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USE OF AGGREGATE FROM GLACIER DEPOSITS IN HIGH-TRAFFIC ASPHALT PAVEMENTS: A POLISH EXPERIENCE

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Abstract. An on-going Polish nation-wide program of construction and re-construction of roads requires a large quantity of aggregate. Aggregate from consolidated rock formations (for the road application) are produced only in the south-west part of Poland. The cost of material transportation from the south to the north or central part of Poland is often higher than the material value itself. In the eastern part of Poland aggregate from glacial deposits was shown to yield high performance crushed aggregate for construction purposes, although they are not widely used in hot mix asphalt (HMA) construction currently. In this paper results from the tests conducted on HMA surface and base layers using aggregate from glacial deposits are presented. HMA samples, asphalt concrete and stone mastic asphalt were designed and tested for rutting. In addition, the cost analysis was conducted in order to compare construction cost for HMA with aggregates from various regions and geological formations. Test results proved that aggregates from the glacier deposits could, indeed, be used for the structural layers in the asphalt pavements.

Keywords: hot mix asphalt (HMA), stone mastic asphalt (SMA), aggregate, local material, rutting, cost analysis.

1. Introduction

Currently, Poland is the European leader in terms of a number of pavement construction projects. An on-going construction and re-construction program includes works on various types of roads: from local to the trans-European corridors. Construction needs are keeping with the growing Polish economical situation and European transportation infrastructure requirements (e.g., higher axle loads).

In hot mix asphalt (HMA) mixes binder content is about 4–6%; proper asphalt film thickness covering aggregate particles (typically about 9–10 μm) plays a leading role for the durability assurance of the asphalt pavement (Sengoz, Topal 2007). Since aggregate content creates about of 94–96% of the HMA, it is especially important to have a properly selected optimal aggregate blend (Piłat, Radziszewski 2010) of high quality aggregate (Abo-Qudais, Al-Shweily 2007; Bulevičius *et al.* 2011). Proper asphalt mixing plant operation is also a key issue for the HMA quality (Sivilevičius 2011). Polish road construction program can be endangered due to the limited access to the high quality crushed aggregates from the consolidated rocks. Up to now, due to the limited number of road construction projects, aggregates crushed from the magmatic rocks (typically, basalt), which are present only in the southwestern part of Poland, were mainly used for the HMA production.

Given the current demand for aggregate due to the increase in pavement construction, the aggregate quarries located mainly in south of Poland which produce aggregate from consolidated rock will be unable to provide the desired amount of material. In addition, aggregate hauling costs to the central or north region of the country are significant (distances of about 500–800 km). Due to these reasons, it is desirable that crushed aggregates from the glacier deposits, which are found in large quantities in northeastern part of Poland, be used for the production of HMA.

Poland, addressing the recommendations of the European Union (EU) for mineral resources, tries to provide dependable access to these resources. One of the goals in the aggregate industry in EU is a long-term program for the adoption of local aggregate resources. Usage of the aggregate from the glacier formation meets those goals.

2. Problem statement and objectives

Based on the literature review, authors' personal experience and initial tests, it may be assumed that it is possible to meet the structural and durability requirements for all layers of asphalt pavements when using of the local, prop-

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erly processed aggregates from these glacier formations for the production of the HMA mixtures.

The objective of this study was to evaluate an application of aggregate from the glacier formation for construction of high-traffic asphalt pavements (category KR6). According to the *Polish Regulations* "*W Sprawie Warunków Technicznych, Jakim Powinny Odpowiadać Drogi Publiczne i ich Usytuowanie*" of 1999 there are 6 road categories (from the lowest KR1 to the highest KR6). For the KR6 road category, there is 14.6×10^6 number of an equivalent standard axles (one standard axel is equal to 100 kN) during the 20 years pavement life with a max axle load of up to 115 kN.

3. Literature study

In this section, the origin of the aggregates from these glacier deposits and the requirements for the aggregates for use in HMA (according to the EN specification) will be briefly discussed, along with the local and world experience in the application of these types of aggregates for asphalt mixes.

