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# Designing asphalt mixes containing reclaimed asphalt pavement (RAP)

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## Abstract

Repairs and reconstructions of asphalt roads and paved areas generate large amounts of construction debris in the form of reclaimed asphalt pavement (RAP). The material milled from the upper layer contains aggregate and asphalt with deteriorating performance parameters as a result of long-term service under variable weather conditions. Since the debris is mostly composed of non-renewable materials, attempts have been made to recycle and utilise it in the preparation of new asphalt mixtures. This study investigates the design of an asphalt mix containing recycled RAP and summarises the testing of its performance parameters. By lowering the mixing temperature and using a two-stage method of RAP heating, it was possible to design an asphalt mix with 90% RAP content; thus, the demand for virgin aggregate and the fuel consumption throughout the mixing process could be effectively reduced.

**Keywords:** reclaimed asphalt pavement (RAP), foamed asphalt

## 1. Introduction

The rehabilitation and reconstructions of asphalt-paved roads involve the removal of the distressed upper layer in the milling process, leaving reclaimed asphalt pavement (RAP) as the waste material. Reclaimed asphalt pavements include asphalt mixes obtained in the process of upper surface milling and the grinding of asphalt slabs removed from the paved surfaces. RAP ought to be wholly reused as the mixture of aggregate and used asphalt and, after recycling, can become a valuable component of the asphalt mix, even though its performance parameters are slightly inferior to those of virgin asphalt pavements due to long service under variable weather conditions. The actual composition of the RAP is nearly identical to the composition of asphalt mixes specified in the literature (BS 598-110, 1998):

- mineral aggregate (about 88%),
- lime flour (about 7%),
- asphalt (about 5%).

According to the authors of the present study, the recycled RAP might be utilised in asphalt mixing, enabling the effective disposal of construction debris and reducing the demand for virgin aggregate. Engineering practice, however, has shown that RAP is seldom used to batch new asphalt mixes and the RAP percentage varies from 10 to 20%.

Currently, the most popular technology of batching an asphalt mix to be used in road paving is Hot Mix Asphalt technology whereby the aggregate and asphalt are heated up to a high temperature in excess of 180°C. This technology, however, is not energy-efficient, leading to considerable greenhouse gas emissions and its environmental impacts are negative. So far, the attempts to use RAP as a surrogate for a virgin aggregate mixture have not met with success. In the context of current asphalt mixing practices, it appears that the amount of RAP material that is left unused remains likely to grow.

The Warm Mix Asphalt technologies are more energy-efficient, producing asphalt mixes with lower temperatures of aggregate coating and binding, some of which require the addition of organic or chemical compounds as admixtures, others involve asphalt foaming or the addition of low-viscosity emulsions or binders of plant origin. Technologies utilising water emulsions are rarely used. This study explores the method of designing a RAP containing asphalt mix batched at WMA (warm mix asphalt) temperature where the RAP and natural mineral aggregate are cycle- mixed with foamed bitumen.

The main objective of the study is to design the RAP-containing asphalt mix of which the performance parameters should be similar to those of hot asphalt mixes made from virgin components. The RAP content in mixes prepared thus should be considerable. The first asphalt mix with 50% RAP content was extensively tested to verify its usefulness in road construction and rehabilitation projects. The next in line came the mix with 90% RAP content, recycled prior to use in order to restore the original aggregate skeleton structure of the batched mix. The mixing temperature is lowered and a novel RAP heating method is implemented during which it has no direct exposure to the burner flame so there is no further deterioration of the mix parameters, moreover, its original properties can be restored. Consequently, the demand for mineral aggregates and for virgin bitumen is reduced and the fuel consumption is lower.

## 2. Testing of asphalt mix with 50% RAP content

The mix to be tested has 50% RAP content. The actual composition of asphalt mix designed thus is given in Table 1.

The testing involved the Marshall stability tests, testing the mix resistance to water and frost-induced damage and resistance to rutting, and estimates were


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made of the energy demand for the asphalt mix production and environmental emission levels per 1 Mg of the asphalt mix.

**Table 1.** Asphalt mix composition – 50% RAP content

| | Material | Proportion | Real composition |
|---|---|---|---|
| 1 | A | 50% | RAP 8/16 2/8 |
| 2 | B | 1% | Lime flour 0/0.63 |
| 3 | C | 49% | aggregate |
| | | | 0/4 50% |
| | | | 4/8 25% |
| | | | 8/16 25% |
| 4 | D | | Bitumen |

### 2.1. Marshall stability test

Asphalt mix specimens prepared by the proposed method were subjected to Marshall stability tests in accordance with the guidelines provided in the standard PN-EN 12697-34: 2007 "Bituminous Mixtures. Test Methods for Hot Mix Asphalts. Section 34: Marshall test" (PN-EN 13108, 2007).

