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# Technological and environmental performance of temperature-reduced mastic asphalt mixtures

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Temperature reduction of mastic asphalt (MA) mixtures can decrease costs and energy demand, as well as health-relevant emissions of particulate matter throughout the life cycle. A state-of-the-art method for temperature reduction is wax modification of the bituminous binder to reduce its viscosity. In this paper, the results of an extensive study. On mechanical performance, particulate matter emission and life-cycle analysis of temperature-reduced MA are presented. Therefore, a reference MA is compared to three temperature-reduced MAs: a state-of-the-art reduction by modification with amide wax (AW) and an alternative method of substituting crushed aggregates by rounded ones. For both methods, a temperature reduction of 30°C can be realised. In addition, a combination of both methods, wax modification and use of rounded aggregates, is investigated. For this combination a reduction of 50°C is possible. The results show that the resistance to permanent deformation is not decreased by using rounded aggregates and that it can be doubled by employing AW regardless of the aggregate shape. Resistance to low-temperature cracking is not affected by any of the studied methods for temperature reduction. Emission analysis reveals that more than 80% of the emitted particulates are below 2.5 µm a.d. (aerodynamic diameter). From a life-cycle perspective, a main benefit of temperature-reduced MAs is the significant decrease in particulate emissions by up to 80% in case of 50°C temperature reduction. Also, up to 20% of production process energy can be saved when the mixing temperature is reduced by 50°C. Application of a wax additive reduces process energy costs, but increases the total life-cycle costs. Based on the considered scenarios, the application of additives is controversial and the substitution of crushed aggregates by rounded aggregates seems to be beneficial.

**Keywords:** mastic asphalt; wax; performance based testing; emission analysis; life-cycle analysis

## 1. Introduction

Among the different asphalt mix types, mastic asphalt (MA) holds a special position due to its composition, application and load transfer. The main components of MA are filler ($\leq 0.063$ mm) with up to 30 M% (percentage by mass) (CEN, 2013) and bituminous binder with 8–10 M%. Thus, up to 40 M% of the mix is considered as mastic, the other part is taken up by coarse aggregates. This is in clear contrast to other asphalt mix types, for example, asphalt concrete with around 10–15 M% of mastic. Due to its composition, MA is applied in the field without

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compaction; it is merely poured and self-compacting. Different from other asphalt mix types, MA transfers load mainly by a stiff mastic and not by coarse aggregate interaction. In addition, the mix does not exhibit air voids. There is a wide range of applications for MA as sealing and surface layer on bridges (Medani, Huurman, Liu, Scarpas, & Molenaar, 2007; Widyatmoko, Elliott, & Read, 2005), as road surface layer for city centres where compaction would endanger historic buildings or as surface layers for walk and bike ways with typical layer thicknesses of 30–50 mm.

Since the mastic is responsible for load transfer, usually hard and in many cases polymer-modified binders are employed for MA. To keep the mix pourable, the viscosity of the mastic and mix has to be low enough at the construction site. Thus, high temperatures of up to 250°C are necessary for mixing and paving. Since more than 70% of the total energy consumption for asphalt mix production are dedicated to the mixing plant (Canada, 2005), MA is especially energy-intensive in production. Also, a number of reports show that workers health is increasingly affected when bitumen is handled at temperatures over 200°C (Hansen, 1991; Kriech & Osborn, 2014; Ruhl, Musanke, Kolmsee, Priess, & Breuer, 2007). For these reasons, a temperature reduction in MA is seen as crucial for enhanced energy efficiency and a healthier work environment. The addition of wax to bitumen is a state-of-the-art procedure to reduce the binder viscosity above the waxes' melting point and reduce the mixing and paving temperature of asphalt mixes (Biro, Gandhi, & Amirkhanian, 2009; Rubio, Martinez, Baena, & Moreno, 2012; Silva, Oliveira, Peralta, & Zoorob, 2010; Wu & Zeng, 2012). Various types of waxes are available and employed with different effects on workability of the mix during production as well as on the performance of the mix in terms of resistance to permanent deformation at high temperatures and to cracking at low temperatures. Due to wax crystallization during cooling of the mix to ambient temperatures, waxes tend to increase the high temperature stability and decrease the low-temperature cracking resistance (Capitao, Picado-Santos, & Martinho, 2012; Cardone, Pannunzio, Virgili, & Barbati, 2009; Edwards, 2009; Edwards, Tasdemir, & Isacsson, 2006; Merusi & Giuliani, 2011).

In this paper, a state-of-the-art modification is compared to a new, efficient alternative for temperature reduction of MA in a comprehensive way. For the state-of-the-art method, an amide-wax (AW)-modified bitumen is used as the binder component for the asphalt mix. In the new method for temperature reduction, crushed aggregates are substituted by rounded aggregates within the MA. This substitution brings a significant temperature reduction potential. The new approach is not applicable to other asphalt mix types, due to the fact that all other mix types are based on coarse aggregate interaction for load transfer and crushed aggregates are crucial for sufficient friction of surface layers. For MA mixtures, the load transfer is realised in a different way as described above and surface layers of MA mixtures are treated by applying bitumen-coated crushed aggregates prior to opening it to traffic to ensure sufficient friction.

