A Bitumen-Based Prototype to Predict the Workability of Asphalt Concrete Mixtures

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Abstract. Having a reliable and repeatable method for measuring the workability of asphalt mixtures for a wide range of asphalt blends is important. The major objective of this paper is to develop a new bitumen-based prototype for the measurement of the workability of different asphalt blends. Correlation and prediction of the mixing temperature with the aid of the developed prototype have been established as a secondary objective of this study. At first, a principle was presented as a basis to develop the workability prototype. The device developed in this study utilized a commercially available motorized Vane Shear Test (VST) apparatus which is mainly used to measure the shear strength of soil. To resemble the aggregate effect while mixing, a specially designed spindle was developed. The VST has been modified to suit the present purpose of the workability test. An accurate torque meter was installed to measure the torque required to rotate the spindle in the blend at a constant revolution. The device was tested with asphalt blends of different ranges of workability. The workabilities of polymer-modified and water-foamed asphalts were evaluated at temperatures of 100, 140 and 180 °C, respectively. It was found that the bitumen-based prototype was able to differentiate the workability in light of the constituents of the studied blends. In addition, the prototype helped in roughly predicting the mixing temperatures of the studied blends based on the concept of Workability Index (WI).

Keywords: Workability · Viscosity · Workability index · Mixing temperature · Modified asphalt · Warm mix asphalt

1 Introduction

The workability of asphalt concrete mixtures affects the construction activities as well as the performance of the pavement in the long-term. Workability is a term used to describe the ease with which the asphalt mixture can be mixed, placed and compacted on the roadway. In other words, the workability can be defined as the movement of an asphalt mixture through construction equipment, handwork, and compactibility on the roadway. Workability is an essential component in acquiring the required density and air voids within a compacted mixture (Airey et al. 2008; Celik and Atis 2008). For asphalt blends that are extremely harsh, and in this way are less workable, it can be more difficult to construct smooth asphalts. Poorly compacted asphalt pavements might

L. Mohammad (ed.), *Advancement in the Design and Performance of Sustainable Asphalt Pavements*, Sustainable Civil Infrastructures, DOI 10.1007/978-3-319-61908-8_2

encounter issues, for example, stripping, raveling and fatigue, which basically result from the increase in the air void content as well as the increase in the rate of oxidative aging of bitumen, and consequently, decreasing the service life of the asphalt pavement (Horan et al. 2012). The higher the temperature, the better the mixture workability, the reason being that the viscosity of the binder decreases as the temperature increases. However, increasing the mixture temperature to get proper workability is not always the best strategy. Unfortunately, excessively increasing the production temperatures of asphalt mixture may cause serious problems, such as compaction problems and an increase in oxidation of the asphalt cement. On the other hand, a better compaction of asphalt pavement results in longer pavement life, lower pavement maintenance, and better pavement performance (McLeod 1967).

Because of the numerous points of interest they have, the utilization of additives is expanding in the asphalt industry, and the workability of their asphalt blends has turned out to be a more imperative issue. Historically, the viscosity of bitumen has been used to decide the mixing and compaction temperatures of the asphalt-aggregate combinations (Yildrim et al. 2000; Bennert et al. 2010). However, there may be a few challenges associated with this; for example, shear rate dependencies (non-Newtonian behavior), non-linearity, or the chemical and/or physical mechanisms between bitumen and different mineral types or additives can alter the rheological properties at different temperatures (Yildrim et al. 2000). In any case, with the utilization of additives in asphalts, the workability changes considerably since the modifiers tend to change the viscosity of the blend. Consequently, compacting modified asphalt mixtures to achieve the desired density may be different from mixtures that utilize unmodified binders. Different testing methods widely used to benchmark the mixing and compaction temperatures, including workability testing, have been discussed in detail elsewhere (Yildrim et al. 2000; West et al. 2010). It was demonstrated that no reliable method for determining the production temperatures has been adopted by all pavement practitioners. The equiviscous principle that is commonly used to determine asphalt production temperatures is no longer feasible for many polymer-modified asphalts as it concludes exaggerated mixing and compaction temperatures (Shuler et al. 1992; Shenoy 2001). Also, in spite the capability of increasing the workability at lower temperatures compared to Hot Mix Asphalt (HMA), the determination of the production temperatures of Warm Mix Asphalt (WMA) is still questionable. Generally, overestimated mixing temperatures can stiffen the bitumen in the form of volatilization and oxidation (Clark 1958). An increase in temperature by 10 °C approximately doubles most oxidation mechanisms (Fink 1958). In particular, polymer additives can break down in bitumen at excessively high temperatures; however, the temperature ranges that cause these detrimental effects are not clearly established (Linde and Johansson 1992; Airey and Brown 1998; Shenoy 2001). Also, numerous studies (e.g. Azari et al. 2003) have demonstrated the significant effect of compaction temperatures on the mechanical performance of compacted asphalt specimens. The workability testing could be considered a simulation of the real process in the mixing plant; therefore, an extension of the current study was performed as an initiative to predict the mixing temperatures of different asphalt mixtures from the developed workability prototype.