The Marshall test was performed on four groups of twelve specimens. In each test, the maximal stability $S$ [kN] and the flow of a formed specimen $F$ [mm] was established under the applied load lower than the nominal value derived by extending the tangent to the load vs flow curve to the point of its intersection with the horizontal no-load line (from point $A$ to $M$, as shown in Figure 1).

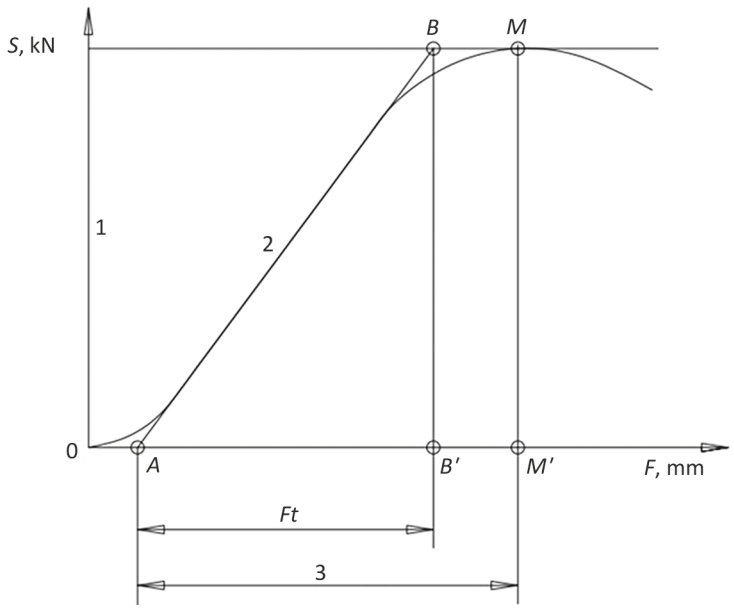


**Fig. 1.** Graphical representation: Stability $S$ vs Flow $F$ in accordance with PN-EN 12697-34 (PN-EN 13108, 2007)

Testing was performed on specimens prepared in accordance with Method I. The specimens to be tested were compacted with 75 rammer blows delivered on each side and left in moulds for 24 hours, at room temperature (about 20°C). Afterwards, they were kept in a heated chamber for 72 hours at 40°C, then stored for 24 days under standard conditions.

The machine used was the 2 Class Marshall stability testing machine: a universal HM-3000 Series Digital Master Loader with a capacity of 50 kN, in accordance with the standard EN ISO 7500-1. The specimens were loaded

at a constant and controlled rate and the resulting deformations were measured simultaneously. The magnitude of the applied force and the flow deformation values were determined using digital force and deformation sensors.

Once the specimens were extracted from the moulds, they were left for four hours before any further operations would commence; the whole test procedure was completed within 32 hours of specimen extraction. The specimens were then placed in a water bath and left there for 40 minutes. The temperatures of the hot bath was precisely controlled and maintained to within a tolerance of 1°C. The tamping rods were cleaned and lubricated, then the breaking head was placed in the bath for thirty minutes in order to heat it up to 60°C. This procedure was repeated in the testing of each group of specimens (twelve items). The specimens prepared thus were placed in the Marshall stability testing machine and loaded at a rate equal to the rate of deformation increment (50 mm/min). The maximal load and deformation were obtained in accordance with the guidelines provided in the relevant standard. The test procedure was designed such that the specimens should be placed in the testing machine no sooner than 40 seconds after removal from the hot bath. Prior to the testing, the height h and diameter $\Phi$ of all specimens were determined. The stability $S$ and flow value $F$ were derived basing on the load vs flow curves, in accordance with the standard PN-EN 12697-34 (PN-EN 13108, 2007). In the case of specimens with a height other than 63.5 mm, the correction factor is applied given by the formula (1):

$$c = 5.2 \cdot e^{-0.0258 \cdot h} \tag{1}$$

For these specimens, stability value is expressed by the formula (2):

$$S = c \cdot S_1 \tag{2}$$

where: $S_1$ – stability derived basing on the flow-vs-stability plot.

Standard deviation of the stability value is expressed by the formula (3):

$$S_S = \sqrt{\frac{\sum_{i=1}^{n} (S_i - S_{sr})^2}{n-1}} \tag{3}$$

where: $n$ – number of tested specimens, $S_i$ – value registered in the $i$-th measurement, $S_{sr}$ – mean value.

