Workability of asphalt mixtures

Natascha Poeran[1, a], Berwich Sluer[1, b]

[1] *QRS, Boskalis Nederland, Nieuw Vennep, Netherlands*

[a] natascha.poeran@boskalis.com
[b] berwich.sluer@boskalis.com

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ABSTRACT

The construction of an asphalt concrete pavement is an affair that requires collaboration between a number of disciplines. Logistics, transport and workmanship are key words in making these alliances successful. Especially, because the temperature dependent behavior of asphalt concrete mixtures hamper the realization of high-quality pavements. Paving at too high or too low temperatures for example, could lead to difficulties during compaction. The inflow of asphalt concrete at optimum paving temperatures thus is a vital first step in the paving process. However, this is very much related to the logistic process,type and accuracy of transport. Fortunately, conventional asphalt concrete mixtures containing penetration bitumen are relatively less sensitive to these types of irregularities. Particularly because skilled asphalt workers can employ their extensive experience with these mixtures. By doing so, they can adequately and timely respond to unexpected circumstances enabling them to ensure the quality of the asphalt concrete pavement. Recent developments in asphalt concrete mixture design and bitumen composition though, have caused quite an increase in the number of available asphalt concrete mixtures. As a result asphalt workers cannot entirely rely on their experience during paving and compaction anymore. The determination of an asphalt concrete's workability in relation to temperature could therefore contribute enormously to the overall asphalt process, from production to construction. Clearly appointing the most favourable temperature windows for paving and compacting of an asphalt mixture will lead to more efficient logistics, proper paving, correct compaction and equally as important to a sense of satisfaction with the asphalt workers. All will result in higher quality asphalt concrete pavements.

To determine the workability of asphalt mixtures a prototype measuring device was developed based on findings from previous research on workability. This new prototype registers the torque exerted on a paddle, while this paddle stirs through a cooling asphalt concrete mixture. The development of the measured torque provides a (relative) indication of a mixture's workability. In an exploratory research program the most suitable test conditions and mixing configuration are determined by testing a variety of asphalt concrete mixtures and bitumen. The results of this research are reported and discussed throughout this paper.

Keywords: Asphalt, Compaction, Quality assurance, Temperature susceptibility, Workability

1. INTRODUCTION

The current range of available asphalt mixtures is quite large and continually growing – from dense to porous, from canary yellow to lurid purple, or even with printing. One explanation for this wide range is fairly obvious: demands on the structural efficiency and performance of pavements require different properties from each mixture. A surface course for a heavily trafficked access road, for example, requires other properties than a base course for a secondary road. In addition, the rise of Design & Construct projects is a powerful motivator for the development of asphalt with a longer service life. Moreover, asphalt is subject to numerous additional requirements not directly related to its primary function. These are not so much structural in nature, but rather relate to appearance, comfort, and noise nuisance. The drive to meet this demand has therefore led to growth in the number of asphalt mixtures. While this increasing diversity satisfies the demand, it also has a downside. Paving teams are now less able to rely on the wealth of experience they possess, because the nature of familiar mixtures has changed. This, in turn, impedes their ability to respond effectively to unexpected situations. One cause, in particular, is the use of modified bitumen instead of penetration bitumen as a binder. The variety of available asphalt mixtures also leads to less frequent use of each individual mixture, which stands in the way of one's ability to gain new experience. Poor conduct during asphalt paving has repercussions for the effectiveness of the subsequent actions, such as compaction, and therefore also on the final quality of asphalt pavements.

Nevertheless, change in the behaviour of asphalt mixtures is a *fait accompli*. However, it is important that this does not have a negative impact on the quality of asphalt pavements. Because a clearer understanding of the workability of asphalt mixtures would greatly contribute to this aim, a study was initiated to describe the workability of individual asphalt mixtures. The purpose of this study is to determine the ideal range of paving temperatures and compaction windows for each mixture. The expected result is tangible workability characteristics, which will provide easier and better control of the common and, especially, the relatively unfamiliar mixtures during pavement construction.

This study picks up where previous studies on the workability of asphalt mixtures left off. A brief summary of the methods and findings of these studies will be presented in the next section. Following this, the current experimental apparatus and study design are explained. Thereafter, the results of the conducted tests are analysed. Finally, conclusions are drawn and recommendations based on these conclusions are presented.

2. LITERATURE REVIEW

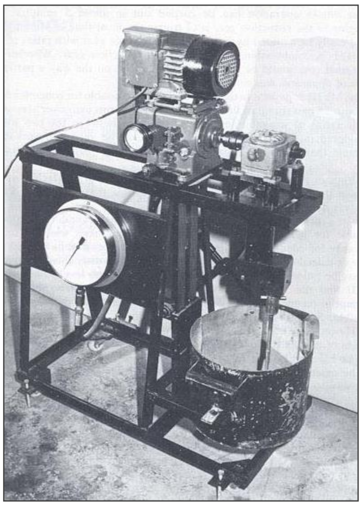
The need for a test which provides insight into the workability of asphalt mixtures is not new. In 1978 Marvillet and Bougault [4] conducted investigations into the workability behaviour of asphalt. Since then, the rise of modified bitumen, bitumen substitutes, recycling, and so forth have made the wish change into a necessity. As a result, the interest in workability has grown and, fairly recently, new studies have been conducted. The majority of these new studies continue in the direction embarked on by Marvillet and Bougault.