## 2. Motivation and objectives

Sustainability of asphalt mixtures employed as pavements for traffic infrastructure need to take into account efficiency in terms of energy and material consumption, cost efficiency and health aspects for workers. Since pavements exhibit in-service lives of 20 years and more, it is not sufficient to only take the point of production and construction into account. It is rather necessary to analyse the complete life cycle of a pavement. Energy consumption and use of bitumen as scarce material is especially relevant for MA due to high production temperature and a higher content of bitumen compared to other asphalt mix types. Thus, this paper presents an

example of a comprehensive assessment of an asphalt mix by presenting an interdisciplinary study on the mechanical performance of MA, emissions relevant to workers' health at production and a comprehensive life-cycle analysis, including material and energy flow as well as costs.

The following objectives were defined:

- Investigate the performance of a reference mix (Scenario 0) and three modified mixes for temperature reduction (by employing AW modified bitumen and/or substituting crushed by rounded aggregates) (Scenarios 1, 2 and 3).
- Analyse aerosol emissions by filter and impactor measurements during production for the reference mix at 240°C and a modified mix at 190°C to estimate the change in health-relevant emissions by reducing the production temperature.
- Combine the findings from lab analysis in conjunction with data from literature to carry out a life-cycle analysis including energy and material consumption, as well as costs over the complete in-service life of a pavement made from the reference mix and two modified mixes.

## 3. Materials

For the presented research, a MA mixture with a maximum nominal aggregate size of 11 mm (MA 11) is used. The filler component is powdered limestone, the coarse fraction is totally crushed (TC) aggregates of porphyritic origin and totally rounded (TR) limestone, respectively. The binder is an SBS-modified PmB 25/55-65 (PG 82-16).

Within a research project (Hofko, Dimitrov, Schwab, & Weiss, 2015), optimised MA mixtures were developed with regard to temperature reduction, mix performance and economic efficiency. As state-of-the-art modifier, four wax types – AW, Fischer-Tropsch wax, montan wax and polyethylene wax – were applied. In addition, an economic alternative to waxes for temperature reduction was investigated as well. Therefore, crushed aggregates were substituted by rounded aggregates within the MA.

The temperature reduction potential for the mixes presented in this paper has been assessed on binder and mix level at an earlier stage of the project (Hofko, Dimitrov, & Hospodka, 2015) and are shown for the mix level in Figure 1. The temperature reduction is given in comparison to the reference mix. To derive the temperature reduction, the mixing torque of the reference mix at 230°C is taken as a benchmark. Details on the mixing torque measurement can be found in Hofko, Dimitrov, et al. (2015). The wax concentration is given in percentage with regard to binder mass. For the waxes, AW shows the highest potential for reduction. Equal potential was found for the mix with 50% substitution by TR. For 100% TR and the combination of 100% TR with 2.5 or 4.0 M% of AW, the reduction potential is even higher (ranging from 36°C to 51°C). Based on these results, the following four scenarios with maximum temperature reduction potential were chosen for further investigation on mix performance, emission and life-cycle analysis within this paper:

- Scenario 0: MA 11 PmB 25/55-65 – production temperature: 240°C (Reference).
- Scenario 1: MA11 + 4 M% AW – production temperature: 210°C ( – 30°C).
- Scenario 2: MA11 100% TR – production temperature: 210°C ( – 30°C).
- Scenario 3: MA11 100% TR + 4 M% AW – production temperature: 190°C ( – 50°C).

Table 1 contains information on the design of the four considered mixtures.

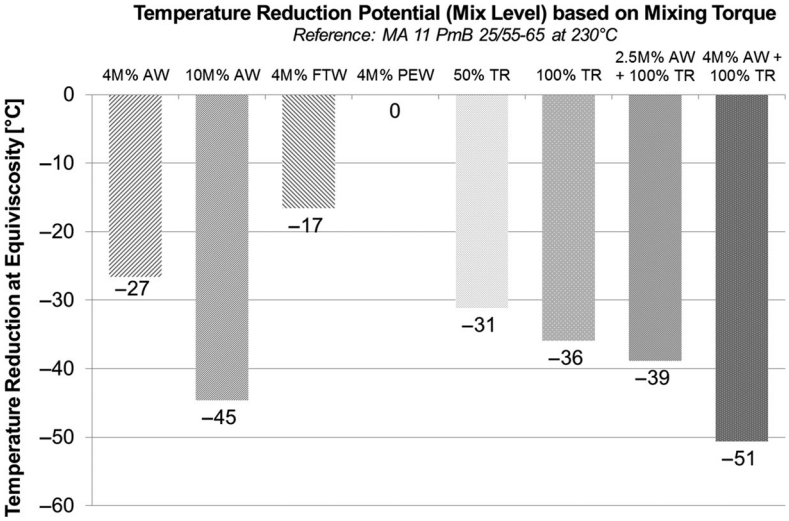


Figure 1. Temperature reduction potential on mix level based on mixing torque.

Table 1. Design of MA mixtures.

| | | Scenario 0 | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|---|
| | | MA 11 | MA11 + 4 M% AW | MA11 100% TR | MA11 100% TR + 4 M% AW |
| Binder | PmB 25/55–65 | 8.20 M% | 7.87 M% | 8.20 M% | 7.87 M% |
| Modifier | AW | | 0.33 M% | | 0.33 M% |
| Filler | limestone | 26.3 M% | 26.3 M% | 26.3 M% | 26.3 M% |
| Aggregates | TC | 65.5 M% | 65.5 M% | | |
| | TR | | | 65.5 M% | 65.5 M% |

## 4. Methods

### 4.1. *Mechanical performance*

To assess and compare the mechanical performance on asphalt mix level, two test methods are applied:

- The Thermal Stress Restrained Specimen Test (TSRST) according to EN 12697-46 (CEN, 2012) on prismatic specimens (50 mm × 50 mm × 200 mm) from a starting temperature of +10°C with a cooling rate of 10°C/h. The crack temperature is taken as a benchmark for resistance to low-temperature cracking. The right picture in Figure 2 shows the test setup.
- The Uniaxial Cyclic Compression Test (UCCT) according to EN 12697-25, Part A (CEN, 2005) on cylindrical specimens (148 mm in diameter, 60 mm in height) at a temperature of +50°C with a block-shaped cyclic compressive loading at 0.5 Hz and an upper stress level of 100 kPa. The permanent, axial strain after 3600 load cycles is taken as benchmark for resistance to permanent deformation. The left picture in Figure 2 shows the test setup.