Standard deviation of the flow (deformation) value is expressed by the formula (4):

$$S_F = \sqrt{\frac{\sum_{i=1}^{n} (F_i - F_{sr})^2}{n-1}} \tag{4}$$

where: $n$ – number of tested specimens, $F_i$ – value registered in the $i$-th measurement, $F_{sr}$ – mean value.

Flow and stability test data are summarised in Table 2.


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**Table 2.** Results of flow stability test

| Marshall flow-stability test | | | | | |
|---|---|---|---|---|---|
| Series | Corrected stability value | | Flow value | | Milestone |
| | Mean value [kN] | Standard deviation [kN] | Mean value [mm] | Standard deviation [mm] | Stability [kN] |
| Series 1 | 11.16 | 0.15 | 2.56 | 0.15 | 8–14 |
| Series 2 | 11.52 | 0.10 | 2.96 | 0.14 | |
| Series 3 | 12.27 | 0.51 | 2.91 | 0.09 | |
| Series 4 | 10.84 | 0.48 | 3.53 | 0.09 | |

## 2.2. Water and frost resistance of asphalt mix

Tests of water and frost resistance were conducted in accordance with the standard PN EN12697-12 (PN-EN 12697, 2018). and the guidelines given in the technical requirements document "Asphalt-Paved Surfaces on Public Roads" (WT-2, 2008).

Indirect tensile tests and the average resilient modulus test were performed in accordance with PN-EN 12697-23 (PN-EN 12697, 2009) using mix specimens of 100 mm in diameter. Testing was done on dry and water-conditioned specimens, as well as water-conditioned and frozen specimens to determine the asphalt mix resistance to moisture and frosting.

The specimens for the indirect tensile tests were first compacted with a Marshall rammer with 75 blows delivered on each side. After compaction, the specimens were left in the moulds for 24 hours at room temperature (about 20°C). After extraction from moulds, the specimens were kept in a thermal chamber at 40°C for 72 hours and then stored for 24 days under standard conditions.

After the curing process, the indirect tensile test was performed on the dry specimens. Specimens to be moisture-conditioned were soaked in water for 24 hours after the conditioning and were then subjected to the testing procedure.

Specimens undergoing a freeze cycle are conditioned in water at the temperature 40°C, then frozen and water-conditioned at a temperature of 25°C.

The indirect tensile strength was determined at a temperature of 25°C. The specimens with a diameter of 100 ± 3 mm 60–65 mm in height were loaded radially at a rate of 50 mm/min via load strips of 12 mm in length with a curved face matching the radius of the specimen. The indirect tensile strength of the individual specimens is derived from the formula (5):

$$ITS_{S(N)} = \frac{P}{\Pi \cdot r \cdot h} \tag{5}$$

where: $ITS_S$ – indirect tensile strength – dry subset [MPa], $ITS_N$ – indirect tensile strength – water-conditioned subset [MPa], $P$ – maximal breaking force [kN], $h$ – height of the specimen [cm], $r$ – radius of the specimen [cm].

Uncertainty in indirect tensile strength measurements is obtained from the formula (6):

$$S_{ITS} = \sqrt{\frac{\sum_{i=1}^{n}(ITS_i - ITS_{sr})}{n-1}} \tag{6}$$

where: $n$ – number of tested specimens, $ITS_i$ – value of the $i$-th readout, $ITS_{sr}$ – mean value.

Results of indirect tensile strength tests are collated in Table 3.

**Table 3.** Indirect tensile strength test data- dry specimens, water-conditioned specimens and those undergoing the freeze cycle

| Tensile strength – dry specimens | | Tensile strength – water-conditioned specimens | | Tensile strength – water-conditioned specimens with the freeze cycle | |
|---|---|---|---|---|---|
| Mean value | Standard deviation | Mean value | Standard deviation | Mean value | Standard deviation |
| *ITS* [MPa] | *ITS* [MPa] | *ITS* [MPa] | *ITS* [MPa] | *ITS* [MPa] | *ITS* [MPa] |
| 1.51 | 0.09 | 1.43 | 0.11 | 1.39 | 0.11 |

The resilient modulus in the indirect tensile test was obtained under the controllable tension rate. The specimens with the height $h$ = 60–65 mm and diameter Φ100 m were dynamically loaded and the resulting displacements were measured along the horizontal axis, level with the horizontal plane passing the specimen's axis normal to the direction of the applied loads. The specimens were subjected to a constant horizontal stress of 250 kPa within 0.124 s, the length of the full cycle being 3 s. The test was performed at a temperature of 15°C. A schematic representation of the tested specimen is shown in Figure 2.