Marvillet and Bougault developed the first prototype workability meter in the 1970s. Their apparatus consisted of a mixing chamber suspended from a rigid frame, in which approx. 15 kg of asphalt mortar was mixed with the aid of a motor-driven paddle at 22 revolutions per minute. During mixing, the temperature in the mixing chamber was gradually increased from 150 °C to 200 °C. The speed was maintained through the use of a *potentiometer* (i.e. a variable resistor). The resistance of the mix was measured by means of that potentiometer and a set of springs. This resistance was then converted to numerical values representing the applied torque. The key findings from the study were:

- An increase in the viscosity of the bitumen has a negative effect on the workability of asphalt mixtures.
- The amount of bitumen in the mix has little or no impact on the workability.
- An increase in the percentage of filler in the asphalt mixture results in poorer workability.
- Angular mineral aggregate results in less workable mixtures in comparison to less angular and/or round mineral aggregate.

Marvillet and Bougault also noted that the workability is not merely a function of mixture properties but also of external factors such as temperature and the design of the prototype workability meter.
Later workability studies have focused mainly on optimizing the workability meter for more accurate determination of the influencing factors. Tao and Mallick at Worcester Polytechnic Institute [6] developed an apparatus in which a torque wrench was used to turn a paddle several revolutions at a number of predetermined temperatures. The value indicated by the wrench was recorded as the resistance of the mixture to mixing. A disadvantage of this arrangement is the discontinuous measurement of resistance. There is a risk that excessively

wide temperature intervals are chosen and characteristic behaviour is not observed. Moreover, the rather low number of measurements hinders the ability to draw reliable, repeatable, and reproducible conclusions about the workability of asphalt mixtures. Also, in an attempt to improve the first French prototype, Dongre [2] designed a workability meter in which the mixing bowl, rather than the paddle, was rotated. As far as known, this study has not yielded any useful results.



Figures 1 & 2: Workability meters developed over the years

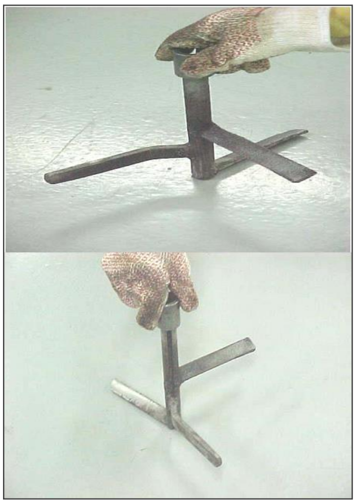


Figure 3: Paddle with blades developed by Gudimettla et al. 2003

In 2003, Gudimettla et al. [3] conducted a similar study on workability using a measurement arrangement consisting of a Hobart mixer connected to an ammeter. Initially, mixing was performed using a dough hook. After several tests with unsatisfactory results, the decision was made to develop a new kind of paddle. This paddle had three blades distributed along the length of the shaft. This vertical distribution of the blades was intended to reduce the likelihood of the creation of a shear plane through the loose mixture. The bottom blade was mounted at 45° to the direction of rotation to prevent the mix from caking on the bottom of the mixing bowl. The middle blade was kept perpendicular to the direction of rotation to prevent segregation. The top blade was inclined 45° to the direction of rotation so as to force the mix downward, into the bowl. Experiments showed that use of this paddle resulted in a significant reduction of noise in the measurement data and reduction of segregation. Although the work of Gudimettla et al. seems promising, it should be noted that the variation in raw measurement data is still relatively large. For this reason, the trends observed after processing are unreliable. Furthermore, the tests were carried out at temperatures of 170 to 120 °C, yet workability characteristics will have to span a wider range of temperatures, down to at least 80 to 70 °C, if one wants to be able to exert influence over the behaviour during compaction.

Building on the work of Gudimettla et al., additional research on workability of asphalt mixtures was conducted by De Bruin et al. [1] in 2011. In this study, use was made of a Bear mixer and two paddles – a screw, and a paddle with blades as previously described. Here, too, the resistance encountered by the paddle was measured using an ammeter. The goal of the De Bruin study was to develop a more representative experiment for the workability in order to obtain more reliable workability characteristics. It was therefore decided to match the rotational speed of the paddle to the rotational speed of the screw drive in the asphalt spreader, which is 35 rpm. Since the mixer could only mix at one rotational speed, 98 rpm, the contact surface of the paddles was reduced proportionally. The temperature was measured with an insertion thermometer at the beginning and end of the test and with an infrared thermometer during the test. The interval within which De Bruin measured is greater than in the Gudimettla study and runs from 160 to 80 °C. In accordance with Gudimettla et al., De Bruin found that the paddle with blades reduces segregation. De Bruin also shows several characteristics after processing of the raw measurement data. The current measurements from the ammeter, however, were not converted to numerical values for the torque, precluding comparison with the earlier results. A notable aspect is the scatter in the raw measurement data, which is also relatively high in this study. This may be a result of the high rotational speed. The reliability of the reported characteristics is therefore still uncertain.

