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Aligning laboratory and field compaction practices for asphalt – the influence of compaction temperature on mechanical properties

F.R. Bijleveld[a]*, S.R. Miller[a1], A.H. de Bondt[b2] and A.G. Dorée[a3]

[a]*Department of Construction Management and Engineering, University of Twente, Post Office Box 217, 7500 AE Enschede, The Netherlands;* [b]*Ooms Civiel bv, Scharwoude, Post Office Box 1, Avenhorn 1633 ZG, The Netherlands*

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The approach used to identify a compaction temperature in the laboratory, based on binder viscosity, provides a single compaction temperature whereas, on-site, a roller operates within a temperature window. The effect on the density and mechanical properties of rolling during a temperature window remains unclear. Consequently, asphalt concrete binder mixtures were compacted in different temperature windows in the laboratory using a Roller Sector Compactor, and the observed phenomena were then related to field study observations. The results show that while similar densities can be achieved in a broad range of temperature windows, other mechanical properties such as fracture energy may decline up to 30% if compacted outside the optimum temperature window. These results indicate that a compaction temperature window should form part of mix design and quality control. The paper proposes specifying a compaction window based on temperatures and the resulting mechanical properties rather than a single compaction temperature.

Keywords: asphalt; compaction; cracking resistance; density; fracture energy; temperature

1. Introduction

Asphalt paving companies require deeper insights into the relationships between compaction operations undertaken on a construction site and the resulting mechanical properties of the constructed asphalt layer (Kassem *et al.* 2008, Leiva and West 2008, Bijleveld 2010). Although the impact and importance of the on-site compaction process on the final quality of the asphalt pavement is recognised, both in scientific journals and in practice, this field is still in its academic infancy. Miller (2010) concluded that the current literature mainly concerned asphalt characteristics from a material perspective, and that only limited attention had been given to systematically map and analyse the effects of the construction process on the quality of the asphalt layer. As such, little is known about how on-site operations impact on asphalt quality.

In current practice, rolling strategies are generally determined on a project-by-project basis, and to an extent by trial and error, using the experience of the operators (ter Huerne 2004, Bahia *et al.* 2006, Schmitt *et al.* 2009, Miller 2010). However, the chosen strategies can quickly become outdated if the variables change or new asphalt mixtures are introduced. This makes it difficult to determine the relationship between on-site compaction operations and the resulting mechanical properties. In addressing one aspect, this paper focuses on the influence of asphalt temperature during the compaction process on the resulting mechanical properties.

Several technologies have been developed to monitor asphalt temperatures during lay-down and compaction using thermal cameras, laser line scanners and thermocouples (Stroup-Gardiner *et al.* 2000, Ulmgren 2000, Lavoie 2007, Miller 2010). Although some of the technologies have progressed into industrial applications, it seems that only few have been accepted widely by the industry and used on-site. This is due to insufficient understanding of the process and a lack of evidence of added value. Appreciating the influence of compaction temperatures on the final mechanical properties could enhance this technology adoption process.

A basic assumption in the literature is that the compaction temperature is a key determinant of pavement quality (NAPA 1996, Asphalt-Institute 2007). The traditional laboratory approach to selecting a compaction temperature is to identify the binder viscosity and then checking this against corresponding binder viscosity–compaction temperature charts. The asphalt mixture is then compacted at this temperature using a standard procedure, and the resulting density and mechanical properties are then measured. This laboratory simulation is dissimilar from the compaction process in practice, where successive roller passes are undertaken, while the asphalt is cooling, until the target density is reached. Non-destructive density measurements and operator observations are used to decide when the target density has been reached, and that no further roller

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*Corresponding author. Current address: Ooms Civiel bv, Scharwoude, Post Office Box 1, Avenhorn 1633 ZG, The Netherlands. Email: fbijleveld@ooms.nl passes are required. Thus, while the existing laboratory approach uses the binder viscosity to determine a single optimum compaction temperature, the on-site roller operator has to determine a temperature window in which to compact as the asphalt cools during construction. As such, it is hard to give operators appropriate guidelines about the temperature window in which they should compact.

Different approaches to determining compaction temperature(s) have consequences for the resulting density and mechanical properties; the significance of which remains unclear. This paper specifically addresses the influence on the density and mechanical properties of compacting at various asphalt temperatures, and suggests a methodology for better aligning laboratory and field compaction in terms of asphalt temperatures. The various approaches and the focus of this study are shown in Figure 1.

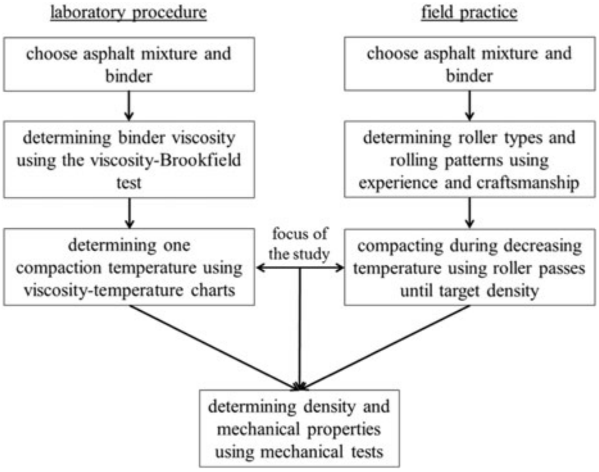

Figure 1. Laboratory procedure and field practice for determining density and mechanical properties.

Previously, Timm *et al.* (2001) argued that there is an ideal temperature window within which to compact an asphalt mixture that will result in a high probability that the desired mechanical characteristics will be achieved. Depending on the cooling rate of the asphalt mixture, this means that there is also an optimum time window in which to compact. If the asphalt mixture is compacted outside these windows, the mechanical properties might suffer. These conditions are illustrated in Figure 2 that schematically shows the changing temperature of the mixture as a function of time. For different mixtures and under different conditions, the ideal compaction window will shift along the timescale.

The objectives of this study are (1) to increase understanding of how compaction outside its optimum temperature window influences the mechanical properties of an asphalt layer, and (2) to develop improved laboratory compaction procedures that more closely simulate field compaction as a step towards better informing and guiding roller operators.

A twofold approach is used to achieve these objectives. First, experiments were conducted in the laboratory. Second, the compaction process was monitored on a construction site to determine whether the phenomena observed in the laboratory also occur in practice. Note that the goal of the field study was not to relate laboratory and field results but to determine whether the phenomena observed in the laboratory also occur in practice. In investigating the effects of compaction temperature, an AC16 binder mixture was compacted at various temperatures and the resulting densities and mechanical properties are then measured.

