Assessing the impact of the incorporation of aramid and polyolefin to hot and warm asphaltic mixture using dry and wet process: A Review

C G Daniel*  
1 Department of Civil Engineering, Pelita Harapan University, Tangerang, 15811, Indonesia.

*Corresponding author's e-mail: christian.daniel@uph.edu

Abstract. The utilisation of polymer has become a prominent trend in the civil engineering industry, one of them is in the production of asphalt for pavement structure. There have been currently a vast range of polymer product variation used in the asphalt production, among which are polyolefin (polyethylene, polypropylene, PET) and aramid. This paper attempts to assess the benefit of the incorporation of the polymer to produce both hot and warm mix asphalt, both by the wet process to develop a modified bitumen, also dry process to form a fibre reinforced mixture. The results indicate that the addition of up to 10% of polyolefin increase the softening point and dynamic stiffness of the bitumen as well as decrease the penetration grade of bitumen by means of wet process. Nevertheless, an extra binding agent is required to prevent the separation between the polymer and bitumen. Furthermore, the inclusion of the polymers using the dry process has been discovered to promote improvements in the mechanical performances of both hot and warm mix asphalt regarding the resistance against rutting, fatigue life, stiffness, tensile and compressive strength, and fracture energy given a wide range of working temperature, as well as reduce binder drain down. These outcomes concluded that the use of polymer as an additive in bituminous mix can combat the failure mechanism in the pavement structures.

1. Introduction
The amount of road infrastructure in Indonesia is not well-spread throughout the country. According to the report by National Statistical Bureau of Indonesia in 2017, the major part of non-highway asphaltic road infrastructure centralised in both Java and Sumatera, leaving a substantial need to improve such situation to ensure the availability of good quality pavements in the entire nation (1) (2). Furthermore, the estimated growth of available vehicle in Indonesia has outgrown the development of the road itself, establishing the necessary need to erect the new infrastructure (3). A road construction, however, may only last so much within its serviceability period before being degraded and needs to be replaced or completely demolished to create a new structure. Such occurrence has been a regular practice in the civil engineering field, thus this raises an issue with the environmental sector regarding the employment of finite resources, such as bitumen. Moreover, the repeated process may come in a considerable expense, ultimately if not designed or constructed properly. Last but not least, the asphalt concrete mix production standard needs an enormous amount of energy to produce the necessary heat (recorded at 4-5 Giga Joule/Ton asphalt production), and thus, generating undesired carbon dioxide (CO₂) pollution (recorded at 0.3ton/ton asphalt production) (4). Therefore, the engineers and scientists have tried to invent advanced materials to enhance the performance and durability of asphaltic material as well as develop a modified production technique to produce a higher quality pavement infrastructure. One of the
available advanced material to date is the polymer substance modifier, while a warm asphalt mix approach is designed to produce the bituminous mixture in a lower temperature to output a substantial reduction in fuel used in the production as well as the greenhouse gas emission by around 25% (5)(6)(7). This research focuses on extracting the information regarding the influence of both aramid and polyolefin (polyethylene and polypropylene) to the mechanical performance of asphalt concrete (AC) mixture both in the typical hot mix (HMA) and warm mix asphalt (WMA), where the incorporation can be classified into two ways: blended with bitumen to create a polymer modified bitumen, called wet method; and incorporate the polymer directly into the mixture, called dry method. The outcomes from both methods are discussed in this paper.

2. Fibre as modifier material in pavement engineering field

2.1. The history of fibre-reinforced asphalt concrete

Fibre as reinforcement material has been widely used in road engineering discipline, it has been started in the early 1920s by the use of asbestos fibre. Asbestos fibre was commonly used as the reinforcing component until the 1970s, when its application was banned following its declaration as a hazardous material (8)(9). Since then, numerous reports have recorded the use of various types of fibre in bituminous mixtures: namely cellulose, reportedly being able to promote binder stability in an open-graded mix, with however, no effect to tensile strength; mineral, such as slag, basalt, asbestos, steel and carbon; and synthetic polymer fibre, among them are polyester, polypropylene, polyethylene and aramid (9). The general premises of the benefits brought by the incorporation of fibre to the asphaltic mixture are to increase stiffness, tensile strength, fatigue resistance, rutting resistance and abrasion resistance, which lead into higher durability as well as life service that result in lower life cycle costs (8)(9). In addition, steel fibre is reported to carry a limited potential of healing capacity to the asphaltic mixture through the process of induction heating (10). Also, the polymer product can either be used as reinforcing material or to alter the characteristics of the binder by directly mixing them, forming a polymer modified bitumen (11). On the other hand, these admixtures could also bring several disadvantages to the mixture. One example is asbestos, which brings an issue to health. Moreover, steel fibre could be exposed to corrosion, which will surely reduce the performance of the bituminous mix. Additionally, polymer fibre tends to absorb moisture, which will later degrade the strength of the asphaltic mixture and introduce moisture damage to it (12)(13). Lastly, the additional fibre will also need more compaction time to avoid the mix to harden and too difficult to be compacted; this is particularly important in an open graded mixture (14). Regardless, the potential brought by the inclusion is proven to be beneficial that such application is encouraged, and the use of fibre-reinforced material remains a common practice to date.