Figure 2. UCCT test setup (left), TSRST test setup (right).

### 4.2. *Emission analysis*

Two different scenarios are analysed: (a) Scenario 0 at 240°C and (b) Scenario 3 at 190°C. Therefore, emissions of the reference mix at standard production temperature and of the mix with 50°C temperature reduction can be investigated and discussed. Both mixes are prepared the same way: In case of mixture with wax modification, the binder and wax are blended before the asphalt mix production (Hofko, Dimitrov, et al., 2015). Aggregates, binder and lab mixer are preheated at the required temperature. Aggregates are preheated for 5 h; binder and lab mixer for 3 h. The fine and coarse aggregates are homogenised in the mixer for 30 s. Subsequently, the binder is added and the mix is homogenised for a mixing time of 3 min at a mixing speed of 40 rpm. In all cases, a constant asphalt mix mass of 22 kg is used for testing. After the initial mixing process, the emission analysis starts: Emissions measurements run for 30 min while the lab mixer mixes the MA with an open cover. Thus, the situation at the construction site when laying MA pavements is simulated in terms of emissions.

#### 4.2.1. *Impactor*

For analysing particulate matter emission (PM10) of asphalt mixes, two single-stage-impactors equipped with quartz fibre filters (Schmidl et al., 2008) are set up with 1 m and 2.5 m distance to the mixer. The filters are pre-cleaned and conditioned at 20°C and 50% relative humidity before every weighing step. For Scenario 3, an additional six-stage-impactor is set up 1 m away from the mixer. Sampling takes place on pre-cleaned Al-foils at 12.8/3.2/0.8/0.2/0.06/0.015 µm a.d. separation stages. Thus, the particle size distribution can be obtained as well. Particulate mass was determined gravimetrically, organic carbon and elemental carbon analysis of the filters is conducted with an OCEC Analyzer (Sunset Lab Inc.) using the EUSAAR 2 protocol (Cachier, Bremond, & Buat-Menard, 1989; Cavalli, Viana, Yttri, Genberg, & Putaud, 2010).

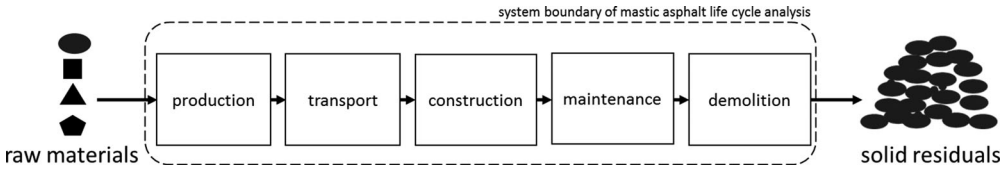


Figure 3. System boundary of the MA life cycle analyses from input of raw materials into the asphalt mixing process to solid residuals from wearing course demolition.

### 4.3. *Life-cycle analysis*

Life-cycle analyses are used to compare the effects of MA modifications. Key to life-cycle approaches is the evaluation of products and services throughout their entire life cycle, from cradle to grave (Hellweg & iCanals, 2014). Typically, the main focus of life-cycle analyses is on environmental performance, but social and economic aspects can also be included. In this study, the two modified MAs (scenario 1 and 3) are compared to a reference mixture regarding their material flows, energy consumption and costs. Life-cycle analyses refer to a 'functional unit' (FU), which is a defined quantity of a product or service of interest, such as a tonne of a produced good or a gigajoule of produced energy. Here, one FU is defined as a stretch of road with a surface layer made of MA (one lane kilometre of the dimension 1000 m $\times$ 3.75 m $\times$ 0.05 m) and a service life of 20 years. The life-cycle stages asphalt production, asphalt transport, construction of the layer, maintenance during in-service life and demolition of the layer after service life are considered (Figure 3).

Resource consumption and selected emissions are analysed by the method of Material Flow Analysis (MFA) (Brunner & Rechberger, 2004). The focus of emission analysis is on emissions of PM10 as these are perceived to be emitted in great quantities while laying of MA, and are known to impose severe human health implications (Pope & Dockery, 2006). The ecological backpacks (particulate emissions) of raw materials' production are also considered. Embodied energy of raw materials (energy consumed for provision of raw materials) and process energy (energy consumed by activities such as asphalt mixing or transportation) are considered in a life-cycle energy analysis (Cabeza, Rincon, Vilarino, Perez, & Castell, 2014). Material and energy costs are components of a life-cycle cost analysis (Hunkeler, Lichtenvort, Rebitzer, Ciroth, & Europe, 2008). Model input data on material composition (Table 1), material density, emission behaviour, embodied energy, energy demand, heating value of fuels, material costs and energy costs are collected from laboratory investigations, scientific literature and databases, and expert interviews. The analyses are computed in the MFA software STAN (www.stan2web.net) and displayed as Sankey diagrams (Riehmann, Hanfler, & Froehlich, 2005; Schmidt, 2008a, 2008b; Vandenoosterkamp, Goorse, & Blomen, 1993). An overview of input data is provided in the supplement information (SI1). Model assumptions are listed in Table 2.