Measuring the workability of asphalt mixtures is an important but also a challenging task. To have a standardized protocol for asphalt mixtures, it is important that the entire protocol is extremely well-defined since any variation could yield significantly different results leading to inaccurate conclusions as to the impact of other parameters. The repeatability of the end test results is, therefore, a critical factor that received much attention in this study. The workability of asphalt mixtures is influenced by many distinctive parameters, for example, production temperatures, aggregate properties (i.e. mineralogy, gradation, the size and shapes) and the type of bitumen used (Tayebal et al. 1998; Delgadillo and Bahia 2008). The influence of these parameters may also vary from case to case, depending on specific mixture characteristics or circumstances. The requirements that assist pavement engineers in the material design and production levels ought to be appropriate for a wide range of materials and boundary conditions. Therefore, sensitive experimental strategies and analytical or numerical fashions, primarily based on fundamental understanding, may be needed to convey sufficient control and predictability in bitumen and asphalt mixture design and production. There had been some attempts to measure the workability of asphalt mixtures directly from the loose mixture (i.e. aggregates coated with bitumen); however, different technical issues such as device geometry challenges or lack of repeatability led these to be not fully successful (Gudimettla et al. 2004). Marvillet and Bougault (1979) introduced an instrument to measure the workability of HMA. The primary principle of this device was a paddle immersed in a container of HMA sample and the torque to maintain the paddle rotating inside the blend at a constant speed was measured. The relationship between temperature and the corresponding measured torque was taken as the workability curve. Generally, they found that as the viscosity decreases, the workability and hence compactability increases for the same mixture. Except for the binder content, the angularity of the aggregate particles and dust content affected the workability results. Also, they warned that if different mixtures have the same workability, it does not guarantee that the mixtures undergo the same compactability. The poor repeatability and scattered data for several of the regressions indicate that the previous trial tests may not be fully dependable in establishing specific relationships between temperature and workability for different asphalt binders (West et al. 2010). There are still some fundamental and obvious problems to overcome.

2 Research Motivation and Objectives

The workability of asphalt mixtures is a basic component in getting the design air void content and, hence, the desired density of the mixture, which leads to greater durability and better performance of asphalt pavements. Researchers have found that compared to the equiviscous principle for determining mixing and compacting temperatures of modified asphalt mixtures, the workability tests predict rationale production temperatures. Previous attempts to measure the workability of asphalt mixtures have found that although the constituents of each mixture are held constant, the workability results cannot be considered repeatable as a range of workability resulted at same temperatures. Therefore, on account of the significance of workability in asphalt development, the current paper intends to present a bitumen-based prototype to quantify the workability of different asphalt mixtures in a standard way. A simple mathematical principle was presented first to obtain a fundamental basis of the current prototype to compare the conditions in the target workability prototype versus a real plant mixing. The current procedure is based only on the bitumen phase and involves the aggregate effect. As a secondary objective, this prototype was used to roughly determine the mixing temperatures of polymer-modified and foamed WMA blends.

3 Principle of Workability

The analysis of workability while preparing asphalt mixtures is very complicated. Presenting a principle for the workability is important before going through with the prototype, to give a basis for its development. The process of mixing and the required torque can be described mathematically in a simple way to enable the prediction of torque for different conditions. The general principle of workability illustrated in this section is based on a simplified derivation. Consider different-sized aggregate particles in contact with each other with the aid of interposed bitumen films. A conceptual diagram of bitumen coated aggregate particles impacting each other during mixing and the internal forces associated with it is shown in Fig. 1. The engineering properties of aggregates, including shape, size, and gradation, in addition to bitumen content, are very important in having the desired workability of asphalt concrete mixtures (Tayebal

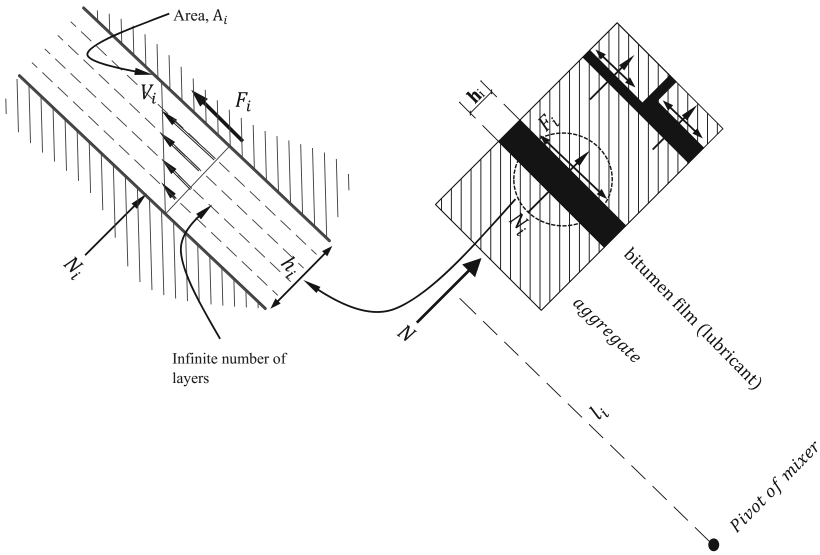

Fig. 1. A Conceptual diagram of aggregate particles and bitumen while mixing and internal forces

et al. 1998; Delgadillo and Bahia 2008). Aggregate occupies approximately 90–95% by weight and 75–85% by volume of an asphalt mixture; therefore, the frictional regime between aggregate particles in the loose stage and during mixing is highly dominant. With the interpose of bitumen layer between aggregate particles, a lower friction coefficient results due to lubrication (Hanz et al. 2011). During mixing, the mobility and manipulation of aggregate particles around one another undergo different lubrication regimes, depending on the bitumen film thickness (or bitumen content), which changes the coefficient of friction between the aggregate particles. The friction force due to the collision of the aggregate particles while mixing is controlled by shearing forces in the lubricant layer. The exerted shear forces depend on the viscous characteristics of the lubricant, as well as the shear velocity distribution in the bitumen film (Stachowiak and Batchelor 2013). Therefore, the friction function, $f(\mu_i)$ has been suggested instead of a constant friction coefficient, μ_i, to consider the variation in the coefficient of friction while mixing. The behavior of the friction coefficient due to the change in the properties or thickness of the lubricant layer can be explained by the Stribeck curve (Stachowiak and Batchelor 2013).

