International Journal of Pavement Research and Technology (2023) 16:1196–1216
https://doi.org/10.1007/s42947-022-00190-x

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Chinese Society of Pavement Engineering

ORIGINAL RESEARCH PAPER

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Dynamic Modulus and Phase Angle of Asphalt Concrete Mixtures Containing Municipal Solid Waste Incinerated Fly Ash as Mineral Filler Substitution

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Received: 2 February 2022 / Revised: 10 April 2022 / Accepted: 12 April 2022 / Published online: 20 May 2022

Abstract
Waste and recyled materials have been introduced in asphalt concrete mixtures as substitute for raw aggregates along with the efforts towards constructing sustainable pavements. Municipal solid waste incinerated (MSWI) fly ash is among the alternative materials that can be be used as substitute for the natural mineral filler. However, the effect of using (MSWI) fly ash on the mechanical properties of bituminous mixtures is fragmented and not thoroughly evluated. Additionally, various studies assessed the performance of asphalt mixtures with (MSWI) fly ash as filler replacement in terms of indirect tensile strength, moisture susceptibility, frost resistance and Marshall stability. Therefore, there is a need for the evaluation and realistic prediction of the performance of asphalt concrete mixtures with (MSWI) fly ash used as filler substitution. The objective of this research study is characterising asphalt concrete mixtures with (MSWI) fly ash used as subtitute for the limestone filler, notably 0%, 25%, 50%, 75% and 100% by weight of aggregates and evaluating their performance in comparison with the control mix. This is conducted mechanistically through linear viscoelastic characterisation. Linear viscoelastic characterisation comprises measurement of the stiffness of the mixture expressed in terms of dynamic modulus and the extent of elastic and viscous response expressed in terms of phase angle. The findings revealed that the use of (MSWI) fly ash in asphalt concrete mixtures as filler substitution increased the rutting resistance up to 50% of incorporation and the resistance to low temperature cracking when incorporated in percentages higher than 25%.

Keywords Dynamic modulus · Phase angle · Asphalt concrete mixtures · Municipal solid waste incinerated fly ash · Filler replacement · Mastercurves

1 Introduction

Characterization of the viscoelastic properties of asphalt concrete mixtures mainly embraces measurement of the extent of elastic and viscous response and stiffness of the asphalt mixture at a given temperature and loading frequency [1]. Complex modulus test is one of the most frequent methods used for linear viscoelastic characterization of asphalt concrete mixtures [2, 3]. This is accomplished by identifying two viscoelastic properties which are the two components of complex modulus, namely, dynamic modulus and phase angle [4]. Dynamic modulus was introduced as a substitution to the resilient modulus in the mechanical empirical pavement design guide (MEPDG) to characterize the asphalt mixture properties and reflects its loading frequency and temperature dependent behaviors, it is defined as the stiffness and absolute value component of the complex modulus stiffness and it characterizes the viscoelastic

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behavior of asphalt concrete mixtures [5, 6]. It is a material characteristic used to reliably determine the ability of a mixture to resist fracture and rutting under defined conditions and measure the mixture's response characteristics that are strongly associated to the occurrence of pavement distresses [5, 7, 8]. At very high temperatures, the asphalt binder is extremely small, thus the dynamic modulus greatly depends on the aggregate's stiffness. However, at low temperatures, the dynamic modulus is dependent on the asphalt binder glassy modulus in addition to the structure of the aggregate [9]. Bi et al. [10] revealed that the dynamic modulus of asphalt mixture is significantly influenced by the type of binder and the binder to filler ratio. Additionally, the authors indicated that there is a good linear correlation between the asphalt complex shear modulus and the asphalt mixture dynamic modulus [10].

On the other hand, the phase angle is the viscoelastic component of the complex modulus that characterizes the extent of elastic and viscous behavior of the asphalt binder, known as the loss and storage modulus [4, 5, 11]. Higher values of phase angle imply a more viscous response under loading with subsequent higher dissipation of energy [12, 13]. Migliori et al. [14] associated the temperature at which the phase angle attained a value of 45° to the development of considerable top-down fatigue cracking in most European pavements [14]. Additionally, Button et al. related the level of low-temperature cracking to the phase angle [15].

The dynamic modulus and phase angle have been commonly used as verifying parameters for the characterization of the tensile viscoelastic properties of asphalt mixtures [16, 17]. As a matter of fact, higher phase angle is required for better cracking performance while higher dynamic modulus is desired to enhance the asphalt mixtures rutting resistance [18].

The dynamic modulus and phase angle of asphalt concrete mixtures are affected by various physical and environmental factors notably aggregate gradation, temperature, frequency, moisture and aging condition [19]. Additionally, other attributes can greatly affect the performance of asphalt concrete mixtures such as the type, texture, shape, gradation, physical and chemical properties of the mineral filler [20]. Mineral filler is defined as a portion of fine aggregate that is passing the 75 μm sieve size at percentages from 70 to 100% according to ASTM standards [21] and defined as a portion of fine aggregate that is passing the 63 μm sieve size at percentages from 70 to 100% according to EN standards [22]. The role of mineral fillers in hot mix asphalt (HMA) is beyond filling air voids. In fact, mineral fillers serve a dual purpose when used in asphalt concrete mixtures and can optimize the properties of asphalt binder [23–25]. From one side, mineral filler is considered inert as the portion that is larger than the asphalt binder film thickness behaves as mineral aggregate and fills the voids between the mineral mix grains and from the other side, it is considered active material as the portion that is finer than the asphalt binder film thickness blends with the binder to form a mastic film that stiffens the mixture [24, 26]. Moreover, mineral fillers affect different properties of asphalt concrete mixture such as workability, durability, fatigue behavior, long-term aging characteristics of asphalt concrete mixtures [27]. Using inadequate amount of filler material may increase the rutting potential of asphalt mixtures and using excessive amount may decrease the resistance of asphalt mixtures in terms of low temperature [28, 29]. Additionally, mineral fillers reduce the moisture damage and improves frost resistance, strengthen the interaction between asphalt binder and aggregates, increase the stiffness of the mixtures by adding rigid materials in less rigid matrix [30].

Mineral fillers differ by geometry, shape, surface texture, surface area, mineral composition and void content which makes their effect on the characteristics and performance of HMA mixtures different [31, 32]. It is well documented that mineral filler exerts a significant effect on the asphalt concrete mixture as well as on the asphalt binder [33, 34]. Actually, asphalt binder viscosity and consistency are primary modified when the asphalt concrete binder and the aggregates are mixed together, a binder-filler mastic is formed referable to the mineral filler fineness that is usually of thicker consistency to ensure aggregate coating and enhance adhesivity and cohesion of HMA mixtures [23]. It is hypothesized that replacing the conventional mineral filler in HMA mixture by a filler of a different material will cause different mixture performance. Similarly, optimum asphalt binder content of HMA mixtures, rheological properties of asphalt binder and mixture properties are also affected by the addition of mineral fillers in HMA mixtures as the surface area of the mineral filler particles is increased [24] Consequently, the selection of the appropriate filler type in asphalt concrete mixtures is very crucial for optimal mixture performance [20, 24].

The use of sustainable alternatives and recycled waste materials in road paving section has significantly increased lately by as a consequence of economic and environmental concerns [20]. Different studies have examined the use of waste as natural or commercial filler substitution in different types of asphalt concrete mixtures [23, 35, 36].

Ground limestone, commonly used as mineral filler in a traditional asphalt concrete mixture, can be substituted by alternative waste materials such as fly ash [37], brick debris [26], zeolite tuffs [28], lime kiln [26], construction demolition waste [38], glass waste powder [20, 39, 40], coal waste powder [20], sewage sludge ash [23], biomass incineration ash [20], waste oyster shells [26], rice husk ash [41, 42], powdered iron [43] asphaltite [44] and others [20].

Municipal solid waste incinerated (MSWI) fly ash, a waste material, is among the long list of material to be used as conventional filler replacement in bituminous mixtures. The rising interest in using fly ash, especially municipal solid waste incineration fly ash, as filler substitution is due to its engineering properties, environmental benefits and its processing cost making it a way to get rid of the waste material while maintaining or even improving the asphalt mix properties [45]. This supports cleaner production by decreasing emissions, air pollution and wastes associated with mining of non-renewable materials [46].

2 Background

Along with the evolution of traffic and road paving industry, construction and non-traditional materials have been evolved [47]. The rationales were the environment protection and the deficiency of traditional materials which have supported the tendency toward being more environmentally conscious and evaluating secondary and tertiary materials and alternative sources to be integrated in the roadway construction sector. As a matter of fact, non-conventional materials are defined as materials that do not have the needed properties as per specifications [48]. Different recycled materials and waste by-products have been examined for utilization flexible pavement from surface to underneath layers [49]. Efforts are being placed toward the effective application of alternative materials and waste by-products in the roadway construction sector to achieve sustainable asphalt pavements [50].

In this regard, various research studies have been conducted to evaluate the use of recycled and waste materials as filler in asphalt concrete mixtures [51, 52]. Sargin et al. [53] investigated the use of rice husk ash in HMA mixtures as substitute for the conventional limestone filler. For this purpose, asphalt concrete mixes were prepared and four different replacement percentages were used: 25%, 50%, 75% and 100%. Based on the findings of this research, the use of 50% of rice husk ash as filler in HMA mixtures enhanced the mixes in terms of Marshall stability and flow [53].

Woszuk et al. [28] investigated the potential use of zeolite tuffs as mineral filler in warm mix asphalt. The alternative zeolite material was used in the mentioned study with two other filler materials: lime and hydrated lime in different proportions. The research outcomes indicated that zeolite tuffs can be used in warm mix asphalt as partial replacement of the traditional lime filler without affecting negatively the properties of the binder. The addition of the hydrated lime in warm mix asphalt improved the frost resistance of the mixture [28].