2. Background

The Asphalt-Institute (2007) defines compaction as the process of compressing a given volume of asphalt into a

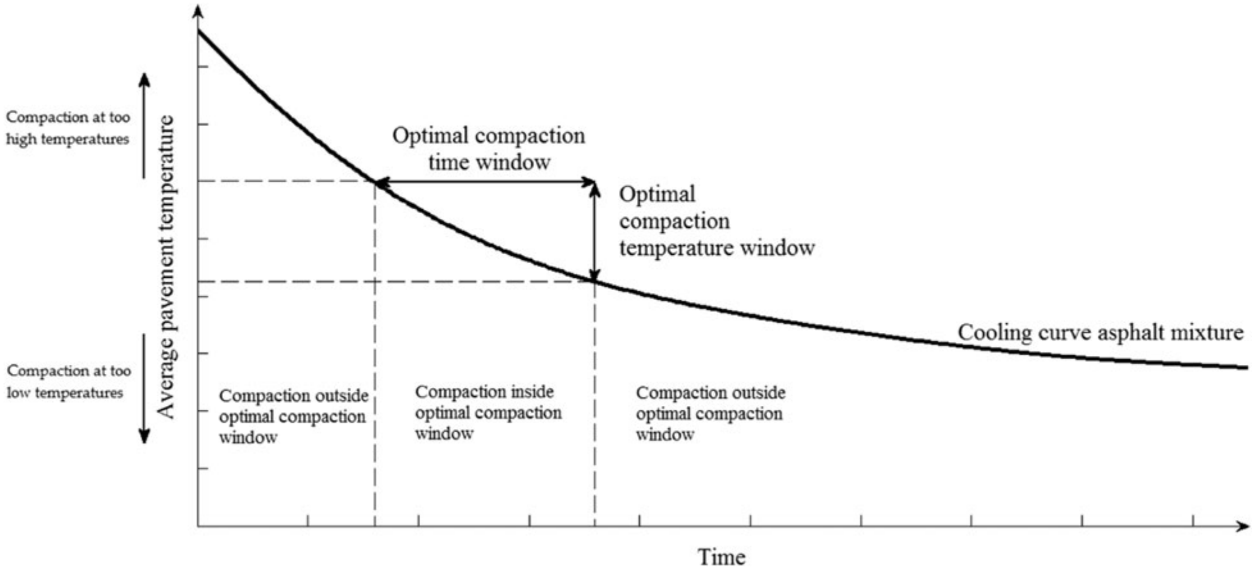

Figure 2. Cooling of the asphalt mixture over time and the optimal compaction window (after Timm *et al.* 2001).

smaller volume. The result is an asphalt mixture with a certain density. Achieving a specific density optimises the mixture's desired characteristics including its strength, durability and resistance to deformation and moisture (Decker 2006). If the mixture is over-compacted, the mixture becomes overfilled and can lose its essential stability. If the mixture is under-compacted, the asphalt mixture can deform under everyday loads leading to rutting and cracking.

Asphalt compaction is achieved through loading the mixture, in practice through successive roller passes. A material that is loaded tends to deform, and this deformation is resisted by counter pressures and internal cohesion (van Stek and Linden 1992). To increase density, the aggregate has to be pushed closer together and this can only be achieved if excessive air is driven out. In loading a relatively uncompacted material, the particle arrangement will change, the volume will reduce and the density will increase. In this process, the fluid in the asphalt mixture lubricates the contact areas between the particles and eases their sliding against each other (ter Huerne 2004). During this process, the angularity of the fine aggregate critically influences the mixture properties (Bahia and Stakston 2003). In essence, the task of roller compactors is to reduce the void content to the desired level and achieve an even surface (Asphalt-Institute 2007).

The roller compaction process can be divided into three phases (ter Huerne 2004, Asphalt-Institute 2007, Bijleveld 2010, Miller 2010): (1) breakdown rolling, where particles are rearranged and air is expelled; (2) intermediate rolling, where the asphalt mixture behaves differently due to its increasing stiffness and the viscoelastic behaviour of the mixture, and sometimes the mixture begins to act tender (Faheem *et al.* 2007) and (3) finish rolling, where the mixture is compressed further until the target density is achieved. From an operational perspective, these phases can be characterised by the types of roller used and the timing and temperature of the compaction process.

Both researchers and practitioners accept that the temperature of the asphalt mixture during the compaction process is critical for the pavement quality (Chadbourn et al. 1998, Timm *et al.* 2001, Willoughby 2003, Delgadillo and Bahia 2008, Masad *et al.* 2009, Schmitt *et al.* 2009). Some suggest that compaction should be completed within a specific temperature range, such as between 90 and 100°C (Floss 2001), others specify either a maximum temperature, generally around 130°C, (Commuri and Zaman 2008) or a minimum temperature between 70 and 80°C (Alexander and Hughes 1989, van Dee 1999). If the compaction temperature is too low, the bitumen is unable to lubricate the mixture, resulting in an open surface that is vulnerable to ravelling. Conversely, if the mixture is too hot, the binder can be too fluid and the resulting aggregate structure weakens because the roller loads displace the material rather than compact it, increasing the likelihood of cracking (Kari 1967, VBW-Asfalt 2000).

In response to these concerns, researchers have developed tools to predict the cooling rate of an asphalt mixture and with that take cognisance of asphalt temperatures during compaction. Chadbourn *et al.* (1998) and Timm *et al.* (2001) developed Windows-based computer programmes, PaveCool and CalCool, to predict the asphalt cooling process. The outputs include the theoretical cooling rate for a specific mix and recommended starting and stopping times for compaction after laying down the material. Since then, researchers have developed practical guides to estimate compaction windows based on local conditions (Wise and Lorio 2004, Mieczkowski 2007, Park and Kim 2013). Although these models provide information about asphalt temperatures throughout the duration of the process, they do not provide operators with guidance regarding temperature windows.

The optimum compaction temperature has traditionally been determined by plotting a log–log graph of bitumen viscosity against temperature, with the ideal compaction temperature coinciding with a viscosity of 0.17 Pa-s (Corlew and Dickson 1968). Following this, Jordan and Thomas (1976), Daines (1985) and Luoma *et al.* (1995) developed tools to predict an optimum temperature window in which to compact, that is, the starting and finishing temperatures between which to compact. The associated levels of viscosity were determined based on practical factors and experience, and this approach seemed to work well. However, Decker (2006) and Bahia *et al.* (2006) argued that determining compaction temperatures through viscosity–temperature plots was no longer appropriate since these traditional approaches sometimes indicate unreasonably high temperatures. Practical experience over the last 20 years in the Netherlands using modified bitumen confirms this (Sullivan and De Bondt 2009).