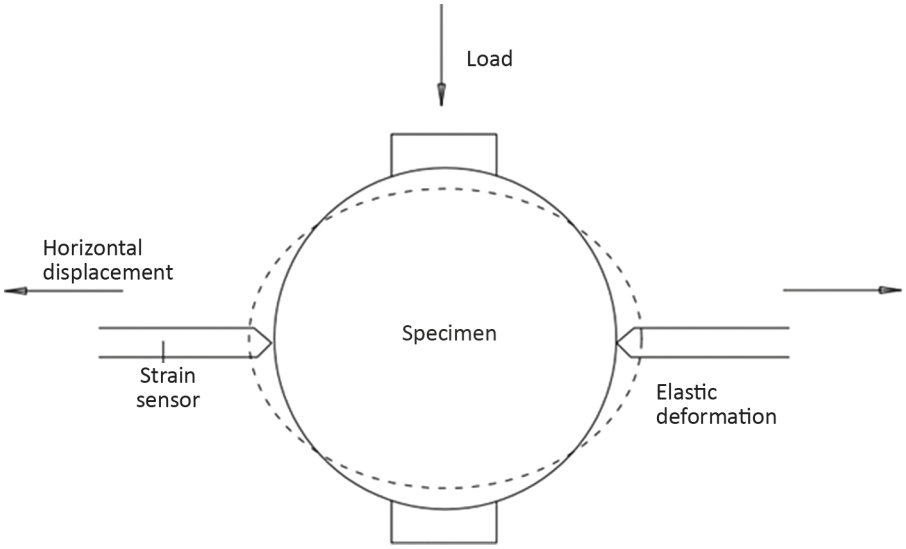


**Fig. 2.** Schematic representation of the resilient modulus measurement in indirect tensile test (own study)

The resilient modulus $S$ is obtained from formula (7):

$$S = \frac{P \cdot (\nu + 0.2732)}{\delta_H \cdot h} \tag{7}$$

where: $S$ – resilient modulus [MPa], $P$ – vertical force [MN], $\nu$ – Poisson ration, $\delta_H$ – horizontal displacement [m], $h$ – height of the specimen [m].

The resilience modulus was read out automatically, each specimen was tested twice, the second test was performed on the specimen rotated by 90°. The mean value of two readouts was obtained to find the reliable resilient modulus value for each specimen.

Uncertainty involved in measurements of the resilient modulus is derived from the formula (8):


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$$S_o = \sqrt{\frac{\sum_{i=1}^{n}(S_i - S_{sr})}{n-1}} \tag{8}$$

where: $n$ – number of tested specimens, $S_i$ – $i$-th readout value, $S_{sr}$ – mean value.

The resilient modulus values for each subset of specimens are summarised in Table 4.

**Table 4.** Results of the resilient modulus testing – dry specimens

| Resilient modulus | | | | | |
|---|---|---|---|---|---|
| Dry specimens | | Water-conditioned specimens | | Water conditioned specimens after a freeze cycle | |
| Mean value | Standard deviation | Mean value | Standard deviation | Mean value | Standard deviation |
| ***S*** **[MPa]** | $S_o$ **[MPa]** | ***S*** **[MPa]** | $S_o$ **[MPa]** | ***S*** **[MPa]** | $S_o$ **[MPa]** |
| 6856.4 | 30.9 | 7050.0 | 22.3 | 6670.7 | 25.6 |

According to the General Directorate for National Roads and Motorways guidelines (WT-2, 2008) resistance to water-induced damage is determined through testing performed on compacted and conditioned specimens (Section 5.5.3.1), yielding (9):

$$ITSR = \frac{ITS_N}{ITS_S} \tag{9}$$

where: $ITSR$ – resistance to water induced damage, $ITS_S$ – indirect tensile strength in dry-air conditions [MPa], $ITS_{Nv}$ – indirect tensile strength after water conditioning [MPa], $ITS_{Nz}$ – indirect tensile strength after water conditioning following the freeze cycle.

Calculated values of water-induced resistance are collated in Table 5.