In a study conducted by Woszuk et al. [26], brick debris, a waste material collected from demolition of buildings, was used in asphalt concrete mixtures as mineral filler. Different asphalt mixes were prepared with several combination of lime and brick filler. The results revealed that the use of this waste material in asphalt concrete mixtures enhanced its thermal cracking resistance however, the use of brick debris as filler replacement in asphalt concrete mixture should be limited to 50% to sustain the adequate stiffness and frost resistance of the mixes [26].

During a laboratory investigation (Tenza-Abril et al. 2014) examined the effect of sewage-sludge ash used as filler on the physical and mechanical properties of bituminous mixtures. Mixes with the waste filler material were assessed in terms of permanent deformation, cantabro, indirect tensile strength, water sensitivity and resilient modulus tests. The results showed that the substitution of the conventional filler from 2 to 3% sewage sludge ash may be used as filler material in asphalt concrete mixtures [23].

Modarres and Rahmanzadeh [20] conducted an experimental program to evaluate the use of coal waste powder and coal waste ash as substitute for the conventional limestone filler in HMA mixtures. The obtained findings revealed that the incorporation of coal waste powder and coal waste ash in HMA mixtures enhanced the Marshall stability, indirect tensile strength and resilient modulus. Additionally, the use of similar proportions of coal waste and limestone filler optimized the properties tested and increased the moisture resistance of the mixes [20].

A laboratory investigation was conducted by Simone et al. [54] to examine the applicability of using glass waste powder as substitute for limestone filler in asphalt concretes mixtures with modified and unmodified asphalt binders. The research study covered three sections including filler, mastic along with mixture characterization. The findings of the investigation revealed that glass powder waste increased the mastic stiffness and showed to enhance the resistance to permanent deformation of the asphalt mixture confirming its suitability of application to be used as surrogate for the natural mineral filler [54].

Arabani et al. [55] assessed the impacts incorporating four different waste types including glass waste powder, waste brick powder, rice husk ash and stone dust to substitute limestone filler in HMA. For this purpose, the properties of the asphalt concrete mixtures were examined by Marshall, indirect tensile fatigue test and indirect tensile stiffness modulus. The results showed that mixes having waste glass powder and mixes having waste brick powder as filler substitute for limestone filler developed higher fatigue life and better performance comparing with the other mixtures [55].

Several studies have been carried out in the past for optimal incorporation of fly ash in bituminous mixtures and to understand the performance of asphalt concrete containing fly ash as a replacement to the mineral filler. The incorporation of alternative materials in bituminous mixtures has become widespread especially with the deficiency of natural resources [56]. In a study in 2016, Mistry and Roy [57] assessed the use of fly ash collected from a thermal power plant, as a substitute for the natural mineral filler up to 4% by weight of aggregates. The results revealed that the partial use of this type of waste material improved Marshall stability and higher strength was observed for the mixes with fly ash substitution compared to the control mix [57]. Additionally Asi and Assa'ad [58] investigated the incorporation of oil shale fly ash in different percentages (0%, 10%, 50% and 100%) in HMA mixtures as filler substitution. The results showed that the use of oil shale fly ash enhanced the strength and the moisture resistance of the mixtures [58]. Also, a research study conducted by Woszuk et al. [37] revealed similar results when evaluating the tensile strength of asphalt mixtures containing two different types of industrial fly ash used as alternative filler replacement. The fly ash used in this study were class F fly ash obtained from the combustion of coal in a power plant and class C fly ash acquired from lignite combustion in a power plant. Asphalt concrete mixes were prepared with three different replacement percentages: 25%, 50% and 75%. The results also revealed that the partial substitution of mineral filler by class F fly ash or class C fly ash had a positive effect on the moisture and frost resistance, confirming the suitability of application of both fly ash classes as substitute for the conventional mineral filler [37]. A comprehensive study was conducted by Tapkin [59] on evaluating the impact of using fly ash obtained from the combustion of coal as filler substitution on the mechanical properties of HMA mixtures. For this purpose, class C fly ash and two different types of class F fly ash were used to partially replace the mineral filler in the bituminous mixtures. The author found out that the use of industrial fly ash in asphalt mixtures enhanced Marshall stability and decreased the flow values. Fatigue life was also increased when using fly ash compared to that of the mix without any fly ash addition especially for the mix containing the coarsest particles of class F fly ash [59]. Gedafa and Suleiman found equivalent results when assessing Marshall stability and flow of asphalt concrete mixes with class C fly ash [60].

Additionally, Romeo et al. [61] carried out a laboratory investigation to evaluate the performance of bituminous mixtures using washed and unwashed stabilized municipal solid waste incinerator fly ash to replace the mineral filler at low and intermediate temperatures. The study outcomes indicated that washed stabilized municipal solid waste incinerator fly ash can be used as substitute for the mineral filler as the mechanical properties of the asphalt mixture prepared with this type of waste material were in good agreement with the mechanical properties of the reference control mix [61].

The outcomes of the research study carried out by Woszuk et al. [37] and Yan et al. [27] revealed that the partial substitution of mineral filler by industrial or municipal solid waste incineration fly ash have negative and positive effects on the low and high temperature properties, respectively, as compared to the control mix [27, 37].

Conversely, Churchill and Amirkhanian [62] investigated the use of coal ash (bottom and fly ash) as aggregate substitute in asphalt concrete mixtures. Three coal ash percentages were (0%, 6% and 8%) used to partially replace fine aggregates in bituminous mixtures. The outcomes of the study demonstrated that the use of coal ash as fine aggregate replacement had a moderate negative effect on short-term tensile strengths [62].

Similarly, Yan et al. [27] evaluated the performance of bitumen mortar containing (MSWI) fly ash by means of softening point, penetration test, dynamic shear rheometer, bending beam rheometer and Brookfield viscosity tests. The experimental findings revealed that the addition of (MSWI) fly ash caused a reduction in phase angle, penetration and creep rate whereas resulted in an increase in complex shear modulus, softening point, rutting factor and creep stiffness. This is an indicator that adding (MSWI) fly ash had a detrimental effect on the bitumen mortar on the high loading frequencies but a positive effect on the low loading frequencies [27].

Finally, during a laboratory investigation, Ali et al. [63] examined the effect of fly ash obtained from burning bituminous coal on the mechanical properties of asphalt concrete mixtures. Therefore, different proportions of fly ash content (0%, 50% 100%) were studied as replacement of the mineral filler. The result of the study indicated that the use of fly ash as substitute for the mineral filler enhanced the stripping resistance and the resilient modulus. Furthermore, substituting the mineral filler by fly ash decreased moderately the performance of asphalt mix in terms of permanent deformation and serviceability index. However, the amount of surface cracking increased when adding fly ash as filler replacement [63].

From the above discussions and literature reviews, it is shown that the incorporation of fly ash in asphalt concrete mixtures as filler replacement has been already applied but the research and lack systematic study. Therefore, it is important to build assessment indicators of (MSWI) fly ash that adapts for asphalt concrete mixtures and to characterize and verify its effect on the performance of asphalt mixtures through comprehensive laboratory testing.

3 Objectives and scope

Achieving sustainability in road construction can be done by incorporating environmentally friendly concepts into this sector such as the use of substitutes for the natural conventional aggregates in HMA mixtures. (MSWI) fly ash is among the list of materials to be used as conventional filler replacement in bituminous mixtures. On the other hand, the effect of incorporation of fly ash, specifically (MSWI) fly ash is still fragmented and at the research stage and is not fully investigated as the findings of the available literature are conflicting and insufficient. Additionally, the outcomes of the existing literature assessed the effect of using such waste material by means of indirect tensile strength, moisture susceptibility, frost resistance, Marshall stability and flow. Moreover, studies that investigate the linear viscoelastic properties and performance properties of asphalt mixtures containing (MSWI) fly ash using dynamic modulus and phase angle is limited. The overall objective of this study is to investigate the use of (MSWI) fly ash as a sustainable replacement of the natural filler extracted from non-renewable resources in asphalt concrete to evaluate the suitability of its application, fill the gaps presented in the existing literature and strengthen knowledge in this field. Moreover, this research study evaluates the performance of bituminous mixtures containing various percentages of (MSWI) fly ash used as a substitute for the conventional limestone filler in terms of overall dynamic modulus and phase angle functions. The extent of work of the ongoing study adopts an experimental investigation that aims at assessing the effect of four different substitution percentages of MSWI fly ash on the performance of asphalt concrete mixtures, notably 0% (control mix), 25%, 50%, 75% and 100% by total weight of mineral filler. Based on the experimental results, the feasibility of incorporating (MSWI) fly ash as filler substitution in asphalt concrete mixtures is investigated comparing with the control mix. Finally, the (MSWI) fly ash of various regions has different performance due to the variation in formation conditions, thus it is important to evaluate the performance of the representative (MSWI) fly ash in one region and its influence on asphalt concrete mixtures.