3.1. Origin of aggregates from the glacier formation

About 1.87 mln years ago, in the Cenozoic era, between the tertiary and quaternary periods there were severe global climatic changes. Low air temperatures together with high snow precipitations caused glacier formations and started the Pleistocene epoch. Glaciations caused significant impact on land relief and geological structure of terrains in the mid latitudes of the northern hemisphere.

The extent of the quaternary glaciation in Europe is shown in Fig. 1. Due to the cyclic climate changes multiple glaciations carved various regions of Europe. It is generally accepted that glaciations occurred in Poland four times. Glacial deposits from the quaternary period are predominantly found in the northeastern region of Poland. These deposits can be further subdivided into five different types, depending on their geological composition and aggregate properties.

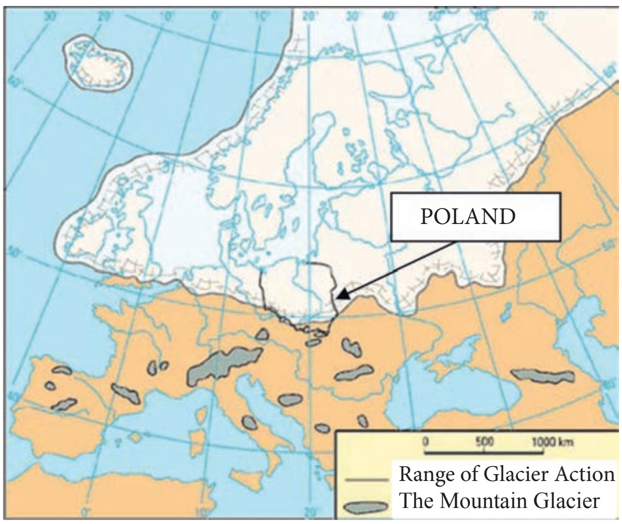

Fig. 1. Range of glacier action in Europe

Glacier deposits are composed mainly with the magmatic and metamorphic rocks and, to a lower extent, sedimentary rocks carried down from the Scandinavian regions to the north of Poland. Aggregates for the road industry are produced mainly by crushing rocks to particles of sizes 2–63 mm (Kamieński, Skalmowski 1957).

3.2. Properties of aggregates for the HMA mixtures according to the EN specifications

Required properties of aggregates for the HMA mixtures are covered by the European specification *EN 13043:2004* "*Aggregates for Bituminous Mixtures and Surface Treatments for Roads, Airfields and Other Trafficked Areas*". This specification is in use in Poland through the national so-called "application document" WT-1 (similar situation with European Specifications and application documents is in all countries of European Union).

Specification *EN 13043:2004* contains aggregate classification requirements only, not specific to any application (road category, asphalt layer, etc.). Requirements specific to an application are covered in each country by its national application document. According to this specification, aggregates are further categorized according to each of the following properties:
- geometrical;
- physical;
- chemical;
- durability.

Aggregate testing method depends on the road category, HMA type and asphalt layer. The higher the road category, the more the aggregate properties have to be studied and stricter the requirements to be satisfied.

Aggregates types currently used in Poland for high traffic asphalt mixtures are intrusive igneous rocks: basalt, gabbro, granite, andesite, paleobasalt and amphibolite. Typical bulk specific gravity for those aggregates are 2.6–3.1 and water absorption up to 0.8%. Polishability of those aggregates are in the range of 48–62 PSV and silica oxides (SiO_2) content 40–85%.

3.3. Local and selected world experiences with the using of aggregates from the glacier formation in HMA

The main problem faced by the Polish construction industry in using gravels and natural sands for road construction is a wide range of government regulations limiting the usage of those materials. Secondly, gravels and natural sands, in general, have been found as a material with lower quality properties (than e.g., basalt) for HMA production. These two factors have resulted in them being used for construction of asphalt pavements for light traffic only. Additionally, a poor understanding of the origin of these glacially deposited rocks may have led to the perception that these aggregate would not perform well under heavy traffic loads (Fisher, Smith 1993). Unlike the earlier Polish Standards, the current (new) European Standards (EN) adopted by Poland have clear-cut regulations regarding the types of aggregate that may be used in pavement construction. While the EN regulations do not prohibit the use of aggregate derived from glacial deposits, a lack of awareness of this fact among the practitioners is still a detriment to its usage.