**Table 5.** Asphalt mix resistance to water and frost (calculation data)

| Tensile strength | | | No freeze cycle | With the freeze cycle |
|---|---|---|---|---|
| $ITS_S$ **[MPa]** | $ITS_N$ **[MPa]** | $ITS_N$ **[MPa]** | ***ITSR*** **[%]** | ***ITSR*** **[%]** |
| 1.51 | 1.43 | 1.39 | 94.70 | 92.05 |
| The value quoted as the milestone | | | 89–104 | 86–103 |

Resistance to water and frosting is determined based on the resilient modulus and indirect tensile strength and is typically expressed as the resilient modulus ratio (RMR) (10):

$$\mathrm{RMR} = \frac{S_2}{S_1} \cdot 100\% \tag{10}$$

where: $S_2$ – average resilient modulus of specimens conditioned without the freeze/including the freeze cycle, $S_1$ – average resilient modulus of specimens not subjected to conditioning.

Calculated values of the mix resistance to water and frosting are summarised in Table 6.

**Table 6.** Calculated asphalt mix resistance to water and frosting

| Resilient modulus | | | Resilient modulus ratio (RMR) | |
|---|---|---|---|---|
| $S_1$ [MPa] | $S_{21}$ [MPa] | $S_{22}$ [MPa] | No freeze cycle | With a freeze cycle |
| | | | RMR [%] | RMR [%] |
| 6856.4 | 7050.0 | 6670.7 | 102.82 | 97.29 |
| The value quoted as the milestone | | | 84–110 | 96–135 |

## 2.3. Rutting resistance

The rutting resistance test was conducted in accordance with the guidelines provided in the technical standard EN 12697-22 (PN-EN 12697, 2007a), involving four runs of tests with 10,000 cycles each.

Mechanical properties were determined using a Matest B038 machine and the tests were conducted under dry-air conditions, in compliance with the standard EN 12697-22 (PN-EN 12697, 2007a). The rutting test apparatus is able to handle the specimens 305 × 305 × 50 or 100 mm in height, 305 × 400 × 50 or 100 mm in height, 200 mm diameter × 50 mm in height, 400 × 500 × 180 mm in height, with an applied wheel load of 700 N, according to EN 12697-22 (PN-EN 12697, 2007a) or 520 N (BS 598-110, 1998). The wheel loading is set using a lever.

The setup consists of a loading wheel laid upon a securely attached specimen. The wheel, located above the table, moves back and forth with a controlled speed, forming ruts on the surface of the test specimen. The vertical clearance of the wheel mechanism under load is less than 0.25 mm.

The rutting test apparatus is composed of:

a) a wheel with a tyre with an outside diameter of 200–205 mm
b) a trackless tyre, made of rubber with a hardness of 80 IRHD, with a rectangular cross section:
   - width $w$ = (50 ± 5) mm,
   - tire thickness (20 ± 2) mm.

Wheel loading $L$ measured on the level of the upper surface of the specimen, in the direction perpendicular to the test bench is derived from the formula (11):

$$L = 700\frac{W}{50} \pm 10 \tag{11}$$

where: $L$ – load applied on the surface level [N], $W$ – tire width [mm].

Load is applied via a loaded cantilever arm. The test bench is designed such that a rectangular lab-prepared test specimen with dimensions not less than 260 mm × 300 mm can be securely fixed. The top surface of the test specimen is in the horizontal position, in the plane adopted for the rutting test. The central point of the test specimen is in a position that ensures its symmetrical movement along the predetermined trajectory.

The test specimen, placed in the holder, passes back and forth in the fixed horizontal plane under the loading wheel, alternatively the loaded wheel moves back and forth passing over the firmly attached specimen. The distance between the tyre centreline and the theoretical central point of the sample must not exceed 5 mm. The central point of the tyre's contact surface executes a simple harmonic motion with respect to the central point of the upper surface of the test specimen; the total covered distance should be 230 ± 10 mm, at the frequency of (26.5 ± 1.0) load cycles within 60 s. The accuracy of the loading wheel position measurements in the vertical direction is ±0.2 mm. The internal temperature was monitored with a dedicated sensor throughout the entire test, and the uniform temperature of the specimen was maintained at 50°C ± 1°C. The length of the straight edge for measuring the dimensions of the specimen


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is 300 mm, and the measuring accuracy is ±1 mm. The calliper gauges used in thickness measurements of the test specimen ensure an accuracy of ±0.1 mm.

Specimens to be tested were prepared in the laboratory in the shape of plates with length $L$ = 300 mm, width $l$ = 260 mm and thickness $e$ = 60 mm. Each set included two test specimens, compacted in accordance with EN 12697-33 (WT-2, 2008).

Specimens prepared in the lab and left unattached were kept under closely monitored conditions: the tested surface remained in the horizontal position at temperatures below 25°C.

The rutting susceptibility was determined for specimens compacted two days previously. The difference in age between specimens subjected to the same series of test fell in the range ±10%. The real age of specimens, expressed as a number of days, is registered in the test data sheet.