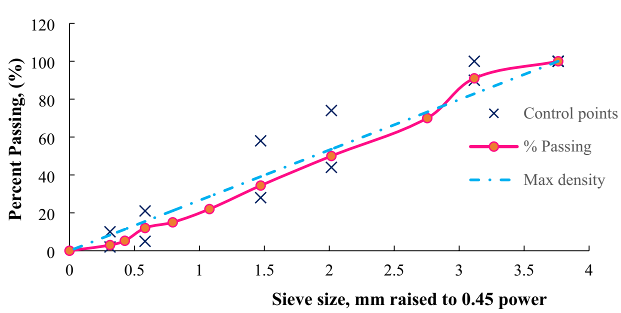

Fig. 1 12.5 mm aggregate gradation

4 Methodology

4.1 Materials

In this study, crushed limestone obtained from different local stockpiles is utilized as coarse and fine aggregates. Figure 1 presents the gradation chart for the blend. Figure 1 also displays the control points (CP) and the maximum density line for the used blend according to AASHTO M 323 [64]. The mix design is dense graded and has a nominal maximum aggregates size of 12.5 mm. The aggregate gradation was selected after checking that it passes the Superpave criteria [65] and the Bailey Conformity Equations [66] from a set of investigated gradations that are commonly used by local contractors. The latter was selected to assess the aggregate gradation to assure a good packing and aggregate interlock so the mix will resist permanent deformation. The performance grade of virgin asphalt used to prepare asphalt concrete mixes was found out to be PG64-10. The used (MSWI) fly ash is obtained from a local municipal solid waste plant. Municipal solid wastes are wastes generated from different sources such as houses, hospitals and industries [67]. These wastes are hazardous when disposed in landfill as they emit harmful gasses. Incineration is a common solution to minimize waste's harmful effects [67]. Actually, incineration is the major treatment method that targets the goal of "Zero waste and Landfill" in the future as it decreases the wastes volume and mass, in addition to achieving energy recovery and disinfection [68]. To determine the properties of (MSWI) fly ash used, chemical and physical characteristics were assessed. Table 1 shows the classification of the (MSWI) fly ash according to its physical properties and chemical composition which are important for evaluating the suitability of the use of (MSWI) fly ash in HMA mixtures. The presence of heavy metals and constituents such as chlorides, aluminum and sulfates as shown in Table 1, is explained by the fact that

Table 1 Chemical and physical properties of (MSWI) fly ash

Element weight (%)	CaO	SiO2	Al2O3	Fe2O3	SO3	MgO	TiO2	P2O5	Na2O	K2O	Cl	MnO	Cr203
	30.49	16.23	10.71	5.79	3.51	2.65	3.29	1.18	0.88	0.66	0.59	0.07	0.06
Insoluble matter (% by weight)	23.33												
Loss on ignition (% by weight)	23.58												
Moisture content (% by weight)	2.56												
Specific gravity	2.421												
Color	Grey												

the used (MSWI) fly ash is not generated from an industrial controlled process [69]. The (MSWI) fly ash used in this investigation is an aluminosilicate ash, plays the role of pozzolanic agent that is stabilized, soaked in water and NaOH solution, as a treatment technique to minimize future release of toxic trace elements and heavy metals and achieve ecological and economic benefits. Solidification or Stabilization is the process of adding chemical curing agents (organic or inorganic) for the purpose of making heavy metals and toxic substances into low toxicity substances [70]. NaOH is an example of inorganic chemical agents [70, 71]. However, fly ash can be used without treatment in asphalt concrete mixtures as it will be solidified by asphalt binder, consequently treatment of fly ash for its application in bituminous mixtures will only reduce the environmental impact and enhance asphalt concrete mixture quality and mechanical properties [72–74]. A high proportion of calcium oxides (CaO) is significantly present (30.49%) in the used waste material as shown in Table 1, which can enhance the adhesion between the aggregates and the asphalt binder and improve the mixture stability making this type waste suitable for use in asphalt concrete mixtures [75]. According to ASTM C618-19, fly ash is classified into two classes class F and class C and its classification is mainly dependent on its chemical composition. The main separator for the different classification is the total content of silica (SiO_2), aluminum (Al_2O_3) and iron oxide (Fe_2O_3) in fly ash as minimum of 50% in class C and 70% in class F [76]. Despite that, the (MSWI) fly ash used herein do not meet the chemical requirements for class C or F as the minimum content of the total content of silica, aluminum and iron oxide is around 32.73%. Similarly, according to the Canadian Standards Association fly ash is mainly classified to the its calcium oxide content into three categories Type F, Type CI and type CH indicating low calcium oxide content (less than 8%), intermediate calcium oxide content (between 8 and 20%) or high calcium oxide content (higher than 20%) [77]. The presence of high content of strong bases such as calcium oxides may reduce asphalt binder aging [78]. Additionally, it is demonstrated that the physical properties and the chemical composition, especially, the content of Al_2O_3, CaO, SiO_2, SO_3 of the fly ash strongly influence the rheological properties of the mastic [37, 79]. Additionally, the research findings of a study conducted by Sharma et al. revealed that higher moisture and thermal cracking resistance are developed in mixtures with high CaO content [80]. Although previous research results showed that ashes with high silica content are less suitable as filler materials, it is established that silica-alumina waste materials in asphalt concrete is found to enhance early and long-term strength, decrease rutting potential and improve durability and temperature sensitivity making its applicability as mineral filler in asphalt concrete mixtures suitable [20, 41, 81].

4.2 Specimens preparation

The (MSWI) fly ash was used to replace the portion of fine aggregates passing the 75 µm sieve size with percentages of 0% (control mix), 25%, 50%, 75% and 100% by total aggregate weight. For every mixture, the mineral aggregates and (MSWI) fly ash filler were heated overnight at the mixing temperature of 160 °C and compacted at a temperature of 150 °C. To simulate the short-term aging, asphalt concrete mixtures were conditioned at 160 °C. This protocol was reported by the NCHRP Report 691 [82]. Three replicates were prepared for each replacement percentages for the dynamic modulus and phase angle testing. Loose asphalt concrete mixtures were compacted using a Superpave Gyratory Compactor (SGC). Asphalt concrete mixtures can be compacted in different ways depending on the type of the test to be conducted, the type of technology being used and the applicable regulations [83]. Gyratory compactor is considered one of the most commonly used device to compact asphalt concrete mixtures along with Marshall compactor, asphalt roller compactor and vibrating compactor [28]. These methods differ in terms of the compaction force, the compaction time, the sample final shape, the aggregate orientation and the way of transmitting the compaction force [84]. The asphalt concrete sample is compacted in a SGC to the needed density or rotation number while being concurrently sheared [85]. The compaction in a SGC reflects better the compaction in real field conditions than Marshall method, bulk densities obtained when compacting a sample in a SGC are higher and closer to field to the filed experience, as well significant coefficients can be determined when using a SGC such as compaction coefficient, mixture resistance index and mixture stability index [86–88]. As a matter of fact, samples in a SGC are subjected to a constant compaction pressure of 600 kPa at a gyration rate of 30 gyrations per minute and at a gyration angle of 1.25° [66]. According to Wrobel et al., this compaction method is essential for very thin layers of asphalt concrete [89]. Furthermore, Tapkin and Keskin found out that samples compacted in a gyratory compactor develop a skeleton that is less susceptible to permanent deformation than samples compacted using Marshall compactor [90]. Calberg et al. found out that mixes compacted with the SGC had lower air voids and higher number of fractured aggregates than mixes compacted with Marshall hammer indicating that SGC mimic the real conditions [91]. For this purpose, cylindrical asphalt concrete cores of diameter 150 mm and height 175 mm were compacted using SGC. The 150 × 110 mm specimens were obtained after coring and sawing the compacted samples from the 150 × 175 mm specimens. The target air void content was set to be 7.0% ± 0.75%. As determined by the Superpave volumetric mix design, the optimum asphalt binder content of the unmodified mix (0% (MSWI) fly ash) was 4.3% by mass. Dynamic modulus and phase angle testing were conducted according to AASHTO T 342 [92]. All asphalt concrete specimens were tested for dynamic modulus and phase angle at three temperatures of 4, 20 and 40 °C and six different loading frequencies of 20, 10, 5, 1, 0.5 and 0.1 Hz. The load level was auto-adjusted to ensure a maximum value of 70 με as maximum axial strain. The averages of the dynamic modulus and phase angle of the three specimens were determined. Time Temperature Superposition Principal was used to develop the dynamic modulus and phase angle mastercurves at a reference temperature of 20 °C.

4.3 Dynamic modulus mastercurves

The sigmoid expression presented in Eq. (1) was used for fitting the dynamic modulus mastercurves:

$$\mathrm{Log}(|E*|) = a + \frac{b}{1 + e^{c-d(\log(\mathrm{fr}))}}, \tag{1}$$

where, $|E^*|$: dynamic modulus, MPa, a, b, c and d: fitting parameters, fr: reduced frequency, Hz.

The fitting parameters can be determined by fitting laboratory tested dynamic modulus mastercurve. To fit the shift factors as a function of temperature, a second-degree polynomial expression is used as shown in equation (2).

$$\mathrm{Log}(aT) = a_1T^2 + a_2T + a_3, \tag{2}$$

where a_1, a_2 and a_3 are regression parameters.

The tested average dynamic modulus values at the temperatures for the control mix are presented in Fig. 2. Additionally, Fig. 2 shows the time temperature superposition principle applied horizontally to shift the dynamic modulus data to construct the dynamic modulus mastercurve. Using equation (1), the horizontally shifted dynamic modulus data values were fitted. Fig. 3 presents the plot of the shift factors along with the fitted shift factor function determined by equation (2) for the control mix.

