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FACTORS DETERMINING THE INHOMOGENEITY OF RECLAIMED ASPHALT PAVEMENT AND ESTIMATION OF ITS COMPONENTS CONTENT VARIATION PARAMETERS

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Abstract. With a view to saving bitumen and mineral substances and also for the purpose of preventing environmental pollution, the old asphalt pavement (AP) may be milled without increasing the thickness of pavement structure and subjected to hot recycling for reuse in the same or any other location. However, the suitability of reclaimed asphalt pavement (RAP) for reuse depends on its composition (the content and gradation of bitumen) and the properties of its components. Hence, the present study aims at providing a systematic analysis of factors that determine the inhomogeneity of RAP. To this end, RAP samples, taken from RAP being loaded from the milling machine onto the transport means and from RAP stored in the territorial storage facilities of asphalt concrete (AC) plants, were examined in an accredited laboratory to determine, for each sample unit, the composition (the content and gradation of aged soluble bitumen), the content of moisture and the gradation of non-extracted granules. The statistical characteristics showing the actual homogeneity of RAP sampled from different sources were also estimated and analysed. Further, there was elaborated a model for comparing the homogeneity of RAP from different sample sets by the max values of standard deviations in the percentage mass passing the sieves and, based on the experimental data, derived the respective regression equation. The results of the performed comparison showed the absence of any statistically significant difference in terms of homogeneity between the three different RAP sample sets, i.e. RAP-1 sampled from the road, RAP-2 taken from the stockpiles being formed in different locations and RAP-3 obtained from RAP kept stockpiled in an open storage facility. The study was finalized by determining, in line with the Specification of Technical Requirements *TRA ASFALTAS 08*, the max content of RAP allowed for inclusion in a hot mix asphalt (HMA) mixture depending on the actual homogeneity of RAP determined.

Keywords: reclaimed asphalt pavement (RAP), homogeneity, statistical analysis, gradation.

1. Introduction

The use of RAP in road construction in the countries with a developed economy each year acquires an increasingly wider extent. The reclaimed (recyclable) asphalt pavement (RAP), as defined in the document *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Guidelines* of 2001, is an asphalt paving material milled or scraped off an existing bituminous pavement, consisting of aggregate and asphalt binder. RAP is used both in hot and cold recycling. A considerable content of RAP is being added in the production of HMA, too.

The reclaimed (recycled) asphalt concrete (RAC) refers to a hot mix recycled (HMR) mixture produced from the combinations of RAP, new aggregate, asphalt cement binder and possibly either rejuvenators or HMR agents (Shoenberger, Demoss 2005).

Due to the variability of RAP material, experience has generally shown that mixture quality can be more easily controlled by using less than 25% RAP (Asphalt Institute 1994).

As can be seen from the data presented in EAPA (the European Asphalt Pavement Association) information publication *Asphalt in Figures 2006*, the quantity in tons of the available reclaimed asphalt as well as its percentage used in hot and cold recycling and also in producting new hot mix asphalt (HMA) mixtures varies from country to country. However, the statistics for Lithuania is not available at EAPA, as no such information is collected and systematized.

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The survey-based data on the use of milled asphalt concrete (AC) by the Lithuanian road constructing companies were first announced at the International Conference on Environmental Engineering (Mučinis *et al.* 2008). These Figs show that milled or scraped off asphalt granules are being used in HMA only by these companies (accounting for about 50%) which operate asphalt mixing plants (AMP) equipped with additional mechanisms for receiving, transporting and dosing RAP. The total volume of RAP milled in Lithuania during the last few years amounts to about 112 thou tons, approx 80% whereof is being added to HMA in the proportion of up to 20%, as required in the aforementioned *The Specification of Technical Requirements for Automobile Road Asphalt Mixtures "TRA ASFALTAS 08"*, and about 20% is being used in the production of cold mix asphalt mixtures.

The available scientific evidence proves RAP (RAC) to be generally suitable for reuse in road construction despite the fact that in the course of road operation the properties of pavement asphalt undergo major changes brought about by the ageing of bitumen.

Bituminous mixtures obtained from hot recycling of flexible pavements demonstrate similar characteristics to new hot mixtures, as long as the recycled materials are correctly characterized and the mix design is properly done (Pereira *et al.* 2004). The first documented case of hot in-place recycling was completed in the 1930s. The interest in asphalt recycling increased in the 1970s because of the petroleum crisis ant the development of a large scale milling machine in 1975 (Carter, Stroup-Gardiner 2007).

Widyatmoko (2008) demonstrates that the asphalt mixtures containing RAP performed at least similar to, or better than the conventional asphalt materials. However, the actual effect of RAP on the mixture properties and field performance of these mixtures is unknown (Daniel, Lachance 2005; McDaniel, Anderson 2001).

In Daniel and Lachance (2005) have presented and discussed the tension and compression dynamic modulus and the compression creep compliance master curves for a control mixture and mixtures containing 15%, 25%, and 40% of the processed RAP. The addition of 15% RAP increased the stiffness of the mixture and decreased the compliance, as would be expected. This indicates that the mixture containing RAP will be more resistant to permanent deformation and less resistant to fatigue and thermal cracking in the field. Mixtures containing 25% and 40% RAP did not follow the expected trends.

In general, the recycled mix has a greater resistance to rutting than the virgin mix. From field studies, rutting performance of the recycled mix has been found better than that of the virgin mix (Aravind, Das 2007b).

Aravind and Das (2007b) maintain that the cost of construction with a recycled mix could be more economical compared to a virgin mix. The percentage of saving in the present example varied between 12.1% and 54.6% for different mixes.

Central plant HMR is one of the popular techniques adapted for RAP materials. In central plant HMR, RAP intended for recycling is combined with a required quantity of virgin asphalt binder and new aggregates in a hot mix plant, located away from the construction site (Aravind, Das 2007b). HMA recycling refers to the process in which RAP is combined with new or virgin materials to produce HMA mixtures (McDaniel, Anderson 2001).

