The Effect of polypropylene fibres on the tensile performance of asphalt mixtures for road pavements

Hayder K. Shanbara*1, 2, Sarah S. Musa3, and Anmar Dulaimi3

1 Department of Civil Engineering, College of Engineering, Al-Muthanna University Al-Muthanna, Samawah, Iraq, hayder.shanbara@mu.edu.iq
2 Department of Civil Engineering, College of Engineering, Al-Muthanna University Al-Muthanna, Samawah, Iraq, almusawysarah@mu.edu.iq
3 College of Engineering, University of Warith Alanbiyaa, Karbala, Iraq; Ministry of Education, Karbala, Iraq; Department of Civil Engineering, Liverpool John Moores University, Liverpool, UK, A.F.Dulaimi@ljmu.ac.uk; a.f.dulaimi@uow.edu.iq
*Corresponding author: hayder.shanbara@mu.edu.iq

Abstract. The tensile strength of asphalt mixtures is one of the main parameters of deterioration and failure in flexible pavements. Hence, in this study, the effects of reinforcing asphalt mixtures, using polypropylene fibers, on their engineering performance were experimentally investigated. A set of cylindrical specimens of asphalt mixtures was prepared and subjected to a compressive load at different testing temperatures in terms of evaluation of the indirect tensile stiffness modulus. Similarly, fatigue (four-point bending) and crack propagate (three-point bending) tests were conducted for different asphalt mixtures made with and without polypropylene fibres. The impacts of such fibres on the engineering properties of asphalt mixtures were studied. The laboratory results revealed that the reinforced mixtures with polypropylene fibres had a noticeable influence on the tensile, fatigue and cracking initiation and propagation of these mixtures.

1. Introduction
Bituminous mixture is the common used material in flexible pavements construction. These materials considered as combined materials that consist of asphalt binder, aggregates, and filler [1, 2] in addition to various kinds of modifiers that might be applied for both processing and performance purposes. Aggregates are the main part that gives the most strength of the asphalt mixtures. Asphalt binder together with filler form the asphalt mastic that acts as an active binder to the aggregates. Thus, such materials play a key role during pavements service life as they are bearing stresses from the traffic and environment [3-9]. In order to achieve long-lasting road pavements, asphalt binder needs to maintain its engineering characteristics in a wide range of service temperatures [10]. At hot climate, asphalt mastic tends to be soft and therefore, rutting is the failure mode on the road surface, and in a cold climate, asphalt mastic tends to be brittle and hard resulting in both thermal cracks and cracks from the applied loads. Besides, segregation and ravelling due to the weak adhesion between the aggregates and the asphalt binder must be avoided. Also, at moderate temperatures, fatigue cracking must be avoided [11]. In order to enhance performance and durability of bituminous mixes, different additives are used such as the addition of waste fillers as a traditional filler replacement which helps in improving both mechanical and durability properties [12-15]. Some cementitious and pozzolanic waste products affect positively on the performance of asphalt mixes [16-18]. Additionally, such materials improve the
performance of the soil strength [19]. The utilization of fibres in asphalt mixtures as a reinforcing material produces effective development in the interaction between the aggregates and the mastic, resulting in preventing the formation and propagation of cracks and extending pavement service life. If accurately engineered, one of the best advantages of utilizing fiber as a reinforcing agent in road pavement is to eliminate crack initiation and propagation and to extend pavements service life [20]. Additionally, using fibers can considerably improve the mixture tensile strength and flexural toughness that considered a great economical feature [21-24]. Therefore, fibres reinforcing asphalt mixtures have great potential to control distresses in roads pavement, as well as reduce or eliminate cracking and permanent deformation [25-27]. Several investigations are conducted on using different fibres in asphalt mixtures [28-30]. Shanbara et al. [31] experimentally examined using of fibres in asphalt mixtures and stated that fibres improve the mixtures’ performance in terms of flexural performance, temperatures susceptibility, moisture damage, and environmental effects. Shanbara et al. [20] concluded that the engineering properties such as stiffness, rutting, and fatigue resistance were enhanced as a result of the positive effects of reinforcing asphalt mixtures using various natural and synthetic fibres. Accordingly, this study investigated, through laboratory tests, effects of utilizing polypropylene fibres as a reinforcing material on the engineering behaviour of asphalt mixtures. Various percentages and lengths of fibres were considered and investigated in terms of obtaining the optimum fibres content and length. Basic engineering behaviour was tested using indirect tensile stiffness modulus, four-point loads and crack propagation tests.