As such, there is a need for a greater understanding of the relationship between the asphalt temperature during compaction and the resulting mechanical properties. It is attractive to evaluate effects in a laboratory setting, where variables can be controlled and isolated. Various studies have indicated that, of the laboratory options, roller compactors most closely reflect field compaction (Renken 2002, de Visscher *et al.* 2006, Muniandy *et al.* 2007, Bijleveld 2010, Mollenhauer and Wistuba 2013, Airey and Collop 2014, Plati *et al.* 2014, Wistuba 2014). The advantages of roller compactors are that they can be preheated and can produce relatively large asphalt slabs, typically 500 mm by 500 mm or 700 mm by 500 mm. As such, several test specimens can be created simultaneously in a single slab.

Muniandy *et al.* (2007) conducted experiments with Stone Mastic Asphalt slabs using a roller compactor.

A compaction procedure was developed that involved 75 passes with 8 kg/cm^2 of pressure to achieve their targeted air voids of 4%. This pressure is not dissimilar to that exerted by rollers in the field. However, the number of passes they used is much higher than typical field compaction and, further, the latter only aims to achieve a target density. Mollenhauer (2009) developed a two-step standardised laboratory compaction procedure using a roller compactor. First, a position-controlled compaction procedure, simulating the paver, is applied to achieve a certain thickness and density. This is followed by a force-controlled compaction procedure to simulate compaction using rollers. Based on the procedures developed by Mollenhauer (2009), research into more accurately simulating field compaction in the laboratory is currently being undertaken by Paffrath *et al.* (2012). However, these procedures do not explicitly take compaction temperatures into account, nor involve a realistic number of roller passes that reflects field practice. More importantly, the existing laboratory compaction procedures offer no clear guidelines for operators.

Overall, asphalt temperatures during compaction are widely acknowledged as crucial for asphalt quality. Considerable research effort has been put into predicting asphalt temperatures throughout the process, but less effort has gone into using asphalt temperatures to provide better guidelines for roller operators. In response, this research focuses on analysing the effect that compacting at various temperatures has on the asphalt's mechanical properties, and on aligning laboratory and field compaction processes to provide operators with guidelines on the optimum compaction window.

3. Materials

The empirical research, incorporating both laboratory experiments and a field study, was conducted using an AC16 Base mixture with a 16 mm maximum size coarse aggregate, 4.5 % bitumen by mass (pen 40/60) and without recycled asphalt. This mixture was chosen since it is frequently used under less than ideal circumstances in the Netherlands. The reason for choosing a mixture without recycled asphalt was to increase the homogeneity of the mixture. Table 1 lists the materials in the asphalt mixture and Table 2 shows the aggregate gradation. The target density of the mixture is 2360 kg/m^3. All the materials were ordered as a single batch to minimise the risk of excessive variability in the raw materials. Samples were taken to determine the penetration grade and the Ring & Ball temperature of the bitumen, and the results showed little variability. The penetration grades of the tested samples were in the range of 50.0–55.0 mm and the softening points between 50.6 and 51.3°C.

Table 1. Raw material composition.

Material	Percentage (by total mass)
Bestone 4/8	21.1
Granite 8/16	33.9
River sand	27.7
Sea sand	7.0
Wigras 40K (filler)	6.0
Bitumen 40/60	4.3

Table 2. Aggregate gradation.

Sieve size	Percentage passing sieve (%)
16.0 mm	96.7
11.2 mm	75.6
8.0 mm	65.0
5.6 mm	51.1
4.0 mm	45.4
2.0 mm	43.0
500 μm	35.6
180 μm	15.2
63 μm	6.0

4. Experimental design and setup

Laboratory experiments were conducted, and then followed up by a field study, to determine the effect of asphalt temperature during compaction on the resulting density and mechanical properties. Compaction temperatures were varied and the resulting density and mechanical properties were analysed. The subsections describe the design of the experiments for both laboratory and field.

4.1. *Laboratory experiments*

All the test materials were produced in the laboratory. Each slab required 47.2 kg of material based on the target density of 2360 kg/m^3 and the targeted slab dimensions of 500 mm by 500 mm and 80 mm thick. The materials were mixed at 180°C for 3 min using an 80 kg mixer to enable compaction in a range of 170–80°C and to keep the mixing process the same for all compaction temperatures. The roller compactor shown in Figure 3 was used to compact the asphalt mixtures according to European Standard EN 12697-33.

In compacting, the asphalt mixture to produce slabs, two alternative compaction procedures were applied using a Roller Sector Compactor:

- Position-controlled compaction: compacting until the desired thickness is achieved (in our case 80 mm);
- Force-controlled compaction: compacting using a specified force (in our case 15 one-directional passes applying 0.30 kN/cm).

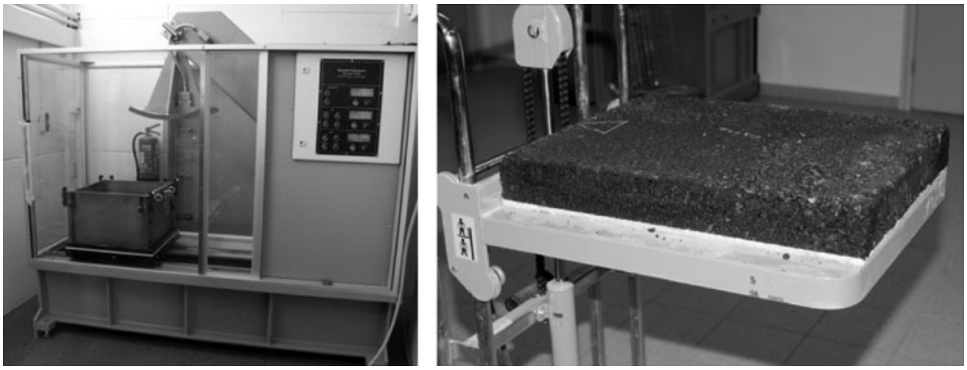

Figure 3. Rolling compactor WSV-2008-KW50/500 and the resulting 500 mm^2 slab.

