Possibilities of Utilization of Alternative Materials within Railway Trackbed

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ABSTRACT: One of the main objectives of the research work carried out by the Department of Railway Structures, Faculty of Civil Engineering, Czech Technical University in Prague is to investigate utilization possibilities of granular recycled materials and by-products within railway structures. This article summarizes results of a research which was carried out between years 2005 and 2012. The main goal of the research was to assess key parameters of granular recycled materials and by-products from the point of view of their possible utilization within trackbed. Three different types of granular materials were investigated. Particularly, these were stabilized fly ash from a coal-fired thermal power plant, recycled asphalt pavement material (RPM) and crushed concrete made by crushing used railway sleepers. For each material the article introduces the most important results gained by testing of laboratory specimens as well as full-scale laboratory models. The stabilized fly ash was investigated for the longest period of time. In 2005, a test section of railway track utilizing the stabilized fly ash within bound trackbed layer was constructed. The article shows results of the test section monitoring gathered between 2005 and 2011.

KEY WORDS: Recycled concrete aggregate, recycled asphalt pavement, stabilized fly ash, laboratory testing, railway trackbed

1 INTRODUCTION

In the Czech Republic more than 12 million tons of construction and demolition waste are generated annually. Moreover, the energy production generates approx. 15 million tons of coal combustion products. Only a certain part of these amounts is being used in an effective way. To extend the possible ways of utilization of these materials, further testing and observations are necessary to contribute to knowledge base whereupon come up with recommendations for their practical utilization. This research dealt separately with three selected materials: recycled crushed concrete aggregate, recycled asphalt pavement material and stabilized fly ash.

2 RECYCLED CRUSHED CONCRETE AGGREGATE

Utilization of recycled crushed concrete aggregate (RCA) as a road sub-base layer or railway sub-ballast in the Czech Republic often meets with professional public scepticism connected with an uncertain resistance of such material. A possible reason might be negative experience arising from utilization of a low-quality RCA or RCA containing a significant share of impurities, such as crushed clay brick, mortar and wood. On the other hand, as it has been shown in some studies (Arm 2001, Aurstad et al. 2009) pure, well-sorted RCA may have mechanical and strength parameters at least comparable with natural crushed stone. Moreover, a growth in stiffness of unbound layers with RCA was observed as a result of its self-cementing properties. In this study, recycled crushed concrete aggregate made by crushing discarded railway sleepers manufactured in 1980's was investigated.

The laboratory testing program on specimens was based on guidelines for natural crushed stone mixtures (OTP 25 640/06). Afterwards, to confirm satisfying result gathered by testing specimens, a series of measurements on laboratory models was conducted including evaluation of effect of cyclic loading (Lidmila and Horníček 2011, Šablatura 2012).

2.1 Laboratory investigation of basic parameters

The laboratory investigations were focused on physical parameters, mechanical strength and resistance of RCA. Moreover, the compressive strength of cubic specimens cut from the concrete particles after primary crushing was determined to verify the quality of concrete used for the sleepers' production. Results of performed laboratory tests are summarized in Table 1 and commented below.

Table 1: Results of performed laboratory tests and values required by RIA guidelines

Parameter	Testing method	Required value	Reached value
Modified Proctor density	EN 13286-2	-	1870 kg.m^{-3}
Resistance to freezing and thawing	EN 1367-1	4 %	2.9 %
Resistance to fragmentation (LA test)	EN 1097-2	50 %	23 %
Cubic compressive strength of concrete	EN 12390-3	-	40 MPa

Particle size distribution: The RCA underwent a sieve analysis without any modification except screening on 32 mm screen in the recycling centre. It was found, that the content of fraction 0/16 in recycled concrete aggregate exceeded the allowable range by approx. 4 %.

Compressive strength: The average cubic compressive strength was over 40 MPa, which corresponds to the strength class of concrete used for the sleepers' manufacturing. Thus, any significant degradation of the concrete during the sleepers' service was not observed.

Proctor modified test: The proctor modified test gave a maximum dry density of 1870 kg.m^{-3} at an optimum water content of 8.5 %. These values are accordant with other studies recently carried out.