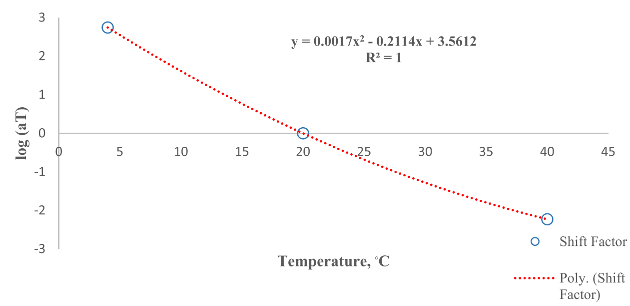

Fig. 3 Temperature shift factor function for the HMA control mix

4.4 Phase angle mastercurves

The phase angle is an indicator of the elastic and viscous properties of the asphalt mixture being tested. It is defined as the angle at which the stress lags the strain [7, 93]. A pure viscous material has a phase angle of 90° and a pure elastic material has a phase angle of 0°. The phase angle is a crucial parameter to better understand the storage modulus and the viscous/extent of loss modulus [94]. The phase angle can be determined from the dynamic modulus test at a given temperature and frequency. It is expressed using the mathematical expression presented in Eq. (3).

$$\delta = \frac{T_i}{T_\mathrm{p}} \times 360°, \tag{3}$$

where, T_i is the time lag, expressed in seconds, between a cycle of stress and strain. T_p is the time for a cycle of stress, expressed in seconds.

The phase angle mastercurves can be developed using the same temperature shift factors used for the dynamic modulus mastercurves. The developed phase angle mastercurves should be a single smooth curve assuming that the asphalt

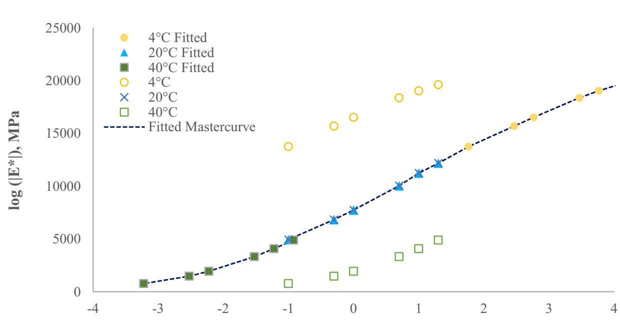

Fig. 2 Dynamic modulus mastercurve for the HMA control mix

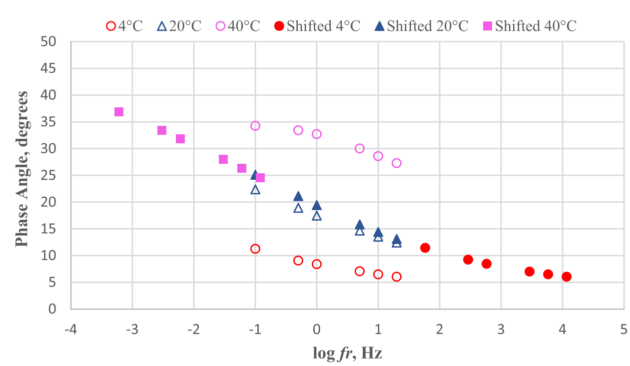

Fig. 4 Phase angle mastercurve for the control mix

concrete material is thermo-rheologically simple [4]. Figure 4 presents the phase angle mastercurve for the control mix having 0% (MSWI) fly ash as filler substitution. Figure 4 also shows the tested phase angle data value which were shifted horizontally using shift factors. The shifted phase angle data values shown in Fig. 4 form a smooth curve except for some deviating points.

It is documented that fitting the phase angle mastercurve has been an issue due to the lack of models to accurately fit this behavior [94]. Additionally, while there are many models to predict the dynamic modulus, there are fewer to predict the phase angle [4]. Consequently, an approximate and simplified relation between the dynamic modulus and the phase angle is introduced in 1982 by Booji and Thoone presented in Eq. (4) [95]:

$$\delta(\omega) \approx \frac{\pi}{2}\frac{d\log(|E*(\omega)|)}{d\log(\omega)}, \tag{4}$$

where $\delta(\omega)$ and $|E^{*}(\omega)|$ are the phase angle and the dynamic modulus in the angular frequency domain, respectively. The ordinary and angular frequency are related by Eq. (5).

$$\mathrm{fr} = \frac{\omega}{2\pi}. \tag{5}$$

A mathematical expression is presented in Eq. (6) expressing the phase angle in radian in the ordinary frequency domain after substituting Eq. (5) into Eq. (2) and differentiating it with respect to $\log(\omega)$.

$$\delta(\mathrm{fr}) \approx -\frac{\pi}{2}\alpha\gamma\frac{e^{\beta+\gamma(\log(\mathrm{fr}))}}{(1+e^{\beta+\gamma(\log(\mathrm{fr}))})^2}, \tag{6}$$

where $\delta(\mathrm{fr})$ is the phase angle, rad. fr is the reduced frequency, Hz and α, β, and γ are fitting parameters.

Figure 5 shows the phase angle mastercurve fitted using Eq. (6) along with the tested phase angle values.

In 2015, Yang and You [96] proposed a modified version of equation (4) given as the following:

$$\delta(\omega) \approx a\frac{\pi}{2}\frac{d\log(|E*(\omega)|)}{d\log(\omega)}, \tag{7}$$

where a is a fitting parameter. Equation (8) can be obtained using the relationship between ordinary and angular frequencies and Eq. (1). Figure 6 presents the phase angle mastercurve for the control mix using Eq. (8).

$$\delta(\mathrm{fr}) \approx -c\frac{\pi}{2}\alpha\gamma\frac{e^{\beta+\gamma(\log(\mathrm{fr}))}}{\left(1+e^{\beta+\gamma(\log(\mathrm{fr})}\right)^2}. \tag{8}$$

A new model to fit the phase angle mastercurve was proposed in 2016 by Rahman [94]. The method uses the

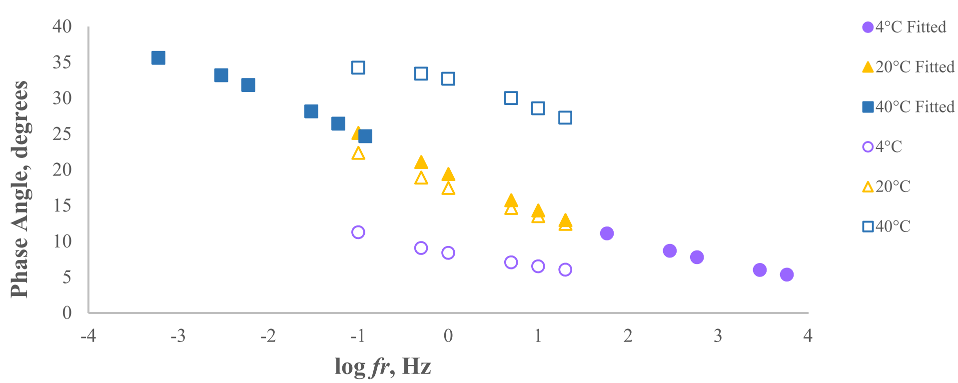

Fig. 5 Phase angle mastercurve fitted by Eq. (6) for the control mix

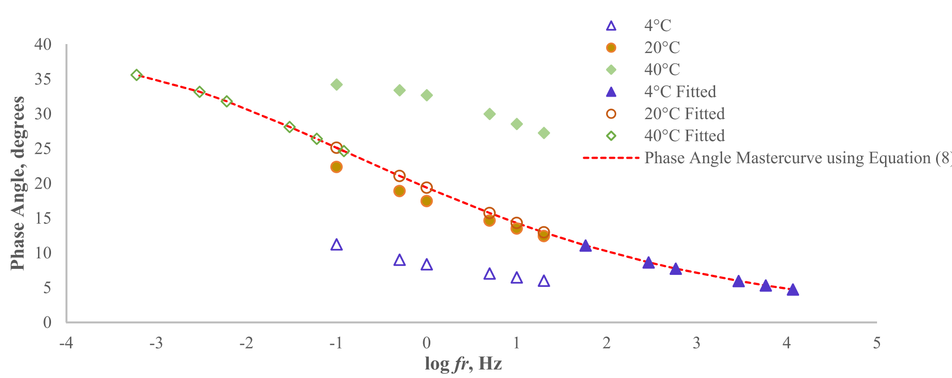

Fig. 6 Phase angle mastercurve fitted by Eq. (8) for the control mix

mathematical expression shown in Eq. (9). The fitted mastercurve using Eq. (9) is presented in Fig. 7.

$$\delta(\mathrm{fr}) = \varsigma + \tau \log(\mathrm{fr}) - \mu \frac{\pi}{2} \alpha\gamma \frac{e^{\beta+\gamma(\log(\mathrm{fr}))}}{\left(1 + e^{\beta+\gamma(\log(\mathrm{fr}))}\right)^2}, \quad (9)$$

where ς, τ, μ, α, β and γ are fitting coefficients.

Equations (6) and (9) will be considered for fitting the phase angle mastercurves. Figures 8, 9, 10, 11 and 12 show the phase angle mastercurves using Eqs. (9) and (10) for the mixes having 0%, 25% 50%, 75% and 100% (MSWI) fly ash as natural filler replacement, respectively.