With the new EN standards there is a possibility for using these aggregate and natural sands if they pass the specified requirements. New asphalt mixture requirements, according to European Standards, are based on functional classification (somewhat similar to the *US Performance Grade System for Asphalt Binders*). In addition, European Standards allows the use of so-called "empirical asphalt mixtures design" method which focuses on the final mixture properties rather than materials' properties itself. Example of gradation points for the binder course in asphalt concrete (AC) mixtures, with both empirical and functional mix design, are shown in Fig. 2.

It can be noticed that the gradation range at 2 mm sieve is 8 times wider for functional asphalt mixture design method than for the empirical method. This wide functional range is much more flexible during design process and allows for the use of a naturally-graded aggregate. At the upper limit the allowable amount of particles passing 2 mm sieve may be as high as 50%. This may result in fine mixes.

For the specialists of US, where aggregates from glacial formation (mainly igneous) are widely used, it can be rather complicated to understand why exactly those aggregates are questioned in Poland. Since the local experiences are always important (e.g. in selection of material types, technologies, etc.) authors per analogium remind the case of selection "restricted zone" in Superpave mixes. In the US, the concept of restricted zone was initially introduced as a part of Superpave mix design procedure to avoid the production of mixtures that were believed to cause premature failure under traffic loads. However, during 80th Annual Meeting of the *Transportation Research Board* (TRB) the aggregate industry looked with skepticism on the restricted zone because removing those particles complicates aggregate production and adds to production costs. Indeed, the restricted zone initially was established as part of Superpave's consensus guidelines, that is, by agreed-on expert opinion rather than research or experience (Kuennen 2001). El-Basyouny and Mamlouk (1999) voiced this opinion in 1999 during the 79th TRB. In 2001 during 80th TRB, at least two papers cast doubt on whether the restricted zone should be observed. It was stated that good performance of the mixture can be achieved with fine-graded bituminous mixtures, and there is no relationship between the Superpave restricted zone and HMA rutting or fatigue performance (Hand, Epps 2001). Studies showed that good HMA performance can be achieved with fine-graded mixtures with gradations plotting above, through and below the restricted zone. They also confirmed no relationship between the Superpave restricted zone and HMA rutting or fatigue performance. Other authors (Hand *et al.* 2001) have also shared their experience that the restricted zone alone is not necessary to characterize gradation to ensure acceptable rutting performance.

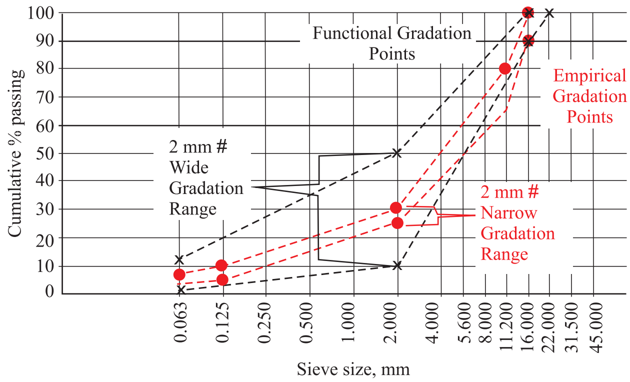

Fig. 2. Comparison gradation points for empirical and functional asphalt mixtures designing method for binder course dense mixture

Recent European and US experiences have shown that discussion and exchange of knowledge are very important during requirements modifications. That fact seems to be important especially in accordance with application in Poland of the new European standards and shortage of aggregate for the road construction.