Resistance to fragmentation: The resistance to fragmentation (Los Angeles) was determined in compliance with RIA guidelines on three samples with fraction of 8/32. The average LA value less than 23 safely satisfies relevant requirements (LA value of 50).

Resistance to freezing and thawing: The test results revealed also good resistance to freezing and thawing on fraction 8/16. After 10 freeze-thaw cycles only 2.9 % of particles passed the 4 mm sieve, while the maximum allowable value is 4 % passing.

2.2 Full-scale laboratory testing

The bearing capacity of substructure layers on railways administrated by RIA is expressed as deformation modulus, which is evaluated from a static plate load test. The plate with diameter of 300 mm is loaded in two load cycles up to the maximum bearing pressure of 0.2 MPa for the subgrade and sub-ballast and 0.1 MPa for materials with low bearing capacity. The deformation modulus is then calculated from the second load cycle according to formula:

$$E_{def} = \frac{1.5 \times p \times r}{y}$$

where

E_{def} = deformation modulus [MPa],
p = maximum load pressure [MPa],
r = radius of the load plate [m],
y = total settlement in the 2^{nd} load cycle [m].

To evaluate the influence of water content of the RCA layer on bearing capacity and its development in time, three laboratory models were built-up and investigated. A small testing box measuring 0.79 x 0.90 x 0.46 m was used. A 50 mm thick layer of clay simulated the subgrade on which a nonwoven geotextile providing separation and a 250 mm thick layer of RCA with gradation of 0/32 mm were laid. The water content of RCA layer during assembly was 9.8 %, 8.4 % and 7.1 %. The deformation modulus was determined on the surface of RCA layer just after its compaction and then again after 7 days. The sample with water content approaching the optimum value (8.4 %) showed 200% increase in E_{def} from 44.1 to 131.1 MPa during 7 days of curing, whilst the other specimens showed only around 80% growth (from 42.1 to 75.4 MPa and from 37.0 to 68.5 MPa).

A full-scale laboratory model was then built-up in a testing box measuring 2.1 x 1.0 x 0.8 m deep. The model consisted of a 280 mm thick clay layer, simulating the subgrade with low bearing capacity (E_{def} = 6.3 MPa), nonwoven geotextile providing separation, a 150 mm thick RCA layer and 300 mm of railway ballast, fraction 32/63 mm, on which a half of railway sleeper B 91 S/1 was placed. The model was subjected to 250 000 load cycles with a minimum force of 2 kN and a maximum force of 42 kN. The deformation modulus was determined on the surface of each layer during both assembling and dismantling the model. On the surface of RCA layer the deformation modulus was 15.0 MPa and 23.5 MPa, respectively.

When investigating the possible reason of different observations concerning the self-cementing behaviour of RCA, an important distinction in processing the RCA was found. The first part of RCA, used for laboratory testing specimens and testing in the small testing box, was processed within approx. 24 hours including primary and secondary crushing and screening. Whereas the second part of RCA used in the full-scale laboratory model was subjected to changing weather conditions for about three months between the primary and secondary crushing. This might negatively affected the self-cementing properties of the RCA.

2.3 Evaluation of test results

Pure RCA made from used railway sleepers proved a good mechanical strength and resistance. Both resistance to fragmentation and resistance to freezing and thawing met safely requirements stated in RIA guidelines. Under the identical conditions, the bearing capacity detected on the surface of RCA layer in the small testing box was at least comparable with the bearing capacity of a layer made of natural crushed stone. The layer of RCA gave values of the deformation modulus E_{def} between 37 and 44 MPa, while for the natural crushed stone mixtures were reported values of E_{def} ranging from 29 to 37 MPa (Krejčiříková and Břešťovský 2011). A significant increase in the bearing capacity of RCA in time was observed, which was attributed to its self-cementing properties. Any exposure of RCA to weathering during its processing or storage may lead to loss of the self-cementing properties.