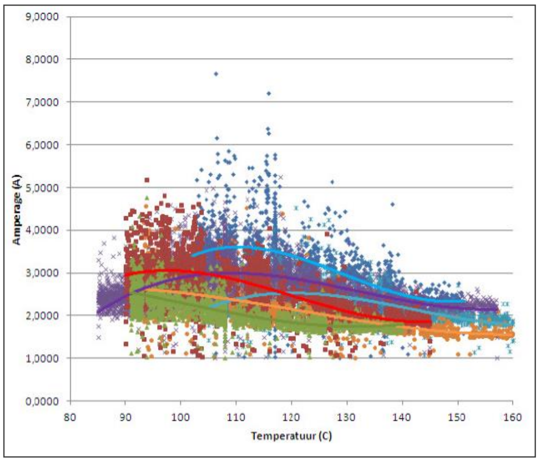


Figure 4: Raw workability data (De Bruin et al., 2011)

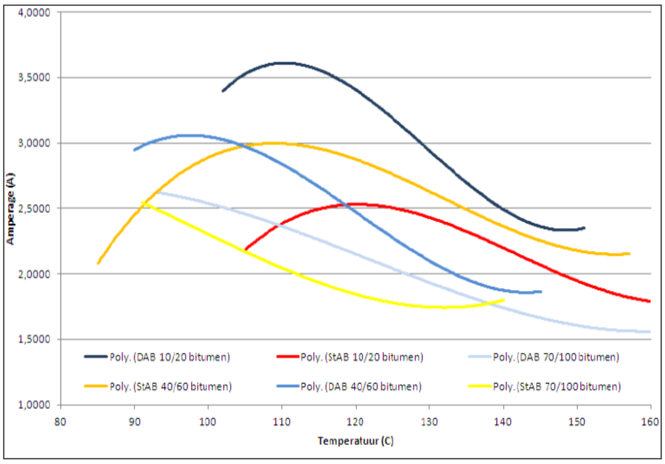


Figure 5: Workability characteristics after filtering of raw data (De Bruin et al., 2011)

Literature shows that despite the efforts focused on the workability of asphalt mixtures, a demonstrably suitable test apparatus, test procedure, and analysis method have yet to be established. However, a number of the findings and experiences described in the literature serve as very valuable starting points for a new development initiative. It is clear, for example, that a workability meter with motor-driven paddle and fixed mixing bowl is the most promising basic measuring setup. Moreover, the findings of several studies confirm that the paddle with specifically placed blades produces less measurement noise, reduces segregation, and prevents the creation of shear planes. Incidentally, it is suspected that the noise in the measurements is largely attributable to the method of data acquisition. After all, the conversion of a resistance measured through an ammeter to a final value for the torque results in the accumulation of measurement uncertainties. In addition, continuous recording of the quantities concerned would improve the quality of the measurements, as this approach obviates the need for interpolation.

With regard to the test procedure, the rotational speed of the paddle seems to have a significant influence on the measurement data. To present, rotational speeds of between 5 and 30 rpm have provided the most useful data. The range of temperatures within which measurements have been conducted is also very narrow and excludes lower temperatures, which are fundamentally the most important. Finally, the amount of material to be tested ranges from 5 to 20 kg, and the influence of the batch size on the measurement is not described.

3. DEVELOPMENT OF BOSKALIS WORKABILITY METER PROTOTYPE

With the decision to start with a concept based on an apparatus consisting of a fixed mixing bowl and a motor-driven paddle, the starting point for a new prototype workability meter was established. Although the mixing bowl does not rotate, the height can be adjusted automatically, which makes a workability test much less labour-intensive. An additional advantage is that the mixing bowl can be raised while the paddle is already in motion, so the initial resistance that must be overcome remains low, which prevents overloading of the measuring system. It also allows the height of the bowl to be changed during the test. In all likelihood, the paddle will not completely eliminate the creation of a shear plane. Should such a layer of air nevertheless develop, any disruptive influences on the measurement data can be minimized by changing the vertical position of the mixing bowl.

