Cracking indices and effects of synthetic fibers on the mechanical properties of cold recycled asphalt mixtures

Mohammad Sadeghi[1] and Mohammadreza Sabouri, Ph.D., P.E.[2*]

[1]Graduate Research Assistant, National Center of Asphalt Technology (NCAT), Auburn University, Alabama, USA
Email: mzs0274@auburn.edu

[2]Assistant Professor, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran
Email: sabouri@sharif.edu (Corresponding author)

ABSTRACT

Despite their environmental and economic benefits, cold recycled asphalt mixtures are not widely used partly because of their inadequate mechanical properties. This study evaluates the validity and practicality of the flexibility index and CTIndex for emulsified asphalt cold recycled mixtures. Modifications in I-FIT analysis and a modified IDEAL-CT cracking index for mixtures without cement have been proposed and evaluated. It was found that the revised IDEAL-CT index can better capture the crack resistance of cold recycled mixtures with and without fibers. Polypropylene, A-glass, para-aramid and polyester synthetic fibers were added to emulsified asphalt cold recycled mixtures in different lengths and contents. IDEAL-CT and dry and wet ITS were used to determine the optimum fiber lengths and contents. The combined effects of the optimized fibers and cement were evaluated using IDEAL-CT, dry and wet indirect tensile and I-FIT testing. The performance tests showed that the addition of fibers generally increased the dry tensile strength and crack resistance, reduced the wet tensile strength and increased the moisture sensitivity. Except for the A-glass fibers, shorter lengths and lower fiber contents generally increased the strength, but decreased the crack resistance. In most cases, the combined use of fibers and cement retained the favorable properties of the mixtures having cement, but compensated for their inherent crack resistance defects. In some cases, the combined use of cement and fibers produced similar or better results than the control mixture having a higher emulsified asphalt content. The polypropylene and polyester fibers showed the most promising results overall.

Keywords: Cold recycling, Emulsified asphalt, Fiber, Cement, Reclaimed asphalt pavement

1. Introduction

Efficient and economical road transportation systems are required for modern society. Road transportation consumes the largest share of transportation energy (U.S. Energy Information Administration 2023) and imposes a substantial environmental impact on the planet. Given the significant cost, energy consumption and greenhouse gas emissions of conventional construction and maintenance methods, the development of alternative materials and innovative construction technologies is of importance (Fakhri et al. 2021, Epps 2019).

Pavement recycling can be categorized as being hot or cold recycling methods. Cold recycling has environmental and economic benefits compared to hot mix asphalt (HMA) and hot recycling technologies (Xiao et al. 2018, Morian et al. 2004, Ayar 2018, Thenoux et al. 2007, Alkins et al. 2008, Gu et al. 2019, Jain and Singh 2021, Vamsikrishna et al. 2024, Kumar et al. 2024) and meets the criteria for sustainable pavement (Alkins et al. 2008, Gu et al. 2019). However, cold recycled mixtures tend to have high air void contents, weak early-life strength, relatively high moisture susceptibility and lengthy curing times (Thanaya et al. 2009, Ling et al. 2014, Modarres et al. 2014, Fang et al. 2016, Meknaci et al. 2022, Meneses et al. 2021). Cement and other additives are often used to improve cold recycled mixtures. The addition of cement is almost essential for mixtures in which asphalt emulsion is used (Fang et al. 2016).

Studies have shown that cement can improve the early life and long-term strength, stability, moisture resistance and resistance to permanent deformation of cold recycled mixtures (Issa et al. 2001, Yan et al. 2017, Niazi and Jalili 2009, Xu et al. 2011). However, the increased brittleness of the mixtures lead to concerns about their fracture performance (Xu et al. 2011). The addition of cement to a mixture also increases greenhouse gas emissions, which reduces the environmental benefits of cold recycling. Researchers have found that the addition of 2% cement to an emulsified asphalt cold recycled mixture leads to carbon dioxide emissions similar to HMA (Fang et al. 2016) which is one of the reasons to keep cement content minimum (Fang et al. 2016).

Fiber reinforcement is a promising method for improving the mechanical performance of asphalt mixtures as it increases their tensile strength, energy absorption capacity and toughness (Abtahi et al. 2010, Hoyos et al. 2011, Wu et al. 2023). The addition of fibers to the HMA increases its strength, dynamic modulus, ductility, rutting and fatigue resistance while reducing its moisture and thermal susceptibility (Abtahi et al. 2010, Stempihar et al. 2012, Kaloush et al. 2010, Slebi-Acevedo et al. 2019, Pais et al. 2022). The type, content, length, diameter and surface texture of the fibers can affect the mechanical performance of fiber-reinforced asphalt mixtures (Ferrotti et al. 2014, Kim and Park 2013, Sabouri and Sadeghi 2023).

Table 1 summarizes some studies on the use of fibers in cold and cold recycled asphalt mixtures. As seen, the addition of polypropylene fibers to cement-treated reclaimed asphalt pavement (RAP) improved the resilient modulus of the mixture (Puppala et al. 2009). Studies have shown that the addition of fibers to cold and cold recycled mixtures containing emulsified or foamed asphalt can increase the dynamic modulus, resilient modulus, dry and wet indirect tensile strength (ITS), rutting resistance as well as improve the fracture and fatigue properties (Kim and Park 2013, de S. Bueno et al. 2003, Du 2022, Martinez-Arguelles et al. 2015, Shanbara et al. 2018). The combined addition of polypropylene fibers and cement to cold recycled foamed asphalt mixtures has resulted in better performance than mixtures that only contain cement (Taziani et al. 2016).

Table 1. Studies on the use of fibers in cold and cold recycled asphalt mixtures

Article	Mixture type	Stabilizer/ Additive	Fiber			Key results
			Type	Length (mm)	Content (%)	
(Puppala et al. 2009)	recycled	cement	poly-propylene	-	0.15	Increased resilient modulus with cement addition Best results for combined use of fibers and cement
(de S. Bueno et al. 2003)	cold	emulsified asphalt	poly-propylene	10, 20, 40	0.1, 0.25, 0.5*	Decreased stability and modulus Similar permanent strains
(Shanbara et al. 2018)	cold	emulsified asphalt	glass, hemp, jute, coir	10, 14, 20	0.15, 0.25, 0.35, 0.45, 0.55**	Better stiffness modulus, rutting and moisture resistance and toughness Best results for glass fibers
(Martinez-Arguelles et al. 2015)	recycled	foamed asphalt	poly-propylene	-	0.75, 0.15, 0.3**	Better dry dynamic modulus Increased dry ITS and similar ITSR
(Taziani et al. 2016)	recycled	foamed asphalt, cement	poly-propylene	15, 20	0.75, 0.15, 0.3**	Increased stiffness, ITS and rutting resistance Better performance for combined use of fibers and cement
(Kim and Park 2013)	recycled	emulsified asphalt	poly-propylene	10	0.15*	Increased stability, ITS and rutting resistance
(Du 2022)	recycled	emulsified asphalt	polyester, poly-propylene, pan, lignin, basalt	10 except for basalt	0.1, 0.2, 0.3, 0.4, 0.5**	Best dry ITS at 0.3% fiber content Increased wet ITS, ITSR, rutting resistance and fracture properties Best performance for polyester fibers
(Carpani et al. 2023)	recycled	emulsified asphalt	aramid, poly-propylene	19.05	0.05, 0.1**	Lower compactibility and higher air void content Mostly reduced stiffness modulus and dry ITS, especially at the higher content Lower complex modulus at all reduced frequencies for higher content Improved fatigue resistance
(Jiang et al. 2023)	recycled	emulsified asphalt	polyester	6	0, 0.2, 0.4, 0.6, 0.8	Improved rutting resistance up to 0.3% fibers Improved low-temperature cracking properties up to an optimum content

*Total weight of mixture; **Total weight of aggregate

Charmot et al. (Charmot et al. 2017) evaluated the feasibility of the Illinois flexibility index test (I-FIT) at intermediate temperatures for cold recycled asphalt mixtures. They found that both the fracture energy (G_f) and flexibility index (FI) increased with an increase in the emulsion content and decreased with an increase in the cement content (Charmot et al. 2017). Although some researchers have employed the indirect tensile asphalt cracking test (IDEAL-CT) and the cracking resistance index (CTIndex) to evaluate cracking resistance of cold recycled asphalt mixtures (Diefenderfer et al. 2019, Dong and Charmot 2019), no investigations have been conducted to verify or revise the index. This indicates the need to further investigate the validity and applicability of IDEAL-CT and its corresponding cracking index to cold recycled asphalt mixtures.

2. Objectives

This study aimed to improve the current understanding of the mechanical behavior of cold recycled asphalt mixtures and optimize its performance using fiber-reinforcement. Firstly, it investigated the applicability and validity of the CTIndex for cold recycled asphalt mixtures based on which revised indices were introduced. Secondly, the effects of polypropylene, A-glass, para-aramid and polyester synthetic fibers on the mechanical properties of cold recycled asphalt mixtures with and without cement were evaluated. Testing was performed using different percentages and lengths of fiber to determine the optimum amounts. This study assessed the effects of the addition of cement on the optimum fiber-reinforced mixtures using the IDEAL-CT, dry and wet ITS and I-FIT tests.

3. Materials and Methods

3.1. Materials and sample preparation

The cold recycled asphalt mixtures were prepared with 100% RAP, as employed in a previous field project, without virgin aggregate or additional fillers. The RAP had a nominal maximum aggregate size (NMAS) of 19 mm and met the medium gradation band of AASHTO MP31 (AASHTO 2022a). Fig. 1 shows the RAP gradation as well as the acceptable band. The asphalt content of RAP was found to be 3.5% and 4.1% using centrifuge extraction (ASTM 2024) and ignition method (AASHTO 2022b) tests, respectively. The stabilizing agent was CSS-1h emulsified asphalt with 63% asphalt residue produced from a PG 64-22 base binder. Polypropylene (PP), A-glass (GL), para-aramid (AR) and polyester (PE) synthetic fibers were used to reinforce the cold recycled mixtures.

Table 2 shows the physical and mechanical properties of the fibers used in this study. All fiber types were introduced in the form of loose filaments. The hydraulic cement used was Type III Portland cement classified based on ASTM C150 (ASTM 2022). SBR latex with the properties listed in Table 3 was also used in mixtures containing cement.

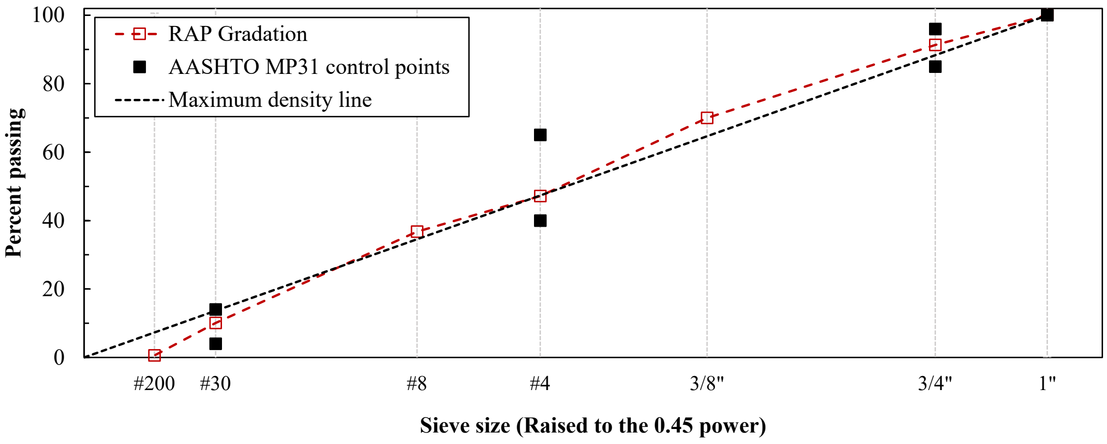


Fig. 1. Gradation of RAP aggregate used in this study

Table 2. Physical and mechanical properties of fibers

Properties	Poly-propylene (PP)	A-glass (GL)	Para-aramid (AR)	Polyester (PE)
Length (mm)	12, 18	12, 18	19	12
Diameter (μm)	35	22	-	-
Tensile strength (MPa)	350-400	3000	3100	-
Elastic modulus (GPa)	3-3.5	70	85	-
Tenacity (cN/dtex)	-	-	-	6.5
Elongation (%)	20	-	-	9.89
Density (g/cm^3)	0.91	2.6	1.44	0.95

Table 3. Properties of SBR latex (Some et al. 2020)

Properties	Standard	Unit	Value
Solid polymer	ISO 3251	%	65.6-66.5
pH value	ISO 976	--	4-5
Viscosity	ISO 1625	mPa.s	<2000

A previous study using the same materials, laboratory equipment and methods as in the current study determined the optimum asphalt emulsion and total water content (i.e., the sum of water present in the asphalt emulsion and added water) to be 6% and 3%, respectively, by weight of RAP (Nikfarjam 2020). With the addition of 2% cement, the optimum asphalt emulsion and total water contents were found to be 4.5% and 4%, respectively (Nikfarjam 2020). These optimum values were utilized in the current study.