RAP must be thoroughly heated to the proper temperature for mixing and compaction. It is important to determine the content of moisture in RAP. When determining batch weights for RAP at the plant, the content of moisture in RAP must be accounted for, just as it is for virgin aggregates (McDaniel, Anderson 2001). Baroux (1980) has presented a formula for estimating the temperature of new mineral substances transferring heat to RAP which depends on the temperature of recycled asphalt mixture (RAM), the content of moisture in RAP, their temperature and content in RAM.

The percentage of RAP incorporated in superpave mixtures is dependent not only on the properties of RAP binder, RAP aggregate (e. g. critical temperature, the blend charts of the aged binder and rejuvenator added, RAP gradation etc.), but also on the requirements for superpave mixtures (e.g. volumetric properties, mechanical and performance properties, etc.). Changes in the fractions (e.g. from mesh No. 4 to No. 8 in the study) of RAP incorporated can effectively effect the possible percentage of RAPs (Shen *et al.* 2007).

Because RAP is removed from an old roadway, in addition to the original pavement materials, it may also include patches, chip seals and other maintenance treatments. Base, intermediate and surface courses from the old roadway all get mixed together in the RAP. RAP from several projects is sometimes mixed in a single stockpile, although this mixing is not encouraged (McDaniel, Anderson 2001).

Over the service life of asphalt pavement (AP), the old binder in it gets aged and the aggregate degrades. Further reclamation process may also contribute to the inhomogeneity of the recycled pavement material. The milled material is ready for use, fairly clean and relatively uniform. Consequently, asphalt recycling is a more demanding and qualified task, requiring extra knowledge and experience compared to producing overlays of virgin asphalt (Karlsson, Isacsson 2006).

The variability is to a great extent a question of careful handling of RAP materials. One way to limit the variability of reclaimed material is to consider unwanted impurities of the old road (e.g. road markings, coal tar and soil) and sources of homogeneities such as crack seals and patches. Another way of reducing the variability is to thoroughly mix the reclaimed materials. If the variability is sufficiently low, it should be possible to more accurately modify deficiencies in, for example, aggregate gradation, binder content and stiffness, provided that the proportion of virgin material added is high enough (Karlsson, Isacsson 2006).

There is, however, very little information concerning the characteristics of reclaimed bitumen and how to treat it best for reuse as a binder. Due to the fact that aged AP during the process of hot milling is exposed to high temperatures, such properties of bitumen as penetration and softening point undergo a change. It should be noted that the average percentage decrease in penetration is 17%, comparised with the average decrease in penetration during hot mixing which is 35%. Changes in penetration range from 0 to 32%, and in softening point from 0 to 11% (Stock 1985).

The AP mixture used in Kampur city, India, included virgin bitumen 80/100 with penetration 87.5 dmm and the softening point at 49.5 °C. The examination of two RAP samples taken from the operated pavement revealed a decrease in bitumen penetration down to 26 and 18.5 dmm respectively, whereas the softening point showed an increase up to 69.5 and 78.5 °C respectively (Aravind, Das 2007a).

Widyatmoko (2008) analysed four RAP samples taken from the APs, which had been in use for 9, 7, 6.5 and 3 years respectively. The estimated values of penetration and softening point varied from 7 to 16 dmm and from 70 to 87.2 °C respectively, indicating severely age-hardened bituminous binder. The results also show large variations in temperature susceptibility, as indicated by penetration index (PI) values ranging from +0.5 to +1.7. Fresh, unaged bitumen for road pavements would generally have a PI in the range from −1.5 to +0.7, typically close to 0. It is also known that the temperature susceptibility of bitumen reduces as bitumen hardens (such as due to ageing).

The physical and chemical properties of aged RAP binder may be recovered using the rejuvenating or the softening agents. The interaction of these agents with the binder is a complicated dynamic process (Doh *et al.* 2008; Kim *et al.* 2006; Shu *et al.* 2008; Stroup-Gardiner, Wagner 1999).

Huang *et al.* (2005) carried out a laboratory study in which the blending process of RAP with virgin HMA mixture was analyzed through controlled experiments. One type of screened RAP was blended with virgin (new) coarse aggregate at different percentages. A blended mixture containing 20% of screened RAP was subjected to staged extraction and recovery. The result from this experiment indicated that only a small portion of aged bitumen in RAP actually participated in the remixing process; other portions formed a stiff coating around RAP aggregates, and RAP functionally acted as "composite black rock". Inclusion of RAP in HMA mixtures had the positive effect on forming a favourable layered system to enhance the pavement performance.

According *TRA ASFALTAS 08,* the inhomogeneity of RAP represents one of the major factors for its limited use in the production of recycled HMA. The effect of RAP inhomogeneity on the variability of recycled HMA gradation may be estimated by applying the technique of stochastic modelling (Sivilevičius, Vislavičius 2008) or the method of linear programming (Aravind, Das 2007a).

The objective of the present study is to overview the available scientific sources on the subject and, based on the findings of this overview, to systematize the factors contributing to the inhomogeneity of RAP and its increase and investigate experimentally the actual homogeneity of RAP milled in Lithuania by the way of estimating the statistic characteristics of RAP gradation, bitumen content and moisture content which determine the max content of RAP allowed for inclusion into HMA being recycled.

2. Factors determining the homogeneity of RAP

The homogeneity of AP to be reclaimed depends on different factors that may be grouped by three stages of pavement life-cycle, as shown in Table 1.

The initial inhomogeneity of a newly laid AP manifests itself as the lack of uniformity in the distribution of bitumen content and its gradation across the entire area of pavement. This type of inhomogeneity occurs due to systemic and random errors during the technological process of HMA production in the AMP (Petkevičius, Sivilevičius 2008). A further decrease in the homogeneity of produced HMA occurs upon keeping the HMA in a storage silo, loading it onto the truck and then to the acceptance hopper of the asphalt paver and also upon placing and compacting it with the asphalt paver (Karalevičius, Sivilevičius 2005). Generally, the AP is strengthened by adding a course of geogride (Laurinavičius, Oginskas 2006; Vaitkus *et al.* 2007), which upon being milled along the entire length or at certain areas of the pavement passes through the RAP, hence affecting its homogeneity.