Crucial to the success of the workability meter is the data registration. In order to continually monitor the temperature three sensors are used. One sensor is located in the bottom of the bowl and is in contact with the asphalt. The middle blade of the paddle is fitted with the second sensor. The third is an infrared thermometer, located above the mixing bowl. The bowl height is also continually tracked with the aid of a sensor. Even more important than the temperature registration and bowl height is the way the workability is measured and the unit in which this is expressed. In principle, the asphalt provides resistance to mixing in the form of torsion exerted onto the paddle. It was therefore decided to express the workability as torque in this study. A mixture with poor workability will produce a higher torque and vice versa. In this prototype direct torque measurements are done with the use of a shaft-to-shaft rotary torque sensor with an encoder. This sensor is located between the drive shaft and the paddle and uses strain gauges to directly measure the torque applied to the paddle. This eliminates compounding of measurement uncertainties. The encoder ensures that the output speed matches the set speed 99.9% of the time.

Figure 6: Impression of new prototype workability meter

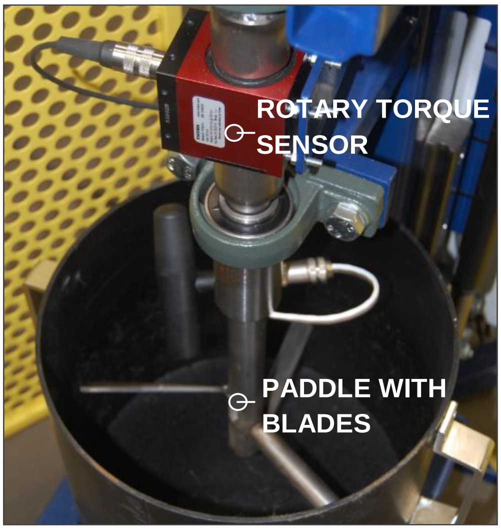


Figure 7 (top): Paddle and rotary torque sensor
Figure 8 (bottom): Control via touchscreen

The workability meter is operated via touchscreen. The mix data, maximum duration, lower temperature limit, upper torque limit, bowl height, and rotational speed can be set before starting a test. Based on the data entered, the apparatus stops if any limit is exceeded. The test can, of course, also be stopped manually at any time. It is also possible to monitor the measurements in real-time during the test. Although the sensors measure continuously, the display is updated with one new data point from the 'live' datalog every ten seconds. The data intended for analysis is stored every second.

4. DEVELOPMENT OF BOSKALIS WORKABILITY TEST PROTOCOL

The provisional test protocol was established by experimentally observing which settings and conditions provide the most accurate data. The initial values for a number of parameters were, however, set based on conclusions drawn from the literature. In examining the literature remarkably it was found that the majority of the studies focused on the workability behaviour of asphalt mixtures at temperatures above 120 °C, while it is in fact the lower temperatures that are critical during paving. Moreover, the critical temperature windows differ per type of bitumen. Instead of setting fixed limits, it was decided to match the initial and final temperature of the test to the characteristics of the bitumen concerned. The initial temperature should be as close as possible to the prescribed mixing temperature. The test can be ended as soon as the temperature of the mix has dropped to the softening point. After all, at temperatures below the softening point of the bitumen an asphalt mixture can no longer be properly compacted, and therefore knowledge of the workability behaviour at lower temperatures is of no value.

Opinions seem to be divided concerning the mass of the test mix, because these varied between 5 and 20 kg. Because the variation in batch size has shown no appreciable effect on the accuracy of the measurements, during this study the mass of the sample was selected as appropriate to the designed prototype. Taking into account the placement of the sensors, the maximum capacity of the mixing bowl was determined. Then the mixing bowl was filled to the indicated height with a number of types of asphalt mixtures, from which it was determined that the mass of the test samples was 20±1 kg. Previous research also showed that the optimal speed probably lies somewhere between 5 and 30 rpm. It has also been shown that the rotational speed is of great influence on the quality of the measurement. The decision was therefore taken to perform a number of identical series of tests in which only the motor speed is varied. In addition, the maximum duration of a workability test was estimated to be one hour, based on the expectation that the temperature of an asphalt mixture would drop from the mixing temperature to ring and ball temperature within this amount of time.

A varying number of asphalt mixtures were tested at each rotational speed. An effort was made to try as many different types of asphalt as possible to investigate the effect of differences in mix composition. In addition, four different types of bitumen were tested in each test series: two standard penetration bitumens, one hard penetration bitumen (EME), and one modified bitumen. The mineral aggregate in all the mixtures was identical. A list of the tested asphalt mixtures with corresponding specific temperature limits is presented in table 1.