3 RECYCLED ASPHALT PAVEMENT MATERIAL

As it has been shown in some studies, mechanical strength of recycled asphalt pavement material (RPM) without further modification usually is not sufficient for its utilization within road sub-base layers or railway sub-ballast. For instance, natural crushed aggregates, mostly utilized for these purposes, give California bearing ratio (CBR) values about 100 and higher, whereas reported CBR for RPM ranges from 3 to 19 (Li et al. 2007, Wen and Edil 2009). In 2010 a field test on a compacted, 200 mm thick RPM layer was carried out. A set of four static plate load tests was performed. During the first load cycle an extensive settlement of the plate was observed, leading in two cases even to a test failure. The ratio between the deformation modulus calculated from the second and first load cycle ($E_{def,2}/E_{def,1}$) was more than 4, while the maximum allowable value is 2. Similar situation recurred after further compaction, when the $E_{def,2}/E_{def,1}$ ratio was even higher. Such high values of the ratio advert to considerable permanent deformations generated within the first load cycle (ARCADIS 2010).

Significant efforts had been made to find out different techniques increasing mechanical strength of RPM. For instance, Li et al. (2007) reported an increase in mean CBR from 9 to 84 by blending the RPM with 10 % of Class C fly ash. Wen and Edil (2009) showed that addition of 14 % of high-carbon fly ash to RPM increased the CBR from 19 to 129.

The abovementioned technique requires application of additional ingredients to improve mechanical properties of RPM. Different approach is to utilize only adhesive properties of contained bitumen. Heating the RPM causes a decrease in bitumen viscosity, which enables better workability, eases compaction and improves mechanical strength of RPM. Laboratory investigations were performed to analyse the relation between compaction temperature and the rate of compaction and CBR, respectively. An optimum compaction temperature was then evaluated and further followed. Other investigations were focused on evaluating the impact of RPM composition on its mechanical strength. A laboratory model was assembled allowing determination of deformation modulus on the surface of RPM layer and drilling cores.

3.1 Laboratory testing specimens

Laboratory specimens of RPM were prepared using proctor modified testing method. The temperature was measured on the surface of each layer after finishing its compaction. The average value was taken as a compaction temperature, to which investigated properties (bulk density, CBR) were related. As it can be seen from figure 1, the relations between compaction temperature, and both bulk density and CBR were almost linear.

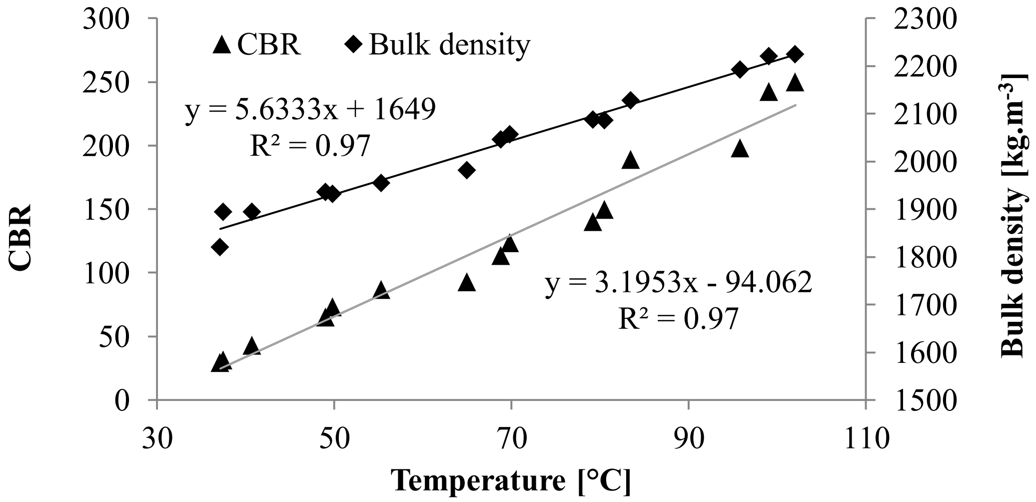

Figure 1: Relation between compaction temperature, bulk density and CBR

The bulk density increased from about 1890 kg.m^{-3} to 2220 kg.m^{-3} by rising the compaction temperature from 40 °C to 100 °C. In the same temperature range, the CBR improved from about 35 to more than 240. Based on these experiences an optimum compaction temperature of 70 °C (approx. 160 °F), providing CBR more than 100, was chosen for further research.