In the course of operation, the AP is exposed to the effects of climate and weather and the axial load of transport means and this leads to the decrease in the value of strength coefficient, based on which the required type of repair works is determined (Butkevičius *et al.* 2007). This variable impact contributes to the wear of AP and the occurrence of damages on the pavement surface course such as cracks, pot-holes, ruts, waves and crumbling) (Haryanto, Takahashi 2007). The elimination of these defects requires the use of additional bituminous materials (Fig. 1).

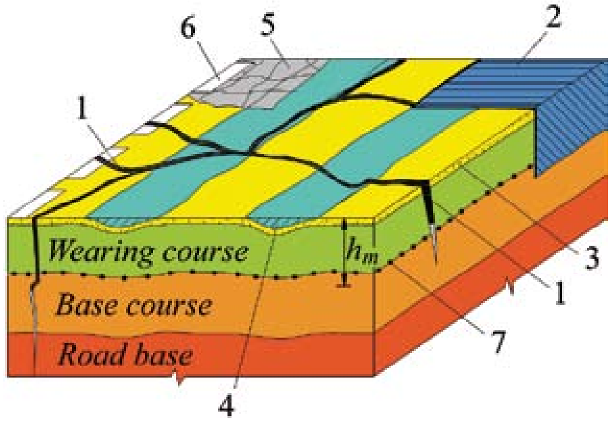

Fig. 1. Fragment showing the distribution of additional materials used for increasing the homogeneity of RAP, improving its surface texture and repairing damages: 1 – paste, emulsified asphalt or bitumen for filling cracks; 2 – asphalt mixture and bitumen priming for filling pot-holes; 3 – bitumen binder and mineral aggregates of surface coating; 4 – asphalt mix or slime for filling ruttings; 5 – layer of emulsified asphalt and filler for sealing the net of cracks; 6 – horizontal pavement marking materials; 7 – geogrid or geotextile with emulsified asphalt; h_m– average depth of milling (normally from 40 to 100 mm)

Table 1. Factors determining the inhomogeneity of milled RAP granules

Pavement life-cycle stages	Factors
AP construction	Inhomogeneity of produced HMA mixture due to variability of gradation of unused mineral substances, systemic and random errors occurring while dosing bitumen and these mineral substances and insufficient blending of all components upon mixing.
	Inhomogeneity of HMA mixture used for constructing road pavement due to variation of its properties upon storage, handling, transportation and construction.
	Inhomogeneity of HMA mixture used for constructing road pavement due to variation of its properties upon compacting.
	Insertion of geogride or geotextile between asphalt surface and bin courses, which upon being milled will pass through the granules of RAP.
AP maintenance and repair	Change of bitumen properties with ageing due to the impact of oxidation, solar radiation, temperature, traffic load, fuel, oil or antifreeze spills and salts.
	Change of AP gradation due to decomposition and wear of grains on pavement surface layer.
	Local use of additional materials for filling cracks (bitumen, paste, emulsified asphalt) and pot-holes (coating, hot and cold mix asphalt mixture) on the AP damaged by deformations.
	Solid use of additional materials for surface coating (slimes, single- or double-layer surface lining, thin layer of asphalt) and filling ruttings on the AP damaged by deformations.
	Temporary filling of pot-holes generally formed on the road pavement in winter season, in particular on street roads, with non-bituminous materials (concrete tiles, debris of ceramic or clay tiles), which upon being milled or crumbled pass through the grains of RAP.
	Uneven distribution on the surface area of horizontal road marking materials which pass through RAP.
Cold milling of AP or crumbling of debris	Removal of pavement wearing course due to unevenness and improper cant of pavement surface, enabling the materials from deeper asphalt courses and road base to pass through the granules of RAP, hence causing variation in their percentage mass.
	Uneven crumbling of grains, when asphalt mixture crumbles via gaskets particles and not through the matrix bitumen, depending on the technology of milling, debris crumbling and sifting and on the properties and temperature of AP layer.
	Uneven homogenising of RAP kept temporarily stockpiled at the road due to technologies used for handling, transporting and storing RAP milled from different segments of AP.
	Technology for transporting, unloading and homogenising, at open or covered storage facility of AC plant, of RAP stockpiled at the road directly from the milling machine transporter or using a loader and conditions of its storage determining its segregational homogeneity.

As a rule, these bitumen materials are either applied in the form of a solid layer of fixed thickness or inserted locally to fill the random cracks and pot-holes or regularly running ruts. The consumption of these materials per unit of AP area varies and depends on the order, in which these damages are distributed, and their dimensions such as depth, width or length. However, the properties of materials applied for eliminating pavement damages in the course of time undergo changes, too. Therefore, upon the expiry of AP operation period, the componential composition of the reclaimable layer appears to be substantially different from that of a virgin AP showing an increase in variation, which happens basically due to uneven process and different degree of its degradation.

The same areas of the AP surface coarse being milled could have been already subjected to hot in-place recycling during the previous repair works using repaving, remixing, remix plus or remix compact technologies, sometimes referred to as "surface recycling" (Karlsson, Isacsson 2006; Sivilevičius 1998). The properties of RAP that had been previously subjected to hot in-place recycling changed, compared to a virgin HMA pavement, and this happened not only due to the addition of bituminous materials or the use of additional HMA mixture of different composition and properties, but also due to the ageing of bitumen occurring during the process of HMA heating with infrared radiation.

When the course (or courses) of RAP is being milled or scraped off and subsequently crumbled, RAP, depending on the depth of the course (h_m), is penetrated by a different amount of repair materials and asphalt from the surface and/or bin courses of pavement. Upon the removal of aged AP, a certain portion of grains gets fragmented and crumbles. While crumbling off the loading transporter of the milling machine, RAP becomes partially homogenised. This is also when the segregational inhomogeneity of RAP occurs.