Table 1: Summary of tested asphalt mixtures

Mixture type	Binder	Initial temperature [°C]	Final temperature [°C]
AC 11 surf	Bitumen 40/60	160	70
AC 11 surf	Bitumen 70/100	160	60
AC 11 surf	PMB - SBS	185	80
AC 11 surf	EME 15/25	185	80
PA 16	Bitumen 70/100	160	60
SMA 11	Bitumen 70/100	160	60

The first test series were performed at 25 rpm and with a batch size of 20±1 kg. A number of difficulties were observed during the first test series. Efforts were made to resolve these problems by making a number of modifications to the test apparatus and the test settings. The following observations and changes were made:

- The asphalt mixtures must be tested in the workability meter as soon as possible after mixing in order to be able to determine the actual time window for processing of the mixture. This also prevents rapid agglomeration, which otherwise results in unexpected flattening of the workability curves.
- Stones which are briefly trapped between the paddle blades and the wall of the mixing bowl cause extremely high peak measurements. To reduce this risk in order to further reduce scatter in the measurements the blades of the paddle were shortened by 15 mm.
- Also noted was that a fairly large amount of fine material was deposited on the wall of the mixing bowl and considerable segregation occurred. These observations also lent credence to the suspicion that the rotational speed was probably too high.
- By the end of the workability measurement all the mixtures had a rather tarnished appearance. In practice, this is considered an indication of the moment at which the asphalt mixture is no longer workable. Strikingly, the sample began to take on this tarnished appearance at the same time the scatter of the measurements began to increase. This coincidence suggests that the onset of tarnishing can be considered a valid termination criterion for the test.

Figure 9: Deposition of fine material on wall of mixing bowl

Figure 10: Thickness of layer of fine material

In the subsequent stage a number of test series with varying rotational speeds were performed. The test conditions are given in table 2.

Table 2: Summary of test series and test conditions

Test series #	RPM	Batch size [kg]	Notes	Observations
1	25	20±1	Original paddle	----
2	25	20±1	Modified paddle	Considerable amount of segregation, caking, scatter. Less peaks in measurement.
3	5	20±1	Modified paddle	RPM unstable – test series terminated
4	15	20±1	Modified paddle	Less segregation, caking and scatter compared to 25 RPM. Less peaks in measurement

The results of the workability measurements at 15 rpm are the most promising: clearly visible trends, relatively little noise in the initial measurement data, relatively little caking of fine material, and therefore less segregation. Figure 11 shows the raw data for the workability measurements done with an SMA 11 70/100 asphalt mixture. Both measurements were performed with the modified paddle. From the graph it can be seen that the scatter at 25 rpm is significantly greater than at 15 rpm. In addition, the data for the measurement at 15 rpm appears to follow a trend. The figure also includes two black, dashed lines. The SMA began to appear duller at the indicated temperatures. From that point onward the scatter also appears to increase more rapidly. Notice that, while both SMA mixtures are identical the loss of cohesion does not occur at simultaneous temperatures. The data measured at 15 rpm is considered more reliable since the loss of cohesion occurs at a more realistic temperature, approximating softening point.

It must also be noted that some of the visually observed noise was caused by the high frequency recording data. The temperature sensors measure the temperature to one decimal place of accuracy. The torque measurements are recorded once per second. Since the asphalt mixtures cooled down at a rate of less than 0.1 °C/s, multiple torque values correspond to the same temperature. For this reason, figure 12 is provided, which shows the same data as in figure 11 but with values averaged per degree. The characteristic of the measurement at 15 rpm is more easily recognized from the raw data than the characteristic at 25 rpm.