To assess the impact of RPM composition on its physical and mechanical parameters after compaction, six different samples were collected from stockpiles at Středokluky asphalt plant in central Bohemia. The sample designated A was collected at a stockpile of crushed and blended RPM (fraction 0/22), while the other samples (B to F) were collected at a stockpile, where materials from different road reconstruction works were placed without further processing. During the collection a visual assessment was done aimed at selecting samples with various properties. An analysis of each RPM sample was carried out including determination of following parameters:

- particle size distribution of contained aggregate,
- binder (bitumen) content,
- softening point of bitumen (Ring and Ball method).

These parameters were expected to have significant influence on the compaction rate and mechanical strength of RPM. Laboratory tests on cylindrical specimens prepared by proctor modified method at compaction temperature of approx. 70 °C were focused on evaluation of bulk density, thermal conductivity, California bearing ratio and compressive strength.

All test results are summarized in table 2 except the particle size distribution. Some important findings concerning following characteristics were made:

Particle size distribution: All RPM samples showed similar particle size distributions of contained aggregates except sample C, which contained significantly higher share of fraction 0/5.6 mm (87 % compared with 50 % to 57 % found among other samples).

Table 2: Summary of results gathered by testing different samples of RPM

	Binder content [%]	Softening point [°C]	Compaction temperature [°C]	Bulk density [kg.m^{-3}]	Thermal conductivity [W.m^{-1}.K^{-1}]	CBR [%]	Compressive strength [MPa]
Sample A	5.08	65.0	71	2088	0.94	110	4.0
Sample B	4.34	71.0	73	2116	0.85	114	3.8
Sample C	6.68	74.1	71	2003	0.81	114	2.1
Sample D	4.75	70.6	73	2040	0.67	104	2.0
Sample E	4.99	64.2	70	1998	0.70	99	2.4
Sample F	4.63	79.0	70	1972	0.91	141	2.0

Binder content: RPM samples contained from 4.3 % to 6.7 % of bitumen. Most of the samples contained 4.6 % to 5.1 %, which is suggested as a standard range.

Bitumen softening point: For samples A, B, D and E, the softening point was found between 64 °C and 71°C. Higher values were gained for sample C (74.1 °C) and F (79.0 °C).

Bulk density: Samples A and B gave values higher by approx. 80 kg.m^{-3} than samples C to F. However, no relevant relation between the bulk density and the RPM composition or the properties of used bitumen was found.

Thermal conductivity: Thermal conductivity measurements revealed values of the thermal conductivity coefficient $\lambda = 0.67$ to 0.94 W.m^{-1}.K^{-1}.

California bearing ratio: The CBR values gained on samples A to E implied good mechanical strength, ranging from 99 to 114 at compaction temperature of 71 °C to 73 °C.

Sample F showed significantly higher mean CBR value of 141, which might be attributed to a relatively lower content of binder of higher stiffness.

Compressive strength: Greatest variations were found in the compressive strength. Whilst samples A and B reached 4.0 MPa and 3.8 MPa, respectively, samples C to F showed only about half this value accompanied by visible crumbling during their manipulation. The samples with greatest compressive strength were these with highest bulk densities.

3.2 Measurements in the small testing box

A laboratory model was assembled in a small testing box measuring 0.79 x 0.90 x 0.46 m. The model consisted of 185 mm thick layer of clay, simulating subgrade with a low bearing capacity ($E_{def} < 5$ MPa), nonwoven geotextile providing separation and approx. 150 mm thick layer of RPM sample A. The RPM was compacted by a vibrating plate compactor in one layer. It was aimed to reach the designed thickness and bulk density more than 2000 kg.m^{-3}. The surface temperature of RPM layer after compaction was 69.8 °C. After 24 hours enabling cooling of the RPM layer, the static plate load test was performed. The measurement showed deformation modulus of 17.4 MPa and the $E_{def,2}/E_{def,1}$ ratio of 1.6. The thermal conductivity measurements revealed mean value of $\lambda = 0.64$ W.m^{-1}.K^{-1} which is accordant to values gained on specimens.