To achieve the best dispersion of fibers in the mixtures, several trials were performed and the following method was selected: First, the loose fiber filaments were manually disentangled to enhance their uniform distribution. Next, the fibers and dry RAP were mixed for 30 s. Pre-mixing water was then added and mixed for 60 s. Emulsified asphalt was then added and mixed for an additional 60 s. For mixtures containing cement, cement was added in the final step and mixed for 30 s.

Emulsified asphalt was modified for mixtures containing cement by adding 4% latex (ratio of the weight of the dry polymer of latex to the residue of emulsified asphalt) and 0.5% sulfur (by the weight of the dry polymer of latex) at 70°C and mixed for 30 min using a low-shear mixer. These values had been determined in a previous study using the same materials, laboratory equipment and methods as in the current study based on the rheologic properties of the binder (Nikfarjam 2020).

Fibers of different lengths and contents were used, as shown in Table 4, based on the typical values in the literature and laboratory evaluations. Mixing was difficult with the 0.3% PP and PE fiber contents; thus, contents greater than 0.3% were not pursued. Similarly, 0.2% AR fibers resulted in "balling" of the fibers; thus, contents greater than 0.1% were not tested. The optimum fiber lengths and contents were determined and then used in the next part of the study to evaluate the combined effects of the fibers and cement.

Table 4. Lengths and percentages of fiber used in the first part of study

Properties	Poly-propylene (PP)	A-Glass (GL)	Para-Aramid (AR)	Polyester (PE)
Length (mm)	12, 18	12, 18	19	12
Contents (% by weight of RAP)	0.1, 0.2, 0.3	0.1, 0.2, 0.3	0.05, 0.1	0.1, 0.2, 0.3

3.3. Methods

3.3.1. ITS

Dry and wet ITS tests were performed on 100 mm in diameter Marshall specimens at 25°C and a 50 mm/min loading rate according to ASTM D6931 (ASTM 2017) and AASHTO PP86 (AASHTO 2021). After mixing, the asphalt mixtures were compacted using 75 blows of a Marshall hammer, were extruded from the molds after 1 h and then were cured for 48 h in a forced draft oven at 60°C. This was sufficient to achieve a constant weight. Next, the samples were cooled at 25°C for 24 h. Wet ITS samples were conditioned at 25°C for another 24 h before testing. The curing protocol was selected based on the standard procedures outlined in Section 8.5 of AASHTO PP86 (AASHTO 2021) and practicality considerations. The indirect tensile strength ratio (ITSR) is defined as the ratio of conditioned ITS to dry ITS and is used to evaluate the moisture resistance of samples.

3.3.2. Illinois flexibility index test (I-FIT)

I-FIT was performed according to AASHTO T393 (AASHTO 2022c) at 25°C and a 50 mm/min loading rate. After mixing, the cold recycled mixtures were compacted with 30 gyrations of the Superpave Gyratory Compactor (SGC) to produce cylindrical samples with a diameter of 150 mm and a height of 160 mm. Compacted samples were then cured for 72 h in a forced draft oven at 60. This curing duration was found to be sufficient to achieve constant mass and was also practical for laboratory scheduling. Following curing, the samples cooled at 25°C for another 72 h before testing. Two cylindrical 50-mm thick discs (which produced four semicircular specimens) were obtained from the middle of each SGC sample as per AASHTO T393 (AASHTO 2022c). A total of 8 semicircular samples were tested for each case and the average values of the fracture energy (G_f) and flexibility index (FI) were calculated as shown in Eqs. (1) and (2), respectively.

$$G_f = \frac{W_f}{Area_{lig}} \times 10^6 \tag{1}$$

$$FI = \frac{G_f}{|m|} \times 0.01 \tag{2}$$

where FI is the flexibility index, G_f is the fracture energy (J/m^2), $|m|$ is the absolute value of the slope at the inflection point (kN/mm), W_f is the work of fracture (the area under the load-displacement curve (J) and $Area_{lig}$ is the ligament area (ligament length × specimen thickness (mm^2).

3.3.3. IDEAL-CT

The IDEAL-CT test was performed according to ASTM D8225 (ASTM 2019) which evaluates the crack resistance based on the CTIndex, a fracture mechanics–based parameter. The higher the index value, the greater the crack resistance expected for the asphalt mixture. Samples for the IDEAL-CT test were prepared following the same procedure as the ITS samples—that is, 100 mm Marshall specimens compacted with 75 blows and cured in a forced-draft oven at 60 °C for 48 hours. The test was performed at 25 °C using a loading rate of 50 mm/min. The calculation of CTIndex is meant to be performed near the most critical point: the inflection point of the post-peak side of the load-displacement curve (Zhou 2019). At this point, stiffer and more brittle materials have a higher slope; therefore higher rate of deterioration and less resistance towards cracking. Inflection point is difficult to accurately determine as it requires smoothing and fitting of the data points (Zhou 2019). IDEAL-CT developers have examined more than 200 HMA load-displacement curves with the approach proposed by Al-Qadi et al. (Al-Qadi et al. 2015) for the I-FIT (Zhou 2019). They found the average ratio of the load at the inflection point to the peak load to be about 0.75 with a standard deviation (SD) of 0.05. Therefore, the range of data pertaining to 0.85 to 0.65 for the peak load on the post-peak side of the curve has been suggested for use when calculating the CTIndex (Eqs. (3) through (5)) (Zhou 2019). In these equations, $|m_{75}|$ has been calculated using a linear regression between P_{85} and P_{65}. Fig. 2 shows the parameters of the load-displacement curve used for the calculation of CTIndex (Zhou 2019).

$$CT_{index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \tag{3}$$

$$G_f = \frac{W_f}{D \times t} \times 10^6 \tag{4}$$

$$|m_{75}| = \left|\frac{P_{85} - P_{65}}{l_{85} - l_{65}}\right| \tag{5}$$

where t is the specimen thickness (mm), l_{75}, l_{85}, l_{65} are the displacement at 75%, 85% and 65% of the peak load after the peak, respectively (mm), P_{85}, P_{65} are 85% and 65% of the peak load (mm), respectively, D is the specimen diameter (mm), G_f is the failure energy (J/m^2) and W_f is the work of failure (J).

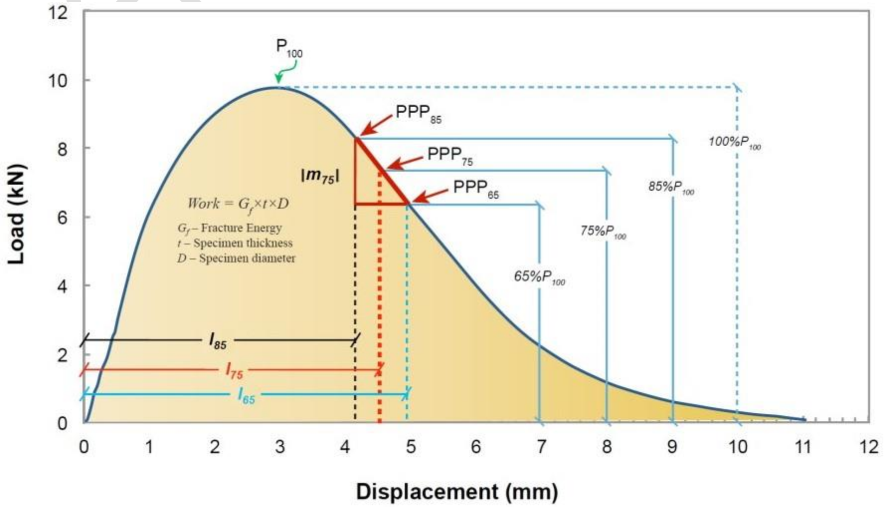


Fig. 2. IDEAL-CT load-displacement curve and its parameters, (adapted from (Zhou 2019))

In the current study, an investigation of the location of the inflection point for cold recycled mixtures was performed. Based on the results, two revised indices were proposed for cold recycled mixtures.

3.4. Mixture naming convention

As the effects of the addition of fibers on the properties of cold recycled mixtures with and without cement were the goal of the study, two control mixtures were defined. Mixture 6E was the base control mixture containing 6% emulsified asphalt and 3% total water without other additives. Mixture 4.5ME2C was the cementitious control mixture containing 4.5% emulsified asphalt (modified using latex and sulfur), 4% total water and 2% cement. The mixture naming convention for those containing fibers is shown in Eq. (6).

$$X + \alpha Y \beta \tag{6}$$

where X is the control mixture (either 6E or 4.5ME2C), α and β are the fiber content (by weight of RAP) and fiber length (mm), respectively, and Y is the fiber type (PP, GL, AR, PE). For example, "6E+0.1PP12" is the base mixture with 6% emulsified asphalt reinforced with 0.1% polypropylene fiber with a length of 12 mm.

4. Results and Discussion

Sample preparation and mix design in this study followed AASHTO MP-31(AASHTO 2022a) and AASHTO PP-86 (AASHTO 2021) without controlling the air voids. However, total air voids of IDT and IDEAL-CT samples were measured for comparison. Total air voids were 13.8 and 13.3% for base control mixture and cementitious control mixture, respectively. All the samples having synthetic fibers, with and without cement, had air voids in the range of 12.2% to 13.4%. Air voids were mostly within one percent of the respective control mix, minimizing the effects of varying volumetric properties on the performance of mixtures.

4.1. Validity of I-FIT and IDEAL-CT

Analysis of I-FIT results following the AASHTO T 393 procedure (AASHTO 2022c) involves fitting two separate curves to the load–displacement data. A sixth-degree polynomial is fitted to the pre-peak portion of the curve, while a four-term Gaussian function is applied to the post-peak data. While the polynomial fitting is relatively straightforward, the Gaussian fitting requires more complex calculations to determine the coefficients, as described in Eq. (7).

$$P_2(u) = \sum_{i}^{n=4} d_i \, exp\left[-\left(\frac{u - e_i}{f_i}\right)^2\right] \tag{7}$$

Where $P_2(u)$ is the post-peak load, u is displacement, and d,e, and f are fitting coefficients. Upper and lower bounds of +10 and –10 are assigned to the coefficients d and e. Lower bound for the coefficient f governs the first derivative of the fitted curve and can produce abnormal slope values if not carefully selected. To find the optimum value of f, an iterative approach is used by testing a descending set of candidate values: $f_{\text{bounds}} = \{0.9, 0.7, 0.5, 0.3, 0.1, 0.05, 0.01, 0.005, 0.001\}$. The process continues until a value of f is found that satisfies three predefined, visually based fitting criteria.

The initial investigation of the I-FIT data followed AASHTO T393 procedure (AASHTO 2022c) and showed that the minimum required coefficient of determination (R^2) of 0.997 specified by the post-peak fitting curve cannot be achieved in most cases, especially for samples containing cement. Therefore, a program was developed using MATLAB software where, instead of specifying a minimum R^2, all the values of f_{bounds} were investigated to determine which f-value resulted in the maximum R^2. This f-value then was used to determine the inflection point. If that inflection point passed the three visual-based criteria mentioned in the specification, the program calculated the G_f and FI values. If no appropriate inflection point was found, the f-value corresponding to the second highest R^2 was used and the process was repeated. This process continued until a proper inflection point was found.