In total, 18 slabs were produced, 12 using the position-controlled procedure and 6 applying the force-controlled procedure. The settings for the Roller Sector Compactor are shown in Tables 3 and 4 for the position- and force-controlled compaction procedures respectively. These settings are based on the compaction procedures developed by Mollenhauer (2009). The literature suggests that it is important to compact the asphalt mixture in distinct phases in order to achieve a certain particle orientation and to expel the trapped air. The asphalt slabs produced using the height-controlled procedure were compacted in two phases, first to a height of 84 mm using a relatively low force and, in a second phase, to 80 mm using a larger force. The force-controlled compaction procedure was divided into a pre-compaction phase, a smoothing phase (to simulate screed levelling) and finally the main compaction phase.

The slabs were compacted at mixture temperatures varying from 80 to 170°C and afterwards placed in one of four categories: slabs compacted in the temperature ranges

Table 3. Settings for the position-controlled compaction procedure.

Required settings for position-controlled procedure	Chosen setting
Starting load (as a line-load)	0.04 kN/cm
Moving speed of the mould	240 mm/s
Pause of the mould at the turning point	0.2 s
Loading speed/height decrease of the segmented slab	First phase: 1.60 mm per roller pass Second phase: 0.30 mm per roller pass
Maximum allowed load	1.00 kN/cm
Final height of the slab	First phase: 84 mm second phase: 80 mm
Number of passes after final thickness is achieved	15 passes (one directional)
Temperature of the mould and segment	80°C

Table 4. Settings for the force-controlled compaction procedure.

Required settings for force-controlled procedure		Chosen setting
Starting load (as a line-load)		0.04 kN/cm
Moving speed of the mould		240 mm/s
Pause of the mould at the turning point		0.2 s
Pre-compaction	Loading speed of the segmented slab	0.1 mm per one-directional pass
	Pre-compaction starting load (line-load)	0.1 kN/cm
	Number of passes applying pre-load	2 one-directional passes
	Unloading speed of the segmented slab	0.1 mm per one-directional pass
Smoothing	Load during smoothing-phase (line-load)	0.02 kN/cm
	Number of roller passes during the smoothing-phase	15 one-directional passes
Main compaction	Main compaction load (as a line-load)	0.30 kN/cm
	Number of passes to reach the main-compaction load	15 one-directional passes
	Number of passes to unload	15 one-directional passes

of 80–100°C, 100–135°C, 135–155°C and 155–170°C. The asphalt temperature was measured using three thermocouples inserted in the side of the slab at different heights.

During the compaction process, the number of roller passes and the force per roller pass are automatically recorded and, using those parameters, the total compaction energy can be derived from Equation (1).

$$E_{\text{tot}} = \sum_{i=1}^{n} (P \cdot t). \tag{1}$$

where E_{tot} is compaction energy (Nm), n is number of the roller pass; P is force per roller pass (N); t is decrease in layer thickness per roller pass (m).

Nine cores, each 100 mm in diameter, were removed from each of the 500 mm square slabs and their densities and certain mechanical properties were measured. The densities of the cores were determined according to EN-12697-9. An indirect tensile strength (ITS) test was carried out on six cores, providing an indication of the resistance to cracking (NAPA 1996), and a cyclic triaxial compression (CC) test on the other three, providing an indication of the resistance to rutting (Erkens 2002). These tests were chosen as they determine parameters that are relevant to the typical damage seen with this kind of mixture (with base and binder layers).

The ITS tests were conducted according to EN-12697-23. The specimens were conditioned at 5°C for 4 h so that the results could provide information about thermal cracking (NAPA 1996). The ITS, the work of fracture (W_{f}) and the fracture energy (G_{f}) are derived from this test. The G_{f} was calculated according to the RILEM TC 50-FMC specification (1985). The ITS-data were computed according to the EN Standard, and the W_{f} was computed as the area under the load–displacement curve (Equation 2) and the G_{f} was obtained by dividing the W_{f} by the ligament area (Equation 3), a procedure in line with Wen (2013).

$$W_{\text{f}} = \int_{0}^{\alpha} P \times du \tag{2}$$

where, W_{f} is work of fracture (N.mm); P is load (kN); u is displacement (mm).

$$G_{\text{f}} = \frac{W_{\text{f}}}{D \cdot H} \tag{3}$$

where G_{f} is fracture energy ((N mm)/mm^2); W_{f} is work of fracture (N mm); D is diameter of the specimen (mm) and H is height of the specimen (mm).

The CC tests were conducted according to the national standard established in the Netherlands (test 62) loaded with a periodical loading pulse using the Nottingham Asphalt Tester (NAT). The confining pressure (0.05 MPa) was applied by placing the specimen in a rubber socket and applying a vacuum to the specimen. To reduce friction, two layers of plastic with silicon oil between them were placed on both the top and the bottom of the asphalt specimens (Erkens 2002). The specimens were conditioned at 40°C for 4 h and then 10,000 400 ms per second pulses of 0.45 MPa were applied. The analysis revolves around comparing the cumulative plastic strains.

4.2. *Field study*

The phenomena observed in the laboratory were then checked against those obtained in a practical setting during a field study. The field study took place in the town of Dirkshorn in the north of the Netherlands. The surfacing of a 1600 m^2 area surrounding an agricultural warehouse formed the setting for the field study. The underlying layer consisted of a well-compacted 350 mm of recycled concrete granulate. The asphalt was produced at an asphalt plant approximately 8 km from the construction site.

Bulk compaction of the asphalt layer was undertaken using a 10 tonne combination tandem roller with all the joints further compacted using a small 2.5 tonne tandem roller. The combination roller had four pneumatic tyres on the front and a steel drum roller at the rear. The design of this pneumatic-tyred roller (PTR) provides a kneading action through the tyres. PTRs can be used in the breakdown or intermediate compaction phases (Asphalt-Institute 2007). These rollers usually cause deformation that are removed in the final, finish rolling, stage. However, with a combination roller, any such deformations are removed immediately by the steel drum mounted at the rear.

During the field study, the following measurements were taken:

- The movements of the paver and rollers were monitored using high-accuracy D-GPS equipment to determine the stops of the paver and the number of roller passes;
- The surface temperature behind the screed of the paver was continuously measured to determine the initial lay-down temperature using a laser line scanner;
- The in-asphalt and the surface temperatures were measured using thermocouples and an infrared camera at static points alongside the paving lanes to determine the cooling curve of the asphalt mixture throughout the process. At these points, the density was measured after every roller pass using a nuclear gauge.