3.3 Evaluation of test results

It was approved that increasing the temperature of RPM is a possible way to reach higher rate of its compaction. The reached bulk density of RPM was from 97 % dependent on the compaction temperature. Similar relation was observed for the CBR value, which indicates the mechanical strength. At the compaction temperature of 70 °C the mean CBR value for different RPM samples ranged from 99 to 141, which is comparable with CBR of natural crushed stone. The static plate load test on laboratory model of RPM layer showed ratio of $E_{def,2}/E_{def,1} = 1.6$, which implies development of permanent deformation at an allowable rate. Regarding the thermal insulating properties, the RPM performed better with thermal conductivity coefficient $\lambda < 1.0$ W.m^{-1}.K^{-1} compared to natural crushed stone with $\lambda \approx 2.0$ W.m^{-1}.K^{-1}. This might be beneficial for protecting the subgrade against freezing.

4 STABILIZED FLY ASH

In April 2005, a 330 m long test track section was established at Smiřice railway station where stabilized fly ash (SFA) was used in trackbed for the first time in the Czech Republic. The primary objective of laying a layer of SFA was rainwater and freeze protection of the subgrade. The secondary objective was monitoring of effects of the SFA layer on load-bearing capacity of the trackbed. Stabilized fly ash from Chvaletice Power Plant denoted “R4 formula” and containing 52 % of fly ash, 25 % of flue gas desulfurization gypsum, 3 % of CaO and 20 % of water was used. The SFA was mixed in the mixing centre of Chvaletice Power Plant. In general, produced SFA is not stored but dispatched by trucks straight from the mixing centre to the laying site. Fresh SFA generates hydration heat and gradually hardens. The optimum workability time is up to 4 hours after mixing.

4.1 Laboratory investigations

Prior to the establishment of the test section, laboratory tests of basic mechanical and physical parameters essential for application in the trackbed were performed in compliance with Czech standards (ČSN). The results of laboratory tests are presented in table 3. A part of the laboratory tests were full scale tests of the SFA layer. Six models of trackbed construction were assembled and investigated in a testing box measuring 2.1 x 1.0 x 0.8 m. The results proved a possibility of designing a protective layer of SFA with a minimum thickness of 150 mm provided the deformation modulus of the subgrade $E_{def} > 30$ MPa.

Table 3: Basic mechanical and physical parameters of stabilized fly ash

Parameter	Testing method	Reached value
Maximum dry density	ČSN 72 1015, method B (modified Proctor test)	$\rho_{dmax} = 1310$ kg.m^{-3} $w_{opt} = 20$ %
Uniaxial compressive strength (unsaturated)	ČSN 73 6125	1.04 MPa (7 days curing)
Freeze-thaw resistance	ČSN 73 6125	6.07 MPa (162 days curing)
Permeability	ČSN 72 1020, F method	3.5×10^{-8} m.s^{-1} (162 days curing)
Thermal conductivity coefficient	ISOMET 2104 device	0.7 W.m^{-1}.K^{-1} at moisture content $w_n = 40$ %

4.2 Establishing the test section

The test section at Smiřice railway station was established in track no. 3 during its reconstruction. The Smiřice railway station is situated on the Pardubice – Liberec railway line with an axle load of 22.5 tons. A cross sectional view of the test section is shown in figure 2.