Table 5 shows the average maximum R^2 achieved for samples with and without cement. As shown, the average value for all samples was 0.9883, which is less than the minimum required value of 0.997 in the specification. This suggests the need to define a new minimum acceptable R^2 for cold recycled asphalt mixtures.

Table 5. Average maximum R^2 for post-peak fitting curves in I-FIT test

Test conditions	Total number of samples	Average R^2	SD of maximum R^2
without cement	36	0.9963	0.0034
with cement	36	0.9803	0.0245
all samples	72	0.9883	0.0191

No inflection point was found for eight of the samples containing cement (out of 36 samples). Fig**. 3** shows the load versus displacement for a sample with inflection point compared to one without. These observations suggest the need for exploring alternative performance indices or revising the existing test methods and parameters for cold recycled asphalt mixtures containing cement.

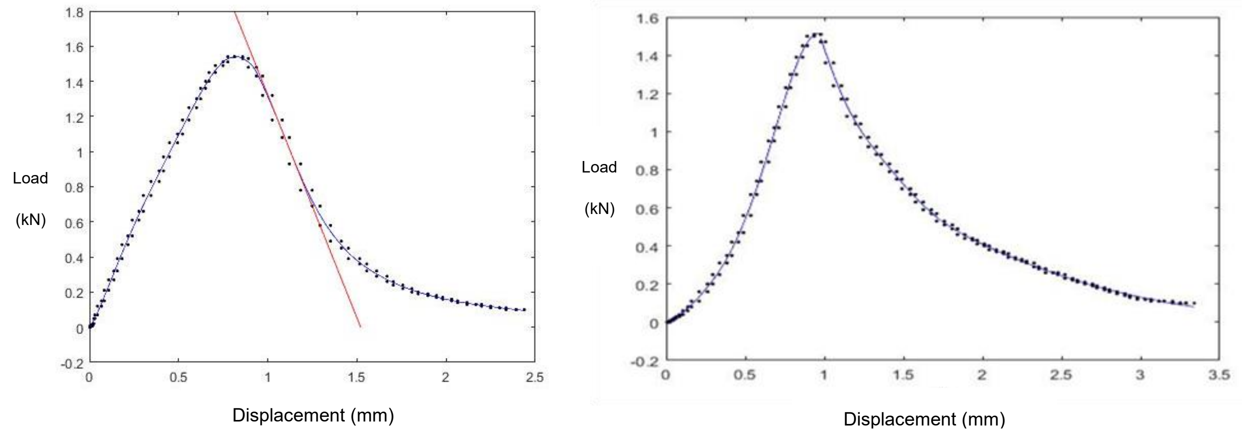


Fig. 3. I-FIT load-displacement of two sample with and without inflection point

For samples missing and inflection point, FI was not calculated; however, G_f, which does not rely on the inflection point, has been used for comparison. As for IDEAL-CT, the current CTIndex equations are based on studies performed on HMA and no thorough investigation of the assumptions regarding the location of the inflection point for cold recycled mixtures has been carried out.

In the current study, 52 cold recycled samples without cement were evaluated to determine the location of the inflection point using the procedure proposed by Al-Qadi et al. [38] which also has been used by the developers of IDEAL-CT (Zhou 2019). Table 6 summarizes the locations of inflection points for samples without cement with and without fiber. As seen, without cement, the addition of fibers did not noticeably affect the load at the inflection point to the peak load ratio. The average ratio was approximately 0.85 which is 0.10 higher than the value suggested by current IDEAL-CT specifications (0.75), yet a similar SD was obtained for the ratio. It appears that, for cold recycled mixtures without cement, a 0.75% to 0.95% peak load range can provide a more reasonable and effective measure for evaluating the cracking resistance. The range of 0.65 to 0.85 formulated in the CTIndex equation would underestimate the slope and, consequently, provide a less accurate measure of the cracking resistance of the cold recycled mixtures.

Table 6. Location of inflection point for samples without cement

Sample description	Total number of samples	Load at inflection to peak ratio	
		Average	SD
without fiber (samples with 3% total water and emulsified asphalt contents from 1.5% to 6.5%)	16	0.8364	0.0604
with fiber (4 fiber contents of 0.05% to 0.3%)	36	0.8471	0.0482
all samples	52	0.8438	0.0519

Based on these results, for cold recycled asphalt mixtures, a revised index called the "cold recycling crack tolerance" (CTCR), is proposed as shown in Eq. (8). This index is essentially similar to CTIndex, except that l_{75} and $|m_{75}|$ have been replaced by l_{85} and $|m_{85}|$, respectively.

$$CT_{CR} = \frac{t}{62} \times \frac{l_{85}}{D} \times \frac{G_f}{|m_{85}|} \times 10^6 \quad (8)$$

where l_{85} is the displacement at 85% of the peak load after the peak (mm) and $|m_{85}|$ is the absolute value of the slope of the regression line for all points between P_{85} and P_{65}.

In order to compare CTCR and CTIndex, the exact inflection point was determined for each sample using the method explained in AASHTO T393 (AASHTO 2022c) and was used to calculate the CTAnalytical. The results are shown in Table 7. As seen, CTAnalytical had the lowest SD and coefficient of variation (COV) among all indices. This could possibly be due to the assumption-free formula; however, its calculation is more complicated than CTCR and CTIndex, which makes it harder to implement for general purposes. The results show that CTIndex was higher by about 43% compared to CTAnalytical results, which caused overestimation of the cracking resistance. Although the SDs and COVs were similar for CTCR and CTIndex, the former led to a notably lower average difference than CTAnalytical and outperformed the traditional CTIndex. Given the complexity of calculations for CTAnalytical, CTCR is recommended for evaluation of cold recycled mixtures without chemical additives.

Table 7. Comparison of CTCR and CTIndex

Sample description	Average SD	Average COV (%)	Average difference from CTAnalytical (%)	Total number of samples
CTAnalytical	12.6	25.4	-	52
CTIndex	23.8	26.2	43.2	
CTCR	19.1	28.1	7.7	

Fig. 4 visually compares the results for CTCR and CTIndex with CTAnalytical for mixtures without cement using the line of equity. The results show consistently higher CTIndex values and greater departures from the line of equity compared to CTCR, further demonstrating the effectiveness of CTCR in minimizing the overestimation that arose using CTIndex.

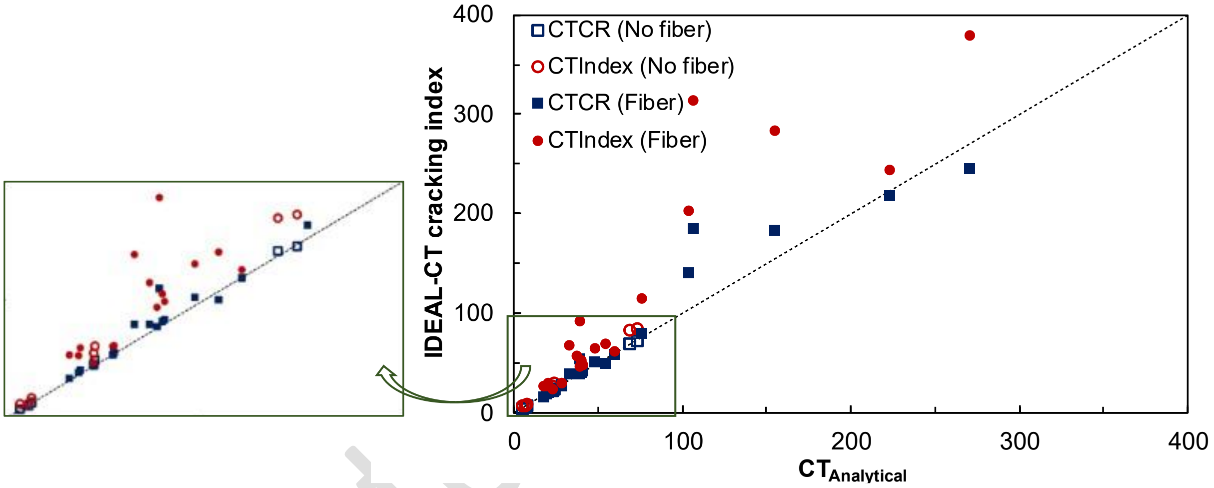


Fig. 4. CTCR vs. CTIndex with CTAnalytical for mixtures without cement

The same approach was used for mixtures containing cement to find the location of the inflection point. Evaluations showed that more than half of the samples containing cement did not show any acceptable inflection point. For these samples, a value of 1.0 was assigned as the ratio of the load at the inflection point to the peak load. Table 8 reveals that samples containing cement at different emulsion contents altered the inflection point position compared to samples without cement. The samples either had no inflection point or had one that was much closer to the peak load (average ratio of 0.9350) compared to the samples without cement. The results in Table 6 and Table 8 also reveal that samples with cement showed greater variability of this ratio compared to samples without cement. Based on these results and considering the scope and limitations of the current study, CTIndex and similar indices that rely on the determination of an inflection point appeared to not be able to assess the performance of cold recycling mixtures containing cement. It appears that failure energy is the best indicator of cracking resistance in the IDEAL-CT test for cold recycled samples with cement.

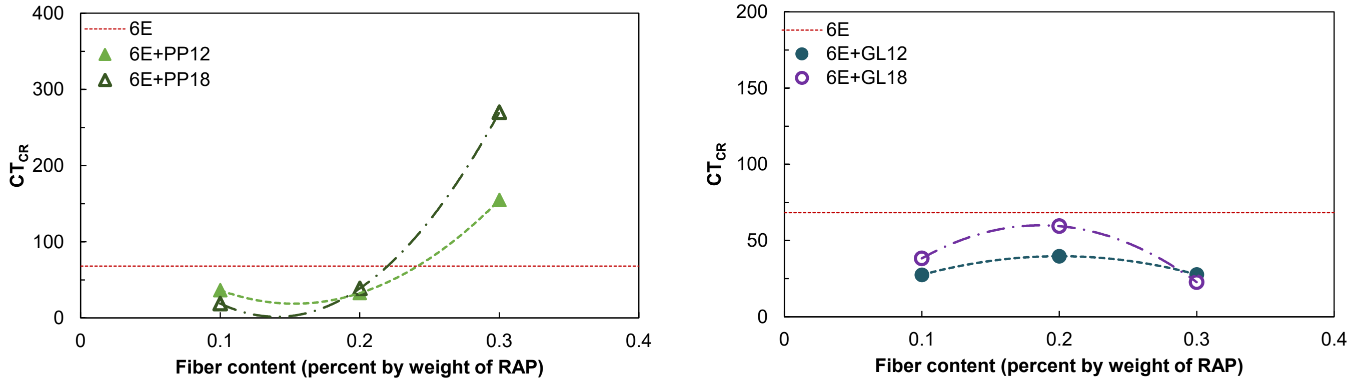
Table 8. Location of inflection point for samples containing cement

Sample description	Total number of samples	Load at inflection to peak ratio	
		Average	SD
without fiber (samples with 3% and 4% total water, emulsified asphalt contents of 1.5% to 6.5% and 2% cement)	14	0.9019	0.1303
with fiber (4 fiber contents added to cementitious control mixture)	12	0.9737	0.0636
all samples	26	0.9350	0.09952

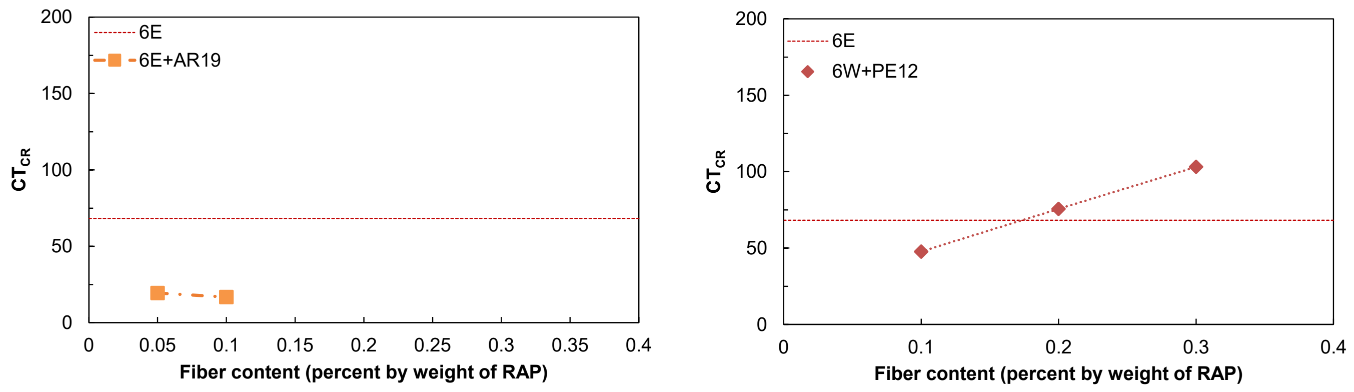
The results provided here are limited in scope and testing and should not be generalized. Further evaluations are required using different cold recycling mixtures representing a wider range of mix design variables, as well as comparison with field observations, to determine which index can most reliably measure the cracking resistance of cold recycled mixtures.