2. Materials
Crushed coarse and fine aggregates were collected from the Bardon quarry, UK with asphalt concrete close graded surface course with 14 mm aggregates maximum size. The aggregates gradation and its physical characteristics are displayed in Tables 1 and 2. The mineral filler was used as limestone dust. A conventional asphalt binder with 100/150 penetration grade was utilized for asphalt mixtures preparation. Table 3 shows the asphalt binder properties. Polypropylene fibers were provided by Liverpool John Moores University / Pavement Lab and used in this study, and their characteristics are presented in Table 4.

| Property                        | Value |
|--------------------------------|-------|
| Coarse aggregate               |       |
| Bulk particle density, Mg/m³   | 2.62  |
| Apparent particle density, Mg/m³| 2.67  |
| Water absorption, %            | 0.8   |
| Fine aggregate                 |       |
| Bulk particle density, Mg/ m³  | 2.54  |
| Apparent particle density, Mg/ m³| 2.65  |
| Water absorption, %            | 1.7   |
| Traditional mineral filler     |       |
| Particle density, Mg/ m³       | 2.57  |

Table 1. Selected aggregates gradation.

| Sieve size (mm) | 14 | 10 | 6.3 | 2 | 1 | 0.063 |
|-----------------|----|----|-----|---|---|-------|
| Passing %       | 100| 80 | 55  | 28| 20| 6     |
| Specification limits | 100| 77-83| 52-58| 25-31| 14-26| 6     |

Table 2. Physical characteristics of the selected aggregates.
Table 3. Asphalt binder properties.

| Property                          | Value   |
|----------------------------------|---------|
| Appearance                       | Black   |
| Penetration at 25 °C (0.1 mm)    | 141     |
| Softening Point (°C)             | 43.5    |
| Kinematic viscosity at 135 °C (mPa.s) | 179     |
| Density (g/cm³)                  | 1.02    |

Table 4. Polypropylene fiber characteristics.

| Fibre               | Value   |
|---------------------|---------|
| Diameter (mm)       | 0.1     |
| Unit weight (kg/m³) | 900     |

3. Testing procedure
This research aims to examine the impact of including polypropylene fibres on the engineering characteristics of bituminous mixtures. In order to examine such characteristics, some laboratory tests were conducted.

3.1. Indirect tensile stiffness modulus test
In order to measure the strength of the samples, the indirect tensile stiffness modulus test apparatus (Figure 1) was used according to the methodology described in the European Committee for Standardization [32]. Different cylindrical samples with a diameter of 100 mm and a thickness of 63.5 mm were prepared using an electronic mixer and Marshal compactor (Figure 2). A uniaxial compressive force was applied by a Cooper Research Technology HYD 25 testing machine with 5 measuring pulses. The average of these applied pulses is then calculated to simulate the indirect tensile stiffness modulus of the asphalt mixtures.
Figure 1. Indirect tensile stiffness modulus test apparatus.

Figure 2. Specimens mixer and Marshall compactor.
3.2. Four-point bending fatigue test

Four-point bending fatigue test (Figure 3) consists of the loading and supporting and clamps, and bottom plate. This test was performed following the European Committee for Standardization [33]. A steel rolling compactor was utilized to compact the prepared slab samples (Figure 3). The compacted samples have the dimensions of 50 mm in thickness, 405 mm in length, and 300 mm in width. Following the compaction stage, the slabs were extruded and sawed to achieve prismatic beams with 50 mm thickness, 405 mm length, and 50 mm width. The fatigue life determined as the number of load applications that resulted in a reduction of 50% of the initial stiffness.