Due to the application of a normal force, N_i, the magnitude of the friction force, F_i, that can be exerted between any two plane surfaces (i) of particles in contact and in motion relative to each other can be calculated using the Coulomb equation.

$$F_i = f(\mu_i) N_i \tag{1}$$

From the basic principle of the relationship between shear rate, $\dot{\gamma}_i$, and shear stress, τ_i, for a Newtonian fluid, the tangential reaction force, F_i, is a product of contact area (A_i), local viscosity (η_i) and relative velocity between the surfaces (V_i) divided by film thickness, h_i i.e.:

$$F_i = \frac{\eta_i V_i A_i}{h_i} \tag{2}$$

From the above equation, it can be concluded that, physically, the lateral reaction force between two aggregate particle surfaces, F_i, is the result of many different mechanisms, which depend on contact geometry and topology, properties of the bulk and surface of the aggregate particles, displacement and relative velocity of the particles and viscosity of the present lubricant or bitumen. Therefore, the normal force, N_i, between two adjacent particle surfaces (i) while mixing can then be calculated as:

$$N_i = \frac{\eta_i V_i A_i}{h_i f(\mu_i)} \tag{3}$$

The total torque, q, required to keep mixing aggregate particles displaced at different radial distances l_i from the pivot of mixing (Fig. 1) can be calculated as follows:

$$q = \sum N_i l_i \tag{4}$$

Considering the torque is temperature (T) and time (t) dependent, substitution yields:

$$q(T,t) = \sum \frac{\eta_i V_i A_i}{h_i f(\mu_i)} l_i \tag{5}$$

Different properties of asphalt mixtures (such as WMA) change during the mixing time. The workability index, $WI = q(T,t)^{-1}$, can be used for a relative comparison of the change in workability during mixing of different asphalt mixtures. The WI shows how easy or how difficult a bitumen-aggregate blend is to handle during the mixing process. Unlike the modified mixtures, Eq. (5) infers that the WI of the unmodified mixtures is close to the linearity with respect to temperature.

From Eq. (5), it can be concluded that assuming the position of each aggregate particle or l_i is constant, the torque or the workability depends on different factors and, therefore, should be studied while developing the workability device. For the unmodified mixtures, the torque depends on the amount and properties of aggregate. Also, the properties of the asphalt binder used are functions of temperature. It is also quite clear that the viscosity of the lubricant is an important parameter for calculating the workability of asphalt mixtures. The asphalt binder content affects the torque needed to keep the aggregates slipping while mixing. The asphalt binder thickness is mainly dependent on its content, considering two bitumen films made up of equispaced layers; for same surface velocity, different thicknesses of bitumen film will undergo different velocity gradients, V_i/h_i. Thicker films need less force to shear as they contain more single layers compared to the thinner films (Stachowiak and Batchelor 2013). Therefore, the viscous resistance and hence the torque are inversely proportional to the film thickness of bitumen. To compare the results between different asphalt mixtures, the properties of aggregates should be kept constant. Although it can be recognized as a limitation, including the interactions between bitumen and aggregate would complicate the process. According to the above discussion, the aggregate properties enormously affect the workability of asphalt mixture. This conclusion is consistent with the experimental work by Gudimettla et al. (2004). Therefore, to reduce errors in measuring the workability of different blends as well as maintaining the possibility of repeatability, the sample preparation should be standardized. Also, to accurately predict the mixing temperatures of an asphalt mixture, a unique practical temperature-workability relationship should be gained, which is not possible based on the previous discussion.

4 Configurations of Developed Workability Prototype

4.1 Description of the Proposed Prototype

A pictorial view of the whole workability prototype developed herein can be seen in Fig. 2. To apply torque, the device developed in this study made use of a commercially available motorized VST apparatus that is mainly used to measure the shear strength of soil. The VST apparatus has been modified to suit the workability test purpose. The torsional spring has been replaced with a rigid steel rod to directly transfer torque measured with the aid of a sensitive torque meter. The VST apparatus was placed on the top surface of an oven. A 60 cm length and 0.5 cm diameter steel rod was attached to the VST apparatus, and the rod was impeded through the top vent of the oven. A specially designed spindle was immersed in a specially designed cylindrical bowl (70 mm diameter and150 mm height) containing the asphalt blend and was attached to the bottom of the rod. The oven was used to maintain the blend at a specific temperature in degrees Celsius. All the data of the torque meter were obtained and recorded by an automated sensitive torque meter attached to a data reader. The values of the torque were measured at different times excluding the initial readings of the first two seconds close to the stationary position as the torque values are very high and, therefore, not representative. The temperatures used in this study were chosen as 100, 140 and 180 °C, which is the temperature range over which asphalt mixtures are normally subjected to through different construction stages. Once the equipment was developed, the spindle configuration was fixed for any type of blend to be tested, which maintains the results comparable for different asphalt blends. Moreover, research was employed to evaluate the impact of various blend constituents on the workability of asphalt.