4.2. Effect of fibers on the properties of cold recycling mixtures (without cement)

Fig. 5 and Fig. 6 show the IDEAL-CT results for cold recycled mixtures (without cement) reinforced with four types of synthetic fiber. The CTCR results in Fig. 5 show that the addition of optimum length and contents of PP and PE fibers increased the crack resistance of the mixtures. The results also suggest that the cracking resistance of the cold recycled asphalt mixtures was sensitive to the fiber length and content. Based on Fig. 5, the best cracking performance for PP and PE was obtained with 0.3% fiber; both outperformed the control mixture. However, GL showed the best results at 0.2% and AR either caused the mixture performance to decline or show no improvement. It was also observed that the use of 18-mm PP and GL fibers produced better CTCR results than the 12-mm fibers. Lower optimum content for GL and AR suggests that lower % elongation of fibers might play an important role in activating the fibers quicker.



(a) (b)

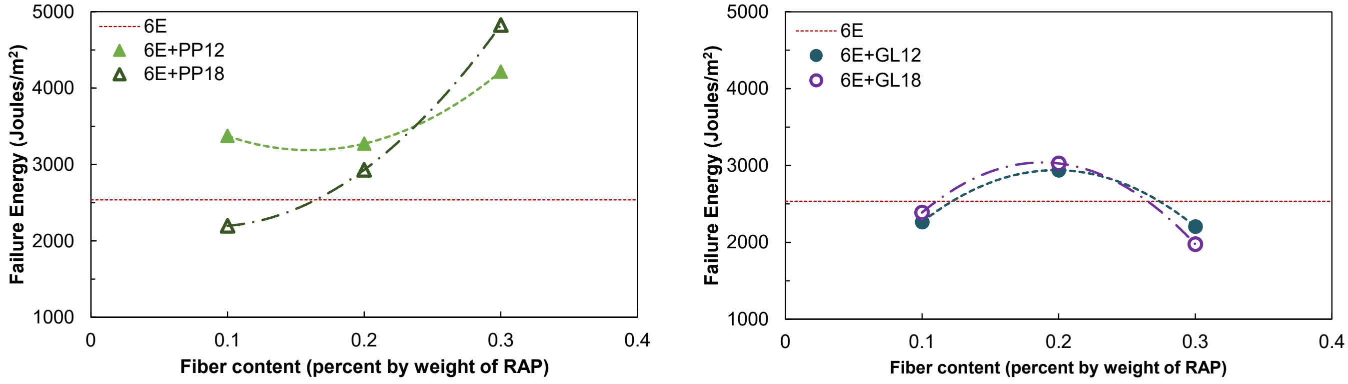


(c) (d)

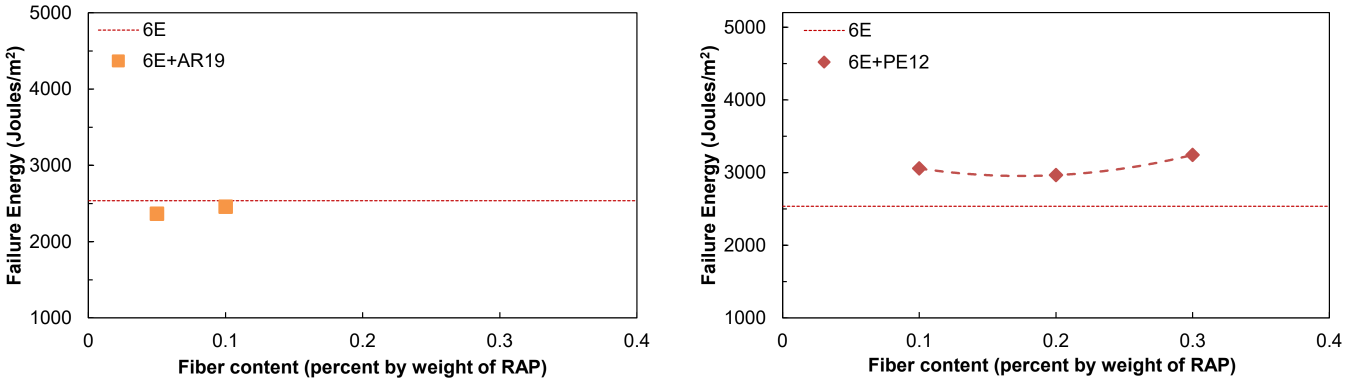
Fig. 5. CTCR results for mixtures containing: (a) PP fibers; (b) GL fibers; (c) AR fibers; (d) PE fibers

Fig. 6 shows the IDEAL-CT failure energy results for cold recycled mixtures (without cement) reinforced with one of the four types of synthetic fiber. The results indicated that good agreement exists between the CTCR and failure energy, as their overall trends were similar with greater sensitivity to the fiber length and content for CTCR. Greater fiber lengths and contents generally tended to produce higher failure energy values, but the results were strongly dependent on the type of fiber. Overall, within the range of contents and lengths used in this study, greater lengths and contents seem to be more effective for improving the cracking resistance of cold recycled mixtures based on the IDEAL-CT data.

Moreover, for the same fiber contents, the ratio of failure energy of the mixes with fibers and the base control mix is higher than the ratio of the CTCR. I should conclude that the slope of the curves in the post-peak section is different between the mixes with and without fibers



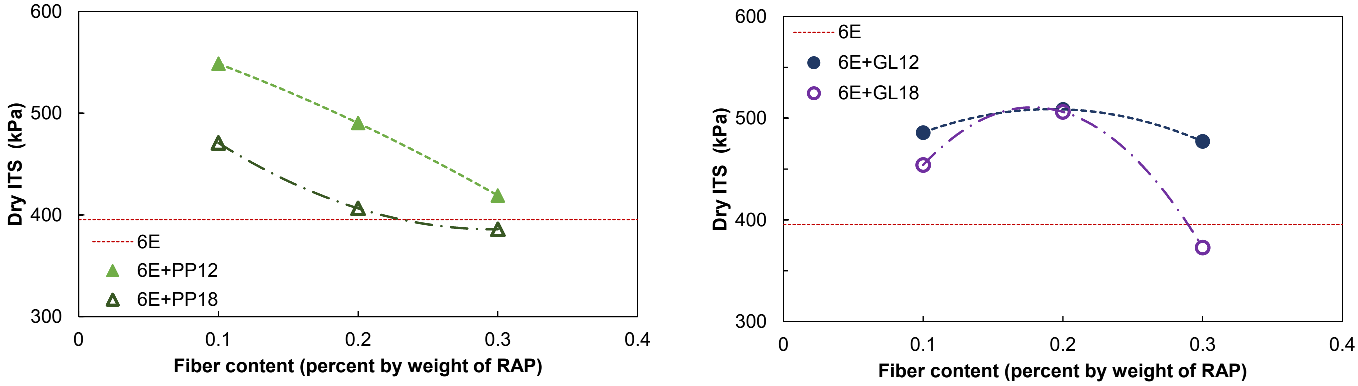
(a) (b)



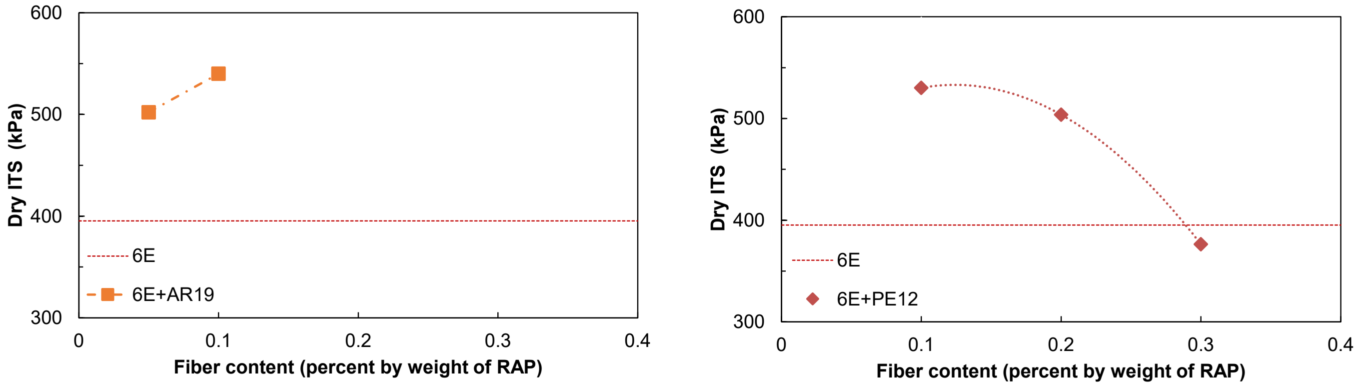
(c) (d)

Fig. 6. Failure energy for mixtures containing: (a) PP fiber; (b) GL fiber; (c) AR fiber; (d) PE fiber

Fig. 7 shows the dry ITS results for mixtures containing different types of fiber. Although a few combinations of variables showed slightly lower results than the base control mixture (6E), the addition of fiber generally improved the dry strength. The optimum results for GL occurred at 0.2% for both lengths tested. However, the best results for all other types of fiber were obtained at 0.1%, which is the lowest content tested for PP and PE. The greatest increase compared to the base control mixture was about 40% with the addition of 0.1% 12-mm PP fibers. The ITS results followed a trend similar to that of the IDEAL-CT results for the GL fibers with the best results being achieved at a 0.2% content. However, the best ITS results for the PP and PE fibers occurred at lower contents and lengths, which contrasts with the trend observed in IDEAL-CT. As expected, the cracking resistance and strength are competing properties and both should both be considered to determine the optimum fiber content and length.