2.2. History and properties of aramid and polyolefin fibre

Aramid and polyolefin are both the main clusters of synthetic polymer fibre; both of them share a long history and application throughout the century. The history of aramid fibre could be traced back to 1938 when nylon was the first commercialised, followed by the introduction of Nomex fibre by Dupont Co. in 1962 (15). Since then, aramid can be associated with the term “Kevlar” under the brand of Dupont. The production process of aramid can be described in the following way (16)(17). Firstly, the condensation between two monomers called 1,4-Para-Phenylenediane (PPD), and Terephthaloyl Dichloride (TDC) occurs to form Poly Para-phenylene terephthalamide (PPD-T), whose molecular structure is described in figure 1. PPD-T is then washed to eradicate the acidic substance. Afterwards, the dry PPD-T is extruded from a spinneret inside a robust acidic liquid, in order to form the orientation and structure of the fibre by means of coagulation and crystallisation process. The final stage is to dry the fibre filament, which already develops its physical tensile strength. The molecular structure of aramid contributes to the physical properties, where the aromatic ring structure generates the high thermal stability, and the para configuration forms the stiffness and strength of the fibre (18). Altogether, aramid fibre has the tensile strength and modulus of approximately 4 GPa and 180 GPa, respectively. Moreover, the physical attributes of aramid fibre can be maintained to be about 80% of them at the temperature of 200°C, making it insensitive to temperature change. However, aramid is prone to plastic
deformation when subjected to compressive loading, suffering under the effect known as “kink bands” (18)(15).

Figure 1. Molecular structure of aramid fibre (18)

Nowadays, aramid is widely used in the aerospace industry. For instance, the combination of aramid and carbon fibre is commonly used as structural parts in the commercial aircraft and choppers. Such application exploits the capacity of aramid to absorb energy as well as its high tensile strength and stiffness, which are found out to be 2-4 times and 25-30% larger than that of steel and glass fibre, respectively. It is also commonly used as conveyor belt due to its high fatigue resistance as well as excellent adhesion with rubber. More than that, Kevlar products can also be used as safety suits and gloves for the firemen and safety operatives. Lastly, aramid serves as a component of bulletproof armour for being an energy-absorbent material (15)(19).

Meanwhile, the polyolefin is a class of a synthetic polymer thermoplastic type which can be further classified into two subcategories, such as polyethylene (PE) and polypropylene (PP). The term “polyethylene” was firstly invented by a French chemist named Pierre Eugene Marcellin Berthelot in 1869, though the first discoveries were remarked by Pechmann in the 1890s and later by Staudinger in 1920, during which it was introduced through the concept of high molar mass macromolecules obtained from polymerisation process which created a covalent bond between small monomers. Polyethylene has two different sub-clusters, namely Low-Density Polyethylene (LDPE) and High-Density Polyethylene (HDPE), both of which come from a similar process with only a small variation in terms of the reaction pressure. LDPE was firstly found in 1933 by Fawcett and Gibson as an unintentional, waxy solid, by-product of a reaction between ethylene and benzaldehyde on a massive pressure (more than 1000 atm). HDPE was discovered two decades later by Philips along with the discovery of nickel and chromium oxide/metal oxide on silica/alumina as catalysts to produce polyethylene under significantly lower pressure. On another occasion, Ziegler (1953) developed another way to construct polyethylene by using triethyl aluminium as the catalyst to create a low molecular weight polyethylene. Later on, Kaminsky developed a new method to produce PE utilising compound named methyl aluminoxane (MAO) as an activator for metalloocene catalysts, which is approximately 100 times more reactive than that of the Ziegler’s catalyst (20)(21). The documents show that the production of HDPE as plastic products has already exceeded 50 million tons in 2018 (22). In terms of physical and mechanical properties, LDPE and HDPE exhibit distinctive performances. Regardless of the density, which ranges from 0.92-0.94 for LDPE and 0.94-0.97 for HDPE, the differences become more evident regarding the melt temperature, tensile strength, and tensile modulus. LDPE will melt under the heat of 115-122°C, whereas HDPE will melt in 135-140°C (23)(24). Moreover, the tensile strength of HDPE doubles the strength of LDPE, which ranges from 17-34 MPa. Lastly, the tensile modulus of LDPE ranges from 140-210 MPa, whereas the stiffness of HDPE is approximately five times higher than LDPE, ranges from 550-1250 MPa (25)(26).