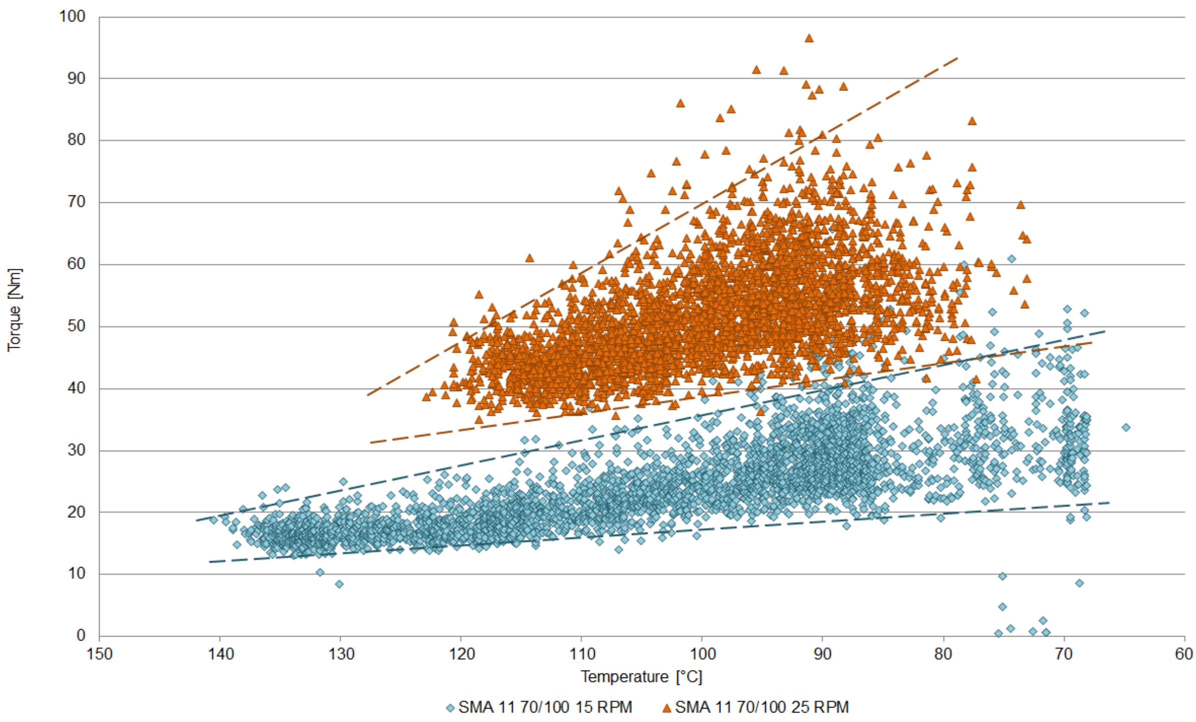


Figure 11: Raw data for workability measurement of SMA 70/100 at 25 and 15 rpm

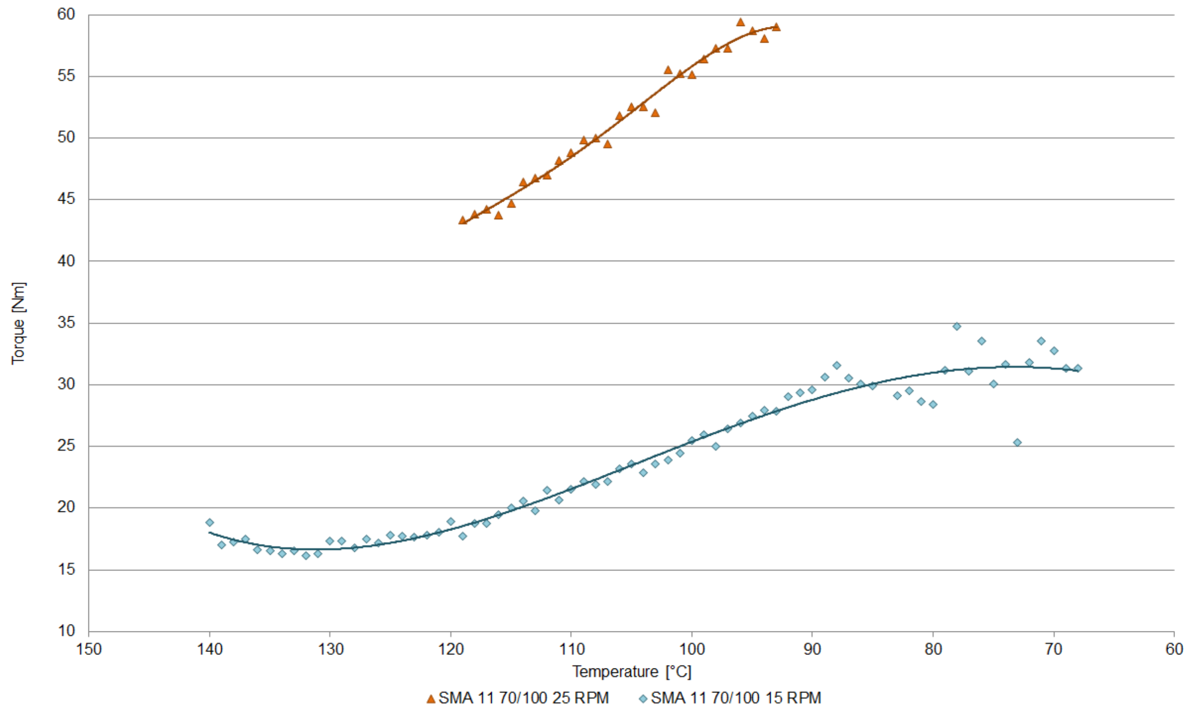


Figure 12: Workability data for SMA 11 70/100 at 25 rpm and 15 rpm with measurement values averaged per degree

For all of these reasons, the decision was taken to use the measurements conducted at 15 rpm to develop an analytical method with which workability characteristics can be established in a statistically sound manner. The results of test series IV, the measurements at 15 rpm, and the employed analysis method will be elaborated in the following section. An overview of the test protocol provisionally considered most suitable is given in table 3.

Table 3: Summary of settings and conditions for test protocol workability

Batch size [kg]	Rotational speed [RPM]	Initial temperature [°C]	Final temperature [°C]
20	15	prescribed mixing temperature of bitumen	softening point of bitumen *or* when mixture becomes tarnished
▪ Asphalt mixtures should be tested immediately or as soon as possible after mixing			
▪ A paddle with specifically positioned blades is used			

5. DISCUSSION OF WORKABILITY TEST RESULTS & ANALYSIS METHOD

In the fourth series of tests, the workability characteristics of six asphalt mixtures were determined at 15 rpm. The results, averaged per degree, are shown in figure 13. A striking feature of the figure is that all curves seem to trace a similar S-shaped path. This pattern reflects the expectation. At the start of a test, an initial resistance must be overcome by the paddle. Subsequently the resistance will drop, because the workability of the mixtures is good at higher temperatures. As the temperature decreases, the resistance gradually increases. As the temperature approaches the softening point of the bitumen, the rate of rise of the measured torque slowly begins to drop. This is due to the formation of agglomerates in the mixture. This is also the point at which the asphalt clearly becomes more tarnished in appearance. At a certain point the formation of agglomerates has progressed so far that the mixture loses cohesion. This moment corresponds to the right-hand inflection point. From that temperature onward, the resistance against the paddle therefore only becomes lesser.