Three lanes, each 86 m long, were surfaced alongside each other with an 80 mm base layer (AC 16 Base 40/60 pen without reclaimed asphalt pavement). Given the aim

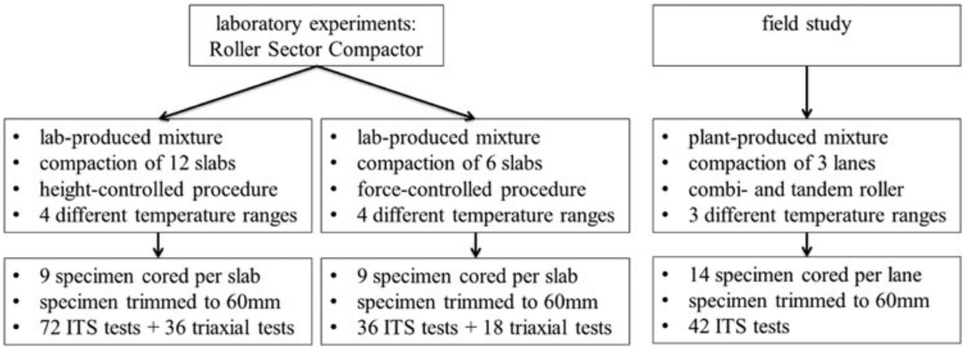

Figure 4. Laboratory and field study overview.

of studying the influence of compaction temperature on density and mechanical properties, the compaction process had, to some extent, to be guided. Here, the compaction temperatures and time frames were specified, with roller operators instructed when to start and when to finish compacting. The compaction of Lane 1 took place while the asphalt was within a temperature range of 150°C (first roller pass) to 90°C (last roller pass). Lane 2's compaction took place between 130 and 80°C, and the compaction of Lane 3 took place between 100 and 50°C. Immediately after construction, 14 cores were extracted from each lane to evaluate their properties. As with the laboratory specimens, the cores were trimmed to a diameter of 100 mm and height of 60 mm. Next, in the laboratory, the densities of the specimens were determined, and ITS tests conducted to determine their resistance to cracking.

Figure 4 summarises the laboratory and field tests undertaken.

5. Laboratory experiments and field study results

The effects of the various compaction temperatures on the compaction effort and energy, the viscoelastic mix behaviour, the resulting density and the mechanical properties are described for both the laboratory experiments and the field study. The temperature variability during the compaction processes is also addressed.

Note that, no direct comparison is made between the results of the laboratory experiments and those stemming from the field study for two reasons. First, because the field-study mixture appeared coarser than the mixture used in the laboratory and, second, because it rained heavily the night before the field study and the granular base layer was somewhat saturated. This situation means that the validity of comparing field study and laboratory results would be questionable. Here, we would emphasise that the purpose of the field study was not to accurately determine a relationship between laboratory and field results but rather to study whether the phenomena observed in the laboratory took place in practice.

5.1. *Results of laboratory experiments*

5.1.1. *Asphalt temperature variability during compaction*

In the laboratory, three thermocouples were used to measure the bottom temperature, the in-asphalt temperature and the surface temperature of each slab. Afterwards, the temperature variation within the slab was analysed. The maximum temperature difference measured within a single slab was 14°C. The average temperature spread within a slab was 9°C, with the standard deviation of the single slab measurements varying between 2 and 8°C, and averaging 5°C.

In the position-controlled compaction process, the average number of roller passes per compaction phase was 28 (one-directional passes of approximately 2.3 s per pass). As such, each compaction phase in the laboratory took approximately 1 min. During this compaction process, the asphalt mixture cooled on average by 2°C.

5.1.2. *Effect of compaction temperature on compaction energy*

Figure 5 illustrates the compaction energy (in Nm) for the various compaction temperatures used with the position-controlled compaction procedure. It can be seen that, as the compaction temperature decreases, the required compaction force and compaction energy increase. The most obvious explanation for this is that cooler bitumen is more viscous and, as a consequence, more force is necessary to bring the particles closer together.

At low temperatures, a large force and considerable energy were required to achieve the target density. Using the Roller Sector Compactor, forces above 30 kN could be achieved. It should be noted that such forces are currently not a realistic option in practice, and that this situation seems unlikely to change given current roller compaction technology. As shown in Figure 6, where the maximum load is plotted for different compaction temperatures, forces of such a magnitude are required if compaction starts below 110°C. At compaction temperatures above 150°C, the required force has dropped to such an extent

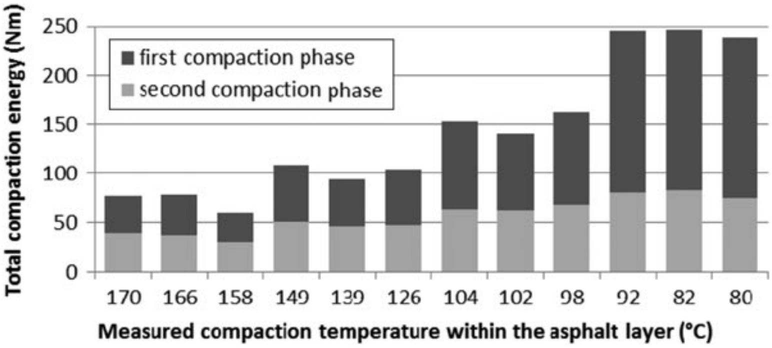

Figure 5. Compaction energy for different laboratory compaction temperatures.

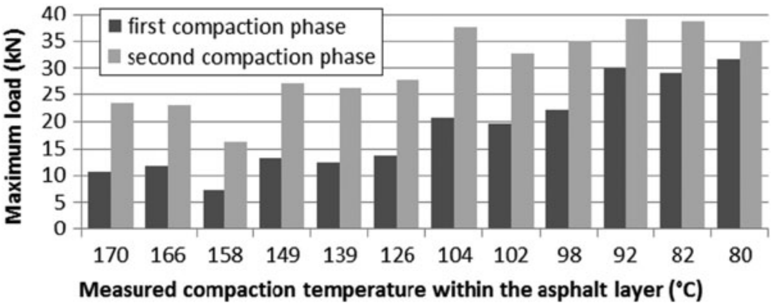

Figure 6. Peak load for different laboratory compaction temperatures.

that, in a practical situation, it would be necessary to use a light roller to avoid the bitumen being squeezed out of the skeleton and coming to the surface.

It is generally accepted that an asphalt mixture exhibits both viscous and elastic characteristics (Figge 1987, van Stek and Linden 1992, VBW-Asfalt 2000, ter Huerne 2004, Asphalt-Institute 2007). This was also apparent in the laboratory tests. Although the samples in the laboratory were compacted to a thickness of 80 mm, the measured heights, after cooling and conditioning, were found to vary between 81.5 and 82.5 mm.