4.5 Mastercurve coefficients

Table 2 summarizes all the fitting coefficients of the dynamic modulus, shift factors and phase angle functions. It is important to note that Eq. (9) is employed in this study to develop the comparison between the phase angle mastercurves of the bituminous mixtures as it shows better

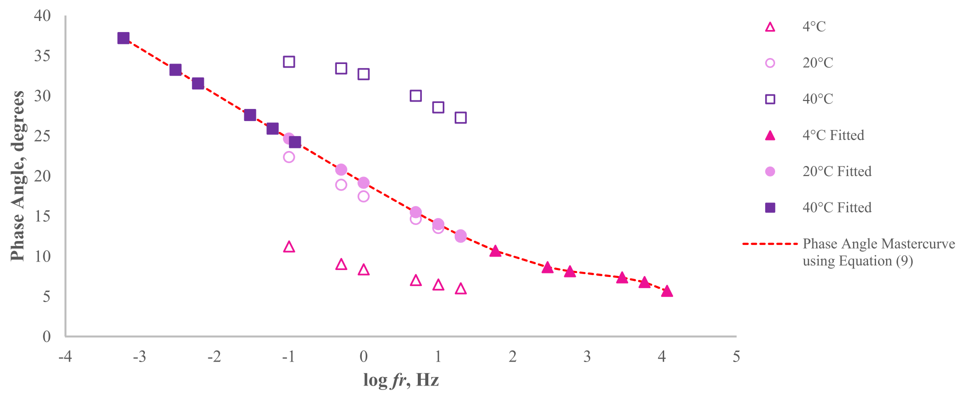

Fig. 7 Phase angle mastercurve fitted by Eq. (9) for the control mix

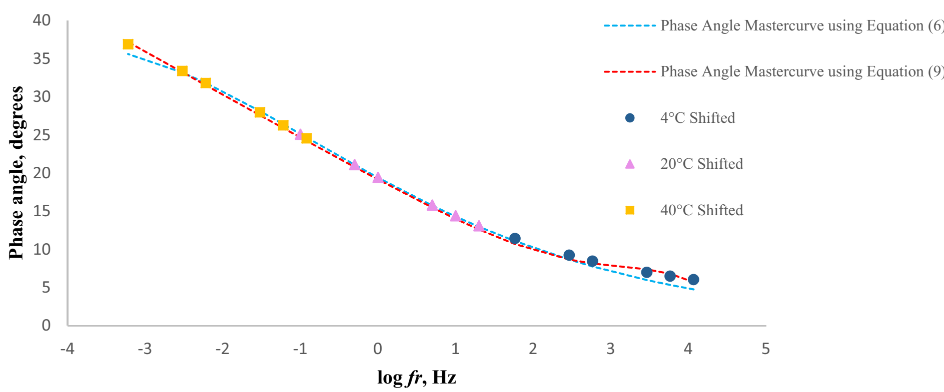

Fig. 8 Phase angle mastercurve for the control mix

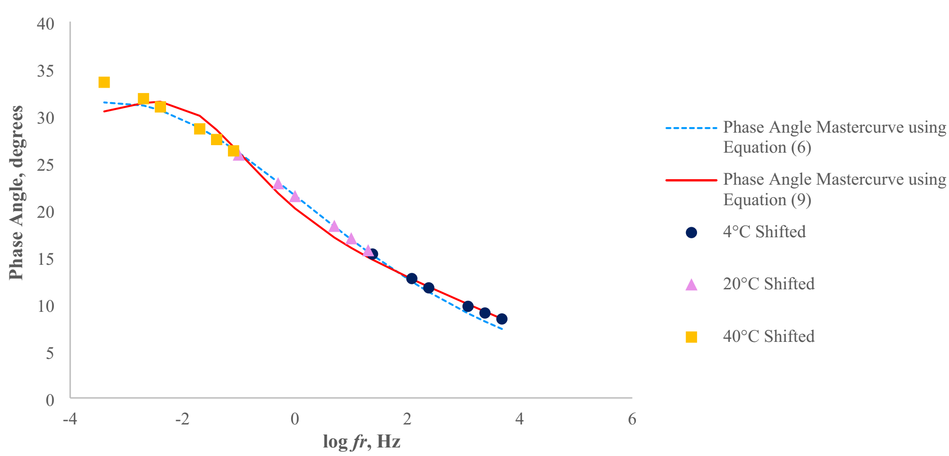

Fig. 9 Phase angle mastercurve for mixes with 25% (MSWI) fly ash filler substitution

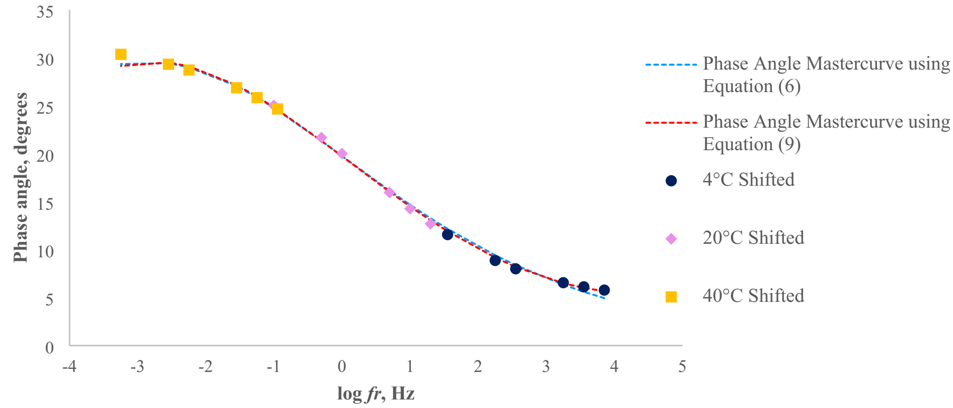

Fig. 10 Phase angle mastercurve for mixes with 50% (MSWI) fly ash filler substitution

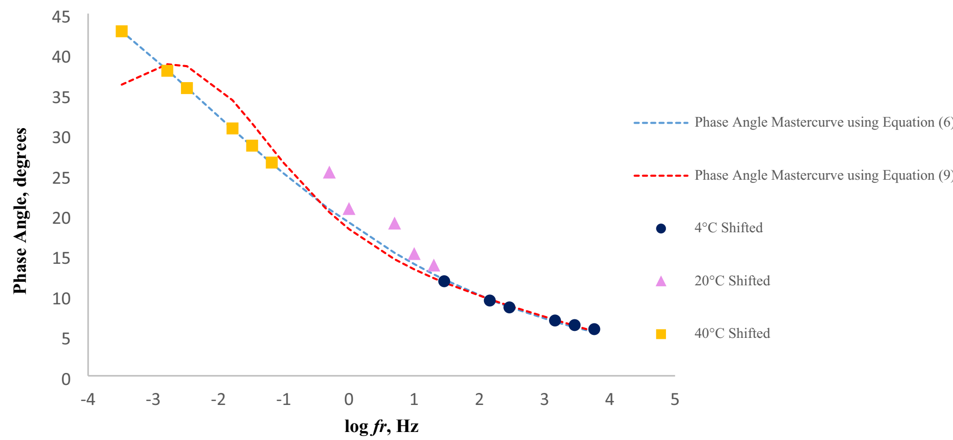

Fig. 11 Phase angle mastercurve for mixes with 75% (MSWI) fly ash filler substitution

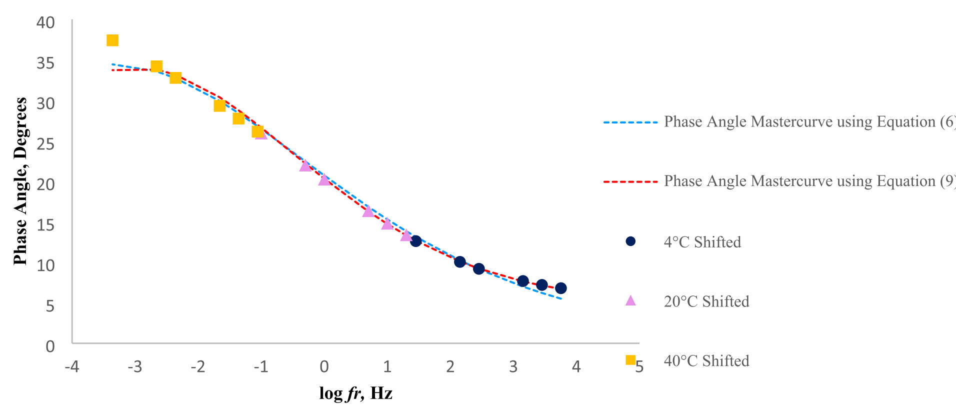

Fig. 12 Phase angle mastercurve for mixes with 100% (MSWI) fly ash filler substitution

accuracy and analyze the partial and total replacement of the natural limestone filler by (MSWI) fly ash.

Additionally, the dynamic modulus mastercuves values were fitted using Eq. (1) and the shift factors functions were fitted using Eq. (2). In general, the coefficient of determination values, R^2 shown in Table 2, of the dynamic modulus, shift factors function and phase angle mastercurves fitted by the non-linear regressions represented by Eqs. (1), (2), and (9), respectively, achieved a considerable accuracy.

In general, the coefficient of determination values, R^2 shown in Table 2, of the dynamic modulus, shift factors function and phase angle mastercurves fitted by the non-linear regressions represented by Eqs. (1), (2), and (9), respectively, achieved a considerable accuracy level for the control mix and all mixes having partial or total (MSWI) fly ash filler replacement, as the values of R2 are all higher than 0.95 and close to 1. This indicates that the equations have a high degree of accuracy for fitting these measured data for the modified and unmodified mixes.