An interesting observation is the great similarity between the measurements of the two stone skeleton mixtures, SMA and PA. From the characteristics it can be seen that the SMA is more workable at higher temperatures. This is due to the greater percentage of mastic in the SMA. The workability of both mixtures then decreases at approximately the same rate, and the inflection points are located in the same area. Furthermore, the stone skeleton mixtures are less workable in comparison to the dense asphalt mixtures. This observation is in agreement with the practical experience. Also noteworthy is the difference in slope of the dense and stone skeleton mixtures. It appears more continuously graded mixtures possess a longer period of workability. Here, too, it is easy to distinguish the difference between bitumens. The workability of the AC 11 mixtures with two softer, non-modified bitumens is better than the workability of the mixtures with the modified and hard penetration bitumen. Moreover, the inflection point for these mixtures seems to occur earlier than for the mixtures with penetration bitumen. These results indicate that the measured workability behaviour is consistent with the actual behaviour at a jobsite.

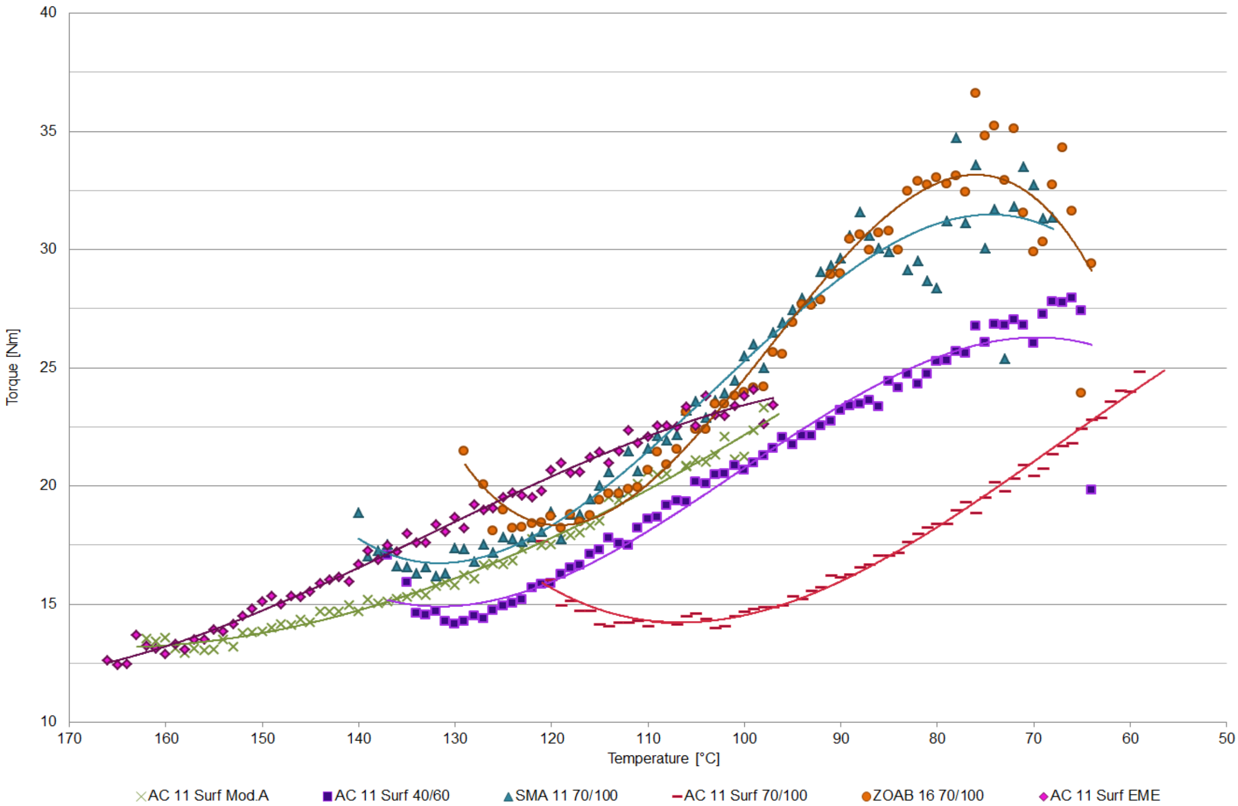


Figure 13: Workability characteristics of test series IV, at 15 rpm, averaged per degree