## 5. Results and discussion

### 5.1. *Mechanical performance*

The resistance to permanent deformation and to low-temperature cracking was investigated for all four scenarios. The objective is to keep the mechanical performance at the same or higher level compared to the reference MA mixture.

#### 5.1.1. *Resistance to permanent deformation*

Figure 4 shows the results for the resistance to permanent deformation at high temperatures tested in the UCCT at $+50$°C for 3600 load cycles. Figure 4 shows the permanent, axial strain

Table 2. Model assumptions of the five life-cycle stages.

| | |
|---|---|
| *Production*: Combustion of pulverised lignite as source of production energy, 0.1 M% loss as solid residuals during production process, particulate emissions from energy production, no emission of particulates from asphalt material. | |
| *Transportation*: Transport distance 50 km, 0.1 M% loss as solid residuals during transportation process, particulate emissions from diesel combustion (transportation). | |
| *Construction*: 0.1 M% loss as solid residuals during construction process, particulate emissions from diesel combustion (building machinery) and laying of MA (Table 5). | |
| *Maintenance*: No maintenance in first 10 years after construction. Annual replacement of upper 3 cm wearing course for 20 $m^2$ per FU from 10 years after construction on, 0.1 M% loss as solid residuals both during transportation and placing of repairing material, potholes and road abrasion not considered, particulate emissions from diesel combustion (transportation and building machinery), laying of MA and asphalt milling (dust), dust generation 10% of area-specific construction emission. | |
| *Demolition*: Demolition of wearing course by mobile milling drum, particulate emissions from diesel combustion (building machinery) and asphalt milling (dust), dust generation 10% of area-specific construction emission. | |

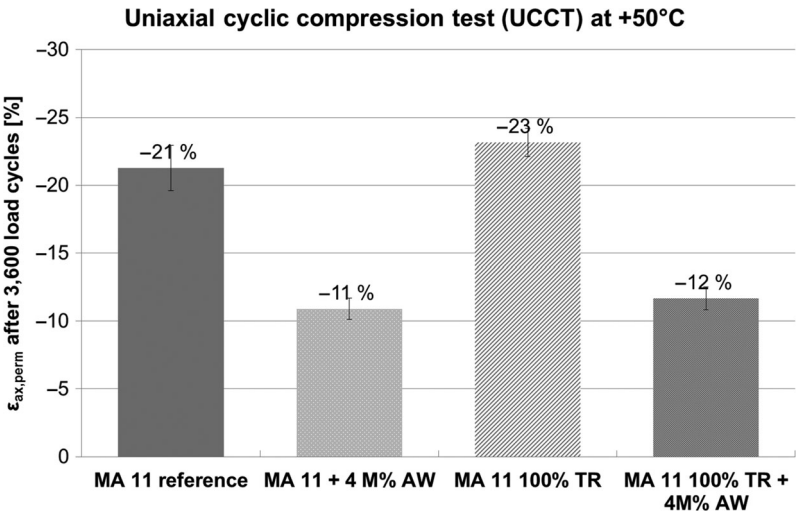


Figure 4. Uniaxial Cyclic Compression Test.

after 3600 load cycles. The data are given as mean values from three single tests, including error bars that indicate the standard deviation of the results. The reference mix with TC aggregates results in axial strain of − 21%. Scenario 1 with 4 M% AW suffers only about half the permanent deformation of the reference mix ( − 11%) and Scenario 2 for which the crushed aggregates were substituted by rounded aggregates results in similar deformation as the reference mix ( − 23%). The combined Scenario 3 with TR and 4 M% AW shows similar results as Scenario 1 ( − 12%).

This indicates that the substitution of aggregates does not change the resistance to permanent deformation significantly and that the addition of AW strongly increases the resistance by about 50% no matter which aggregates are used for the mixture.

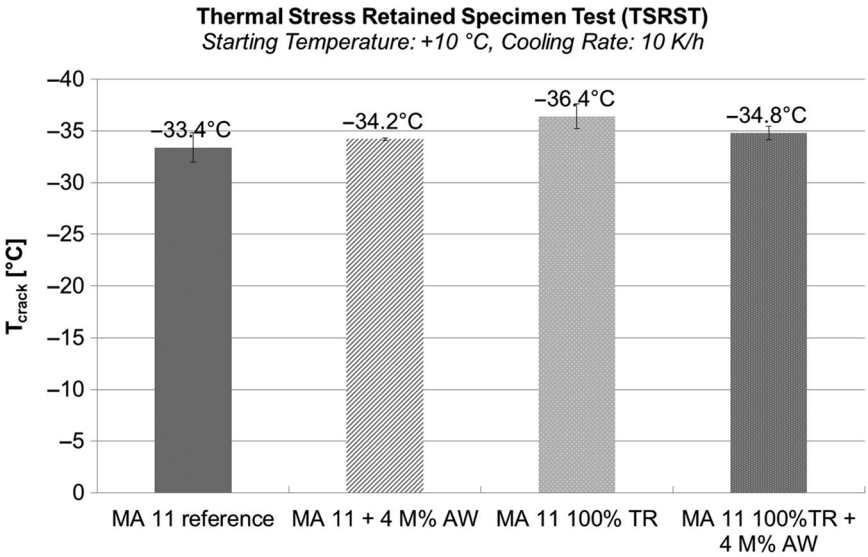


Figure 5. Thermal Stress Retrained Specimen Test.