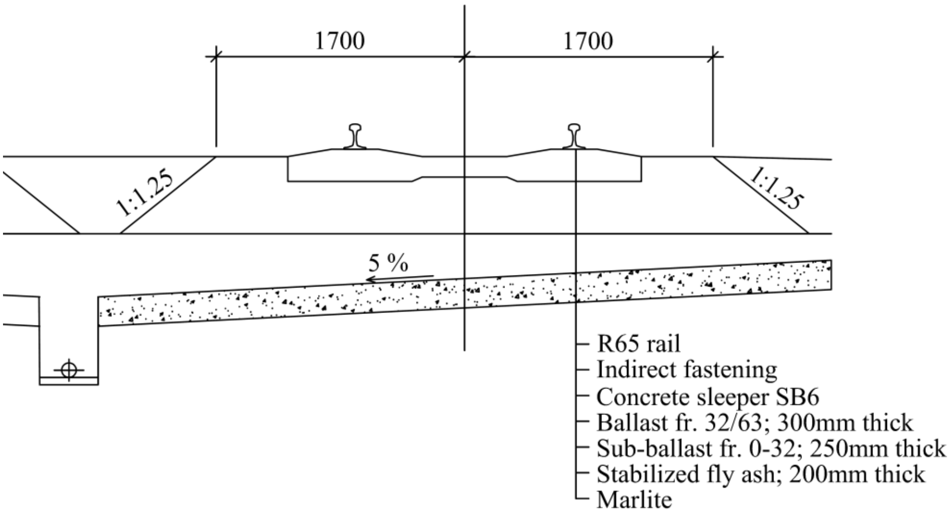

Figure 2: Cross-sectional view of the test section with protective layer of stabilized fly ash

Three measurement profiles (designated P1, P2 and P3) were selected for a long-term monitoring of behaviour of the SFA protective layer. P1 and P3 profiles were situated close to the beginning and the end of the trial section respectively, whilst P2 profile was placed approx. in the middle. Prior to construction of the protective layer, the old track panels were removed and the old trackbed was extracted to level of newly designed subgrade with a one-sided slope of 5 %. The subgrade was formed by marlite at various degrees of weathering. Marlite is classified as a rock highly susceptible to water. The SFA was transported from mixing centre of the Chvaletice Power Plant to the construction site by large volume truck trailers. Here the SFA was reloaded onto standard trucks and tipped on the subgrade where it was levelled by a grader to the designed thickness and transverse slope and then compacted. The total time between mixing the SFA in the mixing centre and its compaction ranged from 3 to 4 hours. The average moisture content of the transported SFA was 21.5 %.

4.3 Test section monitoring

A five-year testing plan was designed for the long-term monitoring of the structural layer of stabilized fly ash. In-situ tests were performed in P1, P2 and P3 measurement profiles every year in the spring and winter season. These tests included static plate load tests on the surface of sub-ballast and the surface of the SFA layer. The in-situ tests were complemented by laboratory tests. Four SFA cores were taken from each trial hole using drilling device with a 100 mm drill crown for bulk density and the uniaxial compressive strength testing.

Static plate load tests: Measurements of deformation modulus on the surface of sub-ballast (crushed stone mixture fr. 0/32) showed an ongoing consolidation during the first half-year after the construction completion (an increase in E_{def} from 80 MPa to 160 MPa). The consequent pattern implies an average value of the deformation modulus of sub-ballast around 130 MPa. Deviations from this value followed the cycle of seasons in the year so that in spring these values were by ca. 20 % higher than values gained in autumn of the same year. The deformation modulus measured on the surface of SFA layer significantly increased for a period of approx. 2 years after the construction (see figure 3). After this period, a 10 to 20 mm thick layer of partially degraded material formed on the SFA surface. This resulted in reduction of the deformation modulus. According to the latest measurements, it may be stated that the deformation modulus on the surface of SFA reached value of ca. 350 MPa.