Subsequently an analysis method was developed to determine the optimal workability window for tested mixtures in a statistically sound manner. The points of departure for development of this method were *objective assessment* and *uniform applicability*. Observations relating to changes in the behaviour of the mixtures and their relationship to the progression of the measured workability characteristics were therefore not taken into account during development of this method. A number of analytical methods were evaluated. The method based on the pattern of the scatter in the torque measured during a workability test appears to be the most promising. The analysis considers the standard deviation of the measured torque over a moving time interval of 180 seconds. The standard deviation calculated during the first interval serves as reference level for the scatter. Subsequently, a 95% margin was established based on the reference scatter. Continuous overshooting of this margin indicates the presence of an inflection point. The corresponding temperature at the time of the first margin-overshoot is associated with the lower limit of the workability window. At lower temperatures the mixture is therefore no longer workable. The results of this analysis for the tested mixtures are shown in table 4.

Table 4: Lower limits workability window of tested mixtures

Mixture type	Binder	Lower workability limit [°c]
AC 11 surf	Bitumen 40/60	122
AC 11 surf	Bitumen 70/100	114
AC 11 surf	PMB - SBS	149
AC 11 surf	EME 15/25	153
PA 16	Bitumen 70/100	113
SMA 11	Bitumen 70/100	126

Clearly observable is the distinct division between the penetration bitumens on one hand and the modified bitumen and EME on the other. The lower limits of the mixtures with regular penetration bitumen lie between 113 and 126 °C. This is an average of 30 °C lower than those of the other two mixtures. It also appears the workability window of a 40/60 mixture is shorter than that of a 70/100 mixture. These findings are in agreement with practical experience. Also it should be noted that the calculated temperatures consistently correspond to the start of the left-hand inflection point of the workability characteristic curves. From this inflection point, the torque increases rapidly and the workability decreases. Accordingly, the association between the temperature at the inflection point and the boundary of the workability window seems valid.

6. CONCLUSIONS AND RECOMMENDATIONS

The results of the study confirm the supposition that it is possible to establish characteristics that describe the workability of asphalt mixtures. The trends of the workability graphs appear to be representative of the actual processing behaviour of asphalt. The difference in the workability of different types of asphalt mixtures and bitumen were observed and in line with the practical experience. It was found, however, that the measurement apparatus used and the applied test protocol are important for assurance of the reliability and practical applicability of the characteristics. In particular, the method of data acquisition and recording, the rotational speed of the paddle, and the shape of the paddle are of great influence. Which changes to the prototype apparatus and the test protocol serve to improve the accuracy and usefulness of the workability data will have to be determined experimentally. The already initiated development of a statistically robust analysis method will also contribute to the uniform, objective assessment of the measured characteristic.

Some suggestions for a follow-up study:

- Optimization of the paddle and bowl, to reduce segregation and agglomeration. This will manifest itself in further reduction of the scatter in data.
- Reconsideration of the material from which the bowl is made. A material that is less prone to the caking of fine material may reduce the segregation and, accordingly, scatter in the measurements. In addition, a thinner layer of caked material will reduce the risk of larger particles becoming briefly trapped between the paddle and the wall of the mixing bowl. This will also reduce scatter.
- Establishing correspondence between the actual cooling of an asphalt mixture under the influence of weather conditions and the cooling of an asphalt mixture tested in the laboratory. The information can, at this point, be linked to research conducted by ASPARi [5] [7] on the establishment of asphalt cooling curves during construction. By linking the results of the measured workability to the cooling curves, recommendations concerning the available paving time at expected weather conditions can be derived for each individual asphalt mixture.
- Continue and expand the research on the influence of workability in relation to a mixture's compactability. In this way compactability windows could be described as well leaving the asphalt paving process less prone to unexpected laying and compacting circumstances.

REFERENCES

[1] De Bruin, B. et al., Bepaling verwerkbaarheids- en verdichtbaarheidsparameters asfaltmengsels (Determination of workability and compactibility parameters of asphalt mixtures), BAM Wegen T&O, Utrecht, 2011.

[2] Dongre, R. and Salomon, D., New workability device for asphalt emulsion cold mixes and hot-mix asphalt, Dongre Laboratory Services Inc., 2006.

[3] Gudimettla, J. et al., Workability of hot mix asphalt, National Center for Asphalt Technology, Auburn University, Auburn, 2003.

[4] Marvillet, J. and Bougault, P., Workability of bituminous mixtures; Development of a workability meter, Proceedings of the Association of Asphalt Paving Technologists, Denver, 1979.

[5] Miller, S. et al., Proefproject Aziëhavenweg (Pilot project Aziëhavenweg), University of Twente/ASPARi & BAM Wegen T&O, Enschede, 2008.

[6] Tao, M. and Mallick, R., Effects of warm-mix asphalt additives on workability and mechanical properties of reclaimed asphalt pavement material, Journal of transportation research record, 2009.

[7] Vasenev, A. et al., Prediction of the in-asphalt temperature for road construction operations, University of Twente, www.aspari.nl, Enschede, 2012