On the other hand, the development of polypropylene follows a similar direction to that of polyethylene since both of them come from the identical monomer, from which their molecular structures are basically the asymmetric chain of α-olefins with general formula CH2=CHx (x represents
an alkyl group) (27). The melting point and tensile strength of PP is slightly higher than PE, while the stiffness is almost the same as HDPE (28)(29). PP currently serves as the second most popular ingredient of almost every plastic-based product that exists these days, with the estimated value on global market at 155.57 billion dollars in 2026, with the projected production volume to 88 million metric tons at the same timeframe (30).

Another one of the most remarkable derivatives of polyolefin is polyethylene terephthalate (PET), also known under the brand Dacron (31) by Dupont, where 30% of the fabricated product is utilised as plastic bottles and other plastic-related products (32). PET is formed from the extrusion of synthesis product of ethylene glycol and terephthalic acid. It has a higher melting temperature than the other ethylene derivatives (up to 275°C) (33) with the stiffness up to 4 GPa and strength of 80 MPa (34). All of these establish the significant role of PET as one of the principal components of lightweight materials.

3. The application of aramid and polyolefin fibre in bituminous mixture

3.1. Wet vs dry technique

Many synthetic polymer compounds can be used to enhance the characteristic and performance of a bituminous mixture, among them are aramid and polyolefin products. In particular, polyolefin can be poured directly into the heated bitumen to form a polymer-modified bitumen (PMB). Polyolefin, along with other types of polymer such as Styrene-Butadiene-Styrene (SBS), EVA, etc. are typically associated with this method of incorporation. The technique used is called the wet method. Meanwhile, aramid can also be used through direct integration to the mixture of bitumen, aggregate and filler, in a process called dry method. The differences between both techniques are illustrated in figure 2 (35). In the wet process, the polymer is blended with the neat bitumen to form a polymer modified binder (step a-b). The modified bitumen is then mixed together with aggregates to form the AC mixture (step d). Meanwhile, the neat binder is directly mixed with aggregates as well as the polymer (step c-e) in the dry process (36)(37).

![Figure 2. Description of wet and dry process (35)](image)

However, the wet process suffers from a significant issue of segregation that occurs when the polymer-bitumen mixture is not stirred continuously, where the olefin molecules and bitumen do not form a stable reaction; hence olefin molecules will come up on top due to their lower density (38). The segregation phenomena are linked to asphaltene, which is the main component of bitumen whose density
is high, and form is stiff and waxy solid (39). Figure 3 depicts exactly this mechanism, which takes place even at a high temperature (40). The mixture earns more stability as the temperature declines, indicating that a polymer modified bitumen can be categorised as a thermodynamically unstable product. Stability can only be promoted by the kinetic process of constant stirring (41)(42).

Figure 3. SEM Figure of the separation between polymer molecule and bitumen (40)

3.2. Chloride penetration test

The inclusion of polyolefin using the wet method has been found to improve the rheological and mechanical performances of the bitumen. These effects include penetration and softening point, which can be summarised in figure 4 (42)(43)(44)(45).

Figure 4. Effect of (left) PE and (right) PP to penetration and softening point of modified bitumen (42)(43)(44)(45)

It is apparent from the charts that the softening point of the PMB has increased while the penetration grade is reduced by increasing the dosage of polyolefin. Furthermore, another research has found that the inclusion of polyolefin could enhance the complex shear modulus (G*) of the bitumen (35)(44). Conclusively, the addition of polymer product will increase the stiffness, which supports the general knowledge that a PMB holds a significantly higher stiffness than the standard bitumen product. Consequently, the finding also implies that the addition of polyolefin product will yield a higher resistance to permanent deformation (rutting). Thus, the PMB product is suitable to be applied to a high traffic load in high-temperature regions (46)(47). On the other hand, the segregation and instability issues can be solved by means of a chemical solvent named Maleic Anhydride (MA) which enables the polymer molecules to be dispersed uniformly and form a high stability mixture (43), captured by figure 5.
Additionally, PET is also occasionally used as a bitumen modifier, which the application was reported to increase the dynamic shear modulus (G*), and consequently, resistance against rutting for a stone mastic asphalt (SMA) mixture, as shown in figure 6 (48). Further application of PET PMB could also promote the significant use of recycled asphalt mixture with the enhanced results in terms of softening point, tensile strength and moisture susceptibility, with a lower value of penetration, indicating a stiffer material (figure 7) (49)(50). It is interesting that the enhancement is not necessarily in the linear proportion with the increase of polymer dosage; rather, the benefit declines after a specific dosage of approximately 6%. That being shown, it can be concluded that after the critical dosage, the presence of the polymer becomes unused, and even, disturb the bonding inside the mixture. Moreover, the same issue regarding segregation and instability also need to be taken into account for the results. Therefore, the aforementioned treatment with a dispersal promotor substance is recommended.

From the gathered results, it can be concluded that the incorporation of polyolefin, be it PE, PP, or PET, has improved each aspect of the mechanical properties of the bitumen. However, the proper dosage is a consideration, and as suggested from the outcomes, the optimum effect to the results is evident until approximately the dosage of 6%, beyond which the presence of the substance becomes negligible and does not help to improve the performance furthermore. This amount of dosage can then be established...
as the critical dosage. Aside from it, more researches need to be conducted to establish the general dosage for the application in various types of asphaltic mixtures.