(a) (b)

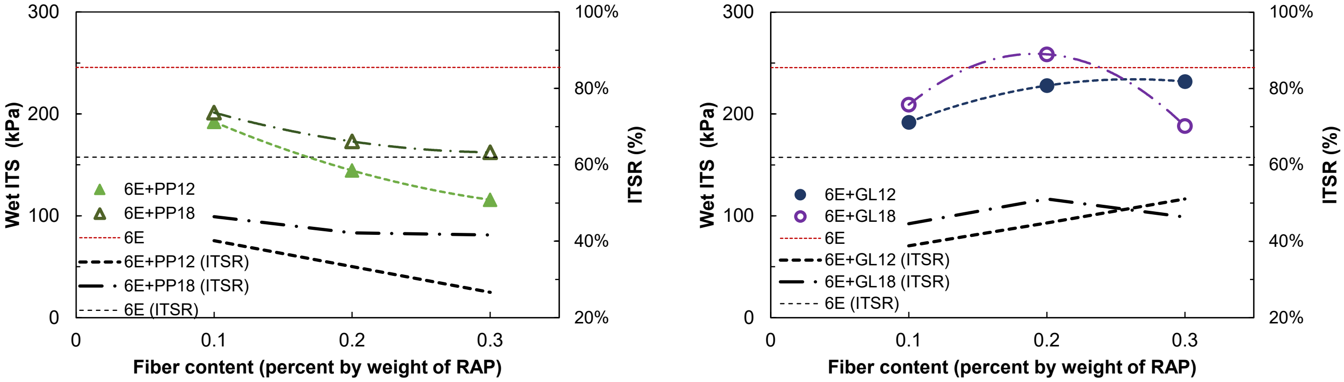


(c) (d)

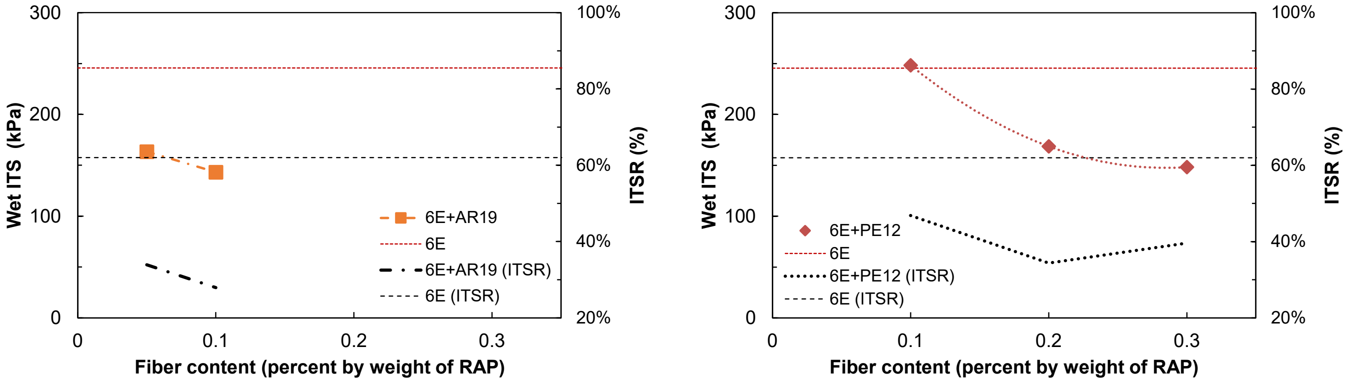
Fig. 7. Dry ITS results for mixtures containing: (a) PP fiber; (b) GL fiber; (c) AR fiber; (d) PE fiber

Fig. 8 provides the wet ITS and ITSR results for different fiber types. The results suggest that the fibers generally either caused a decrease in the wet strength of the cold recycled asphalt mixtures or resulted in similar performance compared to the base control mixture (6E). This brings up concerns regarding the moisture resistance of these mixtures. GL fibers generally showed the best moisture resistance among the fibers tested. Also, lower fiber contents and greater fiber lengths generally increased the moisture resistance compared to greater fiber contents and lower fiber lengths.

Because the addition of fibers generally increased the dry strength of the mixtures, the ITSR values were also expected to decrease in the presence of fibers. Fig. 11 shows that the ITSR values were mostly below 50% and were all lower than the ITSR for the base control mixture (62%). It could be concluded that the addition of these types of fiber to the cold recycled asphalt mixtures should increase the moisture susceptibility of the mixtures.



(a) (b)



(c) (d)

Fig. 8. Wet ITS results for mixtures containing: (a) PP fiber; (b) GL fiber; (c) AR fiber; (d) PE fiber

The optimum lengths and contents of the fibers were determined by considering IDEAL-CT as well as the dry and wet ITS results. In the case of GL fibers, selecting the optimum content was simple as the best IDEAL-CT and ITS results were obtained at 0.2%. The optimum length for GL fibers was 18 mm because it produced the best CTCR and wet ITS values that were similar to the dry ITS results for 12-mm fibers.

For AR fibers, 0.1% was selected as the optimum content because of the increase in dry strength and similar cracking resistance compared to the other content tested. For PP and PE, although the best dry and wet strengths were obtained at 0.1% fiber content, better crack resistance was achieved at 0.3%. The base control mixture already met the minimum dry ITS requirement of 310 kPa in accordance with AASHTO MP31 (AASHTO 2022a) and the use of cement, which is inevitable in many cases, is expected to improve the strength and moisture resistance. Therefore, improving the cracking resistance was more important, especially with cement. As such, 0.3% was selected as the optimum content of the PP and PE fibers. Similarly, 18 mm was selected as the optimum length of the PP fibers. Table 9 summarizes the optimum contents and lengths of the fibers tested.

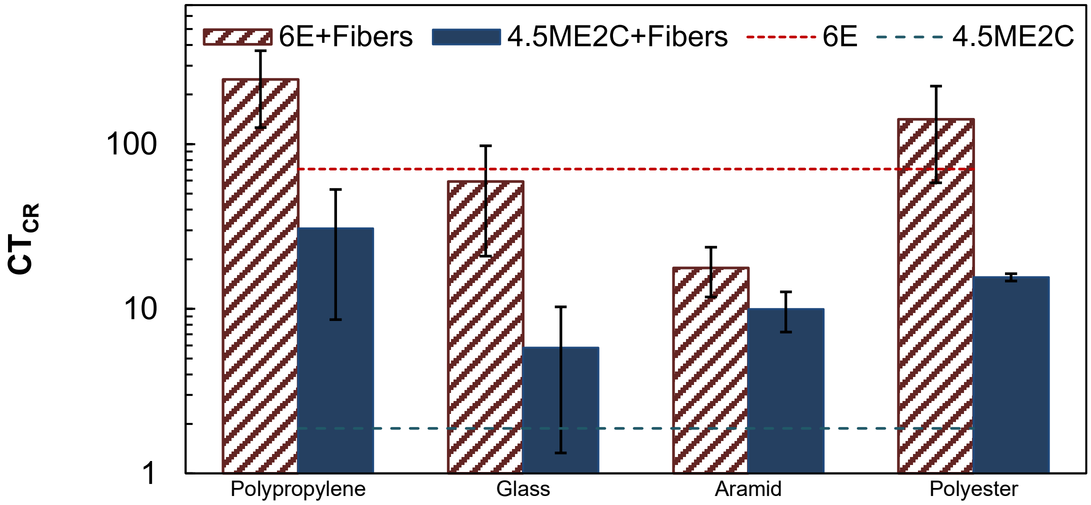
Table 9. Optimum contents and length of fibers

Properties	Poly-propylene (PP)	A-glass (GL)	Para-aramid (AR)	Polyester (PE)
optimum content (% by weight of RAP)	0.3	0.2	0.1	0.3
optimum length (mm)	18	18	19	12

4.3. Combined effect of fibers and cement

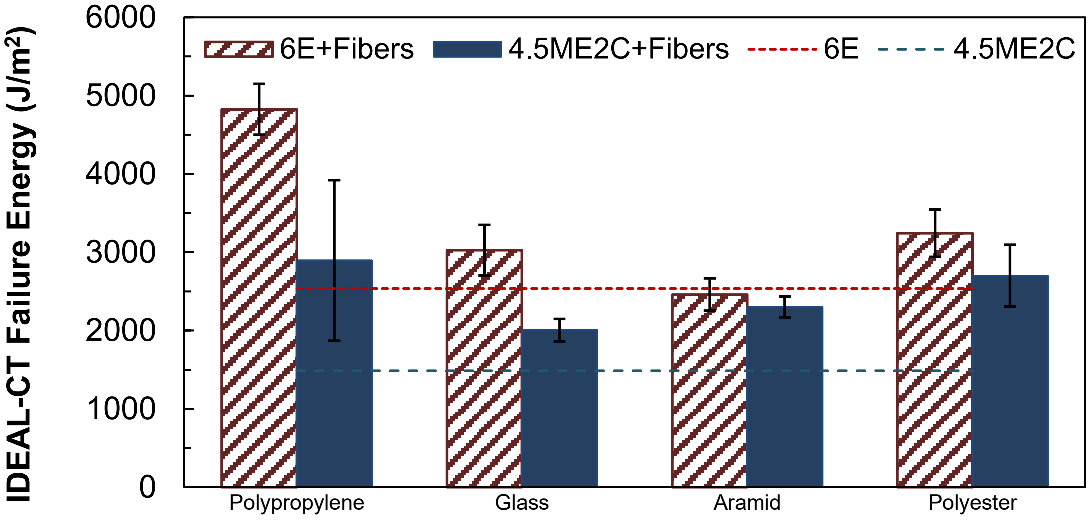
Fig. 9 and Fig. 10 show the CTCR (In a log scale) and failure energy results from the IDEAL-CT test for mixtures reinforced with the optimum fiber contents and lengths with and without cement. Error bars, where applicable, represent plus and minus one standard deviation. The CTCR and other indices which require inflection point determination cannot be reliably used to evaluate the cracking resistance of mixtures containing cement nor to compare the mixtures with and without cement. Therefore, this index has been used to only provide an overall comparison of mixtures without cement.

The results indicate that the addition of PP and PE fibers considerably increased the CTCR and failure energies compared to the base control mixture (6E). The addition of GL fibers increased the failure energy but decreased the CTCR. The addition of AR significantly decreased the CTCR. Compared to the cementitious control mixture (4.5ME2C), the combined use of fibers, cement, and SBR latex significantly improved the CTCR and failure energy for all types of fiber. The PP and PE fibers with cement and latex almost doubled the failure energy and significantly improved the CTCR compared to 4.5ME2C. These two mixtures resulted in an even higher failure energy than 6E, which had 1.5% more emulsified asphalt and no cement. It can be concluded that the combined use of additives might lead to decreased optimum emulsion content without compromising the failure energy and provide a more economical alternative.



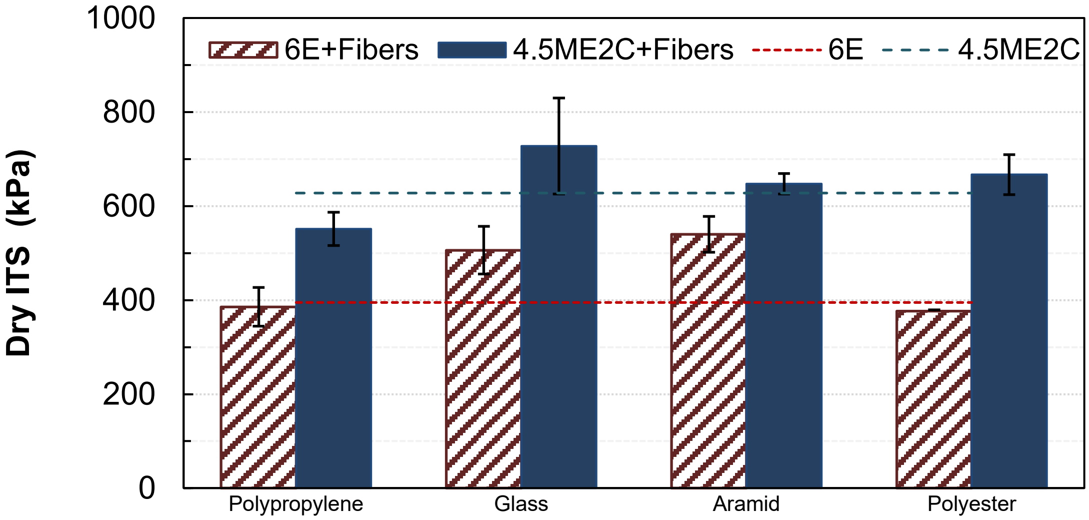
	Polypropylene	Glass	Aramid	Polyester
6E+Fibers	247.4	59.3	17.7	141.8
4.5ME2C+Fibers	30.8	5.8	10.0	15.5
6E	70.5	70.5	70.5	70.5
4.5ME2C	1.9	1.9	1.9	1.9

Fig. 9. CTCR for mixtures reinforced with different fibers with and without cement