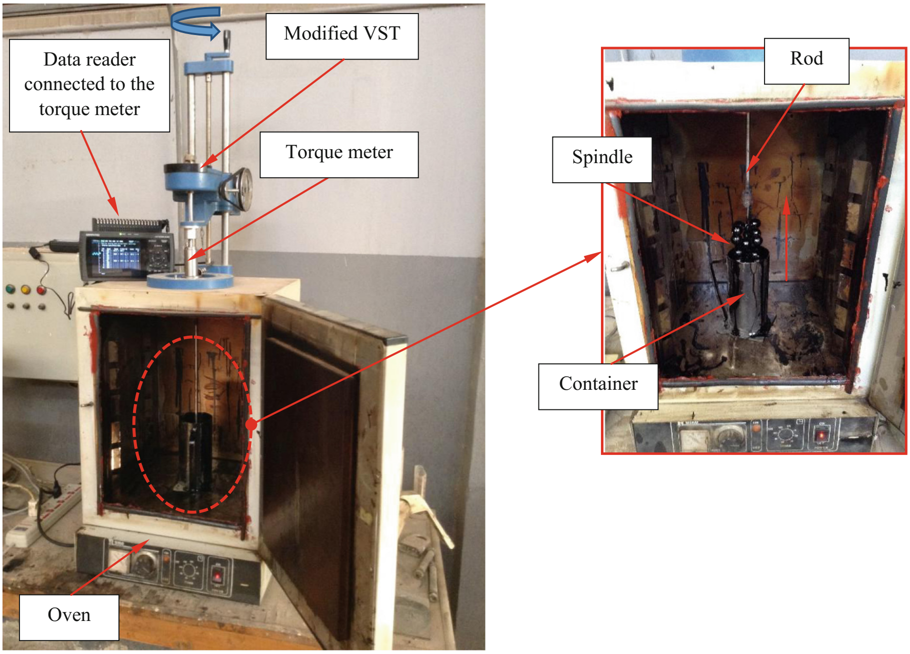

Fig. 2. Pictorial view of the proposed method

4.2 Design and Fabrication of the Spindle

The design of the spindle was built on the findings drawn from Eq. (5). Keeping the bitumen volume constant, the significant differences in the workability were hypothesized to be caused by different shapes and sizes of aggregates and the aggregate–bitumen interactions. To make sure all samples consist of the same sized aggregates and distribution, an appropriate amount of metallic balls in asphalt blends were chosen to ensure a representative aggregate distribution. The particle size is another parameter which has an important influence on the workability of asphalt blends. It can be even more important when the modified asphalt blends are tested at different concentrations for comparing the effect of additive content on the workability of asphalt. Therefore, care should be taken to take a representative sample of the asphalt blend. Each aggregate particle influences its surrounding bitumen layer and its characteristics, such as thickness. Stiffness can be altered by changing the type of aggregate. Mixtures with the same aggregate and asphalt binder would have different workabilities at multiple testing trials. An asphalt mixture can be considered a granular paste in which the asphalt binder plays the media role. The same proportions of one aggregate can have different sizes, and this changes the mobility (i.e. workability) of the particles within the bitumen as the interfacial properties between the particles and bitumen change. This hypothesis may be dominant in modified asphalts, especially for adhesion promoter additives which act on the surface of the aggregate. Various shapes of aggregate might be present during crushing in the quarries starting from rounded to flaky and elongated aggregates. Also, the arrangement or distance between aggregate particles while mixing is one of the most important parameters affecting the workability of its granular paste. While mixing, the position of different aggregate particles varies from time to time. Changes in the internal structure of the asphalt mixture can lead to changes in the workability of the blend. Aggregate characteristics and gradation may overwhelm binder effects. The fabricated spindle (Fig. 3a) is a unit composed of five rows spaced at a 15 mm vertical distance; each row is formed by joining the center of four-connected 20 mm diameter aluminum balls ninety-degree angles. Odd rows (3 rows) were rotated 45 degrees in the horizontal plane with respect to the even ones (2 rows). The geometry of the fabricated spindle is also shown schematically in Fig. 3b. The height of the bitumen sample was kept at 85 mm, just covering the upper balls and leaving a 5 mm gap between the lowest point of the lower balls and the bottom of the container. The geometry and the gap between the aluminum balls and the inner wall of the cylindrical container were chosen as 5 mm to avoid the influence of the boundaries on the measurements. The sample container is heavy enough to prevent rotation along with the spindle while testing. In the current modified VST apparatus, the rotational speed increased to a possible speed of 1/18 rpm, which corresponds to a maximum peripheral or tangential speed of 0.175 mm/s, and for a 5 mm gap between the ball and inner wall of the container, a maximum instantaneous shear rate of 0.035 s^{-1} will be yielded. Because of the importance of the volumetric characteristics of the aggregate and bitumen, the amount of aggregate content was calculated by volume and weight. Although it was difficult adding more balls, the aluminum balls represent approximately 35% by volume and 85% by weight of the bitumen blend used, which were hypothesized to be close enough to resemble realistic aggregate properties (e.g. percentage).