The other possible application is the dry method. Aramid can be used with this practice as a fibre reinforced material, which may also be applied in combination with polyolefin. Such combination has become widely popular nowadays, with quite extensive research has been performed to examine the effect on the characteristic of asphaltic mixture. The application of aramid fibre will enhance the mechanical performance physically following its capability to withstand its work even when mixed at a high temperature. Thus, the reinforcing mechanisms are mainly in the form of adhesion and friction between aramid and asphalt matrix so that load transfer between fibre and matrix is enabled, which is comparable to the mechanism of steel bar in a reinforced concrete structure (51)(52). Such mechanism is clearly illustrated in figure 8, where the filament is displaced after a specimen is subjected to tensile loading, leaving a so-called micro-crack due to the loss of adhesion between aramid and asphalt matrix.

**Figure 8.** Bonding mechanism of fibre reinforcement (Left) before and (Right) after cracking (51)

The load transfer mechanism can be explained by observing the pull-out test mechanism and result, illustrated in figure 9, where the examinations were performed at room temperature. The graph could also indicate the impact of having a different loading speed on the performance and mechanism. In combination with the research of Park (52)(53), the full picture of the mechanism can be explained in the following manner. Firstly, at the high temperature, the bitumen matrix has begun to transform into more viscous state, and therefore, the presence of interface bonding and load transfer mechanism between the fibre and mortar matrix becomes critical to ensure that the matrix failure, in which the mortar will become sufficiently deformed, will occur in the end. On the other hand, at relatively low temperature, or high loading speed, the bitumen remains in its stiff/elastic state, and as a result, fibre-matrix adhesion has not gained the full potential and becomes prone to the interface failure. These could also then magnify the benefit brought by the fibre at high temperature.

**Figure 9.** (Left) Pull-out test setup apparatus and (right) pull-out test results with various loading rate at room temperature (51)
The research about the dry method application has been extensively executed. As for the implementation of polyolefin only, investigations conducted using Marshall stability and indirect tensile tests to check the effect on the performance of asphalt concrete mix. Several conclusions that can be drawn from the researches are the increase of fibre dosage up to 1% of total weight of mixture will improve the Marshall stability and fatigue life of bituminous mixture by 58% and 27% respectively, whereas flow is reduced by 142%. Furthermore, the addition of more dosage of the fibre minimises the amount of permanent deformation and air voids, as well as raises elastic modulus of the dense asphalt mix. These phenomena indicate a raise in stiffness of the mix (54)(55)(56).

Meanwhile, there are several contributions of aramid-polyolefin to the mechanical performance of bituminous mix as highlighted in this paper. Firstly, the inclusion in a hot mix asphalt will establish an extended secondary stage as well as a lower creep coefficient from triaxial test that indicates a higher resistance to permanent deformation, both tested with the hot and warm mix asphalt with 0.05% dosage of fibre mixture weight (12)(57)(58). Another paper reveals the effect of fibre length and dosage to the resistance of rutting, both of which are illustrated in figure 10. A lower creep coefficient indicates the less deformation impacted by the cyclic loading subjected to asphaltic mortar specimens. It is apparent that the increase of fibre dosage and length brings a beneficial effect to the mixture resistance. Additionally, the coefficient of the long fibre with a dosage of 0.1% is somehow equivalent to that of the short fibre with 0.5% dosage (51). The results indicate that the mixture becomes stiff enough to withstand more impact without suffering any permanent deformation, which in turn could cause inconvenience should the condition implemented to the real pavement structure.

Figure 10. Creep coefficient as a result of cyclic (left) triaxial (12)(57) and (right) uniaxial loading test (64)

Moreover, both stiffness and fatigue life of the modified mixture with 0.05% dosage of fibre, hot and warm mix, show inclination trends as indicated by the higher value of dynamic modulus depicted in figure 11. Notice that the increase of both parameters for the hot mix mainly occur at the low strain/load level, indicating that the contribution of both fibres is more obvious in a road with high traffic speed. Conversely, the stiffness of warm mix asphalt specimens is not significantly affected by the existence of the fibre, whilst the fatigue life of the specimens is in contrast with the result of hot mix asphalt, indicating a possible different direction of development for a road with the warm mix asphalt applied to it (figure 12). Last but not least, the effect of temperature is also shown herein where the difference in stiffness due to fibre modification mainly appears at the high temperature (59)(60).
Furthermore, tensile strength and energy exhibits the benefit of the fibre additives, both in hot and warm asphalt mixture, ultimately at the high temperature as shown in figure 13 (left), for indirect tensile test and figure 13 (right) for direct tension test results. The results, linked with the outcome of stiffness, yield a conclusion about the better exhibition of fibre-reinforced asphalt mixture at high temperature, where bitumen becomes more viscous, hence allow the fibre to react as a bonding agent to promote more adhesion between aggregate and the matrix and generates a mixture with higher capacity to undergo extra deformation before cracking (51)(61).