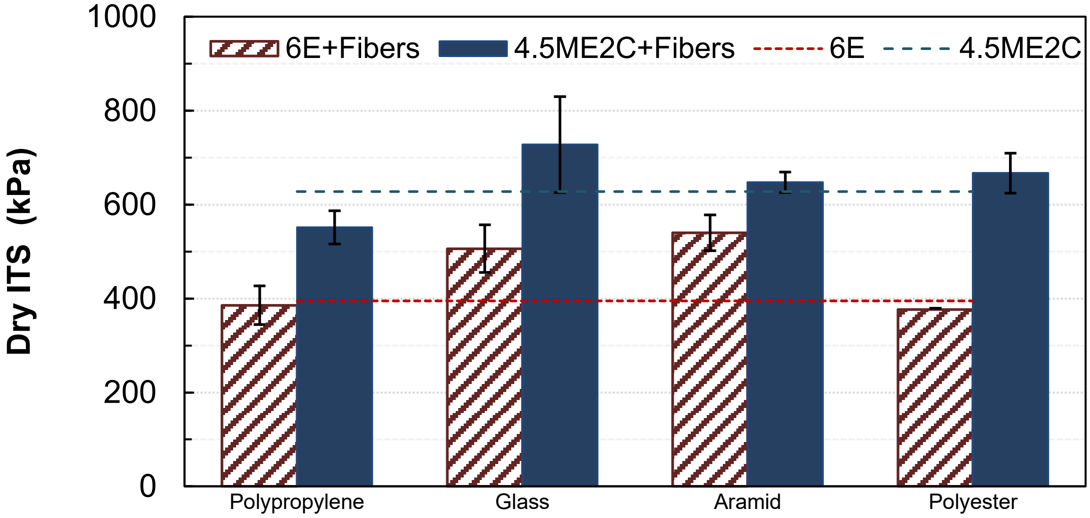
	Polypropylene	Glass	Aramid	Polyester
6E+Fibers	4824.8	3027.0	2459.0	3242.9
4.5ME2C+Fibers	2894.7	2005.6	2300.5	2700.7
6E	2535.7	2535.7	2535.7	2535.7
4.5ME2C	1487.9	1487.9	1487.9	1487.9

Fig. 10. Failure energy for mixtures reinforced by different fibers with and without cement



	Polypropylene	Glass	Aramid	Polyester
6E+Fibers	385.9	506.2	540.1	376.4
4.5ME2C+Fibers	551.5	728.1	647.7	667.2
6E	395.3	395.3	395.3	395.3
4.5ME2C	627.6	627.6	627.6	627.6

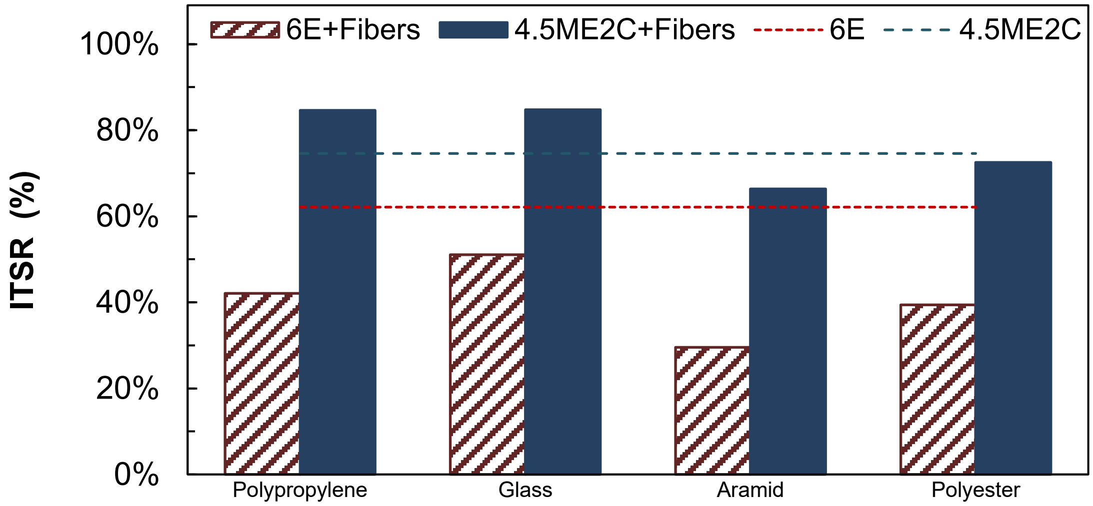
Fig. 11 shows the dry ITS results for mixtures with optimum fiber contents and lengths with and without cement. All mixtures showed similar or better strength values than the base control mixture (6E). Additionally, the combined use of fibers and cement increased the strength over that of the cementitious control mixture (4.5ME2C), except for PP fiber. Moreover, the combined use of fiber and cement increased the values considerably over that of 6E, which had 1.5% greater emulsified asphalt content. The results show that the use of fibers with or without cement can effectively increase the dry strength.



	Polypropylene	Glass	Aramid	Polyester
6E+Fibers	385.9	506.2	540.1	376.4
4.5ME2C+Fibers	551.5	728.1	647.7	667.2
6E	395.3	395.3	395.3	395.3
4.5ME2C	627.6	627.6	627.6	627.6

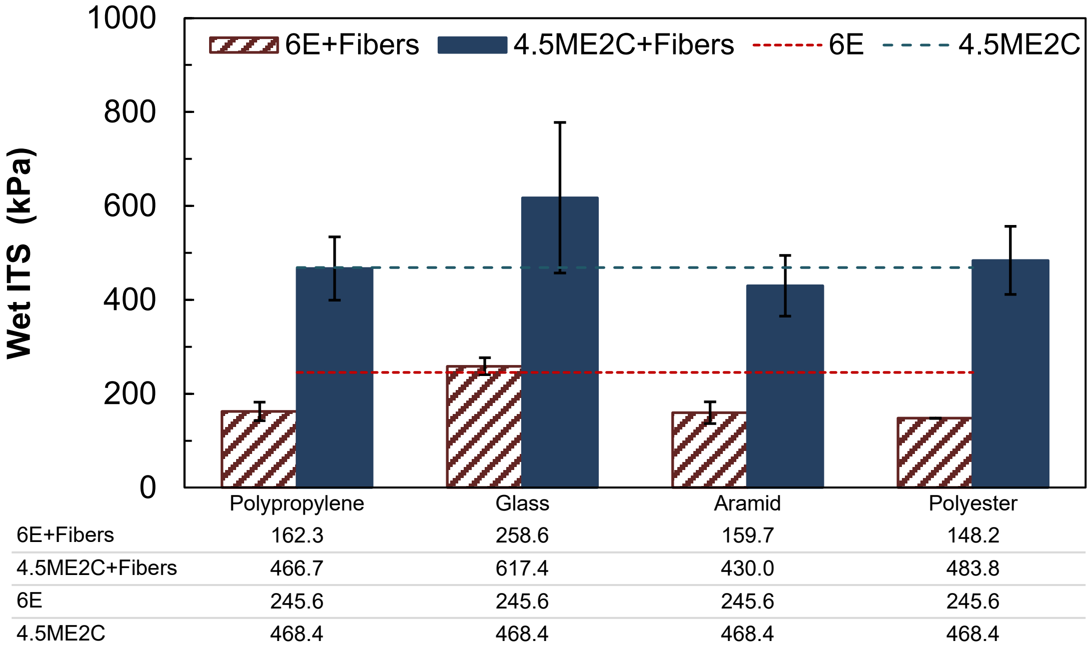
Fig. 11. Dry ITS for mixtures reinforced by different fibers and combined use of fibers and cement

The wet ITS and ITSR results for mixtures with optimum fiber contents and lengths with and without cement are shown in Fig. 12 and Fig. **13**. The mixtures with optimum fiber contents showed a lower wet strength than the base control mixture (6E), except for GL. The ITSR values were also below the value for 6E; however, the combined



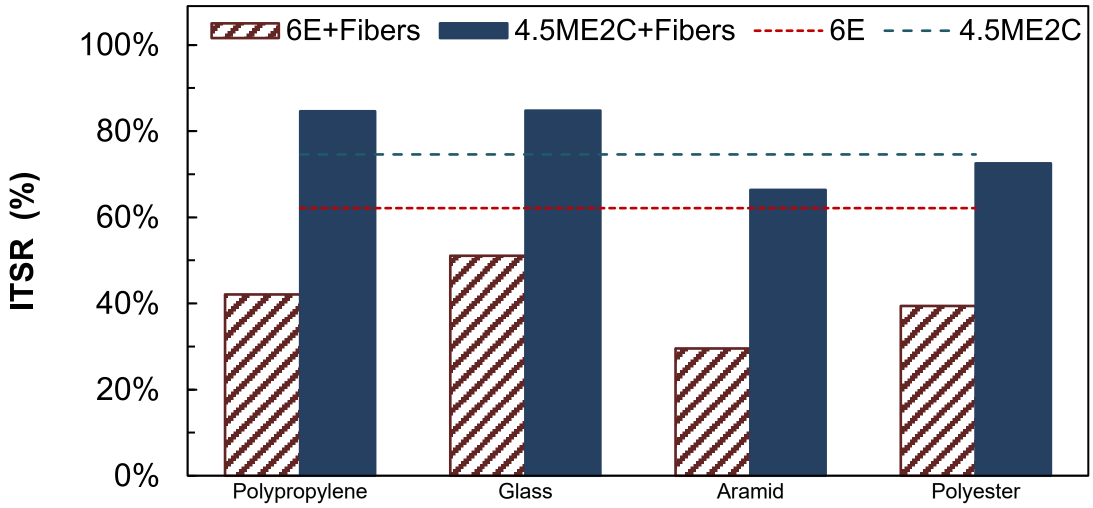
	Polypropylene	Glass	Aramid	Polyester
6E+Fibers	42.1%	51.1%	29.6%	39.4%
4.5ME2C+Fibers	84.6%	84.8%	66.4%	72.5%
6E	62.1%	62.1%	62.1%	62.1%
4.5ME2C	74.6%	74.6%	74.6%	74.6%

use of fibers and cement produced wet strength and ITSR values that were comparable to or better than the cementitious control mixture (4.5ME2C). This demonstrates the effectiveness of cement for improving the moisture resistance of mixtures containing fibers. The highest overall wet ITS and ITSR results corresponded to the mixture having GL fibers and cement. The wet ITS and ITSR results for the combined use of fibers and cement were considerably higher than for 6E, which had 1.5% greater emulsified asphalt content. The results show that the combined use of fibers and cement can effectively eliminate the increased moisture susceptibility of the mixture caused by the use of fibers.



	Polypropylene	Glass	Aramid	Polyester
6E+Fibers	162.3	258.6	159.7	148.2
4.5ME2C+Fibers	466.7	617.4	430.0	483.8
6E	245.6	245.6	245.6	245.6
4.5ME2C	468.4	468.4	468.4	468.4

Fig. 12. Wet ITS for mixtures reinforced by different fibers and combined use of fibers and cement



	Polypropylene	Glass	Aramid	Polyester
6E+Fibers	42.1%	51.1%	29.6%	39.4%
4.5ME2C+Fibers	84.6%	84.8%	66.4%	72.5%
6E	62.1%	62.1%	62.1%	62.1%
4.5ME2C	74.6%	74.6%	74.6%	74.6%

Fig. 13. ITSR for mixtures reinforced by different fibers and combined use of fibers and cement