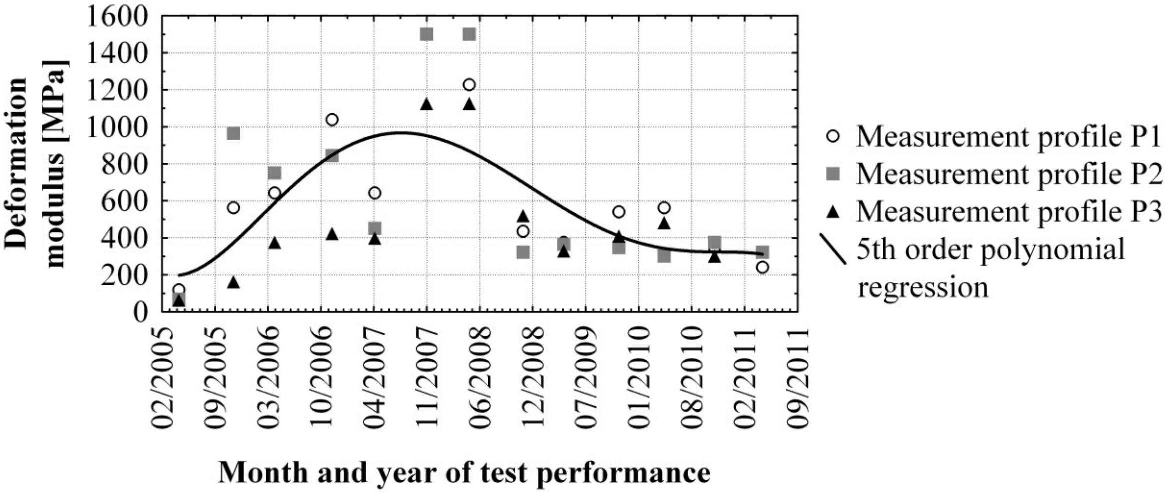

Figure 3: Results of static plate load tests on the SFA protective layer surface (Lidmila 2011)

Thermal conductivity: In 2010, the coefficient of thermal conductivity λ of the SFA layer SFA was measured in each trial hole during the spring measurement campaign. The measurements were performed using the ISOMET 2104 device with a surface probe.

The mean value of the thermal conductivity coefficient $\lambda = 0.82\ W.m^{-1}.K^{-1}$ reached for the mean moisture content of the SFA layer $w_n = 45.5\%$ is in accordance with laboratory results presented in table 3.

Permeability: The objective of the permeability measurement on cores was to determine the filtration coefficient k. The permeability measurements were performed in compliance with the ČSN 72 1020 standard, method F – permeability measurement in the pressure chamber designed for low permeability materials. In total, 32 permeability measurements on cores of SFA were performed. In the long-term perspective, the permeability coefficient development may be considered steady and the protective layer of SFA may be characterised as low permeable to impermeable with filtration coefficient $k = \pm 1.0.10^{-7} m.s^{-1}$.

Bulk density: No dramatic falling or rising trend of the bulk density of the SFA layer was identified during monitoring the test section. Higher values of bulk density were measured in the P2 measurement profile than in P1 and P3 profiles. Reverse analysis of water content measurements of the SFA during its compaction showed that in the P2 profile in particular the actual moisture content of the spread SFA most approached the optimum moisture content specified in laboratory conditions.

Compressive strength: In total, 119 cores were subjected to testing during 6 years of the test section monitoring. The uniaxial compressive strength was growing during first 2 years following the test section construction (spring 2005 to spring 2007). After this time the uniaxial compressive strength stabilized at around 5.0 MPa.

4.4 Evaluation of the test section monitoring

The establishment and operational verification of the test section for a period of 6 years provided a coherent set of information concerning the behaviour of SFA protective layer in a real trackbed construction. Presented results clearly confirm that the application of SFA "R4 formula" from the Chvaletice Power Plant was a beneficial solution for the protection of subgrade formed by marlite. The protective layer of SFA fulfilled the three following basic assumptions; it prevented the penetration of rainwater onto the subgrade surface, provided a sufficient thermal insulation and increased the load-bearing capacity of the trackbed.

Following general principles must be observed to enhance the bearing capacity of the trackbed by means of stabilized fly ash:

- The suitability of the application of SFA in the trackbed according to results of a geotechnical survey in the planned section of the railway track must be assessed,
- A suitable formula of SFA must be designed based on laboratory tests,
- The preset technological criteria and procedures in the SFA application must be precisely abided.

5 CONCLUSIONS

The article shows findings gained by study of three different materials: recycled crushed concrete aggregate, recycled asphalt pavement material and stabilized fly ash. The feature observed within all three materials was their possible utilization within railway trackbed. The aim was to learn strengths and weaknesses of these materials. Based on these pieces of knowledge gained, the goal was to offer a proposal of proper technological procedures for materials' processing. Adherence to the proposed recommendations enables decrease of risks associated with utilization of these materials in practice, whilst the benefits resulting from their application are preserved.

Laboratory tests of recycled crushed concrete aggregate and recycled asphalt pavement material showed that these materials are, based on observed criteria, suitable for utilization within railway trackbed. Moreover, these materials proved to have some beneficial features compared with natural crushed stone, such as self-cementing properties or better thermal insulating properties.

Regarding the stabilized fly ash, the observations took place on test section as well as within laboratory tests. The SFA proved to have positive effect on the load-bearing capacity of the trackbed as well as on the protection of subgrade against rainwater and freeze.

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