Another critical finding is obtained by drawing a comparison between the strength and fatigue life of the asphalt mortar specimen filled with a 19-mm long fibre and 38-mm fibre, where the latter generates better outcomes than the former, as shown in figure 14 by performing semi-circular bending tests. The results indicate that the fibre-reinforced asphalt mixture performs better under high-temperature conditions, as the bitumen becomes more viscous, allowing the fibre to act as a bonding agent and improve the adhesion between aggregate and the matrix, leading to a mixture with higher capacity to undergo extra deformation before cracking.
and direct tension test to obtain toughness (left) and fatigue life (right). The higher phenomena can be attributed to the more significant bonding length, and thus, larger interface area possible between the fibre and the mortar matrix. Both the bonding capacity/adhesion and the frictional interface area contribute to the final mechanical performance of the bituminous mixture. Furthermore, it is also apparent that higher values of tensile strength, toughness or fracture energy and fatigue life can be achieved by adding more fibre to the equation. However, there is also a critical value in which the optimum condition between mechanical performance and the efficiency, beyond which the additional amount of fibre will become less usable and the improvement seems to be negligible (62)(63).

The case presented herein concludes the amount of 0.1% of aramid-polyolefin fibre combination to become the critical dosage (64). Thus, the fibre amount, as well as fibre length, are of paramount parameters to achieve the optimum performance of an asphalt mixture. All the combined knowledge could bring the conclusion that the length, or dimension, of the fibre is more critical to the performance than merely the dosage. This could also be understood from the point of view given in figure 8, which the load transfer mechanism will not be sufficient once the amount of fibre exceeds the needed dosage, and instead, will get clumped and become unnecessary inside the mixture. In contrast, the correct dosage and orientation as well as the length of fibre will ensure the bonding to occur well, and the load transfer mechanism could be performed swiftly. On the other hand, the fibre-reinforced hot asphalt mixture exhibits a less component loss than the control mixes as shown through the Cantabro test, indicating higher resistance to stone loss or ravelling (65). Further assessments also find the positive impact brought by the fibre to the identical mix configuration by mitigating the drainage of the specimens as well as increasing the tensile energy by almost 50% in the dry condition. However, as the moisture begins to partake, the improvement is reduced greatly by almost 40% of the initial finding, confirming the susceptibility of the fibre to moisture (66)(67).

Lastly, another most well-known polymer that is normally employed to the modified asphalt concrete (AC) mix using the dry method is PET, which comes normally in the form of recycled plastic products as a partial substitution of aggregates. Till nowadays, the substitution with the dosage up to 1% one-fourth of the total aggregate can improve fatigue life about twice the control mix (68), whereas the dosage up to one-fourth of the total aggregate decrease rut depth until approximately half of it (69). Furthermore, the replacement could also improve Marshall stability, amplifies the compressive strength by almost 10%, as well as reduces the flow or drainage of the mixture in a direct proportion to the dosage increase. Such applications and positive impacts can be linked to the high natural melting point of PET, which enables to maintain the strength and integrity within the blending temperature (70)(71).

4. Conclusion

The application of polymer product as an admixture in bituminous mixtures has become a regular practice nowadays. There are currently various polymers available to be used, among them are aramid and polyolefin, with two methods of application: the wet process, wherein the polymer is blended with...
the heated bitumen and stirred to form a uniform Polymer Modified Bitumen; and dry method, wherein the polymer is blended directly with the aggregates and bitumen to create a so-called fibre-reinforced asphalt mixture. While aramid is traditionally linked to the dry process due to its capability to withstand the mixing heat, polyolefin can also be used to create the PMB product. Nevertheless, both can also be combined to create a fibre-reinforced asphalt concrete mix, whether hot or warm mixture. The gathered outcomes regarding the application of polyolefin in the wet method have suggested the critical dosage of 6% mixture to achieve the optimum mechanical performance of the mix in terms of, stiffness, penetration and softening point of bitumen, as well as tensile strength and resistance of rutting, whereas the excessive dosage does not guarantee further improvement to the results. However, suitability between bitumen and polymer is already a well-known issue, and one of the possible solutions is to add Maleic Anhydride as the dispersal promoter to avoid the segregation and separation of components. Meanwhile, polyolefin can also be employed using the dry method, with similar effects to the mechanical properties have been discovered where the dosage of up to 1% of mixture weight is taken into account. However, the more popular choice is to combine aramid and polyolefin to the asphaltic mixture using the dry method, which is backed up by numerous researches. First of all, the reinforcement effect can be divided into three mechanisms, which is also load- and temperature- dependent: interfacial bonding/friction between the physical form of aramid and asphalt matrix, adhesion brought by the polyolefin, and load transfer between fibre-matrix; at which the benefit is more apparent at high temperature and low loading speed due to the viscous nature of bitumen that is activated in such situations. The inclusion of aramid-polyolefin combination has several effects on the mechanical performance of both hot and warm bituminous mixture. Firstly, the fibre reinforcement increases the resistance to rutting by approximately 57% and 21% for hot and warm mix asphalt, respectively. The increased amount and length of fibre also increase improvement. Secondly, the fibre will enhance the stiffness and fatigue life of both types of mixture, mainly when subjected to low-frequency loading that is translated to high-speed traffic for the hot mix. In contrast, the same improvement for a warm mix is found within a high strain-level loading. Such inconsistency is worth exploring more in the future. Moreover, tensile strength and toughness of both hot and warm mix asphalt are also improved by the inclusion of the fibre. However, the benefit lasts only until a precise dosage of fibre, after which the states improve quite insignificantly, and thus, nearly negligible. It is also found that the higher length of the fibre contributes to the better performance of the mix. Conclusively, the specific combination of aramid-polyolefin fibre with 0.1% dosage of mix weight and a longer dimension works best to improve the characteristics of the bituminous mixture within the high working temperature using the three working mechanisms. This could be attributed to the network formed between the fibre and mortar matrix, and the interface bonding between them that boost the performance of the mixture. Furthermore, the fibre reinforcement will also react positively when injected to the open graded / Stone mastic asphalt to reduce the potential of raveling. Lastly, PET could contribute to the increase of fatigue life and lower rut depth by employed as partial aggregate substitution. This synthesis is able to sum up the benefits brought by the three most polymer substances to the mechanical and physical characteristics of the bituminous mixture. There is a consideration that the enhanced moisture susceptibility brought by the inclusion of the polymer products due to their capability to absorb the water.