The average content of bitumen (%) in milled RAP granules ($\overline{B}_{RAP}$) is generally higher than in virgin HMA pavement ($\overline{B}_{HMA}$), i.e. $\overline{B}_{RAP} > \overline{B}_{HMA}$. The increase of bitumen content in RAP by an average value $\overline{B}_{MRM}$ is explained by a higher average content per mass unit of road pavement of bitumen materials consumed during the maintenance and repair works (viscous road bitumen, polymer modified bitumen, emulsified asphalt or polymer modified emulsion):

$$\overline{B}_{RAP} = \overline{B}_{HMA} + \overline{B}_{MRM}. \quad (1)$$

The content (percentage of mass) of binder over 100% aggregate in the AC of pavement wearing course shall range from 5.2% for AC 0/16 S-V and 0/16-V to 8.0% aggregate for AC 0/5-V by *Construction Recommendations R 35-01*. For coating the road with a single layer of crushed stone processed by 1.2–1.5% bitumen, the total amount of bitumen required increases in average by 7.4% and makes up 8.6–8.9%. If it is required to cover the road with a double layer, this extra amount makes up in average 7.7% meaning that the total amount of bitumen required increases to 8.9–9.2%. For single treatment of pavement with crushed stone not subjected to processing by bitumen, the total content of bitumen required averages to 9.4%, and in case of double treatment it makes up on average 9.5%. For single treatment of road surface with cationic or polymer modified emulsified asphalt susceptible to fast decomposition, the extra demand for emulsified asphalt in average ranges from 8.6% to 14.5% and, in case of a double treatment, it makes up 12.9%.

The variation of RAP gradation compared to a virgin HMA pavement depends on the content of materials consumed for eliminating pot-holes, treating the surface and producing slime and on the size of their fractions. If the quantity of any single or several adjacent narrow fractions in repair materials is high, the section of RAP gradation broken-line appears to be steeper (the difference between the percentage mass passing the adjacent sieves increases).

RAP removed from different roads and streets is delivered to the territorial storage facility of the AMP and stored there in a single stockpile formed without any sorting. RAP of different origin and composition collected in a single stockpile can hardly get homogenised, therefore its inhomogeneity is determined by an aggregate effect of all factors presented in Table 1.

The homogeneity (inhomogeneity) of RAP is estimated based on the variation parameters of each selected quality indicator: variance σ^2 or standard deviation σ. The total variance of ready-for-use RAP i component content or its property indicator ($\sigma^2_{i_{RAP}}$) is calculated by the following additive model:

$$\sigma^2_{i_{RAP}} = \sigma^2_{i_1} + \sigma^2_{i_2} + \sigma^2_{i_3}, \quad (2)$$

where $\sigma^2_{i_1}$ stands for the variance of i component in the new AP; $\sigma^2_{i_2}$ refers to the variance of i component increased due to the use of additional repair materials, changing the componential structure of asphalt, and due to the ageing of bitumen at the end of AP operation period; $\sigma^2_{i_3}$ means the variance of i component increased due to the fact that RAP removed from pavements of different roads and streets is stored unsorted in a single stockpile and also due to its segregation.

The actual homogeneity of ready-for-use RAP added in producing HMA mixture depends on all factors grouped and presented in Table 1, the actual parameters whereof are of a stochastic nature and may substantially vary. Therefore, the actual values for the content of RAP components as well as for the variances of their properties $\sigma^2_{i_{RAP}}$ and standard deviations $\sigma_{i_{RAP}}$ will be determined based on the experimental data rather than using theoretical models.

3. Research into the homogeneity of RAP used in Lithuania

3.1. Research methodology

For determining the actual homogeneity of RAP and its variation due to segregation and mixing processes, occurring when RAP is being loaded on the truck, transported, releases from the truck bodywork and collected using a wheeled loader into a stockpile, RAP was sampled from the following three sources:

– RAP-1 taken from the road, to be more specific, from the road section containing RAP granules spilled while RAP was crumbling from the transporter loader of the milling machine to the bodywork (sample size $n = 9$);

– RAP-2 obtained from four stockpiles of milled RAP started being formed on the territory of different asphalt mixing plants (sample size $n = 21$);

– RAP-3 sampled at random from the top of RAP stockpile formed at the open storage facility of an AMP (sample size $n = 43$).

The sample units were sized in such a way as to enable the determination of RAP gradation, the content and properties of aged soluble bitumen and also the formation of Marshall samples with different content of RAP subsequently tested to determine the dependence of recycled HMA mixture properties on the content of RAP.

Next, each sample unit was reduced to the mass required to enable the extraction of bitumen (0.5–1.0 kg). The aged soluble bitumen separated in *Infratest 20-1100* model automatic binder extraction machine using trichloroethylene solvent was further tested to determine its standard properties such as penetration, softening point, breaking point, penetration index, dynamic viscosity, kinematic viscosity and density, which will be discussed in the follow papers. The aggregate was screened through a set of standard laboratory sieves. Sample units from RAP-1 and RAP-2 sample sets were taken and tested in 2007–2008, i.e. at the time when the *Construction Recommendations R 35-01* prescribing the use of 0.09 mm, 0.25 mm, 0.71 mm. 2 mm. 5 mm, 8 mm, 11.2 mm, 16 mm and 22.4 mm laboratory sieves were in force. In 2009, these *Recommendations* were replaced by the *TRA ASFALTAS 08* currently in force in Lithuania, therefore, the sample units from RAP-3 sample set were screened after the extraction of bitumen using 0.063 mm, 0.125 mm, 0.25 mm, 0.5 mm, 1 mm, 2 mm, 5.6 mm, 8 mm, 11.2 mm, 16 mm and 22.4 mm standard laboratory sieves. This set of sieves was also used for screening 15 samples with non-extracted granules from RAP-3 sample set; hence screened samples enabled us to determine the gradation of granules. For each of the 43 RAP-3 sample units, prior to the extraction of granules, the content of moisture was determined.

The next step included the estimation of statistical characteristics for the sample units of the 3 sample sets (RAP-1, RAP-2, RAP-3) through the use of SPSS software data processing package. The characteristics of data variation (variance and standard deviation) were used for determining the homogeneity of RAP by bitumen content, gradation, size of granules and moisture content. However, the *SPSS* program does not perform the check for the presence of outliers, i.e. sampling observations which differ in value from the rest to the extent, making it reasonable to assume that they belong to another population or that a measuring error has occurred. After the exclusion of outliers (if any had been identified), the adjusted statistical characteristics were estimated, too.