The thicknesses of the laboratory samples were again measured after 110 h, and had not changed from those measured after 23 h. From this, the conclusion was drawn that any viscoelastic behaviour is complete within 23 h of compaction. An analysis of how the layer thickness varies with compaction temperature shows that viscoelastic behaviour is greater at higher compaction temperatures. However, the measurements were not sufficiently precise to determine an exact relationship.

5.1.3. *Effect of compaction temperature on density and mechanical properties*

The densities of the specimens at the applied compaction temperatures are shown in Table 5. The results show that the target density (2360 kg/m^3) could be achieved at all compaction temperatures, even down to 80°C. The densities within a single slab, based on nine sample cores, were found to be reasonably homogenous. The standard deviation of density within one slab varied between 4 and 12 kg/m^3. Also, the air void contents were reasonably homogenous varying between 5.2% and 6.5%.

The test results also show that the position-controlled compaction procedure produces samples with higher densities than the force-controlled compaction procedure. This difference can be attributed to the maximum allowable loads applied to the asphalt mixture, which was higher with the position-controlled compaction procedure (1.00 kN/cm) than during force-controlled compaction (0.30 kN/cm).

From the mechanical tests, it can be concluded that although the target density can be achieved at all the temperatures tested, the measured mechanical properties vary with the compaction temperature. The sensitivity is illustrated in Figure 7 where the G_f is plotted against compaction temperature for the position-controlled slabs. The test results for the force-controlled compacted samples are not shown but produced a similar trend. From the test results, it is clear that the samples compacted in the 135–155°C temperature range have a significantly higher G_f than samples compacted at either higher or lower temperatures. The G_f of the samples compacted in the 135–155°C range is approximately 1.0–2.0 N.mm/mm^2

Table 5. Compaction temperature and density (laboratory specimens).

Experiment	Compaction temperature (°C)	Density (kg/m^3)
Position-controlled	170	2363
	166	2365
	158	2381
	149	2367
	139	2365
	126	2360
	104	2386
	102	2389
	98	2387
	92	2390
	82	2367
	80	2368
Summary results	Density range (12 slabs)	2360–2390
	Average density (12 slabs)	2374
	SD density per slab (nine cores)	4–12
Force-controlled	169	2351
	166	2349
	140	2372
	138	2370
	89	2340
	88	2357
Summary results	Density range (six slabs)	2340–2372
	Average density (six slabs)	2356
	SD density per slab (nine cores)	8–11

Note: SD, standard deviation.

(or 20–30%) higher than the cores compacted at other temperatures. The G_f and the small differences in density were analysed and the differences in G_f could not be explained by the small differences in density between the slabs. Thus, it is apparent that it is possible to achieve the target density while starting the compaction process at temperatures outside the 135–155°C temperature range, this might well reduce the potential G_f by as much as 30%.

The results of the triaxial cyclic compression tests showed a relatively high standard deviation in cumulative axial strain within a single slab compared to the differences between slabs. The values for the cumulative axial strain were between 3.6% and 4.4% of the permanent deformation whereas the standard deviation within one slab was up to 1.1% of the permanent deformation. This made it impossible to discern a clear relationship between compaction temperature and resistance to rutting. This issue, of a large variation in permanent deformation values, was similarly raised by de Visscher *et al.* (2006). A useful aim for future research would be to improve the sample preparation and test procedures to minimise experimental variation; a goal achieved by Muraya (2007) for gyratory compaction.

5.2. *Results from field study*

5.2.1. *Asphalt temperature variability during compaction*

During the field study, the asphalt temperature was monitored at various points throughout the entire construction process: at the asphalt plant, at the asphalt truck as the mix was released into the paver hopper and behind the paver screed. The average asphalt temperature at the silo of the plant was determined to be 161°C. The construction site was 8 km from the plant, with typical journey times between 10 and 15 min. The asphalt temperature, as the mixture was released into the hopper, was measured with an infrared pistol. The average temperature for Lane 1 was 165°C, for Lane 2 it was 157°C and for Lane 3 it was 156°C.

The analysis of the GPS measurements showed that the paver had operated at a consistent speed of approximately 4.5 m/min across all lanes. However, six paver stops were observed for asphalt truck changeovers and an analysis of the laser line scanner results showed that the surface temperature had cooled to approximately 135°C during the

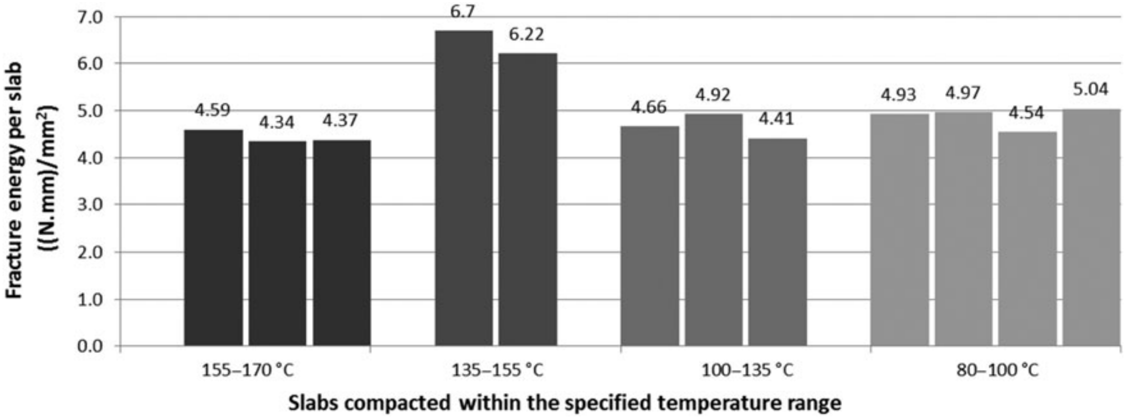

Figure 7. Fracture energy for different laboratory compaction temperature ranges.

stops. Rainfall also caused the surface temperature to drop to approximately 135°C at some locations, while the in-asphalt temperature remained at approximately 165°C. No cores were extracted at locations where excessive temperature differences were observed.

Further analysis of the GPS measurements showed that the operators of both rollers had approached compaction in a consistent manner. The operator of the combination roller concentrated on bulk compaction, and the small tandem roller was used on all joints and in small areas. Despite the apparent consistency in roller patterns, it appeared that a few metres at each end of the lanes received fewer roller passes than the rest of the lanes. Given this situation, cores were not extracted from the ends of the lanes.

