compensate those disadvantages such as stiffening and cost in polymer modifications and to provide more effective reinforcement of surface or base course of roadway HMA itself in three-dimensional direction, the recycled plastic fiber-reinforced HMA is proposed in this study.

This study developed new plastic fibers as reinforcing media for HMA. The unique dimension of the developed fiber is capable of having good dispersion without fiber’s balling, and utilizing recycled chips of PET (Polyethylene terephthalate) decreases the unit price of fibers. Recycled PET fibers with the melting point of 250-260 °C were free from the fiber's balling at high temperature above 180 °C and no need additional process or equipment to mix fibers in an asphalt plant except throwing a fiber bag into a mixer when doing dry-mixing process for 20-30 seconds. The dispersion of fibers in HMA without any noticeable fiber's balling was observed in uncompacted mixtures got from an asphalt plant when paving a test-bed in this study.

Indirect cyclic fatigue tests were done to observe distinguishable indirect toughening effect between the fiber-reinforced specimen and the plain HMA. The 13 mm dense-graded PET fiber-reinforced HMA of 0.4% and 0.8% fiber contents in specimen's weight maintained the indirect cyclic loading cycles until about 2 times to 7 times higher values than the plain HMA did. In case of the 19 mm coarse-gradation for the base course of HMA, the 0.4% fiber-reinforced HMA maintained loading cycles about 4 times higher than the plain HMA did. Extending loading cycle up to fatigue failure would be caused by the toughening effect of fibers in HMA.

In addition, according to the fiber's toughening effect through indirect toughness tests, toughness indices within the pre-peak represent slight differences among specimens.

However, post-peak toughness indices of fiber-reinforced HMA are distinguishably higher than those of the plain HMA, the maximum toughness index of fiber-reinforced HMA resulted in 1.5 times higher than that of the plain HMA. The residual strength after peak of the fiber-reinforced HMA is also about 1.7 times higher than the pain HMA did.

To propose a more explainable phenomenological fatigue behavior of HMA considering the bridging effect of fiber, four-point bending beam fatigue tests were performed. PET fiber-reinforced specimens maintained 1.5 to 3 times higher loading repetitions than those of the plain HMA in all cases of 1,000 $\mu\varepsilon$ and 1,500 $\mu\varepsilon$ peak-to-peak strain levels. The toughening effect of fibers in HMA may be the cause of extending fatigue life up to fatigue failure.

In conclusion, adding a small amount of fibers into HMA led to significant enhancements in the phenomenological indirect and bending beam fatigue life compared to the conventional HMA. Higher toughness indices of the PET fiber-reinforced HMA compared to the plain HMA mean that load carrying capacity may prolong the performance life of HMA with the effect of fiber's bridging across aggregate surface or damaged area, although further experiments in different temperatures and loading conditions need to be done to verify those effects in more analytical view points.

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