It seems that in Europe there are two main groups of countries presenting different potential with regard to aggregates production of both crushed and natural aggregates. The countries of Central and Eastern Europe may increase their production, while the Western European countries will probably present stagnancy (Menegaki, Kaliampakos 2010). Poland has a relatively low production of aggregates due to the lower degree of economic development but it is still in the increasing stage. It can be expected that the glacial deposits in Poland should provide aggregates for a very long time; for example glacier deposits in North Ireland (much smaller than those in Poland) were calculated to have a lifespan conservation potential up to about 300 years (Knight *et al.* 1999). In addition, in the research conducted in Taiwan (Kuo *et al.* 2010.) it was demonstrated that crushed waste concrete can also be successfully used for the HMA production. As it was proved in the study by Airey *et al.* (2008), aggregate blend gradation has significant effect on the aggregate degradation under compaction. This phenomenon varies by the mixture type. Aggregates from the glacier formations are typically resistant to the impact damage and they can be used in the pavement surface layer, e.g. in the gap-graded mixtures.

4. Test program

The program of this study was divided into the following five steps:

1. binder type and aggregate sources selection;
2. HMA mixture design (based on the optimum air void content and water susceptibility);
3. HMA specimens preparation and testing (slabs laboratory compaction and testing for rutting resistance);
4. test results analysis;
5. cost analysis.

4.1. Materials

The HMA samples tested in this study were laboratory-produced SMA and AC mixtures. In this section the aggregates and binders used in this study are described.

Mineral aggregate

The biggest source of aggregates from the glacier formation in Poland is in north-eastern region of the country. In a region of about 40 000 km^2 there are well recognized 402 deposits with aggregates from which 159 serve as active quarries.

For this research, fine and coarse aggregate from the glacier deposits were selected. Aggregates from ten most typical deposits were further selected for an in-depth investigation. Based on this analysis, three aggregate sources were finally selected for the HMA production. Those three sources were similar in terms of their petrographic properties and offers a wide range of gradation allowing preparation of various mixes (SMA and AC). In addition, typical carbonate fillers were used.

According to the EN specification, aggregate may be classified as coarse if the particle size is between 2.0–4.5 mm and fine if between 0.063–2.0 mm. Fillers must have at least 70% of grains passing 0.063 mm sieve size. The required list of tests for fine and coarse aggregates, according to *EN-13043:2004* and the national application document (WT-1), is shown in Table 1.

Table 1. List of tests conducted for the aggregate from the glacier formation

No.	Coarse aggregate	Fine aggregate
1	Gradation	Gradation
2	Dust content	Dust content and quality
3	Flat and elongated particles content	Fine aggregate angularity
4	Coarse aggregate angularity	Specific gravity
5	Los Angeles abrasion value	Light and coarse impurities content
6	Specific gravity	
7	Bulk density	
8	Absorption	
9	Freezing-and-thawing resistance	
10	Petrographical description	
11	Light and coarse impurities content	
12	Chemical composition	

Based on the tests conducted it was confirmed that aggregates used in this study meet all the requirements for both coarse and fine aggregates for aggregate for HMA mixtures for all pavement layers. Selected test results and requirements are shown in Table 2. Requirements presen-

Table 2. Test results and requirements for the aggregate from the glacier formation used in the study