Table 2 Fitting coefficients for all mixes with different (MSWI) fly ash replacement percentages

Fitting coefficients													
Mix	Dynamic modulus, $\|E^*\|$				Shift factors, log a_T			Phase angle					
	a	b	c	d	a_1	a_2	a_3	ς	τ	μ	α	β	γ
Control mix	− 0.28	4.668	− 2.13	0.43	0.0017	− 0.21	3.56	18.95	− 5.65	− 0.53	− 0.65	5.22	− 1.24
	$R^2=0.9986$				$R^2=1$			$R^2=0.9966$					
25% Fly Ash	0.94	3.439	− 1.66	0.45	0.0011	− 0.18	3.28	17.62	− 2.51	0.30	1.01	− 2.41	− 1.21
	$R^2=0.9736$				$R^2=1$			$R^2=0.9669$					
50% Fly Ash	0.81	3.551	− 1.81	0.45	0.0017	− 0.21	3.56	− 60.88	7.84	2.35	7.83	− 1.29	− 0.28
	$R^2=0.9713$				$R^2=1$			$R^2=0.976$					
75% Fly Ash	0.88	3.49	− 1.74	0.47	0.0011	− 0.19	3.39	13.91	2.74	1.09	− 2.02	2.74	1.09
	$R^2=0.9701$				$R^2=1$			$R^2=0.9611$					
100% Fly Ash	1.03	3.30	− 1.81	0.49	0.0013	− 0.19	3.39	3.34	− 1.58	− 0.49	− 1.01	0.86	1.01
	$R^2=0.9656$				$R^2=1$			$R^2=0.9773$					

5 Results and discussion

This section provides the analysis of the findings of the experimental work conducted in this research. Consequently, the outcomes are discussed in detail for each substitution percentage. Taking into account the scope of the research study, the discussion of the findings includes a descriptive comparative analysis with the intention of evaluating the effect of using (MSWI) fly ash as surrogate for the natural mineral filler in different percentages on the properties of asphalt concrete mixtures, namely, dynamic modulus and phase angle. Such a discussion provides a framework for additional experiments and analyses.

Figure 13 presents the fitted dynamic modulus mastercurves in semi-log scale. To conduct analysis, the frequency domain is divided into three regions: low, mid and high frequency. The low frequency domain ranges between 10^{-4} and 1 Hz, the mid frequency domain ranges between 1 and 10^2 Hz and the high frequency domain ranges between 10^2 and 10^4 Hz. The high and low frequencies domains correspond to the low and high-temperature behavior of the asphalt material. A summary of the statistic parameters concerning the analysis, including the standard deviation and the coefficient of variation (CV) of the dynamic modulus and the phase angle for the mixes having different (MSWI) fly ash filler replacement percentages are shown in Table 3. The positive or negative sign next to each number in the standard deviation column explains if the dynamic modulus or phase angle is higher or lower compared to that of the control mic having 0% (MSWI) fly ash as filler replacement.

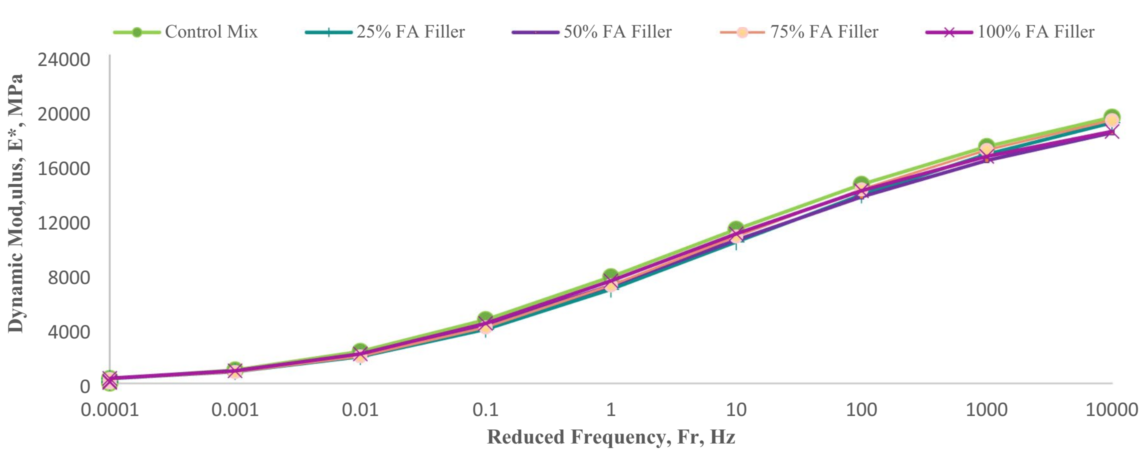

Fig. 13 Dynamic modulus mastercurve in semi-log scale

Table 3 Statistical parameters of the dynamic modulus and phase angle of the different mixes compared to the control mix

Function compared to 0% FA	Mix	Low frequency range		Mid frequency range		High frequency range	
		Standard deviation	CV (%)	Standard deviation	CV (%)	Standard deviation	CV (%)
Dynamic modulus	25% FA	(−) 401.35	13.12	(−) 798.41	7.39	(−) 697.18	4.16
	50% FA	(−) 302.11	9.64	(−) 373.38	3.21	(−) 850.11	5.11
	75% FA	(−) 434.34	14.31	(−) 634.22	5.81	(−) 646.16	3.85
	100% FA	(−) 155.82	4.81	(−) 384.26	3.46	(−) 797.49	4.78
Phase angle	25% FA	(−) 4.08	16.15	(+) 1.74	11.85	(+) 2.01	23.75
	50% FA	(−) 1.19	4.38	(+) 0.44	3.18	(−) 0.29	4.36
	75% FA	(+) 2.54	8.51	(−) 0.18	1.38	(−) 0.12	1.74
	100% FA	(+) 0.92	3.21	(+) 0.79	5.65	(+) 0.46	6.36

5.1 Dynamic modulus

The use of predominantly calcic (MSWI) fly ash as substitution of the natural mineral filler has a significant influence on the mechanical properties of asphalt concrete mixtures. Actually, for the entire range of reduced frequencies, mixes having different percentages of (MSWI) high calcium fly ash as filler replacement produce lower dynamic modulus values compared to that of the control mix.

At low reduced frequencies, lowest value of dynamic modulus standard deviation is developed for mixes with full filler replacement and highest value of dynamic modulus standard deviation is developed for mixes with 75% filler replacement. At mid frequency range, lowest value of dynamic modulus standard deviation is developed for mixes with 50% filler replacement and highest value of dynamic modulus standard deviation is developed for mixes with 25% filler replacement. At high frequency range, lowest value of dynamic modulus standard deviation is developed for mixes with 75% filler replacement and highest value of dynamic modulus standard deviation is developed for mixes with 50% filler replacement. It can be concluded that higher differences in dynamic modulus values are observed at the low frequency range and lower differences are observed at the high frequency range.

The findings for the reduction in dynamic modulus values of asphalt concrete mixtures from the increase of (MSWI) fly ash for any replacement percentage and loading frequency is consistent with the findings of Hassan and Al-Shamsi [97] and Yinfei et al. [98]. In the context of dynamic modulus, substituting limestone filler by high calcium (MSWI) fly ash decreased the abilities of asphalt concrete mixtures to resist low-temperature cracking and rutting [98]. Additionally, this is consistent with the outcomes of Wang et al. in the context of using a filler that has high calcium content. The authors found out that the fillers having high content of calcium oxides showed to have higher rutting potential [99]. However, these findings are opposite to the results of Mirković et al., although it should be noted that they used similar type of fly ash and found that the performance of the modified mixtures was better comparing with the control mix [75].

5.1.1 25% (MSWI) fly ash filler

The 25% (MSWI) fly ash replacement resulted in lower dynamic modulus values for the entire range of reduced frequencies. At low reduced frequency range, the average standard deviation was 401.35 with an average coefficient of variation of 13.12%. At mid reduced frequency range, the average standard deviation is 798.41 with an average coefficient of variation of 7.39%. At the high reduced frequency range, the average standard deviation is 697.18 with an average coefficient of variation of 4.16%. Thus, higher differences of dynamic modulus values are developed at the mid and high frequency ranges compared to the control mix counterpart.

5.1.2 50% (MSWI) fly ash filler

The 50% (MSWI) fly ash replacement resulted in lower dynamic modulus values for the entire range of reduced frequencies. At low reduced frequency range, the average standard deviation was observed to be 302.11 with an average coefficient of variation of 9.64%. At mid reduced frequency range, the average standard deviation is 377.38 with an average coefficient of variation of 3.21%. At the high reduced frequency range, the average standard deviation is 850.11 with an average coefficient of variation of 5.11%. Thus, highest differences of dynamic modulus values are observed at high frequency range compared to the control mix counterpart.

5.1.3 75% (MSWI) fly ash filler

The 75% (MSWI) fly ash replacement resulted in lower dynamic modulus values for the entire range of reduced frequencies. At low reduced frequency range, the average standard deviation was found out to be 434.34 with an average coefficient of variation of 14.31%. At mid reduced frequency range, the average standard deviation is 634.22 with an average coefficient of variation of 5.81%. At the high reduced frequency range, the average standard deviation is 646.16 with an average coefficient of variation of 3.85%. Thus, highest differences of dynamic modulus values are observed at mid and high frequency ranges compared to the control mix counterpart.

5.1.4 100% (MSWI) fly ash filler

The total (MSWI) fly ash replacement resulted in lower dynamic modulus values for the entire range of reduced frequencies. At low reduced frequency range, the average standard deviation was found out to be 155.82 with an average coefficient of variation of 4.81%. It can be noted, that the full replacement of (MSWI) fly ash caused the lowest difference of the dynamic values compared to the other partial replacements. At mid reduced frequency range, the average standard deviation is 384.26 with an average coefficient of variation of 3.26%. At the high reduced frequency range, the average standard deviation is 797.49 with an average coefficient of variation of 4.78%. Thus, highest differences of dynamic modulus values are shown at high frequency range compared to the control mix counterpart.

5.2 Phase Angle

The use of (MSWI) fly ash as partial or total filler replacement in bituminous mixtures results in different effects on the phase angle. Mixes with 25% (MSWI) fly ash filler replacement develop lower phase angle values compared to that of conventional mix at low frequency range and higher values at the mid and high frequency ranges compared to that of the control mix.

Mixes with 50% (MSWI) fly ash filler replacement develop lower phase angle values at the low and high frequency ranges and higher at the mid frequency range compared to the control mix.