### 5.1.2. *Resistance to low-temperature cracking*

Figure 5 presents results of the TSRST for all 4 considered scenarios. The data shown in the diagram are cracking temperatures $T_{crack}$ at which the specimen fails due to the cryogenic (temperature induced) stress exceeding the tensile strength of the material. Results are given as mean values derived from three single tests together with the standard deviation.

The cracking temperature $T_{crack}$ of all mixtures ranges between −33 and −36°C. All mixes can therefore be considered as highly resistant to thermal cracking. The cracking temperature is especially low compared to other asphalt mix types. This is due to the fact that a high content of binder is present in MA, which is the main factor for stress relaxation upon cooling. Taking the scattering of results into consideration, no significant impact of wax addition or the substitution of aggregates can be found. This is interesting in terms of wax addition, since it is known that the crystallization of waxes tends to increase the stiffness of asphalt mixtures and therefore lower the resistance to thermal cracking (Edwards, 2009). This effect was not found for MA with 4 M% of AW.

## 5.2. *Emissions at mixture production*

The quantitative analysis of the PM10-filters shows that high concentrations of particulate matter are emitted at the mixture process. The difference in particulate matter concentrations between scenario 0 (Table 3), mixed at 240°C and Scenario 3 (Table 4), mixed at 190°C is significant. While both mixes emit mostly organic carbon (OC), Scenario 3 produced only about 25% compared to Scenario 0. The concentration data received at the mixture process is used for calculating a rough estimate of the emission at the construction site (Table 5). Two values are derived, emissions per mass unit of laid MA (mg/kg) and emissions per area of laid MA (g/m²). When comparing these values for Scenario 0 and 3, we see an even stronger decrease for the calculated emission (roughly 80%) than for the concentration measurements (roughly 75%). For the calculation, a steady-state approach and modelling of the physical conditions by a logarithmic function are employed.

Table 3. PM10 filter analysis of Scenario 0 at 240°C.

| Experiment 1 | PM10 (mg/m³) | OC (mg/m³) | OC in PM10 (%) |
|---|---|---|---|
| Filter 1 (1 m) | 10.0 ± 0.2[a] | 10.0 ± 0.3 | 100 |
| Filter 2 (2.5 m) | 7.2 ± 0.2 | 7.0 ± 0.2 | 97 |
| Experiment 2 | | | |
| Filter 1 (1 m) | 9.4 ± 0.2 | 9.5 ± 0.3 | 100 |
| Filter 2 (2.5 m) | 7.8 ± 0.2 | 6.4 ± 0.2 | 82 |

[a]Error is a result of propagation of uncertainty (such as weighting error, instrument error).

Table 4. PM10 filter analysis of Scenario 3 at 190°C.

| | PM10 (mg/m³) | OC (mg/m³) | OC in PM10 (%) |
|---|---|---|---|
| *Experiment 1* | | | |
| Filter 1 (1 m) | 2.9 ± 0.2 | 2.7 ± 0.2 | 93 |
| Filter 2 (1 m) | 2.6 ± 0.2 | 2.5 ± 0.2 | 96 |
| *Experiment 2* | | | |
| Filter 1 (1 m) | 2.4 ± 0.2 | 2.0 ± 0.2 | 83 |
| Filter 2 (1 m) | 1.9 ± 0.2 | 1.7 ± 0.2 | 90 |

Table 5. Calculated PM10 emission for both scenarios.

| Scenario | Emission (mg/kg) | Emission (g/m$^2$) |
|---|---|---|
| 0 | 740 | 5.3 |
| 3 | 148 | 1.1 |

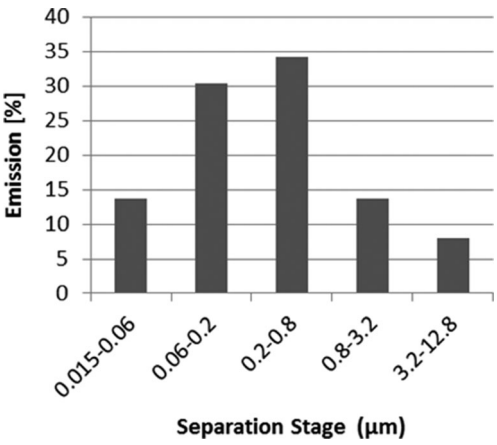


Figure 6. Particle size distribution of emission of Scenario 3.

A particle size distribution for the emissions is recorded for Scenario 3 (Figure 6) by using a six-stage-impactor. The results of this analysis show that a significant part of the particulate matter emitted is below 10 µm a.d. At least 78% of the particulate matter is below the particularly health-relevant value of 2.5 µm a.d.

### 5.3. *Life-cycle analysis*

Three scenarios, the reference mix (Scenario 0), MA 11 + 4 M% AW (Scenario 1) and MA 11 100% TR + 4 M% AW (Scenario 3) are analysed across their life cycles regarding material flows, energy flows and costs. That is, the standard production, the state-of-the-art method with 30°C temperature reduction and the new, alternative method (including the use of rounded aggregates with 50°C temperature reduction) are compared. Model frame and model assumptions are given in Section 4.3, model input data are listed in SI1.