![Figure 3. Four-point bending fatigue test and steel rolling compactor apparatus.](image)

3.3. Crack propagation (three-point bending) test

The crack propagation test was carried out to evaluate the tensile strength and fracture toughness of asphalt mixtures in terms of the potential for crack propagation, as shown in Figure 4. In this test, the maximum applied load in which the asphalt samples contain a crack (notch) was determined to assess mixtures resistance to crack propagation based on the European Committee for Standardization [34]. Several fracture modes can be realized based on the geometric considerations such as the notch length, inclination angle, and supporting width with the applied load. Sample geometries for fracture mode II were 0.5 of the span ration (s/r) where (s) is the span length and (r) is sample radius, notch length 100 mm and notch width is 0.35 mm.
4. Results and discussion

The findings of laboratory investigations are displayed in three separate aspects including:

4.1. Indirect tensile stiffness modulus

Based on literature, five different fibres content (0.2, 0.25, 0.3, 0.35 and 0.4) % of the total dry aggregates with three different fibres length (20, 14 and 10) mm were investigated in terms of indirect tensile stiffness modulus test at 20 °C. After the optimization process to select the optimum fibres content and length, it was found that 0.3% is the optimum fibre content and 14 mm is the optimum fibre length as shown in Figure 5. Figure 6 shows the stiffness values obtained from indirect tensile stiffness modulus tests at different temperatures. For each mixture, the average of five repeated samples was calculated. Generally, the stiffness modulus of reinforced mixtures increased due to the positive effects of the polypropylene fibres at all temperatures. This improvement is considered as a result of the random three dimensional reinforcement in such mixtures. Also, the stiffness modulus of asphalt mixtures was significantly affected by the temperatures. The test was carried out at four different temperatures (5 °C, 20 °C, 40 °C, and 60 °C).
**Figure 5.** Fibres optimization.

**Figure 6.** Indirect tensile stiffness modulus of all mixtures at different temperatures.
4.2. Four-point bending fatigue

Figure 7 shows a typical number of loading cycles (fatigue life) obtained from the four-point bending fatigue test. These values were measured at the normal definition of failure, at which the stiffness at given cycles (N) decreased to half of its initial value measured at the 100th cycles. It can be clearly seen that the reinforced asphalt mixture with the polypropylene fibres has improved fatigue life by about 41% as compared to the conventional mixture. This test was achieved at room temperature (20 °C).

![Figure 7. Fatigue results.](image)

4.3. Crack propagation (three-point bending)

The results of three-point bending tests are presented in Figure 8 for both reinforced and unreinforced asphalt mixtures. The values in this Figure represent the maximum force that the asphalt sample can carry up to failure. Adding polypropylene fibres in asphalt mixtures as a reinforcing material means the higher the load-bearing capacity of such mixtures. The fracture toughness of the asphalt mixtures has a direct correlation with the load-bearing capacity. Since fracture toughness is a function of the maximum load-bearing capacity of specimens, it is developed as a result of reinforcing asphalt mixtures using polypropylene fibres. At low temperature, fracture toughness depends on the asphalt binder and aggregates as the elastic behaviour of the asphalt binder, whereas at moderate temperature crack propagates through the asphalt binder, which is affected by the temperature as a result of the viscoelastic performance of the asphalt binder [35]. Consequently, this test was conducted at a low temperature (5 °C).
5. Conclusion
In this study, the influences of using polypropylene fibres as a reinforcing material in asphalt mixtures were investigated, by considering the optimum fibres content and length. The main conclusions of this study can be summarized as follows:

- The influence of adding polypropylene fibres in asphalt mixtures as a reinforcing material was found to be significant at different temperatures in terms of indirect tensile stiffness modulus. The stiffness modulus of reinforced mixtures developed by about 30% for all temperatures.

- The polypropylene fibres incorporated mixtures showed longer fatigue life (approximately 41%), compared with the conventional mixture.

- The polypropylene fibres reinforced asphalt mixtures was found to improve load-bearing capacity and fracture toughness of such mixtures, compared with the conventional mixtures. The positive effects of using fibres increase the ability of asphalt mixtures to resist crack initiation and propagation.

6. References
[1] Bonica, C., E. Toraldo, L. Andena, C. Marano, and E. Mariani, The effects of fibers on the performance of bituminous mastics for road pavements. Composites Part B: Engineering, 2016. 95: p. 76-81.

[2] Shanbara, H.K., F. Ruddock, and W. Atherton. The Linear Elastic Analysis of Cold Mix Asphalt by Using Finite Element Modeling, in The Second BUiD Doctoral Research Conference 2016, The British University in Dubai: The British University in Dubai, 14th May 2016.