3.2. The size of RAP granules and the content of water and bitumen in them

The size of RAP granules used in the production of HMA mixture shall be such as to enable their melting at high temperature transferred by overheated mineral substances or by gases circulating in the additional drying drum designed for drying and heating these mineral substances. To this end, it was important to reduce the max size of RAP granules which depends on the properties of AP being milled, ambient temperature, technical parameters of the milling machine, wear degree of rotating drum cutters and the technology of milling (the depth of milling and the travel speed of the milling machine). As required under *R 35-01*, the max size of milled RAP granules must not exceed the size of max diameter grains in HMA to be recycled by more than 1.4 times.

The gradation of granules determined for 15 samples of RAP-3 set before the extraction of bitumen (Fig. 2) shows that the milling machine is able to crush the old AP into granules smaller than 22.4 or 31.5 mm in size. The share of granules smaller than 2 mm in average makes up about 25% (max 33%, min 13%). After the extraction of RAP-3 granules, the share of granules smaller than 2 mm in size was in average 51.5%. The max standard deviation s_p = 10.9% was observed with respect to the content of granules sifted through an 8 mm sieve with the average percentage mass passing the sieve $\overline{p} = 62\%$. In RAP granules remained unfragmented upon milling, a certain content of mineral filler and fine aggregate was found. Being exposed to a high temperature in the AMP, smaller size RAP granules due to melting of binder disintegrate faster hence facilitating the replacement of aged bitumen.

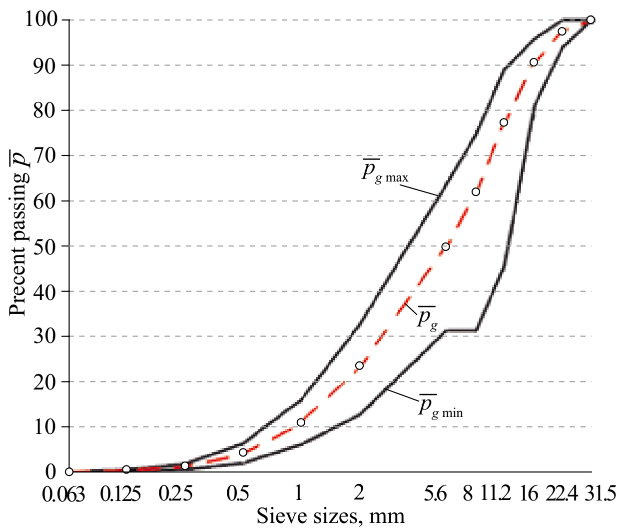

Fig. 2. Gradation of non-extracted granules of milled AP being recycled (RAP-3) (sample size n = 15)

In frequent cases, milled RAP granules may contain precipitation water, filtered upon their transportation or storage, which must be evaporated under the impact of high temperature during the technological process of recycling. The higher the content of moisture in RAP granules, the more heat power is required for dewatering granules.

The findings of research presented in Table 2 show that 43 sample units taken from the top of RAP-3 open stockpile contained in average 3.4% of moisture. The content of moisture found in RAP granules varied from min 0.7% to max 6.5% (range 5.8%). The standard deviation of moisture content in RAP granules $s_{w_{RAP}} = 0.93\%$ shows that its distribution within a stockpile is not uniform. The variation of moisture content in stockpiled RAP depends on the intensity and duration of precipitation, water evaporation and infiltration to the deeper layers of the stockpile and on the humidity of delivered and stockpiled RAP.

Baroux (1980) presented the following empirical formula for estimating the required temperature for the mixture of mineral substances crumbling from the drying drum of the AMP or the fractions of dosed and sieved hot aggregate, transferring heat to cold and humid RAP granules:

$$T_{h.a} = \frac{T_{HMA} - M_{RAP} \times T_{RAP}}{1 - M_{RAP}} + W_{RAP} \frac{4M_{RAP}}{1 - M_{RAP}} \left(637 - T_{RAP}\right), \quad (3)$$

where $T_{h.a}$ – temperature of hot aggregate, °C; T_{HMA} – required temperature of recycled HMA mixture, °C; M_{RAP} – ratio of RAP granules mass in recycled HMA mixture, in decimal fractions; T_{RAP} – temperature of RAP granules, °C; W_{RAP} – content of moisture in RAP granules, in units.

For instance, if the content of RAP granules (M_{RAP} = 0.2) with the temperature T_{RAP} = 18°C and the min 0.7% content of moisture (W_{RAP} = 0.007) makes up 20%, the $T_{h.a}$ due to the need of dewatering must be increased by 4.3°C; when the content of moisture in such granules is max, i.e. 6.5% (W_{RAP} = 0.065), $T_{h.a}$ must be increased by 40.2°C (the range 35.9°C). When RAP granules have the average 3.4% content of moisture, $T_{h.a}$ shall be increased by 21.0°C.

RAP must be homogenous. The standard deviation of bitumen content in 5 sample units (n = 5) shall not exceed 0.6% for ≤ 10% RAP and 0.5% for 11–30% RAP, as required under *R 35-01*. As seen from the test findings in Table 2, sufficient homogeneity by standard deviation of bitumen content was observed only in RAP-3 (s = 0.35%). One sample unit from RAP-2 set appeared to contain as much

Table 2. Statistical indicators for moisture content in milled RAP granules and for content of old soluble bitumen binding RAP grains

Statistical indicators	Moisture content in milled granules (RAP-3), % (n = 43)	Content of soluble bitumen, % over 100% aggregate			
		RAP-3, stored in an open stockpile (n = 43)	RAP-1, taken upon milling from the road (n = 9)	RAP-2, stored in open stockpiles started being formed at 4 different facilities	
				(n = 21)	n = 20 without outliers
Min	0.70	3.66	4.39	4.99	4.99
Max	6.50	5.43	6.58	22.31	8.27
Range	5.80	1.77	2.22	17.32	3.28
Mean	3.40	4.85	5.78	6.98	6.22
Variation	0.87	0.12	0.45	13.01	0.71
Std. deviation	0.93	0.35	0.67	3.61	0.84
Skewness	0.09	–0.85	-1.05	4.20	0.64
Kurtosis	3.51	1.92	1.91	18.55	0.11

as 22.31% of bitumen which was subsequently assigned to outliers and excluded; therefore, the adjusted statistical characteristics were estimated using the sample of n = 20 size. RAP-1 and RAP-2 do not satisfy the applicable standards in terms of homogeneity (s = 0.67% and s = 0.84% respectively). Therefore the content of such RAP to be added while producing recycled HMA mixture shall be less than 10%.