#### 5.3.1. *Resource consumption and emissions*

460 tonnes of materials are needed for production of one lane kilometre MA road surface layer as defined above. Including losses and repairing materials over the assumed life cycle of 20 years, this sums up to 470 tonnes per FU. For one FU, approximately 300 tonnes of aggregates (crushed or rounded), 130 tonnes of filler, 35 tonnes of bitumen and – in Scenario 1 and 3 – 1.5 tonnes of additive are needed. At the end of the life cycle, 470 tonnes of solid residuals remain per one lane kilometre, most of it (460 tonnes) as demolished surface layer. Particulate emissions throughout the life cycle are listed in Table 6. Complete Sankey diagrams of material flows are provided in the supplement information 2 (SI2).

In the considered reference scenario (Scenario 0), 40 kg of particulates $\leq$ 10 µm a.d. are emitted per FU. These emissions can be reduced by temperature reduction (Scenarios 1 and 3) by up to 40%. With up to 50% of the total emitted particulates over the life cycle, the laying process of MA causes the dominant share. Also, provision of production energy (here: combustion of pulverised lignite) and production of bitumen contribute essentially to the total emissions (see Table 6).

From a methodological perspective, the scope of considered materials needs to be amended for a closed material balance. One reason is that particulate emissions originate both on the material level (emission of particulates from MA) and on the energy level (combustion of fuels). Thus, fuels are to be included at the input side of the material balance, and the number of considered emissions at the output side is to be extended (e.g. $CO_2$). However, a closed balance (including all emissions) is intricate as some flows may perish in the uncertainties of other flows of a considerably larger quantity (for example, emitted quantities may range in the dimension of mg/FU, while other material flows amount to up to several hundred tonnes).

#### 5.3.2. *Energy*

Over the life cycle, 500–600 GJ are consumed per FU. In each scenario, the process energy consumption of the production exceeds the embodied energy of the raw materials (Figure 7).

Production causes up to 90% of the total process energy demand and can be reduced by up to 10% in Scenario 1, and up to 20% in Scenario 3. Although the application of an additive can reduce the process energy input, it increases the total embodied energy per FU due to the comparatively energy-intensive production of additives. The substitution of crushed by rounded aggregates allows reduction of mixing temperature. Thus, by application of rounded aggregates, the production process energy can be saved and the total embodied energy of one FU can be reduced as rounded aggregates are less energy intensive in production compared to crushed aggregates.

#### 5.3.3. *Costs*

The material and energy costs per FU add up to €30,000–35,000 (Figure 8). 99 percent of the total costs allocate to the life-cycle stage ‘production’. Contributing up to 95% to the total costs,

Table 6. Emissions of particulates $\leq 10\,\mu m$ a.d. ($PM_{10}$) per FU: ecological backpack of raw materials plus process emissions from energy production, construction and demolition activities and placing of hot MA. For a complete reference list, see SI1.

| | | Scenario 0 (reference mix) | | | Scenario 1 | | | Scenario 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Particulates (kg/kg) | Material demand (t/FU) | Particulates (kg/FU) | Share (%) | Material demand (t/FE) | Particulates (kg/FU) | Change compared to scen. 0 (%) | Material demand (t/FU) | Particulates (kg/FU) | Change compared to scen. 0 (%) |
| *Ecological backpack (particulate emissions) of raw materials* | | | | | | | | | | |
| Aggregate (crushed) | 1.98E – 06 | 306 | 0.6 | 1.4 | 310 | 0.6 | 1.3 | 0 | 0.0 | NA |
| Aggregate (rounded) | 1.62E – 06 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 | 304 | 0.5 | NA |
| Filler | 2.42E – 06 | 128 | 0.3 | 0.7 | 124 | 0.3 | – 3.1 | 130 | 0.3 | 1.7 |
| Bitumen | 2.65E – 04 | 39 | 10.3 | 24.3 | 37 | 9.9 | – 4.0 | 37 | 9.9 | – 4.0 |
| Additive | 2.56E – 06 | 0 | 0.0 | 0.0 | 2 | 0.0 | NA | 2 | 0.0 | NA |
| *Process emissions* | | | | | | | | | | |
| Production (energy) | | | 7.4 | 17.6 | | 6.8 | – 9.0 | | 6.0 | – 18.7 |
| Transport (energy) | | | 0.5 | 1.2 | | 0.5 | 0.0 | | 0.5 | 0 |
| Construction (energy, placing of asphalt) | | | 19.9 | 47.0 | | 12.0 | – 39.6 | | 4.1 | – 79.2 |
| Maintenance (energy, demolition dust, constr. activity) | | | 1.3 | 3.0 | | 1.3 | 0.0 | | 1.3 | 0 |
| Demolition (energy, demolition dust) | | | 2.0 | 4.7 | | 2.0 | 0.0 | | 2.0 | 0 |
| Total | | | 42.3 | 100 | | 33.3 | – 21.3 | | 24.6 | – 41.8 |