[3] Shanbara, H.K., F. Ruddock, and W. Atherton, Rutting prediction of a reinforced cold bituminous emulsion mixture using finite element modelling. Procedia engineering, 2016. 164: p. 222-229.

[4] Delaporte, B., H. Di Benedetto, P. Chaverot, and G. Gauthier, Linear viscoelastic properties of bituminous materials: from binders to mastics (with discussion). Journal of the Association of Asphalt Paving Technologists, 2007. 76.

[5] Moon, K.H., A.C. Falchetto, J.Y. Park, and J.H. Jeong, Development of high performance asphalt mastic using fine taconite filler. KSCE Journal of Civil Engineering, 2014. 18(6): p. 1679-1687.
[6] Shanbara, H.K., F. Ruddock, and W. Atherton, A viscoplastic model for permanent deformation prediction of reinforced cold mix asphalt. Construction and Building Materials, 2018. 186: p. 287-302.

[7] Delaporte, B., H. Di Benedetto, P. Chaverot, and G. Gauthier, Effect of ultrafine particles on linear viscoelastic properties of mastics and asphalt concretes. Transportation Research Record, 2008. 2051(1): p. 41-48.

[8] Hesami, E., B. Birgisson, and N. Kringos, Numerical and experimental evaluation of the influence of the filler–bitumen interface in mastics. Materials and structures, 2014. 47(8): p. 1325-1337.

[9] Dulaimi, A., H.K. Shanbara, and A. Al-Rifaie, The mechanical evaluation of cold asphalt emulsion mixtures using a new cementitious material comprising ground-granulated blast-furnace slag and a calcium carbide residue. Construction and Building Materials, 2020. 250: p. 118808.

[10] Shanbara, H.K., F. Ruddock, W. Atherton, and N.A. Nassir, Mechanical Properties of Ordinary Portland Cement Modified Cold Bitumen Emulsion Mixture. International Journal of Civil and Environmental Engineering, 2018. 12(5): p. 576-581.

[11] Liao, M.-C., J.-S. Chen, and K.-W. Tsou, Fatigue characteristics of bitumen-filler mastics and asphalt mixtures. Journal of Materials in Civil Engineering, 2012. 24(7): p. 916-923.

[12] Dulaimi, A., H. Al Nageim, K. Hashim, F. Ruddock, and L. Seton, Investigation into the Stiffness Improvement, Microstructure and Environmental Impact of A Novel Fast-Curing Cold Bituminous Emulsion Mixture, in Euraspah & Eurobitume Congress 2016: Prague, Czech Republic.

[13] Dulaimi, A., H. Al Nageim, F. Ruddock, and L. Seton, Microanalysis of Alkali-Activat ed Binary Blended Cementitious Filler in a Novel Cold Binder Course Mixture, in The 38th International Conference on Cement Microscopy 2016: Lyon, France.

[14] Dulaimi, A., H. Al Nageim, F. Ruddock, and L. Seton, Assessment the Performance of Cold Bituminous Emulsion Mixtures with Cement and Supplementary Cementitious Material for Binder Course Mixture, in The 38th International Conference on Cement Microscopy 2016: Lyon, France.

[15] Dulaimi, A., H. Al Nageim, F. Ruddock, and L. Seton, A Novel Cold Asphalt Concrete Mixture for Heavily Trafficked Binder Course. International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, 2015. 9(15): p. 734-738.

[16] Al Nageim, H., A. Dulaimi, F. Ruddock, and L. Seton, Development of a new cementitious filler for use in fast-curing cold binder course in pavement application, in The 38th International Conference on Cement Microscopy 2016: Lyon, France. p. pp. 167-180.

[17] Dulaimi, A., H.A. Nageim, F. Ruddock, and L. Seton, Laboratory studies to examine the properties of a novel cold-asphalt concrete binder course mixture containing binary blended cementitious filler. Journal of Materials in Civil Engineering, 2017. 29(9): p. 04017139.

[18] Dulaimi, A., H. Al Nageim, F. Ruddock, and L. Seton, Performance Analysis of a Cold Asphalt Concrete Binder Course Containing High-Calcium Fly Ash Utilizing Waste Material. Journal of Materials in Civil Engineering, 2017.