References
[1] Badan Pusat Statistik. No Title. 2019.
[2] Katadata.co.id. 2017 No Title
[3] INDONESIAN COMMERCIAL NEWSLETTER (ICN). 2012 The development of road infrastructure INDONESIAN COMMERCIAL NEWSLETTER
[4] Yang R, Ozer H, Kang S and Al-Qadi I L 2014 Environmental impacts of producing asphalt mixtures with varying degrees of recycled asphalt materials Int. Symposium on Pavement LCA
[5] Zaumanis M 2011 Asphalt is going green: Overview of warm mix asphalt technologies and research results from all over the world Lambert Aca. Pub.
[6] Rubio MC, Martínez G, Baena L, Moreno F. 2012 Warm mix asphalt: An overview J. Clean. Prod. 24 76–84
[7] Mazumder M, Sriraman V, Kim H H and Lee S J 2016 Quantifying the environmental burdens of the hot mix asphalt (HMA) pavements and the production of warm mix asphalt (WMA) Int J. Pavement Res. Technol. 9 3 190–201

[8] Serfass J P and Samanos J 1996 Fiber-modified asphalt concrete characteristics, applications and behavior Asph. Paving Technol. 65 193–230.

[9] McDaniel R S 2015 Fiber Additives in Asphalt Mixtures NCHRP SYNTHESIS 475

[10] Apostolidis P 2017 Experimental and numerical investigation of induction heating in asphalt mixtures Delft Univ. Technol.

[11] Venturini L, Monti F. 2020 Graphene-enhanced recycled asphalt pavements. in: Springer, editor. proceedings of the 5th international symposium on asphalt pavements & environment (APE) Springer 44–54

[12] Delft T 2016 DIBEC Dutch Fibre Trading Delft

[13] Aramid Fiber [Internet]. Greece: Fibremax Ltd. [cited 2020 Mar 30]. Available from: http://wwwaramid.eu/advantages---disadvantages.html

[14] National Asphalt Pavement Association (NAPA) - US Department of Transportation Federal Highway Administration. Designing and Constructing SMA Mixtures — State-of-the-practice. Lanham, Maryland; 2002. Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiktrr d0qTrAhXicnOKHQSPATcQFjABegQBBAB&url=https%3A%2F%2Fwww.ill-asphalt.org%2F%2F5114%2F4890%2F3754%2FNAPA-QIP122-DesigningAndConstructingSAMAMixtures.pdf&usg=AOvVaw3aC5WL2iN86iwuJdDk9K2r

[15] Jassal M and Ghosh S 2002 Aramid fibres - An overview Indian J. Fibre Text Res. 290–306

[16] Aramid 1994 Fiber of poly para-phenylene terephthalamide from the Netherlands Int. Trade Comission (Washington, D.C: U.S)

[17] Zwaag V D S 2009 Structure and properties of aramid fibres. In: Handbook of textile fibre structure - fundamentals and manufactured polymer fibres Woodhead Publish. Limited 394–412

[18] Chang K 2001 Aramid fibers 41–5

[19] Dupont (TM) 2019 No Title Dupont

[20] Hutley T J and Ouederni M 2016 Polyolefins—The History and Economic Impact. In: AlMa’adeed MA, Krupa I. ed. Polyolefin compounds and materials - fundamentals and industrial applications Springer Cham 13–50