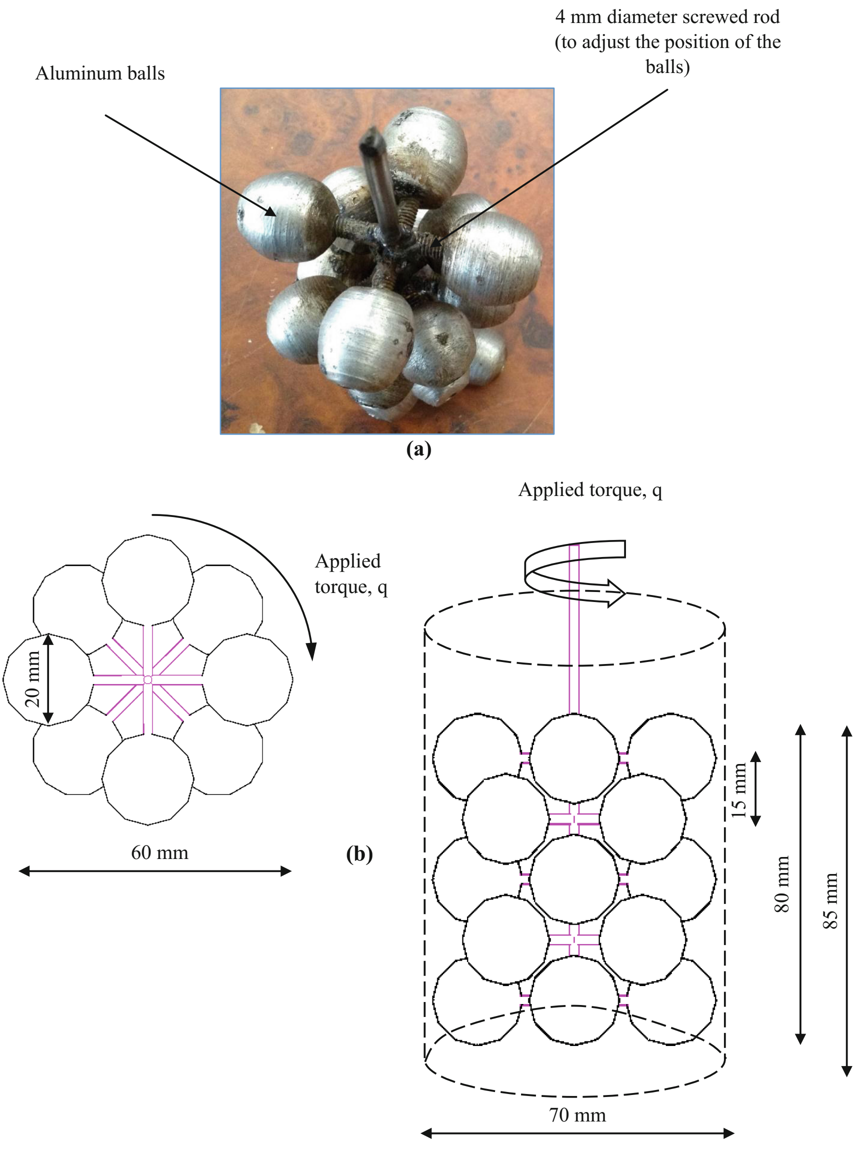

Fig. 3. Configuration of the designed spindle: (a) an oblique view of the fabricated spindle and (b) a schematic showing the geometry of the designed spindle (plan view (left side) and elevation view)

5 Workability of Polymer-Modified and Warm Mix Asphalt

Due to the wide utilization of polymer additives and water foaming in the asphalt industry, the workability measurement of their blends turned out to be an imperative issue and was determined with the aid of the developed prototype. For simplicity, it is usually assumed that the modified asphalt binders are Newtonian, i.e. their viscosity is constantly proportional to the shear rate, however, this leads to an inaccurate estimation of the mixing and compaction temperatures resulting from the equiviscous principle. Recognizing the potential problems with using this method, the linear temperature-viscosity relationship assumed for unmodified binders may not be valid for modified asphalt binders. According to Yildrim et al. (2000), the viscosity of polymer-modified asphalt binders is significantly affected by the shear rate; this effect was very small in the case of unmodified asphalt binders and can be ignored during the viscosity measurements. Regarding the WMA and foaming technology in particular, the inclusion of pressurized air and quantity of cold water into a hot bitumen phase produces volumetric effects that make asphalt testing a challenge. The air bubbles formed after evaporation of cold water into hot bitumen result in foamed asphalt. After the injection, the foamed bitumen expands rapidly, and after some time (about a few minutes in the case of water-based foaming) it reaches its maximum volume followed by a rapid collapse process and a slow, asymptotic return to its original volume. This makes measuring the viscosity of the foamed binder difficult, or in other words, not feasible. No bubbles should be present in the asphalt binder when tested using the current viscosity protocols. The foamed asphalt can be considered a two-phase system where the bitumen phase encloses another phase of air bubbles formed by the evaporation of cold water into the hot bitumen. The bitumen phase in this system should have the same viscosity as that of the tank bitumen at the same temperature. However, the overall viscosity or workability of the foamed bitumen (if we consider the asphalt-air two-phase system as a whole) is lower than liquid tank bitumen at the same temperature.

6 Materials and Preparations

In the current study, the developed prototype was verified with the aid of three asphalt blends: two different polymer-modified bitumen blends (PMB1 and PMB2) and water foamed bitumen. Paving bitumen (penetration 60/70) commonly used in Egypt from Suez refinery was used to produce the blends. The polymer-modified blends were prepared in an appropriate container equipped with a high shear mixer. A known quantity of the asphalt binder was added to the container and heated to 180 °C, followed by the addition of 3% (by the weight of bitumen) of the polymer additive. Each bitumen-polymer blend was continuously stirred for 2 h at 2000 rpm. In the case of foamed prepared bitumen, there are several lab-scale foaming machines, however, to prepare the foamed bitumen, the procedure discussed in (Goh and You 2011) has been adopted in this study. The syringe-based system for generating foam is less expensive and capable of producing good quality foam, provided that a field foaming effect can be ensured. The most important is ensuring that the bitumen is heated to the desired temperature before injecting the cold water. In this study, the water was injected at rates of 1.5 and 3% (by the weight of bitumen) at the bottom of the container, which results in an acceptable foaming. However, in order to produce acceptable foam, the water must be pressurized suddenly in a short period of time (usually within a second). Afterward, a spatula was used to disperse the bubbles generated in the entire volume of bitumen. The prepared blends were then immediately poured in the spindle container for testing. For the polymer modified bitumen, the torque data was recorded after the blend reached target temperatures (after 1 h heating), while for the foam prepared bitumen, a single point torque was recorded every 20 s at the target temperature.

7 Discussion

7.1 Workability Index (WI)

After the prototype configuration was finalized, further testing was done for verification. The philosophy behind utilizing the polymer-modified and WMA, in particular, is that their workabilities are still questionable. This information was then examined to decide the impact of individual constituents on the workability of the studied blends. The torque required to maintain a constant rotational rate of a specially designed spindle while submerged in the samples of asphalt blends at a specific temperature was measured. Plots of the WI data at the temperature points are shown in Fig. 4. The WI at different temperatures shows that the blend gets more workable as the temperature increases and vice versa. As for the polymer-modified bitumen, a one point workability value was measured as shown. The polymer-modified bitumen is less workable than the tank bitumen. The workability of WMA is particularly time-dependent. The workability data for the WMA were recorded at different times (except for the first 2 s) and plotted as shown in Fig. 5. One of the promising benefits marketed about using WMA is the improved workability at decreased production temperatures. There is a great interest in discerning how this increased volume affects the workability of asphalt. According to the derived Eq. (5) and the experimental results presented herein, it can be seen that the WI, which is the reciprocal of the torque, q, is affected by different factors. For example, the foaming effect increases the volume of bitumen, and therefore, the thickness of bitumen film changes with the time of mixing; and the film thickness decreases with the increase of mixing time, which increases the applied