Mixes with 75% (MSWI) fly ash filler replacement produces higher phase angle values at the low frequency range and higher values at the mid and high frequency ranges compared to the values of the unmodified mix.

Finally, mixes with full filler replacement produce higher values of phase angle over the entire range of reduced frequency compared to the control HMA. Consequently, at high temperatures, higher values of phase angles are developed with the increase of (MSWI) fly ash. However, at low temperatures, a general decrease in phase angles values is observed with the increase of (MSWI) fly ash. This is in agreements of the results obtained in the investigation of Hassan and Al-Shamsi [97].

The findings of phase angle are consistent with the findings of Hassan and Al-Shamsi and Yinfei et al. at some ranges of reduced frequency and replacement percentages and opposite at other ranges and substitution percentages [97, 98]. In the perspective of phase angle, the reduction of phase angle at high temperatures designates that the asphalt concrete mixtures with (MSWI) fly ash had higher resistance to permanent deformation than the control mix. This is the case of 25% and 50% (MSWI) fly ash replacement. This is consistent with the findings of Hassan and Al-Shamsi [97] and Yinfei et al. [98]. For the case of higher replacement percentages (75% and 100%), higher values of phase angle indicate lower resistance to permanent deformation than the control mix. This conclusion for the increase in phase angle for the mix having 75% and full (MSWI) fly ash replacement was opposite to that of Hassan and Al-Shamsi [97] and Yinfei et al. [98].

At high frequency range, the outcomes revealed that the substitution of the mineral filler by 50% and 100% (MSWI) fly ash lowered the phase angle values leading to low-temperature cracking as the viscous portion of asphalt concrete mixture is decreased with the decrease of phase angle [100]. As a matter of fact, lower viscous portion of asphalt concrete mixtures at low temperatures is more susceptible to cracking [101]. This is consistent with the outcomes revealed from the study of Hassan and Al-Shamsi and Yinfei et al. and opposite to the outcomes of the previously mentioned studies for the 25% and full replacement of (MSWI) fly ash [97, 98].

5.2.1 25% (MSWI) fly ash filler

The use of 25% (MSWI) fly ash as substitution to the mineral filler results in lower phase angle values for the low reduced frequency range only. At low reduced frequency range, the average standard deviation was found to be 4.08 degrees, with an average coefficient of variation of 16.15%. At mid reduced frequency range, the average standard deviation was found out to be 1.74 degrees with an average coefficient of variation of 11.85%. At the high reduced frequency range, the average standard deviation was observed to be 2.01 degrees with an average coefficient of variation of 23.75%. Consequently, the highest difference in phase angle values is observed at the low temperature range.

5.2.2 50% (MSWI) fly ash filler

The use of 50% (MSWI) fly ash as substitution to the mineral filler results in lower phase angle values for the low reduced frequency range with an average standard deviation of 1.19 degrees and a coefficient of variation of 16.15%. The use of 50% (MSWI) fly ash as filler replacement resulted in higher phase angle values for the mid and high frequency range. At mid reduced frequency range, the average standard deviation was found out to be 0.44 degrees with an average coefficient of variation of 3.18%. At the high reduced frequency range, the average standard deviation was observed to be 0.29 degrees with an average coefficient of variation of 4.36%. Consequently, the highest difference in phase angle values is developed at the high temperature range.

5.2.3 75% (MSWI) fly ash filler

The use of 75% (MSWI) fly ash as substitution to the mineral filler results in higher phase angle values for the low reduced frequency range with an average standard deviation of 2.54 degrees and a coefficient of variation of 8.51%. The use of 75% (MSWI) fly ash as filler replacement resulted in higher phase angle values for the mid and high frequency range. At mid reduced frequency range, the average standard deviation was found out to be 0.18 degrees with an average coefficient of variation of 1.38%. At the high reduced frequency range, the average standard deviation was observed to be 0.12 degrees with an average coefficient of variation of 1.74%. Consequently, the highest difference in phase angle values is shown at the low reduced frequency range.

5.2.4 100% (MSWI) fly ash filler

The total (MSWI) fly ash replacement resulted in higher phase angle values for the entire range of reduced frequencies. At the low reduced frequency range, the average standard deviation was found out to be 0.92 degrees with a coefficient of variation of 3.21%. At the mid reduced frequency range, the average standard deviation was found out to be 0.79 degrees with an average coefficient of variation of 5.65%. At the high reduced frequency range, the average standard deviation was observed to be 0.46 degrees with an average coefficient of variation of 6.36%. Consequently, a complicated nature in phase angle values can be observed throughout the range of reduced frequencies compared with the control mix.

The conclusion obtained from the phase angle was opposite for certain replacement percentages and loading frequencies to that drawn from the dynamic modulus.

Consequently, taking into consideration the combined effect of dynamic modulus and phase angle, ($|E^*|/\sin\delta$) and ($|E^*|\sin\delta$) were calculated as indicators of dynamic modulus combination parameters for rutting and low-temperature cracking, respectively. As a matter of fact, rutting and low temperature indicators are two of the most preferred index parameters for the simple performance test [7]. By definition, simple performance test is a method that precisely measures an asphalt concrete mixture response that is greatly associated with the development of distresses under defined conditions [101, 102].

Yenfei et al. [100] used ($|E^*|/\sin\delta$) as an indicator of combined effect of dynamic modulus and phase angle to assess the resistance to permanent deformation of HMA mixes with fly ash cenosphere. The results confirmed that ($|E^*|/\sin\delta$) was lower for all modified mixes compared to the control mix indicating a reduction of the resistance to permanent deformation of HMA mixtures [100]. Additionally Pellinen and Witzcak [101] used ($|E^*|/\sin\delta$) and dynamic modulus to validate the pavement conditions. The outcomes indicated that there is a very good correlation between fatigue and rutting stiffness parameters and the field performance [101]. The existing literature revealed that the use of fatigue performance parameter ($|E^*|\sin\delta$) is a good indicator to fatigue cracking susceptibility [103].

Figure 14 shows the trend of the rutting performance indicator ($|E^*|/\sin\delta$) with respect to the replacement percentage. To evaluate the rutting potential of HMA mixes, a temperature of 40 °C and a frequency of 0.01 Hz were selected so that asphalt concrete mixes develop elastic behavior. Lower values of ($|E^*|/\sin\delta$) indicates lower rutting resistance. Whereas Fig. 15 shows the trend of the fatigue performance indicator ($|E^*|\sin\delta$) with respect to the replacement percentage. To evaluate the fatigue potential of HMA mixes, the dynamic modulus and the phase angle should be low thus a temperature of 20 °C and a frequency of 10 Hz were

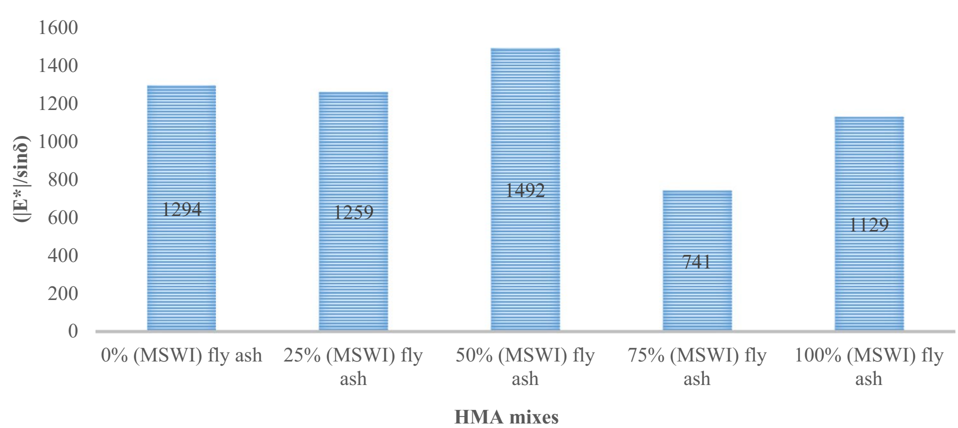

Fig. 14 Rutting performance indicator ($|E^*|/\sin\delta$) of the HMA mixes with different substitution percentages of (MSWI) fly ash

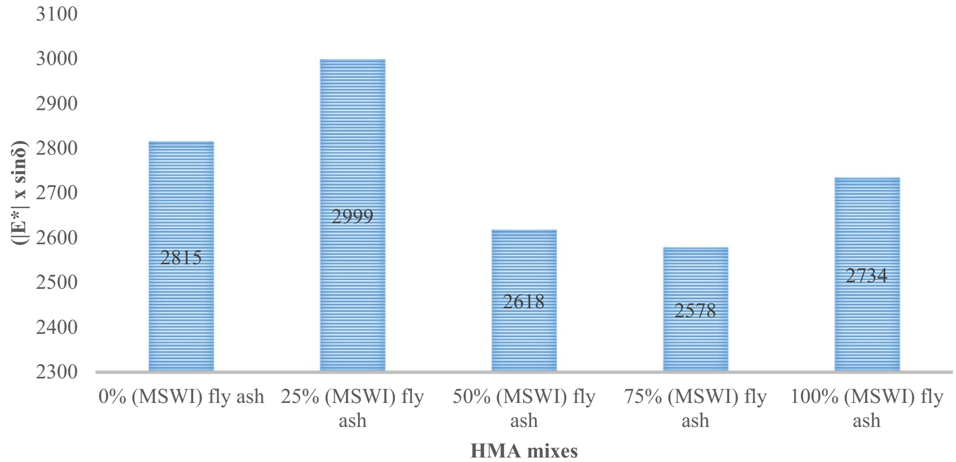

Fig. 15 Fatigue performance indicator (|*E**|sin*δ*) of the HMA mixes with different substitution percentages of (MSWI) fly ash

selected. Lower values of (|*E**|sin*δ*) indicates lower potential of fatigue cracking.