[21] Zhong X, Zhao X, Qian Y and Zou Y 2018 Polyethylene plastic production process Insight – Mater. Sci. 1 1 1–8

[22] Garside M 2018 Global production volume of HDPE resin 2016-2022 (in million metric tons) Statista

[23] Jun L, Yuxia Z and Yuzhen Z 2008 The research of GMA-g-LDPE modified Qinhuangdao bitumen Constr. Build Mater. 22 6 1067–73

[24] Al-Haddad A I and Yi-qi T 2009 Effect of polyethylene on life of flexible pavements Constr. Build Mater. 23 3 1456–64

[25] Sauter D W, Taoufik M and Boisson C 2017 Polyolefins, a success story polymers (Basel) 185

[26] Su B, Zhou Y G and Wu H H 2017 Influence of mechanical properties of polypropylene/low-density polyethylene nanocomposites: Compatibility and crystallization Nanomater Nanotechnol 7 1–11

[27] Mather R R 2009 The structure of polyolefin fibres in: Handbook of textile fibre structure fundamentals and manufactured polymer Fibres Woodhead Publish. Lim. 276-304

[28] Hindle C Polypropylene (PP) British Plastics Fed.

[29] Hinsley N 2016 Polypropylene- Is it different from Polyethylene? Global Plastic Sheeting

[30] Reports & data 2019 Polypropylene market to reach usd 155.57 billion by 2026 | reports and data Global News Wire 1

[31] Petresin.org [Internet]. New York: PET Resin Association [updated 2015; cited 2020 Feb 20]. Available from: http://www.petresin.org/news_introtoPET.asp
[32] Poulikakos L D, Poulikakos L D, Papadaskalopoulou C, Hofko B, Gschösser F, Falchetto A C, et al. 2017 Harvesting the unexplored potential of European waste materials for road construction. Resour. Conserv. Recy. 32–44

[33] Horvath T, Kalman M, Szabo T, Roman K, Zs-olds G and Kollar M, et al. 2018 The mechanical properties of polyethylene-terephthalate (PET) and polyactic-acid (PDLLA and PLLA), the influence of material structure on forming. 11th Hungarian Conf. Mater. Sci.

[34] AZO Materials 2003 AZoM AZO Materials

[35] Brasileiro L, Moreno-Navarro F, Tauste-Martínez R, Matos J, Rubio-Gámez M and del C 2019 Reclaimed polymers as asphalt binder modifiers for more sustainable roads: A review. Sustain. 11 3 1–20

[36] Modarres A and Hamedi H 2014 Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes Mater. Des. 61 8–15

[37] Earnest MD 2015 Performance characteristics of polyethylene terephthalate (PET) modified asphalt 95

[38] Polacco G, Berlincioni S, Biondi D, Stastna J and Zanzotto L 2005 Asphalt modification with different polyethylene-based polymers. Eur Polym. J. 2831–44

[39] Hofko B, Eberhardsteiner L, Fussl J, Grothe H, Handle F and Hospodka M, et al. 2015 Impact of malten and asphaltene fraction on mechanical behavior and microstructure of bitumen Mater. Struct. 1–13

[40] Ho C H, Shan J, Wang F, Chen Y and Almonnieay A 2015 Performance of fiber-reinforced polymer modified asphalt two-year review in northern arizona J. Transp. Res. Board 138–49

[41] Taki Z N M, Abed A H and Al-mosawh H 2019 Based on strength ratio and fracture energy parameters I

[42] Attaelmanan M, Feng C P and Ai A H 2011 Laboratory evaluation of HMA with high density polyethylene as a modifier Constr. Build Mater. 25 5 2764–70.

[43] Vargas M A, Vargas M A, Sánchez-Sólis A and Manero O 2012 Asphalt/polyethylene blends: Rheological properties, microstructure and viscosity modeling Constr. Build Mater. 45 243–50

[44] Roman C, Cuadri A A, Liashenko I, García-Morales M 2016 Partal P. Linear and non-linear viscoelastic behavior of SBS and LDPE modified bituminous mastics Constr. Build. Mater. 123 464–72

[45] Fernandes S, Costa L, Silva H and Oliveira J 2017 Effect of incorporating different waste materials in bitumen Cienc e Technol dos. Mater. 29 1 204–9

[46] Polacco G, Stastna J, Biondi D and Zanzotto L 2006 Relation between polymer architecture and nonlinear viscoelastic behavior of modified asphalts Curr. Opin. Colloid Interface Sci. 230–45

[47] Yu R, Fang C, Liu P, Liu X and Li Y 2015 Storage stability and rheological properties of asphalt modified with waste packing polyethylene and organic montmorillonite Appl. Clay Sci.1–7

[48] Zheng C, Shao-peng W, Zu-huang Z and Jie-sheng L 2008 Experimental evaluation on high temperature rheological properties of various fiber modified asphalt binders 15 135–9