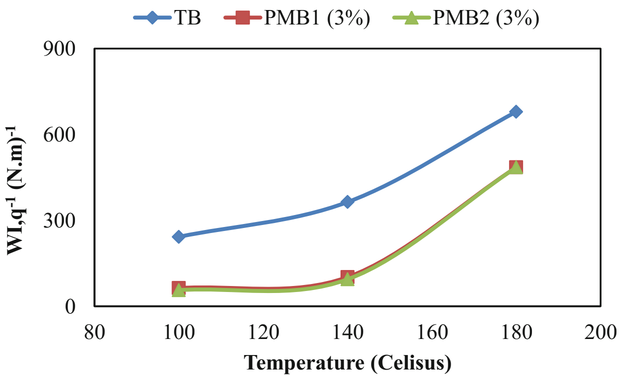

Fig. 4. Workability index for 3% polymer-modified bitumen (PMB1 and PMB2) and tank bitumen (TB)

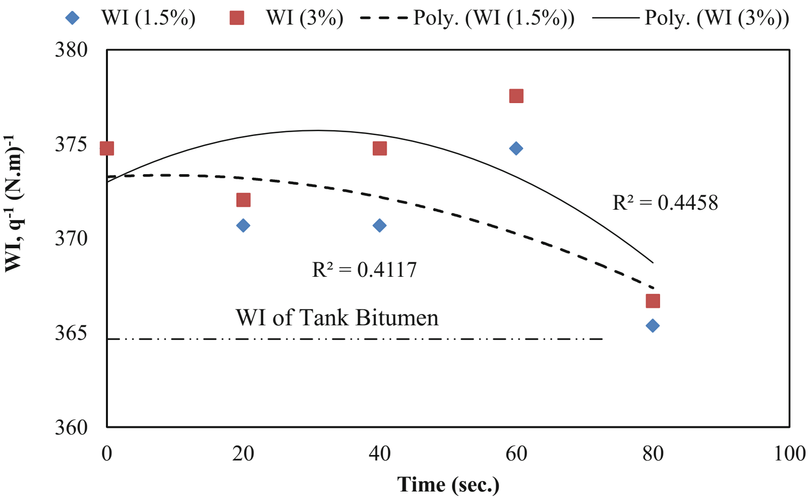

Fig. 5. Workability index vs. testing time for water foamed bitumen (at 140 °C)

torque with time increase. It is also quite obvious from Fig. 5 that mixtures foamed with 3% of water get more workable compared to 1.5% foamed mixtures. Water and air mixed with the bitumen resulted in foam multiple times larger than the original volume. In the real mixing, the contact area between colliding aggregates also changes. As partial lubrication increases due to the inclusion of bubbles in bitumen, aggregate particle contact decreases and wear is decreased, thus increasing the acceleration of the moving part. This shows that mixtures prepared through foamed WMA are more workable in the early stage of mixing compared to mixtures prepared through HMA mixing. In the case of foamed bitumen, the figure shows WI values at 140 °C only. The WI gradually decreases with respect to time until the WI attains the lowest value. Depending on the foaming temperature, foaming is effective over a short period of time. This conclusion has been stated in many research papers (e.g., Jenkins et al. 2000; Diab et al. 2014). The scatter of WI values could be due to the movement of the spindle in a non-homogenous medium, as the bitumen phase is randomly disconnected by air bubbles. Despite the scattered results, a reasonable trend of the WI can be registered. Higher mixing speeds would most likely be better for proper analysis of this scenario. The current mixing process can be different than that in the real mixing plants; for in reality, a mass mixing undergoes turbulent mixing actions in the plant mixers, corresponding to an extremely wide range of applied shear rates (West et al. 2010). The developed prototype is limited to workability results at a low shear rate; however, the results at higher shear rates are not predictable and need further investigation. Finally, the presented prototype was able to differentiate the workability of polymer-modified and foamed WMA.

7.2 Shear Stress Versus Shear Rate for Polymer-Modified Bitumen

First, the relationship between shear rate and shear stress for polymer-modified bitumen was discussed based on the experimental results. The behavior of shear stress versus shear rate was verified experimentally for different levels of shear rates and temperatures. The rotational viscometer (Brookfield DV2T) that measures the viscosity based on the principle that the fluid is sheared between two surfaces following the AASHTO T 316-11 (2011) was used for this testing. The velocity of the #27 spindle can be varied so that the relationship between shear rate and shear stress, from which the ratio of both measures of viscosity, can be recorded. The shear stresses corresponding to shear rates at rotational speeds ranging from 5 to 40 rpm in 5 rpm increments were recorded from the rotational viscometer at different temperatures (100, 140, and 180 °C) and are plotted in Fig. 6a–c, respectively. Much of the possible shear rates with the Brookfield DV2T have been used according to each individual binder and temperature combination allowed.