Properties	Aggregate			Requirements			
	2/5	5/11	11/22	AC for subbase coarse	AC for binder coarse	AC for wearing coarse	SMA for wearing coarse
General gradation category (d/D)	Gc85/15	Gc90/10	Gc90/10	Gc85/20	Gc85/20	Gc90/15	Gc90/15
Gradation tolerance category for coarse aggregate	$G_{20/15}$	$G_{20/15}$	$G_{20/15}$	$G_{20/15}$	$G_{20/15}$	$G_{25/15}$	$G_{25/15}$
Fines content	$f_{0.5}$	$f_{0.5}$	$f_{0.5}$	f_2	f_2	f_2	f_2
Shape of coarse aggregate – flakiness index	FI_{10}	FI_{10}	FI_{10}	FI_{30}	FI_{25}	FI_{20}	FI_{20}
Percentage of crushed and broken surfaces in coarse aggregates	$C_{90/1}$	$C_{90/1}$	$C_{90/1}$	$C_{90/1}$	$C_{90/1}$	$C_{95/1}$	$C_{100/0}$
Resistance to fragmentation of coarse aggregate – Los Angeles coefficient	LA_{30}	LA_{25}	LA_{25}	LA_{40}	LA_{30}	LA_{25}	LA_{20} LA_{23}
Density	2.71	2.70	2.72	NR	NR	NR	NR
Resistance to freezing and thawing	F_1	4/8 mm F_1 8/16 mm F_1	8/16 mm F_1 16/31.5 mm F_1	F_4	F_1	F_{NR}	F_{NR}
Resistance to freezing and thawing, 1% NaCl solution	$F_{NaCl}5$	4/8 mm $F_{NaCl}5$ 8/16 mm $F_{NaCl}8$	8/16 mm $F_{NaCl}8$ 16/31.5 mm $F_{NaCl}5$	F_{NR}	F_{NR}	$F_{NaCl}7$	$F_{NaCl}7$
Coarse lightweight contaminators	$m_{LPC}0.1$	$m_{LPC}0.1$	$m_{LPC}0.1$	$m_{LPC}0.1$	$m_{LPC}0.1$	$m_{LPC}0.1$	$m_{LPC}0.1$

ted here are according to the Polish standards (WT-2) for the heavy traffic road category (KR-5-KR6).

Asphalt binder and fiber

Two types of asphalt binders were used in this study: non-modified 35/50 binder (for AC HMA mixtures) and polymer modified binder, PmB 45/80-55 (for SMA HMA mixtures). These binders meet the requirements of European specifications *EN 12591:1999* "*Bitumen and Bituminous Binders – Specifications for Paving Grade Bitumens*" and *EN 14023:2005* "*Bitumen and Bituminous Binders. Framework Specification for Polymer Modified Bitumens*" for non-modified and polymer modified binders, respectively. Note, that non-modified asphalt binders in Europe are classified based on their penetration range (test at 25 °C). For example, for the binder 35/50 the min penetration grade is 35 and max penetration grade is 50. The polymer-modified asphalt binders are classified based on their penetration range and min ring-and-ball (R&B) test temperature. For example, for the PmB 45/80-55 the min penetration grade is 45 and max penetration grade is 80 while the min R&B temperature is 55 °C.

To minimize the draindown for the SMA mixture, cellulose fibers in the amount of 0.3% (weight of the total HMA mixture) were also added.

4.2. HMA mixture design

In Poland, three types of HMAs are typically used: AC for base and subbase layers and SMA as well as mastic asphalt (MA) for surface layers.

For further analysis, common asphalt pavement structure as it is constructed in Poland was chosen. This structure consists of the following layers: improved subbase (asphalt), base and surface. For this structure, following asphalt mixtures were selected:

– improved subbase (asphalt) layer: AC 16 P or AC 22 P (AC with a max aggregate size of 16 or 22 mm, respectively);
– base (or binder) layer: AC 16 W or AC 22 W (AC with a max aggregate size of 16 or 22 mm, respectively);
– surface layer: SMA 8 or SMA 11 (SMA with a max aggregate size of 8 or 11 mm, respectively).

For these mixtures, according to the Polish Requirement (WT-2), min binder content was selected (min binder content and gradation of all six mixes is shown in Table 3).

For the determination of air voids content and Indirect Tensile Strength Ratio (ITSR), three series of each mixture type were prepared (each of series with a different binder content): with a min binder content, with a min plus 0.3% binder content and with a min plus 0.6% binder content. For the rutting tests, only one mixture series for each mixture type was prepared and tested: the one with an optimum, based on the air void and ITSR tests, binder content.