5.2.2. *Effect of compaction temperature on density progression*

Field measurements were taken using a nuclear density gauge to assess density progression during the compaction process. The density progression and the cooling of the asphalt mixture over time for Location 1 within Lane 1 are shown in Figure 8. The results show that the density first increases, then slightly decreases, once a certain temperature is reached, and again increases on successive roller passes. This is probably due to the viscoelastic behaviour of the mixture, where the material springs back and the density reduces. The plotted results are typical of all the three lanes that were monitored. The density progression during compaction, which is not dissimilar to that in the laboratory experiments, shows that it is still possible to achieve the target density at lower asphalt temperatures although compaction becomes progressively more difficult.

5.2.3. *Effect of compaction temperature on density and mechanical properties*

The samples taken from the field and analysed in the laboratory show that the density for the three lanes varied between 2322 and 2369 kg/m^3. These values are within the performance-based specification range. This shows that also in practice the desired density can be achieved in different compaction temperature windows.

Further, the samples taken from the field show that, even though the target density is achieved, the ITS and G_f can vary significantly depending on the compaction temperature. The lane in which the operators started the compaction process, when the asphalt mixture was at approximately 150°C, showed significantly better results for resistance against cracking, with a 10–25% higher ITS, than the lanes where the compaction process started at 130°C or 100°C, as shown in Figure 9. As with the laboratory results, these differences in ITS values could not be explained by the small differences in density.

Thus, similar patterns to those observed in the laboratory were found in the field study. Given the effects of the compaction temperature on the asphalt's mechanical properties, the temperature during compaction is clearly an important parameter in determining the resistance to cracking, at least for this specific asphalt mixture.

6. Reflection and discussion

Both the laboratory and field results show that, depending on the compaction temperature, mechanical properties can vary significantly despite the target density being achieved. One possible explanation is that the weight of

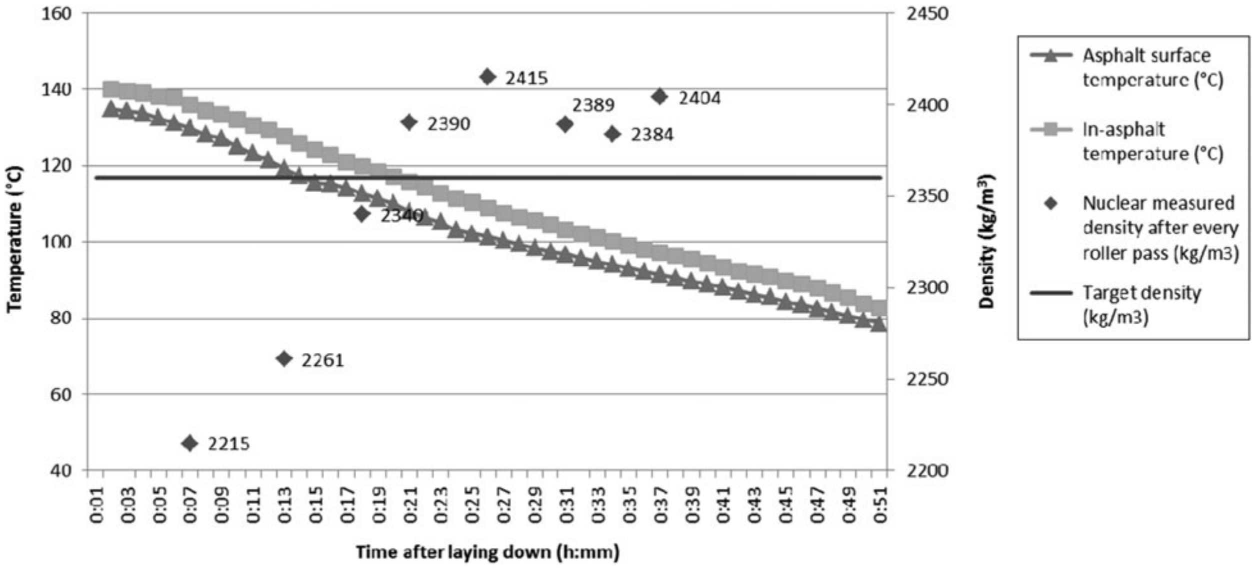

Figure 8. Sample cooling curves and density progression after successive roller passes in the field study.

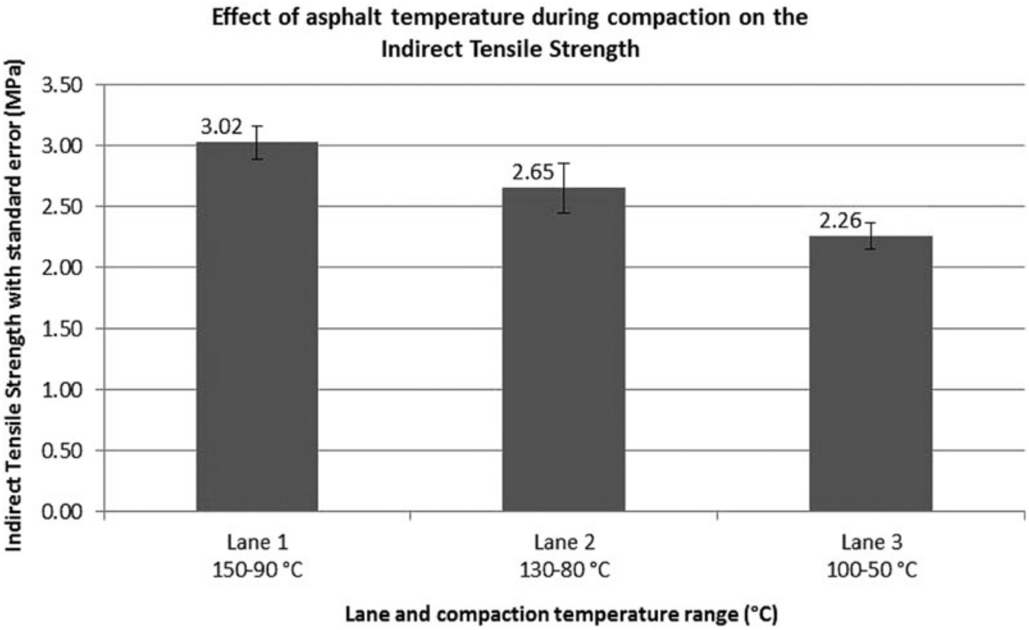

Figure 9. Indirect Tensile Strength for different compaction temperature ranges in the field study.

the roller leads to micro-cracks being created. The results show that the compaction process when using an AC 16 Base (with conventional bitumen 40/60 pen) should ideally start when its temperature is in the range of 135–155°C. If the compaction process starts outside this window, it is still possible to achieve the target density but a lower G_f should be anticipated, possibly by up to 30%. As a consequence, the layer may deteriorate more rapidly than expected, leading to higher repair costs for as well as possible penalties for road closures. These findings have practical consequences for the industry and implications for asphalt compaction theory.