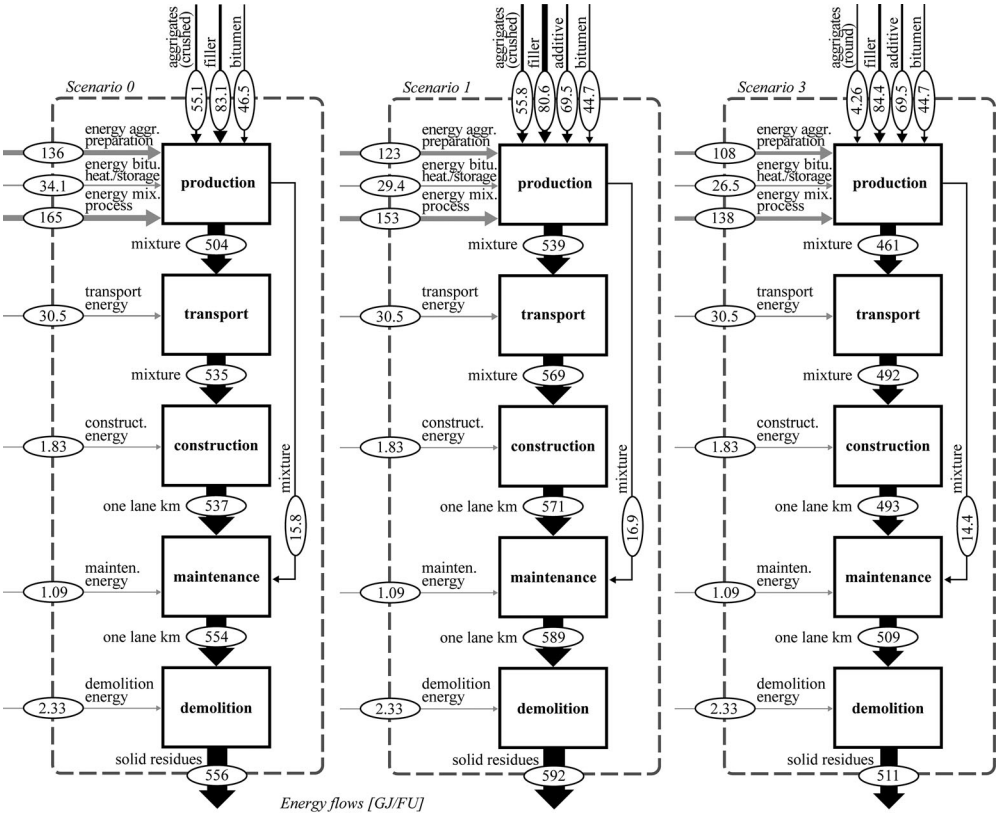


Figure 7. Sankey diagrams of embodied energy (black arrows) and process energy (grey arrows) in GJ/FU for the three scenarios. System boundaries are illustrated as broken lines, life-cycle stages as boxes.

material costs exceed by far the process energy costs (95% vs. 5%). Bitumen is the most cost-intensive material in all scenarios. Energy costs of the production process dominate the total life-cycle process energy costs and can be reduced by 10% per scenario, analogous to the energy savings. Although these cost savings per FU seem to be low on an absolute scale compared to material costs, they can sum up to considerable savings on a business level due to scale effects, that is, when multiple lane kilometres are produced.

Though applying an additive reduces the energy costs on a business level, it increases the total production costs due to the relatively high material prize. Rounded aggregates are comparatively cheap and contribute both to reducing energy costs and material costs.

From a life-cycle perspective, a main benefit of modified MAs in comparison to the reference scenario is the significant decrease in particulate emissions. Also, up to 20% of production process energy can be saved when the mixing temperature is reduced from 240°C (Scenario 0) to 190°C (Scenario 3). Application of an additive reduces process energy costs, but increases the total life-cycle costs. Based on the considered scenarios and from a comprehensive energy and cost perspective, the application of additives is controversial and the substitution of crushed aggregates by rounded aggregates beneficial.

The results are based on the given state of information, and the analyses are in parts based on estimations (see SI1) and are subject to uncertainties as a consequence of limited availability and accuracy of cost, material and energy data. The transferability of the results to other