Table 3. HMA mixtures gradation and asphalt content

	AC 16 P	AC 22 P	AC 16 W	AC 22 W	SMA 8	SMA 11
Min binder content, %	4.0	3.8	4.4	4.2	6.6	6.9
Sieve size, mm	Aggregate gradation, percent passing					
31.5	100	100	100	100	100	100
22.4	100	98.4	100	97.4	100	100
16	96.9	82.6	95.7	72.7	100	100
11.2	92.0	74.3	73.2	64.5	100	90.6
8	72.7	63.7	61.6	58.2	92.2	57.6
5.6	63.0	57.6	55.2	51.6	53.7	43.5
4	52.5	50.6	46.3	41.5	34.4	33.9
2	34.5	34.1	25.3	31.2	24.3	22.4
1	26.0	25.7	19.1	23.3	20.6	18.6
0.5	19.1	19.0	14.5	17.0	17.6	15.7
0.25	13.5	13.5	10.7	11.9	15.1	13.2
0.125	8.8	8.9	7.5	7.7	12.8	11.0
0.063	5.4	5.6	5.0	4.8	9.9	8.3

All HMA samples were laboratory prepared. Mixing temperature was selected based on the binder temperature corresponding to the viscosity of 0.2 Pa×s.

For the air voids content and ITSR tests, specimens were compacted using Marshall Hammer with 75 blows per side and 25 blows per side, respectively.

5. Test procedure

For the ITSR tests, European Specification *EN 12697-23:2003* "*Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 23: Determination of the Indirect Tensile Strength of Bituminous Specimens*" was followed. Tests were conducted using both dry specimens (reference value) and specimens which were vacuum-saturated with water, then conditioned in water for 72 h (water temperature was 40 °C) and then subjected for a one cycle of freezing and thawing (specimens was fully immersed in water during all the time). The ITSR value was calculated as a ratio of indirect tensile strength for the conditioned and referenced specimen.

Rutting tests were conducted following *EN 12697-22:2003+A1:2007* "*Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 22: Wheel Tracking*". Tests were conducted at 60 °C "in air" following procedure B (Fig. 3a). Square shaped specimens (305×305 mm) were compacted following *EN-12693-33:2003+A1:2007* "*Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 33: Specimen Prepared by Roller Compactor*" (Fig. 3b). Height of specimens depended on the pavement layer for which the mixture is designated and was equal to:

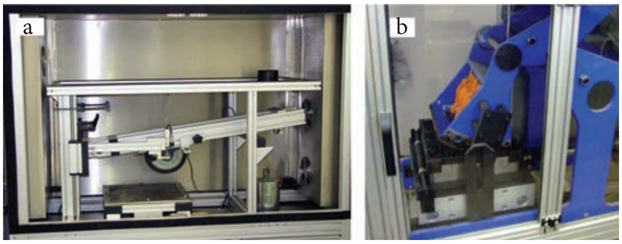

Fig. 3. Test setup for (a) rutting test and (b) slab compaction

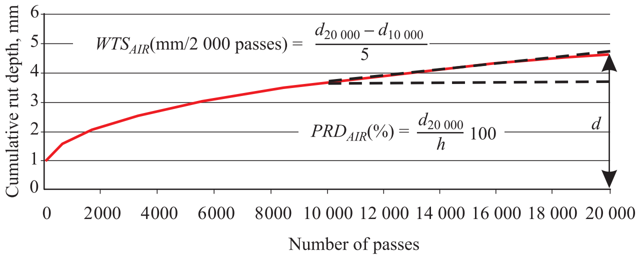

Fig. 4. Typical rutting test results

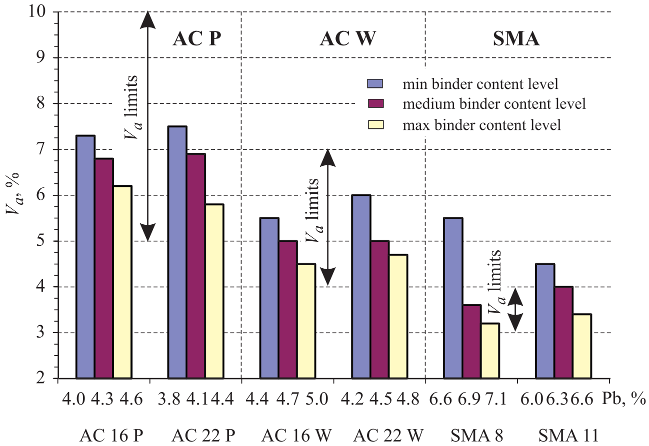

Fig. 5. Air voids determination for different mixes and binder contents

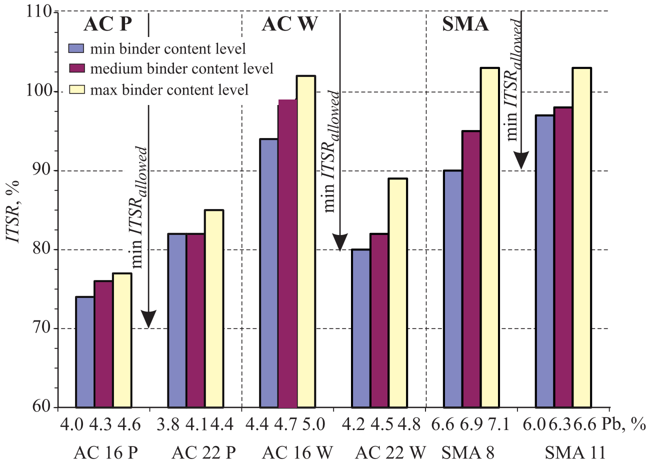

Fig. 6. Test comparison for indirect tensile strength ratio (ITSR)

– 50 mm for the surface layer (SMA mixtures);
– 70 mm for the base layer (AC W mixtures);
– 100 mm for the improved subbase surface layer (AC P mixtures).

For rutting a rubber-made wheel with a diameter of 200 mm is used. The load of the wheel is equal to 0.7 kN. During testing 20 000 wheel passes are conducted in about 6.5 h.

Using the LVDT, rutting depth is continuously monitored (in 25 positions of the specimen) while testing. Based on those measurements the so-called "proportional rutting depth" (PRD_{AIR}) and "wheel tracking slope" (WTS_{AIR}) are calculated. PRD_{AIR} is expressed in percent as the final obtained rutting depth (d) to the initial specimen thickness (h) while WTS_{AIR} is expressed as the slope of the rutting depth in mm/2000 passes (calculated after first 10 000 passes). Typical test result is shown in Fig. 4.

6. Test results

Results of determination of the air voids content for six different mixes with three different binder content levels are shown in Fig. 5. It can be seen that for AC and SMA mixes with aggregates from the glacial formation it is indeed possible to reach the required air void content. Although it is labor intensive and time consuming, it is also possible to meet the requirements for SMA mixes where the required air void (V_a) content range is narrow. For these mixes the aggregate blend limits are very narrow, hence multiple numbers of iterations are required to attain the desired mix design.

Results of tests for the HMA resistance to the water influence are shown in Fig. 6. Test results indicate that it is possible to meet the ITSR requirements using HMA with an aggregate blend composed with a glacially deposited aggregate. In addition, it can be noticed that the ITSR value depends on the mixture type, gradation and binder content.

Based on the V_a and ITSR values, an optimal binder content was selected for each mixture type (4.3% for AC 16 P mixture; 4.1% for AC 22 P mixture; 4.7% for AC 16 W mixture; 4.5% for AC 22 W mixture; 6.9% for SMA 8 mixture and 6.6% for SMA 11 mixture). Specimens with this optimal binder content were then prepared and tested for rutting. Rutting test results, shown in

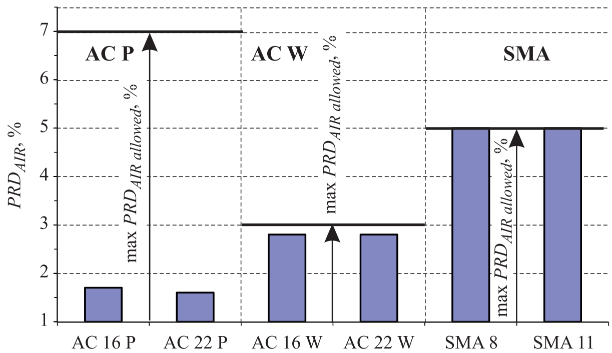

Fig. 7. Comparison of proportional rutting depth values

Fig. 7, indicate that the requirements for the proportional rutting depth (PRD_{AIR}) max value were met for all six tested mixture types. However, it can be noticed that for the SMA mixtures, although the requirements were satisfied, the test results were close to the limits. For the AC mixtures designed for the improved subbase layers the obtained PRD_{AIR} values were far below the limits.