[19] Al-Khafaji, Z.S., Z. Al Masoodi, H. Jafer, A. Dulaimi, and W. Atherton, The Effect Of Using Fluid Catalytic Cracking Catalyst Residue (FC3R)" As A Cement Replacement In Soft Soil Stabilisation. International Journal Of Civil Engineering Technology Volume, 2018. 9: p. 522-533.

[20] Shanbara, H.K., F. Ruddock, and W. Atherton. Improving the Mechanical Properties of Cold Mix Asphalt Mixtures Reinforced by Natural and Synthetic Fibers. in International Conference on Highway Pavements & airfield Technology. 2017.

[21] Yang, J.-M., H.-O. Shin, and D.-Y. Yoo, Benefits of using amorphous metallic fibers in concrete pavement for long-term performance. Archives of civil and mechanical engineering, 2017. 17(4): p. 750-760.

[22] Wu, S., Q. Ye, N. Li, and H. Yue, Effects of fibers on the dynamic properties of asphalt mixtures. Journal of Wuhan University of Technology-Mater. Sci. Ed., 2007. 22(4): p. 733-736.
[23] Shanbara, H.K., F. Ruddock, and W. Atherton, Stresses and Strains Distribution of a Developed Cold Bituminous Emulsion Mixture Using Finite Element Analysis. Science and Technology Behind Nanoemulsions, 2018: p. 9.

[24] Shanbara, H.K., A. Dulaimi, F. Ruddock, W. Atherton, and G. Rothwell. Cold and hot asphalt pavements modelling. in Bearing Capacity of Roads, Railways and Airfields - Proceedings of the 10th International Conference on the Bearing Capacity of Roads, Railways and Airfields, BCRRA 2017. 2017.

[25] YE, Q. and S. WU, Rheological Characteristics of Polyester Fiber Modified Asphalt Mastic [J]. Journal of Highway and Transportation Research and Development, 2009. 9: p. 007.

[26] Bo, P., D. Zhi-yong, and D. Jing-liang, Road performance comparison of different asphalt mastics. Journal of Traffic and Transportation Engineering, 2007. 3: p. 012.

[27] Chen, J.-S. and K.-Y. Lin, Mechanism and behavior of bitumen strength reinforcement using fibers. Journal of materials science, 2005. 40(1): p. 87-95.

[28] Shanbara, H.K., A. Shubbar, F. Ruddock, and W. Atherton, Characterizing the Rutting Behaviour of Reinforced Cold Mix Asphalt with Natural and Synthetic Fibres Using Finite Element Analysis, in Advances in Structural Engineering and Rehabilitation. 2020, Springer. p. 221-227.

[29] Shanbara, H.K., F. Ruddock, and W. Atherton, Predicting the rutting behaviour of natural fibre-reinforced cold mix asphalt using the finite element method. Construction and Building Materials, 2018. 167: p. 907-917.

[30] Shanbara, H.K., A. Dulaimi, F. Ruddock, W. Atherton, and G. Rothwell. Evaluation of rutting potential in cold bituminous emulsion mixture using finite element analysis. in Bearing Capacity of Roads, Railways and Airfields - Proceedings of the 10th International Conference on the Bearing Capacity of Roads, Railways and Airfields, BCRRA 2017. 2017.

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

[32] European Committee for Standardization - Part 26, BS EN 12697: Bituminous mixtures - Test methods for hot mix asphalt - stiffness, British Standards Institution, London, UK, 2012.

[33] European Committee for Standardization - Part 24, BS EN 12697: Bituminous mixtures - Test methods for hot mix asphalt - Resistance to fatigue, British Standards Institution, London, UK, 2012.

[34] European Committee for Standardization - Part 44, BS EN 12697: Bituminous mixtures — Test methods for hot mix asphalt, Crack propagation by semi-circular bending test, British Standards Institution, London, UK, 2010.

[35] Somé, S.C., Fredj, M.A., Nguyen, M.-L., Feeser, A. and Pavoine, A. (2017) Multi-parametric characterization of mode I fracture toughness of asphalt concrete: Influence of void and RA contents, binder and aggregate types. International Journal of Pavement Research and Technology.