[49] Ahmadinia E, Zargar M, Karim M R, Abdelaziz M and Ahmadinia E 2012 Performance evaluation of utilization of waste Polyethylene Terephthalate (PET) in stone mastic asphalt Constr. Build. Mater. 36 984–9

[50] Sreram A, Leng Z, Padhan R K and Qu X 2018 Eco-friendly paving materials using waste PET and reclaimed asphalt pavement HKIE Trans Hong Kong Inst. Eng. 25 4 237–47

[51] Apostolidis P, Liu X, Daniel G C, Erkens S and Scarpas T 2019 Effect of synthetic fibres on fracture performance of asphalt mortar Road Mater. Pavement Des. 0 0 1–14

[52] Park P, El-Tawil S and Naaman A E 2017 Pull-out behavior of straight steel fibers from asphalt binder Constr. Build. Mater. 144 125–37

[53] Wheat M 2007 This study was supported by the US Department of Transportation, Office of the Secretary Grant DTOS59-06-G-00026

[54] Tapkin S 2008 The effect of polypropylene fibers on asphalt performance Build Environ. 43 6 1065–71

[55] Bayat R and Talatahari S. 2016 Influence of polypropylene length on stability and flow of fiberreinforced asphalt mixtures Civ. Eng. J. 2 10 538–45
[56] Ahmed A I 2012 Laboratory investigation into the impact of polypropylene fiber content on temperature susceptibility of dense graded mixtures 5 4 424–38
[57] Kaloush K, Waheed A, Zeiada, Biligiri K P, Rodezno M C and Reed J Evaluation of fiber-reinforced asphalt mixtures using advanced material characterization tests
[58] Mello L G, Kaloush K E and Biligiri K P 2008 Evaluation of fiber reinforcement in hot mix asphalt using advanced material characterization tests First Pan. Am. Geosynth. Conf. Exhib. 2-5 March 2008, Cancun, Mex. 0–7
[59] Ho C H, Shan J, Wang F, Chen Y and Almonnieay A 2016 Performance of fiber-reinforced polymermodified asphalt: Two-year review in Northern Arizona Transp. Res. Rec. 2575 138–49
[60] Stempihar J J, Souliman M I and Kaloush K E 2012 Fiber-reinforced asphalt concrete as sustainable paving material for airfields Transp. Res. Rec. 2266 60–8
[61] Daniel C G failure performance of synthetic fibre-reinforced warm-mix asphalt FAILURE PERFORMANCE OF SYNTHETIC FIBRE
[62] Apostolidis P, Liu X, Daniel C G and Erkens S 2019 fracture performance of synthetic fibre-reinforced asphalt mortar fracture performance of synthetic fibre-reinforced asphalt mortar section of pavement Engineering Faculty of Civil Engineering and Geosciences Delft University of Technology Department of C
[63] Daniel C G, Liu X, Apostolidis P, Erkens S and Scarpas A 2019 Impact of synthetic fibres on asphalt concrete mix Bitem. Mix Pavements VII 2019 0–0
[64] Daniel C G 2020 Analysis of the effect of using fiber aramid-polyolefin on the strength, stiffness, and durability of warm-mix asphalt J. Tek. Sipil ITB 27 1 9–16
[65] Takaikaew T, Tepsriha P, Horpibulsuk S, Hoy M, Kaloush K E and Arulrajah A 2018 Performance of fiber-reinforced asphalt concretes with various asphalt binders in Thailand J. Mater. Civ. Eng. 30 8
[66] Slebi-Acevedo C J, Pascual-Muñoz P, Lastra-González P and Castro-Fresno D 2019 Multi-response optimization of porous asphalt mixtures reinforced with aramid and polyolefin fibers employing the CRITIC-TOPSIS based on Taguchi methodology Materials (Basel). 12 22
[67] Slebi-Acevedo C J, Lastra-González P, Indacochea-Vega I and Castro-Fresno D 2020 Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers Constr. Build Mater. 234 117224
[68] Baghaee Moghaddam T, Soltani M and Karim M R Evaluation of permanent deformation characteristics of unmodified and Polyethylene Terephthalate modified asphalt mixtures using dynamic creep test Mater. Des. 2014 53 317–24
[69] Rahman W M N W A and Wahab A F A 2013 Green pavement using recycled Polyethylene Terephthalate (PET) as partial fine aggregate replacement in modified asphalt Procedia Eng. 124–8
[70] Saiyari D M, Contreras L R Z, Cabanag K L N, De Alday H A, L. P J P and Manio M V M 2016 Effects of Temperature in Mechanical Properties of Stone Mastic Asphalt (SMA) Mixture with Waste Polyethylene Int. Conf. Environ. Qual. Concern, Control Conserv.
[71] Ahmad A F, Razali A R, Razelan I S M 2017 Utilization of polyethylene terephthalate (PET) in asphalt pavement: A review. IOP Conf. Ser. Mater. Sci. Eng. 203 1