6.1. *Practical consequences for the paving industry*

It is apparent that an asphalt team needs to be aware that compaction outside the optimum compaction window can significantly impact on quality. However, there are other aspects of the process and other disciplines that should heed these results. The significance of our findings should be considered when specifying an asphalt mix or planning logistics. A designer of a mixture should take into account that the quality will be influenced by the compaction temperature and thus include the sensitivity to temperature differentials in the mix and in the pavement design. A planner of the logistical process should recognise that delays in asphalt delivery could lead to lower lay-down temperatures, which could result in compacting outside the optimum window. To reduce these risks, a planner could opt to use an additional asphalt truck or choose to use a material transfer vehicle in order to reduce temperature differentials.

Further, the results are relevant to quality control. If only the density is used as a criterion, any reduction in quality due to compacting outside the optimal temperature range will go undetected. For quality purposes, the compaction temperature needs to be monitored during the process. Nowadays, suitable equipment for monitoring temperatures during the process is widely available, and becoming increasingly affordable, such as laser line scanners, infrared cameras and thermocouples (Ulmgren 2000, Lavoie 2007, Miller *et al.* 2011,Vasenev *et al.* 2012), and rollers can be tracked using GPS to determine the number of roller passes applied at each location (Krishnamurthy *et al.* 1998, Miller 2010, Gallivan *et al.* 2011). By adopting such enhanced process and quality control, a higher asphalt quality can be achieved.

The results of this study are also important within the context of accepting a completed project. If a client accepts a project without recognising that the compaction temperature can significantly affect the pavement quality, they may accept a road that fails to match up to the intended quality goals. To reduce this risk, a client could stipulate that the contractor must monitor compaction temperatures and pass this information over in a delivery file. Including contractual requirements regarding the monitoring of key parameters would reduce the risk of accepting a poorly constructed deliverable.

6.2. *Implications for asphalt compaction theory*

The experimental results show that the temperature of the mixture when compaction starts significantly influences the pavement quality. For this reason, the compaction window for rollers should be based on the compaction temperature and the associated mechanical properties rather than solely on bitumen viscosity and density – the latter is common practice (Corlew and Dickson 1968, Jordan and Thomas 1976, Luoma *et al.* 1995, Asphalt-Institute 2007). This conclusion is in line with those of Decker (2006) and Bahia *et al.* (2006) who similarly postulate that determining the compaction temperature from viscosity–temperature plots is no longer sufficient. Some researchers have suggested that compacting at lower temperatures is possible, but have only considered density as a criterion (Schmitt *et al.* 2009). The results of this study show the importance of distinguishing between achieving the target density and the intended mechanical properties. Achieving the target density may indeed be possible at lower temperatures, but the mechanical properties would likely suffer.

7. Future work

This study has demonstrated that it is possible to incorporate the compaction temperature in laboratory compaction procedures when using laboratory roller compaction equipment. However, test specimens are compacted in a relatively narrow temperature range, whereas field compaction takes longer and is therefore conducted across a wider temperature window. A challenge for future research is to develop new laboratory compaction procedures based on determining a temperature window rather than a single temperature and then controlling the frequency of roller passes when the asphalt cools. If it were possible to alternate asphalt cooling with roller passes, one could more closely simulate field compaction. This would be much more efficient than running trial-and-error experiments during real construction projects and could lead to clearer guidelines for roller operators.

Further, laboratory procedures need to be improved to reduce the variability in density within and between slabs. This could possibly be achieved by automating the filling of the mould with the asphalt mixture related to the pre-compaction of the paver and by standardising mixing techniques to achieve homogeneous asphalt mixtures.

Further research should also be devoted to conducting experiments to determine the effects of various compaction strategies, as observed during real construction projects, on the pavement's asphalt quality for various asphalt mixtures. Roller compactors may play an important role in this future laboratory-based research since they more closely simulate field compaction and, according to de Visscher *et al.* (2006) and Mollenhauer and Wistuba (2013), produce slabs that are more representative, in terms of composition and internal structure, of full-scale constructions. This claim could be validated by using X-ray imaging to determine particle distribution at a range of compaction temperatures.

8. Conclusions

The standardised approach to determining the ideal temperature for asphalt compaction in the laboratory fails to reflect the actual field compaction process. The existing approach in the laboratory, based on binder viscosity, provides a single compaction temperature, whereas the on-site roller operator has to determine a temperature window in which to compact. The different approaches have consequences for the resulting density and mechanical properties. However, the significance of these consequences is unclear and this makes it difficult to provide appropriate guidelines to roller operators.

This paper has focused on the relationship between the asphalt temperature during compaction and the mechanical properties of the asphalt layer. This relationship was assessed in the laboratory using a Roller Sector Compactor and in a field study. In the latter, the rollers were tracked using D-GPS and the asphalt temperature monitored using a laser line scanner, infrared cameras and thermocouples. The results show that the compaction process should ideally start within a certain temperature window. If the compaction process starts outside this temperature window, it is still possible to achieve the target density, but the asphalt's mechanical properties will suffer. In our tests with a representative base layer, compacting outside the optimum compaction window could decrease the G_f by up to 30%. This exposes a contractor to the risks associated with a shortened pavement lifespan and possible extra maintenance costs. The risk for clients (infrastructure agencies), if their prime criterion for acceptance is density, is that they accept substandard work that does not fulfil all their quality goals. Practice needs to be aware of the significance of asphalt temperature during compaction. Improved designs and enhanced quality control are feasible, and could be used to achieve a higher asphalt quality. In terms of asphalt compaction theory, the paper proposes defining roller compaction windows based on a temperature range, and the resulting mechanical properties, rather than on bitumen viscosity at a single compaction temperature and the desired density.

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Notes

1. Email: s.r.miller@utwente.nl
2. Email: adebondt@ooms.nl
3. Email: a.g.doree@utwente.nl

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