The spacing between the specimen and the mould is measured with gauge callipers. The procedure adopted in the measurement of the rut depth accumulation is as follows:

a) Stabilising the temperature,
b) Wheel passage after the temperature has stabilised,
c) Test procedure.

The first readouts after the testing began were taken at the wheel's vertical displacement point. The readings were repeated at least seven times within the first hour; they were then taken once after each 500 load applications.

The vertical position of the wheel was determined as the average value of the specimen profile over a distance of ±50 mm around the central point of the area subjected to loading in the central point of the trajectory measured at 25 equally spaced points. The vertical position of the wheel was measured without stopping the wheel.

Calculation procedure and results

1. Wheel-track sloping under dry-air conditions $WTS_{AIR}$
   The wheel track sloping, expressed in mm per $10^3$ load cycles is obtained from the formula (12):

$$WTS_{AIR} = \frac{(d_{10\,000} - d_{5000})}{5} \tag{12}$$

   where: $WTS_{AIR}$ – wheel track sloping (mm/$10^3$ load cycles); $d_{5000}$, $d_{10000}$ – rut depth after 5,000 load cycles or 10,000 load cycles, respectively (mm).
2. Average wheel-track sloping
   Testing done on two specimens giving the average $WTS_{AIR}$. When the test is completed before 10,000 load cycles are applied, the wheel track sloping is derived based on the linear section of the rut depth accumulation plot.
3. Average rut depth $RD_{AIR}$
   The rut depth in the test material after $N$ cycles is the average rut depth obtained for two specimens, rounded to the nearest ±0.1 mm.

$$RD_{AIR} = \frac{\sum_{i=2}^{2} d_{10\,000}}{2} \tag{13}$$

   where: $RD_{AIR}$ – average rut depth after $10^4$ load cycles (mm), $d_{10\,000,i}$ – rut depth after $10^4$ load cycles (mm).
4. Average proportional rut depth $PRD_{AIR}$
   The proportional rut depth in the test material after $N$ load cycles is expressed at the average proportional rut depth calculated for two (or more) specimens, rounded to ±0.1 mm.

$$PRD_{AIR} = \frac{\sum_{i=2}^{2} \frac{d_{10\,000\,i}}{h_i}}{2} \cdot 100\% \tag{14}$$

where: $PRD_{AIR}$ – average proportional rut depth after $10^4$ load cycles (%), $d_{10\,000,\,i}$ – rut depth in test specimen $i$ after $10^4$ load applications (mm), $h_i$ – indicates the thickness of test specimen $i$ (mm).

The results are collated in Table 7.

**Table 7.** Asphalt mix resistance to permanent deformation

| | $d_{5000\,i}$ | $d_{10\,000\,i}$ | $WTS_{AIR}$ | $WTS_{AIRŚR}$ | $RD_{AIR}$ | $h_i$ | $d_{10\,000\,i}/h_i$ | $PRD_{AIR}$ |
|---|---|---|---|---|---|---|---|---|
| | [Mm] | [mm] | [mm/10³ load cycles] | [mm/10³ load cycles] | [mm] | [mm] | [–] | [%] |
| 1 | 1.48 | 4.51 | 1.20 | 1.30 | 5.0 | 60.9 | 0.074 | 8.25 |
| 2 | 1.6 | 5.44 | 1.41 | | | 59.8 | 0.091 | |
| 3 | 1.69 | 4.69 | 1.28 | 1.36 | 5.2 | 61.9 | 0.076 | 8.57 |
| 4 | 1.47 | 5.79 | 1.45 | | | 60.5 | 0.096 | |
| 5 | 1.95 | 5.91 | 1.57 | 1.44 | 5.4 | 59.9 | 0.099 | 8.93 |
| 6 | 1.75 | 4.81 | 1.31 | | | 60.1 | 0.080 | |
| Average value | | | | 1.37 | Average value | | | 8.59 |
| Milestone value | | | | 0.05–2.00 | Milestone value | | | 5–39 |

## 2.4. Energy demand for asphalt mixing

The energy demand for production of the innovative asphalt mix was determined based on the average consumption of fuel oil in the prototype mixing plant. The oils used in the test program were light fuel oil with a calorific value of about 42.5 MJ/kg and heavy fuel oil with a calorific value of 40.9 MJ/kg. Fuel oil consumption in successive test runs is shown in Table 8.