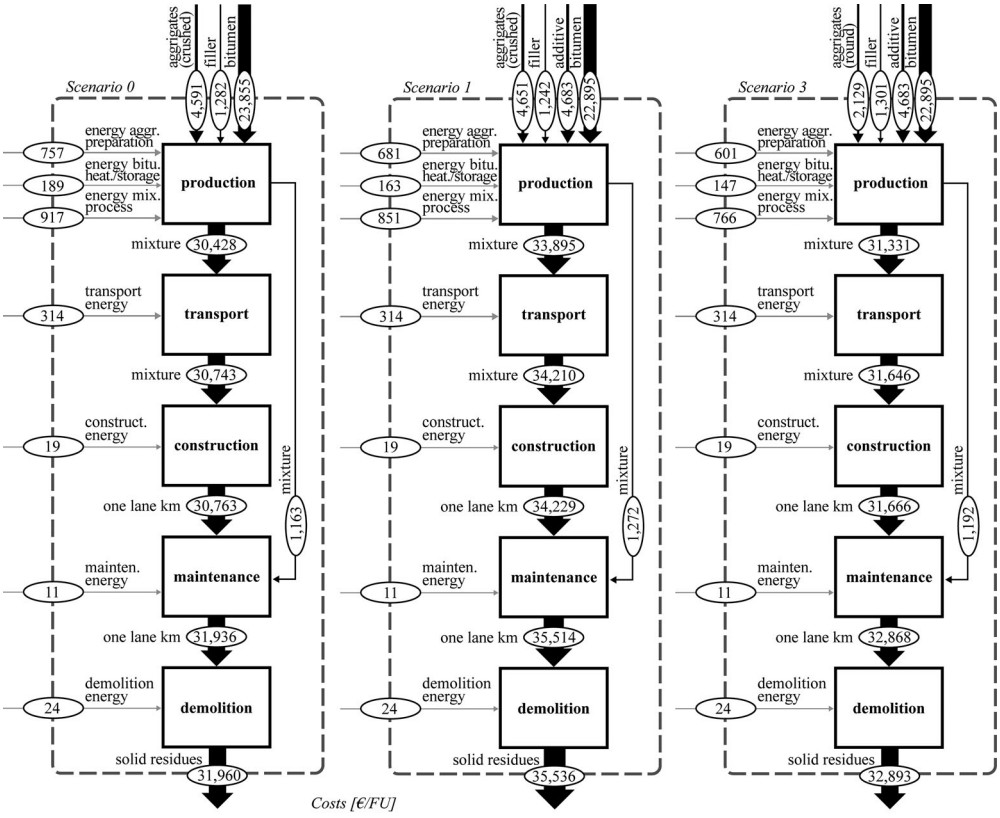


Figure 8. Material costs (inputs from above), energy costs (inputs from the left) and total costs (output) per FU of the three scenarios. System boundaries are illustrated as broken lines, life-cycle stages as boxes.

geographical, technical or economic conditions is limited. The data situation can be improved by additional emission measurements at a production plant or a construction site, and by collection of differentiated data on energy consumption and on the cost structure of MA production.

## 6. Summary and conclusions

This paper presents an interdisciplinary study on the mechanical and environmental performance of temperature-reduced MA mixtures. Four different mixtures are compared:

- a reference mix MA 11 PmB 25/55 65 with a standard production temperature of 240°C (Scenario 0),
- a state-of-the-art temperature-reduced mix MA 11 + 4 M% of AW as binder modification with a production temperature of 210°C (temperature reduction: 30°C) (Scenario 1),
- an efficient, alternative way of temperature reduction for which crushed aggregates used in the reference mix are substituted by rounded aggregates (MA 11 100% TR) with a production temperature of 210°C (temperature reduction: 30°C) (Scenario 2) and
- a combination of wax modification and rounded aggregates (MA 11 100% TR + 4 M% AW) with a production temperature of 190°C (temperature reduction: 50°C) (Scenario 3).

For all four mixtures, the mechanical performance in terms of resistance to permanent deformation at high temperatures was obtained by UCCT according to EN 12697-25, as well as the resistance to low-temperature cracking by TSRST according to EN 12697-46. To assess health-relevant emissions of aerosols at construction site, emission measurements were carried out with impactors in the lab during mix production. A life-cycle analysis was carried out for a FU of one lane kilometre (1000 m × 3.75 m × 0.05 m) to investigate energy, cost and emissions over the complete in-service life (20 years) of a MA pavement.

The following conclusions can be drawn from the results:

- Substitution of crushed aggregates, which are required according to European standards for MA mixtures, by rounded aggregates allow for equal temperature reduction as modification of the binder with 4 M% of AW. In both cases, the production temperature can be decreased by 30°C. Combined use of rounded aggregates and 4 M% of AW leads to a temperature reduction potential of 50°C.
- The resistance to permanent deformation for the mix with rounded aggregates is equal to the reference mix. Rounded aggregates do not have a negative effect on permanent deformation at elevated temperatures (50°C). Addition of 4 M% of AW as a binder modification increases the resistance to permanent deformation by nearly 50% regardless of the aggregate shape.
- The resistance to thermal cracking at low-temperatures is equal for all four tested mixes. All mixes exhibit crack temperatures between −33 and −36°C. Thus, all mixes can be considered as highly resistant to low-temperature cracking. AW modification does not make MA mixtures more prone to cracking.
- In terms of particulate matter emissions (PM10), the measurements reveal that more than 80% of the emissions are organic carbon. A reduction of the production temperature from 240°C to 190°C (−50°C) reduces the emissions to 20%. The particle size distribution of the emitted matter show that about 80% of the particulate matter is below the particularly health-relevant value of 2.5 μm a.d.
- The life-cycle analysis indicates that about 40 kg of particulates (PM10) are emitted throughout the life cycle of one FU MA surface layer (Scenario 0). These emissions can be reduced by 40% when the production temperature is reduced by 50°C. Fifty percent of the total emitted particulates are caused by the laying process.
- Ninety percent of the total process energy is required by the production stage of MA. This energy demand can be reduced by 10% when the production temperature is reduced by 30°C and by 20% when the temperature is reduced by 50°C.
- From the total material and energy costs of one lane kilometre of about €33,000, 99% allocate to the production. 95 % of the total costs are material costs. Energy costs can be reduced by 10 and 20% for temperature reduction of 30 and 50°C, respectively.

The results presented in this paper are based on an extensive study which is limited to laboratory investigations so far. The next step of the research includes large-scale production of all mentioned MA mixtures, as well as construction of test fields on the public road network including regular monitoring to validate results found in the lab and develop more accurate data for further life-cycle analysis.

Further studies on the life cycle of modified MAs will focus on the life-cycle stages ‘production’ and ‘construction’, as these are mainly affected by changes to the asphalt composition and mixing temperature. Effects of modifications on material aging will be investigated, as varying life times may alter the life-cycle analyses. Also, the effect of modified material composition on

recyclability can be a part of further research. Despite its limitations, this project shows the benefits of innovative MAs, especially regarding energy demand and particulate emissions, while improving the engineering properties of MA products for road pavements.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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## Supplemental data

Supplemental data for this article can be accessed at doi:10.1080/14680629.2016.1141703.

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