The rutting performance indicator (|*E**|/sin*δ*) slightly decreased by 2.7% for the HMA mix having 25% (MSWI) fly as substitute for the limestone filler as shown in Fig. 14. Thus, it can be concluded that, in terms of rutting, the incorporation of 25% of (MSWI) fly ash in asphaltic mixtures resulted in almost similar rutting behavior. The rutting performance indicator (|*E**|/sin*δ*) significantly increased by 15% for the HMA mix having 50% (MSWI) fly ash as substitute for the limestone filler. Consequently, mixes with 50% (MSWI) fly ash developed higher rutting resistance compared with the control mix. The rutting performance indicator (|*E**|/sin*δ*) slightly decreased by 43% and 13% for the HMA mixes having 75% and 100% (MSWI) fly ash as substitute for the limestone filler, respectively. Thus, it can be concluded that the use of 75% and 100% of (MSWI) fly ash as filler substitution increased the rutting potential of asphaltic mixtures.

The use of (MSWI) fly ash in asphalt concrete mixtures as substitute for the natural mineral filler increased the rutting resistance up to 50% of incorporation. Higher substitution percentages resulted in lower HMA mixtures rutting resistance. This is consistent with the findings of Hassan and Al-Shamsi [97] that revealed a decrease in the (|*E**|/sin*δ* parameter indicating lower resistance to permanent deformation of HMA mixes, although it should be noted that they used municipal solid waste incinerator ash as surrogate for the fine aggregates. However, the authors suggested a limiting percentage of 20% of municipal solid waste incinerator ash to be used in HMA mixes [97]. Additionally, the results were also in agreement with those of Yinfei et al. who found out that the use of fly ash cenosphere lowered the rutting resistance of HMA mixes [98].

The low temperature performance indicator (|*E**|sin*δ*) considerably increased by 6% for the HMA mix having 25% (MSWI) fly as substitute for the limestone filler as shown in Fig. 15. Thus, it can be concluded that, in terms of fatigue cracking, the incorporation of 25% of (MSWI) fly ash in asphaltic mixtures increased the potential of fatigue cracking of the mix. The low temperature performance indicator (|*E**|sin*δ*) significantly decreased by 7%, 8% and 3% for the asphalt concrete mixes having 50%, 75% and 100% (MSWI) fly ash as substitute for the limestone filler. Consequently, mixes with 50%, 75% and 100% (MSWI) fly ash developed higher fatigue cracking resistance compared with the control mix.

The use of (MSWI) fly ash in asphalt concrete mixtures as substitute for the natural mineral filler increased the resistance to low-temperature cracking when incorporated in percentages higher than 25%. This is opposite to the results obtained from the research conducted by Wu et al. [103]. The authors found out that the use of graphite powders as filler in asphalt concrete mixtures resulted in lower (|*E**|sin*δ* indicating a decrease in the HMA mixture stiffness [103].

6 Conclusions

In this paper, the effect of using (MSWI) fly as alternative material to replace the natural limestone filler on the properties of asphalt concrete mixtures was investigated. The application of municipal solid wastes such as (MSWI) fly ash in asphalt mixtures instead of mineral filler promotes cleaner production and develops green construction materials in the road paving sector by decreasing emissions, air pollution and solid wastes.

The following points can be drawn based on the obtained experimental results as the main conclusions from this research study:

1. Based on the chemical composition, the (MSWI) fly ash, an alternative material generated from the combustion of municipal solid waste, has been used in this

investigation instead of traditional limestone filler to produce new HMA mixtures. A high proportion of calcium oxides (CaO) is significantly present (30.49%) along with moderate content of silica (16.23%) in the used waste material as, this can enhance the adhesion between the aggregates and the asphalt binder and improve the mixture stability making this type waste suitable for use in asphalt concrete mixtures. Additionally, the (MSWI) fly ash used in this investigation do not meet the chemical requirements for class C or F as per ASTM C618-19 as the minimum content of the total content of silica, aluminum and iron oxide is around 32.73%.

2. The phase angle model prediction had very good to excellent correlations with the measured phase angle values as indicated by a very high coefficient of determination R^2, which denotes how well the regression model fits the measured data value.
3. The use of (MSWI) fly ash as partial or full filler replacement in asphalt concrete mixtures lowered the dynamic modulus values at low, mid and high reduced frequencies ranges compared to its conventional control asphalt mix counterpart. In the context of dynamic modulus, substituting traditional limestone filler by (MSWI) fly ash decreased the abilities and stiffness of asphalt concrete mixtures to resist low-temperature cracking and permanent deformation as lower values of dynamic modulus were developed for modified mixes compared to the control mix and all dynamic modulus mastercurves were below the curve of 0% (MSWI) fly ash replacement.
4. At low reduced frequency range, the incorporation of (MSWI) fly ash as full filler replacement produces the least differences in dynamic modulus values compared to the other partial (MSWI) fly ash replacement percentages having a CV of 4.81%. Whereas, the incorporation of 75% (MSWI) fly ash produces the highest differences in dynamic modulus value with a CV of 14.31%.
5. At mid reduced frequency range, 50% (MSWI) fly ash filler replacement is observed to have the least difference in dynamic modulus values with a CV of 3.21% compared to the control mix. Additionally, comparable differences are shown when using 100% (MSWI) fly ash filler replacement having a CV of 3.46%. Whereas, the incorporation of 25% (MSWI) fly ash produces the highest differences in dynamic modulus value with a CV of 7.39%.
6. At high reduced frequency range, the use of 75% (MSWI) fly ash as filler replacement is shown to produce the least difference in dynamic modulus values with a CV of 3.85% and the use of 50% (MSWI) fly ash produces the highest difference in dynamic modulus values with a CV of 5.11%. Approximate CV values are observed of 4.16% and 4.78% for mixes with 25% and 100% (MSWI) fly ash, respectively.
7. The phase angle of asphalt concrete mixtures with (MSWI) fly ash is reduced at some ranges of reduced frequency and replacement percentages and increased at other ranges and substitution percentages. In the perspective of phase angle, the reduction of phase angle at high temperatures or load frequencies, designates that the asphalt concrete mixtures with (MSWI) fly ash had higher resistance to permanent deformation than the control mix. This is the case of 25% and 50% (MSWI) fly ash replacement at low frequency range indicating that mixes with 25% and 50% (MSWI) fly ash which are less susceptible to permanent deformation than the other replacement percentages.
8. For the case of higher replacement percentages (75% and 100% (MSWI) fly ash), higher values of phase angle are observed indicating that these mixes are prone to permanent deformation than the other substitution percentages.
9. At low temperatures or high frequency range, the substitution of the mineral filler by 50% and 100% (MSWI) fly ash lowered the phase angle values leading to the development of low-temperature cracking as the viscous portion of asphalt concrete mixture is decreased with the decrease of phase angle. Thus, mixes with 50% and 100% (MSWI) fly ash have lower viscous portion of asphalt concrete mixtures at low temperatures and are more susceptible to cracking than the other replacement percentages.
10. The conclusion obtained from the phase angle was opposite for certain replacement percentages and loading frequencies to that drawn from the dynamic modulus. For this purpose, the combined effect of dynamic modulus and phase angle, ($|E^*|/\sin\delta$) and ($|E^*|\sin\delta$) were calculated as indicators of dynamic modulus combination parameters for rutting and low-temperature cracking, respectively.
11. ($|E^*|/\sin\delta$) slightly decreased by 2.7% for the mix having 25% (MSWI) fly. Thus, it can be concluded that the mixes with 25% of (MSWI) fly ash had approximately the same rutting resistance of the control mix. ($|E^*|/\sin\delta$) significantly increased by 15% for the mix having 50% (MSWI) fly ash indicating higher rutting resistance compared with the control mix. ($|E^*|/\sin\delta$) slightly decreased by 43% and 13% for the mixes having 75% and 100% (MSWI) fly ash indicating higher rutting potential compared with the control mix.
12. The use of (MSWI) fly ash in asphalt concrete mixtures as substitute for the natural mineral filler increased the rutting resistance up to 50% of incorporation and

decreased the stiffness for higher substitution percentages leading to higher rutting potential.

13. (|E^*|sinδ) considerably increased by 6% for the mix having 25% (MSWI) fly indicating higher potential of fatigue cracking as compared to the control mix. (|E^*|sinδ) significantly decreased by 7%, 8% and 3% for the asphalt concrete mixes having 50%, 75% and 100% (MSWI) fly ash indicating higher fatigue cracking resistance as compared to the control mix.
14. The use of (MSWI) fly ash in asphalt concrete mixtures as substitute for the natural mineral filler increased the resistance to low-temperature cracking when incorporated in percentages higher than 25%.
15. It is recommended to use at least 25% of (MSWI) fly ash as substitute for the natural mineral filler if the flexible pavement is to be built in low or moderate temperature conditions.
16. It is recommended to use up to 50% of (MSWI) fly ash as substitute for the natural mineral filler if the flexible pavement is to be built in moderate to high temperature conditions.

Acknowledgements The statements made herein are solely the responsibility of the authors.

Funding No funding was received for conducting this study.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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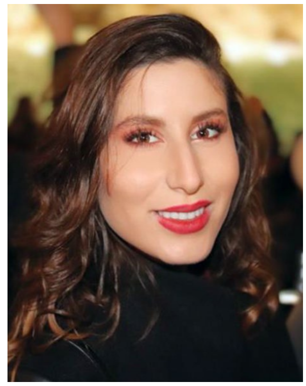

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