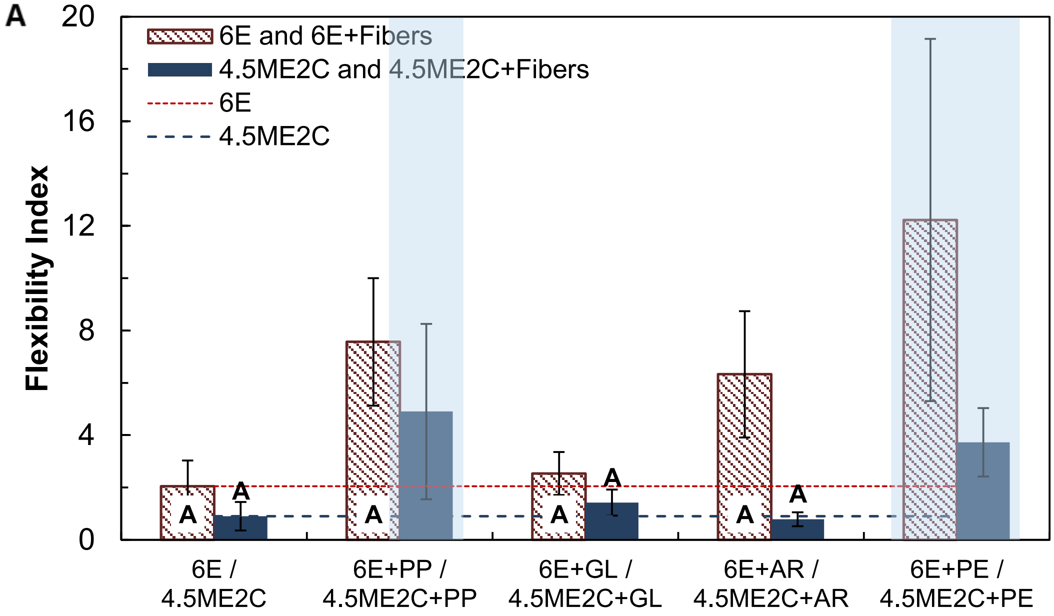
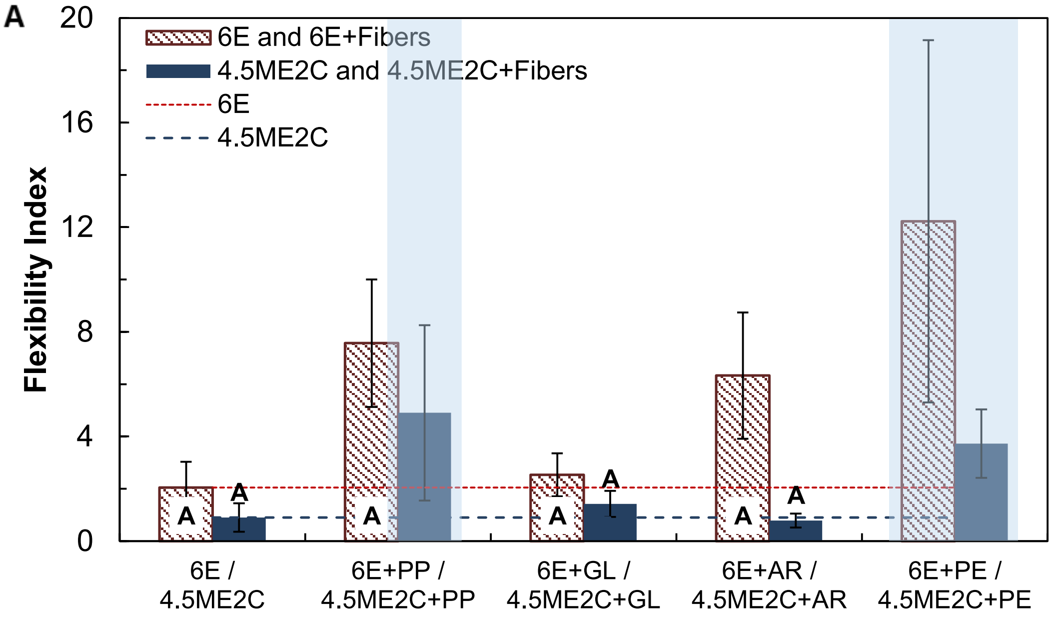
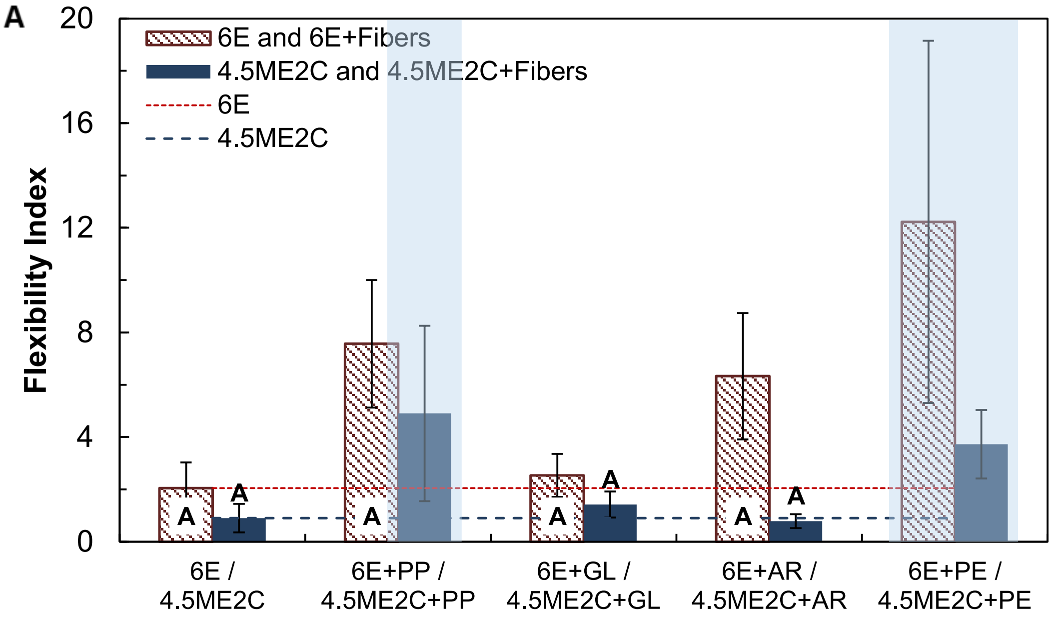


Fig**.** **14** and Fig. 15 show the I-FIT FI and fracture energy results of mixtures with optimum fiber contents and lengths with and without cement. Statistical analysis also was carried out to compare the results with and without cement. One-way analysis of variance (ANOVA) was used at a significance level of 0.05 ($\alpha = 0.05$) to detect statically significant differences assuming a normal population distribution for each factor level, similar variances and independent data. Dunnett's multiple comparison with a control test was carried out at a significance level of 0.05 to determine which mixtures had significantly different results from their respective control mixture (6E or 4.5ME2C). The groupings based on one-way ANOVA and Dunnett's multiple comparison tests are shown in Fig. **14** and Fig. **15**, where "A" represents the same statistical group as the respective control mixture. Mixtures without a letter and highlighted in blue represent the groups with statistically significant differences. Interpretation of results for samples containing cement requires caution, as eight out of the 36 tested samples did not exhibit inflection point and were therefore excluded from the analysis.





As Fig. **14** shows, without cement, PE showed the best overall results and was the only fiber achieving a significant difference from the base control mixture (6E). With the combined use of fiber and cement, all fibers except AR increased the average FI compared to the cementitious control mixture (4.5ME2C). PP and PE showed the best results, both of which were significantly different from the results for 4.5ME2C. The FI of these two mixtures were higher than those for 6E which had 1.5% greater emulsified asphalt content without cement.

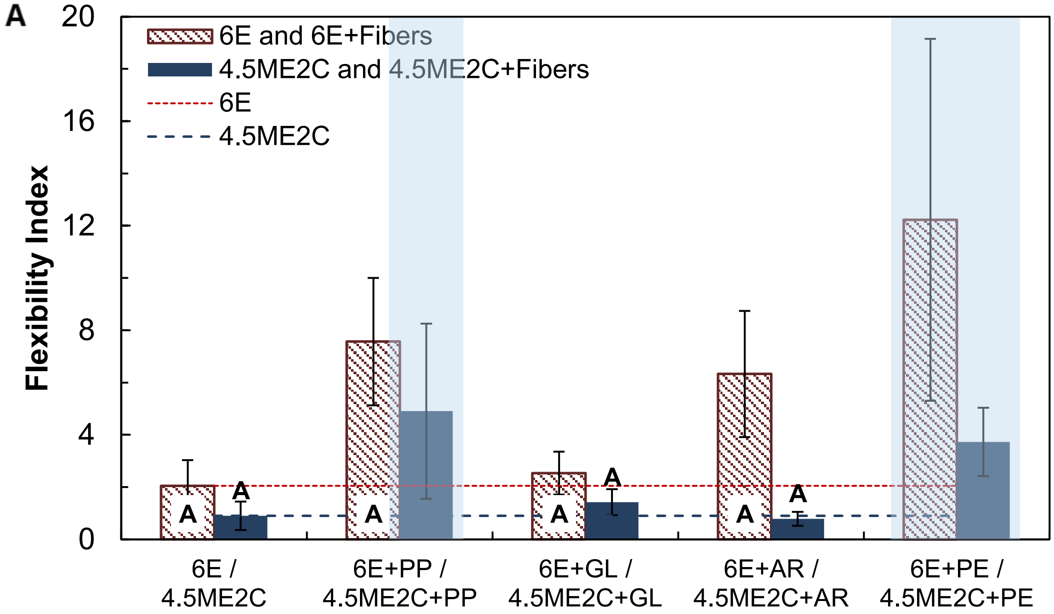


Fig. 14. I-FIT FI for mixtures reinforced by different fibers and combined use of fibers and cement

Fig. 15 presents the fracture energy results. For mixtures without cement, the results showed that adding PP and GL fibers caused a slight increase in fracture energy which was not statistically significant. The addition of AR and PE, on the other hand, increased the fracture energy significantly compared to the base control mixture (6E), showing the effectiveness of fibers in improving cracking resistance. As for the combined effect of fibers and cement, the mixtures with AR fibers showed a lower average fracture energy value than their respective controls, but higher values were achieved for other fibers. The addition of PE fibers caused the greatest improvement in the fracture energy which was statistically different from the cementitious control mixture (4.5ME2C). The result was very close to 6E, further demonstrating the effectiveness of the addition of fibers for improving the cracking resistance by compensating for the negative effects of the 1.5% lower emulsified asphalt content and the addition of 2% cement.

Overall, PE fibers showed the greatest improvement and statistically significant differences for both FI and G_f with or without cement, which was similar to IDEAL-CT results. It could be concluded that the combined use of cement and fibers are a promising approach to improving the cracking performance of cold recycled mixtures containing cement and to obtain a lower optimum emulsion content while producing a more economical and better-performing mixture.

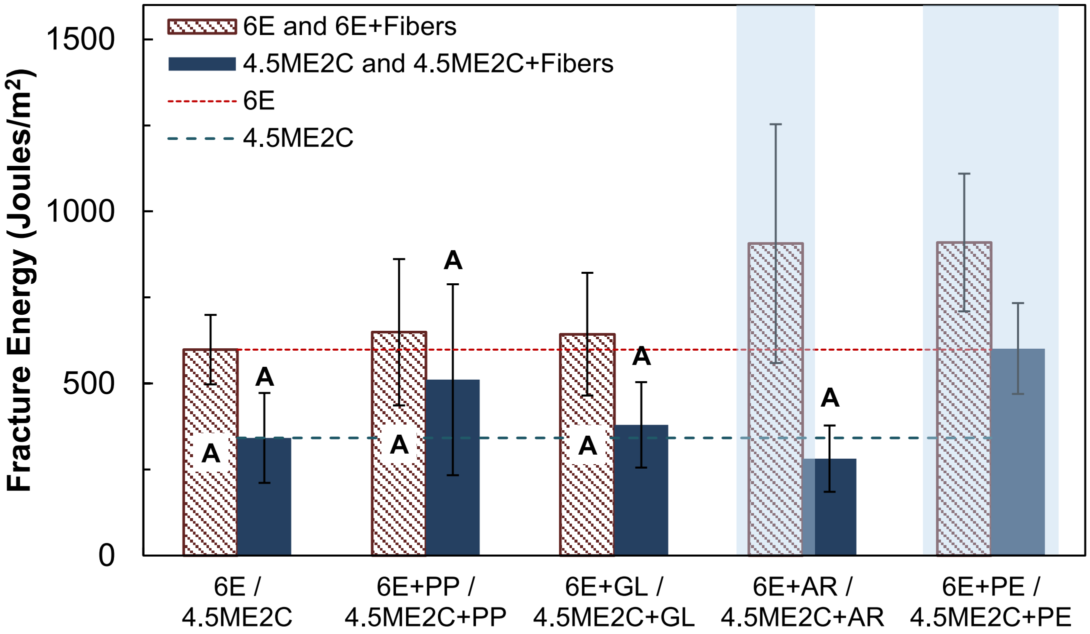


Fig. 15. I-FIT for mixtures reinforced by different fibers and combined use of fibers and cement

5. Conclusions

The current study examined the addition of four types of synthetic fiber to cold recycled asphalt mixtures. The validity and applicability of the I-FIT and IDEAL-CT tests for emulsified asphalt cold recycled mixtures were evaluated and a revised IDEAL-CT index, called CTCR, has been proposed. The performance of cold recycled asphalt mixtures reinforced with different types of fiber were evaluated using the IDEAL-CT and dry and wet ITS tests and the optimum fiber contents and lengths were determined. Finally, the combined effect of the optimum fiber contents and lengths and the use of cement on the performance of the mixtures was evaluated using IDEAL-CT, dry and wet ITS, and I-FIT.