7. Cost analysis

In order to further assess the use of aggregate from glacier deposits in high-traffic asphalt pavements, an economical analysis was also conducted. In the first stage of the cost analysis HMA production costs were assessed while in the second stage the cost of construction of 10 km road section were assessed.

For the second stage of the cost analysis, information from the first stage (HMA cost) was used. In addition to the mixture price HMA transportation and construction costs were also considered. The analyzed road section was an expressway for the heavy traffic (highest road category). The following assumptions were made in calculating the construction costs for a 10 km length of high-traffic (KR5-KR6) road: four lanes (two lanes in each direction) with lane width of 3.5 m and paved shoulder 2.0 m wide. Typical pavement structure for such an application is as follows:

– 5 cm thick surface layer of SMA: SMA 11 S;
– 8 cm thick base layer of AC: AC 16 W;
– 20 cm thick improved subbase layer of AC: AC 22 P.

For the cost analysis three construction locations were considered: one in central part of Poland (Warsaw) and two in the northeast: Bialystok and Augustów (Fig. 8 for the geographical locations of those sites). Various locations were chosen in order to study influence of the distance from the quarry to the HMA final price. Aggregate hauling costs were calculated based on the most distant aggregate quarry – HMA plant (Fig. 8 for distance and hauling price).

The highest cost was obtained for the hauling of melaphyre aggregate from Czarny Bor quarry to Augustów ($27/1000 kg with distance of 672 km) while the lowest hauling cost was for the transportation of the aggregate from the glacier deposits from the quarry located 30 km from the HMA plant in Augustów. Hauling cost in this case was equal to $3/1000 kg. Based on this comparison, it can be seen that the difference in hauling costs can be up to about 9 times. It should also be noted here that the current practice in Poland is the hauling of the aggregate across the whole country instead of using the locally available material.

Fig. 8. Comparison of hauling price and distance for aggregates from south of Poland

Comparison of the HMA (AC and SMA mixtures) production cost is shown in Table 4. It can be seen that, depending on the location, using locally available materials from the glacier deposits can reduce the mixture price by up to 30%.

The calculated cost of construction of 10 km of expressway varies by the location:

– Bialystok, aggregates from the glacier formation used: $12.648 mln, aggregates from south of Poland: $14.865 mln;
– Augustów, aggregates from the glacier formation used: $12.002 mln, aggregates from south of Poland: $15.196 mln.

The economical benefits of using aggregates from the glacier formation for construction of the asphalt pavements are clearly visible. Saving costs on materials allows constructing more of the road section using the money saved.

Table 4. Comparison of the HMA mixture cost for various locations and aggregate types

Aggregate origin		Aggregates from south of Poland			Aggregates from glacier formation	
Construction site location		Warsaw	Białystok	Augustów	Białystok	Augustów
HMA type	SMA 11	75	81	83	67	63
	AC 16 W	62	68	70	55	52
	AC 22 P	61	67	69	54	50

Price in US dollars for 1000 kg of HMA delivered to the construction site.

8. Conclusions

Based on the conducted tests and analysis (evaluation of the technical properties, aggregate market resources and HMA cost analysis) the following conclusions can be drawn:

1. Poland has a relatively large quantity of high quality aggregate from the Cenozoic (tertiary and quaternary) glaciations period.

2. Crushed aggregates from the glacier formations can produce mixes that meet the requirements for high-traffic roads.

3. Due to the high material transportation costs and increasing demand for the quality of pavement aggregate in Poland it is necessary to broaden the aggregate sources by using aggregates from the glacier formation for the construction of road sections in the central and north-east regions of Poland. This will significantly decrease construction costs and provide the much-needed raw materials.

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