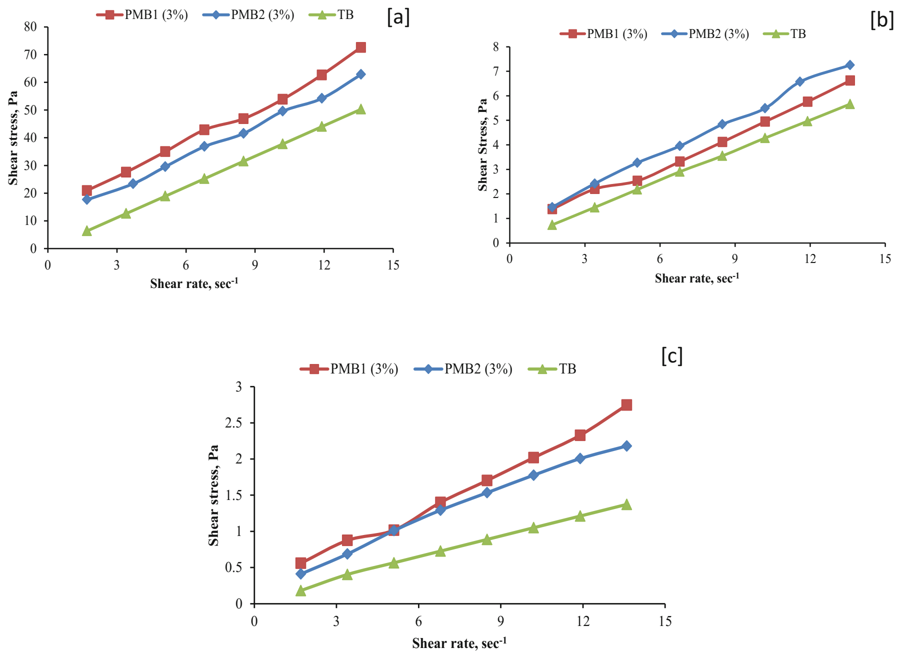

Fig. 6. Shear stress -shear rate characteristic for 3% polymer-modified bitumen (PMB1 and PMB2) and tank bitumen (TB): (a) 100 °C, (b) 140 °C, and (c) 180 °C

Generally, fluids like the tank or neat bitumen compared to the modified bitumen have a loose and homogenous molecular structure which is not significantly affected by shearing. For fluids like the tank bitumen, theoretically, the shear stress is constantly proportional to the shear rate. On the other hand, when the fluids in which a portion of the substance is composed of suspended polymer molecules, the non-Newtonian behavior prevails. During the process of shearing in polymer-modified bitumen, separated long molecules, which are randomly orientated, tend to align, changing the apparent viscosity of the whole fluid (Yildrim et al. 2000; Stachowiak and Batchelor 2013). The relationship between shear stress and shear rate is no longer linear, and deviates from the Newtonian behavior with the increase in temperature, making the estimation of mixing and compaction temperatures for polymer-modified asphalt a challenge. Care is needed with non-Newtonian fluids, as this concept is mainly calibrated for Newtonian fluids as the dominance of non-Newtonian characteristics increases the complexity in determining the mixing and compaction temperatures from the viscosity-temperature curve (equiviscous principle). Although approximate analysis predicts a straight proportionality between shear stress and shear rate, for polymer-modified bitumen this proportionality is lost and a different pattern is observed at different temperatures. Therefore, the workability, as a genuine characteristic, seems to be a distinctive alternative for predicting the production temperatures of different asphalt mixtures.

7.3 Predicting Mixing Temperature of Modified Asphalt Mixtures

The WI of tank bitumen hypothesized as a desired level of workability was used as a reference for the polymer-modified blends (Fig. 4). Table 1 shows the mixing temperatures of tank bitumen and polymer-modified bitumen blends based on the equiviscous principle and WI concept suggested herein. For the PMB1, when compared with the equiviscous principle, the WI data resulted in a predicted mixing temperature about the same. However, in the case of PMB2, the suggested method resulted in less predicted mixing temperature; by about 5 °C as compared to that estimated from the equiviscous principle. In the case of foamed WMA, the WI is higher than that for the tank bitumen. Although there is no proven data, since the WI data is limited to 140 °C in this study, at lower temperatures it is likely that the WMA blends undergo higher WIs, too, resulting in lower mixing temperatures. Therefore, as long as the WI of foamed WMA is higher than that of the tank bitumen, the temperature can be considered a suitable mixing temperature. It can also be seen that every studied blend has a unique relationship between temperature and WI based on the bitumen type. In the case of WMA, the testing temperature seems suitable as a mixing temperature. Mixture tests should be performed in conjunction with the aforementioned WI results to analyze the effects of mixing temperature on the aggregate coating, and the desired mixture and

Table 1. Predicted mixing temperatures of polymer-modified mixtures

	Range of mixing temperatures, °C	
	Equiviscous principle	WI method
Tank bitumen	161.63–165.13	–
3% polymer-modified bitumen		
PMB1	178.3–182.68	180
PMB2	184.47–187.47	180

mechanical properties of the corresponding mixtures; however, this is out of the scope of this research. In another study, Diab (2016) proved the influence of production temperatures on the mechanical properties of the mixtures and cautioned a care should be taken to select the appropriate temperatures to suit different factors (e.g. performance and workability). Determining the mixing and compaction temperatures of asphalt mixtures is a complex issue and needs separate additional studies. In an attempt by Gudimettla et al. (2004), they developed a different device and determined the compaction temperature at which the mixing torque begins to change dramatically as the lowest desirable compaction temperature. However, the initiative to determine the mixing temperature in this paper is just a preliminary attempt that is limited by the use of some data analysis of the developed workability prototype, and more effort is needed to make it more conclusive.

8 Summary and Conclusions

The desired outcome of this study was to develop a fundamental-based prototype to simply measure the workability of asphalt mixtures based on bitumen testing. Also, there was a need to present a method for determining the mixing temperature of different asphalt mixtures. A device that effectively distinguishes between the workabilities of different asphalt mixtures is important. Unfortunately, acceptable laboratory and test conditions have yet to be developed to quantify the workability of asphalt mixtures. The current paper presents a bitumen-based prototype in an attempt to differentiate the workability of different asphalt mixtures. There has been a limited research effort to quantify the workability of asphalt mixtures in the literature. Traditionally, the temperature-viscosity curve is used to determine the mixing and compaction temperatures of asphalt mixtures based on the equiviscous principle. However, it was found that the viscosity of modified binders significantly moves away from (linear) Newtonian toward the non-linear behavior compared to the tank bitumen, especially at higher temperatures. From this issue, researchers paid a lot of attention to the workability of asphalt mixtures in lieu of the equiviscous principle. Before designing the prototype, a simple fundamental derivation was performed to study the factors that could affect the workability of asphalt mixtures. The workability of asphalt mixtures depends on different factors, including binder type, aggregate properties, modifiers, and temperature of the mixture. Therefore, a special spindle was designed and fabricated to obtain repeatable and comparable results by diminishing the sensitivity of the workability results to aggregate properties (the size or gradation, distribution, particle shape, and particle mineralogy). The torque required to maintain the spindle rotation at a specific speed in a sample of asphalt binder was measured. A research effort to evaluate the workability of polymer-modified asphalt binder, as well as water-based foamed WMA, is summarized. The workability prototype presented was able to rank the workabilities of the studied blends in a rational order and compared favorably with one another. In this instance, the foaming results in an improved workability of the mixture which can subsequently allow a decrease in the production temperatures. The prototype aided a rough estimation of the mixing temperature of polymer-modified and foamed bitumen.