The empirical coefficients of distribution, skewness (A) and kurtosis (E) for moisture and bitumen content in RAP samples (Table 2) are lower (except for RAP-2 when n = 21) than the values of their standard deviation s_A and s_E, which depend on the sample size. The distribution may be assumed as being within the normal range when $|A| < 3s_A$ and $|E| < 5s_E$. When n = 9, $3s_A$ = 2.15 and $5s_E$ = 7.00, when n = 20, $3s_A$ = 1.54 and $5s_E$ = 4.96, when n = 43, $3s_A$ = 1.08 and $5s_E$ = 3.54. Hence it may be reasonably concluded that the content of moisture and bitumen in RAP follows the pattern of a normal distribution.

3.3. Gradation of milled RAP and its granules

The gradation of RAP or a virgin HMA mixture is determined from the curve drawn for the total mass percentage passing all sieves. The variation of gradation is expressed in terms of standard deviations in percentage mass passing the sieves (s_p), the values whereof depend on the homogeneity and the arithmetic average of mass percentage passing the sieves ($\overline{p}$).

Theoretically, the highest standard deviation s_p is observed with respect to the content of those grains or particles, making up 50% of the mineral substance mass. Normally, however, the max value of s_p (curve $s_p = f(\overline{p})$ peak) is shifted rightwards and shows correspondence to $\overline{p}$ of about 60 or 70% (Sivilevičius 2003). The correlation $s_p = f(\overline{p})$ obtained, based on the research of gradation in individual samples, makes it possible to measure the homogeneity of RAP taking no account of the mesh size (the size of laboratory sieves) and compare it with the homogeneity of other RAP. The homogeneity of RAP or other HMA mixture is generally determined based on the max value of s_p derived from the regression equation. Knowing that the s_p of percentage mass passing the sieves s_p = 0%, when the average percentage passing $\overline{p} = 0\%$ and $\overline{p} = 100\%$, it was possible to apply the following regression model:

$$s_p = \sqrt{a \times \overline{p}^b \times (100 - \overline{p})^c}, \quad (4)$$

where a, b, c – the respective unknown parameters of the model determining the shape of the curve and its asymmetry (the shift of peak position).

The experimental statistical data for RAP-1, RAP-2, RAP-3 gradation were used for obtaining RAP homogeneity regression equation $s_p = f(\overline{p})$ and their determination coefficients R^2:

– RAP-1 sampled directly from the pavement of road being milled (n = 9)

$$s_p = \sqrt{2.28 \times 10^{-5} \times \overline{p}^{2.385} (100 - \overline{p})^{1.219}}, R^2 = 0.990; \quad (5)$$

– RAP-2 sampled from open stockpiles started to be formed in 4 different facilities of an AMP (n = 21)

$$s_p = \sqrt{2.32 \times 10^{-5} \times \overline{p}^{2.558} (100 - \overline{p})^{1.165}}, R^2 = 0.954; \quad (6)$$

– RAP-3 sampled from a stockpile of material prepared for recycling kept at the open storage facility of an AMP (n = 43)

$$s_p = \sqrt{2.81 \times 10^{-5} \times \overline{p}^{2.587} (100 - \overline{p})^{1.041}}, R^2 = 0.993; \quad (7)$$

– RAP_g-3 sampled from non-extracted granules (n = 15) selected at random from RAP-3 stockpile samples n = 43

$$s_p = \sqrt{5.72 \times 10^{-5} \times \overline{p}^{2.183} (100 - \overline{p})^{1.508}}, R^2 = 0.975. \quad (8)$$

The fact that the values of determination coefficients R^2 approx to 1 shows that s_p by more than 95% is determined by the variation in the $\bar{p}$ Therefore, regression Eqs (5)–(8) may be reasonably deemed reliable. Hence, the ordinates of curves estimated based on these Eq (Figs 3, 4) showing the correlation between the gradation characteristics of each RAP sample may be used for measuring the homogeneity of RAP sampled from different sources.

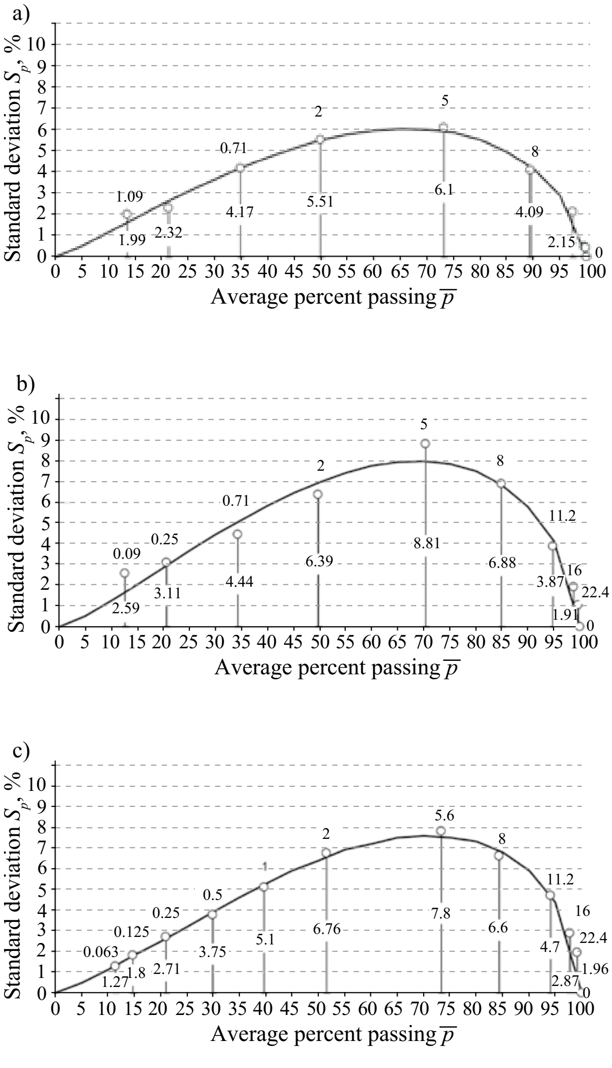

Fig. 3. Correlation between the parameters of milled RAP aggregate gradation variation (s_p) and position ($\bar{p}$) determined for the following samples: a – RAP-1; b – RAP-2, c – RAP-3