**Table 8.** Fuel oil consumption in successive test runs

| Asphalt mix production | Amount of fuel oil used | Oil type | Oil consumption |
|---|---|---|---|
| [Mg] | [kg] | C – heavy oil, L – light oil | [kg/Mg] |
| 2.5 | 12.25 | C | 4.9 |
| 5 | 23 | L | 4.6 |
| 7 | 30.1 | L | 4.3 |
| 5 | 25.5 | C | 5.1 |
| 5 | 26.5 | C | 5.3 |
| 2.5 | 11.5 | L | 4.6 |
| 4 | 19.6 | C | 4.9 |
| 3 | 13.8 | C | 4.6 |
| 2 | 8.8 | L | 4.4 |
| 6 | 28.8 | L | 4.8 |
| | | Average value | 4.75 |

The average fuel oil consumption in successive test runs is 4.75 kg/Mg of the asphalt mix. The average calorific value of the fuel oil used is 41.75 MJ/kg. Energy demand for preparation of the asphalt mix was estimated as the product of fuel oil consumption and its calorific value, in the case considered in the study, it is equal to 198.38 MJ/Mg.


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### 2.5. Emissions of pollutants associated with fuel oil use

Emissions of vapours, aerosols, $NO_x$, $SO_2$, CO, VOCs (volatile petroleum substances) and dust were determined in proportion to fuel oil consumption at a reference asphalt mixing plant with a similar capacity. Data obtained for the reference plant are summarised in Table 9.

**Table 9.** Environmental emissions and fuel consumption at the reference mixing plant

| Emissions | Unit of measurement | Parameter value |
|---|---|---|
| Vapours and aerosols | [mg/Mg] | 121.9 |
| $NO_x$ | [g/Mg] | 18.2 |
| $SO_2$ | [g/Mg] | 5.8 |
| CO | [g/Mg] | 8.5 |
| VOC | [g/Mg] | 12.1 |
| Pyły | [g/Mg] | 6.5 |
| Light fuel oil | [kg/Mg] | 8.3 |

The average fuel oil consumption in successive test runs is 4.75 kg/Mg of the asphalt mix. The average emission levels based on the fuel oil consumption are collated in Table 10.

**Table 10.** Average emission levels

| Emission levels | Unit of measurement | Calculated data |
|---|---|---|
| Vapours and aerosols | [mg/Mg] | 69.76 |
| $NO_x$ | [g/Mg] | 10.42 |
| $SO_2$ | [g/Mg] | 3.32 |
| CO | [g/Mg] | 4.86 |
| VOC | [g/Mg] | 6.92 |
| Dust | [g/Mg] | 3.72 |

### 2.6. Testing of asphalt mix with 50% RAP content – conclusions

The present study demonstrated the feasibility of batching an asphalt mixture with 50% RAP content. This mix was extensively tested to verify its suitability in road construction and rehabilitation and key performance parameters, such as Marshall stability, water and frost resistance and rutting resistance were determined. The investigated asphalt mix seems to have met all normative requirements or milestones. Emissions were determined in accordance with the adopted methodology and the obtained emission values were found to be within the predetermined set limits. All milestones being met, further research and development work is fully merited.

## 3. Testing the asphalt mix with 90% RAP content

Further studies were conducted to verify the feasibility of obtaining the asphalt mixture with 90% RAP content. Tests were conducted in a modified pilot plant to determine the fuel oil consumption during the asphalt mixing and associated emissions. The actual composition of the investigated mixture is specified in Table 11, containing aggregate fractions 0–4, 8–18 and 2–8 mm, RAP with aggregate fraction 0–16, as well as bitumen type 35/50 and 50/70.

**Table 11.** Composition of the asphalt mix

| Constituent material | Proportion [kg/Mg] of asphalt mix |
|---|---|
| Aggregate 0–4 | 20.0 |
| Aggregate 8–16 | 20.0 |
| Aggregate 2–8 | 20.0 |
| Bitumen | 40.0 |
| RAP | 900.0 |

### 3.1. Preparation of asphalt mix

Testing was conducted on homogeneous RAP material obtained by the milling of the upper layer of asphalt paved surfaces. The milled product was first divided in three parts, depending on the aggregate fraction: 0–4 mm, 2–8 mm and in excess of 8 mm. Natural mineral aggregate is divided into three fractions: fine aggregate 0–4 mm, aggregate with grain size 2–8 mm and coarse aggregate 8–16 mm. In the next stage, the drying drum in the pilot plant was filled with RAP and natural mineral aggregate. Dried RAP and mineral aggregate are then delivered to the mixer in precisely controlled doses, by weight. RAP fractions are transported to the RAP dosing chute and to the mixer drum where they are slowly heated. Bitumen in the specified amount is heated up to the working temperature of 140°C ± 5°C and then placed in the decompression chamber of the bitumen dispenser. A jet of water at a temperature of 20°C is injected to the heated bitumen, under pressure of 0.5 MPa. The volume of water is equal to about 3% of bitumen prior to foaming. Foamed bitumen, prepared immediately before dosing, is injected to the mixer during the RAP batching and heating process. The prepared mixture is then heated up to 120°C, homogenised whilst the burner remains off, and then stored in an insulated tank.