9 Recommendations

This prototype worked best in scenarios where the mixing speeds are low; however, due to the limited speeds of the current prototype, the results at higher speeds should be investigated.

Acknowledgments. The authors would like to thank the department of civil engineering laboratories at Aswan University, Egypt for providing the facilities that helped in making this prototype possible.

References

AASHTO T 316-11: Viscosity determination of asphalt binder using rotational viscometer. In: AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing. American Association of State Highway and Transportation Officials, Washington, DC (2011)

Airey, G.D., Brown, S.F.: Rheological performance of aged polymer modified bitumens. J. Assoc. Asph. Paving Technol. **67** (1998)

Airey, G.D., Hunter, A.E., Collop, A.C.: The effect of asphalt mixture gradation and compaction energy on aggregate degradation. Constr. Build. Mater. **22**, 972–980 (2008)

Azari, H., McCuen, R.H., Stuart, K.D.: Optimum compaction temperature for modified binders. J. Transp. Eng. **129**(5) (2003)

Bennert, T., Reinke, G., Mogawer, W., Mooney, K.: Assessment of workability and compactability of warm-mix asphalt. Transp. Res. Rec.: J. Transp. Res. Board **2180**, 36–47 (2010)

Celik, O.N., Atis, C.D.: Compactibility of hot bituminous mixtures made with crumb rubber-modified binders. Constr. Build. Mater. **22**, 1143–1147 (2008)

Clark, R.G.: Practical results of asphalt hardening on pavement life. In: AAPT, vol. 27 (1958)

Delgadillo, R., Bahia, H.U.: Effects of temperature and pressure on hot mixed asphalt compaction: field and laboratory study. J. Mater. Civ. Eng. **20**(6), 440–448 (2008)

Diab, A.: Studying viscosity of asphalt binders and effect of varied production temperatures on engineering properties of HMA mixtures. Can. J. Civ. Eng. (2016)

Diab, A., You, Z., Ghabchi, R., Zaman, M.: Effects of regular-sized and nanosized hydrated lime on binder rheology and surface free energy of adhesion of foamed warm mix asphalt. J. Am. Soc. Civil Eng. **27**(9), 04014254 (2014)

Fink, D.F.: Research studies and procedures. AAPT **27** (1958)

Goh, S.W., You, Z.: Moisture damage and fatigue cracking of foamed warm mix asphalt using a simple laboratory setup. In: ASCE T&DI Congress 2011: Integrated Transportation and Development for a Better Tomorrow, Proceedings of the First T&DI Congress (2011)

Gudimettla, J.M., Cooley, L.A., Brown, E.R.: Workability of hot-mix asphalt. J. Transp. Res. Board **1891**, 229–237 (2004)

Hanz, A., Mahmoud, E., Bahia, H.U.: Asphalt lubricity test evaluation and relationship to mixture workability. In: 90th Annual Meeting of the Transportation Research Board, pp. 23–27, Washington, DC (2011)

Horan, R.D., Chang, G.K., Xu, Q., Gallivan, V.L.: Improving quality control of hot-mix asphalt paving with intelligent compaction technology. Transp. Res. Rec. J Transp. Res. Board **2268**(1), 82–91 (2012)

Jenkins, K.J., Molenaar, A.A.A., de Groot, J.L.A., van de Ven, M.F.C.: Developments in the uses of foamed bitumen in road pavements. Heron **45**(3), 167–175 (2000)

Linde, S., Johansson, U.: Thermo-oxidative degradation of polymer modified bitumen. In: Polymer Modified Asphalt Binders. ASTM STP 1108 (1992)

Marvillet, J., Bougault, P.: Workability of bituminous mixes: development of a workability meter. Proc. Assoc. Asph. Paving Technol. **48**, 91–110 (1979)

McLeod, N.W.: Influence of viscosity of asphalt-cement on compaction of paving mixes in the field. Bituminous and Concrete Mixes. Highway Research Record, No 158 (1967)

Shenoy, A.V.: Determination of the temperature for mixing aggregates with polymer-modified asphalt. Int. J. Pavement Eng. **2**(1) (2001)

Shuler, T., Hanson, D., McKeen, R.: Design and construction of asphalt concrete using polymer modified asphalt binders. In: Polymer Modified Asphalt Binders, ASTM STP 1108 (1992)

Stachowiak, G., Batchelor, A.W.: Engineering Tribology. Butterworth-Heinemann (2013), ISBN 978-0-12-397047-3

Tayebal, A., Malpass, G., Khosla, N.: Effect of mineral filler type and amount on design and performance of asphalt concrete mixtures. Transp. Res. Rec. **1609**, 36–43 (1998)

West, R.C., Watson, D.E., Turner, P.A., Casola, J.R.: Mixing and Compaction Temperatures of Asphalt Binders in Hot-Mix Asphalt. NCHRP Report 648 (2010)

Yildrim, Y., Solaimanian, M., Kennedy, T.W.: Mixing and Compaction Temperatures for Hot Mix Asphalt Concrete. Texas Department of Transportation, Research Report Number 1250-5 (2000)

http://www.springer.com/978-3-319-61907-1

Advancement in the Design and Performance of
Sustainable Asphalt Pavements
Proceedings of the 1st GeoMEast International
Congress and Exhibition, Egypt 2017 on Sustainable
Civil Infrastructures
Mohammad, L. (Ed.)
2018, IX, 326 p. 182 illus., Softcover
ISBN: 978-3-319-61907-1