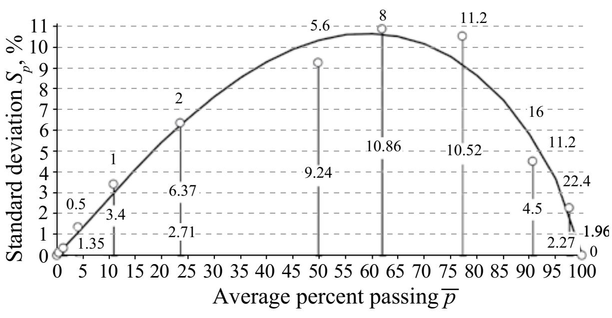

Fig. 4. Correlation between the parameters of RAP-3 non-extracted granules gradation variation (s_p) and position ($\bar{p}$)

RAP-1 ($s_{p,\max}$ = 6.1%, $\bar{p} \approx 65\%$ when) appeared to have the highest degree of homogeneity (Fig. 3), the average homogeneity was observed with respect to RAP-3 ($s_{p,\max}$ = 7.6%, $\bar{p} \approx 70\%$ when) and RAP-2 was found as showing the lowest degree of homogeneity ($s_{p,\max}$ = 8.0%, when $\bar{p} \approx 70\%$). The inhomogeneity ($s_{p,\max}$ = 10.6%, when $\bar{p} \approx 65\%$) of non-extracted granules RAP$_g$-3 (Fig. 4) depends on the technology of milling rather than on the variation of components content in the aged asphalt, therefore, it has no major influence on the performance of recycled HMA mixture.

The check for the presence of any statistically significant difference in s_p of normally distributed sieved grains or particles of RAP samples, taken from different sources, was performed by applying the Bartlett's criterion. The zero hypothesis on the uniformity of variances was verified checking it against the estimated statistic

$$B=\frac{E}{C}=\frac{2.303\times\left[k\times\lg\bar{s}_p^2-\sum_{i-1}^{l}k_i\times\lg s_{p_i}^2\right]}{1+\frac{1}{3(l-1)}\times\left[\sum_{i=1}^{l}\frac{1}{k_i}-\frac{1}{k}\right]}, \qquad (9)$$

where l – the number of RAP samples analyzed (in this particular case, l = 3); $k_i = n_1 - 1$– the number of freedom degrees; n_i– the size of i-sample; $k=\sum_{i=1}^{l}k_i$; $s_{p_i}^2$ – the max-value of RAP i-sample shift variance derived from regression Eqs (5)–(7); $\bar{s}_p^2$ – the average of max variances estimated for all RAP sample sets

$$\bar{s}_p^2=\frac{\sum_{i=1}^{l}k_i\times s_{p_i}^2}{k}. \qquad (10)$$

The random variante B, when the zero hypothesis is satisfied, is distributed approx as χ^2 with l - 1 degree of freedom, provided that all $k_i > 2$. When $B > \chi_{kr}^2$, the zero hypothesis is excluded (variances $s_{p_i}^2$ differ), and when $B > \chi_{kr}^2$, the variances $s_{p_i}^2$ may be assumed as being uniform.

The statistic B = 0.50 derived from the max values of s_{p_i} in the percentage mass of RAP-1, RAP-2 and RAP-3 aggregate passing the sieves (6.1%, 8.0%, 7.6% respectively) using Eq (9) appears to be considerably lower than $\chi_{kr}^2(0.05;\ 3-1)=5.99$. Therefore, given the assumed level of significance α = 0.05, the 3 sets of RAP samples may be reasonably considered as being of uniform homogeneity irrespective of the source of sampling. The average $\bar{s}_p = 7.56\%$ of max s_{p_i} for the three sample sets shows the average homogeneity by aggregate gradation of RAP used in Lithuania; and therefore it may be applied for prediction in designing the composition of recycled HMA mixture.

4. Most allowed content of RAP in recycled HMA

Under the existing Lithuanian standards *LST EN 13108* (part 1 – part 7), adopted in line with the European requirements, the inclusion of reclaimed asphalt (RA) in HMA mixtures being produced is allowed. *TRA ASFALTAS 08* drafted in compliance with the above-mentioned standards requires that the max allowed content of RAP K_i should be calculated according to Eqs (11) and (12) taking into account the homogeneity of RAP. Such a homogeneity is determined by the range of indicators for individual properties (a_i). K_i shall be computed by the general permisible deviations $N_{adm,i}$ depending on the property of RAP and the type of recycled HMA mixture (Table 3):

$$K_i = \frac{0.50 N_{adm,i}}{a_i} \times 100 \quad (11)$$

or

$$K_i = \frac{0.33 N_{adm,i}}{a_i} \times 100, \quad (12)$$

where a_i – the range between the max $x_{i,\max}$ and the min $x_{i,\min}$ values of RAP *i*-property indicator estimated for the sample (min sample size $n = 5$):

$$a_i = x_{i\max} - x_{i\min}. \quad (13)$$

With respect to all properties of base and wearing-base course mixtures, Eq (11) shall apply. It shall be also applied for the softening point of bin course and surface course mixtures. With respect to all other properties, Eq (12) shall apply.

The experimentally determined most content of RAP (mass %) allowed for proportion in recycled HMA mixtures corresponding to the actual homogeneity by the content of individual components of RAP milled in Lithuania is in Table 4.