The results are limited to the test plan and materials used in this study. Generalized conclusions cannot be made at this point, especially for the revised CTCR index. Further evaluations using a variety of mix variables as well as field validation are required to further validate or otherwise revise the index or test parameters. The following conclusions could be made based on the study results:

- Evaluation of I-FIT data showed that the goodness of fit required by AASHTO T393 is not achievable for most cold recycled emulsified asphalt mixtures. Moreover, no inflection point was evident for some samples which contained cement.
- IDEAL-CT results showed that, without cement, the inflection point of the load-displacement curves, on average, were 0.85 of the peak load, with a standard deviation of 0.05. Hence, the CTIndex, which uses a slope of 0.65 to 0.85 of the peak load would be expected to provide a less accurate measure of the cracking resistance of the cold recycled mixtures.
- A revised index that incorporates a range of 0.75 to 0.95 of the peak load to calculate the post-peak slope, called CTCR, has been proposed and evaluated. CTCR was found to minimize the

overestimation observed with the use of the CTIndex and is recommended for use for cold recycled mixtures.

- For mixtures containing cement, no inflection point was evident on the load-displacement curves in most cases. Further investigation of other test methods and/or indices that are independent of the inflection point are required.
- The testing of the addition of four types of fiber showed a potential to significantly increase the dry strength as well as the cracking resistance of the mixtures depending on the fiber type, content and length. However, the addition of the fibers generally decreased the wet strength and intensified the moisture susceptibility of the mixture.
- The combined use of fibers and cement generally improved the cracking resistance characteristics of the mixtures compared with mixtures containing cement only. The positive effects of the use of cement in terms of strength and moisture resistance were either maintained or further improved.
- The combined use of fibers and cement considerably increased the dry strength and moisture resistance over that of the base control mixture having 1.5% greater emulsified asphalt content. Despite the lower amount of emulsified asphalt, similar or better cracking resistance was reported in some cases. CTCR, however, was not fully restored for any type of fibers. The most promising results were obtained for the polyester and polypropylene fibers.
- The combined use of fibers and cement is a promising measure that benefited from the positive qualities of both additives and improved overall performance of the mixtures in some cases.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

AASHTO, 2021. AASHTO PP86-20(2021): Standard Practice for Emulsified Asphalt Content of Cold Recycled Mixture Designs. ASTM Compass.

AASHTO, 2022a. AASHTO MP31-22: Standard Specification for Materials for Cold Recycled Mixtures with Emulsified Asphalt. ASTM Compass.

AASHTO, 2022b. AASHTO T308-22: Standard Method of Test for Determining the Asphalt Binder Content of Asphalt Mixtures by the Ignition Method. ASTM Compass.

AASHTO, 2022c. AASHTO T393-22: Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using the Illinois Flexibility Index Test (I-FIT). ASTM Compass.

Abtahi, S. M., Sheikhzadeh, M. and Hejazi, S. M. 2010. Fiber-reinforced asphalt-concrete–a review. *Construction and Building Materials,* 24(6), 871-877.

Al-Qadi, I. L*., et al.*, 2015. *Testing protocols to ensure performance of high asphalt binder replacement mixes using RAP and RAS.* Illinois Center for Transportation.

Alkins, A. E., Lane, B. and Kazmierowski, T. 2008. Sustainable pavements: environmental, economic, and social benefits of in situ pavement recycling. *Transportation research record,* 2084(1), 100-103.

ASTM, 2017. ASTM D6931-17: Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures. ASTM

Compass.

ASTM, 2019. ASTM D8225-19: Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature. ASTM Compass.

ASTM, 2022. ASTM C150/C150M-22: Standard Specification for Portland Cement. ASTM Compass.

ASTM, 2024. ASTM D2172/D2172M − 24: Standard Test Method for Quantitative Extraction of Asphalt Binder from Asphalt Mixtures. ASTM Compass.

Ayar, P. 2018. Effects of additives on the mechanical performance in recycled mixtures with bitumen emulsion: An overview. *Construction and Building Materials,* 178, 551-561.

Carpani, C., Bocci, E. and Bocci, M. 2023. Characterization of Cold Recycled Asphalt Mixtures including Reinforcing Fibers. *Sustainability,* 15(23), 16209.

Charmot, S., Dong, W. and Xu, X., 2017. *Feasibility of cold recycled asphalt mixture design optimization on the basis of fracture properties using the semi circular bending (SCB) at intermediate temperature.*

de S. Bueno, B.*, et al.* 2003. Engineering properties of fiber reinforced cold asphalt mixes. *Journal of Environmental Engineering,* 129(10), 952-955.

Diefenderfer, B., Boz, I. and Bowers, B., Evaluating cracking tests for performance-based design concept for cold recycled mixtures. ed. *International Airfield and Highway Pavements Conference 2019*, 2019, 220-229.

Dong, W. and Charmot, S. 2019. Proposed tests for cold recycling balanced mixture design with measured impact of varying emulsion and cement contents. *Journal of Materials in Civil Engineering,* 31(2), 04018387.

Du, S. 2022. Effect of different fibres on the performance properties of cold recycled mixture with asphalt emulsion. *International Journal of Pavement Engineering,* 23(10), 3444-3453.

Epps, J. A. 2019. Innovative asphalt pavement technology: paving the way for the world's roadways. *Transportation research record,* 2673(1), 1-16.

Fakhri, M.*, et al.* 2021. Performance Evaluation of WMA Containing Re-Refined Acidic Sludge and Amorphous Poly Alpha Olefin (APAO). *Sustainability,* 13(6), 3315.

Fang, X., Garcia-Hernandez, A. and Lura, P. 2016. Overview on cold cement bitumen emulsion asphalt. *RILEM Technical Letters,* 1, 116-121.

Ferrotti, G., Pasquini, E. and Canestrari, F. 2014. Experimental characterization of high-performance fiber-reinforced cold mix asphalt mixtures. *Construction and Building Materials,* 57, 117-125.

Gu, F.*, et al.* 2019. Structural performance and sustainability assessment of cold central-plant and in-place recycled asphalt pavements: A case study. *Journal of cleaner production,* 208, 1513-1523.

Hoyos, L. R., Puppala, A. J. and Ordonez, C. A. 2011. Characterization of cement-fiber-treated reclaimed asphalt pavement aggregates: preliminary investigation. *Journal of Materials in Civil Engineering,* 23(7), 977-989.

Issa, R.*, et al.* 2001. Characteristics of cold processed asphalt millings and cement-emulsion mix. *Transportation research record,* 1767(1), 1-6.

Jain, S. and Singh, B. 2021. Cold mix asphalt: An overview. *Journal of cleaner production,* 280, 124378.

Jiang, Y.*, et al.* 2023. Laboratory and Field Research on Using Cement and Polyester Fiber to Enhance the Performance of Emulsified Asphalt Cold Recycled Mixture. *Arabian Journal for Science and Engineering,* 48(4), 4937-4951.

Kaloush, K. E.*, et al.* 2010. Evaluation of fiber-reinforced asphalt mixtures using advanced material characterization tests. *Journal of Testing and Evaluation,* 38(4), 1.

Kim, Y. and Park, T.-S. 2013. Reinforcement of recycled foamed asphalt using short polypropylene fibers. *Advances in Materials Science and Engineering,* 2013.

Kumar, R*., et al.* 2024. Bitumen stabilised materials for sustainable pavements: a review. *Road Materials and Pavement Design*, 1-33.

Ling, C., Hanz, A. and Bahia, H. 2014. Evaluating moisture susceptibility of cold-mix asphalt. *Transportation research record,* 2446(1), 60-69.

Martinez-Arguelles, G*., et al.* 2015. Laboratory investigation on mechanical performance of cold foamed bitumen mixes: bitumen source, foaming additive, fiber-reinforcement and cement effect. *Construction and Building Materials,* 93, 241-248.

Meknaci, L*., et al.* 2022. Influence of bitumen emulsion on the curing behaviour of standardised cold bitumen emulsion mortars. *Road Materials and Pavement Design,* 23(sup1), 99-115.

Meneses, J. P. C*., et al.* 2021. Compaction methods of cold recycled asphalt mixtures and their effects on pavement analysis. *Road Materials and Pavement Design,* 22(sup1), S154-S179.

Modarres, A., Rahimzadeh, M. and Zarrabi, M. 2014. Field investigation of pavement rehabilitation utilizing cold in-place recycling. *Resources, Conservation and Recycling,* 83, 112-120.

Morian, D. A., Oswalt, J. and Deodhar, A. 2004. Experience with cold in-place recycling as a reflective crack control technique: Twenty years later. *Transportation research record,* 1869(1), 47-55.

Niazi, Y. and Jalili, M. 2009. Effect of Portland cement and lime additives on properties of cold in-place recycled mixtures with asphalt emulsion. *Construction and Building Materials,* 23(3), 1338-1343.

Nikfarjam, H., 2020. *Performance Evaluation of Cold-Recycled Mixtures (In Farsi).* Sharif University of Technology, Iran.

Pais, J. C., Santos, C. R. and Lo Presti, D. 2022. Application of textile fibres from tire recycling in asphalt mixtures. *Road Materials and Pavement Design,* 23(10), 2353-2374.

Puppala, A. J*., et al.*, 2009. Resilient behavior of cement-fiber treated reclaimed asphalt pavement aggregates. *Contemporary Topics in Ground Modification, Problem Soils, and Geo-Support.* 433-440.

Sabouri, M. and Sadeghi, M. 2023. Investigation on properties of cold recycled asphalt mixtures reinforced with polypropylene fibers. *Amirkabir Journal of Civil Engineering,* 55(3), 5-5.

Shanbara, H. K., Ruddock, F. and Atherton, W. 2018. A laboratory study of high-performance cold mix asphalt mixtures reinforced with natural and synthetic fibres. *Construction and Building Materials,* 172, 166-175.

Slebi-Acevedo, C. J*., et al.* 2019. Mechanical performance of fibers in hot mix asphalt: A review. *Construction and Building Materials,* 200, 756-769.

Some, S. C*., et al.* 2020. Mechanical characterization of asphalt mixes inter-layer bonding based on reptation theory. *Construction and Building Materials,* 242, 118063.

Stempihar, J. J., Souliman, M. I. and Kaloush, K. E. 2012. Fiber-reinforced asphalt concrete as sustainable paving material for airfields. *Transportation research record,* 2266(1), 60-68.

Taziani, E. A*., et al.* 2016. Investigation on the combined effect of fibers and cement on the mechanical performance of foamed bitumen mixtures containing 100% RAP. *Advances in Materials Science and Engineering,* 2016.

Thanaya, I., Zoorob, S. and Forth, J., A laboratory study on cold-mix, cold-lay emulsion mixtures. ed. *Proceedings of the Institution of Civil Engineers-Transport*, 2009, 47-55.

Thenoux, G., Gonzalez, A. and Dowling, R. 2007. Energy consumption comparison for different asphalt pavements rehabilitation techniques used in Chile. *Resources, Conservation and Recycling,* 49(4), 325-339.

U.S. Energy Information Administration, 2023. *Use of energy explained: Energy use for transportation* [online]. Available from: https://www.eia.gov/energyexplained/use-of-energy/transportation.php [Accessed February 19 2024].

Vamsikrishna, G.*, et al.* 2024. Performance evaluation of dense graded emulsion mixes with rejuvenated reclaimed asphalt pavement. *Road Materials and Pavement Design,* 25(4), 860-873.

Wu, S., Haji, A. and Adkins, I. 2023. State of art review on the incorporation of fibres in asphalt pavements. *Road Materials and Pavement Design,* 24(6), 1559-1594.

Xiao, F.*, et al.* 2018. A literature review on cold recycling technology of asphalt pavement. *Construction and Building Materials,* 180, 579-604.

Xu, J.*, et al.* 2011. The impact of cement contents on the properties of asphalt emulsion stabilized cold recycling mixtures. *International Journal of Pavement Research and Technology,* 4(1), 48.

Yan, J.*, et al.* 2017. Early-age strength and long-term performance of asphalt emulsion cold recycled mixes with various cement contents. *Construction and Building Materials,* 137, 153-159.

Zhou, F. 2019. Development of an IDEAL cracking test for asphalt mix design, quality control and quality assurance. *NCHRP-IDEA Program Project Final Report,* (195).