### 3.2. Energy consumption during asphalt mixing

Energy consumption associated with production of the innovative asphalt mix was determined based on the average fuel oil consumption. Fuel oils used in the tests were a light fuel oil with a calorific value of about 42.5 MJ/kg and heavy fuel oil with a calorific value of 40.9 MJ/kg.

Fuel oil consumption in the successive test runs is given in Table 12.

**Table 12.** Fuel oil consumption in successive test runs

| The amount of asphalt mix | The amount of oil used | Fuel oil type | Fuel oil consumption |
|---|---|---|---|
| [Mg] | [kg] | C – heavy, L – light | [kg/Mg] |
| 3.5 | 15.05 | C | 4.3 |
| 4.8 | 21.12 | L | 4.4 |
| 5.6 | 21.84 | L | 3.9 |
| 8 | 36.8 | C | 4.6 |
| 12.1 | 48.4 | C | 4.0 |
| 10.9 | 46.87 | L | 4.3 |
| 6.3 | 25.83 | C | 4.1 |
| 6.5 | 27.95 | C | 4.3 |
| 13.5 | 56.7 | L | 4.2 |
| 8.1 | 31.59 | L | 3.9 |
| | | Average value | 4.20 |


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The average fuel oil consumption in successive test runs is 4.20 kg/Mg of asphalt mix. The average calorific value of the fuel oil is 41.75 J/kg. Energy consumption associated with asphalt mix production, expressed as product of the average fuel oil consumption and its calorific value, is equal to 175.35 MJ/Mg.

### 3.3. Emissions associated with the use of fuel oil

Emissions of vapours, aerosols, $NO_x$, $SO_2$, CO, VOCs (volatile petroleum substances) and dust were determined in proportion to fuel oil consumption at a reference asphalt mixing plant with a similar capacity. Data obtained for the reference plant are collated in Table 13.

**Table 13.** Environmental emissions and fuel consumption at the reference asphalt mixing plant

| Emission | Unit of measurement | Registered value |
|---|---|---|
| Vapours and aerosols | [mg/Mg] | 121.9 |
| $NO_x$ | [g/Mg] | 18.2 |
| $SO_2$ | [g/Mg] | 5.8 |
| CO | [g/Mg] | 8.5 |
| VOC | [g/Mg] | 12.1 |
| Dust | [g/Mg] | 6.5 |
| Light fuel oil | [kg/Mg] | 8.3 |

The average fuel oil consumption in successive test runs is 4.20 kg/Mg of asphalt mix. The average emission values associated with fuel consumption are given in Table 14.

**Table 14.** Average emission values during the tests

| Emission | Unit of measurement | Calculated value |
|---|---|---|
| Vapours and aerosols | [mg/Mg] | 61.68 |
| $NO_x$ | [g/Mg] | 9.21 |
| $SO_2$ | [g/Mg] | 2.93 |
| CO | [g/Mg] | 4.30 |
| VOC | [g/Mg] | 6.12 |
| Dust | [g/Mg] | 3.29 |

### 3.4. Testing of asphalt mix with 90% RAP content - conclusions

The present study has demonstrated the feasibility of designing an asphalt mixture with 90% RAP content. The mix was extensively tested to determine the fuel oil consumption during asphalt mixing and associated emissions in accordance with the adopted methodology.

## 4. Final conclusions

Tests have confirmed the feasibility of using RAP as the skeleton material in asphalt mixtures as an alternative material to natural mineral aggregate used, inter alia, in Hot Asphalt Mixing. At the same time, the performance parameters of RAP containing asphalt mixes are maintained so they can be well used in the construction or reconstruction of upper layers of asphalt roads.

Lowering the asphalt mixing temperature and adopting a novel, two-stage method of RAP heating without direct exposure to the burner flame halted

the further deterioration of its parameters. The addition of small amounts of foamed bitumen helped restore its performance parameters, similar to those of pavements constructed from virgin materials. The mixture requires only a small proportion of virgin aggregate. Thus, the demand for costly new mineral aggregate and virgin asphalt can be reduced and the fuel oil consumption required in the production of asphalt mix is significantly lower.

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