The value K_i, estimated for each property of RAP, varies in different samples. The lowest most content of tested RAP, allowed for proportion in recycled HMA, was determined for RAP homogeneous by the content of bitumen (RAP-2), for RAP homogenous by the content of fine aggregate (RAP-3), it was somewhat higher; and for RAP homogeneous by the content of filler (RAP-2), it appeared to be the highest. For increasing the most content of RAP, allowed for proportion into HMA, RAP must be homogenised.

5. Conclusions

The analysis of studies performed abroad has suggested that the courses of AP being exposed to the effects of climate and weather factors and the load generated by transport means at some point of their service life ceases satisfying the applicable requirements and therefore need to be strengthened, reconstructed or reclaimed. The unsuitability of RAP for reuse is basically determined by the irreversible changes in the properties of bitumen due to its ageing.

The inhomogeneity of RAP depends on the factors of the three stages of road pavement life-cycle, i.e. on the technologies applied for AP construction, repair, maintenance and destruction. Bituminous materials consumed for repairing damages on the wearing course of the road pavement accumulate there and distribute according to the stochastic frequency and size of damages. Having passed through milled RAP, these materials, acting as softening or rejuvenating agents, increase the content of bitumen in RAP and change its properties. The uneven distribution of damages and materials used for their repair "passes down" to RAP, hence affecting its homogeneity. Very limited practical possibilities for homogenising milled RAP and the processes of their segregation during loading, transportation and stockpiling in the majority of cases fail to increase the homogeneity of RAP used in the production of recycled HMA.

According to the max size of granules ($d_{RAP,\max}$ = 32 mm), ready-for-use RAP proves to be suitable for inclusion into the HMA being recycled. The content of moisture in RAP-3 kept in an open stockpile varied from 0.7% to 6.5% (range 5.8%) and averaged to 3.4%. The standard deviation for RAP moisture content (0.93%) shows the uneven distribution of water content within the stockpile, which means that for its evaporation there will be required an extra amount of varying heat transferred by the overheated mineral aggregates.

The variability of bitumen content in RAP from all samples sets determined, based on the values of standard deviations, shows that due to uneven distribution of bituminous repair materials on the road pavement it is always larger (s = 0.67% RAP-1, s = 0.84% RAP-2 without outliers, s = 0.35% RAP-3) than the variability of bitumen content in a new AP. Some samples of RAP, which may show an unusually high content of bitumen, statistically shall be classified as outliers.

If RAP aggregate had been screened through a set of sieves with different size meshes, as required under the na-

Table 3. General permissible deviations $N_{adm,i}$ for the gradation of particle of RAP granules (constant coefficients)

RAP component	For mixtures	
	of surface, bin and wearing-base courses	of road base course
Bitumen	1.0	1.2
Filler (< 0.063 mm)	6.0	10.0
Fine aggregate (0.063–2 mm)	16.0	16.0
Coarse aggregate (> 2 mm)	16.0	18.0

Table 4. The most content of RAP (percentage mass) allowed for proportion in recycled HMA mixtures corresponding to RAP homogeneity by its componential structure and the type of asphalt mixture

RAP component	Sample	Experimentally determined value, mass %			Estimated % of RAP mass K_i in recycled HMA mixtures used in		
		$x_{i,\max}$	$x_{i,\min}$	range a_i	road base courses; Eq (11), $N_{adm,i}$ column 2	wearing-base courses; Eq (11), $N_{adm,i}$ column1	bin and surface courses; Eq (12), $N_{adm,i}$ column 1
Bitumen	RAP-1	6.58	4.39	2.19	27.4	22.8	15.1
	RAP-2	8.22	4.99	3.23	18.6	15.5	10.2
	RAP-3	5.43	3.66	1.77	33.9	28.2	18.6
Filler (< 0.063 mm)	RAP-1	17.1	10.8	6.3	79.4	47.6	31.4
	RAP-2	17.5	7.8	9.7	51.5	30.9	20.4
	RAP-3	14.2	8.4	5.8	86.2	51.7	34.1
Fine aggregate (0.063–2 mm)	RAP-1	45.1	30.1	15.0	53.3	53.3	35.2
	RAP-2	44.9	25.0	19.9	40.2	40.2	26.5
	RAP-3	52.1	19.1	33.0	24.2	24.2	16.0
Coarse aggregate (> 2 mm)	RAP-1	56.5	41.7	14.8	60.8	54.0	35.7
	RAP-2	63.6	40.6	23.0	39.1	34.8	23.0
	RAP-3	70.9	33.7	37.2	24.2	21.5	14.2

tional standards of individual countries, for the percentage mass passing the sieves there would have been obtained different standard deviations, yet the correlative dependence of gradation variation parameters (s_p value) on the parameters of position ($\overline{p}$) would have been the same. This close correlative dependence of s_p on $\overline{p}$ is evidenced by the coefficients of determination R^2, as their value, ranging from 0.954 to 0.993, approx to 1. Therefore, the model for estimating the homogeneity of RAP by the $s_{p,max}$ of mass percentage passing the sieves, the value whereof is derived from the regression equation, proves to be universal. Based on this model, the homogeneity of RAP of different granule size, grade and type and RAP sifted through different sets of laboratory, sieves can be compared.

The homogeneity of all three RAP sample sets determined by of comparing the max variances in the gradation of mass percentage passing the sieves at the significance level α = 0.05 against the Bartlett's criterion ($s_{p,\max}$ = 6.1% RAP-1, $s_{p,\max}$ = 7.6% RAP-3, $s_{p,\max}$ = 8.0% RAP-2) shows that the source of RAP sampling has very little impact on the final results.

The most content of RAP allowed for inclusion in recycled HMA mixtures may vary depending on the type of its homogeneity. The lowest most content allowed for proportion is determined for RAP homogeneous by the content of bitumen (e.g., only 10.2–18.6% of such RAP may be proportion into the mixtures of surface and bin courses). For RAP homogeneous by the content of coarse aggregate and by fine aggregate, the content allowed for inclusion in HMA of the same type may vary from 14.2 to 35.7% and from 16.0 to 35.2% respectively. The max allowable content ranging from 20.4 to 34.1% is determined for RAP homogeneous by the content of filler.

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